FUSE HOLDER DAMAGE INVESTIGATION

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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ABSTRACT

The explosion of fuse holders at a certain 161 kV: 34.5 kV Ameren UE substation in the Potosi area was investigated. The Alternative Transients Program -Electromagnetic Transients Program (ATP-EMTP) was used to model and simulate the electrical behavior of transient overcurrents and overvoltages created by switching events in an effort to identify the cause of damage to a certain fuse holder used to protect the 4.5 MVAR capacitor bank on the 34.5 kV side of the transformer. Simulation results indicated that switching can increase the peak of the transient overcurrent from the normal current operation by up to 9.33 p.u. Thus, the switching phenomenon may play a role in fuse holder damage.

LIST OF TABLES

LIST OF ILLUSTRATIONS

TABLE OF CONTENTS

1. Introduction

The purpose of a power system is to transmit and distribute the electrical energy produced by the generators to the consumers. Since electrical energy cannot be stored in large quantities, the operation of a power system has to be reliable. Power system transients are initiated when there is a sudden change in the network from one state to another. For instance, the opening and closing of switches is the most common cause of power system transients. The time interval when overvoltage transients or overcurrent transients take place is in the range of microseconds or milliseconds. During this time interval, the devices in the power system are subject to high stresses which can cause significant damage [1].

The purpose of this study was to investigate the cause of damage to a fuse holder on the 34.5 kV side of a 161 kV: 34.5 kV substation transformer in the Ameren Distribution System. The fuse holder, which is used to protect a capacitor bank, exploded when the adjacent circuit breaker was closed in order to connect the associated part of the power grid to the system. To investigate this hazardous problem, the Alternative Transients Program -Electromagnetic Transients Program (ATP-EMTP) was used to simulate the situation. ATP has comprehensive modeling capabilities, including a superior graphical interface called ATPDRAW that permits easy modeling of the system. Due to the capacitor bank switching behavior, the damage to the fuse holder could be caused by high frequency oscillations of the voltage and/or current. The following sections describe the investigation into the problem.

1.1 Problem description

Figure 1.1 shows the single line diagram of the relevant portion of the Ameren UE distribution system in the St Louis area. The diagram was provided by Jim Verhaar of the Ameren Distribution System Planning Division.

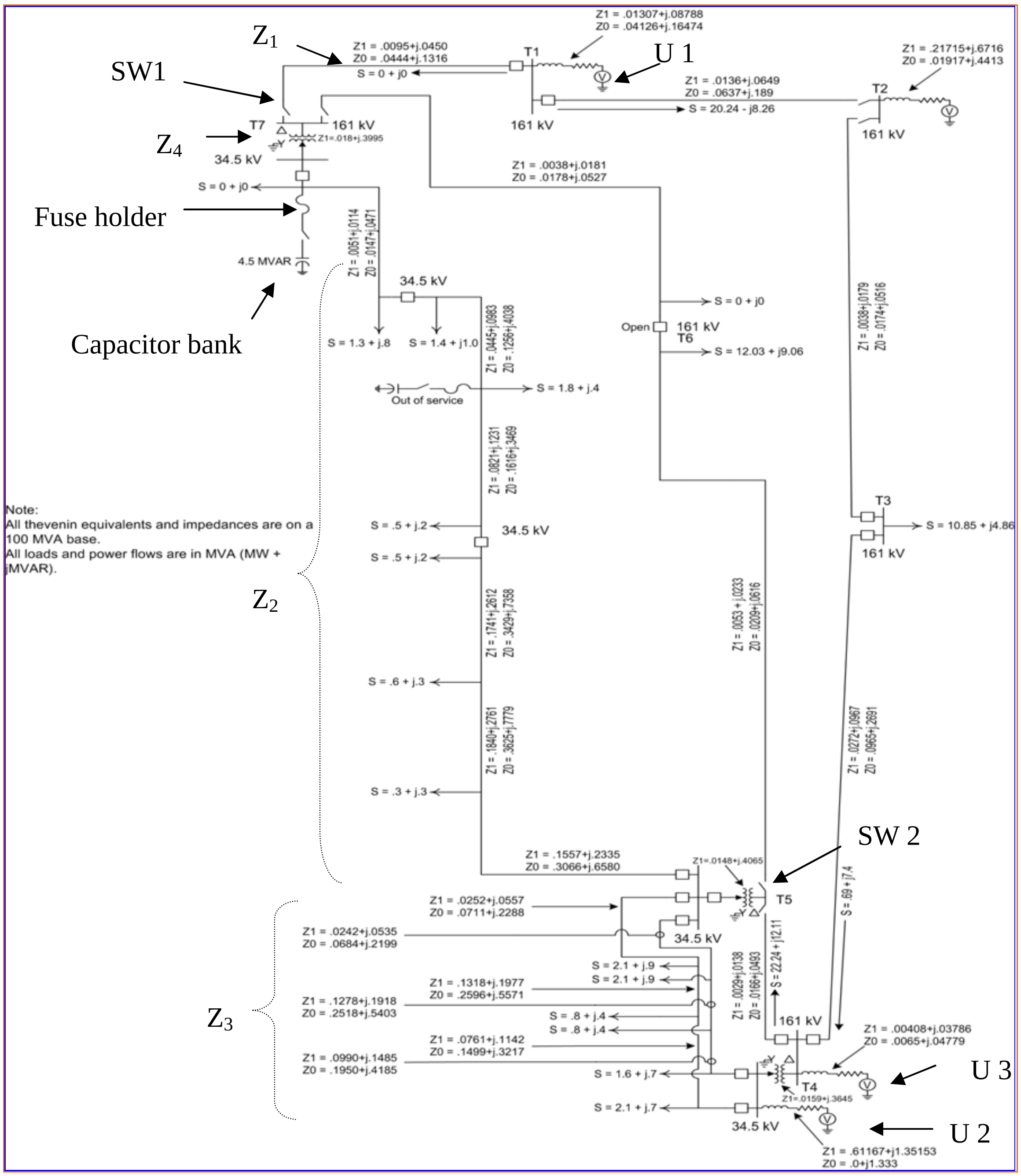


Figure 1.1 The single line diagram of a portion of the Ameren distribution system.

Figure 1.2 shows a single line model of the system shown in Figure 1.1. Breakers SW1 and SW2 connect the 4.5 MVAR capacitor bank and local loads Z_1, Z_2 , Z_3, and Z_4 to the rest of the system, represented by U 1, U 2 and U 3. Loads $Z_{1,}$ $Z_{2,}$ and Z_3 represent the appropriate combinations of line and load impedances. Load Z_4 represents the appropriate Viburnum transformer parameters. The aforementioned critical situation can be described in the following sequential steps:

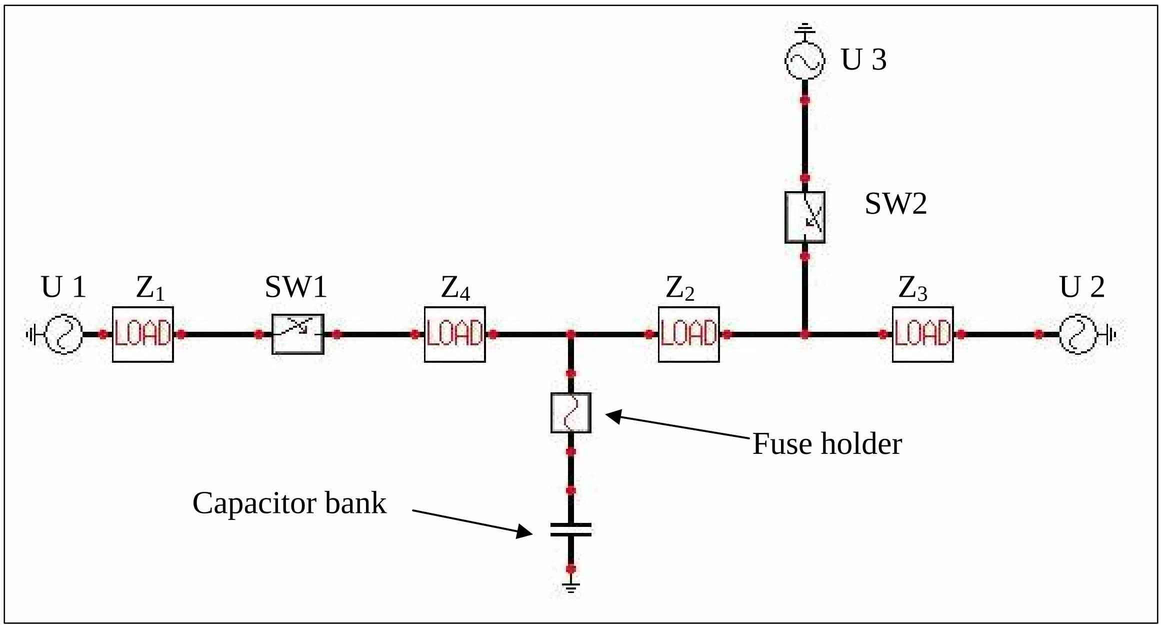


Figure 1.2 The system being considered.

Step 1 (normal condition)

System operation with switches SW1 and SW2 closed.

Step 2 (normal condition)

Switch SW1 is opened while utility U 2 is still operating in normal procedure with switch SW2 remaining closed.

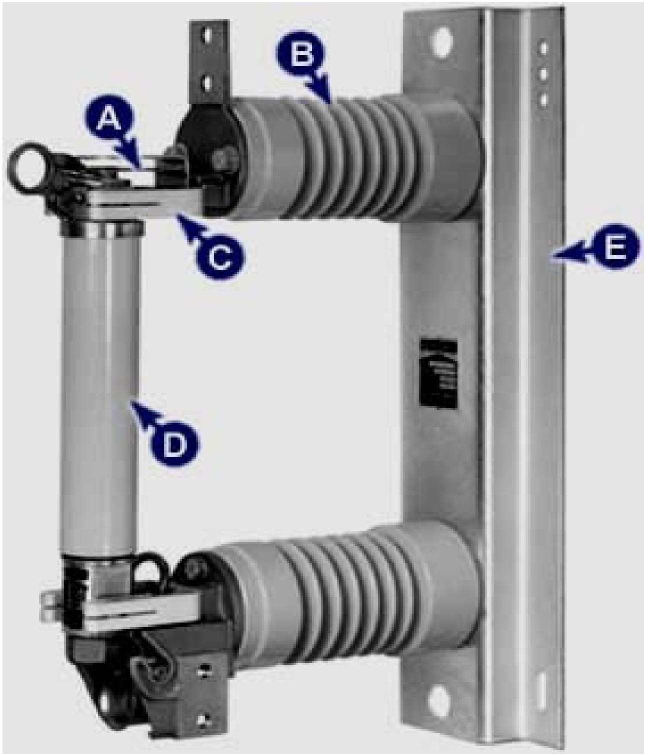
Step 3 (critical condition)

Switch SW1 is re-closed,* and switch SW2 remains closed. The fuse holder, which is connected to the capacitor bank, is blown out.

* The time interval from when switch SW1 is open when it is re-closed is not instantaneous.

1.2 Background information on power fuses

The most commonly used protective device in distribution systems is the fuse. In general, a fuse is a device capable of preventing damage to a power system's equipment when various types of system faults occur. System faults cause damage to equipment or conductors because of overheating due to overcurrent, overvoltage or short circuits. An overcurrent or an overvoltage may melt a conductor, resulting in arcing and the possibility of fire. A short circuit may also cause an explosion. The power fuse is a specialized device for protecting high voltage equipment in the distribution system. Providing an interruption of a permanent fault is the main purpose of the power fuse. It is an economical alternative to the circuit breaker. Generally, power fuses are widely used in the 11 kV through 35 kV portion of the distribution system [2]. A typical power fuse is shown in Fig 1.3.



A.**Stainless-steel latch** provides positive, secure engagement of holder

B.**Choice of porcelain or Cypoxy station post insulators**

C.**Silver-clad copper upper (and lower contact) assemblies** with stainless-steel loading springs — ensure minimum electrical resistance

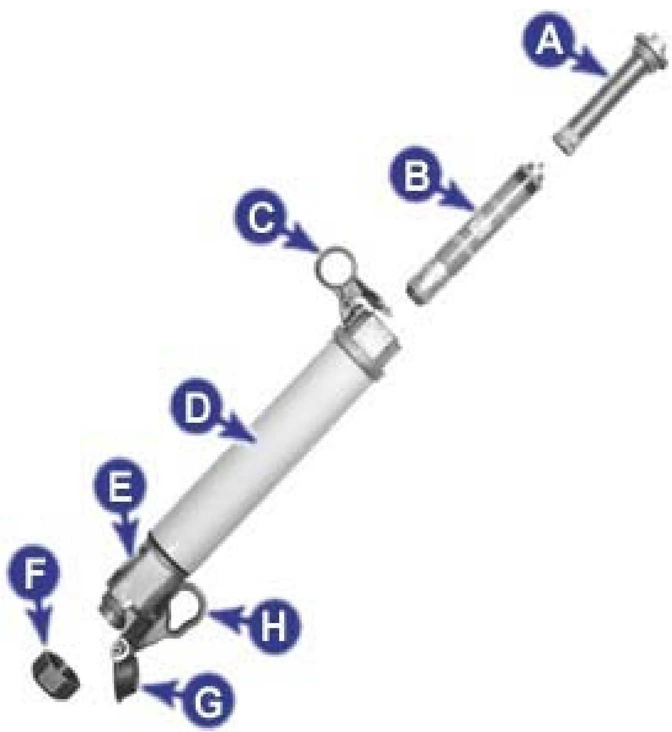
D.**Fuse Holder**

E.Rugged galvanized steel base

Figure 1.3 The surface mount (SM) power fuse [3].

Examining Fig 1.3, the fuse holder (D) is hinged at the bottom and has a spring loaded contact at the top of the upper end. When a fault-clearing operation occurs, the top contact releases and permits the fuse holder to swing and rotate down around its lower, hinged assembly both to give a visual sign of operation and to provide an isolation gap between the two contacts. As a result, the open fuse holder now provides a visible indication that it has been blown out. The fuse holder can be removed from the mount, the surface mount (SM) refill unit replaced, and the fuse holder reinserted in the fuse mount.

Figure 1.4 shows the construction inside the fuse holder. Mounted inside the fuse holder is the SM refill unit shown in Figure 1.5 . Finally, the fuse link, or fusible element, is unted inside the SM refill unit. The fusible elements are usually made of either a nickel-chrome composition for standard melting rates, or helically coiled silver for slower melting rates. The main advantage of a SM refill unit is that it is simple and is therefore a relatively inexpensive device [4, 5].



A. **Spring-and-cable assembly** — stainless-steel spring provides high-speed elongation of arc within refill unit when fuse operates

B. SM Refill Unit — replaced after fault-clearing operation

C. Bronze pull-ring pivots to pry up latch

D. Porcelain-jacketed glass-epoxy sleeve

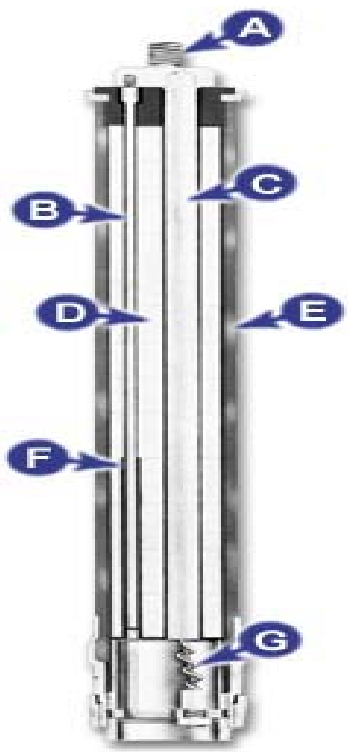
E. Silver-surfaced upper and lower ferrules

F. **Clamping nut** — locks refill unit in place

G. **Gravity-operated rain shield**

H. **Lifting eye**

Figure 1.4 The fuse holder [3]



A. **Upper terminal** — attaches to spring-and-cable assembly

B. Stainless-steel auxiliary arcing rod

C. **Silver-clad copper main arcing rod**

D. **Solid material arc-extinguishing medium**

E. **Filament-wound glass-epoxy tube**

F. **Large-diameter stepped portion of auxiliary bore** — delays arc extinction until sufficient gap is attained to preclude reignition

G. **Fusible element** — helically-coiled silver or pretensioned nickel-chrome — provide precise melting characteristics and nondamageable perfomance

Figure 1.5 the SM refill unit [3].

Table 1.1 The rating of SM power fuse

Fuse Type	kV			Amperes, RMS, Symmetrical		
	Nominal	Maximum	BIL	Maximum	Interrupting	
					60 Hz	50 Hz
SM-20	13.8	17	95	200E or 200K	14 000	11,200
	25	27	125	200E or 200K	12, 00	10,000
	34.5	38	150	200E or 200K	8 ,450	6,760
SM-40	4.8	5.5	60	400E	25,000	20,000
	13.8	17	95	400E	25,000	20,000
	25	29	150	400E	20,000	16,000
SM-4Z	4.8	5.5	60	200E	17,200	13 760
	13.8	17	95	200E	12,500	10,000
	25	27	150	200E	9,400	7,520
	34.5	38	200	200E	6,250	5,000
SM-5S	4.8	5.5	60	400E or 720E	27,000	27,000
	13.8	17	95	400E or 720E	25,000	25,000
	25	27	150	300E	20,000	20,000
	34.5	38	200	300E	17,500	17,500
SM-5SS	13.8	15.5	95	400E	34,000	25,000

1.2.1 The fault-clearing operation

In the event of a fault , when an overcurrent flows through the fuse for a certain amount of time, high pressure gases are developed within the bore of the fusible element. These expel the end of the fusible element, and at the same time, assist in arc extinction. The voltage across each arc contributes to the total voltage across the fuse, and this total voltage results in the current falling to zero. Since the number of arcs is limited, the voltage across the fuse link is not high enough to damage the equipment being protected. The characteristic development of current during the operation of the fuse is shown in Figure 1.6.

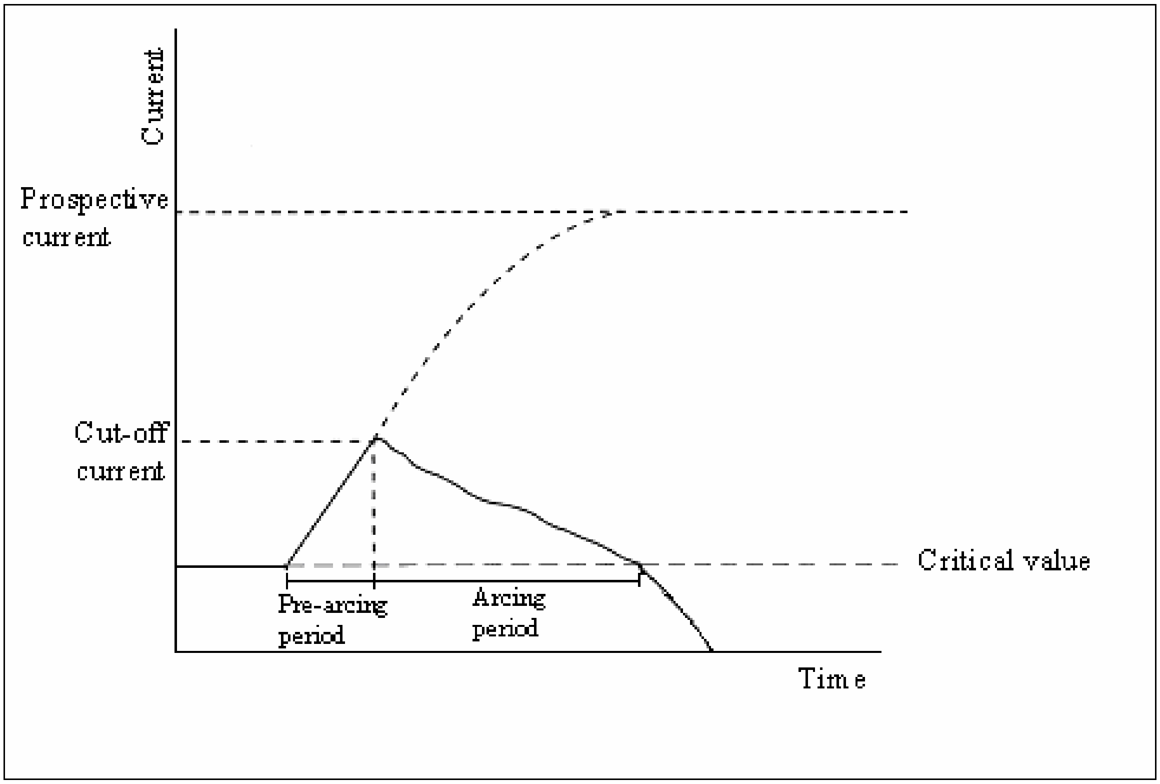


Figure 1.6 The current during the fault–clearing operation [1]

The pre-arcing period is the time interval from the instant when the current exceeds the critical value, until the initial vaporization within the gap and melting of the element occurs. A small capacitance will be presented across the gap because of the small cross-sectional area of the fuse link element [1]. It will charge swiftly because the current continues to flow, which will be maintained by the circuit inductance. The resulting voltage will cause the gap to break down and establish the initial arc. Furthermore, the greater the current that passes through the fusible element, the shorter the time period before melting of the element occurs. This is because the power available to cause the temperature to rise is equal to the difference between the input power and the power dissipated by the fuse link, which is controlled by the temperature of the fusible element, which cannot exceed the melting point of the material. The arcing period is the time interval thereafter needed for the two contacts to become completely isolated and for the current to reach zero [6, 7].

1.2.2 Time-current characteristics

The time-current characteristic is a graph of the response time of the fuse element as a function of the current. It consists of the minimum melt curve and the total clearing curve, and is usually plotted on a log-log scale. A typical time-current characteristic is shown in Figure 1.7. These characteristics vary from one manufacturer to another. The minimum melt curve (MMC) shows the interval of time between initiation of an overcurrent sufficient enough to cause the fuse link to begin to melt, and the instant when arcing starts. The total clearing curve (TCC) shows the interval of time between the beginning of the overcurrent and the moment of final current interruption, when the fuse link is completely cleared of the given current (TCC = minimum melt + pre-arcing period + arcing period) [8].

