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Lightning Induced Over-voltages in Power Transformer and Voltage Spikes in Connected Load

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ABSTRACT OF THE
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Power Transformers are subjected to lightning strokes, which causes the voltage at the secondary side to rise abruptly. The main aim of the report is to investigate the voltage at the medium and low voltage side in electrical system of a power plant when the high voltage power transformers are subjected to lightning strokes. Based on modelling and simulations implemented in EMTP/ATPDraw, the voltage at the 15.75 kV, 6 kV and 0.4 kV is determined to ensure if the transferred over-voltage is within the basic insulation level (BIL) of the connected equipment. Transformer frequency model, surge arrestor, cables and transmission tower are arranged in a single environment of EMTP/ATPDraw. A study is carried out to analyze the transferred transient over-voltage in the low voltage side taking the scenario of direct stroke and back flashover. Combination of different surge arrestor are implemented and analyzed to mitigate the transient voltage transferred to the medium and low voltage side.

Keywords: Transformer, Overvoltage, EMTP, Surge Arrestor, Capacitance, BIL, Back flashover

Preface

I would like to thank Prof.Matti Lehtonen for his valuable assistance and support during my Thesis at Aalto University.
Also, my sincere thanks to the Power System research group who helped me during my work.

Otaniemi, September 28, 2017 Deepak Subedi

Contents

Symbols and abbreviations

Symbols

α	Attenuation coefficient along the tower
C	Capacitance
C_o	Surge propagation velocity
f	Frequency
f_r	Resonance frequency
H	Impedance gain
L	Inductance
R	Resistance
R_f	Tower footing resistance
V_{fo}	Insulator flashover voltage
V_{in}	Input Voltage
V_{out}	Output Voltage
Y	Admittance
Z	Impedance
Z_p	Surge impedance
Z_{Tx}	Coil impedance of Transformer

Abbreviations

ATP	Alternative Transients Program
BIL	Basic Insulation Level
CFO	Critical Flashover Voltage
EMTP	Electro Magnetic Transient Program
FRA	Frequency Response Analysis
HV	High Voltage
kV	Kilo Volt
kA	Kilo Ampere
LV	Low Voltage
MV	Medium Voltage
	Mega Volt
MVA	Mega Volt Ampere
SA	Surge Arrestor
TFR	Transformer

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1 Introduction

1.1 Introduction

Lightning is a meteorological process that has adverse effects on human life. Considering electrical power system point of view, system has to be protected against lightning as huge part of it is exposed to lightning. Components of the power system can be exposed to the transient over-voltages occurring due to the lightning stroke. These over-voltages, are of high magnitude and can cause damage to the connected equipment when necessary protection is not enabled against the lightning surges. Lightning has been one of the the major cause of power outage and has significant damage to the power system and its components. This effects the power quality and the reliability of the system.

The investigation of the lightning surge is necessary to ensure a reliable power system operation as the over voltage caused by the lightning surge is the prime factor considering the insulation coordination of the power system apparatus and protection of transmission and substation equipment. Generally, there are two ways through which lightning causes damage to the power apparatus: (i) lightning increases the voltage across the equipment in such way that the equipment terminals spark-over resulting in short circuit or voltage puncture through the electrical insulation of the apparatus resulting in permanent damage. (ii) melt down or fracture of the apparatus, when the energy handling capacity of apparatus lags the energy of the lightning stroke. The equipment used and connected in the network have a defined basic insulation level (BIL) and when the over-voltage exceeds the defined limit, insulation breakdown occurs and the equipment fails. There are number of strokes within a lightning flash which reduces negative or positive charges from cloud to the ground. The first lightning stroke is more extreme than the later strokes. Small current continuously flows between two strokes which results in the increase of energy injecting the object.

This thesis deals with the transient over-voltage transferred to the medium and low voltage side of the electrical system of a power plant when the high voltage side of the system is subjected to a lightning stroke. The study is carried out using Alternative Transient Program (ATP), a version of electro magnetic transient program (EMTP). The study presented in this work analyses the transient over-voltage of a 400-15.75-6-0.4 kV system under the scenario of direct stroke and back flashover. Power transformer of rating 300 MVA, 415/15.75 kV and distribution transformers of rating 25 MVA and 1 MVA with low voltage side rating of 6 kV and 0.4 kV respectively are used in the study. The maximum amount of lightning current entering the phase wire before the insulator flashovers is analyzed and the same current is used in the simulation for the case of direct stroke. Also, lightning current of 200kA, $1.2/50\mu s$ is used for the case of direct stroke and result is analyzed with the case of back flashover. For the case of back flashover, step voltage impulse of 1640 kV is applied to the phase conductor. This voltage corresponds to the flashover voltage of the insulator string.

1.2 Thesis Objectives

The objective of this thesis are as:-

i. To study and analyze the transferred transient over-voltage due to direct and indirect stroke with different combination of protective surge arrestors in electrical network of a power plant.

ii. To study and model the different components of the system.

iii. To simulate and analyze the transferred transient over-voltage of a 400/15.75/6/0.4 kV network using EMTP/ATPDraw software

iv. To ensure if the transient over-voltage at the 15.75 kV and 6 kV side of the system is within the protective level (basic insulation level) of the connected equipment.

There are two ways in which the transient voltage is generated from the lightning stroke in a electrical system.

i.) Direct Stroke

ii.) Indirect Stroke

1.3 Scope of the Work

The scope of the work can be distributed in several parts. The modelling and simulation are done with the Electro Magnetic Transient Program (EMTP). The transferred transient voltage to the 15.75 kV, 6 kV and 0.4 kV side due to the direct and indirect stroke on 400 kV transmission line entering the substation is studied. The protective measures for the mitigation of transient over-voltage transferred to the medium and low voltage side of the network with different arrangement of protective surge arrestor is also analyzed.

1.4 Thesis Organization

The thesis has been organized into five chapters mainly.

Chapter 1: This chapter presents the general introduction, effects, causes and importance of transient over-voltage studies for protection of system and connected equipment. The chapter also includes the objectives and scope of the thesis.

Chapter 2: This chapter presents the theoretical information regarding different types of transients, causes of the transients, and types of lightning stroke.

Chapter 3: This chapter is related with the modelling of the different components of the power system used for the transient studies such as Power Transformer, Surge Arrestor, Transmission Tower, Distribution Transformer and Cable.

Chapter 4: This chapter presents the simulation studies for different cases of lightning stroke with several arrangements of surge arrestors and the results of the simulation.

Chapter 5: This chapter analyzes the results of the simulation for different cases and presents the conclusion of the thesis.

2 Literature Review

2.1 Transient Over-voltage

An electrical transient is defined as the action of sudden change in the circuit condition which may occur due to switch opening or closing or due to occurrence of fault on a system. The period of transition is very short. During this time, the system components are subjected to tremendous stresses from current or voltage [1].
Transient over-voltages are usually short duration, high magnitude voltage peaks with fast rising edges, referred as surges. The main cause of the transient over-voltages are the lightning strokes which may result in complete outage of an unprotected system. Electrical equipments are subjected to continuous stress by multiple transients due to switching operations of inductive loads such as motors, transformers etc. Switching transients are the result of short-circuit current interruption. These transients are of low magnitude than the lightning transients[2].

2.2 Causes of Transients

The main causes of the transients in power system can be classified into natural and technical cause. The natural cause is associated with the lightning stroke and switching transients are concerned with the technical cause.

Depending upon the shape of the waveform, transients are further classified into:

1. **Impulsive Transients:** It is associated with the abrupt change in the steady state condition of current, voltage or both in either positive or negative or both direction [3]. These transients are analyzed by rise and decay time of the transient. The effects of these transient are localized as the transients are damped instantly by the resistive element of the circuit.
   Impulsive lightning strikes are the main cause of impulsive transients. These transients have a sudden rise followed by an exponential decay.

2. **Oscillatory Transients:** Oscillatory transient is associated with the sudden non-power frequency change in the steady state condition of current, voltage or both which includes both positive and negative polarity [4]. These transient oscillate at the natural system frequency. These transients show damped oscillation with frequency range from few hundred Hertz to Mega Hertz. Oscillatory transients are dominant over impulsive transient as the oscillatory transients are natural transients. These transients generally occur during capacitor energizing and transmission line energizing.

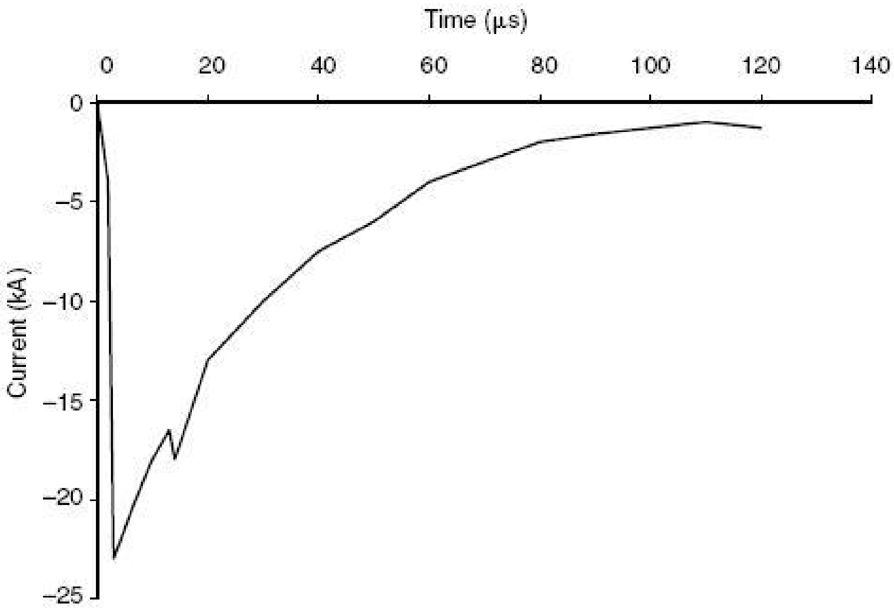

Figure 2.1: Current Impulse transient due to lightning stroke [4].

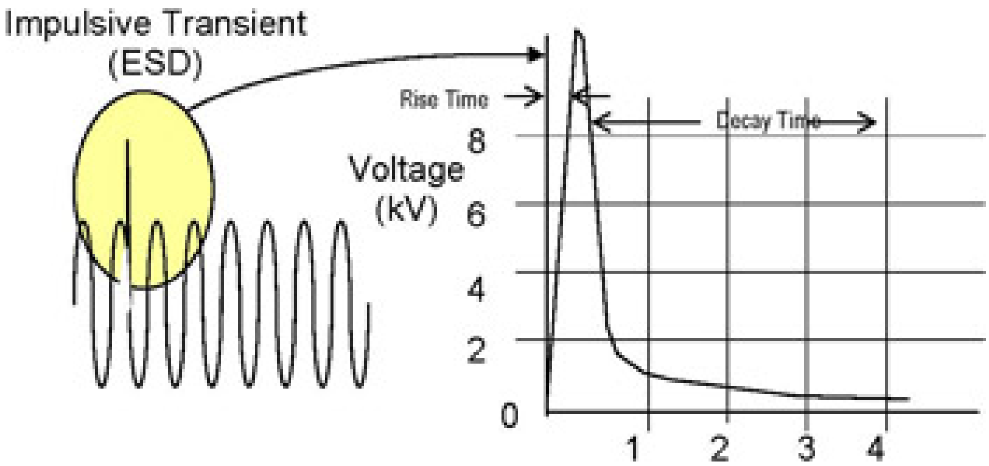

Figure 2.2: Oscillatory Transient waveform [4].

2.3 Lightning Stroke

There are two types of lightning strokes that generates transient voltage in a power system:

1. **Direct Stroke:** During direct stroke, the lightning stroke strikes the phase conductor of the connected transmission line of the network which results in generation of a travelling voltage wave. This voltage is impressed along the terminals of the connected equipment or across the insulator at the end of the line span [8]. The over-voltage propagates through the cable throughout the entire substation causing damage to the equipment along the way. In direct stroke, when it strikes an apparatus, it will be permanently damaged. The presence of the ground wires decreases the probability of the phase conductor being hit by a direct lightning stroke. When the lightning strikes the phase conductor, the current I(t) divides into two equal halves. This current travels in both directions of the conductor. The corresponding travelling voltage wave is:

$$V(t) = 0.5I(t)Z_p$$

where Z_p is the surge-impedance of the phase conductor, $Z_p = \sqrt{L/C}$, L and C are the series inductance (H/m) and capacitance (F/m) per meter.

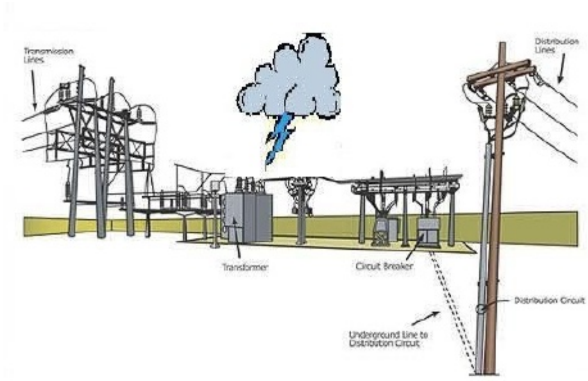

Figure 2.3: Direct Stroke [5].

2. **Indirect Stroke:** In indirect stroke, the lightning stroke strikes the transmission tower or the shield wire resulting in generation of a travelling voltage wave which travels back and forth. This voltage wave is reflected at the tower grounding and at the top of tower which raises the voltage at the tower cross-arm and the insulator string is stressed. Insulator flash-over will occur resulting in short-circuit of the system when the voltage is high enough. Power lines are equipped with shield wire to protect the phase conductor. Back flashover occurs across the insulator string when the transient voltage exceeds the lightning withstand voltage of the insulator [8]. Generation of back flashover occurs

due to multiple reflections along the tower. When the lightning stroke strikes the shield wire of the line, the generated voltage travels to next transmission tower producing multiple reflections and causes backflash across the insulator string.

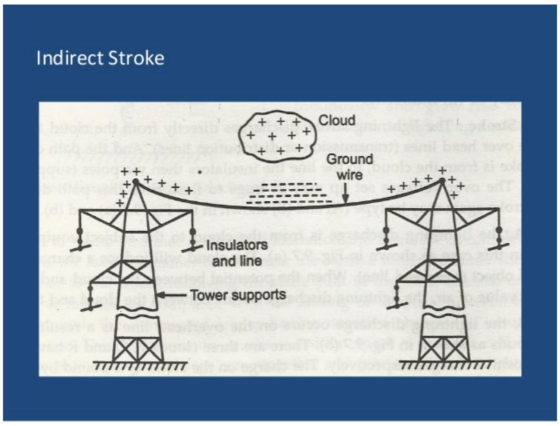

Figure 2.4: Indirect Stroke [5].

2.4 Voltage Impulse

Concerning the amplitude of transient voltage exceeding the peak value of normal A.C operating voltage, there are two kinds of transient voltage [9].

Lightning over-voltage is the first kind which is originated when the lightning stroke strikes the phase conductor of line or substation bus-bar. The stroke injects high lightning current up to about 100 kA or higher resulting in high amplitude of transient voltage in order of Mega Volts. Every stroke is followed by a travelling wave. The steepness of the current (lightning current) determines the voltage rise rate of the travelling wave at its origin. The voltage level can be simply computed by multiplying the current with the effective surge impedance of the line.

Different lightning protection systems, protective surge arrestors and losses damps and distorts the travelling wave. So, there are various wave-shapes of lightning overvoltages within a system.

The second kind is associated with the switching phenomenon. The voltage amplitude depends on the operating voltage, the system impedance and switching conditions influence the wave-shape. The rate of voltage rise is slower in this phenomenon.

There are two parameters that characterizes the impulse waves [9].

1. Front Time
2. Tail Time

Front Time: It is the time by which the wave reaches the peak staring from zero.

Tail Time: It is the time by which the wave reaches 50% of the peak value starting from zero.

A standard lightning impulse has:-

Front Time: $1.2\mu s \pm 30\%$
Tail Time : $50\mu s \pm 20\%$

An empirical formula is used to determine the front time as shown in Figure 2.5 [9].

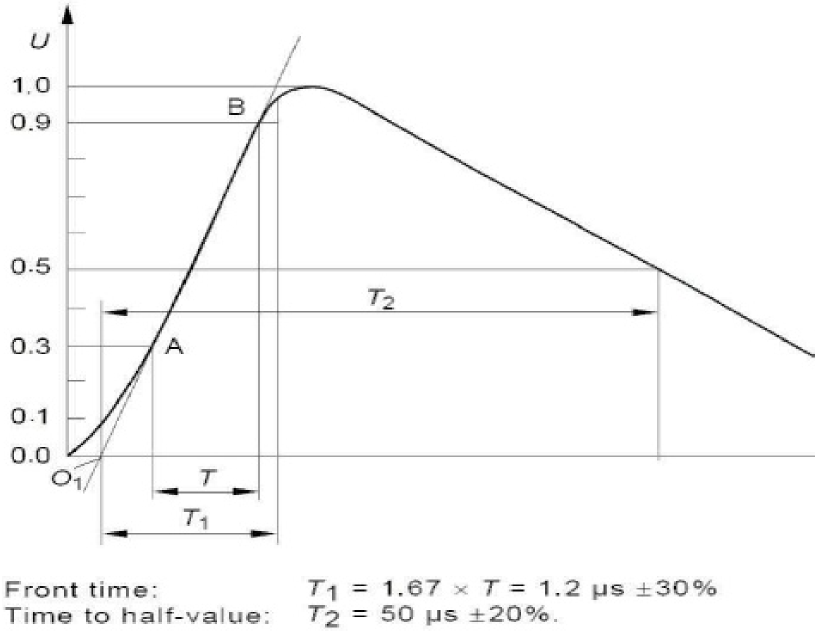

Figure 2.5: Waveform of standard lightning voltage impulse [9].

2.5 Current Impulse

During direct lightning stroke, the striking medium establishes a direct electrical discharge between the cloud and the ground. A current impulse is generated as the discharge is generally a flow of electrons. Figure 2.6 shows a 8/20 μs current impulse waveform.

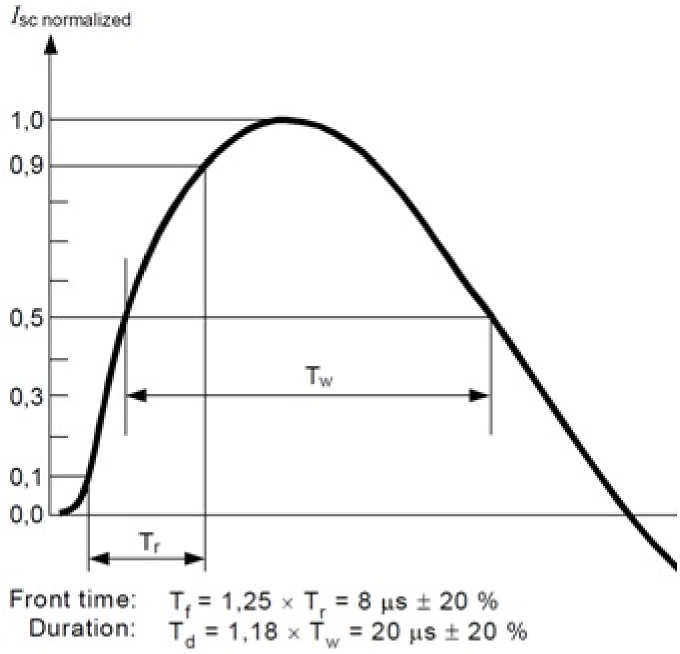

Figure 2.6: 8/20 μs current impulse waveform [9].

3 Modelling

3.1 Power Transformer Modelling

In order to investigate the transmitted transient over-voltage through the transformer, high frequency model of transformer is necessary. This is necessary as the behaviour of transformer is frequency dependent. Power transformer of rating 300 MVA, 415/15.75 kV is used for the study purpose. Studies suggest that the behaviour of transformer being frequency dependent should be taken in account for the simulation of high frequency transients. Several high frequency transformer models have been developed for EMTP [10].

Basically there are two main methods for the modelling of transformer [11]. The first method is based on the mechanical description and geometry of the transformer. This method is quite challenging as the transformer has complicated physical structure. It is difficult to obtain the detailed mechanical description of the transformer except for the manufacturers and the calculation is extensively difficult. The second method is based on the measurement results obtained in the frequency domain. Measurements are carried out in the transformer and the admittance function are calculated. The behaviour of transformer for high frequency introduces resonance because of the capacitive and inductive coupling between the windings, classical models of transformer cannot be used.

In this work the measurement data obtained from the frequency response analysis (FRA) of the transformer is used for the modelling. The FRA of the transformer used in the thesis are in Appendix A. FRA has been generally used for the diagnosis purpose of the transformer but it is also appropriate for the transients study in power systems [6]. Transferred transient over-voltage through the transformer completely depends on inductive and capacitive coupling of the windings. Measurement data obtained from the end to end connection arrangement is used. Admittance of the winding is calculated depending upon the data obtained in the frequency domain.

