Study for Effective Lightning protection System for Floating Roof Tanks in Petroleum Refinery

B.A.T.Bamunuarachchi

159352X

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science in Electrical Installations

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Abstract

Refinery is considered as the foremost division of the Ceylon petroleum corporation which ensures the safety of the operation of process plant as well as for maintaining the required country's demand for petroleum products to enhance the energy sector of the country.
Since the un-interruptible continuous refinery operation is critically important to maintain national requirement of petroleum product and protecting the tanks and process equipment is essential.
In this study, main concern about floating roof large crude oil storage tank facility. The most general method to prevent the possible damage to floating roof crude oil storage tank is using good earthing. The earthing system provides an electrical path to the ground and performance of the earthing system gets better as the earth loop impedance becomes lower.
Since it is among the major concerns currently Refinery engineering staff is struggling with; and a proper method for reducing the sparks due to lightning mainly at critical locations were studied and simulations were done by using the floating roof tank model prepared by using PSCAD software which was validated with the actual model tank tested in the UOM laboratory.
Direct and In-direct surge currents were calculated theoretically for 25 kA, 50 kA, 100 kA and 200 kA surges of 10/350 μS & 8/20 μS by applying calculated surge currents to the tank model.

Finally, by analyzing all the results and the protection methods of different types of grounding devices were studied and proposed adjustable grounding conductor (AGC) with suitable locations as the optimum solution.

Acknowledgement

I would like to express my sincere gratitude to my thesis supervisors Prof. J.R. Lucas and Dr. Asanka Rodrigo for having guidance and for their cordial support throughout the research and the thesis. Dr. Asanka's support and motivations were invaluable driving forces for me for the successful accomplishment of this study. It is for me a great pleasure and a great experience to having work under such a friendlier supervisor, who is having a broad scientific knowledge related to lightning protection and Earthig systems.
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B.A.T. Bamunuarachchi

CHAPTER 1

INTRODUCTION

1.1 Background

Sri Lanka is an island situated between 5^0 to 10^0 in the North latitude and between79^0 to 82^0 in the East longitude in the Indian Ocean. It is seasonally affected by two monsoon winds. The Southwest monsoon is from May to September and the Northeast monsoon is from December to February. There are also inter-monsoon periods and transition periods between the two monsoons. Convective activity causes rainfall during these inter-monsoon periods with thunderstorms and lightning is a frequent phenomenon during these periods [1].

Lightning activity is a sudden, unpredictable, uncontrollable and dangerous phenomenon in nature. A large thunderstorm can produce over 100 lightning flashes a minute [2]. Lightning is a major source for tank fire and plant failures due to equipment damage as they consist most parts of the systems with very sensitive electronics. It is most important to protect tanks and equipment connected to the refinery process system from over voltages due to lightning.

To decrease the oil evaporation effectively, floating roof tanks are frequently used nowadays. The size of tanks is extended progressively according to the crude oil exploration growth world widely. And similarly, hazard of lightning strikes to the large floating roof storage tanks rises additionally.

According to a Swedish review about petroleum storage tank fires which occurred from 1951 to 2003, the number of tank fires reported by worldwide media is in the range of 15 to 20 each year, 31% of which is attributed to lightning [3]. Since 2006, 6 large floating roof tanks lightning fire accidents have occurred consecutively in China. Researchers find some common features after analyzing these accidents [15].

In this study, main concern about floating roof large crude oil tank storage facility. The most general method to prevent the possible damage to floating roof hydrocarbon storage tank is using good earthing. The earthing system provides an electrical path to the ground and performance of the earthing system gets better as the earth loop impedance becomes lower.

1.2 Statement of Problem

So far, considering the issue of lightning protection international standards and even the standards of most countries, only include the protection of buildings (structures) and their contents. Latest IEC 62305 (2010 edition), in its four parts [7] has its content limited to "provides general principles to be followed for protection of structures against lightning, including their installations and contents, as well as persons" [7]. The protection of people in activities in large open areas, where physical installation of Lightning Protection Systems (LPS) is very expensive or even impossible, is not considered. Currently, most injuries and deaths caused by lightning occur justly in these environments, [20]

In a floating roof tank, the roof moves above the hydrocarbon product surface and less conductive neoprene rubber fastening material is used to cover and prevent losses of petroleum product through the floating roof edge. But such sealing material can cause an inferior grounding pathway amongst the roof edge and the tank shell, disturbing the release of lightning flash additional charge currents to ground.

Mostly two typical approaches have been adopted to resolve this issue intended for lightning shield design applications of large floating roof crude oil storage tank, [11], [14], [15]

- Installation of conductive strips around the perimeter of the tank on the secondary seal frontier top at each 3 meters interval. The springiness of conductive strip is most prominent to continue gliding contact with the tank shell to create the electric pathway to tank shell.
- Fixing of flexible Cu cables with minimum cross-sectional area of 25 mm^2 across the tank shell and roof pontoon laterally on the roof stairway for better grounding.

The crude oil tank roofs' diameter is varying from 60m to 80m. Primary seal and secondary seal are installed at the floating roof and primary seal is a mechanical seal and the secondary seal is made out of Neoprene rubber material. The combustible gas space available among the primary seal and secondary seal is liable to reach hazardous limits in the normal operation as well.

1.3 Reported Damages on oil storage tanks at Refinery

Although the conventional precautions were taken to mitigate the lightning surge damages, there were significant tank fires occurred during recent past period at Refinery and Orugodawatta intermediate storage facility. Surge generated by lightning may destroy or damage the sophisticated electronic components of the control system and initiate the tank fires. In order to minimize the damages suitable lightning protection system (LPS) should be installed at appropriate locations. Most of fires reported in the refinery could be controlled and extinguished by in house fire fighters and other trained staff personnel. However, in this thesis report is proposed only the general recommendation for Lightning flash prevention system for floating roof tanks at Refinery. The below table shows the reported cases in the recent past at the refinery

Table 1. 1 Reported tank fires due to lightning in the recent past at the Refinery

Date	Location	Cause of fire	Duration of fire	Extent of damage
2003.11.13	Crude oil tank no 04	Due to lightning	35min	About 30m of rim seal damage Five pontoons damage
2004.03.27	West side of the tank 04 perimeter	Lightning sparks	20min	Damage to the seal
2005.04.12	West side of the tanks 59/03	Lightning surge spark	15min	Ring seal damage
Date	Location	Cause of fire	Duration of fire	Extent of damage
Date	Location	Cause of fire	Duration of fire	Extent of damage
2006.10.26	Tank no 03 82MME 3A (south side of TK 03)	Lightning flash to a crude oil leak through the seal of the 82MME3A mixer shaft	05min	Burn damage to power supply cable mixer belts, belts guard and motor
2007.04 20	Upper tank farm near TK 16	Open flame	10min	Tank shell burns
2009.11.03	OTF TK02	Lightning discharge	20min	Significant damage to the ring primary seal

2013.03.24	OTF TK 02	Lightning strike	1hr	Roof seal damage Warping of few location of the tank shell
2014.10.29	TK03 between 3C and 3B foam pourers	Lightning strike	22min	50m of the skirt was damaged
2016.11.21	Tk 02 crude oil tank	Lightning strike	25min	Visible damage to the TK 02 Primary and secondary seal
2016.12.28	TK 03 crude oil tank	Lightning strike	15min	Center foam injection branch pipe end damage

1.4 Objectives

The major objectives of this research are

1. To find out the effect of lightning on petroleum oil storage tank configurations
2. To find out effect of large floating roof tanks at lightning discharge.
3. To find out effect of surges transmitted to ground through primary and secondary seal assemblies.
4. To propose an effective lightning prevention system for large floating roof crude oil storage tanks at refinery.

1.5 Purpose of Study

1.5.1 Study Area

• Analyzing the prevailing standards and discriminations between realistic implementations

• Studying of effective protection methods using different outlines and different approaches.

• Studying the challenges coming with practical lightning protection installations and risk mitigation due to lightning strikes for the petroleum oil storage floating roof tanks

• Study transient behaviour of Lightning surges and their effects by using software model such as PS-CAD

• Validation of the software model by testing a scaled actual model in the laboratory

• Areas where cost could be minimized by using appropriate protection systems

• Economic Profitability that can be achieved through reducing lightning effects to Refinery oil storage floating roof tanks & apparatus

1.6 Literature Survey

Past studies regarding this topic are limited and most of the studies are about lightning performance on the protection of buildings (structures) and their contents discussed through research papers.
Sri Lanka is situated in lightning prone region close to the equator. Therefore, it is important to study about the lightning protection. The literature survey was assists to understand the mechanism of lightning phenomena and its propagation on several structures and in the soil layers of the ground as well.
Most of the references were based on the industrial environments and few of them were described about the tank structures and their properties related to mechanical strength of the tanks. All lightning protection systems were based on the buildings and towers and not for the petroleum oil storage tanks. Therefore, it has to made more effort to select suitable literature for this aspect and have made lot of assumptions to the actual tank parameters due to non-availability of previous researches regarding this topic. Further it was very difficult to get the approval for testing of operating tank parameters due to high inflammability nature of the petroleum products and hazardous area classifications restrictions govern in the Refinery for usage of non-intrinsically safe instruments for the testing of tank parameters. Finally, approval was obtained for parameter testing of tanks which had been taken for routine maintenance purposes.

1.7 Methodalogy

By using standard formulas create electrical models using simple apparatus such as Resistor, Inductor, and Capacitor etc. for lightning current parallel path impedances of floating roof tank from roof to ground level.
By using PS-CAD software modeling, create a tank model with derived parameters
Designing and constructing a scaled model of floating roof tank with real materials used for construction of actual size floating roof tank, for laboratory testing.
Validating the PS-CAD model using scaled model for the parameters of the tank

Simulate different lightning surges and observe the behaviour of the existing parallel grounding paths

Study the impact of existing parallel paths for the various lightning currents with voltage rises.

Analyze the results and implement findings

Make corrective changes according to the outcome of the model simulations

1.8 Outline of Thesis

The following sections of the dissertation report are arranged as follows. The chapter 2 defines the lightning phenomena and exposure of the refinery tanks, build up a tank characteristics model in PSCAD. lightning impulse model in PSCAD is described in chapter 3. The chapter 4 is described the validation of calculated parameters with scaled model tank. In chapter 5 it describes the results for the simulation model of the PSCAD model and the details of the direct lighting model build up using PSCAD. Then the obtained PSCAD results for the simulated model are described in chapter 6. Finally, the proposed protection mechanism & recommendations are discussed in chapter 7 and 8.

CHAPTER 2

LIGHTNING EXPOSURE OF REFINERY OIL STORAGE TANKS

2.1 Introduction

This study was implemented to examine and appraise the lightning strikes and damages due to lightning in refinery tanks. So as to minimize lightning damages, it is important to diagnose the basics of lightning phenomena. Severe harm to the tank and failure of the apparatus may happen because of lightning strikes. Influences of lightning flash diverge according to the location. Above ground storage tanks are more revelation to the lightning strikes. CPC loses a significant amount of oil products and catastrophe of apparatus due to lightning annually.

Followings have to be considered to protect against lightning

a. Tank stokes by direct lightning

b. Nearby stroke induced to the tank

c. Flashovers to tanks and equipment

d. Side flashy as of lightning strike to oil tank roof or shell

2.2 Mechanism of Lightning

Lightning strike is kwon as a transmission of static electrical charges in a cloud to ground as huge current strike or flash in which remain hundreds of milli seconds for a quick period and perform a discharging route with a few kilometers consisting of massive current among the cloud and the earth. The development of electrical charges in raincloud occurs as a consequence of hot air current force up on a particle in the raincloud (formation of Static charges). Then the charges in the raincloud are divided in to positive and negative charges and positive charges gathers upper portion and negative charges gathers lower portion.

Progression is occurring as per the departure of positive & negative charge midpoints created and this charge variance is excessive sufficient to neutralize. The charge fronts arise from the earth to create an ionized path to neutralize the cloud's charges. Ionization of the air adjacent to the charge midpoints is the progress of "*Stepped Leaders"* then eventual outcome be the progress of lightning flashes. The entire release of accumulated charges from a rain cloud is termed as Lightning Strike or lightning flash. Typically, a flash comprises minus charge transferring from thunder cloud towards the ground. Usually multiple (subsequent) strokes happening in more than half of all lightning flashes. *"Dart Leaders"* are the leaders of consequent strokes. The return stroke which has high current magnitude of up to 200kA of current. Then lightning is defined as momentary huge electrical current discharging phenomena [3].

Lightning flashes are mainly two types viz "*positive flashes*" and "*negative flashes* Negative earth strikes are more frequent whilst positive ground strikes are not experienced commonly and they are in the range of 2 % to 4 % in our country [3].

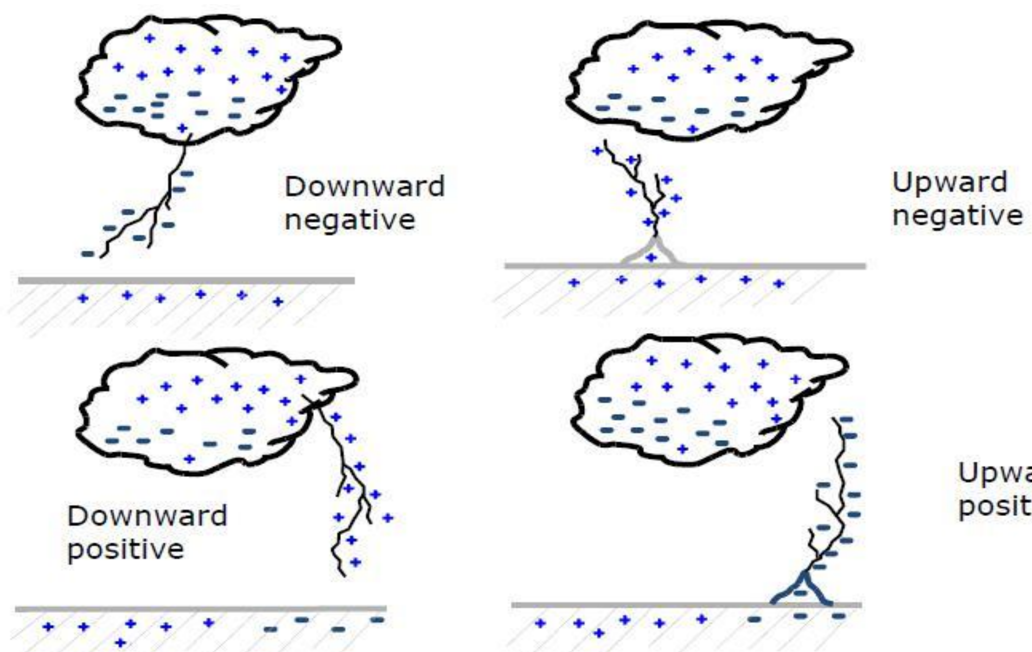


Figure 2. 1 Formation of Lightning Flash [3]

2.3 Lightning Stroke Types

a. Intra Cloud Lightning Flashes

This discharge phenomena are the most frequent category. This lightning flashes arises among reversing charged particulars inside the rain-cloud. Generally, the development happens inside the cloud and it looks like a bright diffusing sparkles seen from the outside of the cloud. Nevertheless, the discharge might occur at the borderline of the rain-cloud and a brightly illuminated line, equal to a cloud-to-ground flash, which is noticeable to faraway.

b. Lightning Flashes among near-by clouds

Lightning flashes among near-by clouds as the name indicates, arises between two dissimilar clouds having diffusing sparks connecting a break of intact atmosphere among clouds.

c. Lightning Flashes ending at the surface of ground *(Cloud-to-ground)*

This type of lightning flash be the greatest detrimental and harmful category of lightning phenomena and this is the lowermost frequent category. However, this is the most sensitive category of lightning strikes to human. These strikes might have negative or positive flashes. Utmost strikes initiate close to the downward charge midpoint (negative) of the rain cloud and then carry a negatively charged current towards the ground. Furthermore, positive ground flashes transmit positive charges to ground and it happens occasionally in this province in Sri Lanka [3].