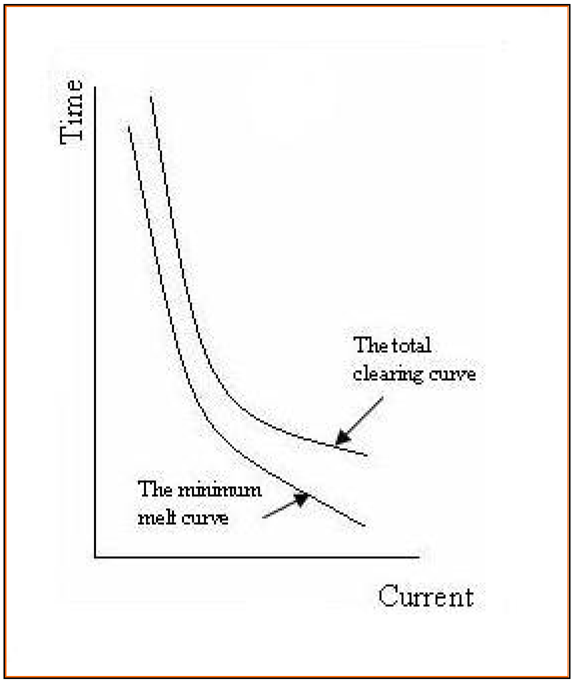


Figure 1.7 Typical time-current characteristics.

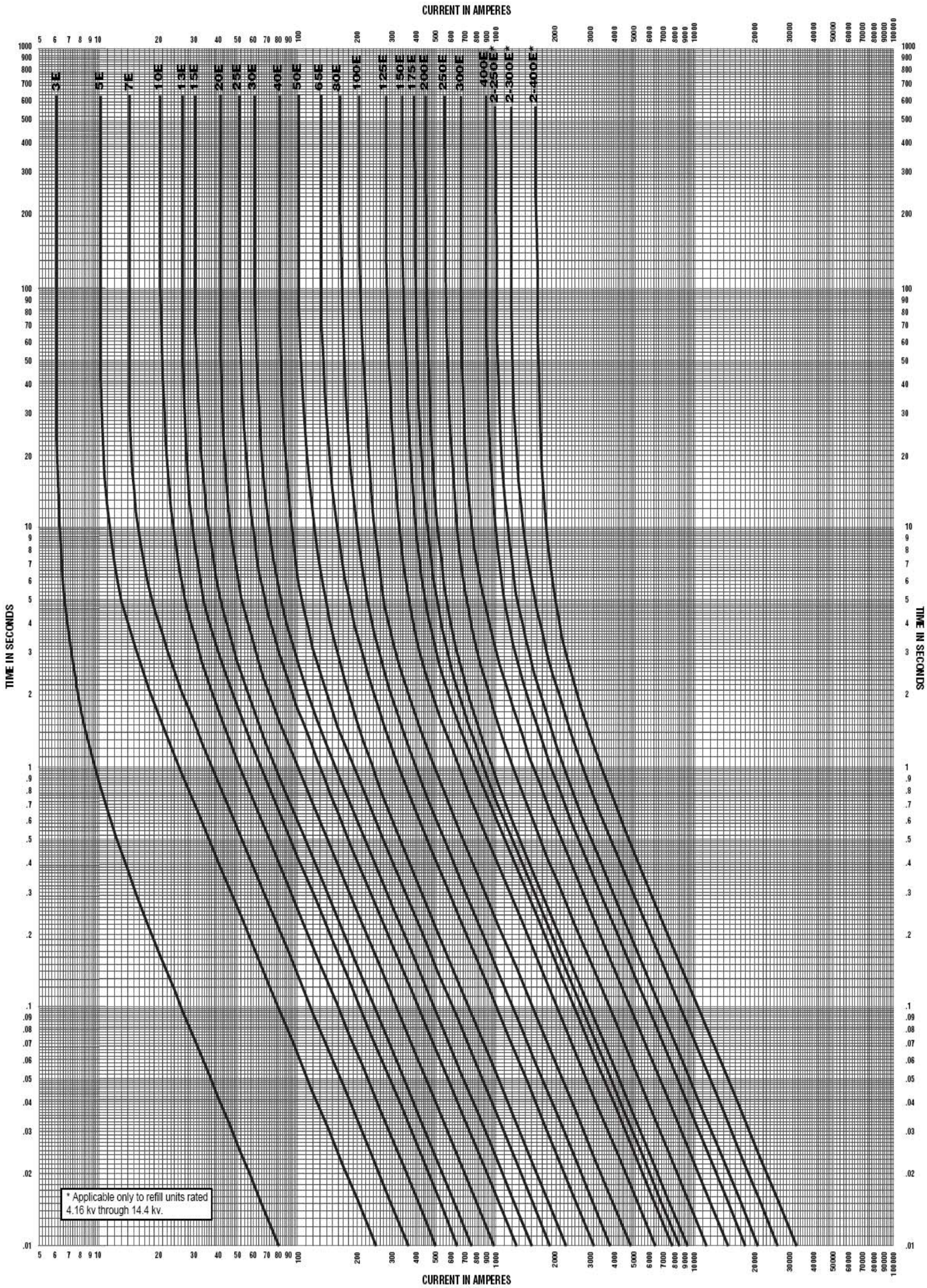


Figure 1.8 Minimum melt times–current characteristic curves.[3]

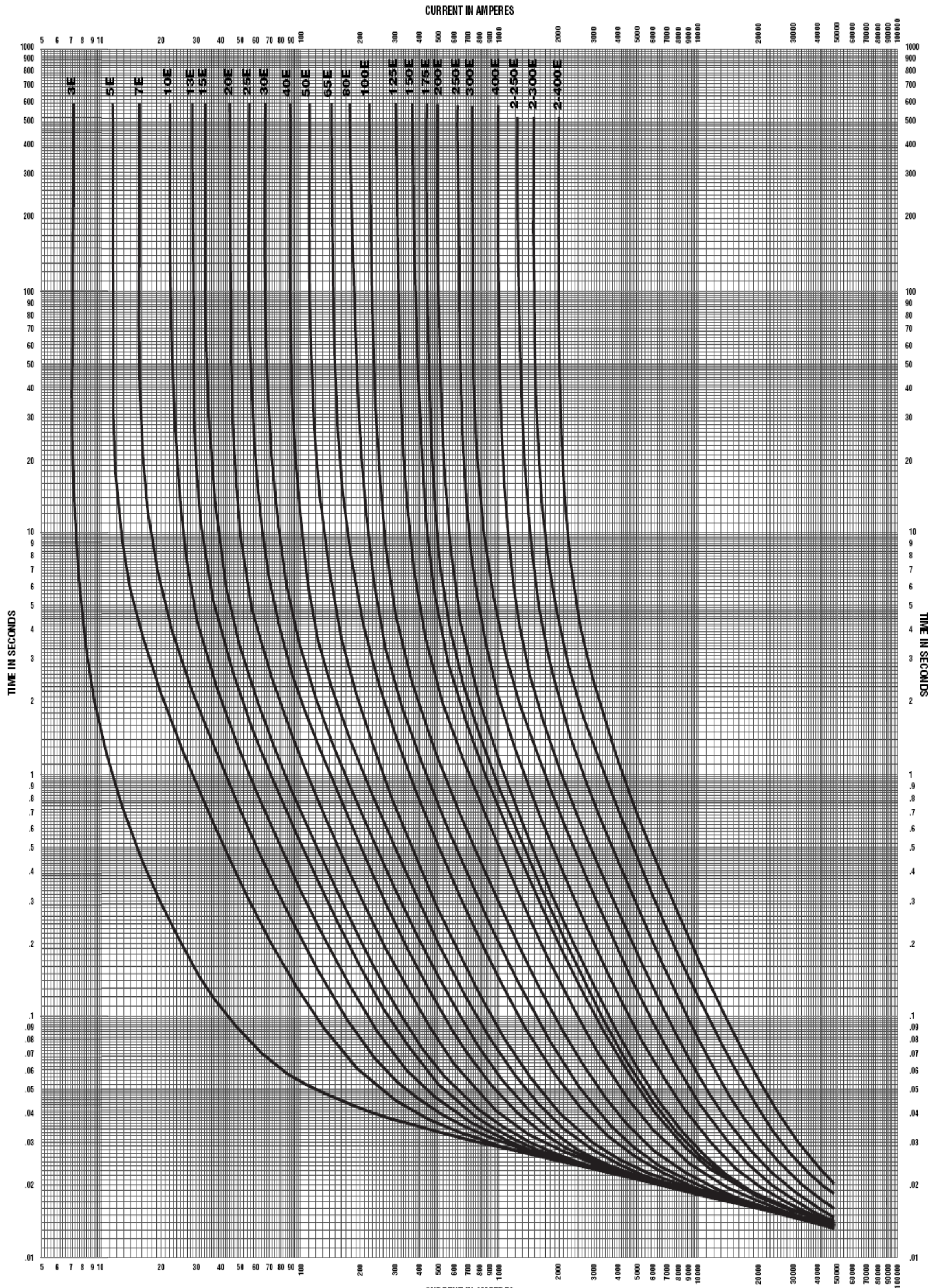


Figure 1.9 Total clearing times–current characteristic curves.[3]

2 Analysis of Capacitor Bank Switching Behavior

The purpose of this chapter is to analyze the switching transient behavior of the capacitor bank. The energizing and de-energizing of the switch can produce significant switching transients, which result in transient overvoltages and transient overcurrents on the electrical system. Those transient overvoltages and overcurrents occur due to the electrical system adjusting itself to a different configuration of components.

In general, transmission lines or conductors are used to carry power from the power plant to the customers. Transient overvoltage can occur when a switch is closed at the peak of a voltage waveform. Generally, the overvoltage can be twice the peak value of the system voltage, due to the reflection characteristics of the transmission line.

To understand the switching transient, the system shown in Figure 1.2 is modeled simply as an AC source, an inductive element and a capacitive element, as shown in Figure 2.1. For simplicity, the transmission line has been represented by inductance only, assuming the resistance of the line to be negligible. Admittedly, in some practical circuits, there would be some resistance in the circuit. It would gradually dampen the oscillation so that the current and the voltage recede to smaller steady state amplitudes. The AC source is represented by $v(t) = E\cos(\omega t)$ and it is assumed to have negligible impedance. Switch SW 1 is assumed to be ideal. When the switch is closed, it is represented by an ideal conductor. The capacitor bank is represented by an ideal capacitor [9, 10].

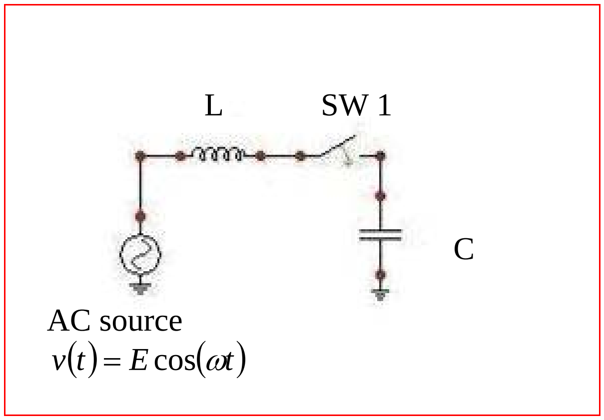


Figure 2.1 The simple model.

If switch SW 1 is closed at t = t_0 , Kirchoff's laws can be used to write the following equations:

$$v(t) = v_L(t) + v_C(t) \tag{2.1}$$

$$v_L(t) + v_C(t) = E\cos(\omega t) \tag{2.2}$$

$$L\frac{d}{dt}\left(i_L(t)\right) + v_C(t) = E\cos(\omega t) \tag{2.3}$$

$$i_L(t) = i_C(t) = C\frac{d}{dt}\left(v_C(t)\right) \tag{2.4}$$

This circuit has two elements for stored energy. Magnetic energy is stored in the inductor, and electrical energy is stored in the capacitor. The current cannot change instantaneously due to the circuit inductance, and the capacitor voltage cannot change instantaneously due to the circuit capacitance. When the switch is closed, energy will oscillate back and forth between the inductor and the capacitor at the resonant frequency. Substituting Equation 2.4 into 2.3 and divided by LC gives

$$\frac{d^2}{dt}\left(v_C(t)\right) + \frac{1}{LC} v_C(t) = \frac{E}{LC}\cos(\omega t) \tag{2.5}$$

Taking the Laplace Transform on both sides of equation (2.5) gives

$$[S^2 V_C(s) - SV_C(0) - \dot{V}_C(0)] + \frac{V_C(s)}{LC} = \frac{E}{LC}\left[\frac{S}{S^2+\omega^2}\right] \tag{2.6}$$

In equation 2.6, $V_C(0)$ represents the initial voltage of the capacitor due to the charges that are trapped in the capacitor bank. Assuming that $\dot{V}_C(0) = 0$, Equation 2.6 becomes

$$S^2 V_C(s) + \frac{V_C(s)}{LC} = \frac{E}{LC}\left[\frac{S}{S^2+\omega^2}\right] + SV_C(0)$$

$$V_C(s)\left[S^2 + \frac{1}{LC}\right] = + \frac{E}{LC}\left[\frac{S}{S^2+\omega^2}\right] + SV_C(0)$$

$$V_C(s) = \frac{E}{LC}\left[\frac{S}{\left(S^2+\omega^2\right)\left(S^2+\frac{1}{LC}\right)}\right] + V_C(0)\left[\frac{S}{S^2+\frac{1}{LC}}\right]$$

$$= \frac{E}{LC}\left(\frac{1}{\frac{1}{LC}-\omega^2}\right)\left[\frac{S}{S^2+\omega^2} - \frac{S}{S^2+\frac{1}{LC}}\right] + V_C(0)\left[\frac{S}{S^2+\frac{1}{LC}}\right]$$

$$= \frac{E}{LC}\left(\frac{1}{\frac{1}{LC}-\omega^2}\right)\left[\frac{S}{S^2+\omega^2}\right] - \frac{E}{LC}\left(\frac{1}{\frac{1}{LC}-\omega^2}\right)\left[\frac{S}{S^2+\frac{1}{LC}}\right] + V_C(0)\left[\frac{S}{S^2+\frac{1}{LC}}\right]$$

$$= \frac{E}{LC}\left(\frac{1}{\frac{1}{LC}-\omega^2}\right)\left[\frac{S}{S^2+\omega^2}\right]-\left(\left(\frac{E}{LC}\right)\frac{1}{\frac{1}{LC}-\omega^2}-V_C(0)\right)\left[\frac{S}{S^2+\frac{1}{LC}}\right]$$

$$V_C(s) = \left(\frac{E}{1-\omega^2 LC}\right)\left[\frac{S}{S^2+\omega^2}\right]-\left(\frac{E}{1-\omega^2 LC}-V_C(0)\right)\left[\frac{S}{S^2+\frac{1}{LC}}\right] \tag{2.7}$$

Taking the Inverse Laplace Transform both sides of equation (2.7) gives

$$v_C(t) = \left(\frac{E}{1-\omega^2 LC}\right)\cos(\omega t)-\left(\frac{E}{1-\omega^2 LC}-V_C(0)\right)\cos\left(\frac{t}{\sqrt{LC}}\right)$$

$$=\left(\frac{E}{1-\left(\frac{\omega}{\omega_0}\right)^2}\right)\cos(\omega t)-\left(\frac{E}{1-\left(\frac{\omega}{\omega_0}\right)^2}-V_C(0)\right)\cos(\omega_0 t)\,;\omega_0 = \frac{1}{\sqrt{LC}} \tag{2.8}$$

From equation 2.8, the complete solution for $i_C(t)$ can be written

$$i_C(t) = C\frac{d}{dt}(V_C(t))$$

$$= \left(\frac{-E\omega C}{1-\omega^2 LC}\right)\sin(\omega t)+\left(\frac{E}{1-\omega^2 LC}-V_C(0)\right)\frac{C}{\sqrt{LC}}\sin\left(\frac{t}{\sqrt{LC}}\right)$$

$$=\left(\frac{-E\omega C}{1-\left(\frac{\omega}{\omega_0}\right)^2}\right)\sin(\omega t)+\left(\frac{E}{1-\left(\frac{\omega}{\omega_0}\right)^2}-V_C(0)\right)(\omega_0 C)\sin(\omega_0 t)\,;\omega_0 = \frac{1}{\sqrt{LC}} \tag{2.9}$$

Equation 2.9 shows that the capacitor current waveform consists of by two sinusoidal terms, proportional to $\sin(\omega t)$ and $\sin(\omega_O t)$, respectively, added together.

MATLAB was used to evaluate the transient switching behavior as represented in equation 2.9 with E = 10 V, L = 6 mH, C = 1 mF, f = 60 Hz, and f_o = 65 Hz. Figure 2.3 shows the resulting capacitor current. As can be seen, it has two dominant frequencies. The higher frequency (65 Hz) is the resonant frequency $f_o = \frac{1}{2\pi\sqrt{LC}}$, and the lower frequency (5 Hz) is the difference between the 60 Hz line frequency and f_o. Another important observation is that the resulting capacitor current is a modulated sinusoid. In reality, the resistance of the line can not be negligible, so the resulting capacitor current will be damped and eventually continue as a normal sinusoid. From equation 2.9, the magnitudes of the transient overcurrents are defined by the coefficient of the $\sin(\omega t)$ term and the $\sin(\omega_O t)$ term.

The results of this section show that after the switching operation takes place, the transient overcurrent will contain with two main frequencies, which are the resonant frequency f_o and the difference frequency between f_o and the line frequency.

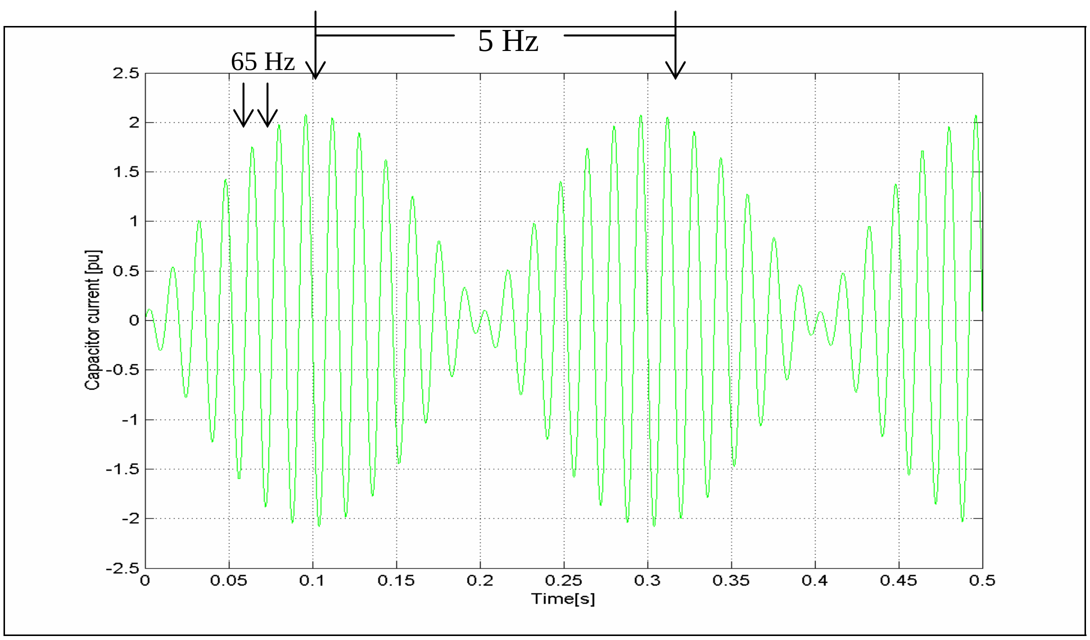


Figure 2.3 Waveforms of capacitor current during 0 -0.5

3 Modeling the Ameren UE Distribution System

This chapter presents the ATP-EMTP modeling and simulation study to investigate the damage to the fuse holder on the 34.5 kV side of the 161 kV: 34.5 kV substation transformer.

3.1 Distribution system description

The single line diagram of the appropriate portion of the Ameren UE distribution system is shown in Figure 3.1. The diagram consists of two main power grids: the high voltage power grid (L_1, L_2) and the intermediate voltage power grid (L_3). The 161 kV high voltage power grid is powered by generators G_1, G_2, and G_3. The 161 kV high voltage power grid is connected to the 34.5 kV intermediate voltage grid by the transformers at Viburnum, Brushy Creek and Fletcher. Customers groups C_A, and C_B are connected to the 34.5 kV side and to generating station G_4. The 4.5 MVAR capacitor bank is connected at the 34.5 kV side of the Viburnum transformer to achieve power factor improvement.

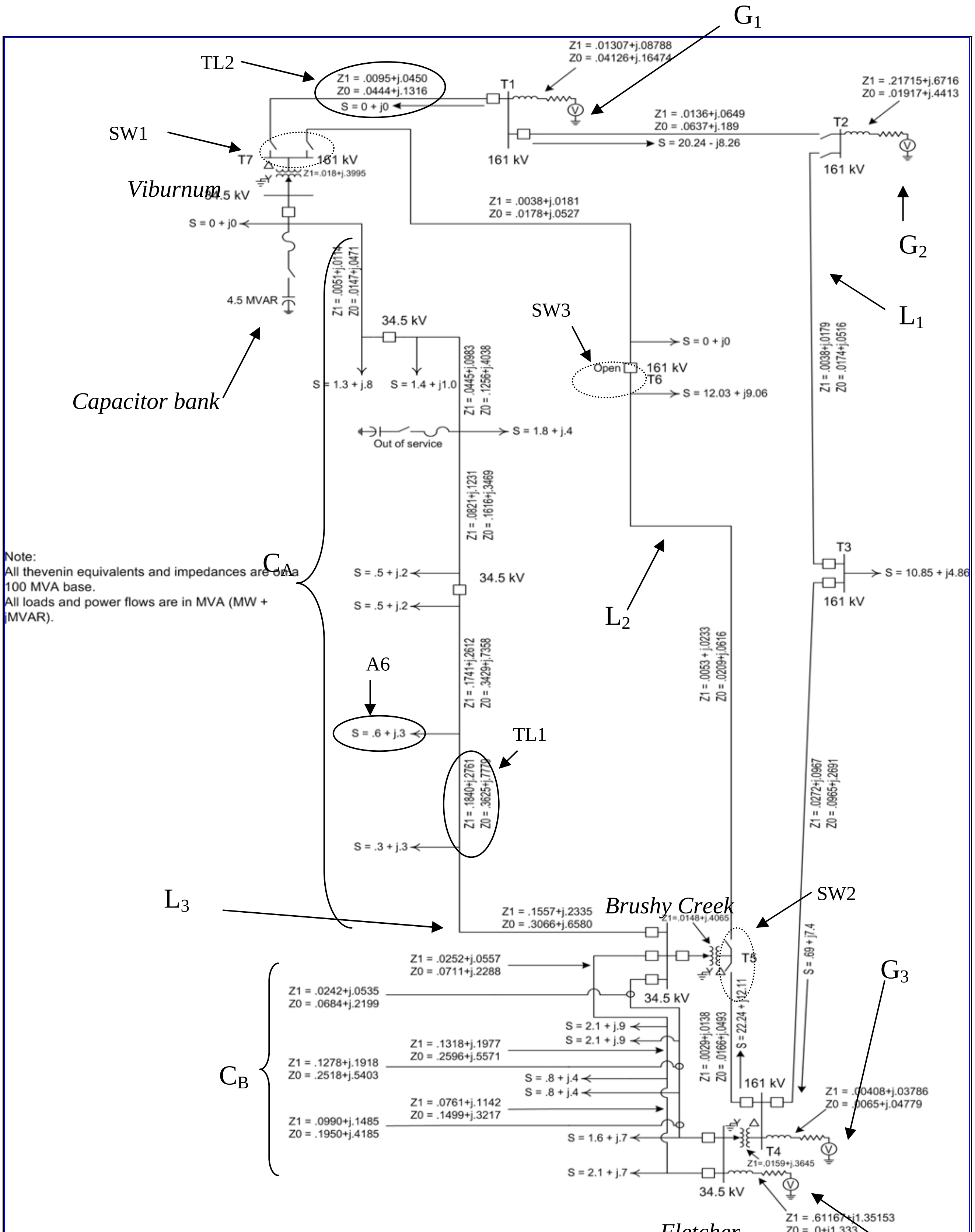


Figure 3.1 The single line diagram of a portion of the Ameren distribution system.