Frequency is in the range of 10 Hz to 10 MHz. The frequency range of FRA can be subdivided as:-

i. In the low frequency range (<20 kHz), transformer winding response is dominated by inductive components.

ii. In the medium frequency range (20-400 kHz), multiple resonance occur due to combination of inductive and capacitive components.

iii. In the high frequency range (>400 kHz), transformer winding response is dominated by the capacitive components.

A power transformer model over wide frequency range has been developed for EMTP [12]. In order to obtain a suitable model for studying the transient response of transformer, the obtained data from the FRA should be converted to admittance response.

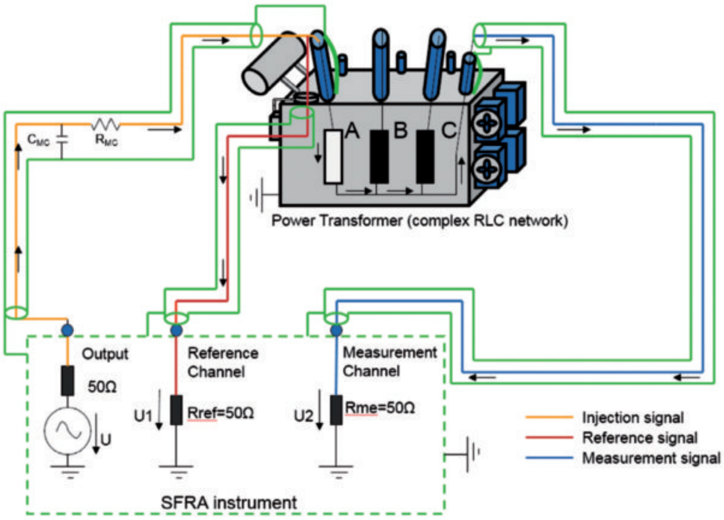

Figure 3.1: FRA end to end test setup [7].

From this computed admittance response, equivalent circuit of transformer is obtained. The FRA data consist of the magnitude and phase angle plot. These data are in the form.

$$|FRA|_{dB} = 20log\left|\frac{V_{out}}{V_{in}}\right| \tag{1}$$

$$\angle FRA = \angle\frac{V_{out}}{V_{in}} \tag{2}$$

Considering the internal impedance of the measuring instrument to be 50Ω.
From Figure 3.1 the coil impedance is:

$$\frac{V_{out}}{V_{in}} = \frac{50}{50 + Z_{Tx}}$$

Z_{Tx} is the coil impedance of the transformer
So,

$$\frac{V_{in}}{V_{out}} = \frac{50 + Z_{Tx}}{50}$$

$$\frac{V_{in}}{V_{out}}.50 = 50 + Z_{Tx}$$

$$Z_{Tx} = \frac{V_{out}}{V_{in}}.50 - 50$$

Let

$$|H| = \left|\frac{V_{out}}{V_{in}}\right|$$

and

$$\angle H = \angle \frac{V_{out}}{V_{in}} \tag{3}$$

Then

$$Z_{Tx} = 50\left(\frac{1}{|H|\, e^{\angle \frac{V_{out}}{V_{in}}}} - 1\right)$$

$$Z_{Tx} = 50\left(\frac{1 - |H|\, e^{\angle \frac{V_{out}}{V_{in}}}}{|H|\, e^{\angle \frac{V_{out}}{V_{in}}}}\right)$$

The admittance can be computed using

$$Y_{Tx} = \frac{1}{50}\left(\frac{|H|\, e^{\angle \frac{V_{out}}{V_{in}}}}{1 - |H|\, e^{\angle \frac{V_{out}}{V_{in}}}}\right) \tag{4}$$

Using the frequency response data, the admittance for the high voltage side, low voltage side and the coupling between high voltage and low voltage are calculated. To calculate the circuit parameters of the three phase winding of the HV side, the first value of corresponding admittance of three phase at frequency 20.05 Hz is considered.
Using the relation shown in equation (4), we get

$$Y_{H1} = 4.364 * 10^{-7} - 1.999 * 10^{-4} jS$$
$$Y_{H2} = 3.395 * 10^{-6} - 1.360 * 10^{-4} jS$$
$$Y_{H3} = 5.838 * 10^{-5} - 1.899 * 10^{-4} jS$$

So,

$$Z_{H1} = 109.157 + 5000.11\ j\Omega$$
$$Z_{H2} = 183.438 + 7348.36\ j\Omega$$
$$Z_{H3} = 1479.08 + 4811.22\ j\Omega$$

Since the impedance of Z_{H1} is inductive at low frequency, thus

$$L_{H1} = 5000.11/\left(2\pi f\right) = 39.69\ H$$

First resonance of the admittance response should be known to calculate the capacitance value. The first resonance frequency is

$$f_{HR} = 4560\ Hz$$

The capacitance is given by

$$f_{HR} = \frac{1}{2\pi\sqrt{L_{H1}C_{H1}}}$$

$$C_{H1} = 3.069 * 10^{-5}\ \mu F$$

For the low voltage side, the first value of admittance at frequency 20.05 Hz is considered.

$$Y_{L1} = 7.0482 * 10^{-3} - 0.0291jS$$
$$Y_{L2} = 4.1058 * 10^{-3} - 0.0218jS$$
$$Y_{L3} = 3.139 * 10^{-3} - 0.0212jS$$

So,

$$Z_{L1} = 7.862 + 32.46\ j\Omega$$
$$Z_{L2} = 8.343 + 44.30\ j\Omega$$
$$Z_{L3} = 6.834 + 46.157\ j\Omega$$

The impedance of Z_{L1} is inductive at low frequency, thus

$$L_{L1} = 32.46/\left(2\pi f\right) = 0.2577\ H$$

The first resonance frequency is

$$f_{LR} = 5250\ Hz$$

The capacitance is given by

$$f_{LR} = \frac{1}{2\pi\sqrt{L_{H1}C_{H1}}}$$

$$C_{L1} = 3.566 * 10^{-3}\ \mu F$$

For the capacitive coupling between the HV and LV winding of the transformer, the first value of admittance at frequency 20.05 Hz is considered.

$$Y_{C1} = 2.64 * 10^{-8} + 99.86 * 10^{-7} jS$$

So,

$$Z_{C1} = 27147 - 1013468.928\ j\Omega$$

The impedance of Z_{C1} is capacitive at low frequency, thus

$$\frac{1}{2\pi f C_{C1}} = 1013468.928$$

$$C_{C1} = 7.83 * 10^{-3}\ \mu F$$

In addition, due to the inductive coupling of the winding, the capacitive effect of the HV side will be transferred to the LV side through the stray inductance. Considering the second resonance frequency from the FRA analysis of the LV side.

$$Y_{HC} = 0.035981 - 0.0271 jS$$

So,

$$Z_{HC} = 17.71965 + 13.359\ j\Omega$$

The second resonance frequency is

$$f_{LR} = 170,000\ Hz$$

The impedance of Z_{HC} is inductive at this frequency, thus

$$L_{LC} = 13.359 / (2\pi f) = 0.0000125\ H$$

The capacitance is given by

$$f_{LR} = \frac{1}{2\pi \sqrt{L_{LC} C_{LC}}}$$

$$C_{LC} = 7.008 * 10^{-2}\ \mu F$$

These values of inductance and capacitance are lumped in order to build a RLC network of the transformer. The transformer model is represented as shown in Figure 3.2.

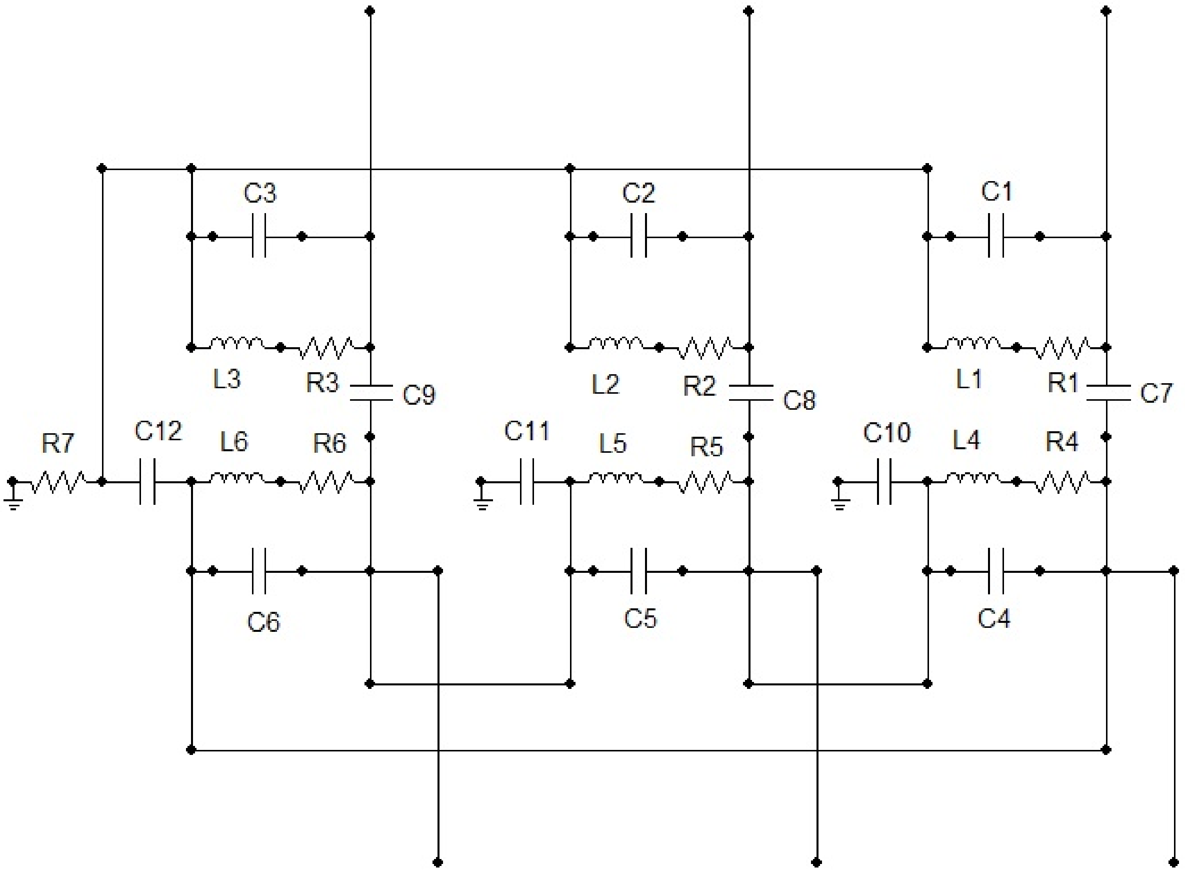

Figure 3.2: High frequency power transformer model.

Capacitance (C1-C3) and inductance (L1-L3) as shown in Figure 3.2 accounts for the winding self capacitance and inductance of the HV winding respectively. Similarly, capacitance (C4-C6) and inductance (L4-L6) represents the winding self capacitance and inductance of the LV winding respectively. Capacitance (C7-C9) is the coupling capacitance between HV and LV winding. Capacitance (C10-C12) represents the capacitive effect of the HV side transferred to the LV side through the stray inductance.

The RLC parameters of the transformer model are as:

Table 3.1: RLC parameters of the Power Transformer

Component	**Value**
R1	0.8231 Ohm
R2	0.8235 Ohm
R3	0.8236 Ohm
R4	0.001053 Ohm
R5	0.001053 Ohm
R6	0.001053 Ohm
R7	1 Ohm
L1	39.69 H
L2	58.34 H
L3	38.19 H
L4	0.257 H
L5	0.351H
L6	0.366 H
C1	$3.069*10^{-11}F$
C2	$2.088*10^{-11}F$
C3	$3.190*10^{-11}F$
C4	$3.57*10^{-9}F$
C5	$2.61*10^{-9}F$
C6	$2.508*10^{-9}F$
C7	$7.008*10^{-8}F$
C8	$7.008*10^{-8}F$
C9	$7.008*10^{-8}F$
C10	$7.83*10^{-9}F$
C11	$7.83*10^{-9}F$
C12	$7.83*10^{-9}F$

In order to validate the transformer model, voltage impulse of 500 kV , $1.2/50\mu s$ was applied in the HV of the transformer and the transferred transient voltage is measured in the LV side. The following voltage response shown in Figure 3.3 and 3.4 were obtained.

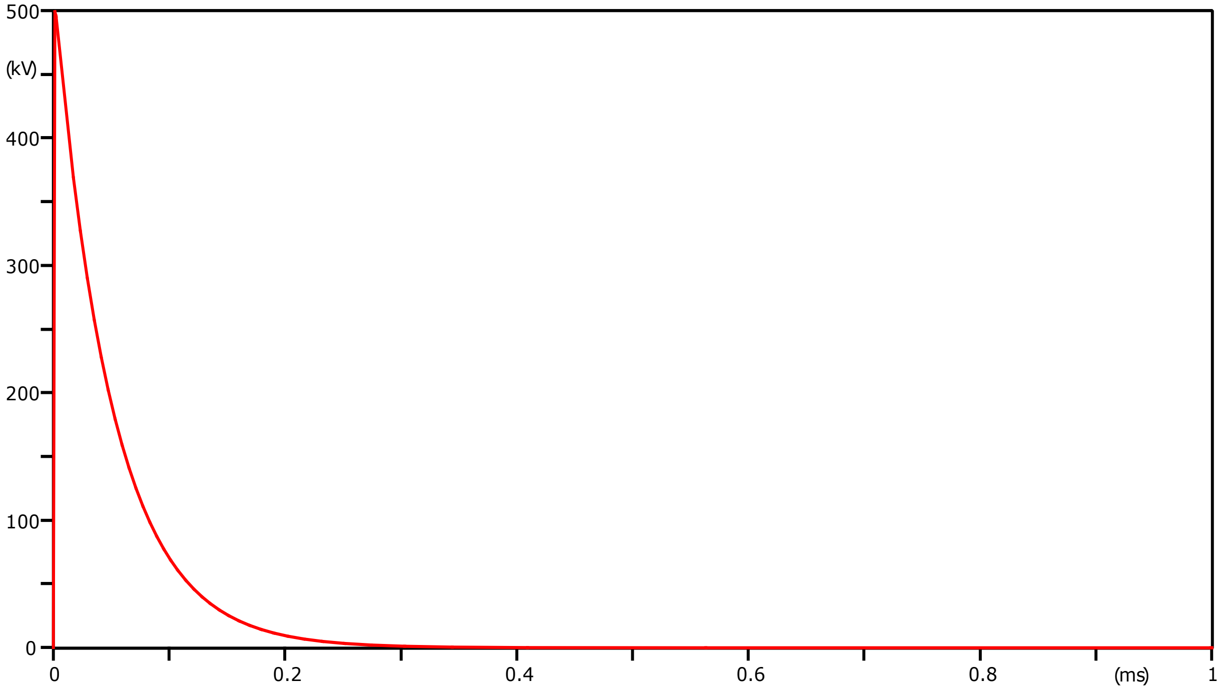

Figure 3.3: Transient over-voltage in HV of the transformer.

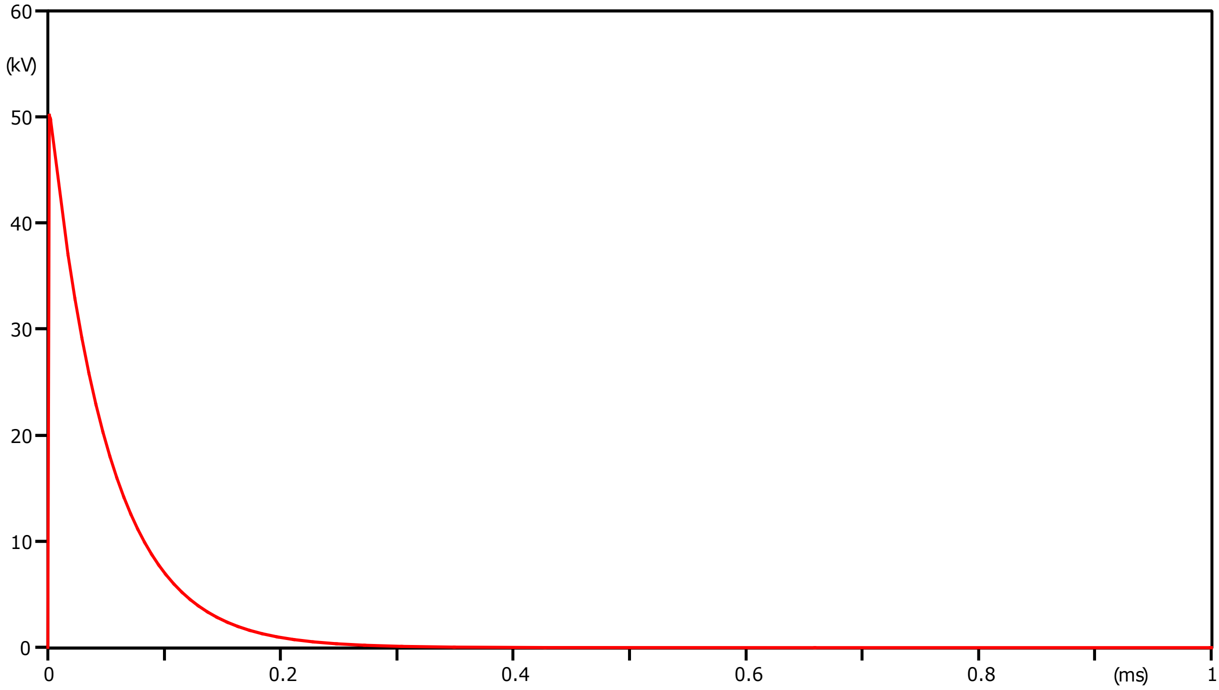

Figure 3.4: Transient over-voltage transferred to LV of the transformer.

3.2 Medium Voltage Transformer Modelling

Concerning the medium voltage transformer, a high frequency model has been proposed by A.Sabiha [13]. This model is suitable for both loaded and unloaded conditions of transformer. The same model has been used in this work for the simulation. This model is based on impedance parameter two-port network theory. The impedance parameters are computed accordingly with input port and output port open circuited. Fourier algorithm is applied on the recorded voltage and current during measurement and the impedance parameters are obtained as a function of frequency. According to the behaviour of the impedance in frequency domain, impedance can be converted to RLC component. First and second resonance frequencies are taken into consideration for the computation of RLC parameters. With both resonance frequencies taken in account, the equivalent circuit obtained is same. This model has a considerable agreement between the simulated and experimental results. So, this model can be therefore used for the transient behaviour of transformer during lightning strokes.

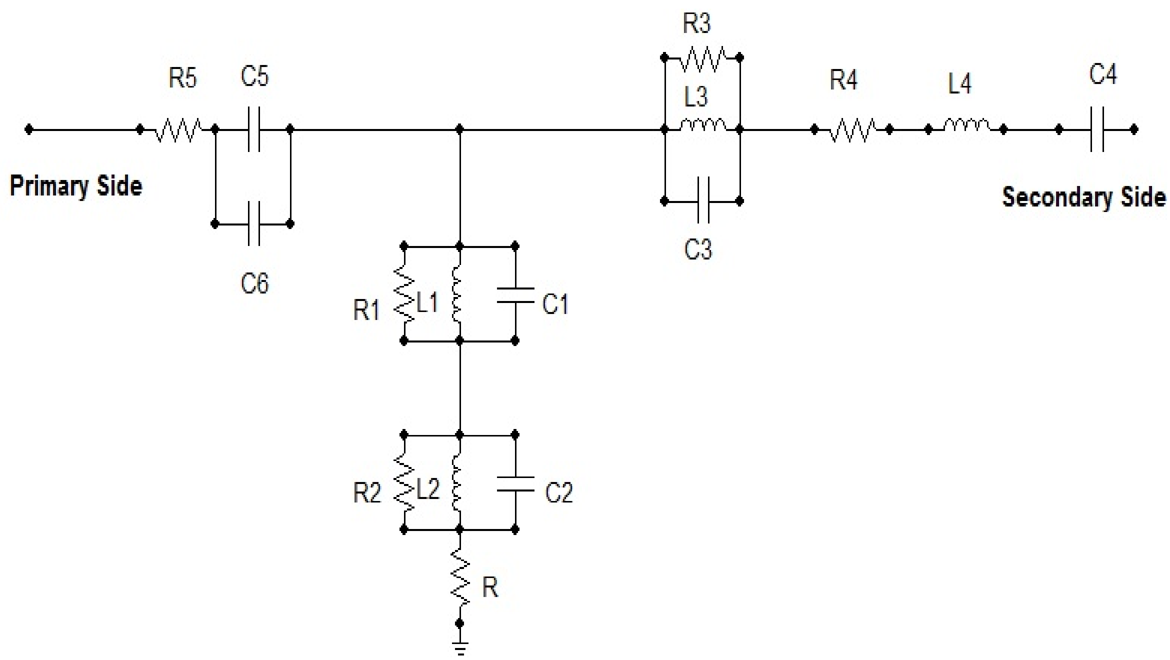

Figure 3.5: High frequency transformer model [13].