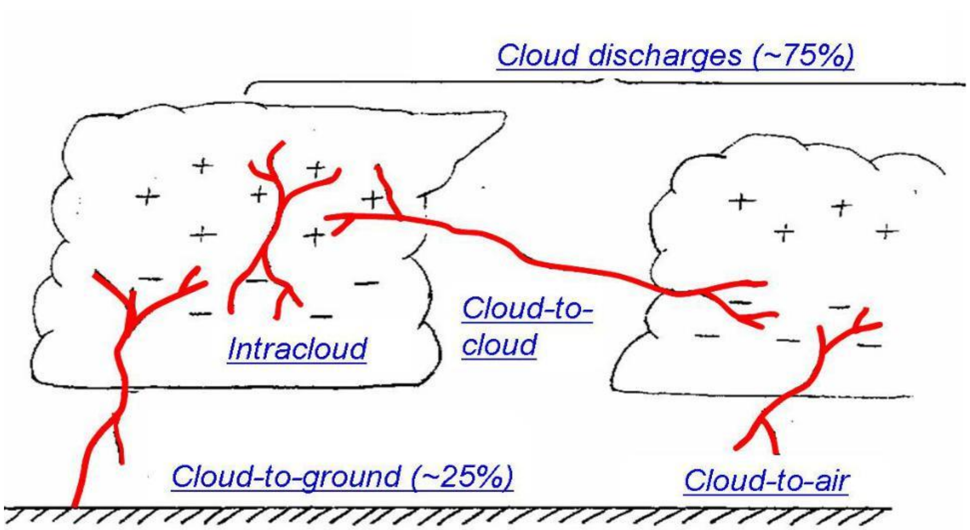


Figure 2. 2 Types of Lightning Flashes [3]

2.4 Ground Flash Density (GFD)

Incidences of lightning strikes at various places have been gathered for a extensive time-frame and the plot is arranged to forecast the possibility of lightning flash. The keraunic level is a structure to define lightning action at a location created upon the sound recognition of thunder-noise. An isokeraunic chart draws outlines of equivalent keraunic level. Lightning keraunic number is countered by ground-flash counters and represents as Ground Flash Density (GFD). The typical quantity of lightning flashes per unit location (area) per unit period (year) at a specific area is kwon as the ground flash density [3].

Figure 2. 3 Isokeraunic Map of Sri Lanka [2]

Table 2. 1 Relationship between Isokeraunic level and lightning flashes per Sq km per year [4]

Thunder days per year	Flashes per km^2 (Ng)
5	0.2
10	0.5
20	1.1
30	1.9
40	2.8
50	3.7
60	4.7
80	6.9
100	9.2

Reproduced from Data of BS 6651

Table 2. 2 Number of Thunder Days

	Colombo				
	2014	**2015**	**2016**	**2017**	**2018**
January	02	09	02	09	09
February	05	11	03	0	05
March	08	12	12	09	15
April	18	18	11	21	17
May	07	10	18	14	04
June	06	10	03	02	01
July	05	02	04	05	02
August	08	05	02	01	01
September	04	03	02	03	03
October	05	08	08	02	07
November	12	12	12	11	12
December	11	13	18	05	09
Total	91	113	95	89	85

Reproduced with Data from Climate Division, Department of Meteorology, 2018.

Since there is no accurate data system available for the lightning strike position, several equations represent the assessment of ground-flash-density (GFD) from the quantity of detected rainstorm days. The lightning incident can be expressed in terms of thunderstorm or days when thunders are heard. These statistics are collected to create an isokeraunic map. The relationship between annual ground flash density (N_g) and thunderstorm days per year (T_d) can be described as the following as rough relationship [3].

$$N_g = 0.04\, T_d^{\,1.25} \qquad (2.1)$$

N_g - No. of Lightning Flashes to the ground per sq. km

T_d - Average Annual keraunic level (thunderstorm-days)

2.5 Lightning Flash Current Amplitude and Dispersment

Lightning flash is the unique pulsation of lightning occurrence and the strike current extent within a lightning stroke is defined with respect to the distribution of probability. Anderson and Eriksson developed the flash current value cumulative distribution of probability. The current magnitude follows a probabilistic rule specified by a greater than the magnitude cumulative probability. The probability of peak current (I_0) being equal or higher than a given value (I_0) can be determined by equation [3].

$$P_{Io} = e^{-0.02878Io} \qquad (2.2)$$

The amplitude of I_0 shall be less than 100 kA because for this study and the peak lightning flash current greater than 100 kA is not significant. The magnitude of lightning flash current following a probabilistic law given by the collective probability of beyond the magnitude of I.

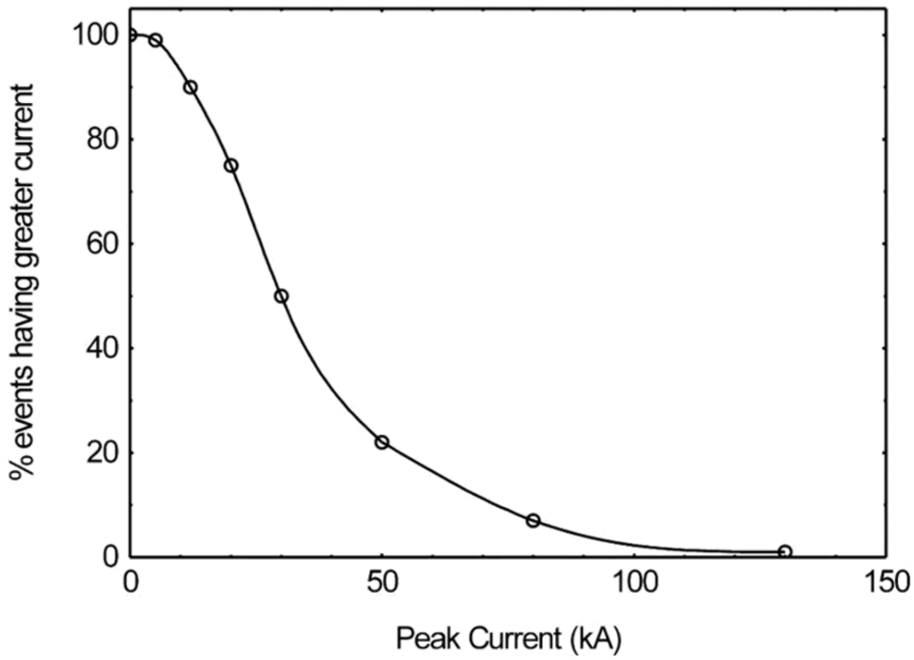


Figure 2. 4 Probability of Lightning Current above considerable range

2.6 Lightning Effects on Large Oil Storage Tanks

Lightning flashes are able to produce higher potentials when it strikes the tank shell or tank floating roof. The large oil storage tanks unveiled to lightning strikes shall be measured to evaluate its lightning behaviour. The initial phase is to describe the lightning action in the area intersected by the contour. This action is considered straightly from the ground flash density (GFD-N_g) (number of strikes to earth per square kilometer per annum). The lightning location and measurement systems are used to get this parameter, and it is assessed moreover as of the thunderstorm day, unless individual measurements are obtainable.

2.6.1 Direct lightning Flash

The lightning flashes affected to the tank roof or tank shell at the refinery exposed area and not enclosed with natural shelters (trees, rocks etc.) or neighboring large substances could be expressed in this manner. Amount of lightning flashes towards above ground tanks annually, are assessed by the formula derived by Eriksson [5].

Amount of Flashes on large metal object (Oil Storage Tank)

Eriksson's equation:

$$N = \frac{N_g}{10}\left(b + 28H^{0.6}\right) \quad (2.3)$$

Where: *H* - tank height

b - tank width (referred as tank diameter)

N_g - Ground Flash Density (GFD)

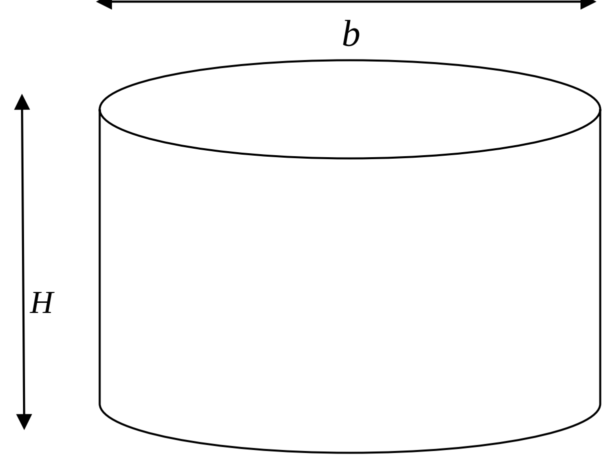


Figure 2. 5 Tank geometry

2.7 Evaluation of Conventional Methods of Roof-Shell Bonding & Earthing

The design of the floating roof tank is convenient for reducing oil evaporation efficiently as the evaporation is the main loss of hydro carbon refining industry. The floating roof is being hovered on the upper interface of volatile petroleum product and a neoprene rubber sealing material which has poor conductive properties is used to closure and avoid volatility losses of hydrocarbon through the frontier floating roof.

This sealing arrangement most probably cause an improper electric contact among the tank roof and the wall of the tank, when releasing accumulated charged current of moving roof owing to lightning strikes. To resolve this matter, three conventional approaches are typically implemented for large floating roof hydrocarbon storage tanks lightning protection design [10].

1. The primary thing is mounting of conductive strip laterally in the perimeter above the secondary seal of moving roof upper contour with interval of three meters, contingent on the springiness of metal alloy strips to sustain gliding connection to the tank shell as to maintain the discharging electrical pathway.

2. The secondary thing is fixing Copper/Monel stranded strips with cross-sectional area of minimum 25 mm^2 linking the tank shell and moving sheet lengthwise on moving ladder and make the earth connection through tank bottom grounding bosh.

3. In addition to above two methods, a roof-shell bonding cables with fixed cable lengths are used to maintain the sound connectivity between floating roof plate and roof ladder, between roof ladder hinge and roof shell etc.

Though floating roof oil tanks have implemented these strategies, lightning strike damages still happen recurrently and this indicate that these approaches failed to guarantee the protection of large crude oil storage tanks. According to the experiments using available protecting measures from lightning flashes, the outcomes showed that once lightning strikes hits the rooftop of tanks, momentary (transient) fragment of the flash could be travelled instantly over the conductive strip and sustainable charge would be passed through Monel (stainless steel) strips and through bonding cables. While lightning flash releasing through, conductive film would produce electrical sparks. Low impedance cables can mitigate the severity of spark relatively.

These shunt paths do not offer a sound, low resistance connection to the tank shell for numerous reasons such as, at lightning frequencies, the roof-shell bonding cable will have very high impedance and this high impedance is less devoted to avoid flashing at the seals.

Since all the personnel in industrial installations commercial, residential and mainly the operations and who are in regular operation and maintenance the equipment that are in contact with electrical systems and machineries should be protected against lightning. To accomplish this kind of protection earthing system of an installation should be designed, defined and installed according to the applicable standards.

Earthing system in the refinery is maintained to obtain the optimum protection against sparking, if not it could lead to catastrophic fires & explosions of storage tanks which would eventually cost a lot of money and tragic fatal accidents. Consequently, under earthing system procedures and standards, the floating roof tank and attachment of all other equipment are interconnected to one another as a grid by means of suitable conductors in order to create an equal level potential (equi-potential bonding) among each other point that will come in contact with the persons.

Equal-potential that is built up and applied to the earthing conductor grid is formed by special earth pits and their accessories such as earth rods and clamps. In addition to protection against the hazards of electrification, an efficient earthing system should be installed in the tank farm where equipment is in contact to explosive material (Oil) and gas which is considered as classified area according to the IEC Ex standards.

The voltage difference between the tank shell and the floating roof is unavoidably a source of spark that definitely leads to an explosion or fire in occurrence of explosive vapours. The position of the flashing is happening in the nastiest possible location, (Zone I Class I location) where have a rich concentration of vaporized hydrocarbons. Therefore, a proper earthing path should be provided to discharge the electrical potential through the tank shell, thus eliminating the risks of fires and sparks.

Lightning strikes are often executed in refinery oil storage tanks and process plant equipment. This causes fires and damages because of overvoltage that happen in the lightning strikes haven't yet been properly investigated. Before initiating this research have deeply researched regarding the presently available technologies and current research projects which are relevant to this task. This literature review given below some of the findings. The use of surge protection to oil storage floating roof tanks and equipment, proposed methods to avoid lightning surges to the tank roofs, most vulnerable affected areas of the tank roof, mitigation techniques, damage probability due to lightning surges and etc.

According to the research paper "The Lightning Risk Evaluation for oil storage large tanks and calculation of Lightning Transient Voltages in Cables considering a Large Industrial site" [16] the authors therefore measured lightning over voltages representing characteristic instances of apparatus in the work places. The outcomes permit for guesstimate of the incidence probability of lightning damage caused by exceeding the break down voltage level of the equipment.

The potential rise (V) of the floating roof against the tank shell through primary & secondary seals

$$V = R \times i(t) + L \times \frac{di(t)}{dt} \tag{2.4}$$

where,

R - Grounding Conductor impedance

i(t) - conductor Current flow

di(t)/dt- gradient of lightning flash current

Resistance of the conductor can be neglected as when lightning strikes at higher frequencies as of huge inductance value of the bonding cable (High current steepness).

Then the above equation can be simplified as follows

$$V = L \times \frac{di(t)}{dt} \tag{2.5}$$

2.7.1 Effects of grounding cable length

Potential rise through ground wire which is use to connect the floating roof to the tank shell and it will be characterized with the formula of inductance of cable and the steepness of in-rush current.

$$V = L \times \frac{di(t)}{dt} \tag{2.6}$$

where,

V - potential across the cable (kV)

L - Inductance of the cable (µH)

di/dt - Gradient of in-rush current (kA/s)

The lead wire Inductance can be denoted as follows [17]

$$L = \frac{\mu_0 \, l}{2\pi}\left(In\frac{2l}{b+c} + \frac{1}{2}\right) \tag{2.7}$$

2.7.2 Surge impedance of roof shell interface

The Conductor impedance can be illustrated as follows [17]

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{2.8}$$

Where,

R- unit length *Resistance*, for individual conductor

L- unit length *Inductance*

G- unit length *Conductance* of the dielectric material

C - unit length *Capacitance*

j- Imaginary unit,

w - Angular frequency

considering a large area, R & G tends to zero, thus the formula for transient impedance can be represented as,

$$Zs = \sqrt{L/C}$$

Where L & C calculated using simplified standard equations as follows,

$$L = \mu * A/l \text{ and} \tag{2.10}$$

$$C = \varepsilon * A/d \tag{2.11}$$

Where,

l = length of wire in mm
A = area of the loop
d = diameter of cable in mm
μ = permeability of conductor material used
ε = permittivity of oil

2.8 Magnitude of Grounding surge currents

For a specified location, the lightning ground flash density (GFD) is identified, then the occurrence as a function of magnitude would similarly be forecasted by using standard graphs issued in IEEE C 62.22 [13].