3.2 The ATP-EMTP model of the three-phase distribution system

A diagram of the three-phase ATP-EMTP model of the Ameren distribution system is shown in Figure 3.2. As in the actual line diagram, the ATP-EMTP model consists of two main lines, line L_1 and L_2, the 161 kV high voltage transmission lines, and line L_3, the 34.5 kV intermediate transmission line. Customer groups C_A and C_B are supplied by the 34.5 kV busses and generating station G_4, while the rest of the system is supplied by the 161 kV busses. Details of the ATP-EMTP modeling are presented in the remainder of this chapter.

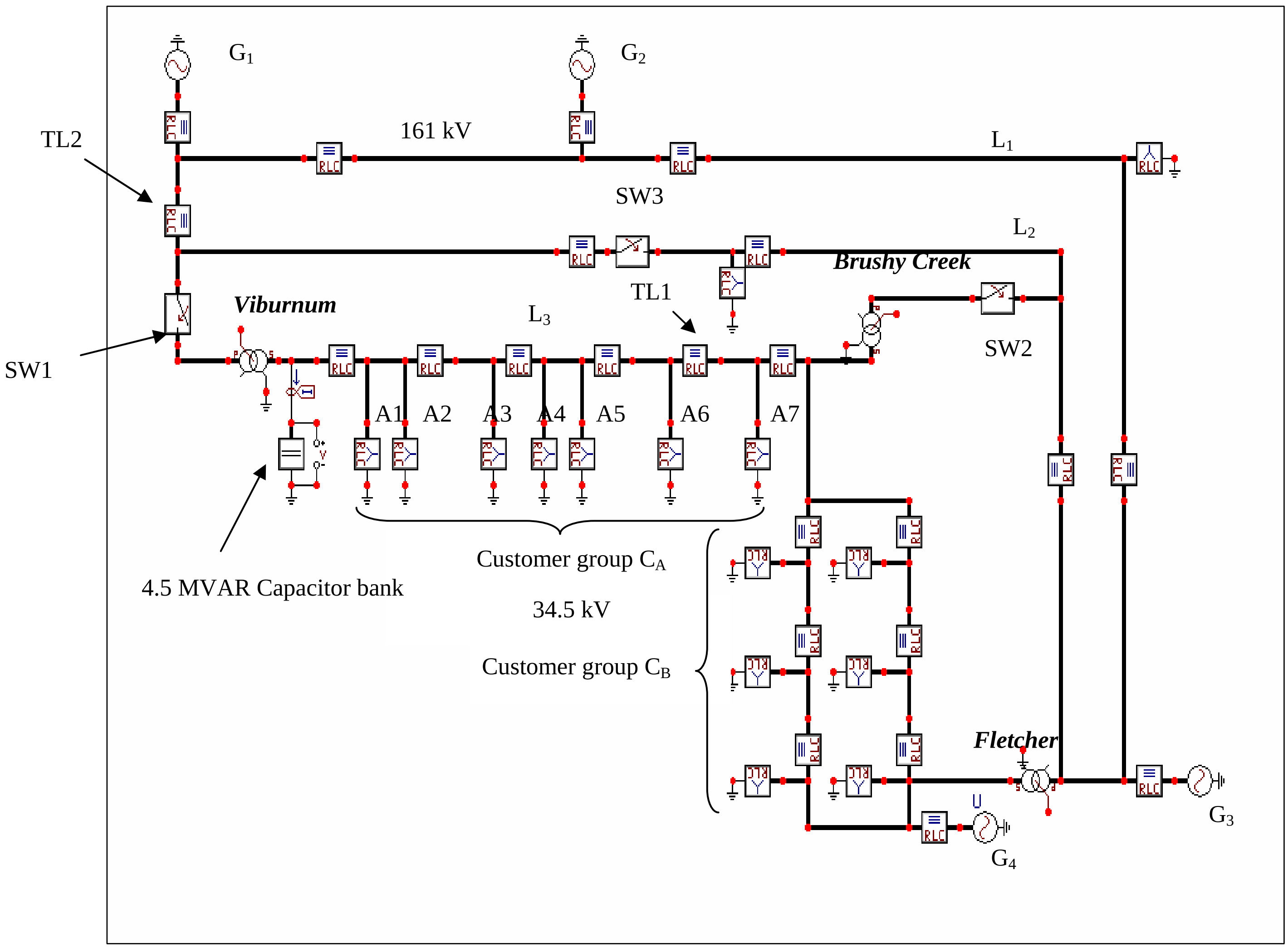


Figure 3.2 ATP-EMTP model of a three-phase distribution system

3.2.1 The transmission line model

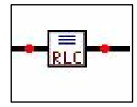
The model of the transmission line is shown in Table 3.1. For simplicity, it is based on the following assumptions:

a. Since the transmission lines are less than 30 miles long, they are assumed to be short, so that the total capacitive susceptance is small enough to be omitted.

b. The leakage in the insulation of the overhead line, and the effect of corona discharge (the phenomena of partial ionization) are negligible. Thus, the conductance between conductors and between conductors and ground are omitted [2, 3].

With these assumptions, each transmission line can be modeled with a series resistance and inductance. Table 2.1 shows the ATP-EMTP transmission line model of two portions (TL1, and TL2) of power grid L_3 and a sample calculation illustrating the method used to convert the data for use in the ATP-EMTP model.

Table 3.1 The transmission line parameters used in the simulations.

Transmission line impedance per phase.	**ATP-EMTP model RLC series (C= 0)** 		
	Phase A	**Phase B**	**Phase C**
Supply system at secondary side 34.5 kV (TL1 in figures 3.1 and 3.2) V_{base}= 34.5 kV $S_{base,3\varphi}$ = 100 MVA Z_{base} = 11.9 Ω Z_0 = 0.3625 + j0.7779 Z_p = 0.1840 + j0.2761	R = 2.1896 Ω L= 10.458 mH	R = 2.1896 Ω L= 10.458 mH	R = 2.1896 Ω L= 10.458 mH
Supply system at primary side 161 kV (TL2 in figures 3.1 and 3.2) V_{base}= 161 kV $S_{base,3\varphi}$ = 100 MVA Z_{base} = 259.21 Ω Z_0 = 0.0444 + j0.1316 Z_p = 0.0095 + j0.0450	R = 2.4625 Ω L= 37.129 mH	R = 2.4625 Ω L= 37.129 mH	R = 2.4625 Ω L= 37.129 mH

Sample calculation:

V_{base}= 34.5 kV

$S_{base,3\varphi}$ = 100 MVA

$$Z_{base} = \frac{\left[\left(V_{base,l-l}\right)\right]^2}{S_{base,3\varphi}}$$

$$= \frac{\left[\left(34.5 \times 10^3\right)\right]^2}{100 \times 10^6} = 11.9\ \Omega$$

Z_0 = 0.3625 + j0.7779, Z_P = Z_N = 0.184 + j0.2761 (given)

According to symmetrical component transformation [4], sequence impedance (Z_L) can be defined as

$$Z_P \cong Z_L \quad \textit{Positive – sequence inpedance}$$

$$Z_N \cong Z_L \quad \textit{Negative – sequence impedance}$$

$$Z_o \cong Z_L + 3Z_n \quad \textit{Zero – sequence impedance}$$

$$[Z_L] = [0.184 + j * 02761] \quad \text{pu}$$

$$= [2.1896 + j * 3.2855] \ \Omega,$$

$Z_L = R + j*X_L = R + j\omega L$

Thus,

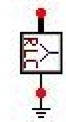
$$[R] = [2.1896] \quad \Omega. \ ,$$

$$[L] = [10.458] \quad \text{mH}$$

3.2.2 The linear load model

The model of the linear load is shown in Table 3.2. along with a sample calculation of the associated resistance and inductance. All of the linear loads were modeled as parallel R-L combinations and connected from phase to ground, which can be considered as wye-connected impedances for the three-phase system.

Table 3.2 The linear load parameter used in simulation

Linear Load	**ATP-EMTP model** **RL parallel (C=0)** 
Supply System at Secondary side 34.5 kV (A6 in Figures 3.1 and 3.2) $V_{l\text{-}l}$ = 34.5 kV S_{load} = 60+ j30 MVA	R = 15.87 Ω L= 21.04 mH

Sample Calulation:

$$Z_P = \frac{(V_{l-l})^2}{S^*_{Load}}$$

$$= \frac{(34.5 \times 10^3)^2}{(60 - j30) \times 10^6}$$

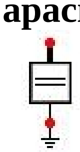
$$= 15.87 + j7.935$$

R = 15.87 Ω , L = 21.04 mH

3.2.3 The capacitor bank model

The model of the 4.5 MVAR capacitor bank is shown in Table 3.3. The capacitor bank is connected to the supply system at the secondary side (34.5 kV), next to the Viburnum transformer. It is a grounded-Wye configuration shunt-connected to the system and modeled as the C combination group in EMTP. It is connected phase-to-phase, which can be considered as a Wye-connection impedance for a three-phase system.

Table 3.3 The Capacitor bank parameter used in the simulations

4.5 MVAR Capacitor bank	**ATP-EMTP model Capacitor** 
Supply System at Secondary side (34.5 kV.) $V_{l\text{-}l}$ = 34.5 kV Q = 4.5 MVAR	C= 10.028 μF

Sample Calulation:

$$X_C = \frac{(V_{l-l})^2}{Q}$$

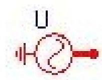
$$= \frac{(34.5 \times 10^3)^2}{4.5 \times 10^6} = 264.5$$

$$C = \frac{1}{X_C \omega} = 10.028 \ \mu F$$

3.2.4 The generator model

The model of the generators is shown in Table 3.4. All of the generators (G_1, G_2, G_3 and G_4 in Figures 3.1 and 3.2) are assumed to be ideal.

Table 3.4 The generator parameters used in the simulations

Generator type	**ATP-EMTP model** **AC 3 phase type 14** 
161 kV Generators* (G_1, G_2, G_3 in Figures 3.1 and 3.2)	U/I = 0 Amp = 227.688 kV frequency = 60 Hz Pha = 0 A1 = 0
34.5 kV Generator* (G_4 in Figures 3.1 and 3.2)	U/I = 0 Amp = 48.79 kV frequency = 60 Hz Pha = 0 A1 = 0

* according to the EMTP-RULES book IV.E, and XIX-G

U/I= 0 (Voltage source)

Amp (The peak value in [V] of the function)

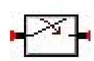
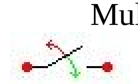
Pha (Phase shift in degrees or seconds depending on A1)

A1 (Phase in degrees)

3.2.5 The switch model

The model of the switches is shown in Table 3.5. All of the switches (SW1, SW2 and SW3 in Figures 3.1 and 3.2) are assumed ideal and time-controlled, and are assumed to have negligible impedance. Each of the three-phase switches consists of an individual switch per phase. All of the three individual switches can be closed and opened independently of each other at any time. T_{open} represents the opening time of a switch, T_{close} represents the closing time of a switch, and I_{mar} represents the current margin. The switch is successfully opened at $T > T_{open}$ if $I < I_{mar}$.

Table 3.5 The switch parameters used in the simulations

Switch Parameter	**ATP-EMTP model**
3 phase switch*	Switch times control 3 phase  I_{mar} = 0.001 A
1 phase switch*	Multi switch 1 phase  I_{mar} = 0.001 A

* according to the EMTP-RULES book VI.A.1.

I_{mar} (Current margin in [A]. Switch opens for t >T-op if $|I| < I_{mar}$.)

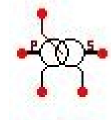
3.2.6 The transformer model

The model for the transformers is shown in Table 3.6. The Brushy Creek and Fletcher transformers are modeled as ideal 3-phase load tap changing (LTC) Delta-grounded wye transformers. For simplicity, the model of the Viburnum transformer is based on the following assumptions:

a. The transformer is operated in the linear region of the transformer magnetizing current. Therefore, under nominal voltage, the transformer is assumed to have no saturation.

b. The flux-current peak value of the linear curve (I_{peak} ,φ_{peak}) and the core exciting losses (Rmag) are evaluated by using excitation test results provided by Ameren.

Table 3.6 Transformer parameters used in the simulations

Transformer Impedance model	**ATP-EMTP model for 3 phase transformer** 
Brushy Creek and Fletcher Substation 3ϕ LTC transformer Delta grounded wye (161/34.5 kV), 60 Hz	Ideal transformer
Viburnum Substation 3ϕ LTC transformer* Delta/ Wye ground (161/34.5 kV) 60 Hz	Pri; V_{RP} = 161 kV R = 19.9839 Ω, L= 1.036 mH Sec; V_{RS} = 34.5 kV R = 0.26423 Ω, L=0.048mH Rmag =33.436 kΩ I_{peak} = 0.31268 A φ_{peak} = 129 Vsec R_{short} = 39.966 Ω Dlead/Y180

* according to the EMTP-RULES book IV.E, and XIX-G

Vrp (Rated voltage in [kV] primary winding.)

Vrs (Rated voltage in [kV] secodary winding.)

Rmag (The resistance of core exciting losses.)

I_{peak} (The peak current value through magnetizing branch (MB) at steady state.)

φ_{peak} (Flux [Wb-turn] in MB at steady state.)

R_{short} (The resistance of short circuit losses.)

Chapter 4 Simulation results

This chapter analyzes the effects of the switching times of switches SW1, SW2 and SW3 when the power grid upstream from the Viburnum transformer is reconnected to the system. This analysis mainly focuses on the characteristics of the three-phase current waveforms of the 4.6 MVAR capacitor bank shown in Figures 3.1 and 3.2 .The customer groups C_A and C_B in Figures 3.1 and 3.2 are supplied by the 34.6 kV bus while the rest of the system is supplied by the 161 kV bus. SW2 and SW3 are normally-closed (NC) and normally-open (NO) three phase switches, respectively. Each switch consists of three individual phase switches. Based on the states of switch operation and system balance conditions, four case studies were considered.

1. Transmission line voltage drops.
2. All three individual phase switches are closed simultaneously.
3. The three individual phase switches are closed in sequence.
4. The phase C contact of switch SW1 bounces.

All simulations start at time T = 0 s and finish at time T = 0.3 s. This represents 18 cycles of a 60 Hz signal.

4.1 Transmission line voltage drops.

This section shows that with SW1 and SW3 open and SW2 closed, there are voltage drops along the transmission line between Brushy Creek and Viburnum resulting in a voltage of only 21.17 kV at Viburnum. When SW1 is closed, the voltage at Viburnum is close to 34.5 kV. Figure 4.1 shows the points along the line in customer group C_A that are simulated.

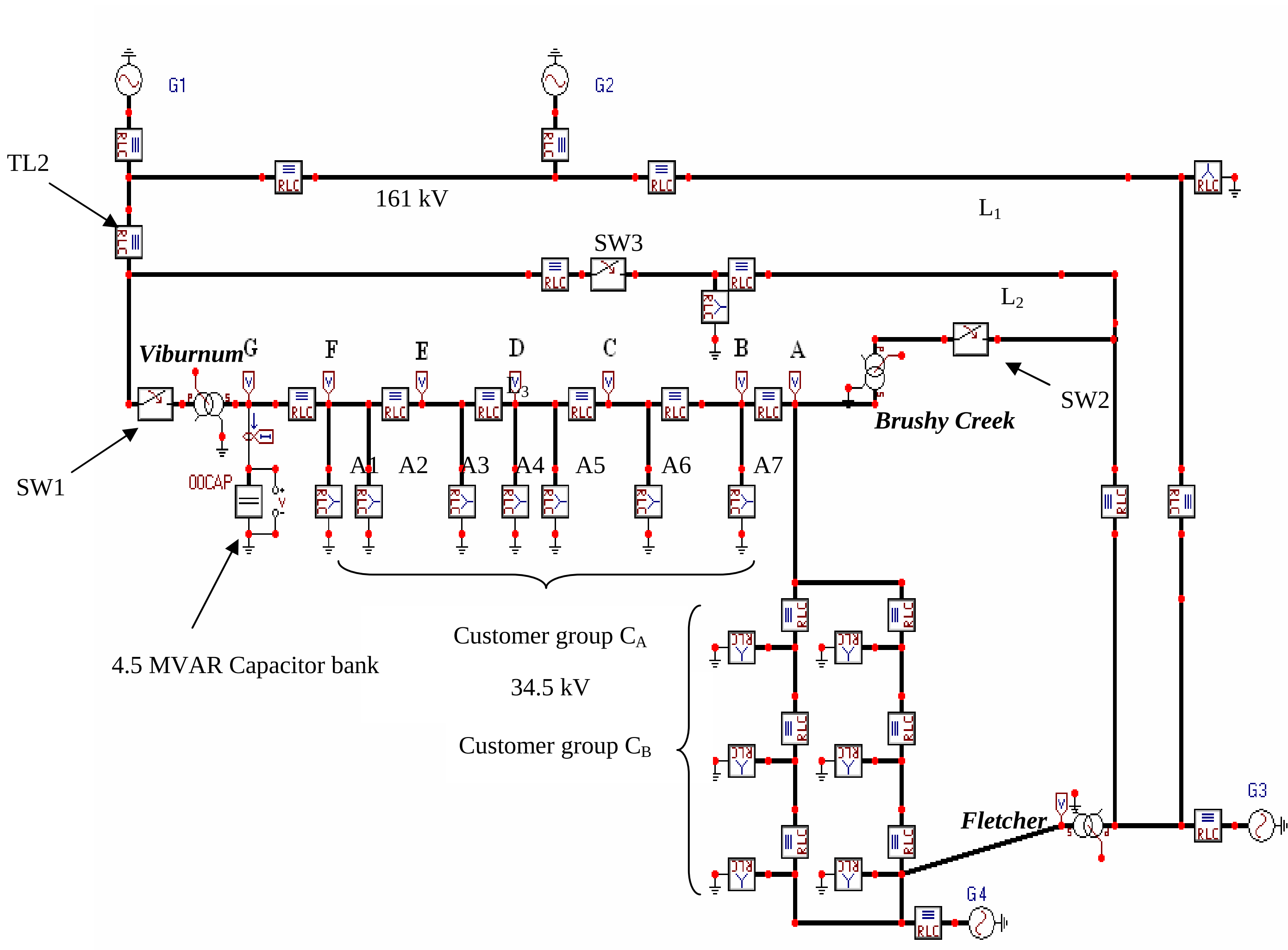


Figure 4.1 ATP-EMTP model of a three-phase distribution system.

4.1.1 Case A SW1 is open.

Figure 4.2 (a) shows only the phase A voltage drop at nodes in the customer group C_A, labeled A-G starting from the Brushy Creek transformer to the Viburnum transformer. Figure 4.2 (b) is a magnified view of the peaks of the voltage waveforms. The result of the simulation shows a drop in voltage with the highest voltage being at the Brushy Creek transformer and a steady drop to the Viburnum transformer. This is because the power is supplied from one side only.