The R,L and C parameters of the transformer are as[13]:

Table 3.2: RLC parameters of the Transformer

Component	**Value**
R1	500 Ohm
R2	558.54 Ohm
R3	1000 Ohm
R4	$1*10^{-6}\ Ohm$
R5	50 Ohm
R	1500 Ohm
L1	0.00856 mH
L2	0.0046 mH
L3	0.0368 H
L4	0.0482 H
C1	$2.1063*10^{-8}F$
C2	$3.02*10^{-9}F$
C3	$5.12*10^{-9}F$
C4	$2.216*10^{-10}F$
C5	$4.22*10^{-10}F$
C6	$1.91*10^{-10}F$

3.3 Surge Arrestor Modelling

Surge protection devices have an important role for the mitigation of the over-voltage due to lightning. This chapter presents the modelling of the surge arrestor using the Pinceti et al.Model where the modal parameters are evaluated. There are multiple models developed to analyze the behaviour of surge arrestor when subjected to different kind of electrical stress [14, 15]. The main problem of the models is the identification of the modal parameters. The mostly used models are presented here.

i. **Frequency Dependent Model (IEEE Model)**

This metal oxide surge arrestor model has been recommended by IEEE working group 3.4.11 [14].

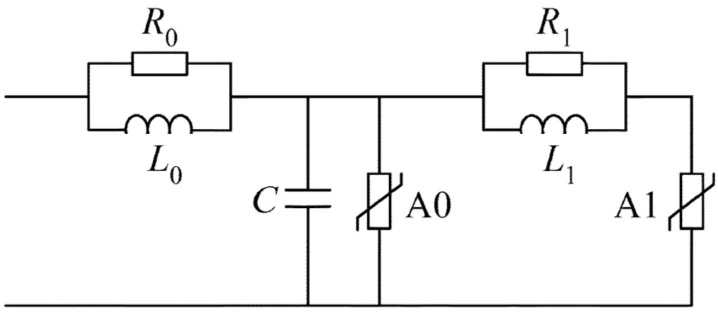

Figure 3.6: Frequency dependent model [14].

The non-linear resistors (A0 and A1) represent the non-linearity of the arrestor. These non linear resistor are separated by a R-L filter. The impedance of the filter is very less under slow front surges but during fast front surges the impedance increases resulting in high current flow in A0 than A1. Therefore, the voltage of A0 is higher than A1, so the arrestor excites with the increasing voltage. Hence, using two sections in the modelling has been found enough for accurate modelling of the surge arrestor.

ii. **Pinceti et al.Model**

This is the simplified model derived from the IEEE model [15]. Only two inductances (L_0 *and* L_1) are used while the resistive elements are eliminated. To avoid the numerical instability, a high resistance of $1M\Omega$ is added. This model does not consider any physical characteristics and only the electrical data are used for determining the modal parameters. The two inductances of the model are defined as:

$$L_1 = \frac{1}{4}.\frac{U_{r1/T2} - U_{r8/20}}{U_{r8/20}}.U_n$$

$$L_0 = \frac{1}{12}.\frac{U_{r1/T2} - U_{r8/20}}{U_{r8/20}}.U_n$$

Here, U_n is the rated voltage of the arrestor in kV, $U_{r1/T2}$ is the residual voltage at 10 kA fast front current surge ($1/T2\mu s$) and $U_{r8/20}$ is the residual voltage at 10 kA current surge with ($8/20\mu s$) time.

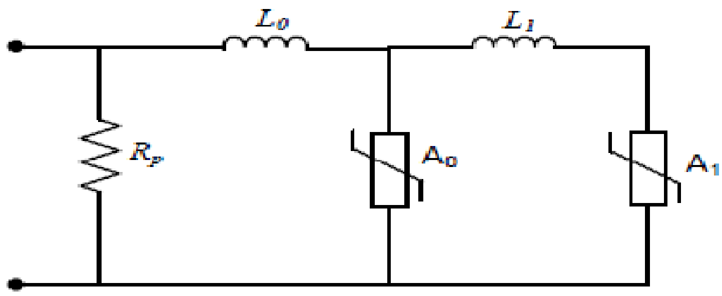

Figure 3.7: Pinceti et al.model [15].

The $U_{r1/T2}$ data is difficult to obtain in most of the data sheets which is the main challenge associated with this model. A method has been devised in [13] to overcome this difficulty and calculate the modal parameters.

$$L_0 = 0.01U_n \tag{5}$$

$$L_1 = 0.03U_n \tag{6}$$

In this work, Pinceti et al. model is used for the modelling of the surge arrestor. The modal parameters (inductances) are computed using the relations (5) and (6). 400 kV, 15.75 kV and 6 kV surge arrestor are modelled to be used in the simulation. The electrical data of the surge arrestor used are as listed in Table 3.3. The non-linear characteristic of the surge arrestor are presented in Appendix B. The V-I characteristic of A0 and A1 are listed in Table B1 and B2 respectively.

Table 3.3: Surge Arrestor Electrical Data

Surge Arrestor (kV)	Classification kA	**Rated Voltage kV**	**Max. COV kV**	**TOV for 1 sec kV**	Maximum Residual Voltage	
					8/20 μs 10 kA kV Crest	**8/20 μs 20 kA kV Crest**
6	10	8.8	7	9.5	21.5	23.8
15.75	10	24	19	27.4	58.4	73.8
400	20	336	269	394	808	881

For the 400 kV surge arrestor, the value of L_0 and L_1 are found 0.00272 and 0.00816 μH respectively.

The model is simulated in ATP with a discharge current of $8/20\mu s$, 20 kA injected to the surge arrestor. A resistance of $1M\Omega$ is connected in parallel. An error of 8.6 % was observed in the residual voltage between the simulated result and manufacturer data sheet. The error was computed using $(U_{ps} - U_p)/U_p$. The modal parameters obtained were taken as the initial values and tuning of the parameters was done. The new parameters were found to be L_0 = 0.01 mH and L_1 = 0.0055 mH. The error for the residual voltage reached 0.14 %.

Similarly, the modal parameters for the 16 kV surge arrestor are L_0 = 0.00019 mH and L_1 = 0.00057 mH. Likewise, the parameters for 6 kV surge arrestor are L_0 = 0.00007 mH and L_1 = 0.00021mH.

The wave-forms of the injected current, residual voltage and absorbed energy are as shown in Figure 3.8, 3.9 and 3.10 respectively.

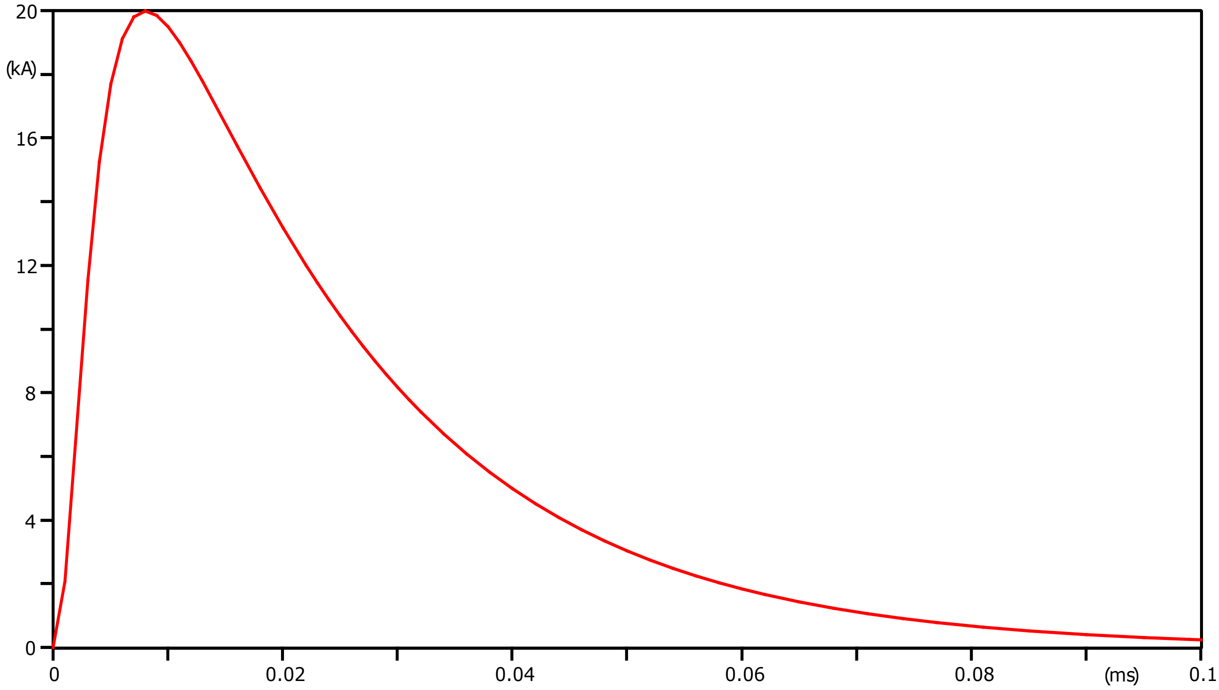

Figure 3.8: Injected current.

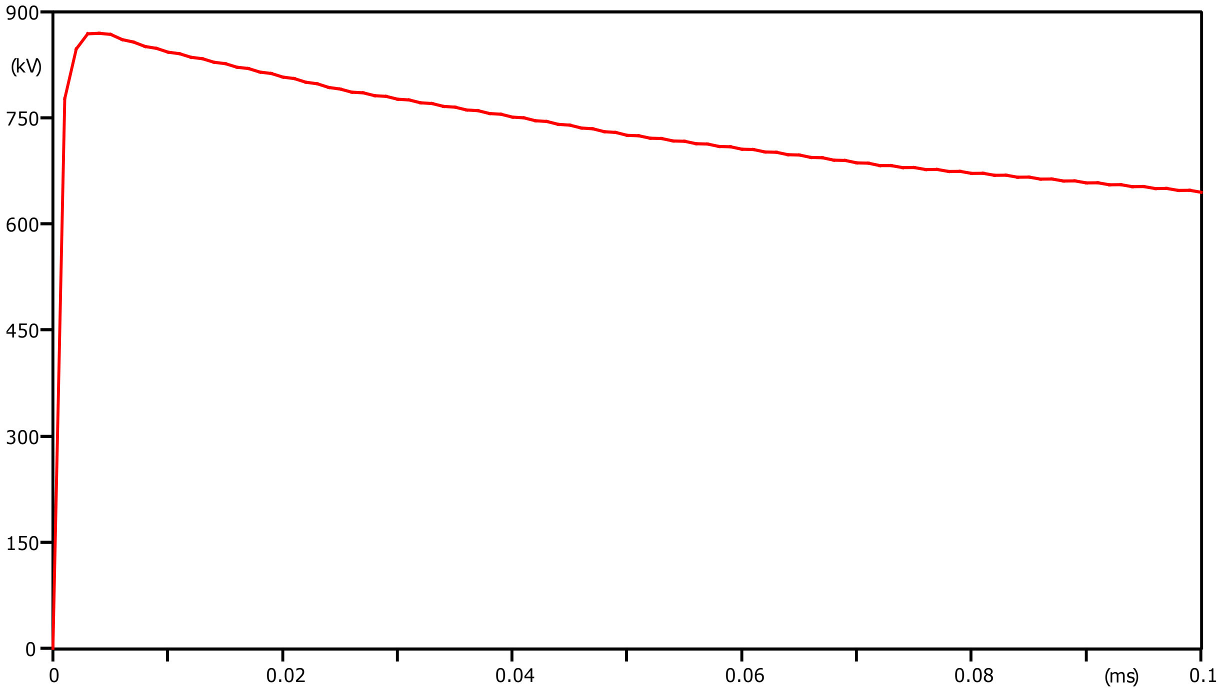

Figure 3.9: Residual voltage.

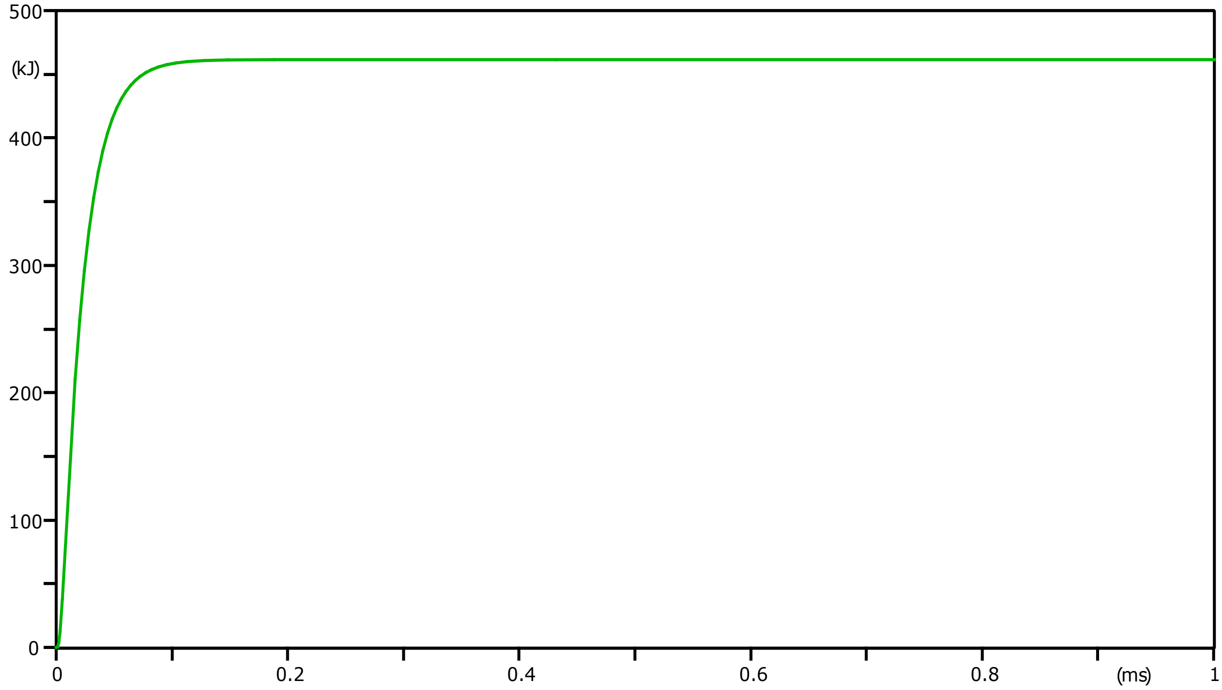

Figure 3.10: Absorbed energy.

3.4 Transmission Tower Modelling

When a transmission tower is hit by a lightning stroke, a travelling voltage is generated. This generated voltage travels back and forth along the tower and when reflected at the ground and top of tower, the voltage at the cross arm increases resulting stress in the insulator string[16]. Insulator are subjected to flashover when the transient voltage due to lightning exceeds the lightning withstand voltage of the insulator. This flashover is termed as the backflash over.

In order to study the induced voltage across the insulator string when subjected to a lightning stroke, a model of the tower is developed. 400 kV double circuit tower configuration is used for the study [17]. Estimation of the surge impedance and the propagation velocity (C_o) is done and implemented in a multistory tower model as shown in Figure 17. Every parts of the tower is represented by distributed parameter model.

The data of the tower structure are H1 = 21.82 m, H2 = 4.71 m, H3 = 16 m and H4 = 4340 m [17]. Tower surge impedance 450Ω is used for Z1, Z2 and Z3 and 200Ω is used for Z4. Tower footing resistance (Zf) of 40Ω is used in the study. Likewise, surge propagation velocity of 300 $m/\mu s$ and attenuation coefficient (α) along the tower 0.89 are taken.

R and L shown in Figure 3.11 represents the resistance and inductance of the transmission tower.

Calculation of the modal parameters:

Z1 = Z2 = Z3 = 450Ω , Z4 = 200Ω

$$R_i = \frac{-2Z_i.ln\alpha}{H1 + H2 + H3}.H_i \tag{7}$$

$$R_4 = -2Z_4.ln\alpha \tag{8}$$

$$L_i = \alpha.R_i\frac{2H}{C_o} \tag{9}$$

$$H = H1 + H2 + H3 + H4$$

Using the relation (7-10), we get

R1 = 21.43 Ω , R2 = R3 = 39.50 Ω , R4 = 44.64 Ω

L1 = 5.98 μH , L2 = L3 = 11.03 μH , L4 = 12.47 μH

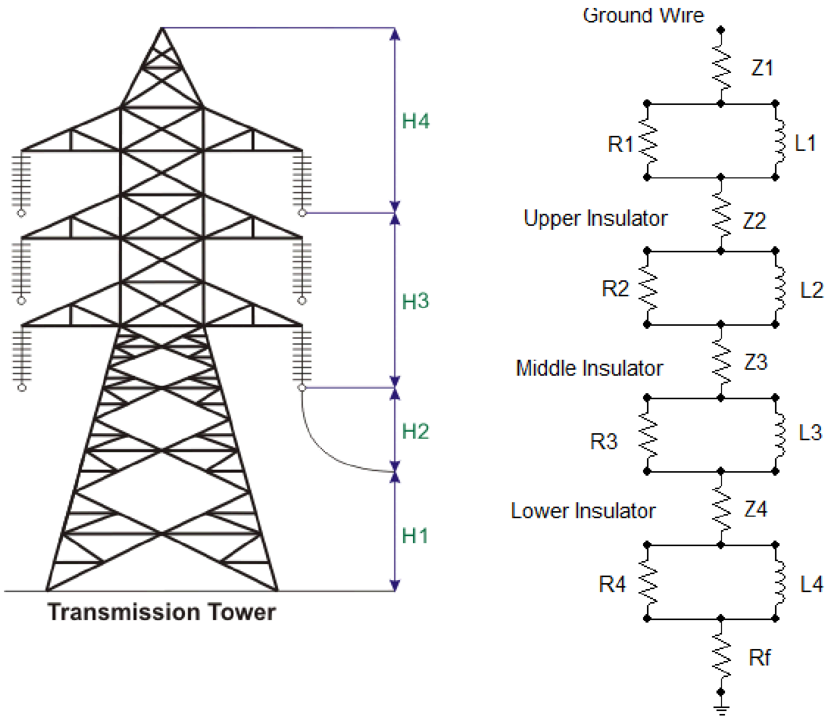

Figure 3.11: Multistory tower model. [16]

Lightning Source Model

The magnitude of impulse current due to lightning discharge is a function of probability [18]. The low discharge levels with lightning current between 5 and 22 kA mostly cause the lightning stroke to strike the phase conductor directly. In this case, the maximum lightning current which may enter the phase conductor without flashover of the insulator string is found to be 26.6 kA. However, the lightning impulse current of larger magnitude may hit the top of tower or shield wire and result in backflash over across the insulator string.
In this work, lightning source is modeled by a current source and a resistance in parallel for the case of direct stroke. This resistance represents the impedance of the lightning path. The impedance is taken to be 400Ω. Step Voltage impulse of 1640 kV is used for the case of back flashover.

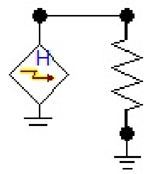

Figure 3.12: Lightning source model.

Back Flashover Model

The shield wires are placed in the top of tower to reduce the number of lightning strokes terminating on the phase conductor. Back flashover occurs when the potential of tower exceeds the lightning impulse withstand voltage or the BIL of the insulator string [8]. Insulator string can withstand impulse voltage of high magnitude having short duration even if the insulator string fails to withstand impulse voltage of long duration.
The critical flashover voltage for the 400 kV insulator string is taken as 1640 kV in this study [19]. The impulse withstand voltage of the insulator string can be calculated using [20].

$$V_{f0} = K_1 + \frac{K_2}{t^{0.75}} \tag{10}$$

where, V_{f0} is the flashover voltage in KV
K_1 is 400*L
K_2 is 710*L
L is the length of the insulator string
t is the time elapsed after lightning stroke in μs

There are multiple factors influencing the induced voltage during back flashover which are as listed below:

i. Front time of lightning stroke current : A lightning flash consists of several strokes which are negative or positive charges from the cloud to the ground in a lightning flash. The voltage withstand capability of the transmission tower insulator string depends on the lightning stroke front time. The shorter front time induces more voltage and as the front time increases, there is a decrease in induced voltage and in return the time for clearing over-voltage increases. Two cases of induced voltage at the tower for lightning current of 20 kA with front time of 1.2μs and 2μs are as shown in Figure 3.13.