While during the operational life time of the tank one destructive flash is anticipated, average max. let through current passed within 25 years will be predicted from the function.

For the calculation of energy dissipation through grounding system, it is important to analyze *Low frequency content* and *High frequency content* is vital for investigating overvoltage.

Everywhere in Colombo suburbs, average thunder days would be 95 each year signifies the Lightning Flash Density is approximately at the value of 9.2. 100kA current is considered as the maximum predictable lightning current using former statistics for the exposure of naturally unshielded.

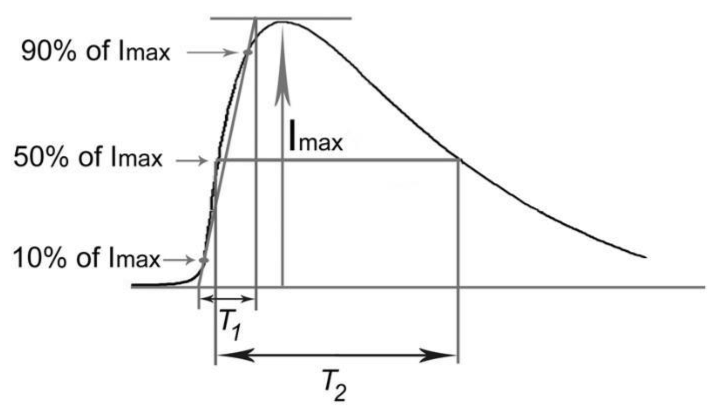


Figure 2. 6 Wave Form shape of Lighting flash

CHAPTER 3

LIGHTNING IMPULSE MODEL IN PSCAD

The tank model is demonstrated as a linear resistance of a piece with V-A characteristic, entered by the user (or a defaulting characteristic can be applied). It is suitable for designing switching surge for simulation of transient behaviour of lightning impulse.

3.1 Determining Steep Front Model Parameters

The impulse surge current applied to the tank model would be the same amplitude and transient wave shape as the surge current of the lightning surge discharge voltage. Impulse surge test current is injected and examine the subsequent ultimate voltage rise.

The approximate current impulse I_{test} is represented by two exponential formulas.

$$I_{test} = I\,(e^{-at} - e^{-bt})$$

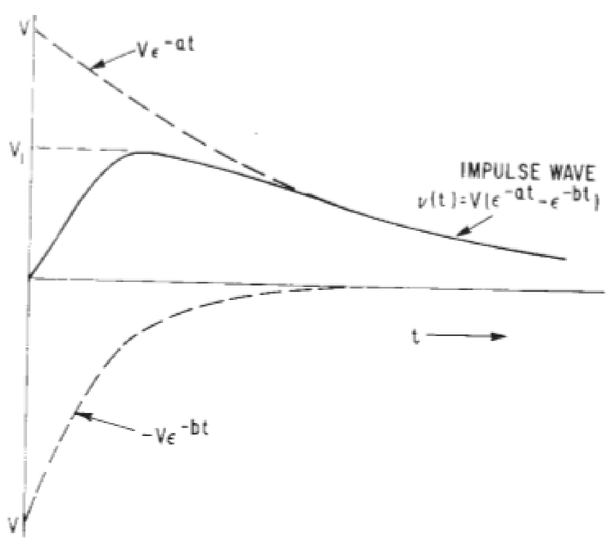


Figure 3. 1 Switching wave form expressed as sum of two exponential functions [21], [22]

3.2 Lightning Impulse Surge Calculation

3.2.1 50kA Lightning Impulse Surge of 10/350 μs (Direct Impulse Surge)

The values of ***I***, ***a*** and ***b*** of the above equation may be determined for the impulse wave if the crest value I_1 and the time to crest t_1 and time to half settle on the tail t_2 are known. This relationship is approximated through use of curves. [22]

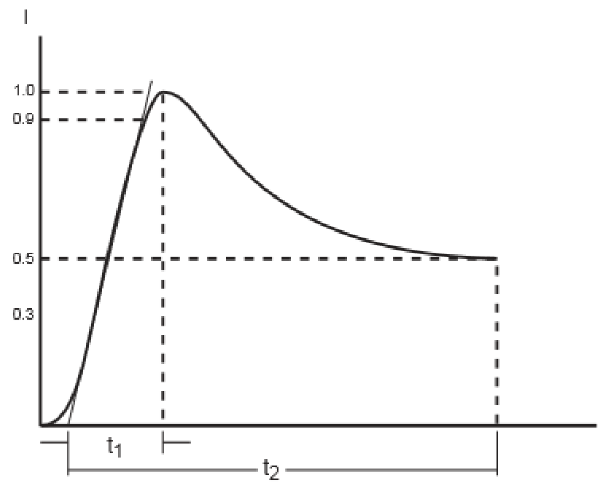


Figure 3. 2 Impulse Wave Specification (Applications of PSCAD™ / EMTDC™)[21], [22]

Consider synthesizing a 10/350 μsec impulse.

$$\frac{t_2}{t_1} = 350/10 = 35$$

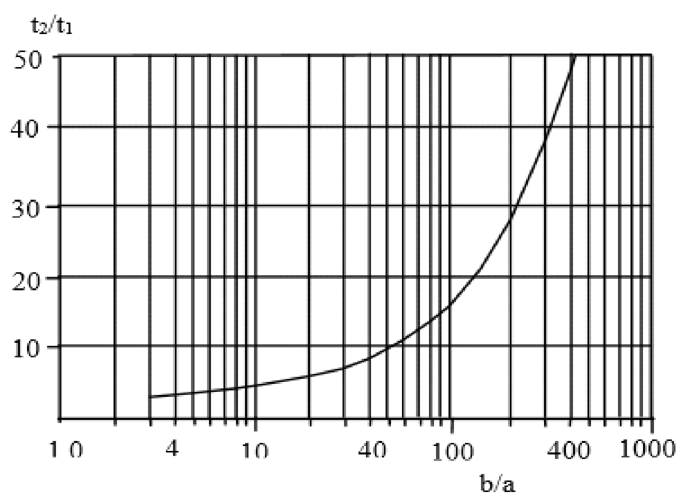


Figure 3. 3 Standard curve for determining b/a [21]

Impulse wave from parameters are determined for known t_1 and t_2 by $I_{test} = I\,(e^{-at} - e^{-bt})$ and b/a can be expressed. According to the standard curve (figure 3.3),

at $t_2/\,t_1 = 35$

Thus $b/a = 250$

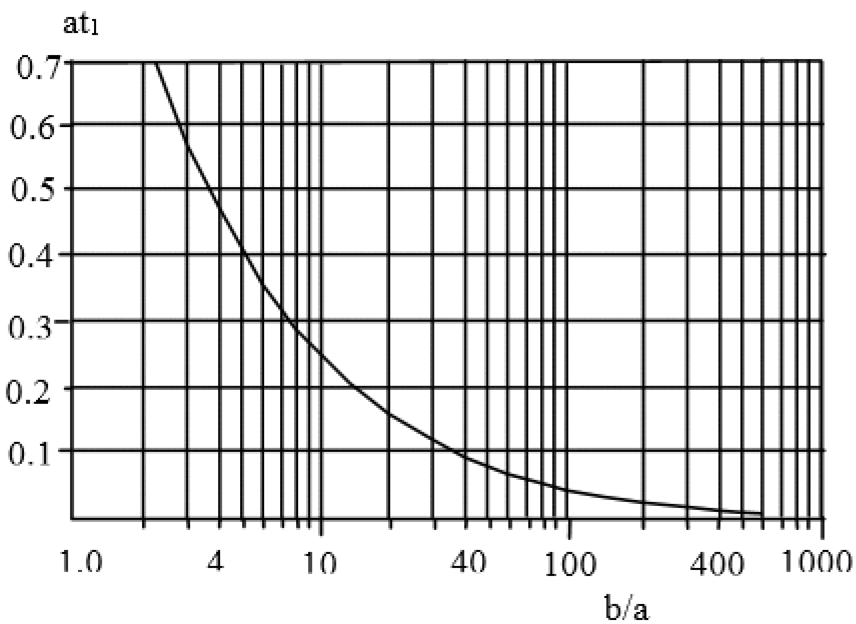


Figure 3. 4 Standard curve for determining at_1 [21]

According to the standard curve (figure 3.4), at $b/a = 250$ →

$at_1 = 0.02$

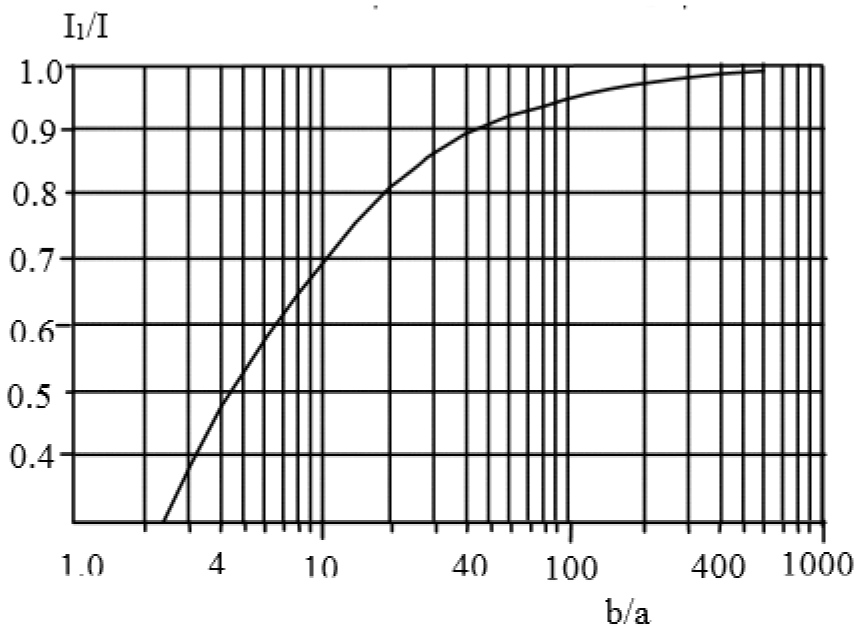


Figure 3. 5 Standard curve for determining I_1/I_2 [21]

According to the standard curve (Figure 3.5),

$$\text{At } b/a = 250$$

$$\frac{I_1}{I} = 0.97$$

Since the 10/350 µs impulse,

$$t_1 = 10\ \mu s$$

From the above standard curve (Figure 4.4), $at_1 = 0.02$

$$\boldsymbol{a = 2 \times 10^3}$$

From equation $b/a = 250$

$$\boldsymbol{b = 5 \times 10^5}$$

From,

$$\frac{I_1}{I} = 0.97$$

$$I_1 = 0.97 \times 50\ \text{kA}$$

$$I_1 = 48.5\ \text{kA}$$

3.2.2 100kA Direct Lightning Surge of 10/350 µs

According to the standard curve (Figure 3.3),

$$\frac{t_2}{t_1} = 35$$

$$\frac{b}{a} = 250$$

According to the standard curve (Figure 3.5),

At $b/a = 250$

$$\frac{I_1}{I} = 0.97$$

Since the 10/350 µs impulse,

$t_1 = 10$ µs

From the above standard curve (Figure 3.4), $at_1 = 0.02$

$$a = 2 \times 10^3$$

From equation $b/a = 250$

$$b = 5 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.97$$

$I_1 = 0.97 \times 100$ kA

$I_1 = 97.0$ kA

3.2.3 25kA Lightning Impulse Surge of 10/350 µs

From the standard curve (Figure 3.3),

$$\frac{t_2}{t_1} = 35$$

$$\frac{b}{a} = 250$$

According to the standard curve (Figure 3.5),

At $b/a = 250$

$$\frac{I_1}{I} = 0.97$$

Since the 10/350 μs impulse,

$t_1 = 10$ μs

From the above graph (Figure 3.4), $at_1 = 0.02$

$$a = 2 \times 10^3$$

From equation $b/a = 250$

$$b = 5 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.97$$

$I_1 = 0.97 \times 25$ kA

$I_1 = 24.25$ kA

3.2.4 75kA Lightning Impulse Surge of 10/350 μs

From the standard curve (Figure 3.3),

$$\frac{t_2}{t_1} = 35$$

$$\frac{b}{a} = 250$$

According to the standard curve (Figure 3.5),

At $b/a = 250$

$$\frac{I_1}{I} = 0.97$$

Since the 10/350 μs impulse,

$t_1 = 10$ μs

From the above graph (Figure 3.4), $at_1 = 0.02$

$$a = 2 \times 10^3$$

From equation $b/a = 250$

$$b = 5 \times 10^5$$

From, $\frac{I_1}{I} = 0.97$

$I_1 = 0.97 \times 75$ kA

$I_1 = 72.75$ kA

3.3 Lightning Impulse Surge Calculation

3.3.1 50kA Lightning Impulse Surge of 8/20 µs (Indirect Impulse Surge)

According to the above standard curves lightning impulse surge can be calculated.