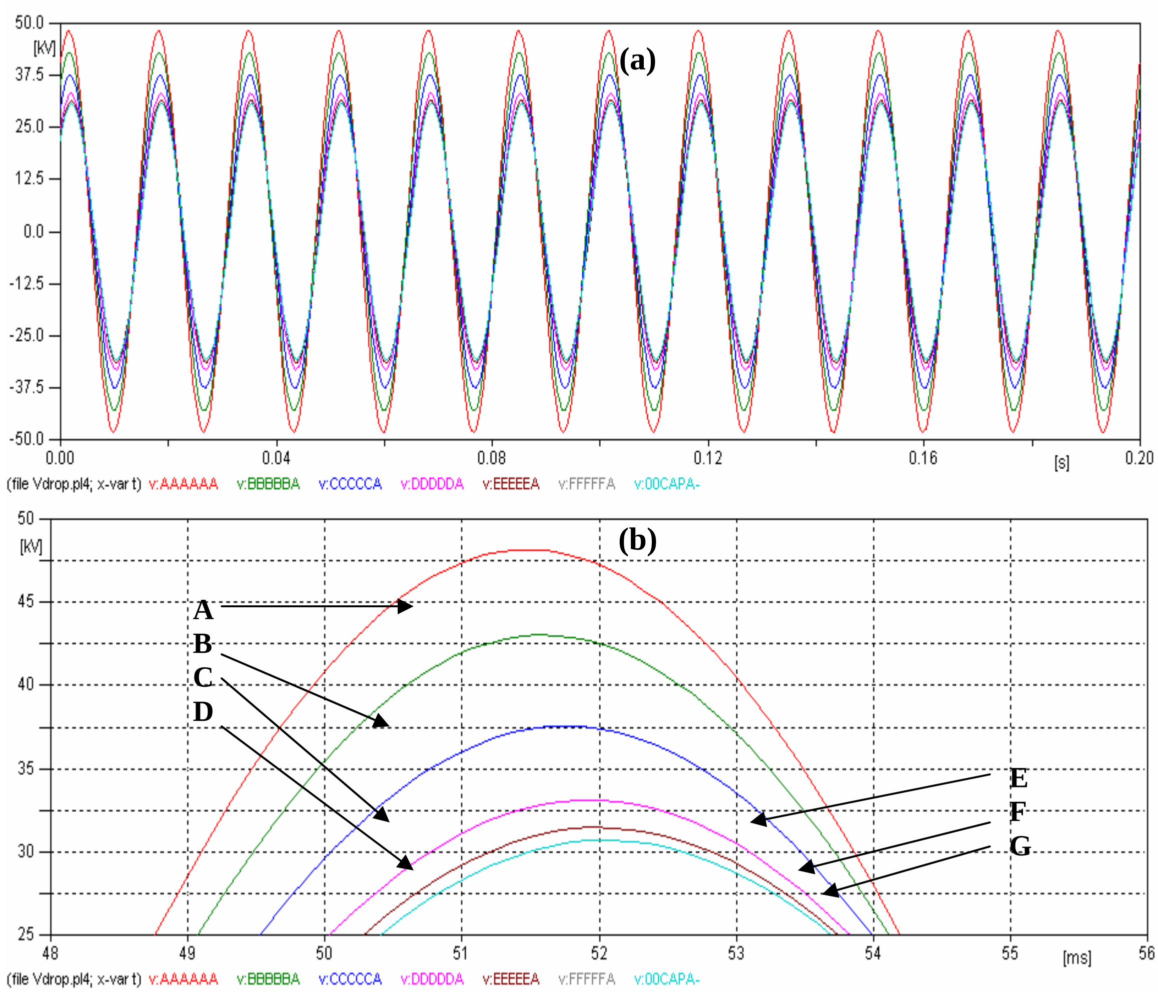


Figure 4.2 Waveforms of voltage from A-G in customer group C_A when SW1 is open. The waveform is shown during (a) 0 – 2 s (b) 0.048 – 0.056 s

4.1.2 Case B SW1 is closed

Similar to case A, Figure 4.3(a) and (b) show the voltages at nodes A-G in customer group C_A , but now SW1 is closed. In this case power is also provided to the customer line though the Viburnum transformer. The voltage drop along the line in this case is much lower than in case A. Hence, the lowest voltage is located at the center of the customer line (at node G), as expected.

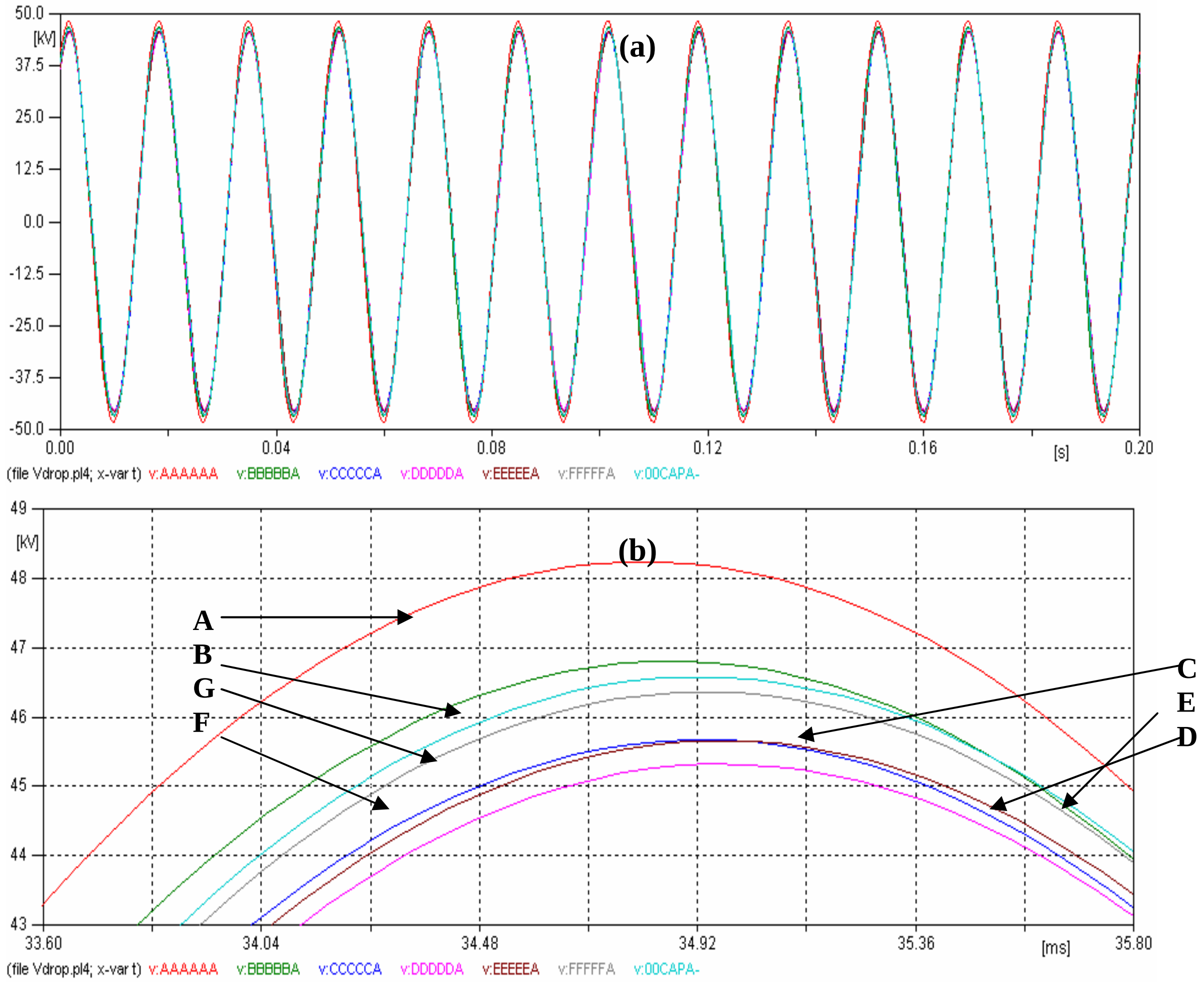


Figure 2.3 Waveforms of voltage in A-G from customer group C_A when SW1 is closed. The waveform is shown during (a) 0 – 2 s (b) 0.033 – 0.035 s

The simulation results for cases A and B are summarized in Table 4.1. In case B, with power from both sides of the consumer group C_A, the voltage is much closer to that desired for normal operation. For case B, the value desired is 34.5 kV. In case A there is a noticeable voltage drop from Brushy Creek to Viburnum.

Table 4.1 The rms voltage A-G from customer group C_A.

Point	rms voltage (kV) in case A	rms voltage(kV) in case B
VA	34.158	34.130
VB	30.431	33.112
VC	26.570	32.298
VD	23.437	32.051
VE	22.249	32.284
VF	21.719	32.786
VG	21.704	32.935

4.2 All three individual phase switches are closed simultaneously.

Table 4.2 shows the operation state of switches SW1, SW2 and SW3 during T = 0 - 0.2 s. During 0 – T_1 s, SW1 and SW3 are open, and SW2 is closed. Power is supplied to customer groups C_A and C_B from the Brushy Creek and Fletcher transformers. At T_1, SW1 is switched from open to closed, and all three substations provide power to customer groups C_A and C_B. ATP-EMTP simulations of the system shown in Figure 4.1 were made to determine the 4.6 MVAR capacitor bank currents as a function of the time T_1, at which all three phase switches in switch SW1 are closed simultaneously. To study the behavior of capacitor current in phases A, B and C, T_1 was chosen to close SW1 at different times throughout a 60 Hz period of the voltage across the 4.6 MVAR capacitor bank. Figure 4.4 shows one of the T_1 closing times. It is the time at which the transient behavior of the voltage and current was most extreme. It was chosen at the negative peak of phase A capacitor current, i.e., at 0.05225 s.

Table 4.2 Switch operation.

Time (s)	SW1	SW2	SW3
0 – T_1	Open	Closed	Open
T_1 – 0.3	Closed	Closed	Open

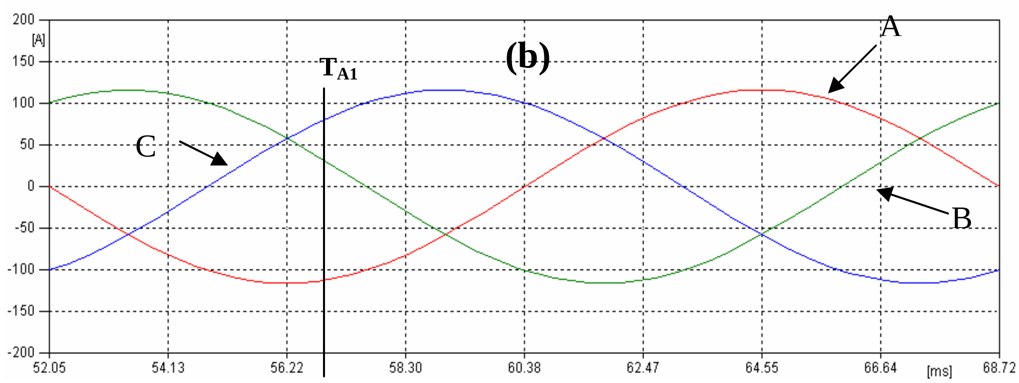


Figure 4.4 The switching time T_{A1} of capacitor current in phase A, B, and C

Figure 4.5 (a) shows the behavior of phase A capacitor current before and after SW1 is closed at T_1 = 0.05622 s, which corresponds to a maximum in phase A current. Figures 4.5 (b) and 4.5 (c) show the same data during 0 - 0.06 s, and 0.05 -0.11 s respectively. From 0 – T_1, the capacitor current is a sinusoid with a small magnitude. This is because power is supplied only from the Brushy Creek and Fletcher substations. At T_1 all three phase switches in SW1 are closed simultaneously at a point near the peak of the phase A capacitor current. Figure 4.5 shows that when SW1 is closed at T_1 = 0.05622 s the phase A capacitor current peak jumps from 116.1 A to -1.612 kA and creates a transient high frequency oscillation that lasts for approximately 2.5 cycles of the 60 Hz line signal. The frequency of the transient is approximately 2747.7 Hz.

Figure 4.6 compares the waveforms of the capacitor currents in phases A, B, and C when SW1 is closed at T_1 = 0.05622 s. Similar to phase A, the transient overcurrents in phases B and C exist for approximately two and a half cycles. The maximum overcurrents are 2.568 kA in phase B and 1.154 kA in phase C.

Figure 4.7 shows the behavior of phase A capacitor voltage before, during, and after SW1 is closed at T_1 = 0.05622 s. The curve shows that the phase A capacitor voltage peak jumps from 30.71 kV A to -52.08 kV and undergoes a transient high frequency oscillation that lasts for approximate 1.5 cycles of the 60 Hz line signal. The frequency of the transient is approximately 2747.7 Hz.

Figure 4.8 compares the waveforms of the capacitor voltages in phases A, B, and C when SW1 is closed at T_1 = 0.05622 s. The maximum peak overvoltages are -52.08 kV in phase A, 58.195 kV in phase B and 49.59 kV in phase C.

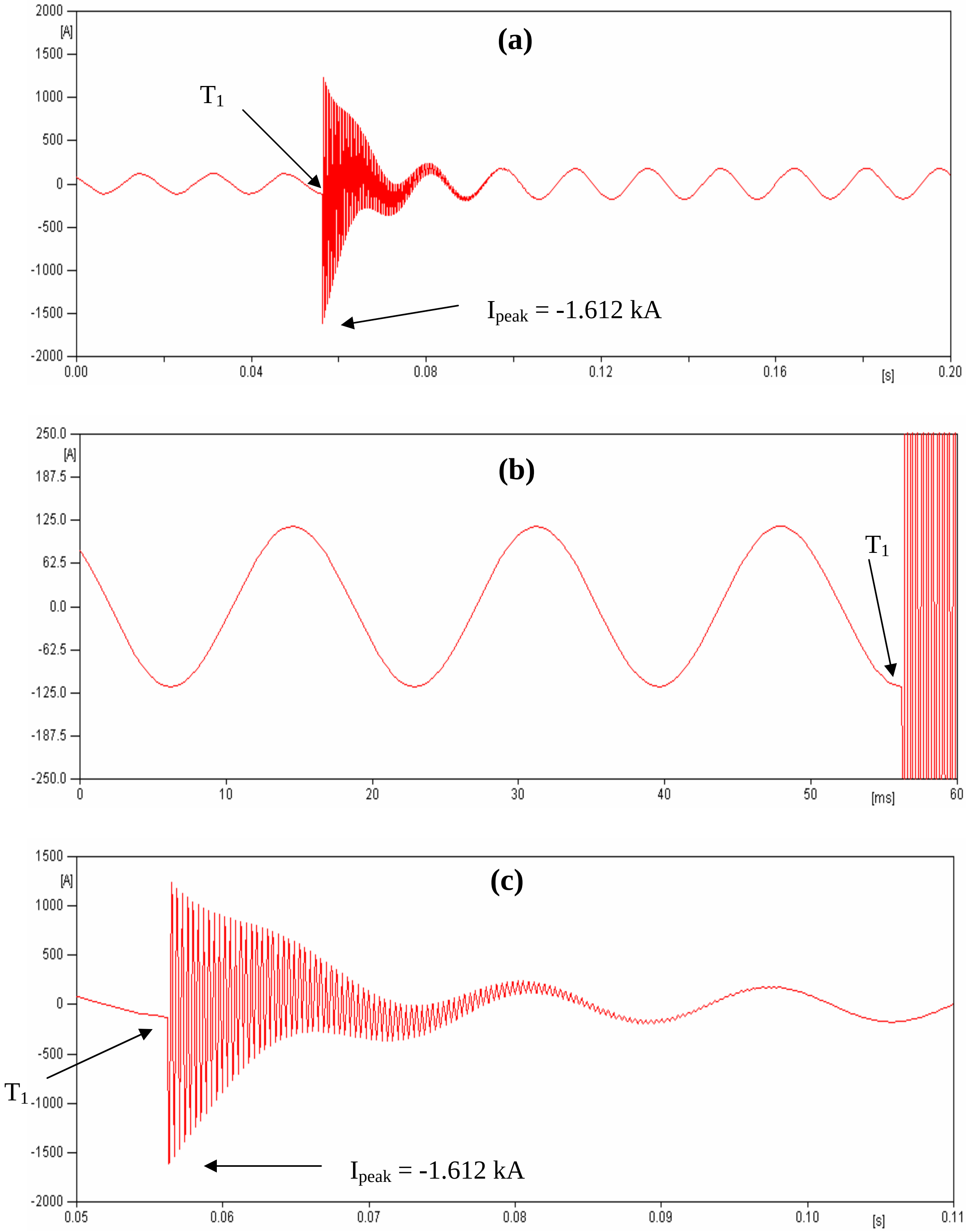


Figure 4.5 Behavior of phase A capacitor current when SW1 is closed at T_1 = 0.05622 s, near the phase A current peak. The waveform is shown during (a) 0 – 0.2 s (b) 0 – 0.06 s (c) 0.05 – 0.11 s.

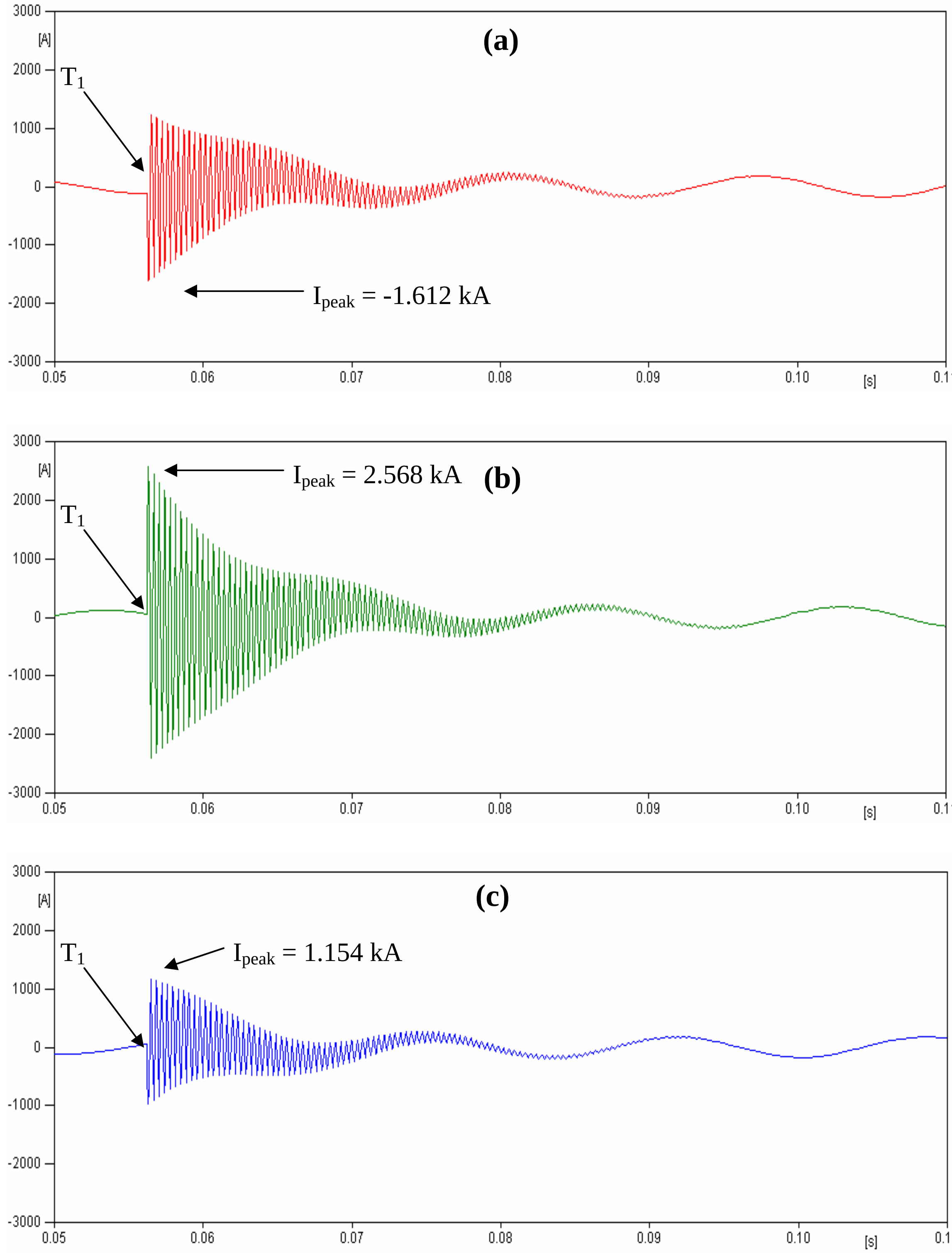


Figure 3.6 Waveforms of capacitor currents during 0.05-0.11 s when SW1 is closed at T_1 = 0.05622 s. (a) phase A, (b) phase B, (c) phase C.

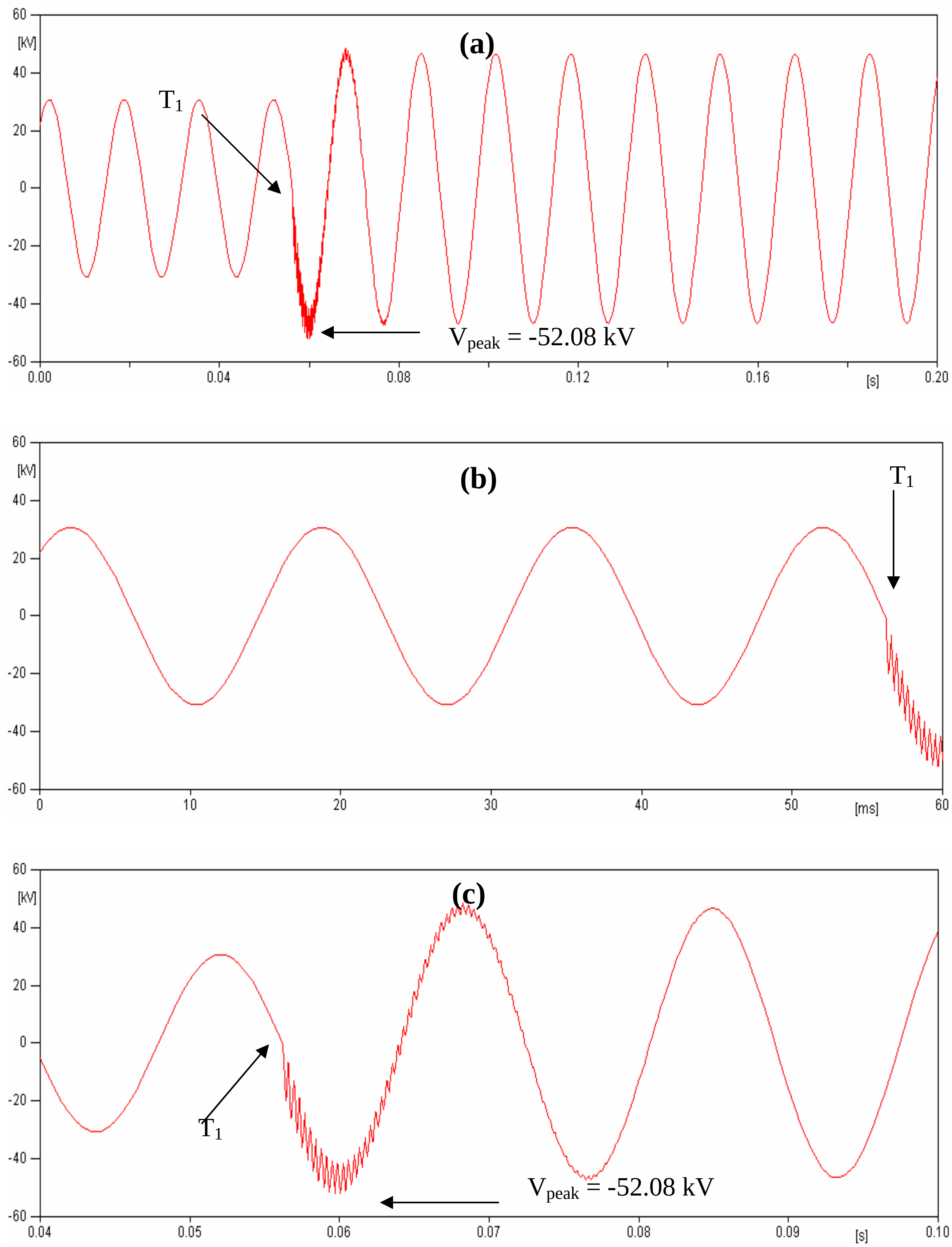


Figure 4.7 Behavior of phase A capacitor voltage when SW1 is closed at T_1 = 0.05622 s. The waveform is shown during (a) 0 – 0.2 s (b) 0 – 0.06 s (c) 0.04 – 0.10 s.