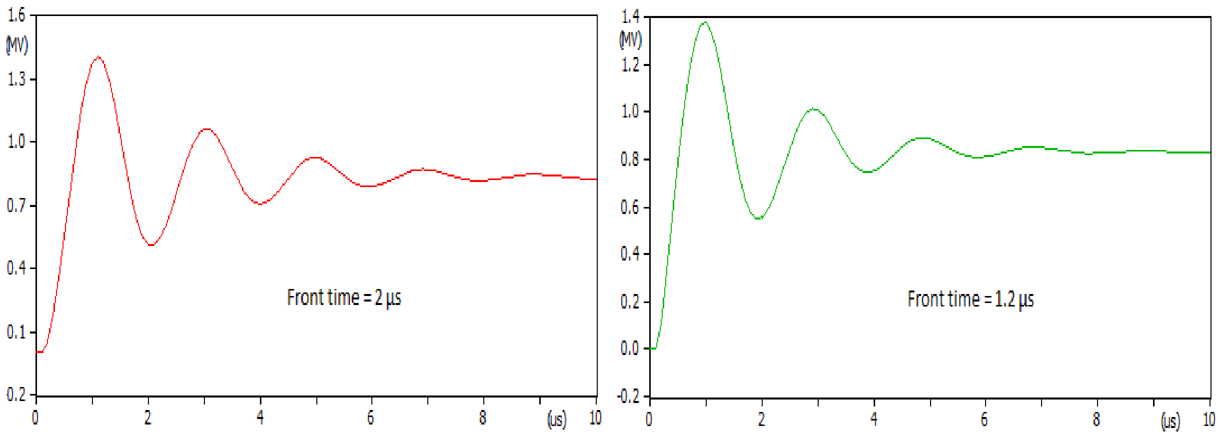

Figure 3.13: Induced voltage for different front time of lightning current.

ii. Striking Distance: With a increase in the striking distance the magnitude of the induced voltage decreases. The induced voltage is highest at the point near to the lightning stroke and is lower at far location from the point of lightning stroke.

iii. Peak of the lightning current: The induced voltage peak increases with the increase in peak of the lightning current.

iv. Tower Footing Resistance: The voltage across the insulator string is affected by the tower footing resistance. Higher the tower footing resistance, higher is the voltage across the insulator string causing back flashover of the insulator string.

Although there are many factors responsible for the induced voltage due to back flashover, in this study the front time of the lightning stroke used is fixed i.e $1.2/50\mu s$ front and tail time respectively. Also, the dead end transmission tower i.e. the tower close to the power transformer is used in the study. Likewise, the peak of the lightning current and tower footing resistance are fixed for the study.

The maximum amount of lightning current that can enter the shield wire during direct strike is analyzed concerning the back flashover of the insulator. The maximum amount of lightning current was found to be 26.6 $kA, 1.2/50\mu s$. Lightning current above this magnitude will cause the flashover of the insulator as the voltage across the insulator string exceeded the critical flashover voltage of the insulator considered in the thesis. Lightning current of 26.6 $kA, 1.2/50\mu s$ is used for the case of direct strike in the study. Also, the maximum amount of lightning current that can enter the phase wire of 400 kV line through the shield wire was observed to be 20 kA. This current is also used as a lightning source in the simulation.

3.5 Power Cable Modelling

The cable impedance has an influence on the transient over-voltage. In order to take the effect of the cable impedance on the over-voltage, the cables used in the network have to be modelled suitable for using in EMTP. The cable capacitance play a vital role in the transient over-voltage being transferred and somehow limit the over-voltage. Frequency dependent model of cable are required in order to study the transient over-voltage. There are several cable models available in EMTP [24]. PI model of cable is used in this study for representing the cable connected between 6 kV of transformer and the 6 kV bus-bar. Likewise, the cable connection between the 6 kV bus-bar and the 6/0.4 kV transformer are also taken into account.
AHXCMK 1*800, 6/10 kV, 800 sq. mm are used for the connection between 6 kV side of the transformer and the 6 kV bus-bar. 4 cables per phase are used for the connection. The R,L and C parameters of the cable are used according to the electrical data sheet of the cable [21]. A Pi-model of the cable is used using the R,L and C data of the cable.

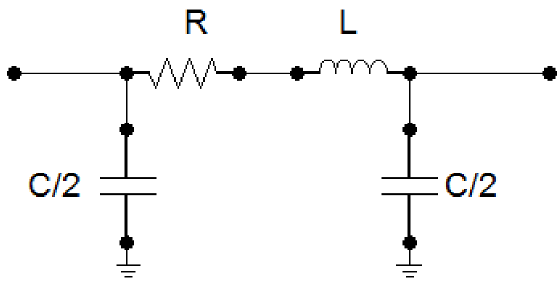

Figure 3.14: Pi-equivalent model of cable.

Cable type AHXAMK-W 3*185Al +35Cu 6/10 kv, 185 sq.mm is used for the connection between 6 kV busbar and the 6/0.4 kV transformer. Cable length of 100 m is used for upstream connection while 50 m for the downstream connection. The R,L and C parameters of these cable are used according to the data provided in the electrical data sheet [22]. The electrical data of the cable is listed in Table 3.4.

Table 3.4: Cable Electrical Data

Cable	R (Ω/km)	L (mH/km)	C ($\mu F/km$)
AHXCMK (1*800)	0.067	0.46	0.75
AHXAMK-W (3*185Al+35 Cu)	0.21	0.34	0.39

4 Simulation

4.1 EMTP-Introduction[23]

The Electro Magnetic Transient program (EMTP) is a software tool used to investigate the electromagnetic transients and the insulation issues associated with it. It is a tool used by the electrical power system engineers. This tool has wide range of modelling capabilities holding electro-mechanical and electromagnetic oscillations in time duration of microseconds. It is generally used for the transient study such as switching surge, lightning surge, insulation coordination, HVDC converter.

It was developed by Hermann Dommel at the Bonneville Power Administration (BPA) in the late 1960s. the program initially consist of around 5000 lines of code which was basically used for the transmission line switching studies. The initial program was difficult to use and one had to have advanced knowledge about EMTP for grasping its capabilities.

Modification and advancement was done in the initial program and Version 2.0 appeared in 1989. This version included significant enhancement to the base code. The enhancement were multi-port frequency dependent equivalent network, multi-frequency initialization, circuit breaker arc model, arrestor models and air-gap.

The current version is 3.0 having enhancement in transformer model (high frequency), dc converter bridge model, 3-phase load flow module, line and cable models, corona models, protection system models.

4.2 ATP Draw [24]

The Alternative Transient Program (ATP) is the most widely used program tool for the digital simulation of electromagnetic and electro-mechanical nature of the transient phenomenon.

ATPDraw is a graphical, mouse-driven pre-processor to the ATP version of the Electromagnetic Transients Program (EMTP) on the MS-Windows platform. The program is written in CodeGear Delphi 2007 and operates with Windows 9x/NT/2000/XP/ Vista. ATP Draw allows the user to build the electrical circuit by selecting the components from the huge palette. The simulation program ATP and different plotting programs can be executed with ATPDraw. The ATP software can predict the various outcomes in a electrical power network which may arise as a function of time specially initiated due to some disturbances.

The ATP has number of available models such as transformers, surge arrestors, machines, cables and transmission lines. It has a interfacing capability to the modules TACS and MODELS that allows modelling of control system and components having nonlinear characteristics such as corona and arcs. TACS and MODELS control system allows simulation of dynamic system that does not consist any electrical netwrok.

Symmetrical and unsymmetrical disturbances such as faults, lightning and different switching operations including commutation of valves are allowed. ATP also allows the frequency response calculation of the phasor networks. Frequency-domain harmonic analysis using harmonic current injection method (HARMONIC FREQUENCY SCAN). The model-library of ATP consists of the following components:

i. Coupled and uncoupled linear, lumped R,L,C elements.

ii. Cables and transmission line with frequency dependent and distributed parameters.

iii Nonlinear inductances and resistances, hysteretic inductor, time-varying resistance, TACS/MODELS controlled resistance.

iv. Nonlinear components such as transformers with saturation and hystersis, surge arrestors and arc.

v. Normal, time and voltage dependent switches, statistical switching.

vi. Valves (diodes, thyristors, triacs), TACS/MODELS controlled switches.

vii Analytical sources: step, ramp, sinusoidal, exponential surge functions, TACS/MODELS defined sources.

viii Rotating machines such as 3-phase synchronous machine, universal machine model.

ix. User-defined electrical components including MODELS interaction.

4.3 Modelling and Simulation of the System

The transfer of surge from the high voltage to the medium voltage and low voltage network in power system is considered to be the most frequent mechanism for the over-voltage generation in the connected load among all possible mechanism. Many studies have been conducted to investigate the transient voltage caused by the lightning stroke on the distribution line.

The various coupling possibilities have to be taken into consideration to interpret the transient over-voltage transferring from high voltage to medium and low voltage network.These possibilities are:-

i. high frequency coupling between the primary winding and secondary winding of power transformer and distribution transformer,

ii. induced over-voltage in the medium voltage network resulting from the injected current due to flashover across the high voltage insulator string.

This chapter presents the transient over-voltage transferred to the medium and low voltage network through the power transformer and distribution transformer. Use of the medium voltage and low voltage surge arrestor at the secondary of the power transformer and distribution transformer is analyzed to mitigate the transient over-voltage coming from the high voltage side of the power transformer. The influence of the surge arrestor on the medium and low voltage network connected load is analyzed through the waveform and the peak voltage profile. BIL of the 15.75 kV generator and 6 kV motors are 68 kV and 29 kV respectively.

In order to investigate the transient over-voltage reaching the medium voltage and low voltage side due to lightning stroke, an accurate model of the power transformer, distribution transformer, transmission tower and surge arrestor is required. An accurate and simplified model for the power transformer, distribution transformer, transmission tower and surge arrestor proposed in Chapter 3 is used in this chapter. The high frequency power transformer and distribution transformer model, transmission tower model,cable model and surge arrestor model are implemented in a single arrangement in EMTP/ATPDraw.

The impact of the cable connecting the switchgears and equipment in the transient over-voltage transfer is also taken into account.
The simulation is performed using the lightning source of $26.6kA, 1.2/50\mu s$ for direct stroke. Also, the simulation is performed with lightning current of $20kA, 1.2/50\mu s$ as this is assumed to be the maximum current that can enter the phase wire of the 400 kV line due to the geometry of the line. A step voltage of 1640 kV is applied on the phase condcutor for the case of back flashover.

The study of lightning induced over-voltage transferred to the medium and low voltage side (15.75 kV, 6 kV and 0.4 kV) of the network is done by analyzing the voltage profile for different scenarios. The single line diagram of the network used in the thesis is shown in Figure 4.1.

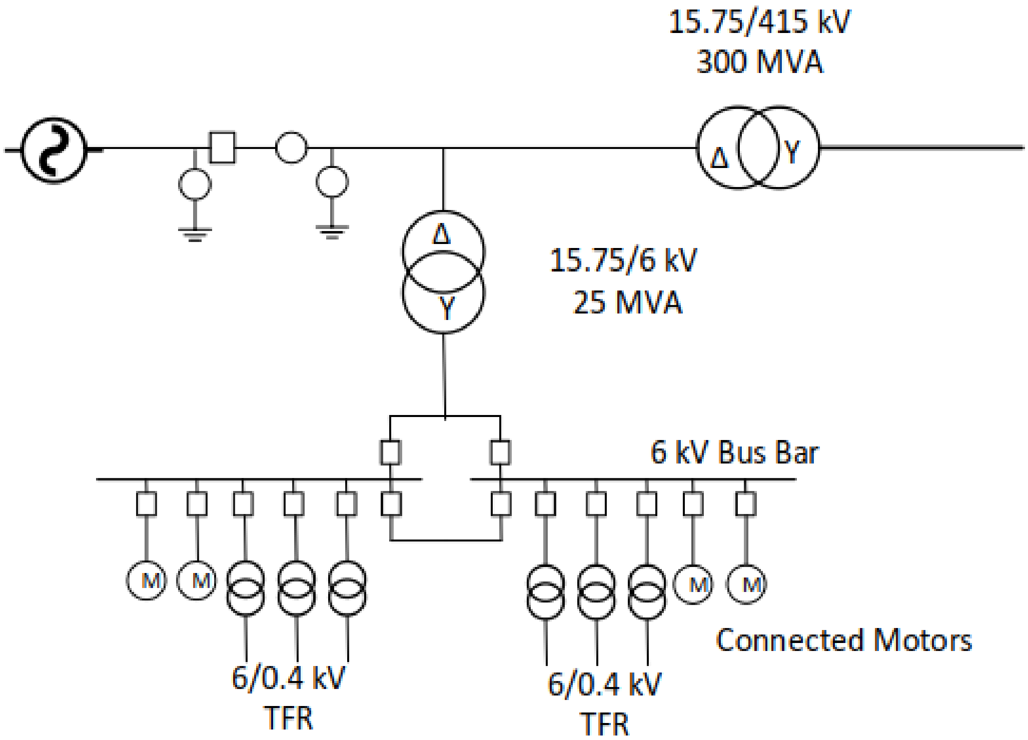

Figure 4.1: Single line diagram of the system.

The considered scenarios for the simulation are:

1. **Direct Stroke**

a. With 400 kV Surge Arrestor

b. With 400 kV and 15.75 kV Surge Arrestor

c. With 400 kV, 15.75 kV and 6 kV Surge Arrestor

2. **Indirect Stroke**

a. With 400 kV Surge Arrestor

b. With 400 kV and 15.75 kV Surge Arrestor

c. With 400 kV, 15.75 kV and 6 kV Surge Arrestor

The overall ATPDraw circuit used in the simulation is shown in Figure 4.2. The points A1, B1, C1, D1, E1 and F1 in Figure 4.2 are the voltage measuring points for the transmission tower voltage, insulator string voltage, 415 kV side voltage, 15.75 kV side voltage, 6 kV side voltage and 0.4 kV side voltage of the circuit respectively.

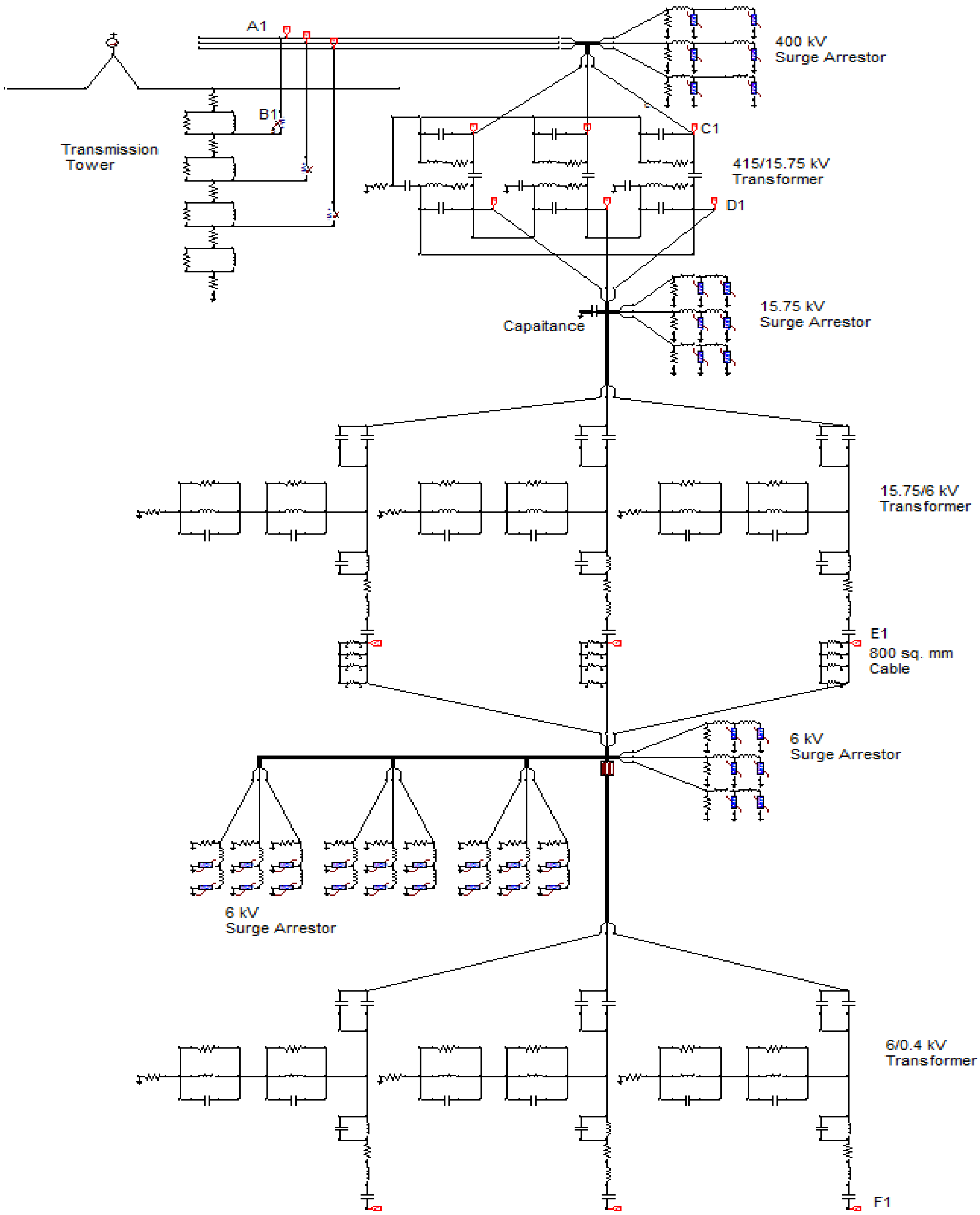

Figure 4.2: Overall simulation model.

A capacitance of 360 nf per phase at the 15.75 kV bus is used in the simulation model as shown in Figure 4.2.

4.3.1 Direct Stroke

In this case the lightning current of 26.6 kA, 1.2/50μs is considered to directly strike the 400 kV phase conductor of the transmission line. The study is carried out with different combination of 400 kV, 15.75 and 6 kV surge arrestor implemented in the system and the corresponding transferred transient voltage at different points of the network are analyzed.

1. **With only 400 kV Surge Arrestor**
   In this case only 400 kV surge arrestor is used in the system and the corresponding transient voltage at different voltage levels are studied. Lightning current of 26.6 kA,1.2/50μs is used. The transient voltages are as shown in Figure 4.3 to 4.7.

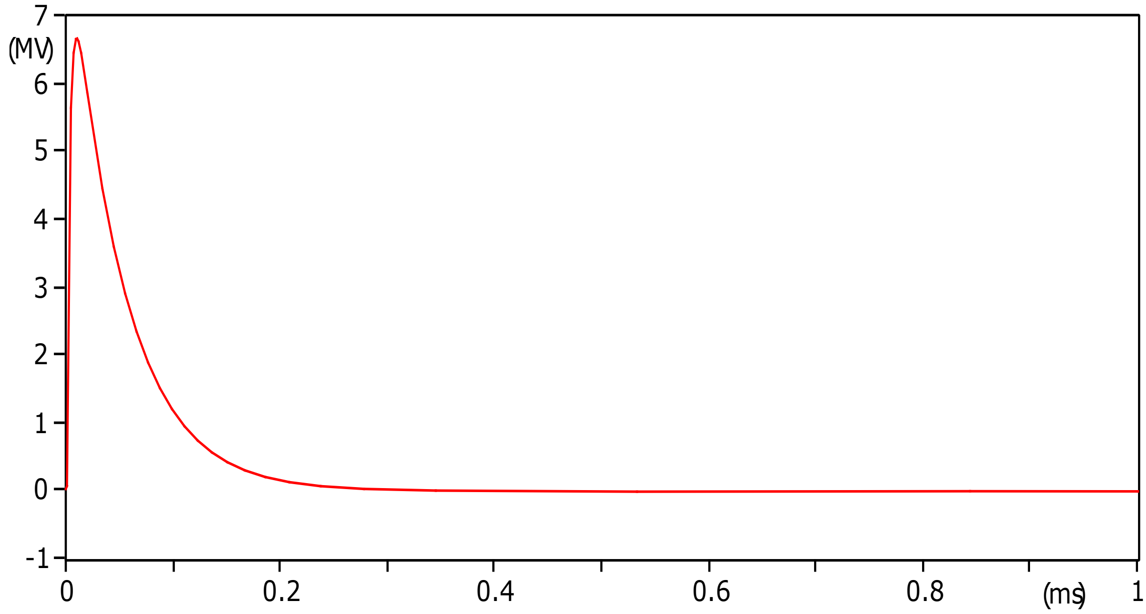

Figure 4.3: Voltage at the transmission tower before 400 kV surge arrestor operates.

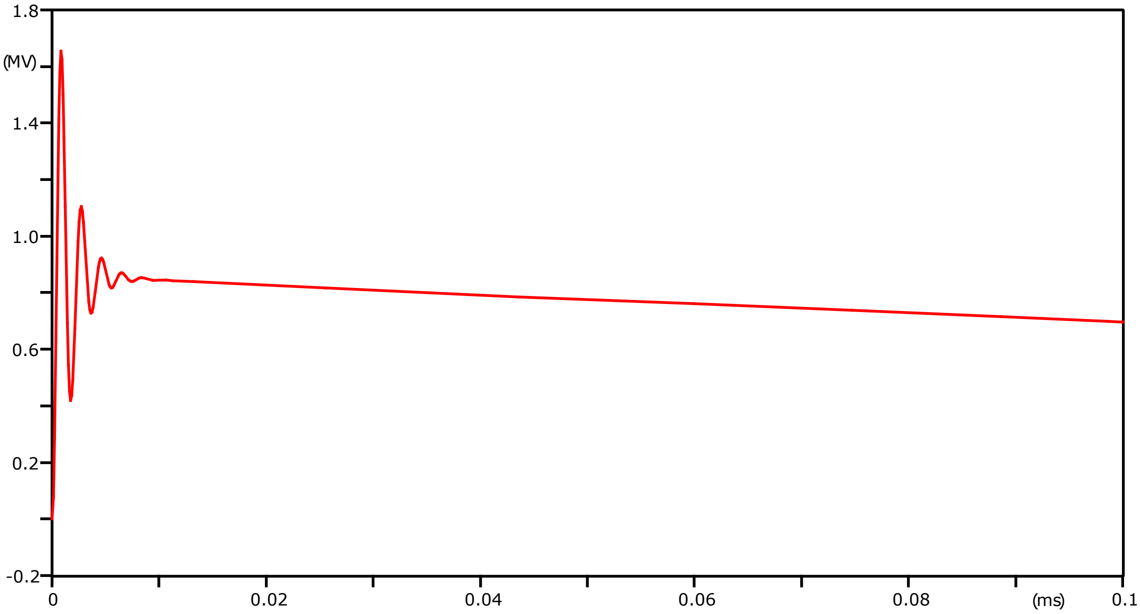

Figure 4.4: Transient voltage at the 415 kV side of the system for the case of 26.6 kA lightning with 400 kV surge arrestor.