According to the standard curve (Figure 3.3),

$$\frac{t_2}{t_1} = \frac{20}{8} = 2.5$$

$$\frac{b}{a} = 3$$

According to the standard curve (Figure 3.5),

At $b/a = 3$

$$\frac{I_1}{I} = 0.38$$

Since the 8/20 µs impulse,

$t_1 = 8$ µs

From the above graph (Figure 3.4), $at_1 = 0.59$

$$a = 7.375 \times 10^4$$

From equation $b/a = 3$

$$b = 2.2125 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.385$$

$I_1 = 0.38 \times 50$ kA

$I_1 = 19$ kA

3.3.2 100kA Lightning Impulse Surge of 8/20 µs

According to the standard curve Figure 3.3,

$$\frac{t_2}{t_1} = 2.5$$

$$\frac{b}{a} = 3$$

According to the standard curve Figure 3.5,

$$\text{At } b/a = 3$$

$$\frac{I_1}{I} = 0.385$$

According to the 8/20 μs impulse,

$$t_1 = 8\ \mu s$$

From the above standard curve (Figure 3.4) $at_1 = 0.59$

$$a = 7.375 \times 10^4$$

From equation $b/a = 3$

$$b = 2.2125 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.385$$

$$I_1 = 0.385 \times 100\text{kA}$$

$$I_1 = 38.5\ \text{kA}$$

3.3.3 25kA In Direct Lightning Surge of 8/20 μs

According to the Figure 3.3,

$$\frac{t_2}{t_1} = 2.5$$

$$\frac{b}{a} = 3$$

According to the Figure 3.5,

$$\text{At } b/a = 3$$

$$\frac{I_1}{I} = 0.385$$

According to the 8/20 μs impulse,

$$t_1 = 8\ \mu s$$

From the above graph $at_1 = 0.59$

$$a = 7.375 \times 10^4$$

From equation $b/a = 3$

$$b = 2.2125 \times 10^5$$

From,

$$\frac{I_1}{I} = 0.385$$

$I_1 = 0.385 \times 25$ kA

$I_1 = 9.5$ kA

3.3.4 75kA In Direct Lightning Surge of 8/20 µs

According to the Figure 3.3,

$$\frac{t_2}{t_1} = 2.5$$

$$\frac{b}{a} = 3$$

According to the Figure 3.5,

At $b/a = 3$

$$\frac{I_1}{I} = 0.385$$

According to the 8/20 µs impulse,

$t_1 = 8$ µs

From the above graph $at_1 = 0.59$

$a = 7.375 \times 10^4$

From equation $b/a = 3$

$b = 2.2125 \times 10^5$

From,

$$\frac{I_1}{I} = 0.385$$

$I_1 = 0.385 \times 75$ kA

$I_1 = 28.5$ kA

3.4 Equations for 10/350μs and 8/20μs Lightning Surge Impulse Current for PSCAD Models

Table 3. 1 Direct and Indirect Lightning Surge Current Equations

Surge Current (kA)	Direct Lightning Impulse Current 10/350μs	Indirect Lightning Impulse Current 8/20μs
25	I_{test}= 24.25 $(e^{-2\,e5\,t}$-$e^{-5\,e5\,t})$	I_{test}= 9.5 $(e^{-0.866e5\,t}$-$e^{-1.732\,e5\,t})$
50	I_{test}= 48.5 $(e^{-2\,e5\,t}$-$e^{-5\,e5\,t})$	I_{test}= 12.5 $(e^{-0.866e5\,t}$-$e^{-1.732\,e5\,t})$
75	I_{test}= 72.75 $(e^{-2\,e5\,t}$-$e^{-5\,e5\,t})$	I_{test}= 28.5 $(e^{-0.866e5\,t}$-$e^{-1.732\,e5\,t})$
100	I_{test}= 97 $(e^{-2\,e5\,t}$-$e^{-5\,e5\,t})$	I_{test}= 25 $(e^{-0.866e5\,t}$-$e^{-1.732\,e5\,t})$

3.5 PSCAD Simulation Models for Direct and Indirect Lightning Surges

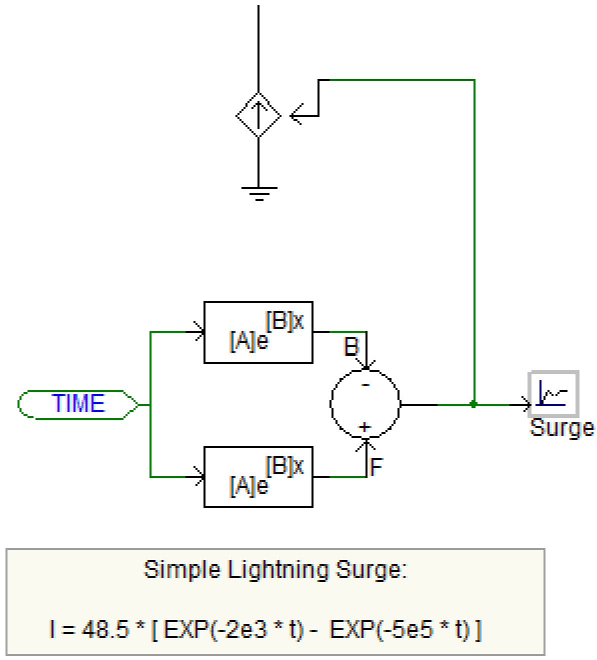


Figure 3. 6 10/350 µs Lightning Surge PSCAD Simulation Model

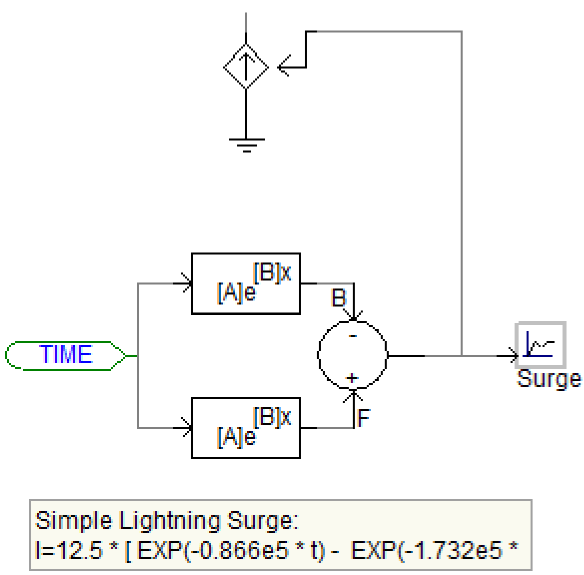


Figure 3. 7 8/20 µs Lightning Surge PSCAD Simulation Model

CHAPTER 4

VALIDATION OF CALCULATED PARAMETERS WITH SCALED MODEL TANK

4.1 Parameters of the Large Floating Roof Crude Oil Storage Tank

In this study it was recognized that the most vulnerable tanks affected by lightning strikes & fires are large diameter floating roof crude storage tanks. Therefore, it was decided to design and construct a small scaled floating roof tank as a model for the validation of the calculated parameters. In this design the identical materials used for the construction of Refinery floating roof crude oil storage tank were used to prepare the small scaled tank model for the lab test. The dimensions were taken according to the quotient of the actual tank.

Figure 4. 1 Practical size of a Refinery Floating roof Crude oil tank in Refinery

4.2 Floating roof Crude oil tank Parameters

Storage Capacity 60,000 MT (73 Million Liters)

Tank Diameter	=	67 m
Tank Height	=	15.8 m
Thickness of the shell	=	16 mm
Diameter of Fl. Roof	=	66.59m
No. of shunts	=	140 Nos.
Width of a shunt	=	55 mm
Gap between Roof & Shell	=	275 mm

4.3 Parameters of the Scaled Model a Floating Roof Crude Oil Storage Tank

A scaled model tank was designed and constructed with following dimensions using real materials as per the actual crude oil storage tanks made in the Refinery.

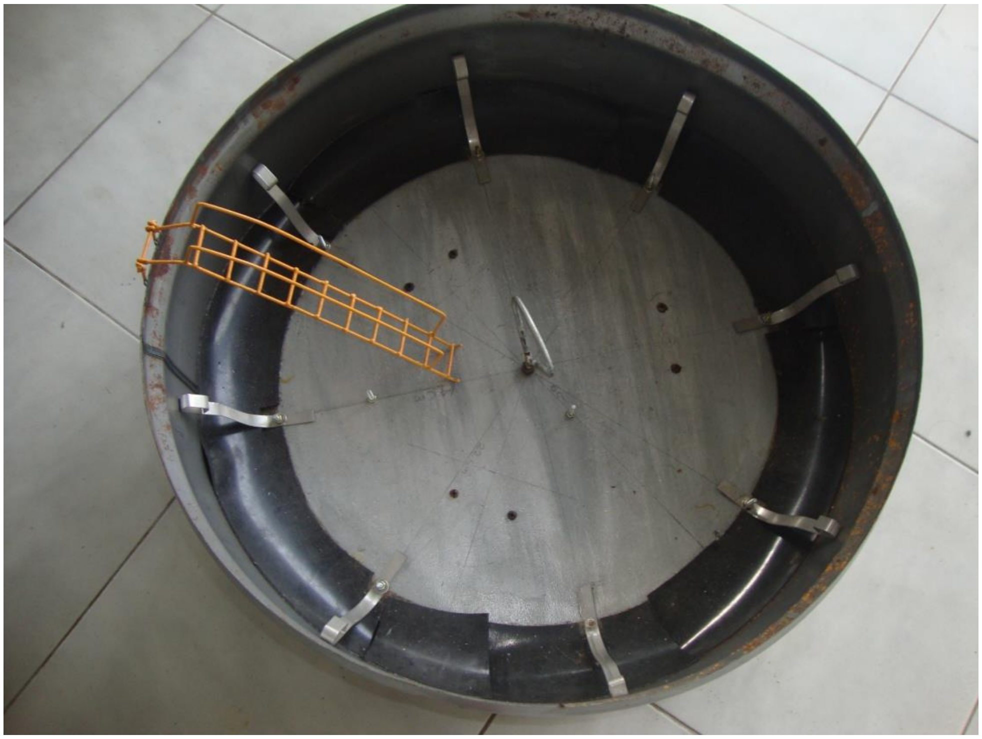


Figure 4. 2 Scaled Tank model (Top View)

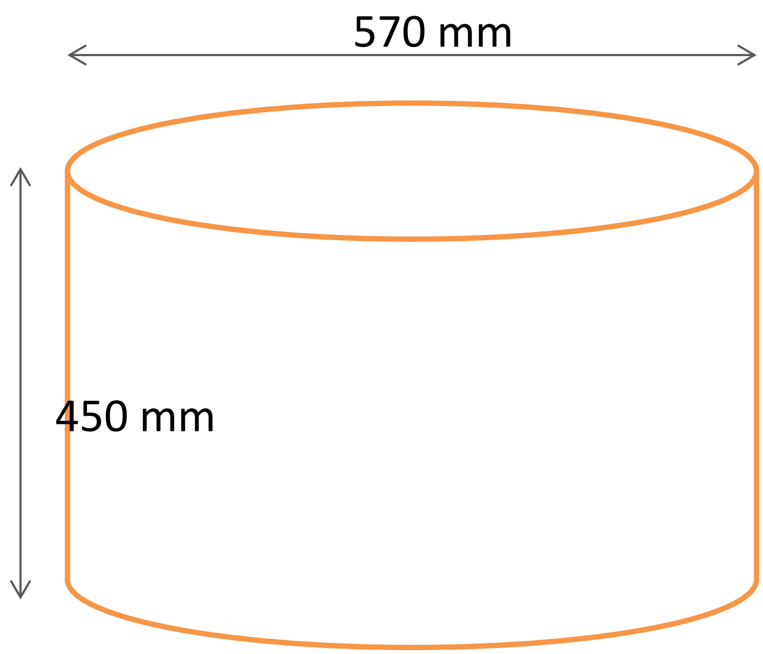
Figure 4. 3 Scaled Tank model (Side view)

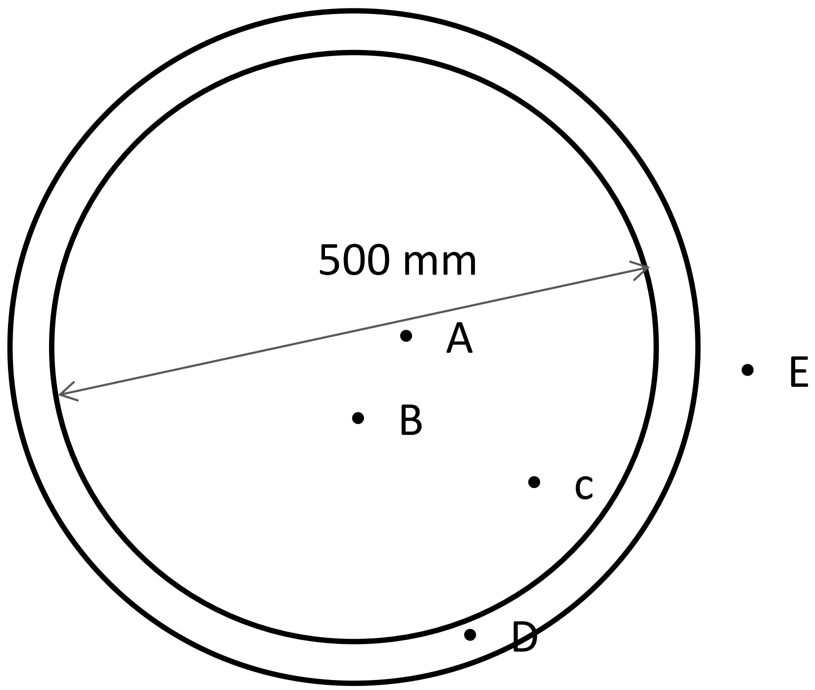
4.4 Floating roof Crude oil tank Model Parameters

Tank Diameter	=	570	mm
Tank Height	=	450	mm
Thickness of the shell	=	1.3	mm
Diameter of Fl. Roof	=	500	mm
No. of shunts	=	8	Nos
Width of a shunt	=	6	mm
Gap Between Roof & Shell	=	35	mm

4.5 Electrical Parameter Measurement of Scaled Floating Roof Storage Tank

L, R & C Values were measured for different locations in the scaled model as per described in following figure 4.4. These Tank model Dimensions and Test point Distances used as the standard measurements and utilized for the calculation of tank parameters. All parameters are calculated and tabulated for further analyzing.





Distance between *Point A* (Center) and *Point B* = 60 mm
Distance between *Point A* (Center) and *Point C* = 140 mm
Distance between *Point A* (Center) and *Point D* = 225 mm
Distance between *Point A* (Center) and *Point E* = 285 mm

Figure 4. 4 Tank Model Dimensions and Test point Distances for measurements

4.6 Laboratory Testing of Designed model of Floating Roof Storage Tank

Constructed model was taken to the laboratory at the University of Moratuwa, for the testing of surge currents behavior through the ladder- shell connection, primary seal, secondary seal, floating roof-ladder interface etc. Due to some technical difficulties at the laboratory surge measuring instruments, applying of surge currents were diverted to measurements of the electrical parameters of the scaled model as the model was constructed using actual material which have used for the construction of actual floating roof tanks in the refinery.