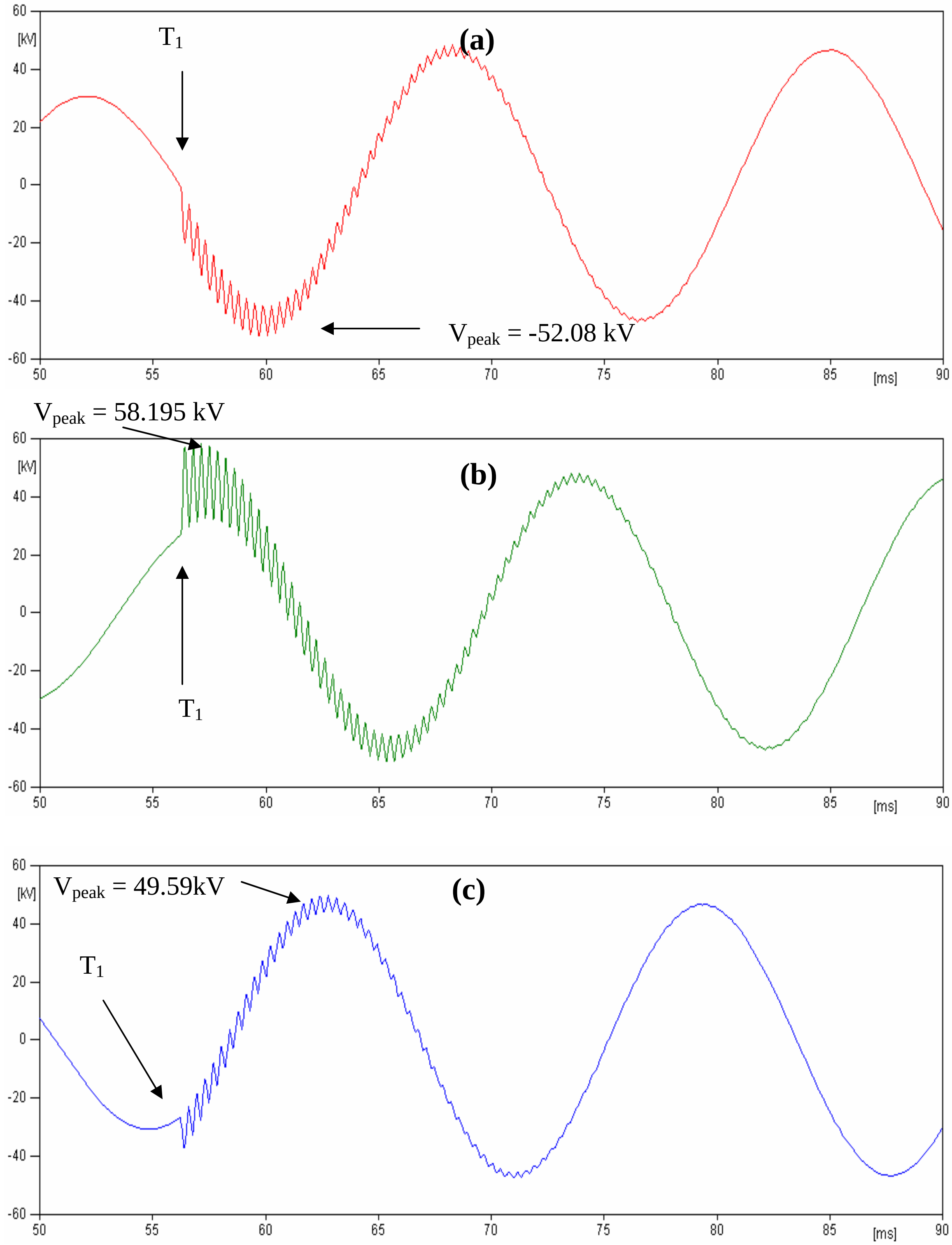


Figure 4.8 Waveforms of capacitor currents during 0.05-0.9 swhen SW1 is closed at T_1 = 0.05622 s. (a) phase A, (b) phase B, (c) phase C.

Simulations like those shown in Figures 4.5 through 4.8 were performed for different values of T_1 throughout the 60 Hz period, having the time step of $6.94*10^{-4}$ s. Table 4.2 shows the resulting peak overcurrent and overvoltage values. The data show that when the three phase switches are closed simultaneously near a current peak in any of the three phases, transient overcurrent oscillations, lasting approximately 2.5 cycles of the 60 Hz line frequency, occur in all three phases. The peak overcurrents vary over from 1.027 to 2.578 kA and the peak overvoltages vary from 49 kV to 58 kV.

Table 4.2 The peak currents (p.u.) in phases A, B, and C, when SW1 phase-A, B, and C

	Time (Ta)	**Va (kV)**	**Vb (kV)**	**Vc (kV)**	**Ia (kA)**	**Ib (kA)**	**Ic (kA)**
1	0.05205	54.227	47.639	-56.245	-2.046	0.379	-2.412
2	0.05274	-50.608	49.758	-57.799	-1.661	1.023	**-2.578**
3	0.05344	-49.597	52.071	**58.197**	-1.156	1.61	-2.568
4	0.05413	-48.232	54.291	57.534	-0.582	2.081	-2.385
5	0.05483	-47.647	56.253	54.21	-0.381	2.413	-2.035
6	0.05552	-49.766	57.605	50.607	-1.025	**2.578**	1.659
7	0.05622	-52.08	**58.195**	49.59	-1.612	2.568	1.154
8	0.05691	-54.299	57.53	48.226	-2.081	2.384	0.581
9	0.05761	-56.26	54.193	47.655	-2.414	-2.044	0.384
10	0.05830	-57.611	-50.607	49.775	**-2.578**	-1.658	1.027
11	0.05899	**-58.202**	-49.611	52.048	-2.569	-1.16	1.606
12	0.05969	-57.525	-48.22	54.307	-2.383	-0.579	2.082
13	0.06038	-54.252	-47.627	56.234	-2.039	-0.376	2.411
14	0.06108	50.607	-49.785	57.616	1.657	-1.029	**2.578**
15	0.06177	49.606	-52.058	**58.2**	1.158	-1.608	2.569
16	0.06247	48.214	-54.316	57.521	0.577	-2.084	2.383
17	0.06316	47.635	-56.242	54.235	0.378	-2.412	2.037
18	0.06386	49.793	-57.622	-50.606	1.031	**-2.579**	-1.655
19	0.06455	52.037	**-58.198**	-49.599	1.609	-2.569	-1.156
20	0.06524	54.286	-57.536	-48.236	2.079	-2.386	-0.583
21	0.06594	56.249	-54.218	-47.624	2.413	2.046	-0.38
22	0.06663	57.602	50.607	-49.762	**2.578**	1.66	-1.024
23	0.06733	**58.196**	49.593	-52.075	2.568	1.155	-1.611
24	0.06802	57.532	48.229	-54.294	2.385	0.582	-2.08
25	0.06872	54.202	47.648	-56.256	-2.045	0.0382	-2.413

4.3 Three individual phase switches are closed in sequence.

The aim of this case is to observe the effects of closing the three phase switches at different times. ATP-EMTP studies were performed to evaluate the transient switching behaviors of the circuit shown in Figure 4.9, which is the same as Figure 4.1 except that SW1 is now replaced with phase switches SW1 A, SW1 B, and SW1 C.

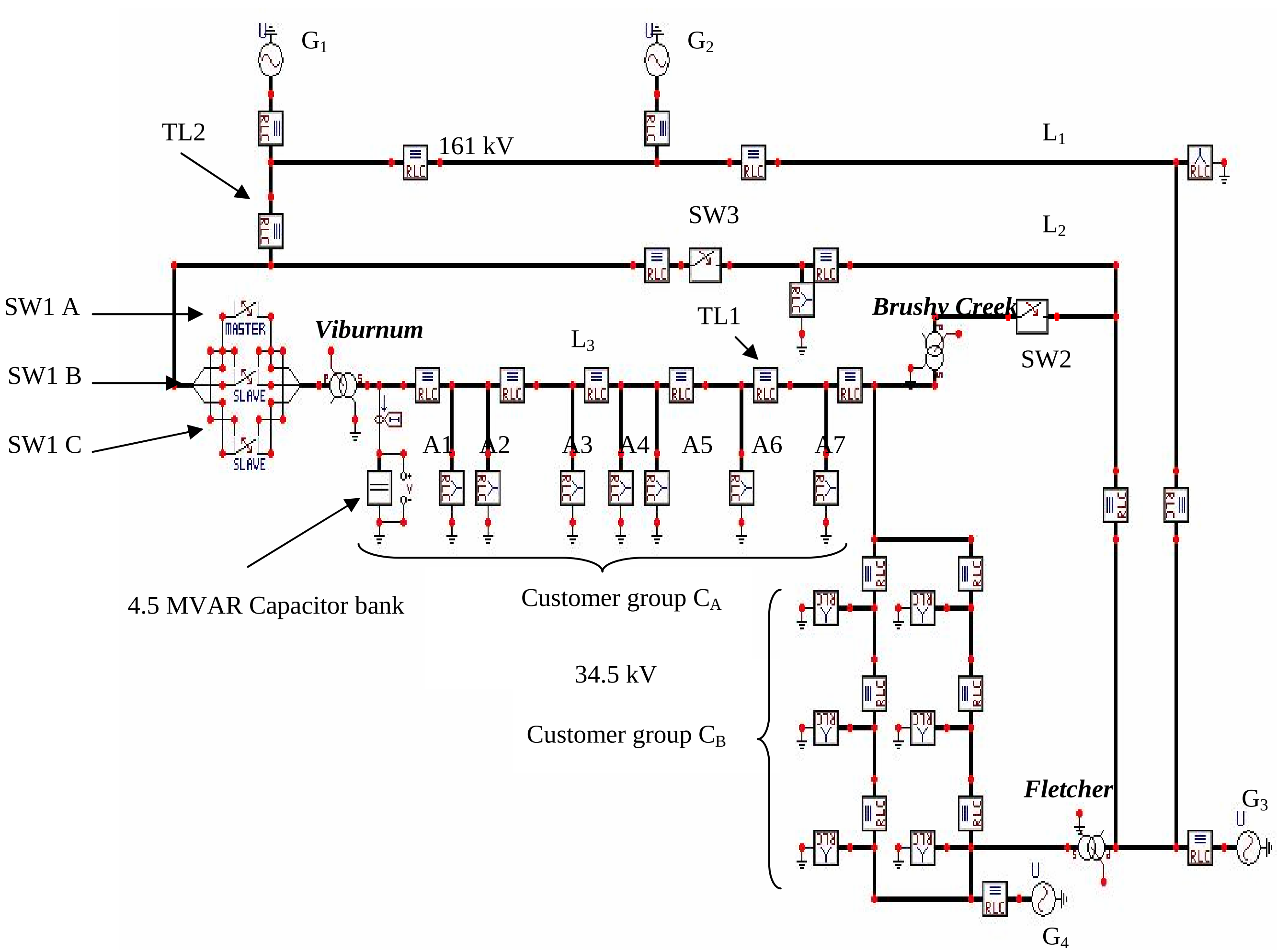


Figure 4.9 ATP-EMTP model of a three-phase distribution system.

Table 4.3 shows the operation of switching SW1, SW2 and SW3 during 0 - 0.2 s. During 0 s – T_2, phase switches A, B, and C in SW1 are all open, SW2 is closed, and SW3 is open. Customer groups C_A and C_B are supplied only from the Brushy Creek and Fletcher transformers. At T_2, SW1 is switched from open to closed. Now three substations provide power to customers groups C_A and C_B. The three phase switches A, B, and C in SW1 are closed at different times. Phase A of SW1 is set to be the master switch. It is closed at time T_a. Phase B of SW1 is set to be a slave switch with closure time T_b, which is delayed 3 ms from the master switch. Phase C of SW1 is set to be another slave switch with closure time T_c, which is delayed 6 ms from the master switch. Simulations were performed to study the behavior of capacitor current, using different values of T_2 throughout a 60 Hz period of the voltage across the 4.5 MVAR capacitor bank.

Table 4.3 Switch operations.

Time (s)	**SW1**			**SW2**	**SW3**
	Phase A	**Phase B**	**Phase C**		
0 – T_2	Open	Open	Open	Closed	Open
T_2 – 0.2	Close at $T_a = T_2$	Close at $T_b = T_2+$ 3 ms	Close at $T_c = T_2+$ 6 ms	Closed	Open

Figure 4.10 shows the waveforms of the capacitor currents in phases A, B, and C when the three phase switches in SW1 are closed at T_a = 0.05391 s, T_b = 0.05691 s, and T_c = 0.05991 s, which was the worst case observed. The large transient overcurrents occur after phase C of SW1 (the last switch) is switched. The peak overcurrents are -2.472 kA in phase A, 2.384 kA in phase B, and 2.304 kA in phase C. Here the transient overcurrents last for approximately two and a half cycles.

Figure 4.11 illustrates the waveforms of the capacitor voltage on phases A, B, and C corresponding to the currents shown in Figure 4.10. The peak overvoltages are -58.595 kV in phase A, 57.53 kV in phase B, and 55.102 kV in phase C.

The relative sizes of the currents between T_b-T_c and after T_c in Figures 4.10 and 4.11 can be explained in terms of delta-grounded wye transformer operation, as given in Table 4.4.

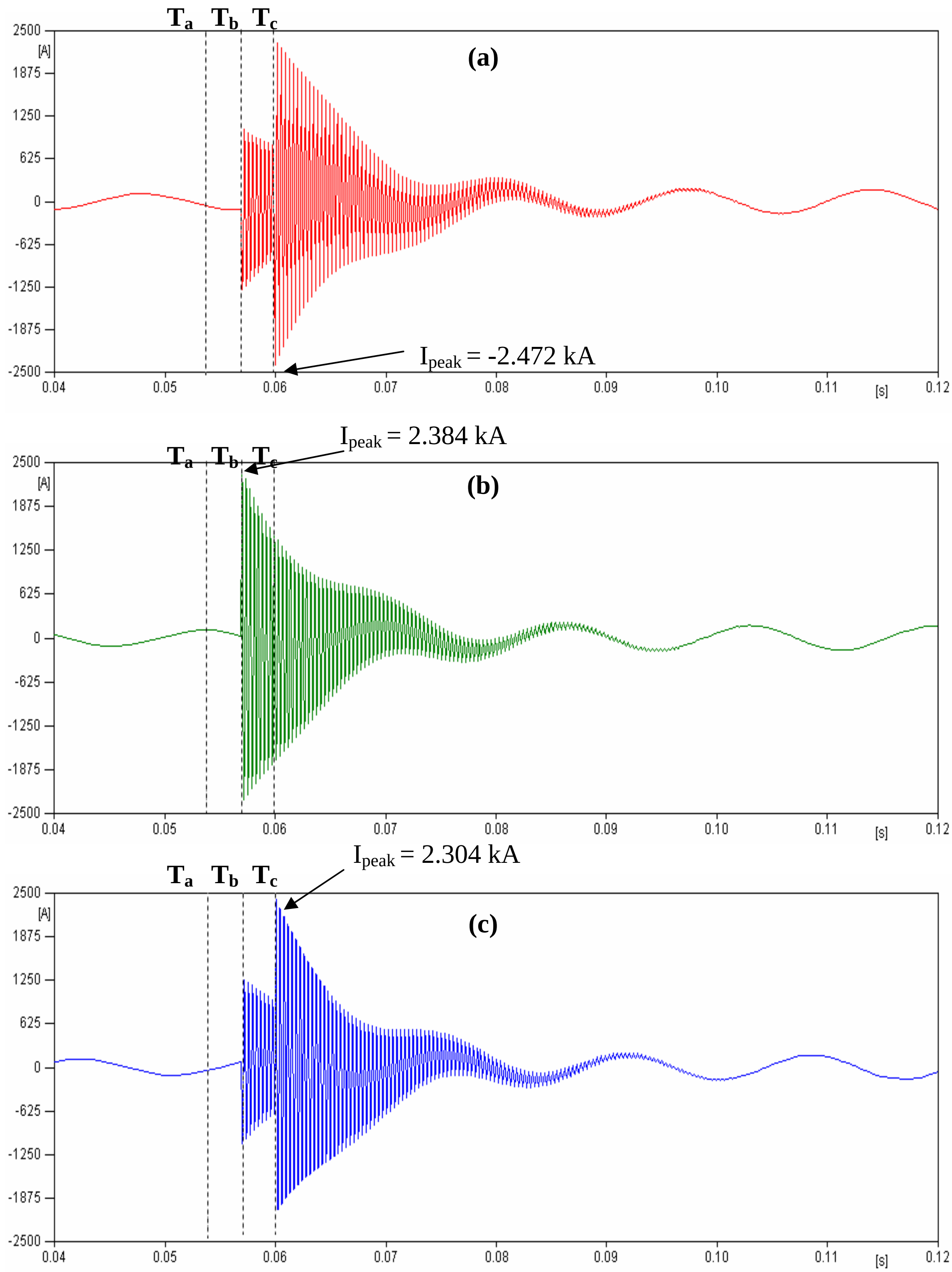


Figure 4.10 Waveforms of capacitor currents during 0.04-0.12 s when SW1 is closed at T_a= 0.05391s. (a) phase-A, (b) phase-B, (c) phase-C.

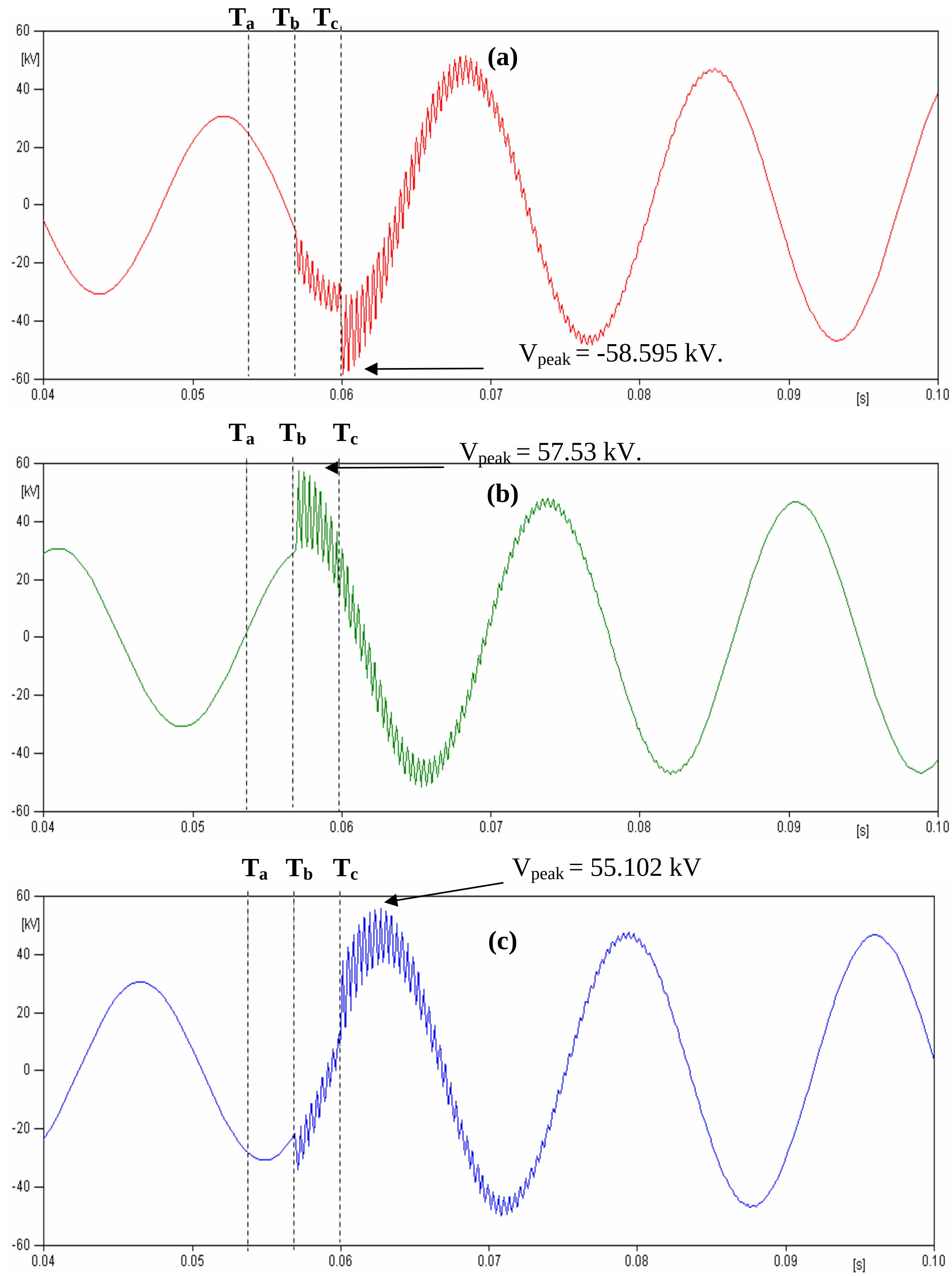
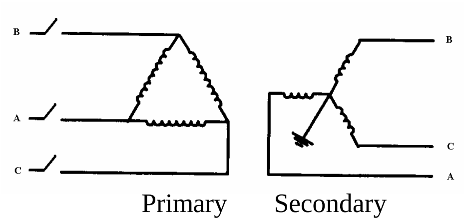
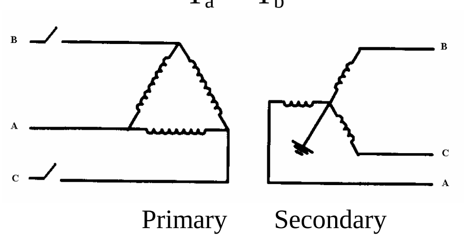
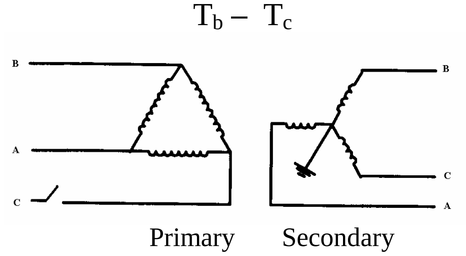
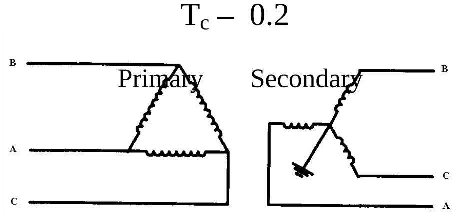


Figure 4.11 Waveforms of capacitor voltages during 0.04-0.1 s when SW1 is closed at T_a = 0.05391s, (a) phase-A, (b) phase-B, (c) phase-C.