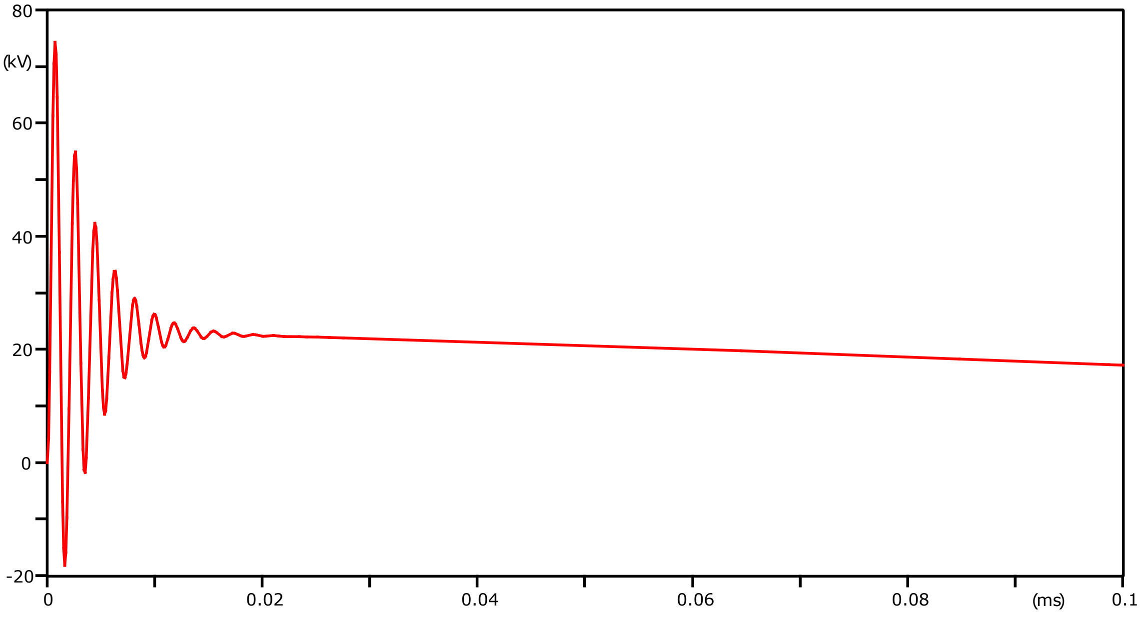

Figure 4.5: Transient voltage at the 15.75 kV side of the system for the case of 26.6 kA lightning with 400 kV surge arrestor.

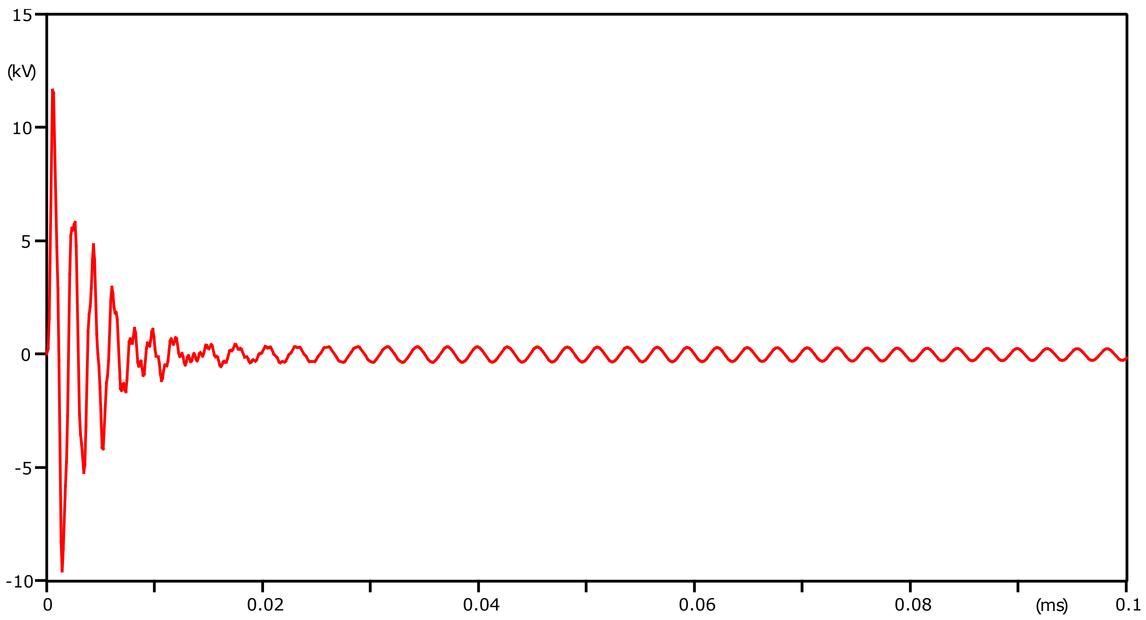

Figure 4.6: Transient voltage at the 6 kV side of the system for the case of 26.6 kA lightning with 400 kV surge arrestor.

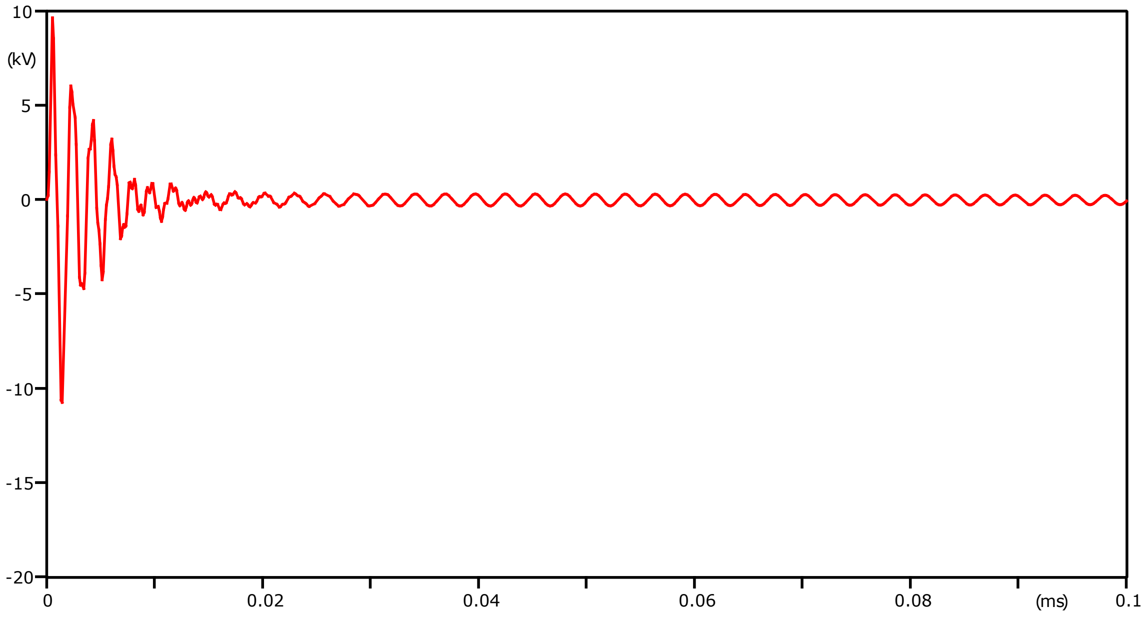

Figure 4.7: Transient voltage at the 0.4 kV side of the system for the case of 26.6 kA lightning with 400 kV surge arrestor.

Also a lightning current of $200kA$, $1.2/50\mu s$ is used for the case of direct stroke. The voltage at the 415 kV side for this case is shown in Figure 4.8.

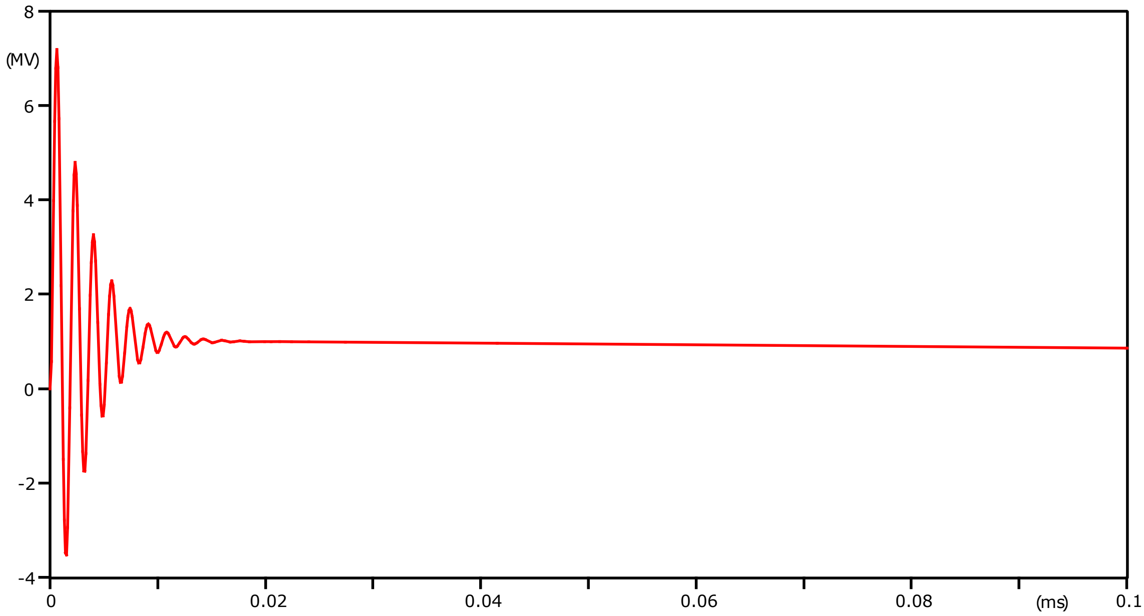

Figure 4.8: Transient voltage at the 415 kV side of the system for the case of 200 kA lightning with 400 kV surge arrestor.

This over-voltage will lead to the immediate back flashover of the insulator and on the other hand, it is extremely unlikely that 200 kA lightning enters the phase wires of the line.

2. **With 400 kV and 15.75 kV Surge Arrestor**

In this case 400 kV and 15.75 kV surge arrestor are used in the system and the corresponding transient voltage at different voltage levels are analyzed. Lightning current of 26.6 kA, 1.2/50μs is used. The transient voltages are as shown in Figure 4.9 to 4.11.

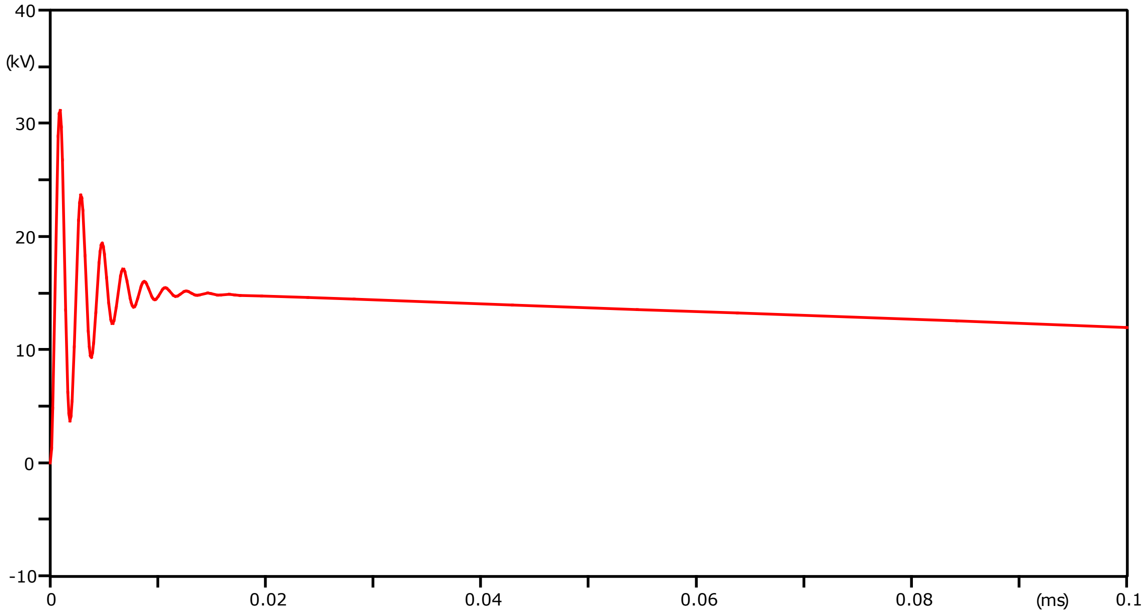

Figure 4.9: Transient voltage at the 15.75 kV side of the system for the case of 26.6 kA lightning with 400 and 15.75 kV surge arrestor.

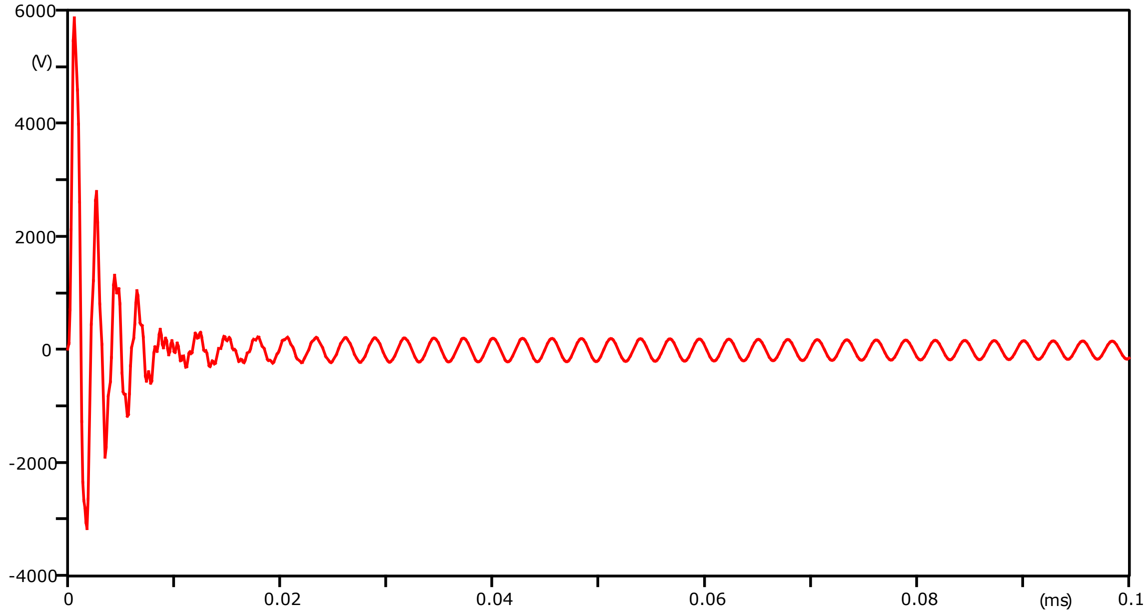

Figure 4.10: Transient voltage at the 6 kV side of the system for the case of 26.6 kA lightning with 400 and 15.75 kV surge arrestor.

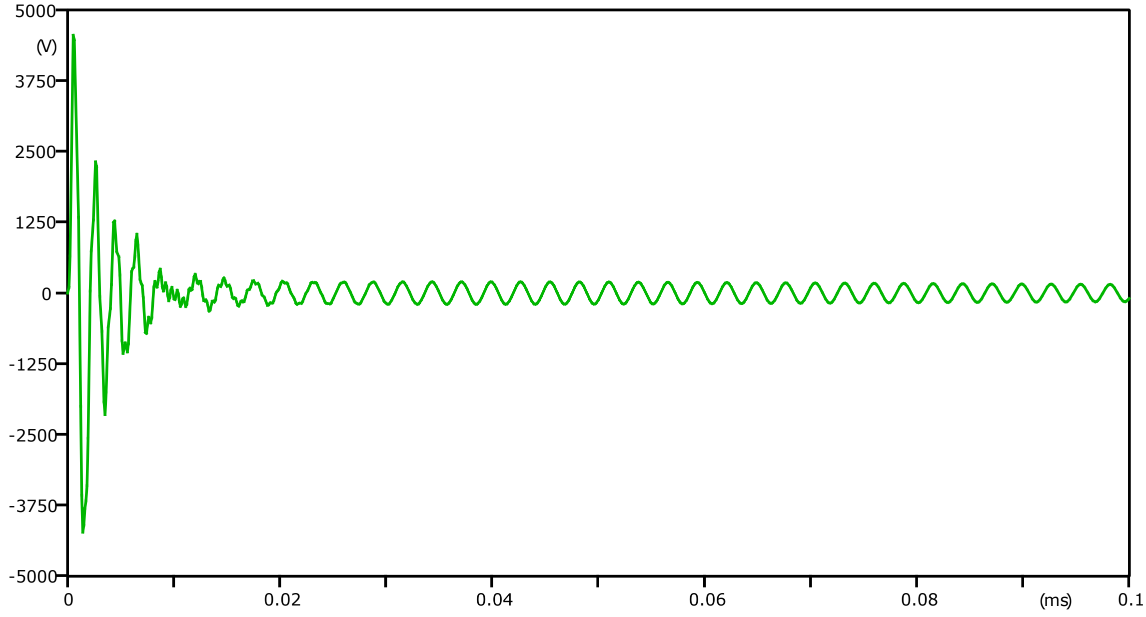

Figure 4.11: Transient voltage at the 0.4 kV side of the system for the case of 26.6 kA lightning with 400 and 15.75 kV surge arrestor.

3. **With 400 kV, 15.75 kV and 6 kV Surge Arrestor**

In this case 400 kV, 15.75 kV and 6 kV surge arrestor are used in the system and the corresponding transient voltage at different voltage levels are analyzed. Lightning current of $26.6kA, 1.2/50\mu s$ is used. The transient voltages are as shown in Figure 4.12 to 4.13.

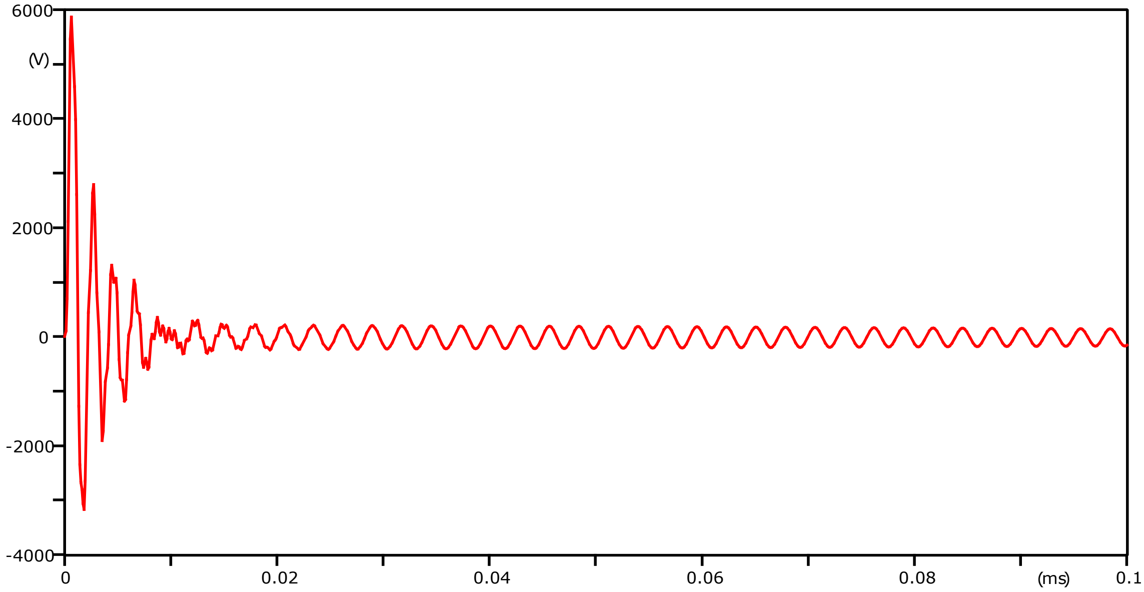

Figure 4.12: Transient voltage at the 6 kV side of the system for the case of 26.6 kA lightning with 400, 15.75 and 6 kV surge arrestor.