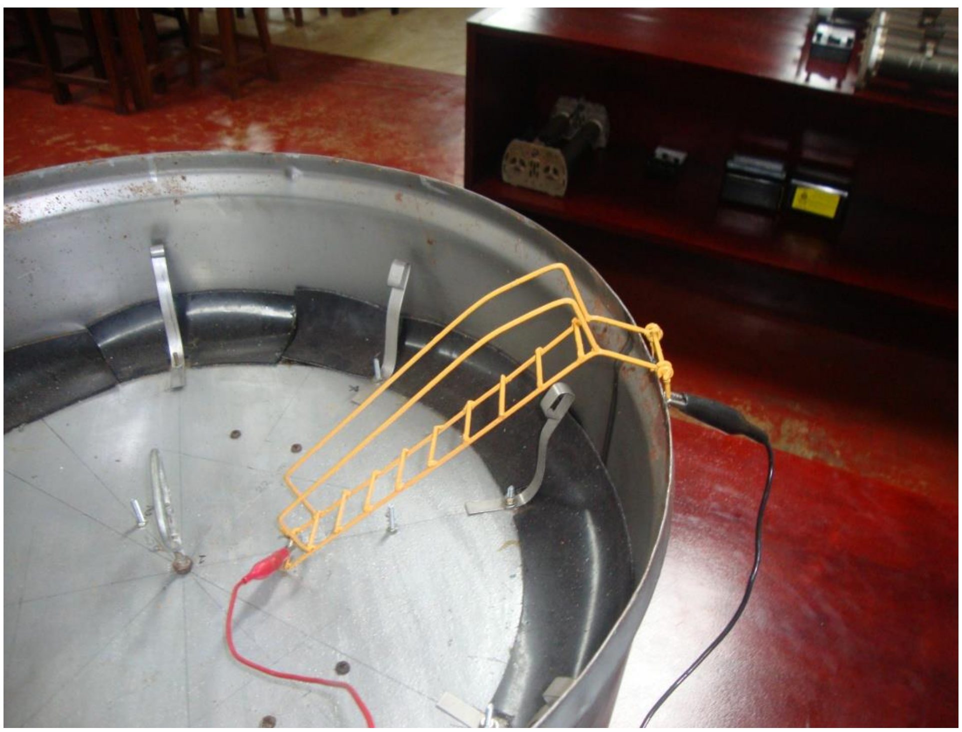


Figure 4. 5 Tank Model under test at UOM Laboratory

Figure 4. 6 Tank Model under test at UOM Laboratory

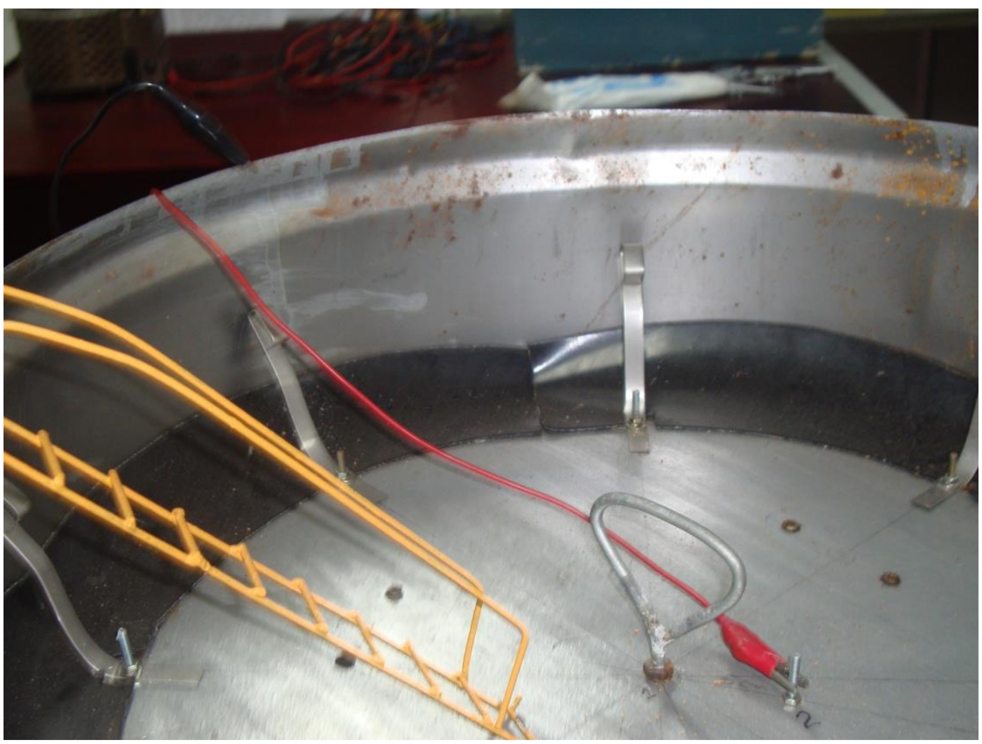


Figure 4. 7 Tank Model under test at UOM Laboratory

4.7 Testing Instruments used for Laboratory Testing

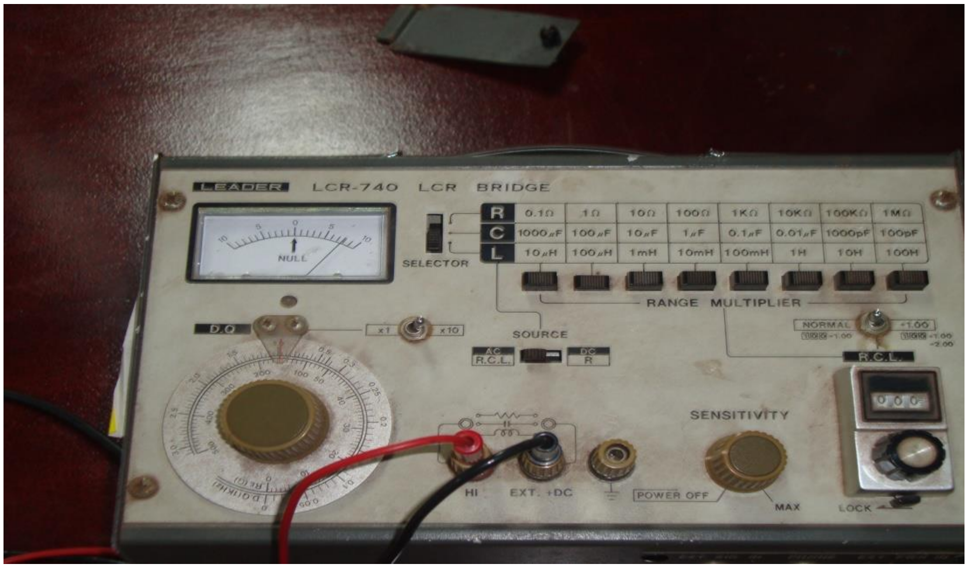


Figure 4. 8 LCR Bridge used for the test (Model LCR 740)

Figure 4. 9 High Resolution TRMS Multi meter used for the test (Model METRAHIT Ultra)

4.8 Measured Values of Characteristics parameters

Table 4. 1 Measured characteristic Values of model tank

Impedance Measurement Point	**characteristic value -L (µH)**	**characteristic value -R (Ω)**	**characteristic value -C (µF)**
Roof & Ladder Connection (pt A B)	82		
Ladder & Shell connecting Hinge	121		
Roof (pt A D)	18	0.234	
Ladder	57	0.183	
Shell	8.2	0.034	
Primary seal assembly			0.634
Secondary seal assembly			0.075
Shunt (pt D E)	62	0.787	0.0846
Earthing Bose		0.43	
Earth Lead		0.02	

Measured parameter values recalculated and de-scaled for determination of weighted equivalent parameters of actual tank characteristics for comparison with the PSCAD model tank for the validation of the model tank and tabulated in table 4.2 below.

4.9 Developed PSCAD Model of a floating roof tank

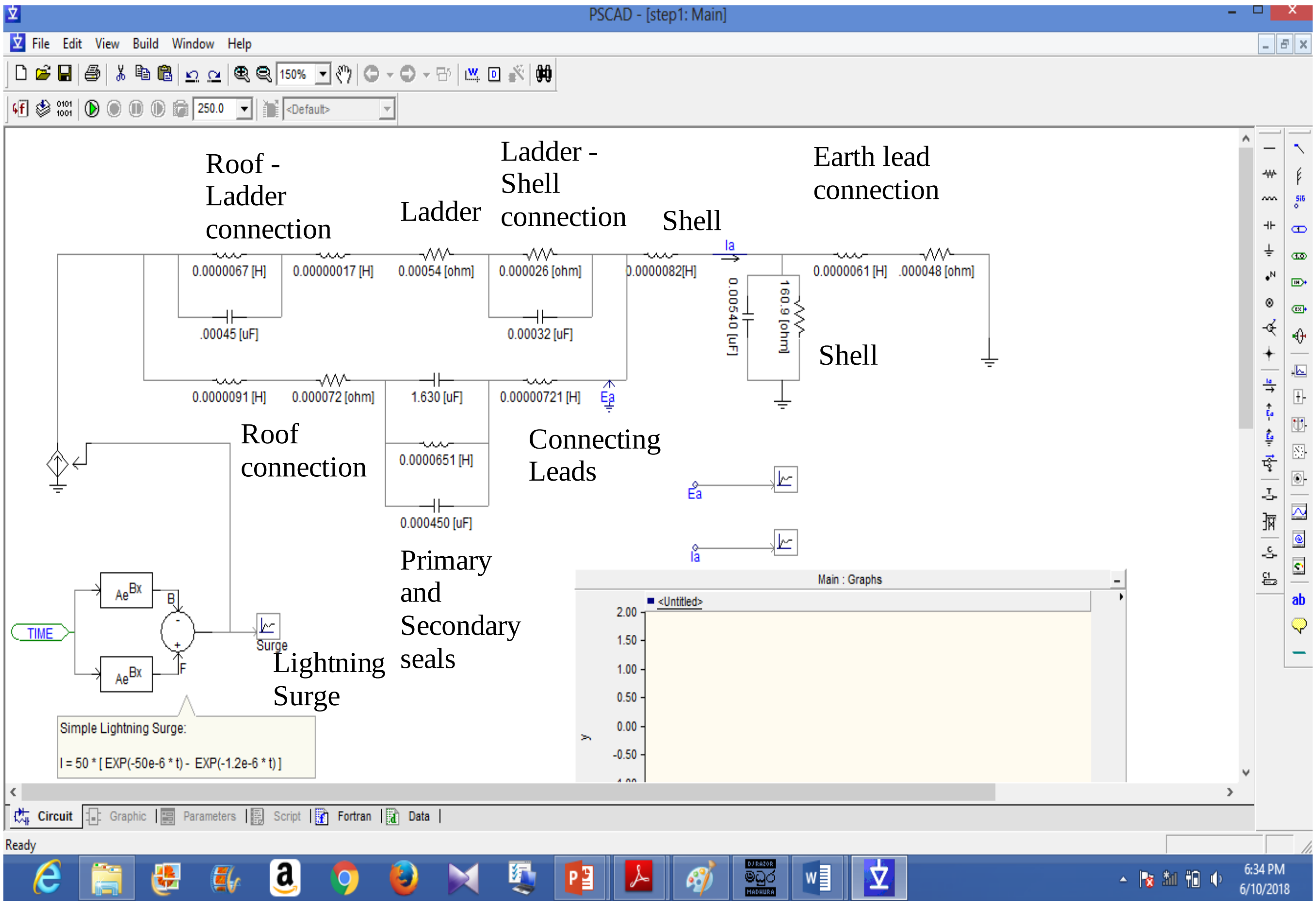


Figure 4. 10 PSCAD Model of a floating roof tank

4.10 Model Tank Test Values Comparison for PSCAD Validation

Table 4. 2 Weighted characteristic Values of model tank and calculated actual values

No.	***Tank component (Location)***	***Weighted Equivalent Impedance (mΩ)***		***Error from Actual (mΩ)***
		Actual Tank	**Model Tank**	
1	Roof & Ladder Connecting wheels	0.067	0.082	0.015
2	Ladder & Shell connecting Hinge	0.097	0.121	0.024
3	Roof	172	234	62.000
4	Ladder	154	183	29.000
5	Shell	21	34	13.000
6	Primary seal assembly	0.0049	0.00663	0.002
7	Secondary seal assembly	0.0328	0.00275	0.030
8	Metallic shoe	8.7	-	-
9	Connecting leads (Shunts)	493	587	94.000
10	Earth Lead	2	36.2	34.200

Comparison of model tank and actual tank parameter values are shown in the Table 4.2 and error variation is shown in figure 4.11

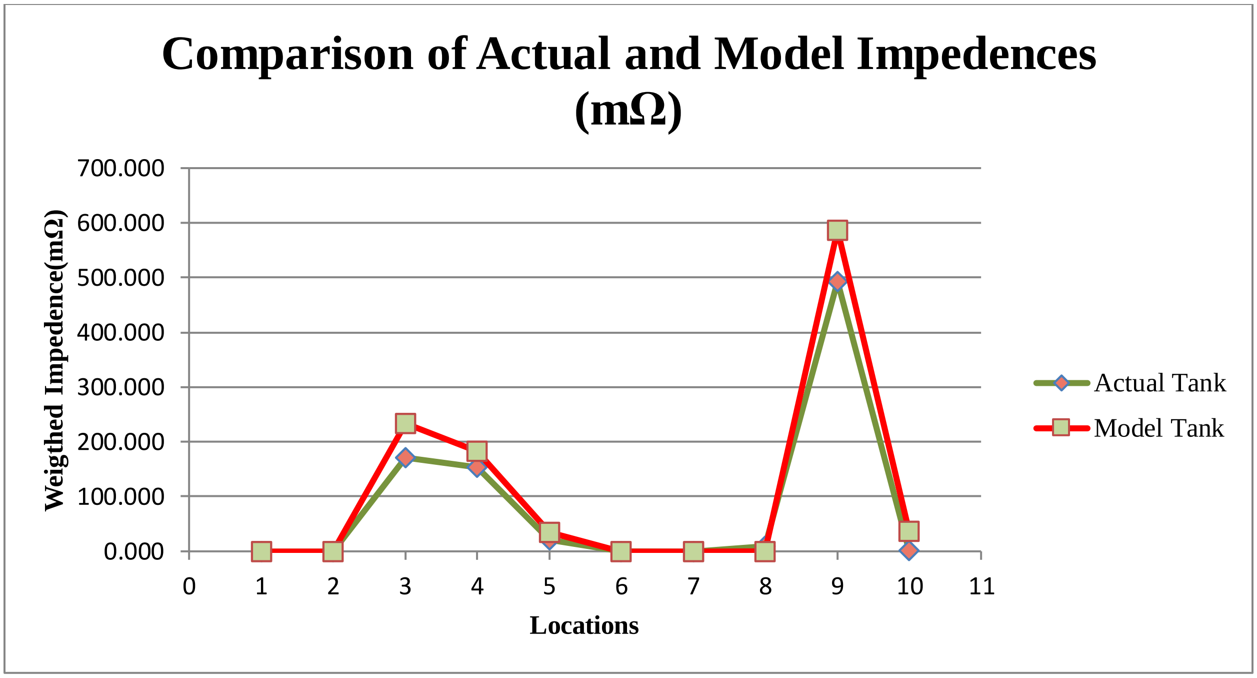


Figure 4. 11 Comparison of Error between Actual Tank & Model Tank

According to the error calculation between actual tank and PSCAD model of the Actual tank is approximately equivalent to the measured and weighted values of the tank model tested. Therefore, PSCAD model is validated against actual tank.

CHAPTER 5

RESULTS FOR THE SIMULATION MODEL

5.1 Results of the PSCAD model for 25kA output and induced surge currents 8/20 µs

By using the simulation model, graphical results were obtained by varying the location of the oil tank for injected and induced surge currents. Peak surge values for each location are tabulated in the below tables.