Table 4.4 Delta-grounded wye transformer between the sequences phase switches operation.

Time	Description
0 – T_a 	Before closing switch SW1, there is no electrical connection between the primary side and the secondary side.
T_a – T_b 	When SW1-phase A is closed, the transformer is still not energized because the input circuit is not complete.
T_b – T_c 	After SW1 phase B is closed, the circuit is completed at phase A-B. The transformer will transform electrical energy from phase A-B (line-to-line at the primary side) to phase B (line-to-ground at the secondary side). In addition phases A-C and B-C are also transformed to phases A and C, respectively (line-to-ground at the secondary side) but more electrical energy will transform to phase B (line-to-ground at the secondary side) because the phase A-B voltage is twice as large as the other two.
T_c – 0.2 	After SW1-phase C, the last switch is closed, the transformer will transform electrical energy equally form the delta primary side to the grounded wye secondary side.

To evaluate the behavior of the capacitor current, simulations like those shown in Figures 4.10 and 4.11 were performed for different values of T_a throughout the 60 Hz period, having the time step of $6.94*10^{-4}$ s. Table 4.5 shows the resulting peak overcurrent and overvoltage values. As can be seen in the table, the worst cases occur when SW1 phase-A (T_a) is closed from 0.05183 s to 0.05391 s (Figure 4.10 and 3.11), and from 0.06016 s to 0.06224 s.

The results show that when the phase switches are closed at different times, large transient overcurrents sometimes occur on all three phases after phase C switch is closed. This is not observed when all three phase switches are closed simultaneously. The worst case overcurrent magnitudes are approximately the same as in case 2. We conclude from this that the relative delays in closing the three phase switches may play a role in fuse holder damage.

Table 4.5 The peak currents (p.u.) and voltages (p.u.) in phases A, B, and C, when SW1 phase-A, B, and C are closed at different times T_{a}, T_b , and T_c.

	Time (Ta)	Time (Tb)	Time (Tc)	V_A (kV)	V_B (kV)	V_C (kV)	I_A (kA)	I_B (kA)	I_C (kA)
1	0.04905	0.05205	0.05505	-49.441	47.637	48.497	-0.869	0.379	0.833
2	0.04974	0.05274	0.05574	-48.104	49.757	47.818	-0.489	1.023	-0.534
3	0.05044	0.05344	0.05644	-49.599	52.071	48.255	0.811	1.610	-0.801
4	0.05113	0.05413	0.05713	-52.009	54.290	49.596	-1.362	2.080	1.162
5	0.05183	0.05483	0.05783	-54.545	56.253	51.189	-1.849	2.413	1.618
6	0.05252	0.05552	0.05852	-56.760	57.605	52.747	-2.204	**2.578**	1.970
7	0.05322	0.05622	0.05922	-58.319	**58.201**	54.139	-2.419	2.568	2.213
8	0.05391	0.05691	0.05991	**-58.595**	57.530	55.102	**-2.472**	2.384	**2.304**
9	0.05461	0.05761	0.06061	-55.378	54.193	**55.541**	2.382	2.044	2.236
10	0.05530	0.05830	0.0613	52.072	-50.607	55.222	2.185	1.658	2.035
11	0.05599	0.05899	0.06199	51.697	-49.611	53.922	1.861	-1.160	1.699
12	0.05669	0.05969	0.06269	50.800	-48.220	51.669	1.405	-0.579	1.241
13	0.05738	0.06038	0.06338	49.445	-47.625	-48.499	0.872	-0.376	-0.834
14	0.05808	0.06108	0.06408	48.105	-49.785	-47.815	0.492	-1.029	0.537
15	0.05877	0.06177	0.06477	49.588	-52.058	-48.247	0.808	-1.605	0.800
16	0.05947	0.06247	0.06547	52.032	-54.316	-49.618	1.367	-2.084	1.167
17	0.06016	0.06316	0.06616	54.534	-56.242	-51.177	1.847	-2.412	1.616
18	0.06086	0.06386	0.06686	56.778	-57.622	-52.770	2.206	**-2.579**	-1.974
19	0.06155	0.06455	0.06755	**58.314**	**-58.198**	-54.137	2.418	-2.504	-2.213
20	0.06224	0.06524	0.06824	58.600	-57.536	-55.113	**2.473**	-2.386	**-2.304**
21	0.06294	0.06594	0.06894	55.403	-54.218	**-55.543**	2.358	2.046	-2.237
22	0.06363	0.06663	0.06963	-52.075	50.607	-55.227	-2.193	1.660	-2.036
23	0.06433	0.06733	0.07033	-51.689	49.593	-53.908	-1.858	1.155	-1.695
24	0.06502	0.06802	0.07102	-50.805	48.230	-51.684	-1.407	0.582	-1.243
25	0.06572	0.06872	0.07172	-49.435	47.651	48.492	-0.866	0.382	0.831

4.4 The phase C contact of SW1 bounces.

Table 4.6 shows the operation of switching SW1, SW2 and SW3 during 0 - 0.2 s. During 0 s – T_1, phase switches A, B, and C in SW1 are all open, SW2 is closed, and SW3 is open. At T_1, all three phase switches in SW1 are switched from open to closed. At T_2, 6 ms later, phase switch C in SW1 bounces off forcing SW1 phase C to open. Thus during T_2 – T_3 phase C in SW1 opens and the others remain the same. At T_3, phase C in SW1 is reclosed. Now three substations provide power to customer groups C_A and C_B. Simulations were performed to study the behavior of capacitor current and voltage, using different values of T_3 throughout a 60 Hz period of the voltage across the 4.5 MVAR capacitor bank.

Table 4.6 Switch operations

<table>
<tr><th rowspan="2">Time (s)</th><th colspan="3">SW1</th><th rowspan="2">SW2</th><th rowspan="2">SW3</th></tr>
<tr><th>Phase A</th><th>Phase B</th><th>Phase C</th></tr>
<tr><td>0 – T_1</td><td colspan="3">Open</td><td>Closed</td><td>Open</td></tr>
<tr><td>T_1 – T_2</td><td colspan="3">Closed</td><td>Closed</td><td>Open</td></tr>
<tr><td>T_2 – T_3
(Bouncing)</td><td>Closed</td><td>Closed</td><td>Open</td><td>Closed</td><td>Open</td></tr>
<tr><td>T_3 – 0.2
(Reclosed)</td><td>Closed</td><td>Closed</td><td>Closed</td><td>Closed</td><td>Open</td></tr>
</table>

The simulation was performed with variable T_1 chosen to correspond to a bad case from section 3.3 and T_2 chosen to be 6 ms later. Thus T_1 is equal to 0.05205 s and T_2 is equal to T_1 plus 6 ms, or 0.05805 s. Due to convergence restraints, 6 ms was the closest time of T_2 to T_1 that could be simulated. The value of T3 was then varied to observe the transients associated with the bounce of phase switch C. Figure 4.12 shows the capacitor current waveforms for the bouncing simulation with T3 equal to infinity, meaning that SW1 phase C never recloses. This simulation represents the waveform of the capacitor current after time T_2.

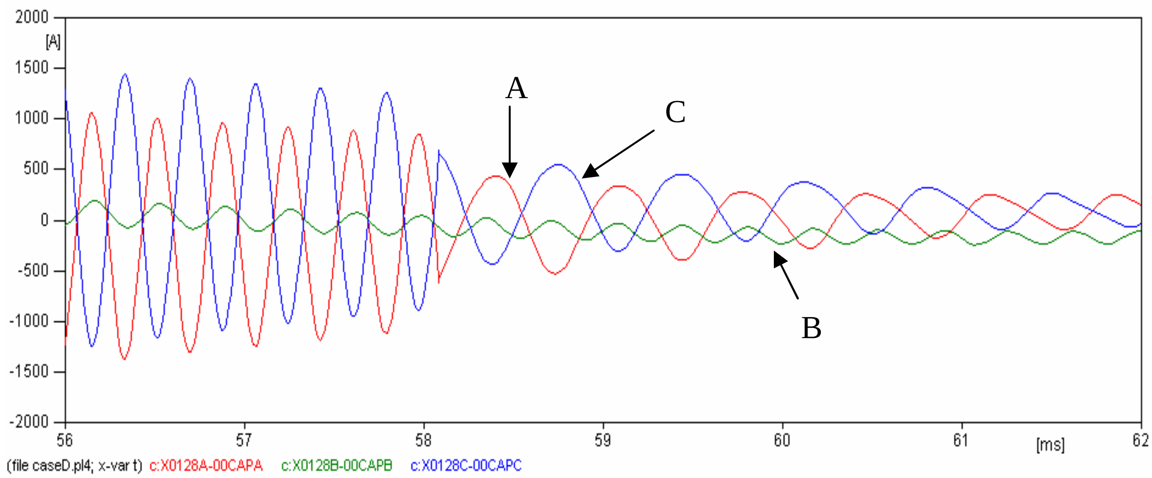


Figure 4.12 the capacitor current waveforms for the bouncing simulation with T3 equal to infinity.

Figure 4.13 shows the waveforms of the capacitor currents in phases A, B, and C with SW1 in phase C re-closed at T_3 = 0.0593 s, which was the worst case observed. The large transient overcurrents occur only in phases A and C after SW1 in phase C (the bouncing switch) is re-closed. The peak overcurrents are 2.053 kA (T = 0.05805 s), and -2.735 kA (T = 0.0593 s) in phase A as shown in Figure 4.13 (a), and -2.422 kA (T = 0.05805 s), and 2.859 kA (T = 0.0593 s) in phase C, as shown in Figure 4.13 (c). Note that the transient overcurrents in phases A and C due to the bouncing of phase switch C are larger than the normal switching transient overcurrents by approximately 35 % in phase A and 21 % in phase C, and they last for approximately three 60 Hz cycles. As shown in Figure 4.13 (b), the capacitor current in phase B is not affected by the bouncing of phase switch C because of the delta-grounded wye transformer operation, as explained Table 4.4.

Figure 4.14 illustrates the waveforms of the capacitor voltage on phases A, B, and C corresponding to the current shown in Figure 4.13. The peak overvoltages are –60.583 kV in phase A, 46.612 kV in phase B, and 56.039 kV in phase C

Simulations like those shown in Figures 4.13 and 4.14 were performed for different values of T_3 from 0.05850 s through 0.06150 s, having the time step of 0.2 ms. Table 4.7 shows the resulting peak overcurrent and voltage values. These peaks can be seen in cycles as the interval between T_2 and T_3 increases. As can be seen in Table 4.7, the largest peak overcurrent occurs when phase switch C in SW1 is re-closed at 0.05930 s, which is 1.25 ms after T_2 (Figures 4.13 and 4.14). Comparing these results to Figure 4.12 it can be seen that when T_3 is close to a peak of phase-C capacitor current it will produce a large overcurrent and overvoltage. This simulation is based on one bounce of one phase switch. It can be seen that the effects of a bounce can increase the value of overcurrents from the normal switching transients by 20-30%. In reality, the phase switch could bounce more than once causing even longer switching transients. Also, the other two phase switches cause bounce.

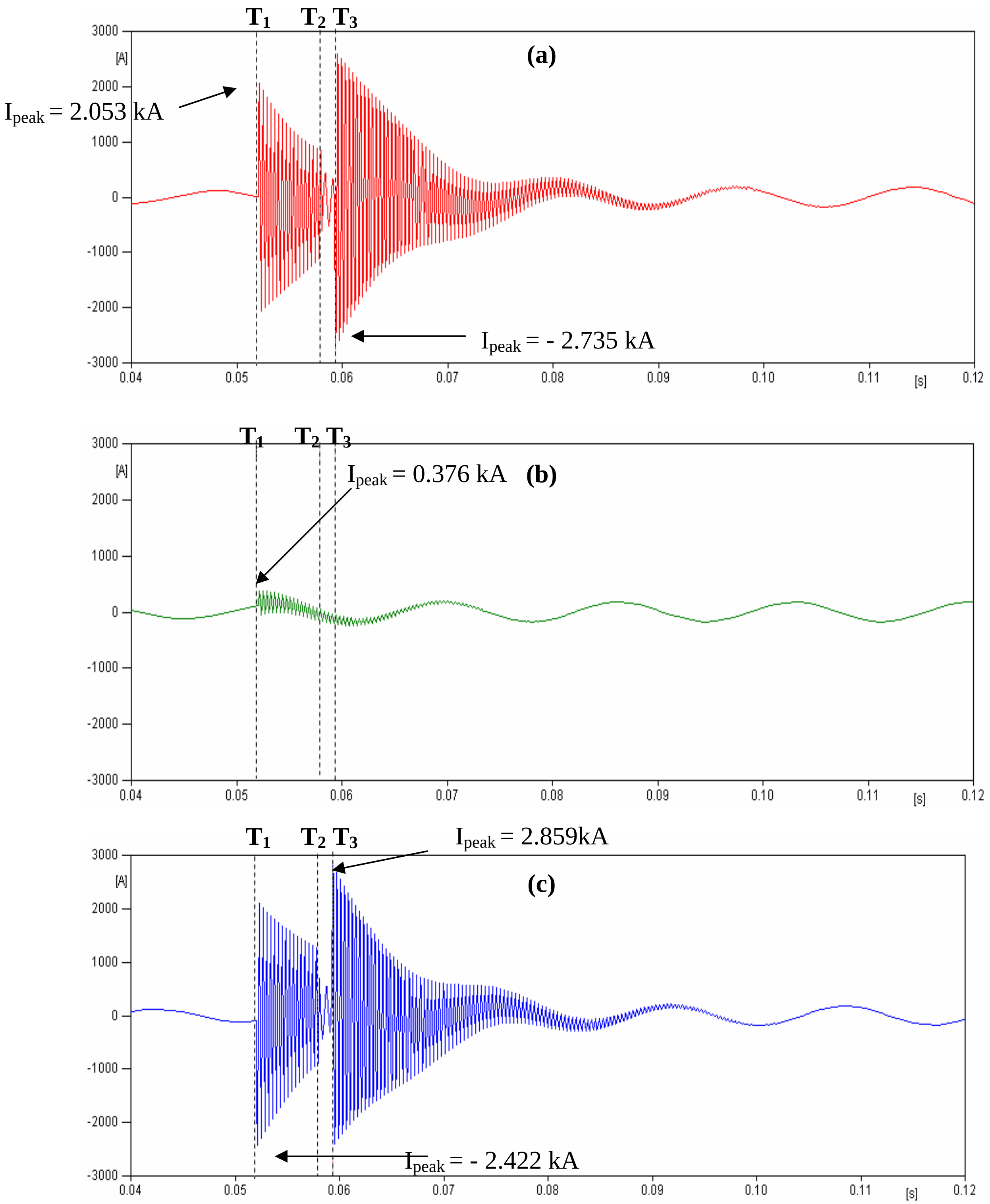


Figure 4.13 Waveforms of capacitor currents during 0.04-0.12 s. SW1 in phase C is reclosed at T_3 = 0.0593 s. (a) phase-A, (b) phase-B, (c) phase-C

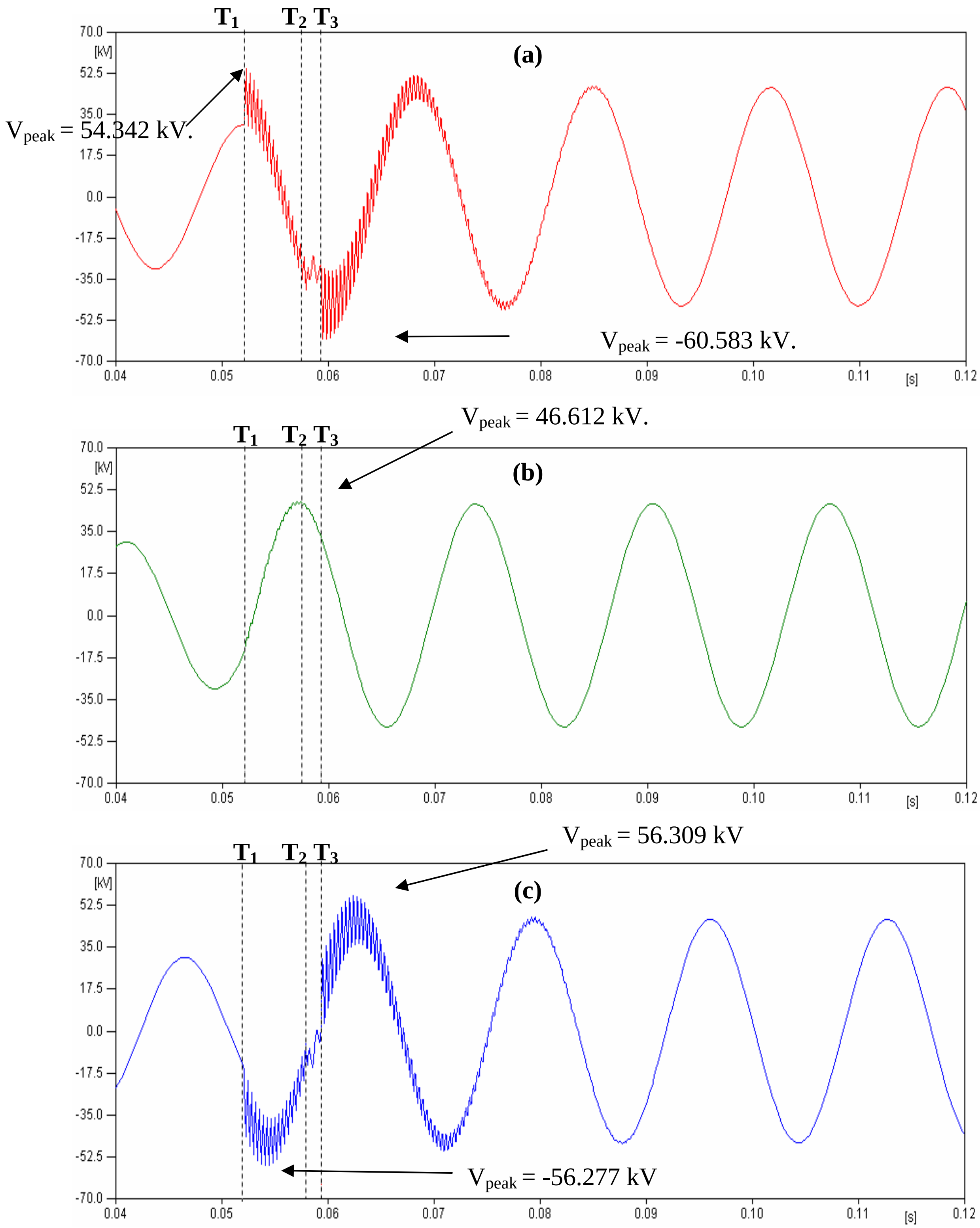


Figure 4.14 Waveforms of capacitor voltages during 0.04-0.12 s. SW1 in phase C is re-closed at T_3 = 0.0593 s. (a) phase-A, (b) phase-B, (c) phase-C

Table 4.7 The peak currents (kA) in phases A, B, and C, when SW1 C is re-closed at different times (T_3)

Time (T_3)	V_A (kV)	V_B (kV)	V_C (kV)	I_A (kA)	I_B (kA)	I_C (kA)
0.05850	**-53.380**	**46.612**	**54.727**	**-2.461**	**0.376**	**2.592**
0.05870	-57.197	46.612	53.787	-2.211	0.376	2.271
0.05890	-51.651	46.612	50.097	-1.094	0.376	1.202
0.05910	-56.576	46.612	53.794	-2.010	0.376	2.181
0.05930	**-60.583**	**46.612**	**56.309**	**-2.735**	**0.376**	**2.859**
0.05950	-55.229	46.612	53.222	-1.775	0.376	1.975
0.05970	-54.955	46.612	52.454	-1.692	0.376	1.762
0.05990	**-59.620**	**46.612**	**56.776**	**-2.537**	**0.376**	**2.769**
0.06010	-58.355	46.612	55.754	-2.402	0.376	2.488
0.06030	-53.243	46.612	53.189	-1.618	0.376	1.846
0.06050	-55.379	46.612	55.314	-2.131	0.376	2.264
0.06070	**-56.000**	**46.612**	**57.096**	**-2.463**	**0.376**	**2.660**
0.06090	-51.232	46.612	54.447	-1.866	0.376	2.034
0.06110	-48.400	46.612	53.646	-1.686	0.376	1.841
0.06130	-49.257	46.612	56.325	-2.129	0.376	2.344
0.06150	-46.364	46.612	55.185	-1.978	0.376	2.108

5 Conclusion

A study of a damaged fuse holder on the 34.5 kV side of a 161 kV: 34.5 kV substation transformer in the Ameren Distribution System was presented. ATP-EMTP modeling was used to simulate the electrical behavior of the system during switching events. The simulation results can be summarized as followed:

1) In the case of all three individual phase switches closing simultaneously, the size of transient overcurrents depends on the time when the switch is closed. When the switch is closed near a phase current peak, a large transient overcurrent can occur in that phase, while the transients in the other two phases are relatively small.

2) In the case of the three individual phase switches closing in sequence, each phase can have a larger transient overcurrent because all the switches may close near a phase current peak. This is in contrast to the previous case in which only one phase usually had a large transient overcurrent.

3) In the case of a phase switch bouncing, the effects of a bounce can increase the peak values of transient overcurrents from the normal switching transients by 20-30%.

The switching phenomenon affects the fuse holder and capacitor bank. According to the simulation, the worst switching phenomenon (bouncing case) can increase the peak of the transient overcurrent from the normal current operation by 9.33 p.u. It can be concluded that the switching phenomenon may play a role in fuse holder damage.

Another possible cause of damage to the fuse holder might be ferroreasonance due to a non-linear inductance (ferromagnetic and saturable) in the transformer, which can produce the abnormal rates of harmonics and transient overvoltage and overcurrent to the system when system is energized.