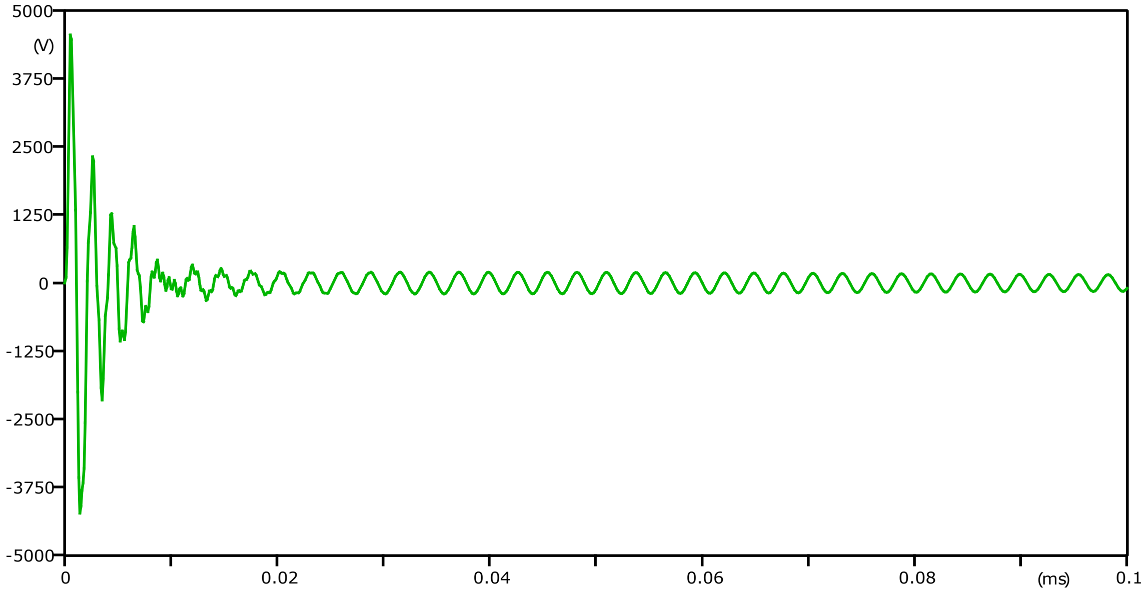

Figure 4.13: Transient voltage at the 0.4 kV side of the system for the case of 26.6 kA lightning with 400, 15.75 and 6 kV surge arrestor.

4. **20 kA lightning current with 400 kV and 15.75 kV Surge Arrestor**
   In this case the lightning current of 20 kA is taken with 400 kV and 15.75 kV surge arrestor arranged in the system. The transferred transient voltages are as shown in Figure 4.14 to 4.16.

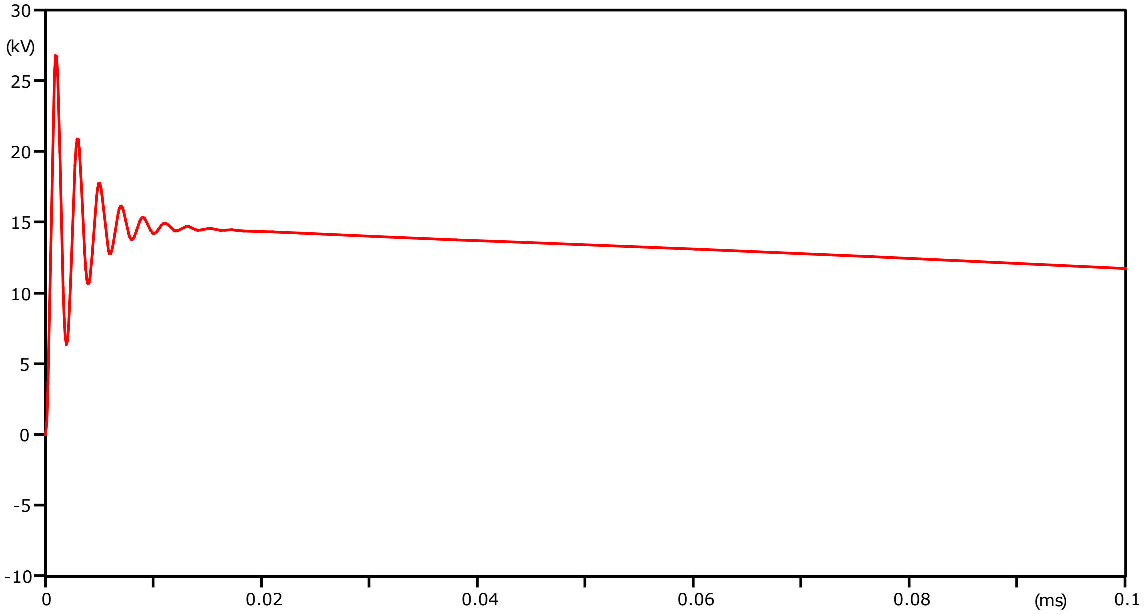

Figure 4.14: Transient voltage at the 15.75 kV side of the system for the case of 20 kA lightning with 400 and 15.75 kV surge arrestor.

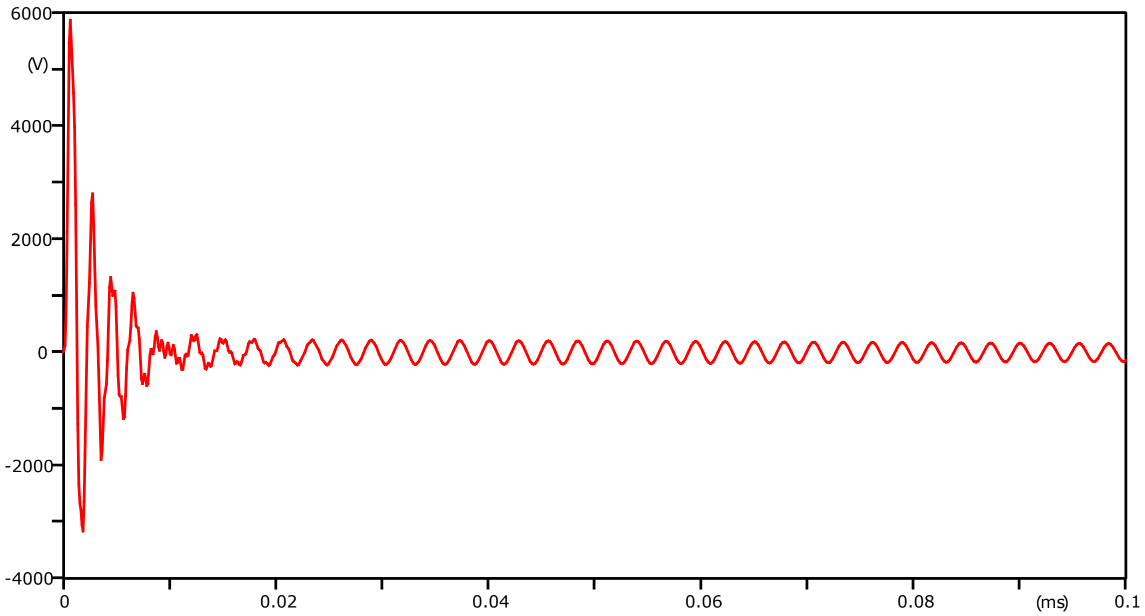

Figure 4.15: Transient voltage at the 6 kV side of the system for the case of 20 kA lightning with 400 and 15.75 kV surge arrestor.

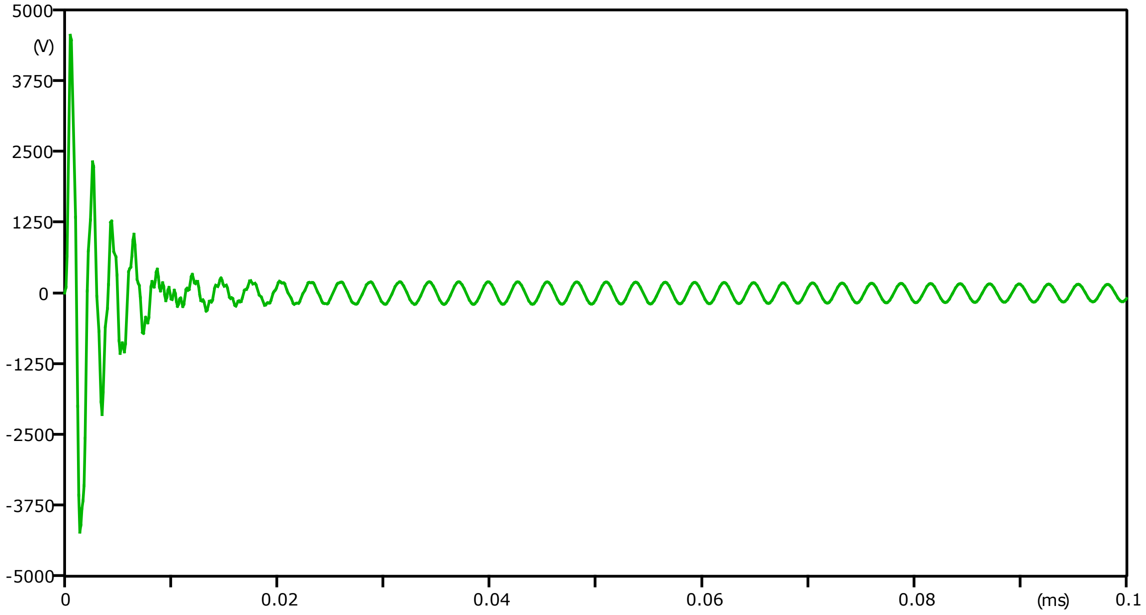

Figure 4.16: Transient voltage at the 0.4 kV side of the system for the case of 20 kA lightning with 400 and 15.75 kV surge arrestor.

5. **20 kA lightning current with 400 kV, 15.75 kV and 6 kV Surge Arrestor**
   In this case the lightning current of 20 kA is taken with 400 kV, 15.75 kV and 6 kV surge arrestor arranged in the system. The transferred transient voltages are as shown in Figure 4.17 to 4.18.

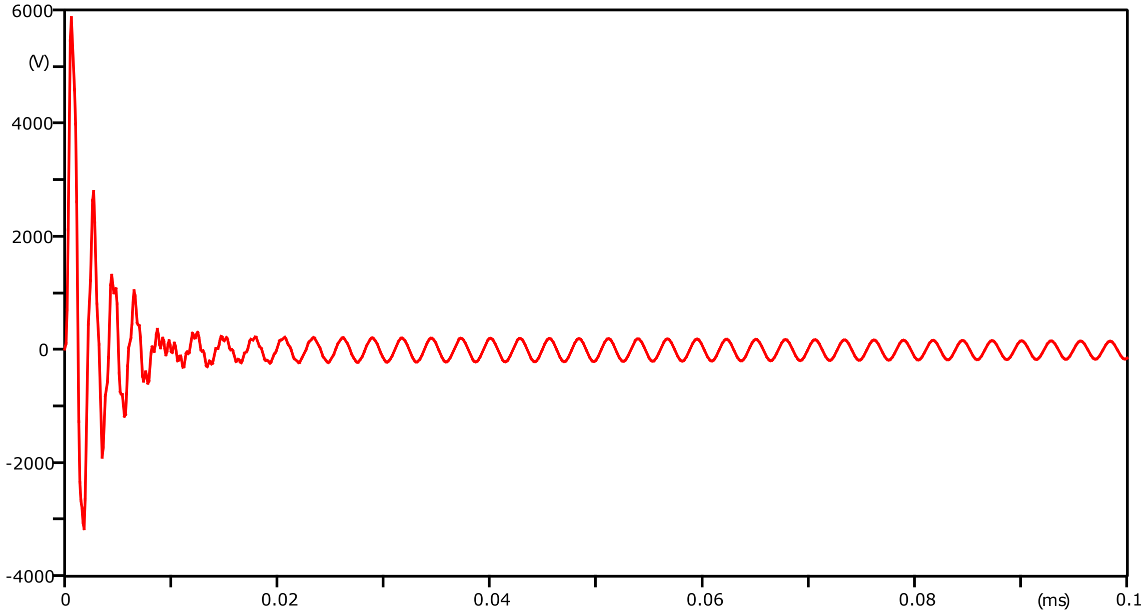

Figure 4.17: Transient voltage at the 6 kV side of the system for the case of 20 kA lightning with 400, 15.75 and 6 kV surge arrestor.

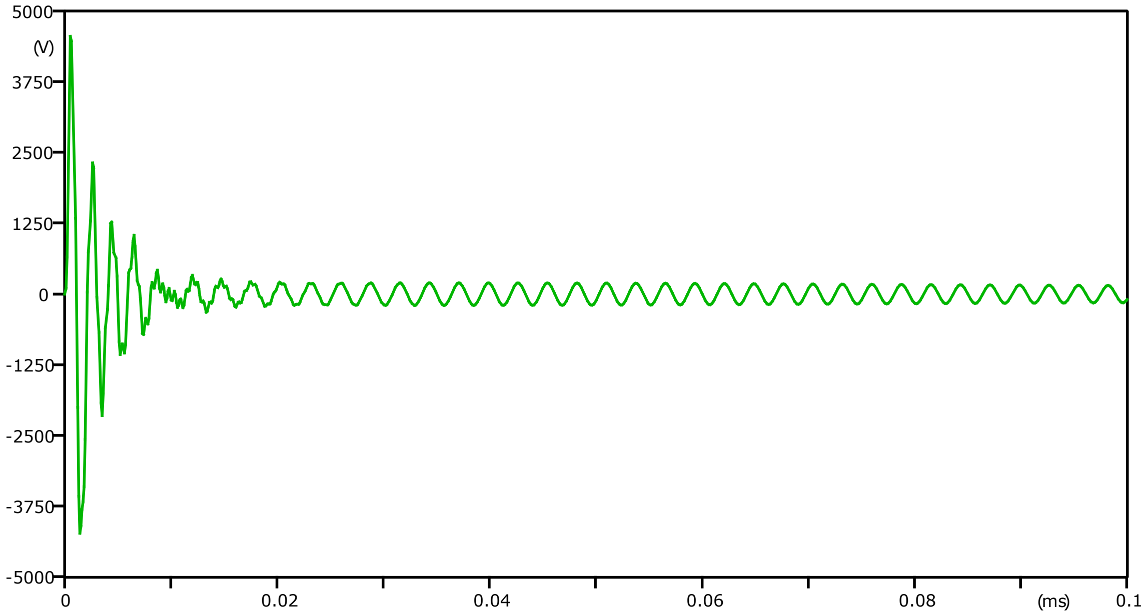

Figure 4.18: Transient voltage at the 0.4 kV side of the system for the case of 20 kA lightning with 400, 15.75 and 6 kV surge arrestor.

4.3.2 Indirect Stroke

In this case the back flashover is modelled using a step voltage of 1640 kV applied to the phase conductor. This voltage corresponds to the flashover voltage of the insulator.

1. **With only 400 kV Surge Arrestor**

   In this case only 400 kV surge arrestor is implemented in the system and the corresponding transferred transient voltage at different point of the network is analyzed. Step voltage of 1640 kV is applied to the phase conductor. The transferred transient voltage are as shown in Figure 4.19 to 4.21.

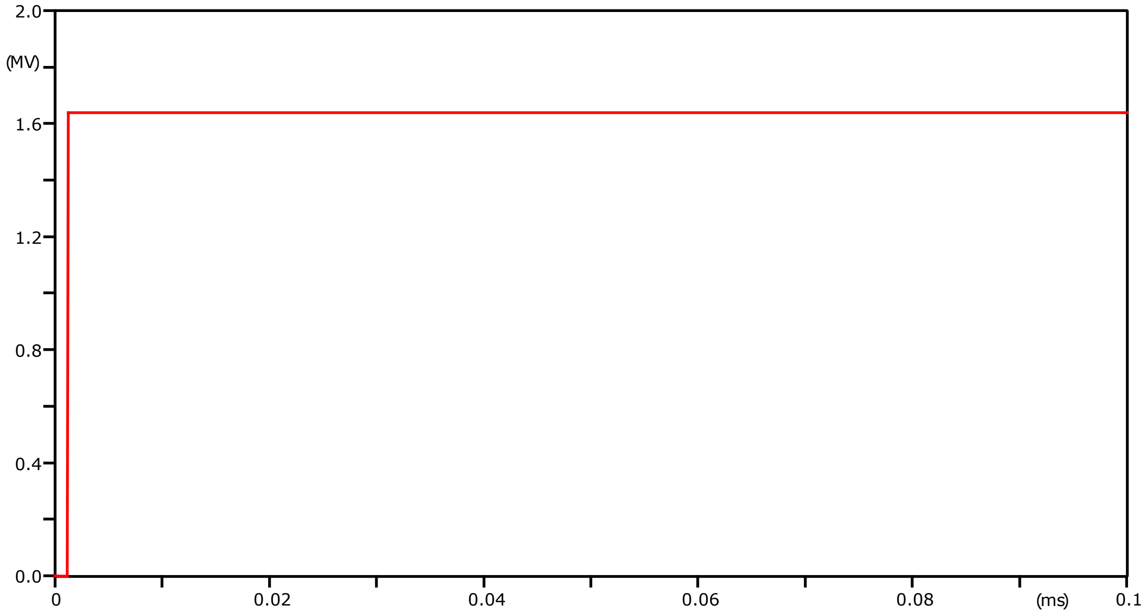

Figure 4.19: Voltage at the 415 kV side for the case of back flashover with 1640 kV step voltage.

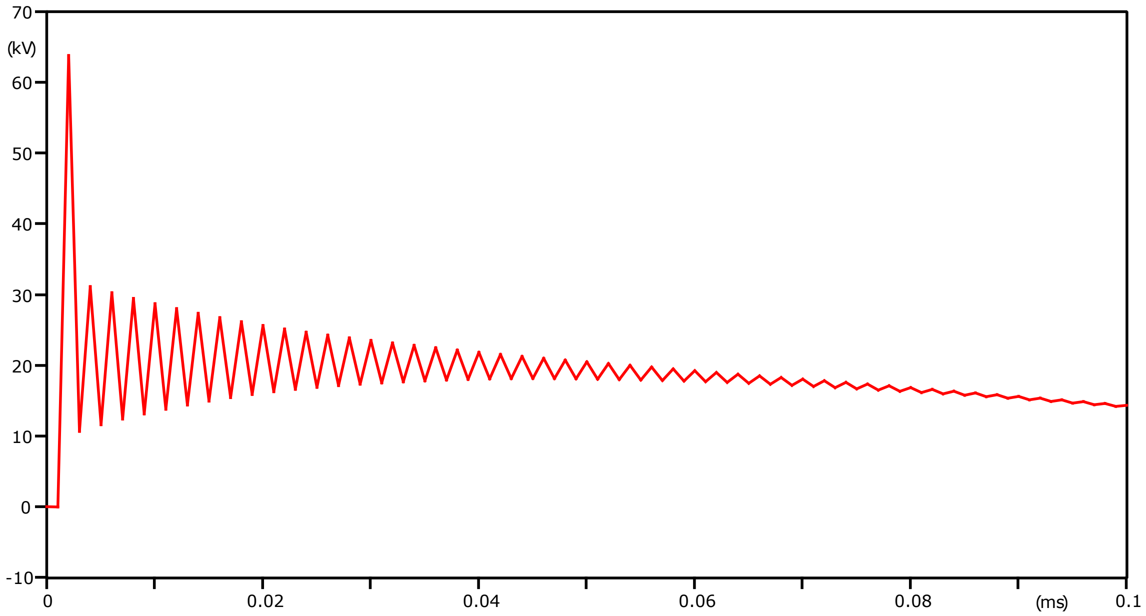

Figure 4.20: Transient voltage at the 15.75 kV side of the system for the case of back flashover with 400 kV surge arrestor.

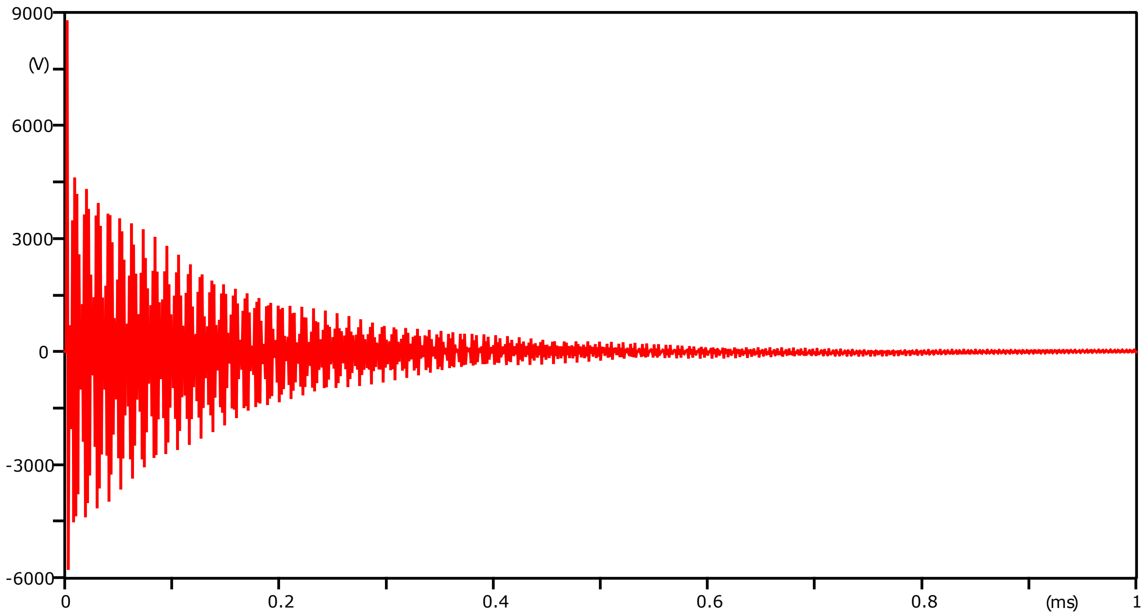

Figure 4.21: Transient voltage at the 6 kV side of the system for the case of back flashover with 400 kV surge arrestor.