Table 5. 1 Tabulated results for 25kA indirect lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	2.375
Primary Seal	1.301
Secondary Seal	1.173

5.1.1 Obtained Graphs for Above Tabulated Values

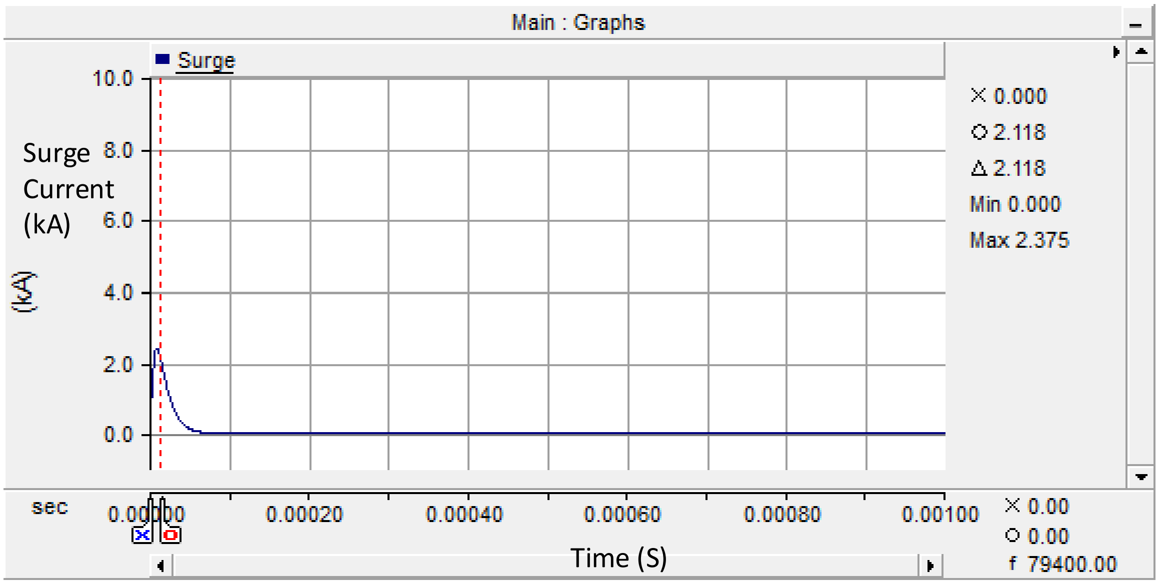


Figure 5. 1 Current through ladder shell connection

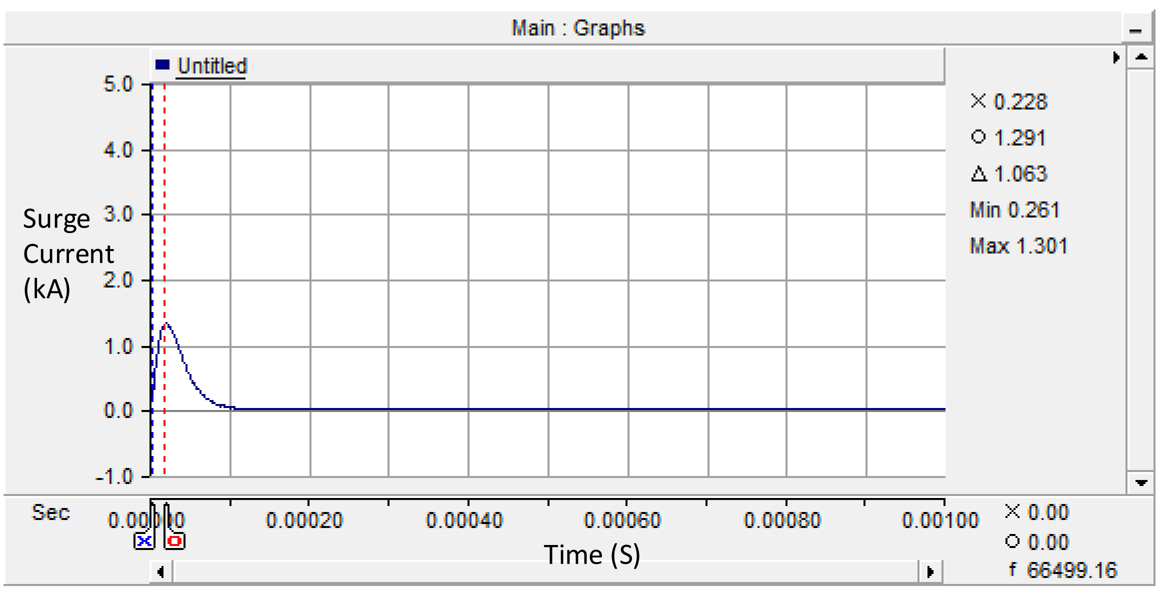


Figure 5. 2 Current through primary seal

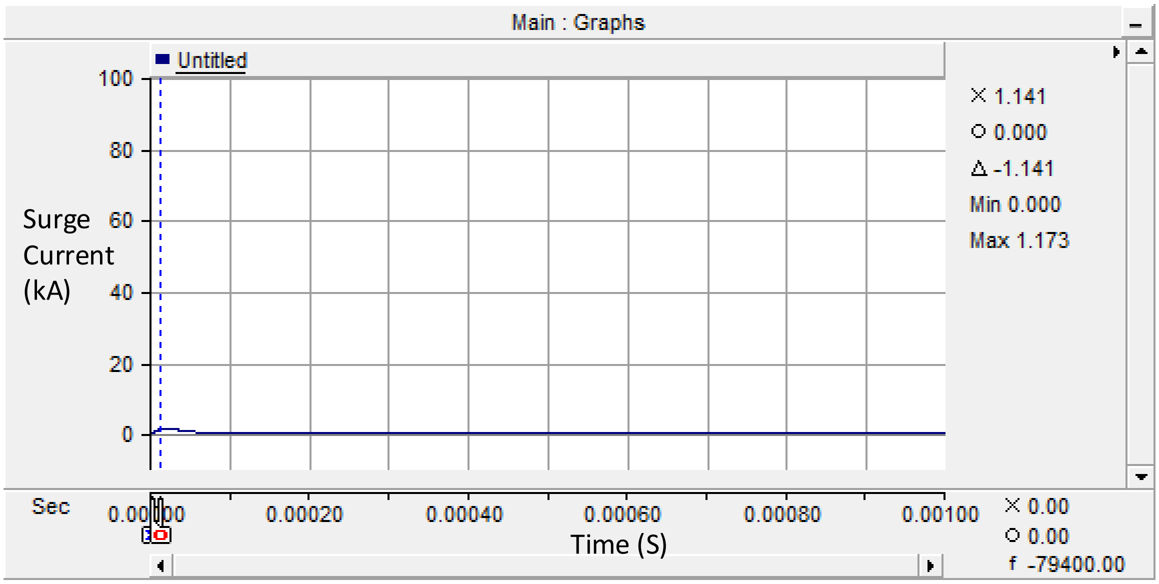


Figure 5. 3 Current through secondary seal

5.2 Results of the PSCAD model for 50kA output and induced surge currents 8/20 µs

Table 5. 2 Tabulated results for 50kA indirect lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	4.750
Primary Seal	2.602
Secondary Seal	2.602

5.2.1 Obtained Graphs for Above Tabulated Values

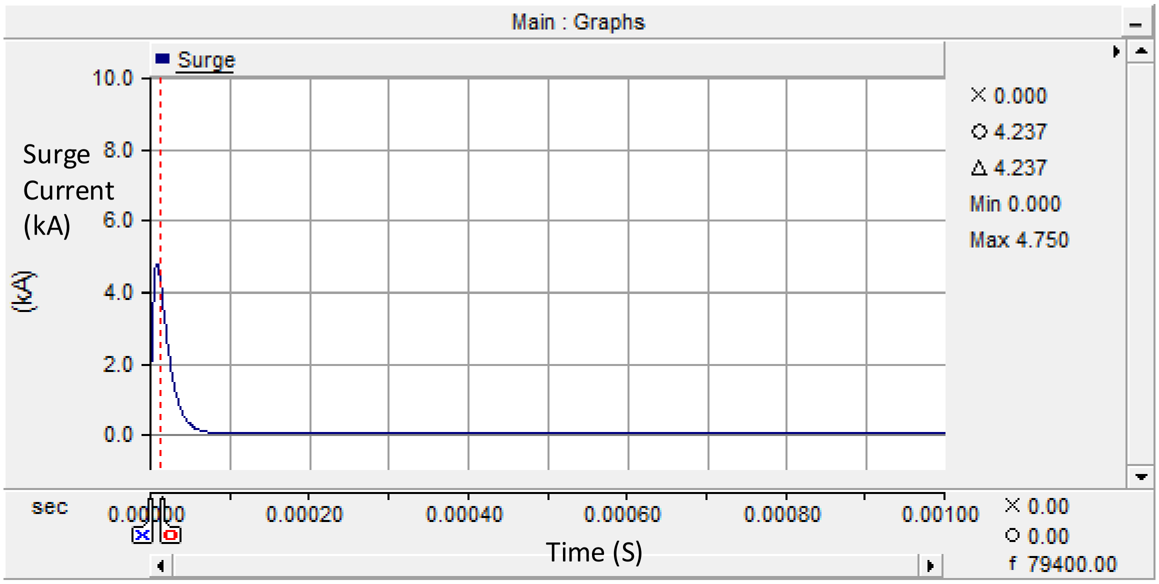


Figure 5. 4 Current through ladder shell connection

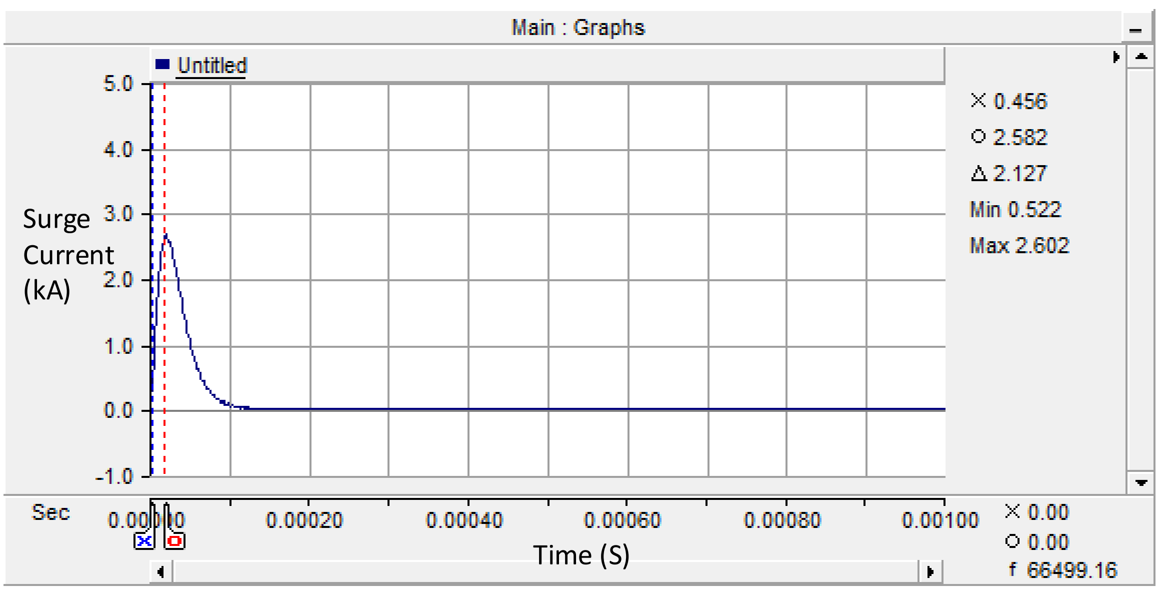


Figure 5. 5 Current through primary seal

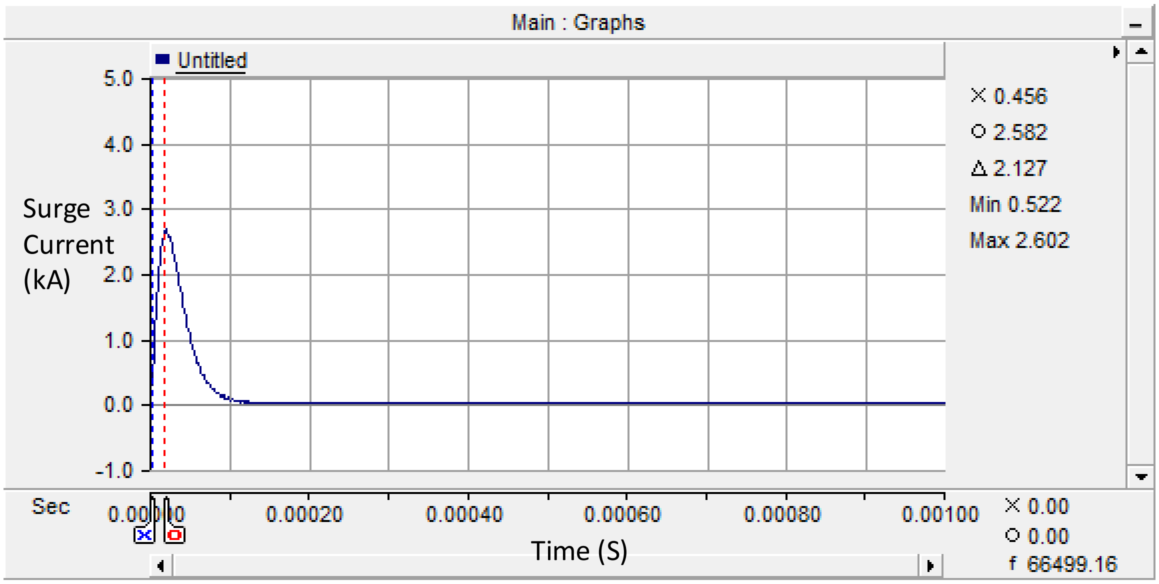


Figure 5. 6 Current through secondary seal

5.3 Results of the PSCAD model for 75kA output and induced surge currents 8/20 µs

Table 5. 3 Tabulated results for 75kA indirect lightning surge

Location	Induced surge current (kA)
Ladder Shell Connection	7.125
Primary Seal	3.903
Secondary Seal	3.519