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Westinghouse

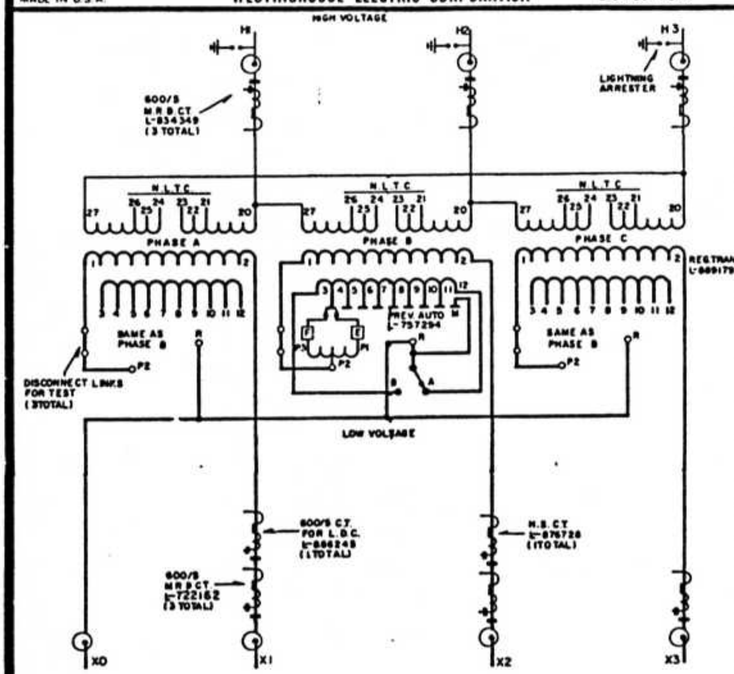
161000 34500Y/19919 VOLTS 60 HERTZ SERIAL	THREE PHASE TYPE SL LOAD TAP CHANGING **TRANSFORMER** CLASS OA/FA/FOA INSULDUR INSULATION	FULL LOAD CONTINUOUSLY 20000/26667/33333 KVA-55°C. RISE 22400/29867/37333 KVA-65°C. RISE GALLONS OIL LTC COMPARTMENT TRANS. TANK

IMPEDANCE ____ % AT 20000 KVA 161000 TO 34500 VOLTS INSTRUCTION BOOK ____

BIL: H.V. WDG. 650 KV., L.V. WDG 200 KV., L.V. WDG. NEUT. 110 KV., L.V. NEUT. BUSH. 150 KV.

APPROX. WEIGHT IN LBS. CORE AND COILS ____ CASE ____ OIL ____ TOTAL ____

MADE IN U.S.A. WESTINGHOUSE ELECTRIC CORPORATION 218 P594 H01A



CONNECTIONS

WINDING	VOLTS	33333 KVA AMPERES	NO LOAD TAP CHANGER POS.	NO LOAD TAP CHANGER CONNECTS	LOAD TAP CHANGER	LOAD TAP CHANGER POS.	CONNECTS P1 ON	CONNECTS P3 ON	CONNECTS R ON
HIGH VOLTAGE DELTA	169050	114	1	23 — 24					
	165025	117	2	22 — 24					
	161000	120	3	22 — 25	—	—	—	—	—
	156975	123	4	21 — 25					
	152950	126	5	21 — 26					
LOW VOLTAGE WYE	31050	558			LOWER	16	4	4	A
	31481	558				14	5	5	A
	31913	558				12	6	6	A
	32344	558				10	7	7	A
	32775	558				8	8	8	A
	33206	558				6	9	9	A
	33638	558				4	10	10	A
	34069	558				2	11	11	A
	34500	558	—	—	—	N	M	M	A
	34931	551			RAISE	2	4	4	B
	35363	544				4	5	5	B
	36794	538				6	6	6	B
	36225	531				8	7	7	B
	36656	525				10	8	8	B
	37088	519				12	9	9	B
	37519	513				14	10	10	B
	37950	507				16	11	11	B

VOLTAGE AND CURRENT RATINGS FOR ODD NUMBERED POSITIONS OF LOAD TAP CHANGER ARE MIDWAY BETWEEN THOSE LISTED ABOVE.
THE 25°C. LIQUID LEVEL IS 16 INCHES BELOW TOP OF HIGHEST MANHOLE FLANGE.
LIQUID LEVEL CHANGES 1.06 INCHES FOR EACH 10°C. CHANGE IN AVERAGE LIQUID TEMPERATURE.
THE TRANSFORMER MUST NOT BE ENERGIZED FROM ANY VOLTAGE SOURCE WHEN NO LOAD TAP CHANGERS ARE OPERATED.
THE LOW VOLTAGE WINDING NEUTRAL MUST BE PERMANENTLY GROUNDED EITHER DIRECTLY OR THROUGH A LOW IMPEDANCE.
IF AN IMPEDANCE IS PLACED IN THE GROUND CIRCUIT, THE VOLTAGE FROM NEUTRAL TO GROUND DURING A FAULT MUST NOT EXCEED 15000 VOLTS.
THE TRANSFORMER TANK IS DESIGNED TO WITHSTAND COMPLETE VACUUM.
THE TRANSFORMER IS DESIGNED FOR OPERATION BETWEEN PRESSURE LIMITS OF 6.5 POUNDS PER SQUARE INCH POSITIVE AND 8.5 POUNDS PER SQUARE INCH POSITIVE.

CONDUCTOR MATERIALS: H.V. AL., L.V. CU.

UNTANKING WEIGHT (HEAVIEST PIECE) 59800 LBS.

H1 H2 H3 (delta) X1 X2 X0 X3 (wye)

RDP 1591 PROPORTION 2½:1 .032 STAINLESS STEEL #7004-19—SATIN FINISH—ETCHED—FILLED WITH BAKED BLACK ENAMEL. [illegible] HOLES FOR 10-32 X [illegible] SCREW.
SIZE [illegible] X 15" AREA 93.858 [illegible] RETURN TO SHARON WORKS, DISTANCE BETWEEN CENTERS OF HOLES ON LONG EDGE 14 [illegible]; ON SHORT EDGE [illegible]

MRISTVEY 10/8/74

REPRODUCE ON BYRON WESTON LEDGER

O[illegible] TRANSFORMER TESTS — WESTINGHOUSE ELECTRIC CORPORATION

[illegible]SE[illegible] ARKANSAS MISSOURI POWER
[illegible] TEST 03/75 PURCHASERS ORDER NO. 44002 G.O. MH35800 S.O. NO. ROP1[illegible]
SL- OA/ FOA/ FOA PHASE 3 HERTZ 60 INSULATING FLUID OIL L.SPEC. /889179 POLA[illegible]TY SUB/PH
[illegible]G H.V. WINDING L.V.
20000/ 26667/ 33333 KVA 20000/ 26667/ 33333
[illegible] 161000 DELTA VOLTAGE 34500 WYE +-10% LTC
TAPS* 169050 165025 161000 156975 152950 -F. C. DELTA

[illegible]ANCES,EXCITING CURRENT,LOSSES AND IMPEDANCE--BASED ON NORMAL RATING,UNLESS OTHERWISE STATED.
[illegible] AND REGULATION ARE BASED ON WATTMETER MEASUREMENTS.
[illegible]REE-PHASE TRANSFORMERS THE RESISTANCES ARE THE SUM OF THE THREE PHASES IN SERIES.

[illegible]L	RESISTANCE IN OHMS AT 75DEG.C. WINDINGS H.V.	L.V.	T.V.	%EXCITE. CURRENT. AT 100%. RATED VOLTAGE	NO LOAD. LOSS WATTS AT 100%. RATED VOLTAGE	%EXCITE. CURRENT. AT 110%. RATED VOLTAGE	NO LOAD. LOSS WATTS AT 110%. RATED VOLTAGE	VOLTAGE	20000 KVA 75 DEG.C. LOAD LOSS WATTS	% IMP	
[illegible]11	19.98390	0.26423		0.2211	27959			161000 TO 34500	71935	7.99	
								169050 TO 37950	67005	8.09	
								152950 TO 31050	69298	7.34	*
								161000 TO 37950	69119	8.19	
								161000 TO 31050	69721	7.[illegible]	*
								169050 TO 31050	70141	7.37	*
								152950 TO 137950	73240	8.48	

	%EXCITE. CURRENT	NO LOAD LOSS			TOTAL LOSS	% IMP
TEST VALUE	0.2211	27959			99894	7.99
GUARANTEE	1.2800	34000			109000	7.92

		100% PF.	% PF.	80% PF.	% PF.
ATION AT 75 DEG.C.	TEST VALUE	0.6782		5.2672	
	GUARANTEE	0.8500		5.7000	

ONLY

UCED CAPACITY ON THESE LTC POSITIONS

*150498 000 *

EBY CERTIFY THAT THIS IS A TRUE REPORT BASED ON FACTORY TESTS MADE IN ACCORDANCE WITH THE TRANSFORMER TEST CODE C57.12.90 OF THE AMERICAN NATIONAL STANDARDS INSTITUTE,AND THAT EACH [illegible]ORMER WITHSTOOD THE ABOVE INSULATION TESTS.

[signature] DATE 7/9/75 APPROVED [signature]

ISER ARKANSAS MISSOURI POWER
IF TEST 05/75 PURCHASERS ORDER NO. 44002 G.O. MH35800 S.O. NO. RDP1991

ATURE RISES--AVERAGE RISE IN DEGREES C. CORRECTED TO INSTANT OF SHUTDOWN OF TRANSFORMER.
NO. * WITH WINDINGS CONNECTED AND LOADED AS FOLLOWS'
NDING 152.950 KV 126 AMP.;
NDING 37.735 KV 510 AMP. UNTIL CONSTANT TEMPERATURE RISE WAS REACHED.

RISE OF WINDINGS BY RESISTANCE.				TOP FLUID RISE	AMBIENT TEMP
H.V.	L.V.	T.V.	GUARANTEE.		
48.0	48.0	0.0	55	42.0	
42.0	47.0	0.0	55	24.0	
47.0	48.0	0.0	55.	31.0	

TION TESTS	WINDING	VOLT RATING	TEST VOLTAGE APPLIED IN KV	DURATION OF TEST IN SECONDS
IED POTENTIAL TESTS				
	H.V.	161000	275.0	60
AGE APPLIED BETWEEN	L.V.	34500	70.0	60
WINDING AND ALL OTHER				
INGS CONNECTED TO CORE	CONTROL	600	1.5	60
GROUND)				

D POTENTIAL TEST

75.0 KV ACROSS H.V. WINDING AT 120 HERTZ FOR 7200 CYCLES.

S

E TO GROUND RESISTANCE AT 20.0 DEG. CENTIGRADE OIL TEMPERATURE EQUALS 1997 MEGOHMS.

UNIT SUCCESSFULLY WITHSTOOD THE FOLLOWING TESTS -
PULSE TESTS APPLIED IN ACCORDANCE WITH ANSI STANDARDS.

PERATURE RISE DETERMINED FROM BASIC DESIGN DATA WHICH HAS BEEN
IFIED BY TEST RESULTS OF SIMILAR TRANSFORMERS.

BOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT
HARON WORKS OF THE WESTINGHOUSE ELECTRIC CORPORATION.

OF TRANSFORMER TESTS

WESTINGHOUSE ELECTRIC CORPORATION

SEM ARKANSAS MISSOURI POWER
F TEST 05/75 PURCHASERS ORDER NO. 44002 G.O. MH35800 S.O. NO. ROP1 1

FICIENCIES AT 75 DEG. C.

100% PF EFFICIENCY	80% PF EFFICIENCY
99.4417	99.3031
99.5030	99.3795
99.5459	99.4330
99.5427	99.4290
99.3551	99.1952

CORONA TEST RESULTS IN MICROVOLTS - 3 PHASE INDUCED TEST

Applied KV	Measured On H1	H2	H3
210	5.2	8.0	7.2
275	10.0	27.0	24.0
Off.	3.4	4.2	4.0
210	5.2	7.7	6.8

BOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT
HARON WORKS OF THE WESTINGHOUSE ELECTRIC CORPORATION.

REPORT OF TESTS
WESTINGHOUSE FORM #491 F

DATE Jul7 10, 1975

PURCHASER Arkansas Missour Power Co.

WESTINGHOUSE GENERAL ORDER NO. MH-35800

APPARATUS SL- LTC

SHOP ORDER NO. RDP15911

RATING 20,000/26667/33333 KVA - 161000 H.V.- 34,500 L.V.

RATIO VALUES

Apply Volts	NL TC	UL TC	Calc. Volts	ØA	ØB	ØC
500	1	16L	53.02	53.11	53.11	53.11
	2		54.32	54.42	54.42	54.42
	3		55.67	55.76	55.76	55.76
	4		57.10	57.20	57.20	57.20
	5		58.60	58.69	58.69	58.69
				59.00	59.00	59.00
		14	59.42	59.50	59.50	59.50
				59.80	59.80	59.80
		12	60.23	60.27	60.27	60.27
				60.60	60.60	60.60
		10	61.05	61.04	61.04	61.04
				61.40	61.40	61.40
		8	61.86	61.85	61.85	61.85
				62.20	62.20	62.20
		6	62.67	62.65	62.65	62.65
				62.99	62.99	62.99
		4	63.49	63.44	63.44	63.44
				63.78	63.78	63.78
		2	64.30	64.24	64.24	64.24
				64.60	64.60	64.60
		N	65.12	65.04	65.04	65.04
				65.38	65.37	65.38
		2R	65.93	65.82	65.82	65.82
				66.15	66.15	66.15
		4	66.74	66.64	66.64	66.64
				66.95	66.95	66.95
		6	67.56	67.45	67.45	67.45
				67.75	67.75	67.75
		8	68.37	68.25	68.25	68.25
				68.56	68.56	68.56
		10	69.18	69.00	69.00	69.00
				69.35	69.35	69.35
		12	70.00	69.82	69.82	69.82
				70.15	70.17	70.15
		14	70.81	70.60	70.60	70.60
				70.95	70.95	70.95
		16	71.63	71.43	71.43	71.43
		15-	70.81	70.60	70.60	70.60
		15+	71.63	71.43	71.43	71.43

THE ABOVE IS A TRUE AND CORRECT RECORD OF DATA OBTAINED FROM TESTS AT THE WORKS OF WESTINGHOUSE ELECTRIC CORPORATION.

PAGES 4 OF 4 PAGES

SIGNED [signature] ENGINEER

LOW VOLTAGE OIL CIRCUIT BREAKER

34.5 KV 1200 Amps Type 34.5GS1500
Serial No. 1-37Y5999 Manufacturer WESTINGHOUSE

Purchase Order No. ARK-MO 45592 Date ____ WO ____ For ____
Spec. No. & Date ____ Date Rec'd ____ Amount ____
Rated Voltage ____ Operating Voltage ____
Interrupting Rating 1500 MVA MVA or Amps Rated Sym. Short Circuit Current At Rated Voltage ____ Amps Impulse Withstand ____ KV

Current Transformers	Ratio	Type	Location
			S.P. 150500
			Viburnum Sub

Relays	No.	Manufacturer	Catalog No.	Type
Phase Over-Current				
Ground Over Current			INDEX ONLY	
Reclosing				
Voltage Unbalance				

Operation	Volts AC	Volts DC	Amps	Remarks
Tripping		70-140	11	MASTER PRINT
Closing		90-130	2	RETURN IMMEDIATELY TO
Heaters	230			E.G. & CONST.
Motor				DRAFTING DIV.

Bushing MFG WH Rating 34.5 KV 1200 Amps. A P & L Stock No. 263-840
Catalog No. 424D788 GR2 Stud Size ____ Terminal ____

Mechanism Type AA7

Notes 5-cycle int.

*150500 000 *

Drawing Number
Outline ____
BCT Curve ____
Conn. Diagram ____
Instruction Book ____

Breaker Mounting Frame
Standard ☐
Extended ☐ ____ "
Oil Per Tank ____ Gals.
Total Weight ____ Lbs.

File ____
Date ____

AMP # 2064

A P & L Company No. 3134P

No.	Location	Breaker Number	Date Installed	Date Removed	Remarks
	VIBURNUM				

RATED SHORT CKT AMPS 22000

1200
AMPS MAX. LOAD

OCB [X]
OCR [ ]
ACB [ ]

CO. NO. 2064

MFG. Whouse TYPE 345GS1500 INT. CAP 1500MVA PHASE 3 MFG. ORDER OR S.O. NO. 1-37Y5999

VOLTAGE 34500 MAX. DESIGN V 38000 NO. TANKS 1 GAL. EACH 170

TYPE TRIPPING 60 CYCLE 5~ INT. Time MIN. TRIP TOTAL WT. 5000

TIME PHASE 1 PHASE 2

PHASE 3 TEST CT. 200KV B.I.L

INST BOOK - 33-[illegible]

OPERATING MECH.

TYPE AA7 SO NO. 37Y5999 CONTROL DIAG. NO. 266C266

HEATER V 230 AC COMP V 230 AC CLOSING V 90-130 DC INST. BOOK 33-125-C2

TRIP V ~~90-130 DC~~ → 70-140 DC E/R CLOSING AMP 2 E/R TRIP AMP 11

BUSHING DATA ASA "L" 31.5

MFG. Wh. SERIAL 061975 CAT. NO.

KEY 392 TYPE S DWG. NO. 424D788GR2

BIL 200 KV VOLT KV 34.5 AMPS 1200

BUSH. CT. YES NO RATIO TYPE

CAPACITANCE XFMR. YES NO WT.

PRESSURE SW. SETTINGS

GOVERNOR OPENS 150

LOW PRESSURE ALARM CLOSE 120

LOW PRESSURE CUTOUT OPENS 110

MFG. DATE 1975

P. O. NO

PRICE

2A SHIPMENT COMPLETE

ARKANSAS-MISSOURI POWER COMPANY
BLYTHEVILLE, ARK.

MARK THIS PURCHASE ORDER NUMBER ON EVERY PACKAGE, BILL OF LADING, & SHIPPING MEMORANDUM.

45592

January 14, 1975

FOR PURCHASING DEPT.

FOR OUR USE ONLY

WORK ORDER 154.1010 - 301
ACCOUNT
REQUISITIONED BY EEK
REQUISITION NO. EK-029

Westinghouse Electric Corporation
1520 First National Bank Building
Memphis, Tennessee 38103

INSTRUCTIONS

SEND THIS TICKET TO PURCHASING DEPARTMENT IN REPORTING RECEIPT OF COMPLETE OR FINAL SHIPMENT ON THIS ORDER.

SEND PARTIAL SHIPMENT REPORT TO PURCHASING DEPARTMENT IN REPORTING RECEIPT OF PARTIAL SHIPMENTS.

ATTACH FINAL PARTIAL SHIPMENT REPORT TO THIS RECEIVING SHIPMENT.

ATTACH REQUEST FOR ADJUSTMENT IN REPORTING EXCEPTIONS IN SPACE PROVIDED.

SHIP TO

ARKANSAS-MISSOURI POWER COMPANY
Storeroom
Ironton, Missouri 63650

PREPAY & ALLOW. ☒ PREPAY & CHARGE ☐ COLLECT ☐	F.O.B.	SHIP VIA.	REQUESTED DEL.	TERMS	SALES & USE TAX
	Dest.	Truck	August 1, 1975	Net	3% Mo.

REC.	ITEM	QUANTITY	UNIT	CAT. NUMBER	DESCRIPTION	UNIT COST
	1	1	Ea.	/	34.5 KV Outdoor Type Oil Circuit Breaker, 3 Phase, 3-Phase, 1200 Amp Cont., 1500 MVA interrupting capacity. (29705)	$12,040.[illegible] Each
	2	1	Ea.	/	Tank Lifters	472.[illegible] Each
					Per Ark-Mo Inquiry No. 74-SD-2 and Westinghouse proposal dated 12/5/74. (Item V-C)	
					Request delivery August 1, 1975 F.O.B. Dest. Adder included above Selling policy 33-000 will apply 9-1-74	
					RU-310	
					Ref: Viburnum 161 K.V. Sta.	
					Recieving Loca: Notify G.O. Engr. Dept. upon receipt of materials (all or part).	

ACCOUNT NO. 154.1010.301

FRT. CHARGES

Jack N. Sinara

DRAWING TRANSMITTAL
FORM 34576 B

SEND APPROVALS OR INQUIRIES TO:

Westinghouse Electric Corporation
1520 First National Bank Building
Memphis, Tennessee 38103

~~4-7-75~~
3-20-75
TRANSMITTAL DATE

S. O. NO.	PROD. CODE	ATTN. CUST. SERVICE REP.	CUST. ORDER NO.	G. O. NO. & DATE-C/N DATE
37Y5999		Fury	45592	MH-37449-YC

CUSTOMER	ULTIMATE USER AND/OR MARKINGS
Arkansas - Missouri Power Company P.O. Box 628 Blytheville, Arkansas 72315	Arkansas - Missouri Power Company Ironton, Mo. 63650

[ ] FOR APPROVAL, TO MAINTAIN SHIPPING SCHEDULE, APPROVED DWGS, MUST BE RECEIVED BY WESTINGHOUSE ON ______
DRAWINGS ARE IN COMPLIANCE WITH YOUR SPECIFIED REQUIREMENTS, DRAWINGS "APPROVED" OR "APPROVED WITH MODIFICATIONS" AUTHORIZE WESTINGHOUSE TO PROCEED WITH THE MANUFACTURE, MODIFICATIONS NOT IN THE CONTRACT OR MODIFICATIONS MADE DURING OR AFTER DRAWING APPROVAL MAY RESULT IN A PRICE CHANGE AND/OR SHIPMENT DELAY.

[X] FOR CONSTRUCTION OR INSTALLATION
THE EQUIPMENT SHOWN ON THESE DRAWINGS (S) HAS BEEN RELEASED FOR MANUFACTURE; ANY MODIFICATION MAY RESULT IN PRICE CHANGE OR SHIPMENT DELAY.