2. **With 400 kV and 15.75 kV Surge Arrestor**

In this case surge arrestor of rating 400 kV and 15 kV are implemented in the system and the corresponding transferred transient voltage is analyzed at different point of the network. The transferred transient voltage are as presented in Figure 4.22 to 4.24.

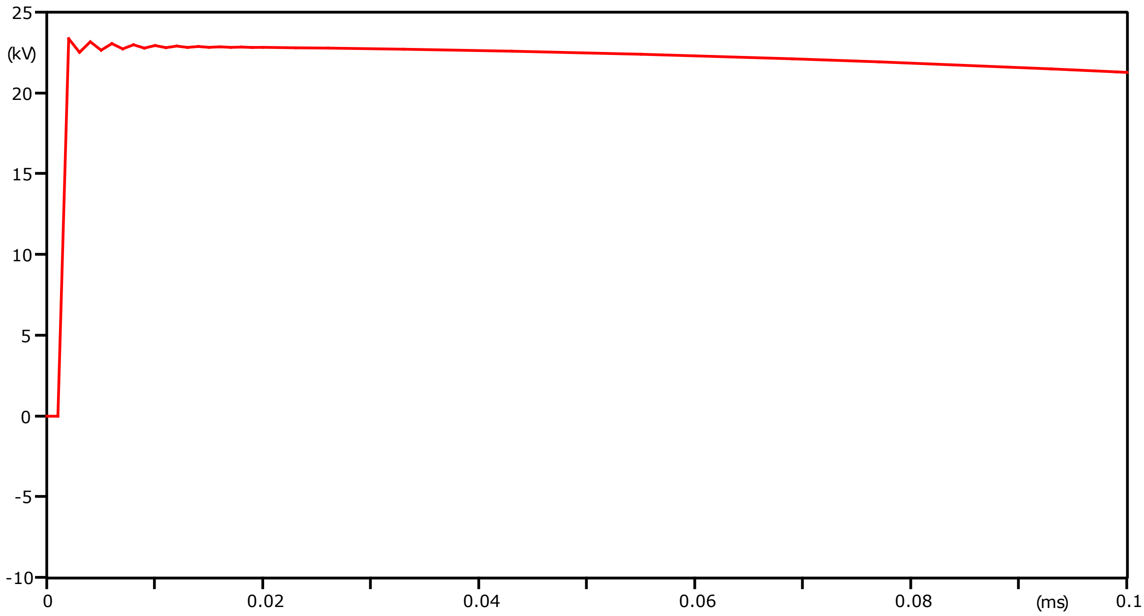

Figure 4.22: Transient voltage at the 15.75 kV side of the system for the case of back flashover with 400 and 15.75 kV surge arrestor.

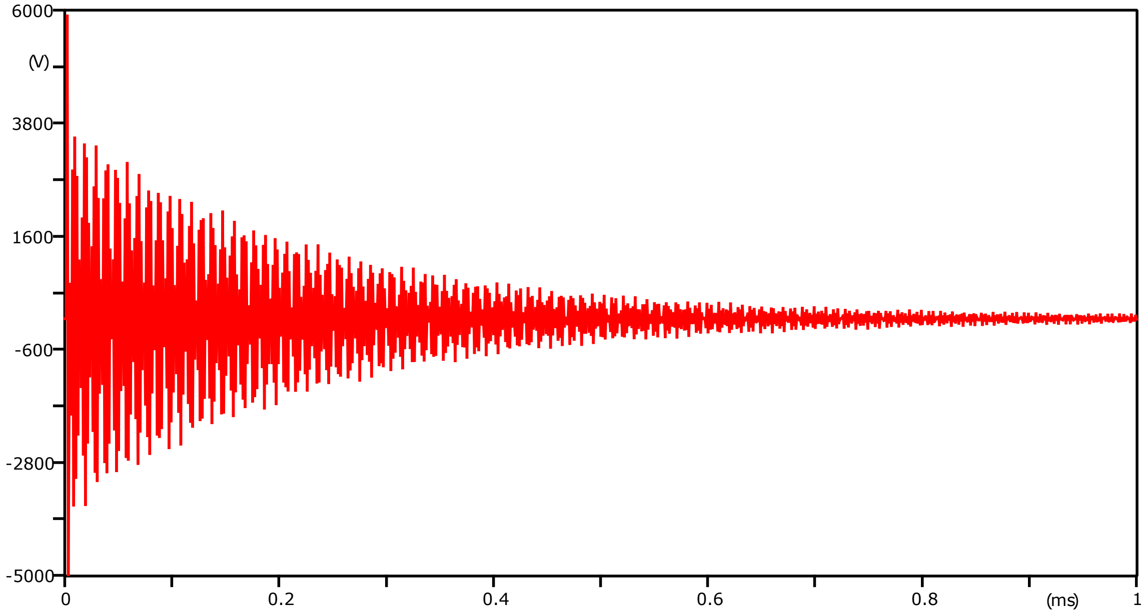

Figure 4.23: Transient voltage at the 6 kV side of the system for the case of back flashover with 400 and 15.75 kV surge arrestor.

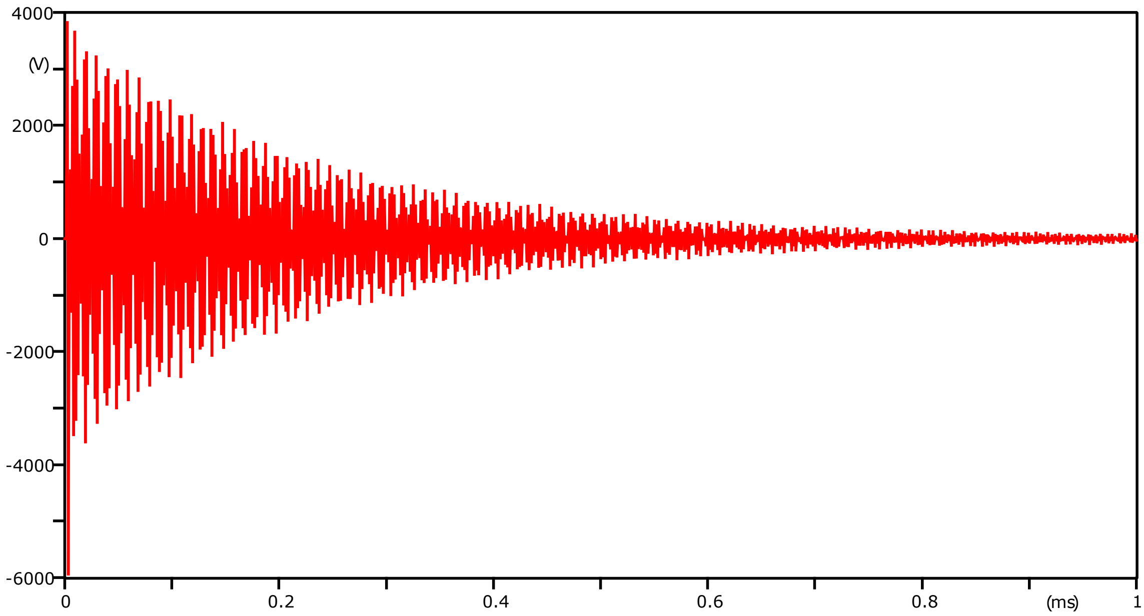

Figure 4.24: Transient voltage at the 0.4 kV side of the system for the case of back flashover with 400 and 15.75 kV surge arrestor.

3. **With 400 kV, 15.75 kV and 6 kV Surge Arrestor**

In this case all three surge arrestors of rating 400 kV, 15.75 kV and 6 kV are used in the system and the corresponding transferred transient voltage is analyzed at various voltage levels within the network. The transferred transient voltage are as shown in Figure 4.25 and 4.26.

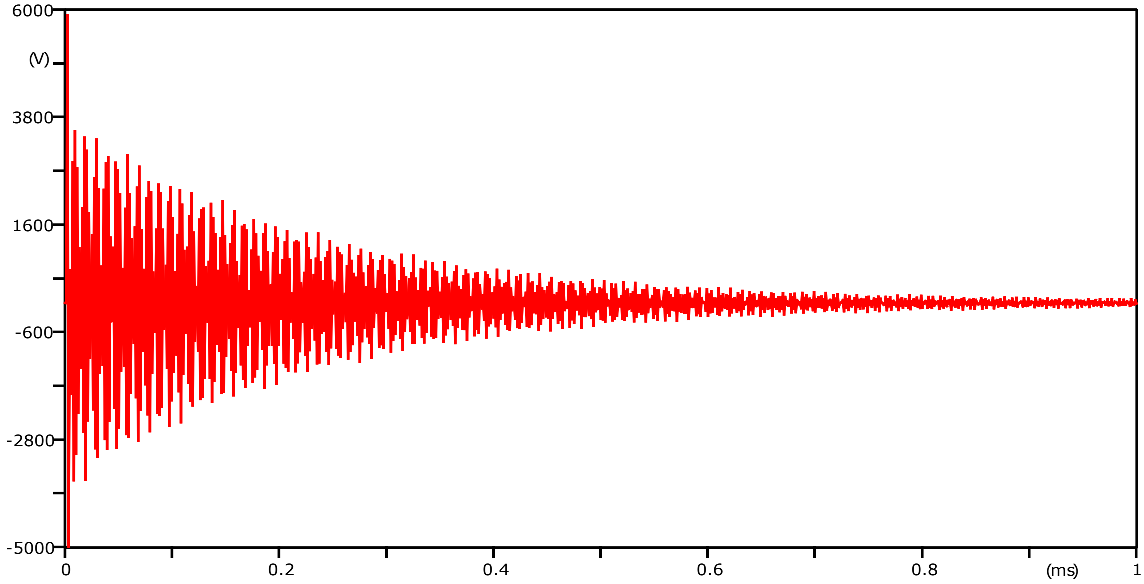

Figure 4.25: Transient voltage at the 6 kV side of the system for the case of back flashover with 400, 15.75 and 6 kV surge arrestor.

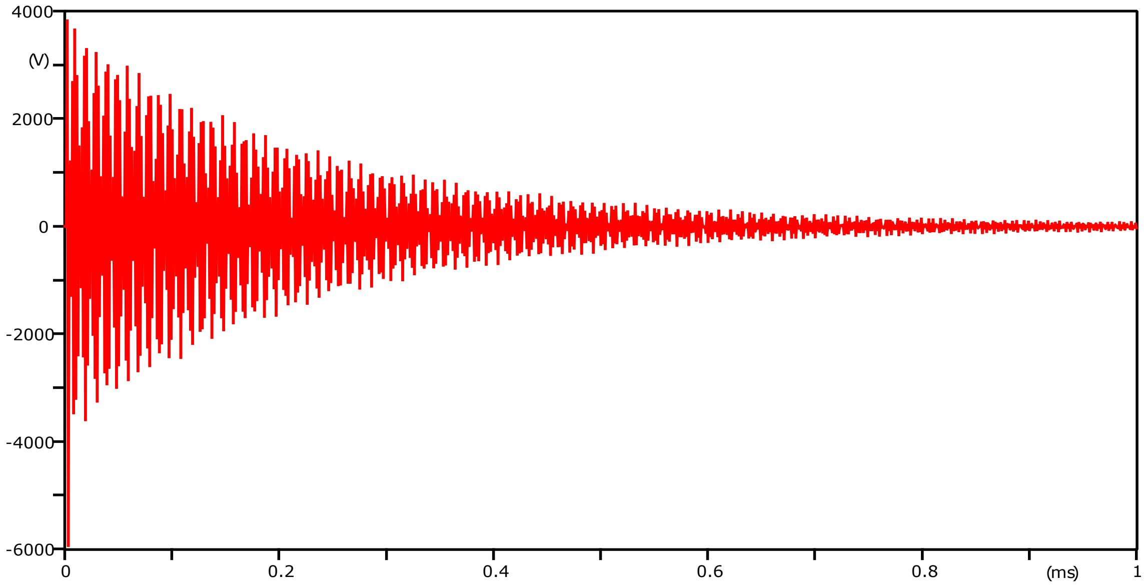

Figure 4.26: Transient voltage at 0.4 kV side of the system for the case of back flashover with 400, 15.75 and 6 kV surge arrestor.

The simulation results obtained for different cases are summarized and listed in Table 4.1.

Table 4.1: Summary of voltage peak for all cases

Case	**Surge Arrestor**	**Voltage Peak (kV)**			
		415 kV	15.75 kV	6 kV	0.4 kV
Direct Stroke 26.6 kA, 1.2/50 μs	400 kV	1650	75	12	9.5
	400+15.75 kV	1650	32	6	4
	400+15.75+6 kV	1650	32	6	4
Direct Stroke 20 kA, 1.2/50 μs	400+15.75 kV	1350	27	5.7	4
	400+15.75+6 kV	1350	27	5.7	4
Back Flashover 1640 kV	400 kV	1640	63	8.8	5.8
	400+15.75 kV	1640	23	6	4
	400+15.75+6 kV	1640	23	6	4

5 Discussion and Conclusion

5.1 Discussion

The peak voltage profile in case of direct stroke is shown in Figure 4.3 to 4.7 for tower voltage, 415 kV, 15.75 kV, 6 kV and 0.4 kV respectively. By comparing the voltage profile of the system with only 400 kV surge arrestor in operation, the voltage peak at the terminal of the primary side is reduced from 6.6 MV to 1.65 MV. A comparison of the voltage profile with and without 400 kV surge arrestor operation is shown in Figure 4.3 and 4.4. The over-voltage is limited due to the behaviour of the surge arrestor. The transient voltage has a peak of 75 kV at the 15.75 kV side of the system. The voltage peak at the 6 kV and 0.4 kV side of the system are 12 kV and 9.5 kV respectively. These can be seen in Figure 4.6 to 4.7. Figure 4.8 shows the voltage at the 415 kV side of the network when subjected to a lightning current of 200 kA. The high overvoltage of this case will lead to the immediate flashover of the insulator string. The shield wire of the transmission line will however restrict the lightning of 200 kA to enter the phase conductors of the transmission line.

Figure 4.9 to 4.11 shows the voltage at different voltage levels with 400 and 15.75 kV surge arrestor in operation. Use of 15.75 kV surge arrestor has limited the voltage at the 15.75 kV from 75 kV to 32 kV as shown in Figure 4.9. Likewise, the voltage at the 6 kV and 0.4 kV side of the network are also reduced to 6 kV and 4 kV respectively as shown in Figure 4.10 and 4.11.

The transient over-voltage at the 6 kV and 0.4 kV side are shown in Figure 4.12 and 4.13 when all three surge arrestor 400 kV, 15.75 kV and 6 kV are in operation. In this case, the transient voltage has the peak of 6 kV at the 6 kV side and 4 kV at the 0.4 kV side. The over-voltage amplitude has a negative peak also which is shown in Figure 4.4, when the protective surge arrestors are present in the system. This is due to the operation of the surge arrestor and the reflections of the travelling wave at the open end of the line.

Figure 4.14 to 4.16 shows the voltage peak at different voltage levels for lightning current of 20 kA with 400 and 15.75 kV surge arrestor in operation. 15.75 kV side of the network has a peak voltage of 27 kV while the voltage at the 6 kV and 0.4 kV side are 5.7 kV and 4 kV respectively. The same values are seen when all three surge arrestors are in the system for the same lightning current.

The case of back flashover is analyzed with different combination of surge arrestors. The back flashover is modelled by applying a step voltage of 1640 kV to the phase conductor of the line. This voltage is taken for all the scenarios. The transferred transient voltage when only 400 kV surge arrestor is used in the system are as shown in Figure 4.19 to 4.21. Figure 4.19 represents the step voltage taken for the modelling of the back flashover. The voltage has a peak of 63 kV at the 15.75 kV side of the system. The transient voltage reaching at the 6 kV side of the transformer has a peak of 8.8 kV while the voltage peak at the 0.4 kV side of the system is at 5.8 kV. The voltage at the 6 kV side is well below the basic level insulation (BIL of 29 kV) and close to the system voltage of the connected motors. Figure 4.22 to 4.24 presents the transferred transient voltage when the system consist of 400 kV and 15.75 kV surge arrestor. The voltage at the 15.75 kV side dropped to 23 kV from 63 kV with and without 15.75 kV surge arrestor respectively. The transient voltage reaching the 6 kV and 0.4 kV end of the network is 6 kV and 4 kV as shown in Figure 4.23 and 4.24 respectively.

All three surge arrestors of rating 400 kV, 15.75 kV and 6 kV are considered in the last study scenario. The transferred transient voltage peaks in this scenario are as depicted in Figure 4.25 to 4.26. The voltage at the 6 kV busbar is at 6 kV while the voltage peak at the 0.4 kV busbar has remained constant at 4 kV. The use of 6 kV surge arrestor has no any effect on the system as the transient voltage reaching the 6 kV side is at the system voltage level and surge arrestor does not operate.

The use of cable in the modelling has limited the transient voltage being transmitted to the low voltage side as the capacitance of the cable are taken into consideration and used in the modelling. The capacitance in the 15.75 kv bus bar has significantly reduced the transient voltage at the 15.75 kV side. The oscillations in the voltage transients at 6 kV and 0.4 side of the network is basically due to the cable impedance. Besides, the response of the transformer, there are two factors that affect the shape of the induced voltage. They are (i) the wave shape of the incident lightning stroke and (ii) the reflection of the induced surge at the surge arrestor location when they operate.

5.2 Conclusion

In order to accurately estimate the transferred transient voltage to the low voltage side of the system from the high voltage side, high frequency modelling of the associated equipment and apparatus is required. The parameters of the models are identified based on the obtained measurement results. The presence of 400 kV and 15.75 kV surge arrestor has strong impact in limiting the transient voltage during both case of direct stroke and back flashover. In both case of direct stroke and back flashover with only 400 kV surge arrestor in the system, the transferred transient voltage at the 15.75 kV side is well above the basic insulation level (68 kV) of the generator in case of direct stroke and almost equal in case of back flashover while the transient voltage at 6 kV bus bar is below the basic insulation level (29 kV) of the connected motor.

The use of 15.75 kV surge arrestor together with 400 kV arrestor has significantly reduced the voltage at the 15.75 kV side of the network. The use of 15.75 kV surge arrestor is required to ensure the protection of the generator connected to the 15.75 kV voltage level for both case of direct stroke and back flashover as the voltage at the 15.75 kV side is higher than the BIL when only 400 kV surge arestor is used.

This surge arrestor is enough to protect the generator against the 20 kA lightning. If higher surge are expected to enter the system, the rating of the surge arrestor should be higher.

In conclusion, the surge arrestors in the 400 kV and 15.75 side are required for the protection of generators and motors from the transient voltage. The results presented may be useful for further studies regarding the insulation coordination of the power system.

For further study, it is recommended to have an experimental setup for all the transformers used in the study in order to obtain more accurate and precise simulation results. As the back flashover depends on number of parameters, study can be performed on different scenarios to ensure proper protection for all the possible scenarios. The surge can be more accurately modelled by proper calculation of the maximum amount of the surge that can enter the transmission tower through the shield wire and investigate how likely is that 26.6 kA surge enters the phase conductor.