5.3.1 Obtained Graphs for Above Tabulated Values

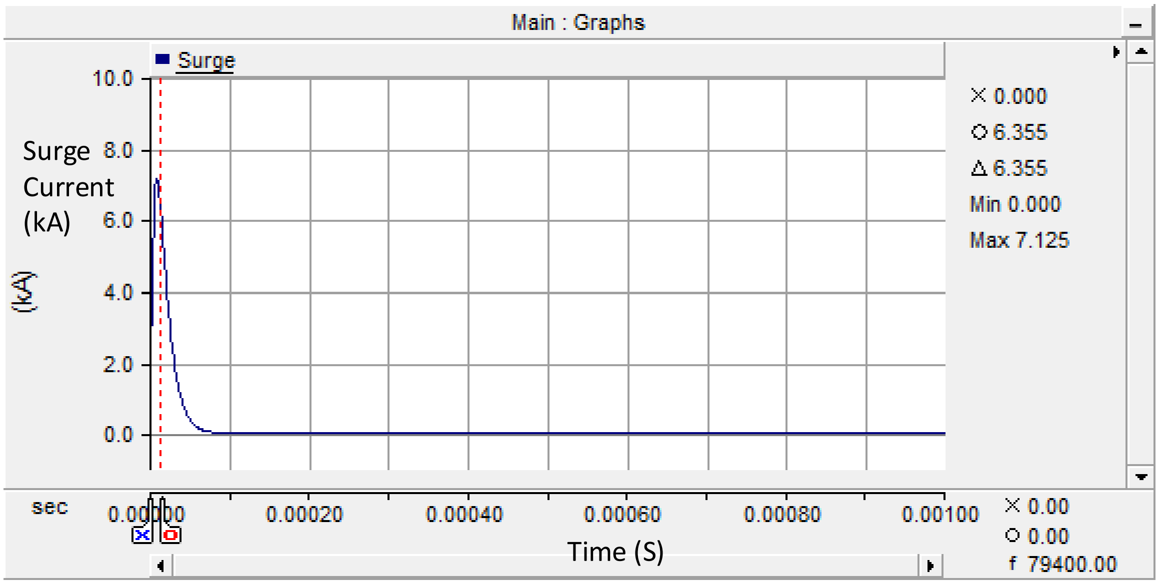


Figure 5. 7 Current through ladder shell connection

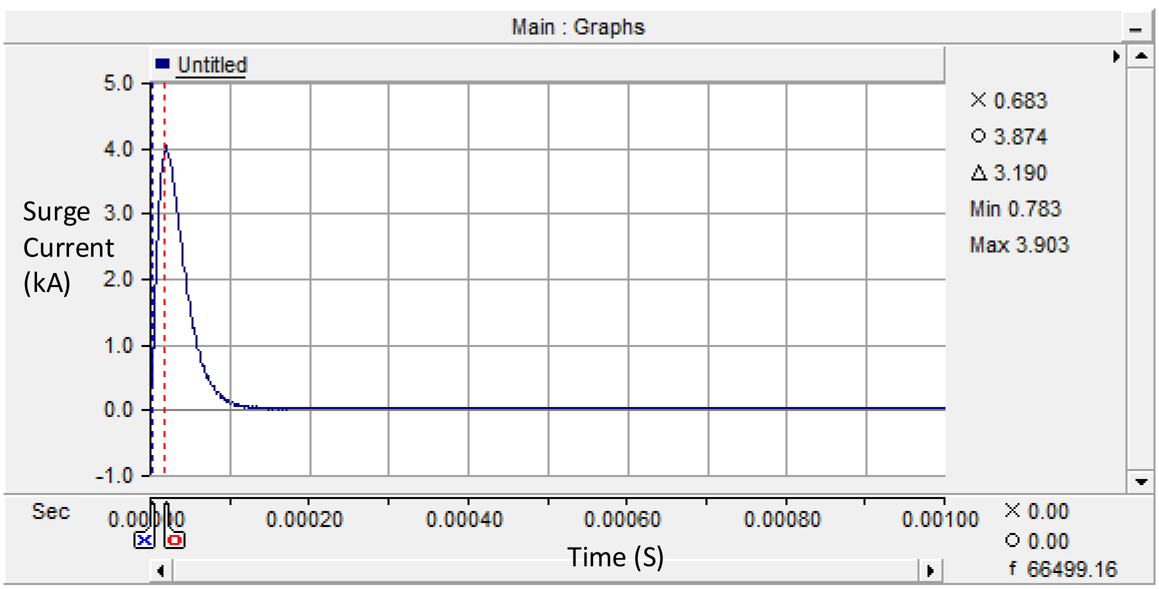


Figure 5. 8 Current through primary seal

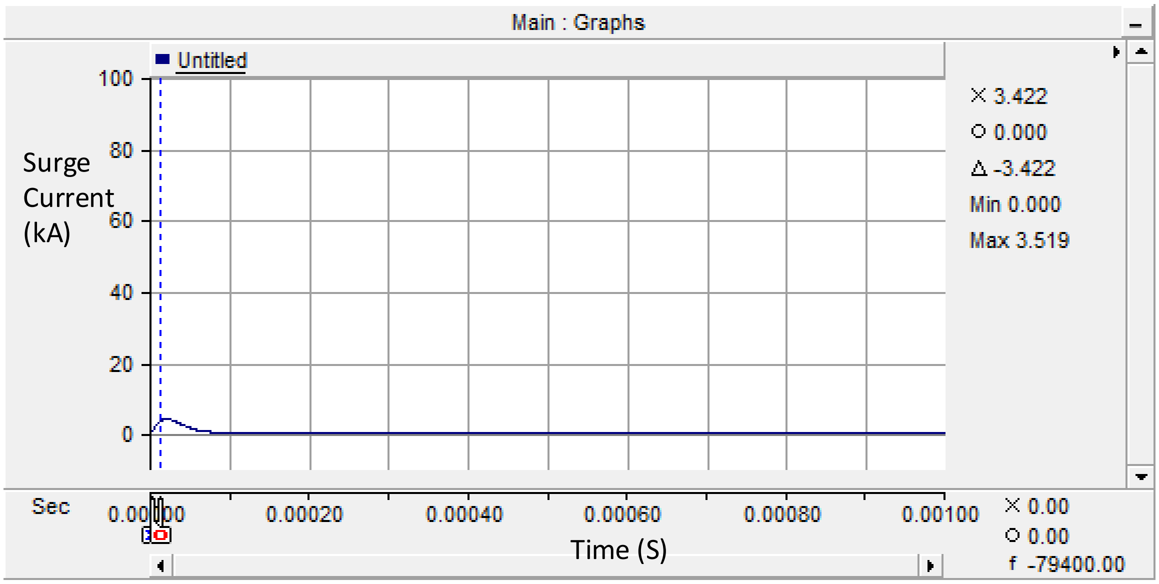


Figure 5. 9 Current through secondary seal

5.4 Results of the PSCAD model for 100kA output and induced surge currents 8/20 µs

Table 5. 4 Tabulated results for 100kA indirect lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	9.500
Primary Seal	5.204
Secondary Seal	5.204

5.4.1 Obtained Graphs for Above Tabulated Values

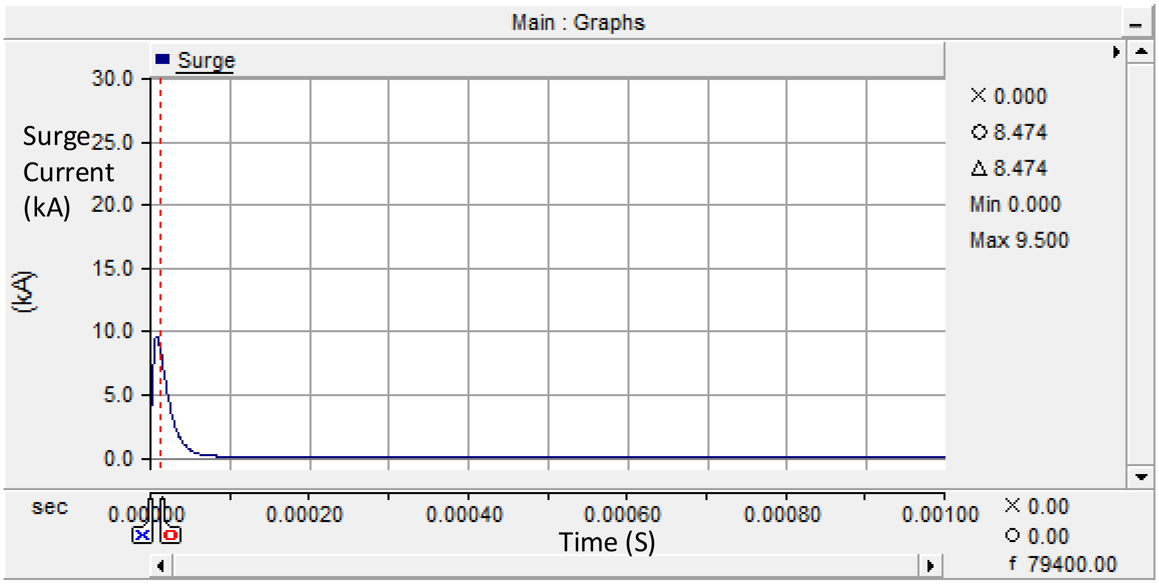


Figure 5. 10 Current through ladder shell connection

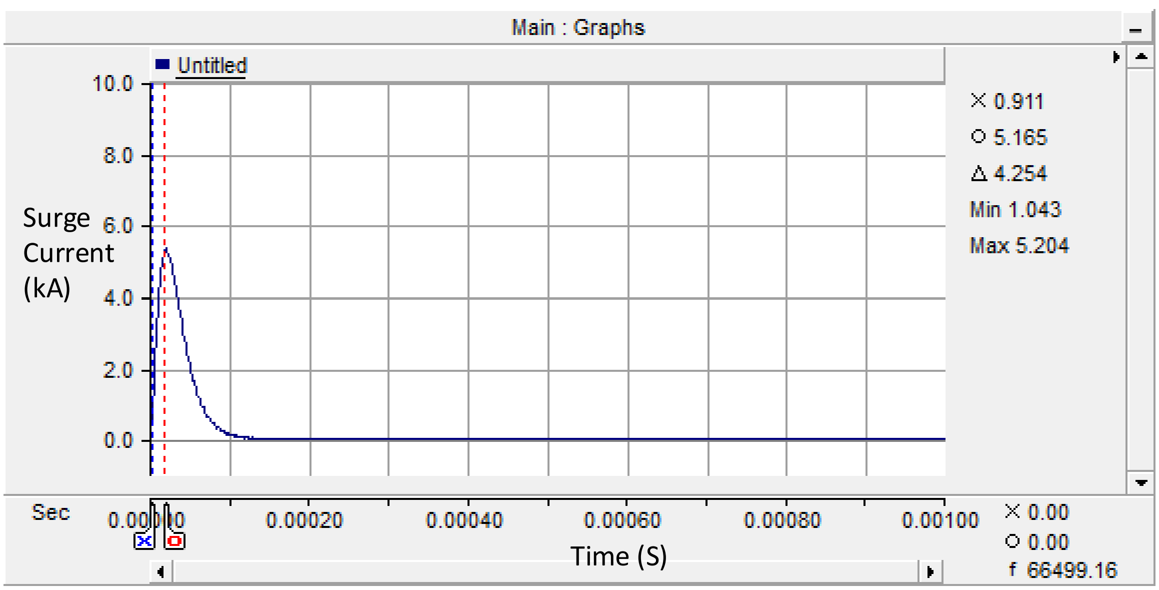


Figure 5. 11 Current through primary seal

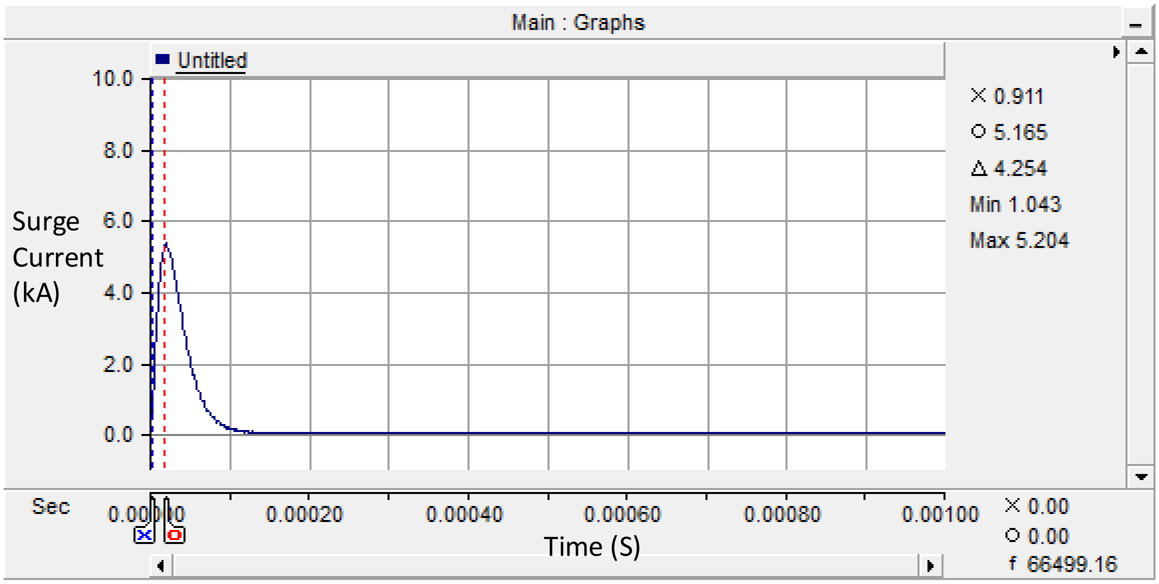


Figure 5. 12 Current through secondary seal

5.5 Results of the PSCAD model for 25kA output and induced surge currents 10/350 µs

Table 5. 5 Tabulated results for 25kA direct lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	23.623
Primary Seal	15.136
Secondary Seal	12.471