[ ] AFTER FIELD CHANGES

[X] Finals

SPECIFIC CUSTOMER INSTRUCTIONS ARE DETAILED IN NOTES
* TYPE OF REPRO Mylar

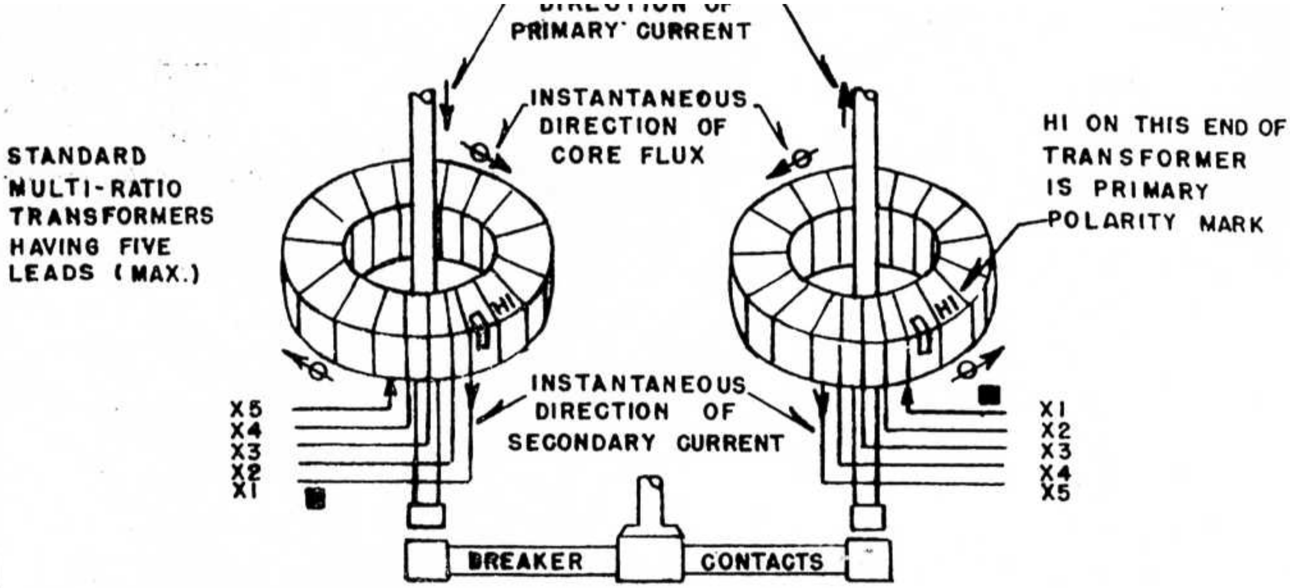
DRAWINGS: APPROVAL STD./SKETCH	APPROVAL PAPER REPRO	CONSTRUCTION OR INSTALL PAPER	CONSTRUCTION OR INSTALL * REPRO	AFTER FIELD CHANGES PAPER	AFTER FIELD CHANGES * REPRO	INSTR. BOOKS BND.	INSTR. BOOKS UN-BND.	MAIL DWGS. TO
		3	1			3		Arkansas - Missouri Power Company - P.O. Box 628
								Attn: Mr. Earl King - Blytheville, Arkansas 72315
		1				1		Memphis Customer Service - Mr. C.M. Fury
THIS LINE FOR DIVISION USE ONLY T/S	T/S	T/S	T/S	T/S	T/S	T/S	T/S	Trafford PCB TC-201 C/S - J.S. Karas Trafford PCB TC-253 Engr. - D.S. Eckels

ITEM	QUANTITY	DESCRIPTION
1	1	Type 34.5-GS-1500 - 1200 Amps.

DWG. NO.	SUB	DRAWING TITLE
2064C58-1		Breaker Outline - ANSI-24 Dark Gray Paint Finish
266C266-4		Control Diagram - 125V DC Close & Trip - 230V AC Compr. & Htr. PH/FEQ 1-phase - 60 Hz.
518B340-1		Transformer Connection Diagram 1200/5 Ratio on Location 1U-3U-5U-2U-4U-6U Accuracy C-200 Thermal 1.0
512A354-1		Transformer Ratio Diagram
512A352-3		Transformer Polarity Diagram
542326-C		Transformer Excitation Curve
701C208-5		Condenser Bushing Outline - Chocolate porcelain - Std. Creep - 424D788 G01
33-255-1		Breaker Instruction Book
33-125-C2		Mechanism Instruction Book

 Finals 4-7-75

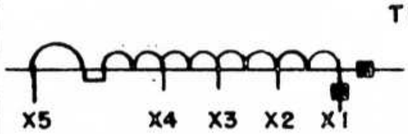
S.O. 39 Y7881 | SUB. 3
D.
SUB. 2 WAS FILM NO P16856
DWG. RETRACED NO CHANGES. R.H.
M.K.B. 7-7-70
P19535 WM/RH



WHITE POLARITY MARK ABOVE TERMINAL X1 INDICATES LIKE POLARITY FOR THE MARKED PRIMARY (THE END OF THE BREAKER TERMINAL OPPOSITE THE BREAKER CONTACTS) AND THE MARKED SECONDARY (TERMINAL X1). WHEN INTERMEDIATE TAPS ARE USED THE TAP NUMERICALLY NEAREST X1 HAS THE SAME POLARITY AS X1.

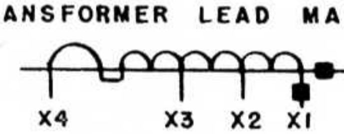
FIG 1

TRANSFORMER LEAD MARKING



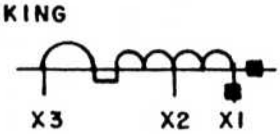
5 LEAD

FIG. 2



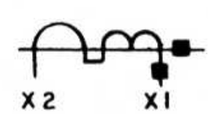
4 LEAD

FIG. 3



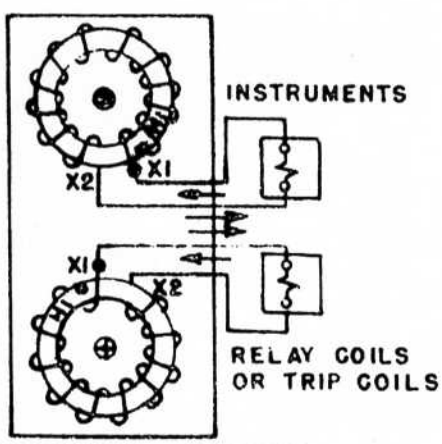
3 LEAD

FIG. 4



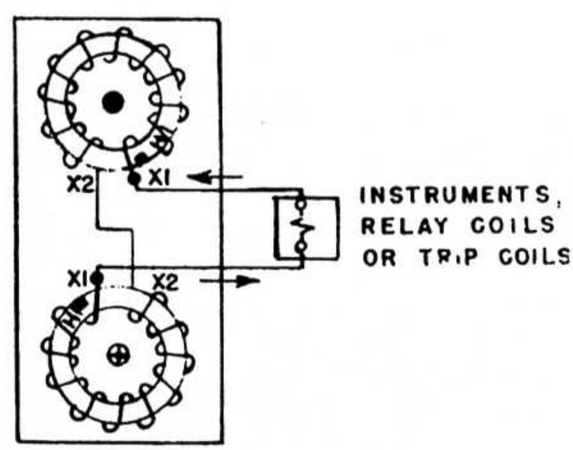
2 LEAD

FIG. 5



TRANSFORMERS CONNECTED INDEPENDENTLY

FIG. 6



TRANSFORMERS CONNECTED IN SERIES

FIG. 7

WESTINGHOUSE ELECTRIC CORPORATION

512 A 352

TITLE TYPICAL BUSHING TYPE CURRENT TRANSFORMER - POLARITY - LEAD MARKING - CONNECTION - FOR POWER CIRCUIT BREAKER

DIV. - PCB

PLANT LOCATION TRAFFORD, PA. USA

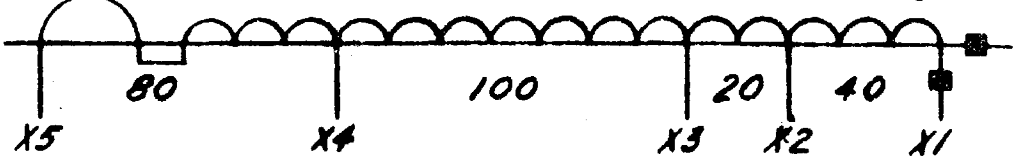
FORM 31951

6300

WESTINGHOUSE ELECTRIC CORPORATION – DIVISION Pwr Cir Bkr PLANT LOCATION Trafford, Pa.

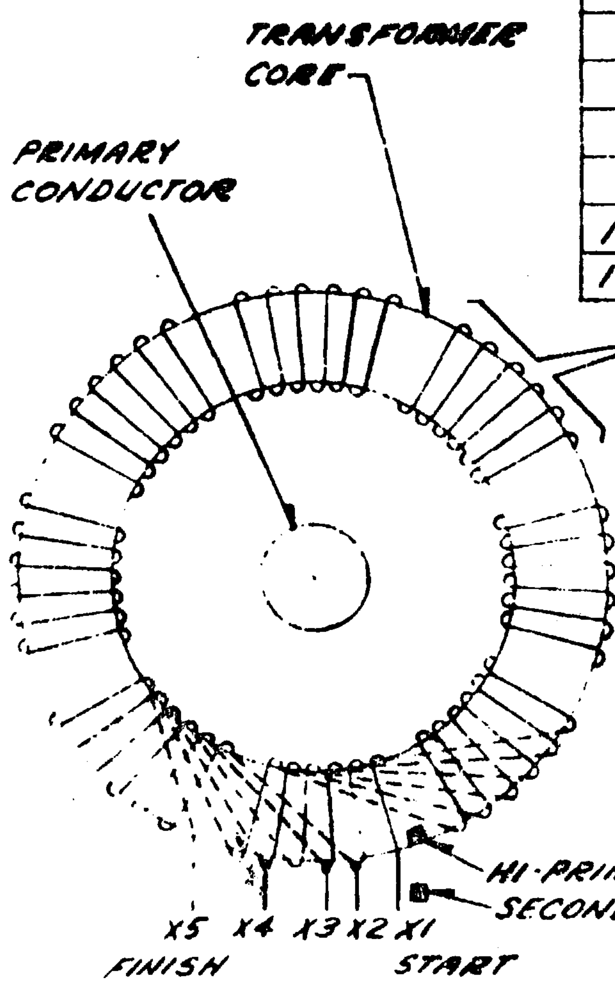
TITLE CONNECTION CHART FOR 1200 TO 5 AMPERE MULTI-RATIO BUSHING TYPE CURRENT TRANSFORMER

DEVELOPMENT OF WINDING GIVING NUMBER OF TURNS BETWEEN TAPS.



CONNECTION CHART

CURRENT RATIO	TURN RATIO	SECONDARY TAPS
100 TO 5	20 TO 1	X2 - X3
200 TO 5	40 TO 1	X1 - X2
300 TO 5	60 TO 1	X1 - X3
400 TO 5	80 TO 1	X4 - X5
500 TO 5	100 TO 1	X3 - X4
600 TO 5	120 TO 1	X2 - X4
800 TO 5	160 TO 1	X1 - X4
900 TO 5	180 TO 1	X3 - X5
1000 TO 5	200 TO 1	X2 - X5
1200 TO 5	240 TO 1	X1 - X5



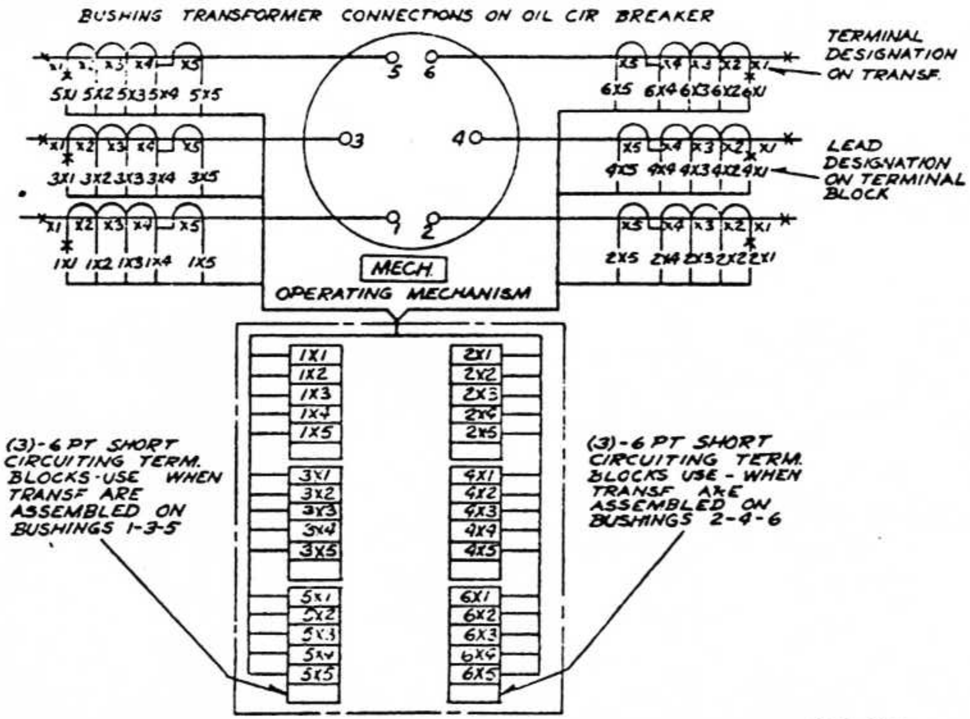
SECONDARY CONDUCTOR - CONSISTS OF NECESSARY WINDING SECTIONS, EACH SECTION FULLY DISTRIBUTED AROUND THE CORE TO PERMIT EACH TAP SECTION TO BE FULLY DISTRIBUTED.

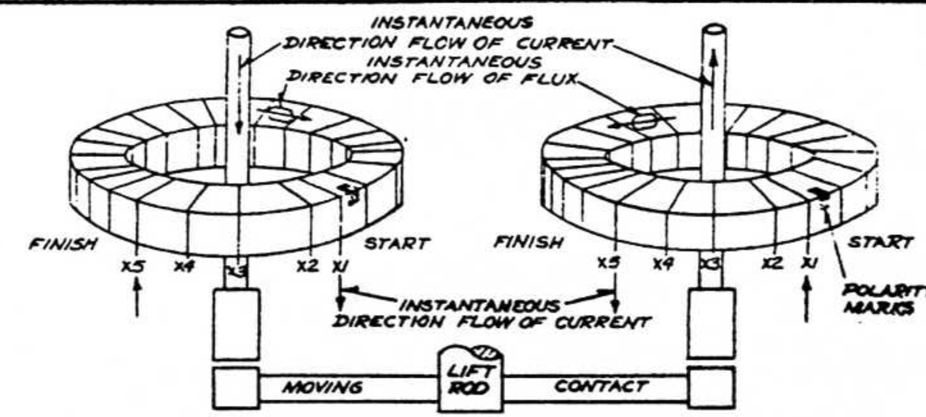
NOTE: POLARITY MARK ADJACENT TO TERMINAL X1 INDICATES "LIKE POLARITY" FOR THE MARKED PRIMARY "H1" (THE END OF THE BKR. TERMINAL OPPOSITE THE BKR CONTACTS) AND THE MARKED SECONDARY "X1." WHEN INTERMEDIATE TAPS ARE USED, THE TAP NUMERICALLY NEAREST X1 HAS THE SAME POLARITY AS X1.

512A354

518B340

BUSHING TRANSFORMER CONNECTIONS ON OIL CIR BREAKER





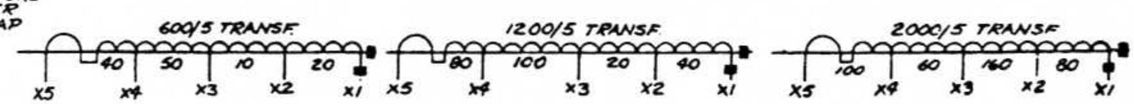
	600 AMP NOMINAL RATIO	SEC TAPS	1200 AMP NOMINAL RATIO	
	50 TO 5	X2-X3	100 TO 5	*
*	100 TO 5	X1-X2	200 TO 5	*
	150 TO 5	X1-X3	300 TO 5	*
*	200 TO 5	X4-X5	400 TO 5	*
	250 TO 5	X3-X4	500 TO 5	*
*	300 TO 5	X2-X4	600 TO 5	*
*	400 TO 5	X1-X4	800 TO 5	*
	450 TO 5	X3-X5	900 TO 5	*
*	500 TO 5	X2-X5	1000 TO 5	*
*	600 TO 5	X1-X5	1200 TO 5	*

SEC TAPS	2000 AMP NOMINAL RATIO	
X3-X4	300 TO 5	*
X1-X2	400 TO 5	*
X4-X5	500 TO 5	*
X2-X3	800 TO 5	*
X2-X4	1100 TO 5	*
X1-X3	1200 TO 5	*
X1-X4	1500 TO 5	*
X2-X5	1600 TO 5	*
X1-X5	2000 TO 5	

* THESE RATIO HAVE SECONDARY WINDINGS FULLY DISTRIBUTED AROUND THE CORE

WHEN ONLY THREE TRANSFORMERS PER BREAKER ARE FURNISHED THEY WILL BE ASSEMBLED ON BUSHINGS 1-3-5 UNLESS OTHERWISE SPECIFIED ON ORDER

SINGLE RATIO TRANSFORMERS WILL BE WIRED TO THE TERMINAL BLOCKS AND THE TERMINAL BLOCKS MARKED WITH BOTH THE TRANSFORMER LEAD AND THE BUSHING NUMBER IE 1X1-1X2, 3X1-3X2, 5X1-5X2 MULTI-TAP TRANSFORMERS WILL BE CONNECTED TO THE TERMINAL BLOCKS AND THE TERMINAL BLOCKS WILL BE MARKED TO CORRESPOND



DEVELOPMENT OF WINDING GIVING THE NUMBER OF TURNS BETWEEN TRANSFORMER TAPS

Westinghouse Electric Corporation

TITLE BUSHING TYPE CURRENT TRANSFORMER CONNECTIONS ON OIL CIRCUIT BREAKER

DIMENSIONS IN INCHES - SCALE

APPD P. M...

APPD

APPD

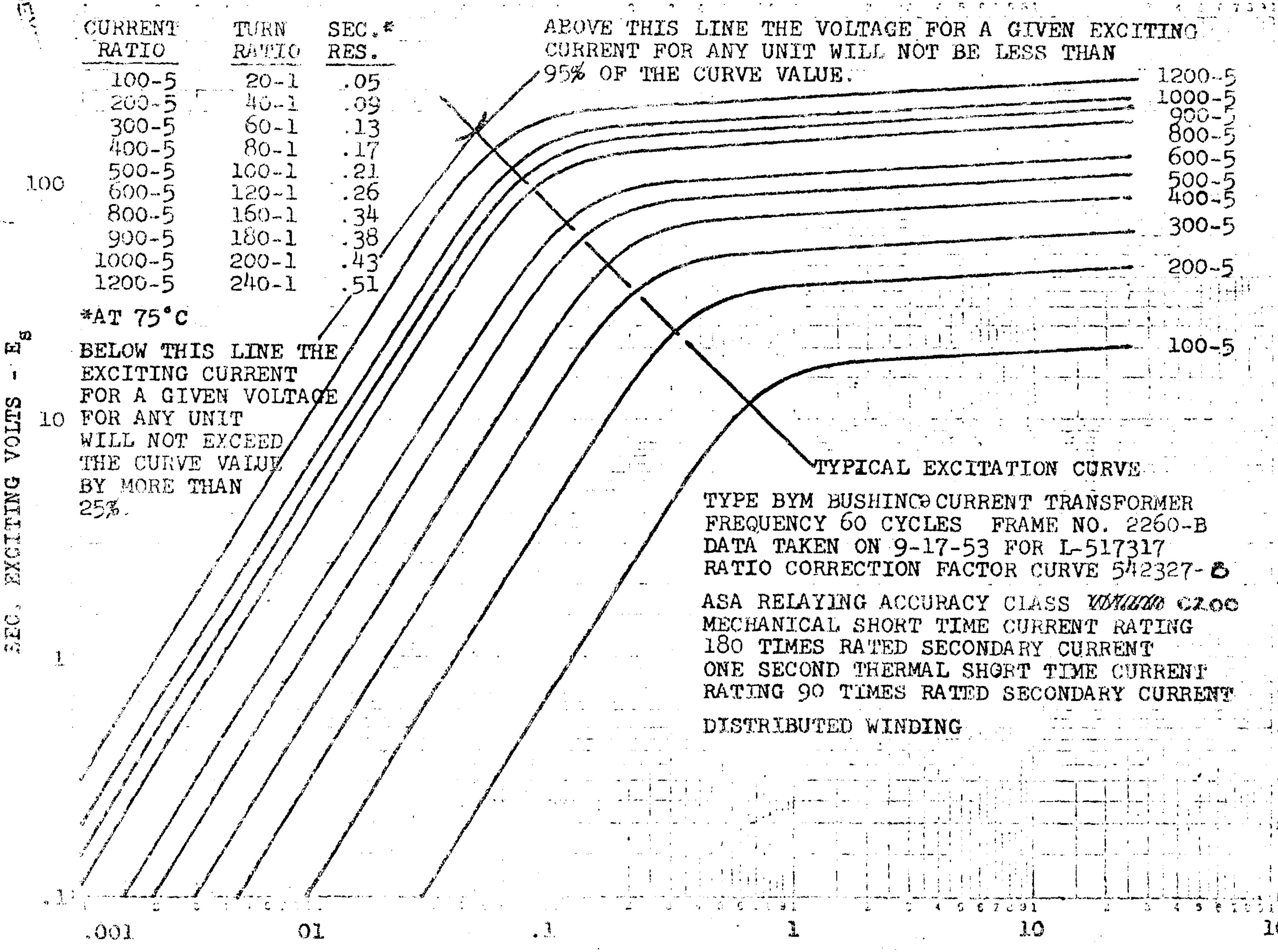
REF DWG 517B814

CHANGE

518B340

69

20148



TYPE BYM BUSHING CURRENT TRANSFORMER
FREQUENCY 60 CYCLES FRAME NO. 2260-B
DATA TAKEN ON 9-17-53 FOR L-517317
RATIO CORRECTION FACTOR CURVE 542327-B

ASA RELAYING ACCURACY CLASS C200
MECHANICAL SHORT TIME CURRENT RATING
180 TIMES RATED SECONDARY CURRENT
ONE SECOND THERMAL SHORT TIME CURRENT
RATING 90 TIMES RATED SECONDARY CURRENT

DISTRIBUTED WINDING

J. W. PELTIS
CURVE NO. 542326-C
6-29-70
2-17-71

1200-5 MR CURRENT RATIO L-SPEC. 694340
CURVE NO. 542326-C
POWER CIRCUIT BREAKER ENGINEERING