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A Frequency Response Analysis

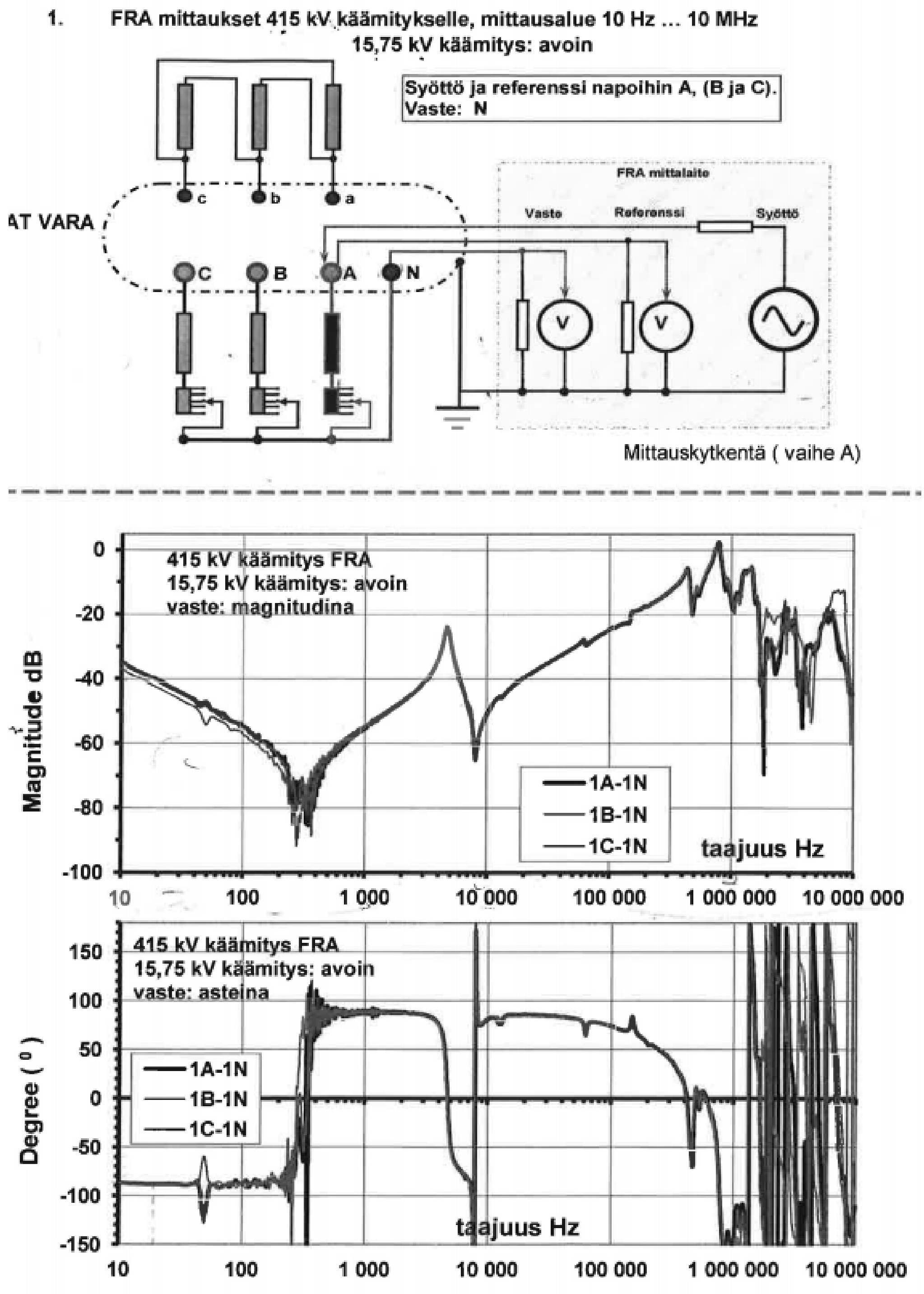

Figure A1: Frequency response analysis of HV side of power transformer

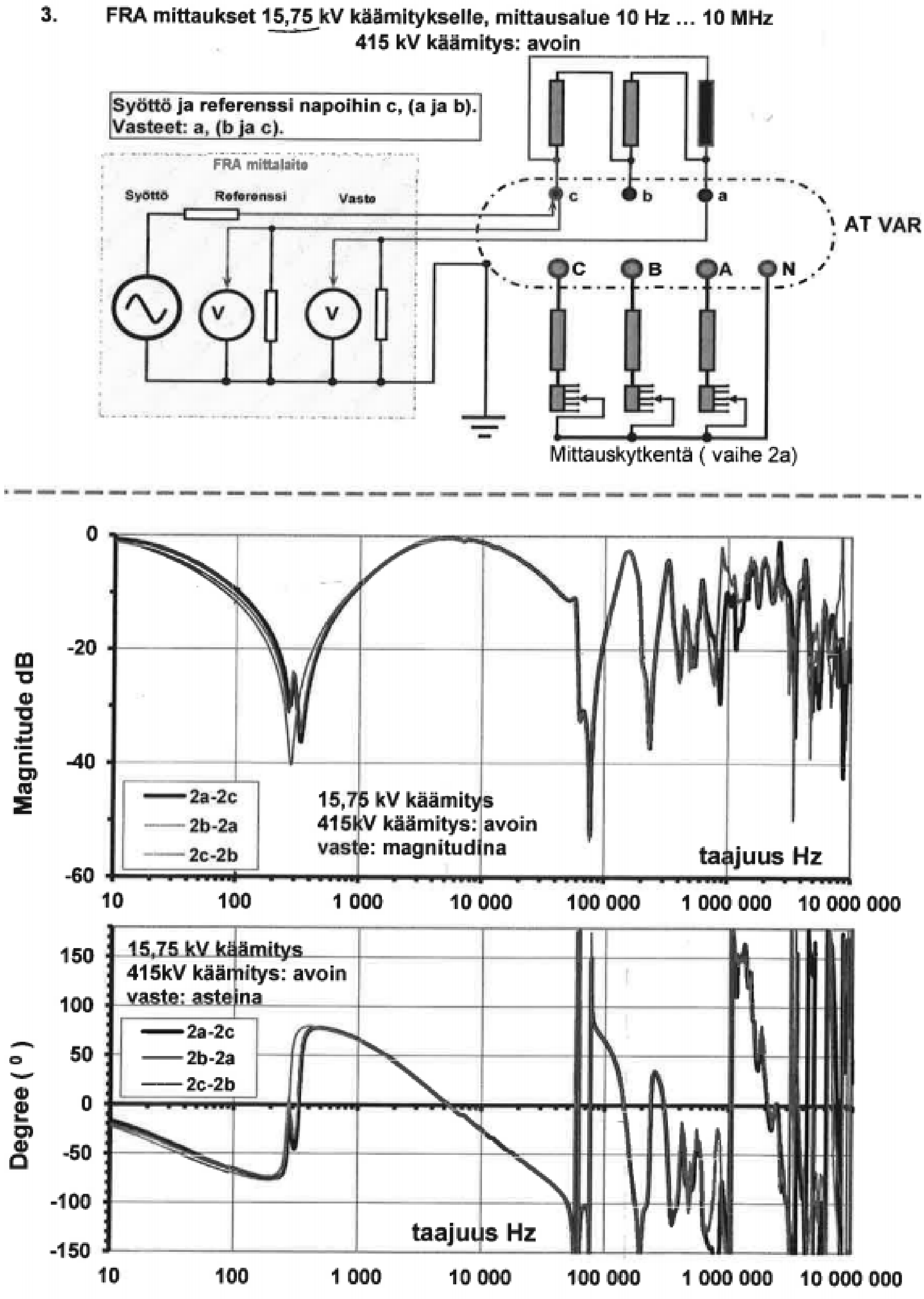

Figure A2: Frequency response analysis of LV side of power transformer

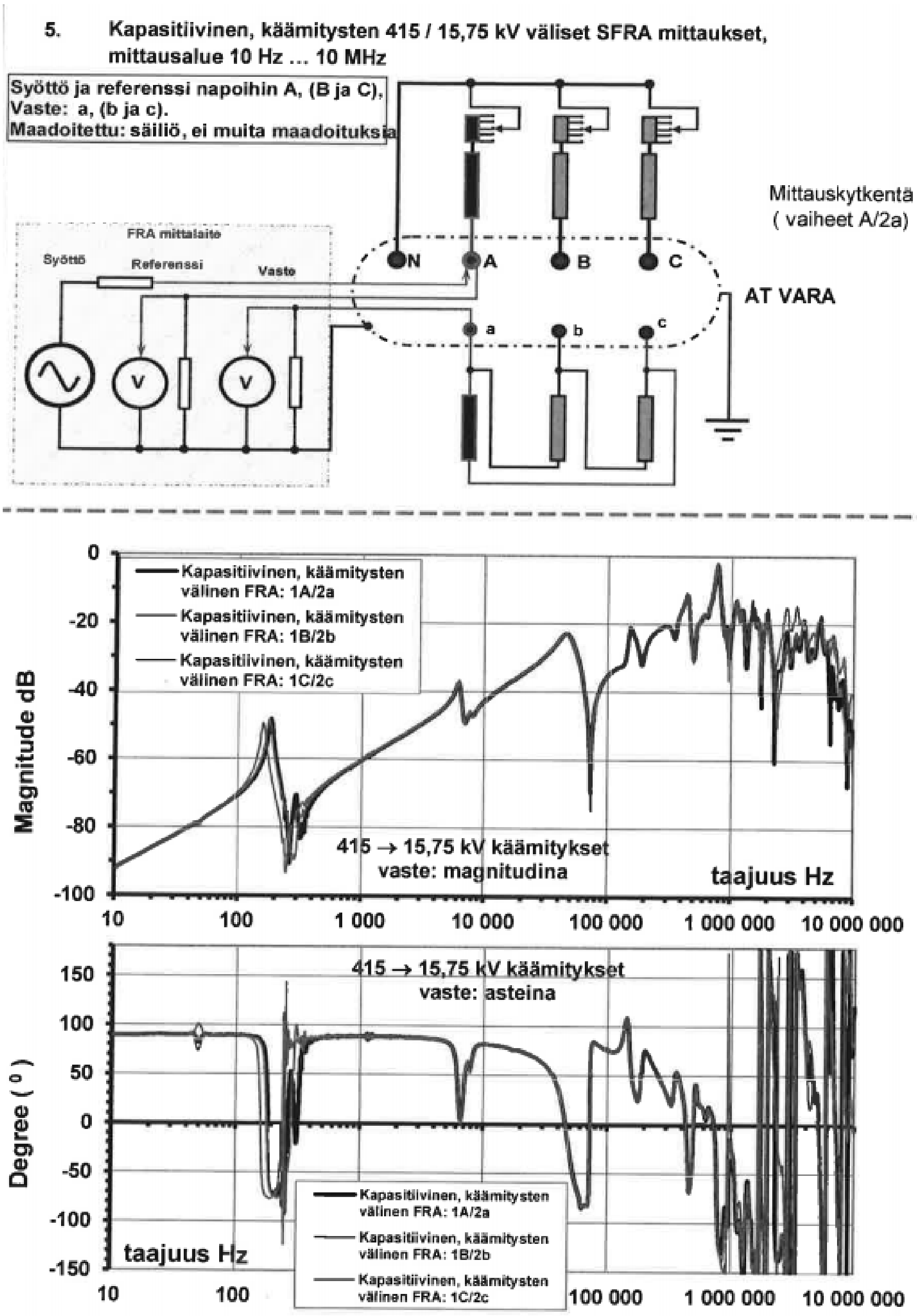

Figure A3: Frequency response analysis between LV & HV windings of power transformer

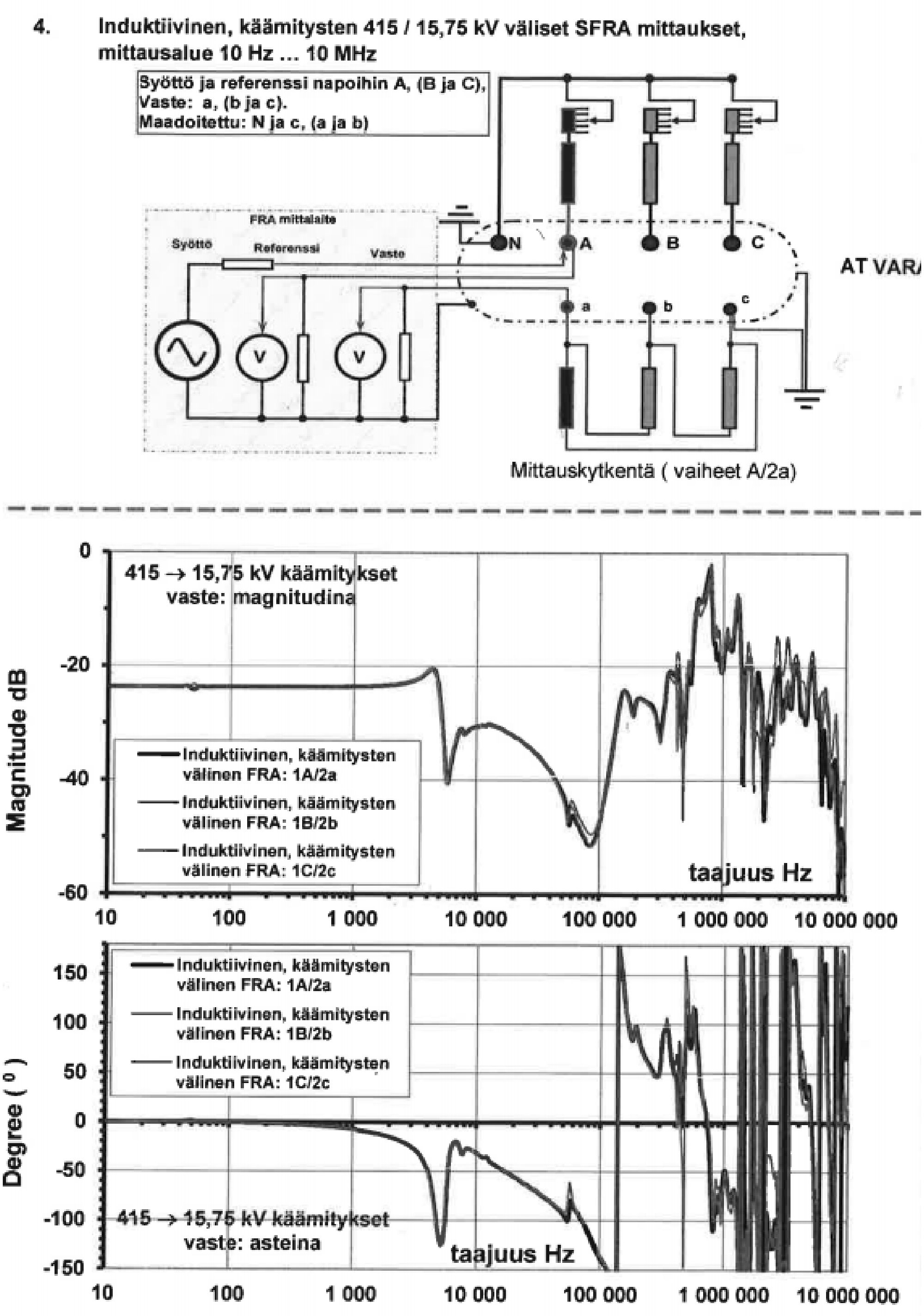

Figure A4: Frequency response analysis between LV & HV windings of power transformer

B Surge arrestor non linear characteristics

The non linear characteristic of the surge arrestor are as:

Table B2: V-I characteristic of A_0 and A_1

I(kA)	$A_0(PU)$	$A_1(PU)$
$2*10^{-6}$	0.81	0.623
0.1	0.974	0.788
1	1.052	0.866
3	1.108	0.922
10	1.195	1.009
20	1.277	1.091

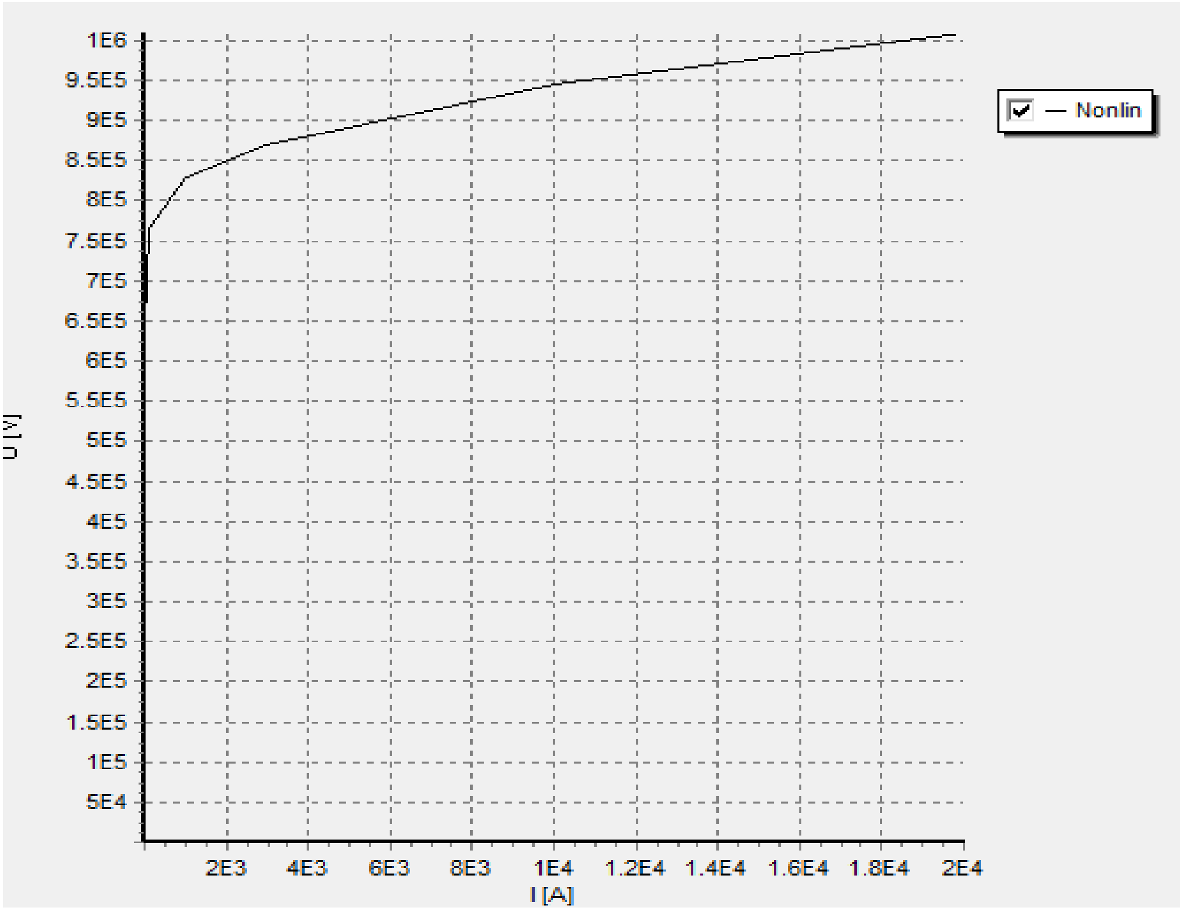

Figure B1: Non linear characteristic of non-linear element A0

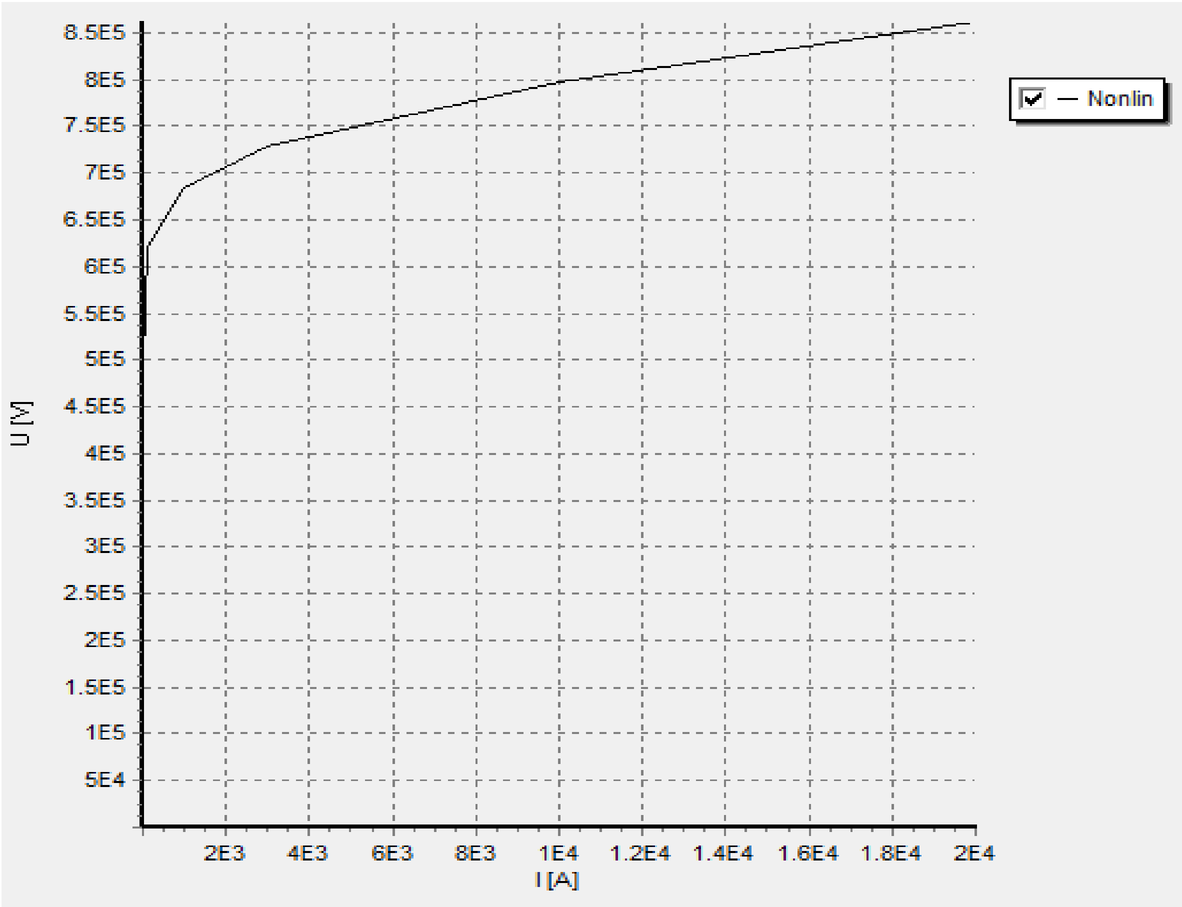

Figure B2: Non linear characteristic of non-linear element A1