5.4.1 Obtained Graphs for Above Tabulated Values

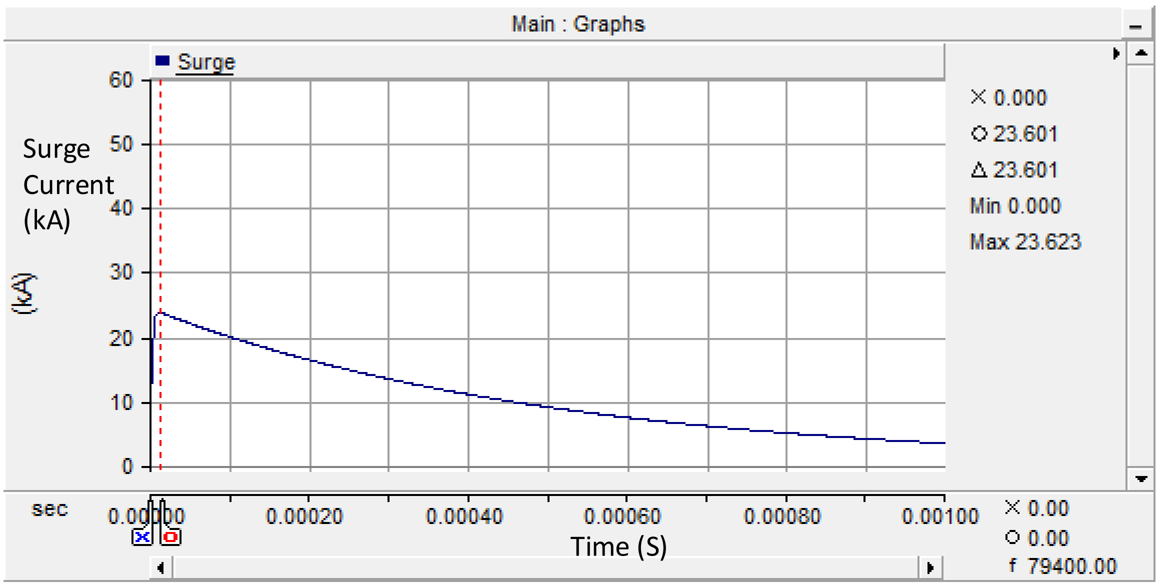


Figure 5. 13 Current through ladder shell connection

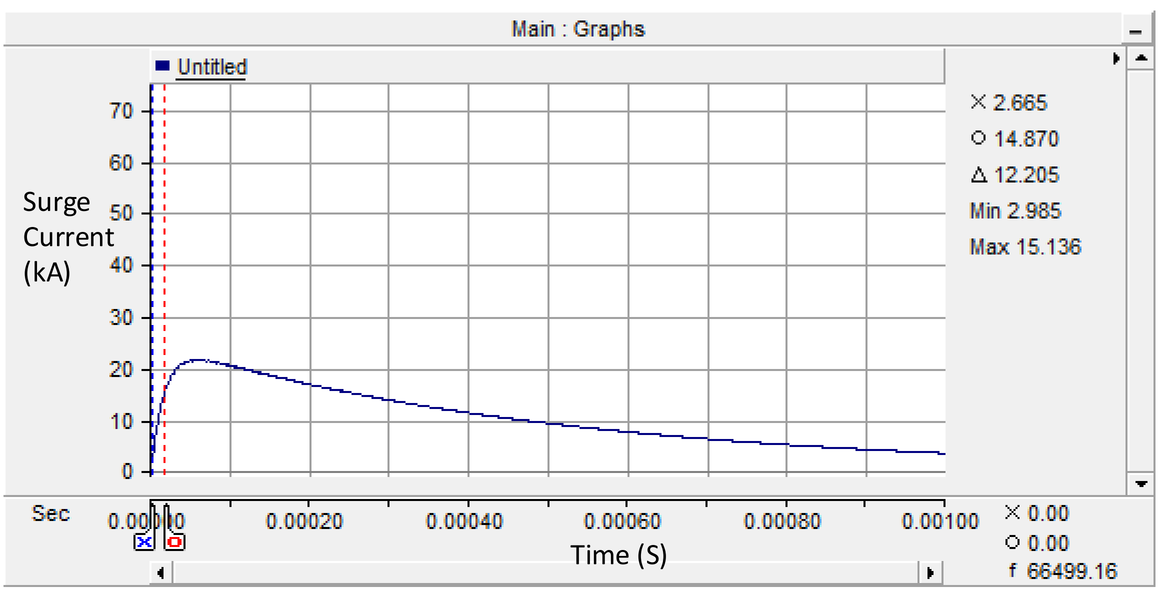


Figure 5. 14 Current through primary seal

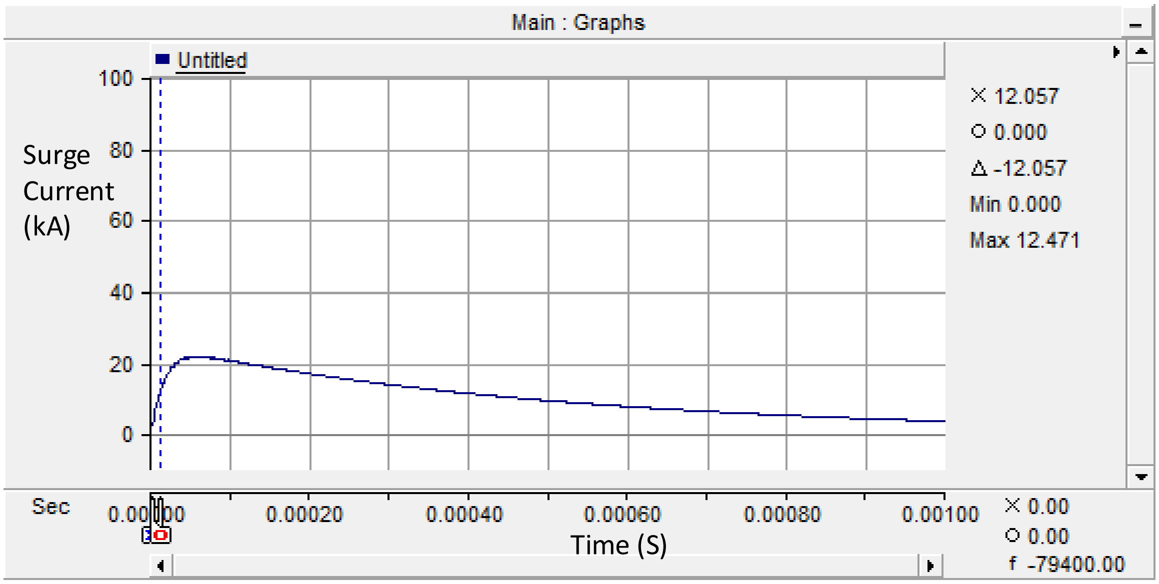


Figure 5. 15 Current through secondary seal

5.6 Results of the PSCAD model for 50kA output and induced surge currents 10/350 µs

Table 5. 6 Tabulated results for 50kA direct lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	47.246
Primary Seal	30.272
Secondary Seal	24.943

5.6.1 Obtained Graphs for Above Tabulated Values

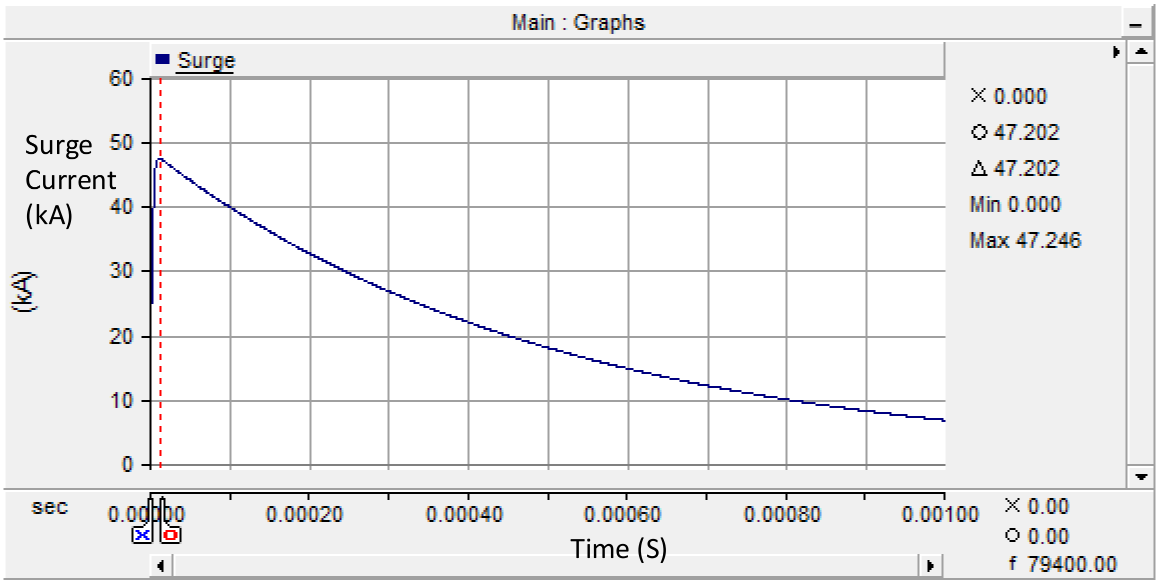


Figure 5. 16 Current through ladder shell connection

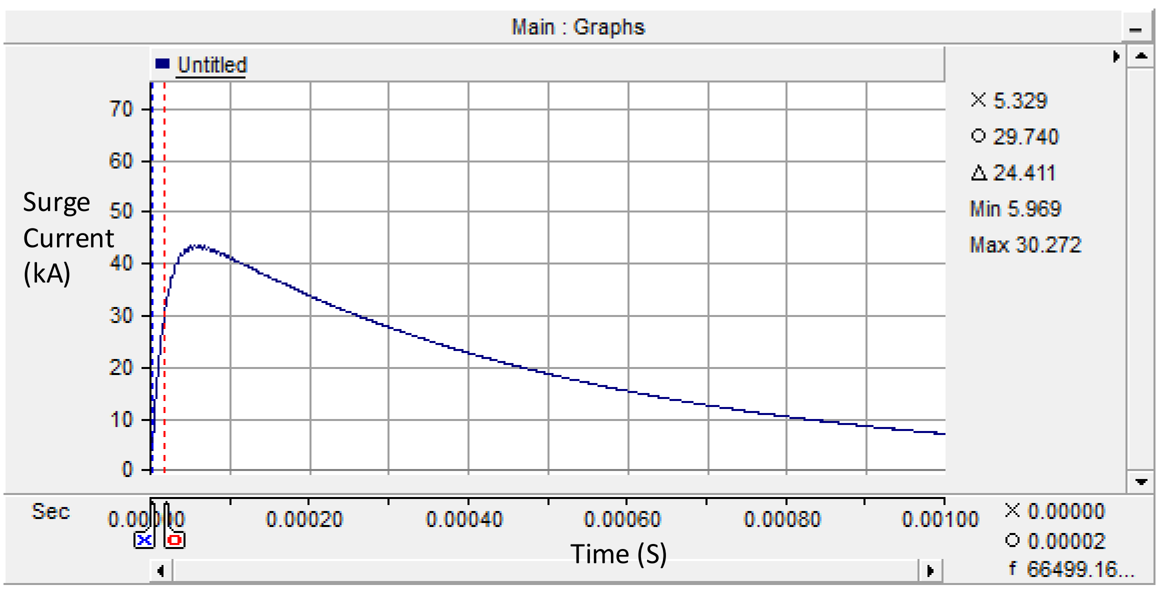


Figure 5. 17 Current through primary seal

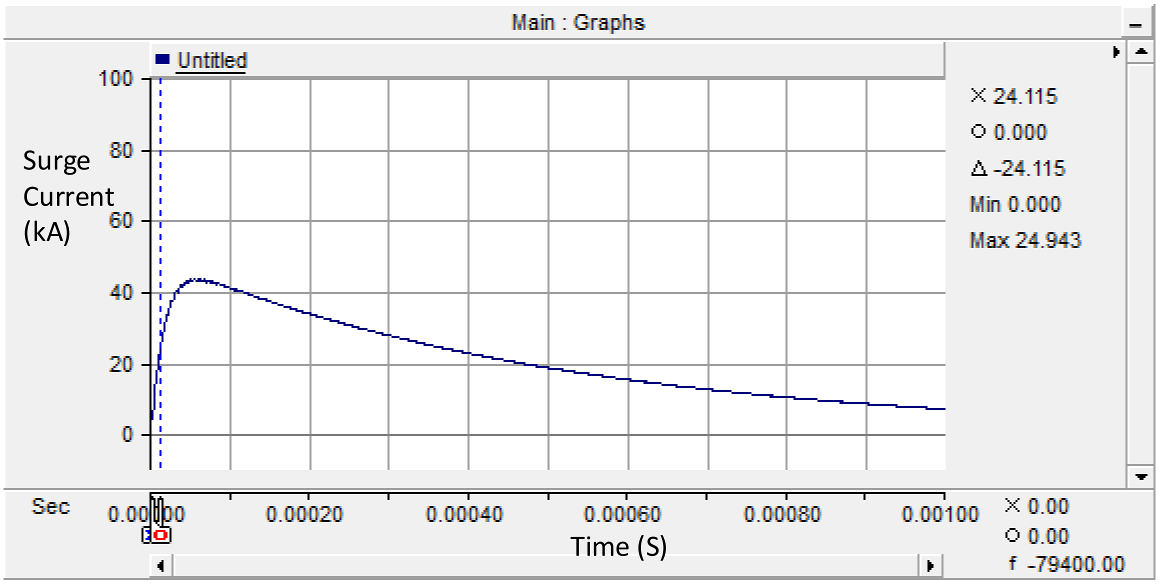


Figure 5. 18 Current through secondary seal

5.7 Results of the PSCAD model for 75kA output and induced surge currents 10/350 µs

Table 5. 7 Tabulated results for 75kA direct lightning surge

Location	**Induced surge current (kA)**
Ladder Shell Connection	70.870
Primary Seal	45.408
Secondary Seal	37.414

5.7.1 Obtained Graphs for Above Tabulated Values

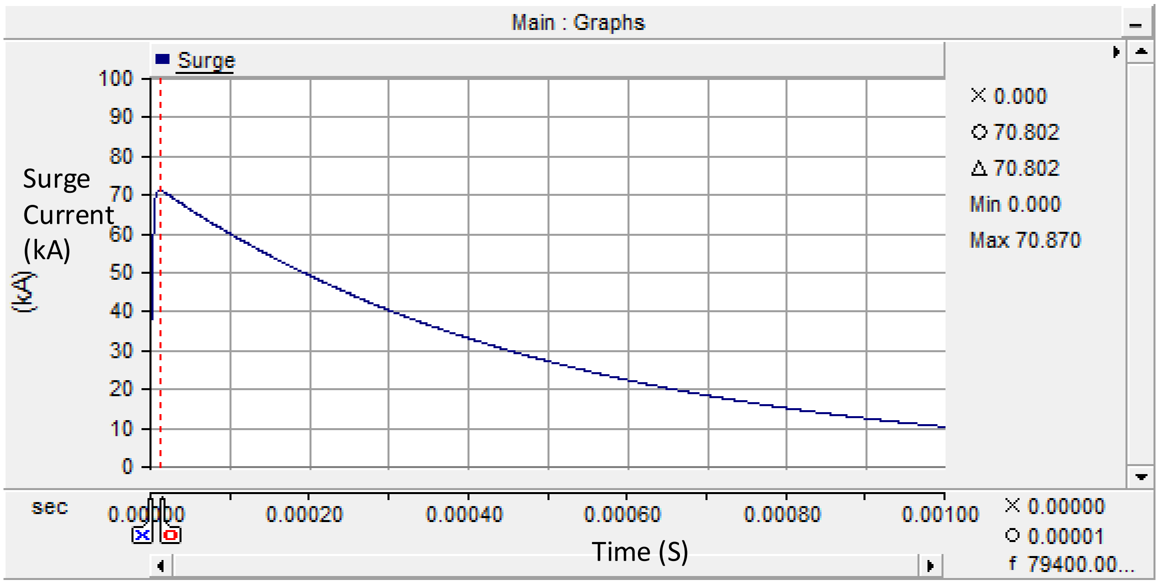


Figure 5. 19 Current through ladder shell connection

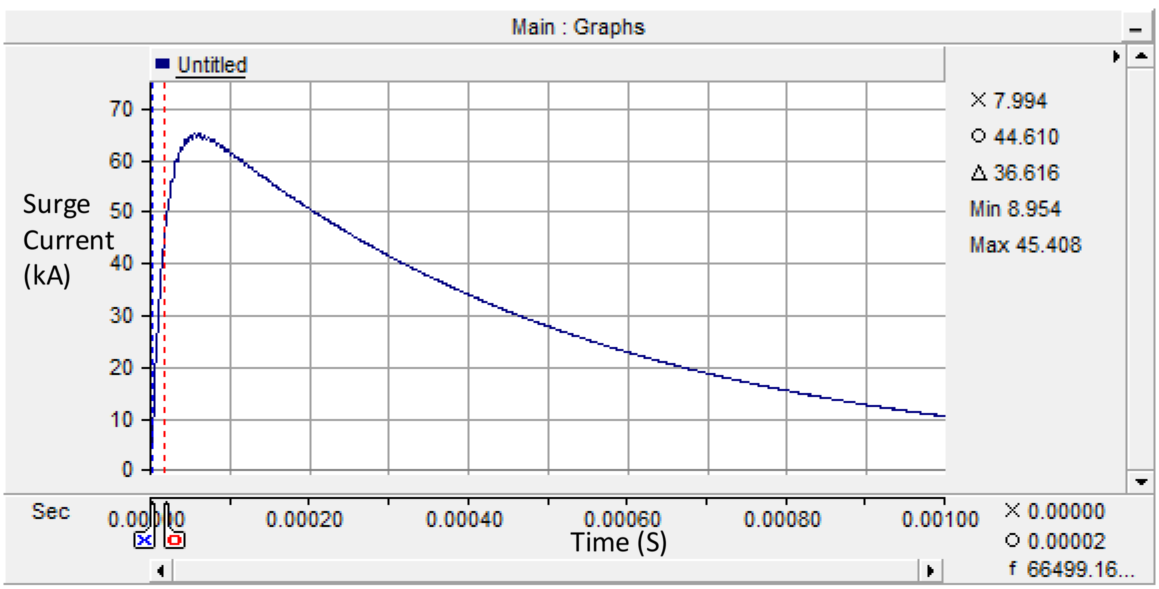


Figure 5. 20 Current through primary seal

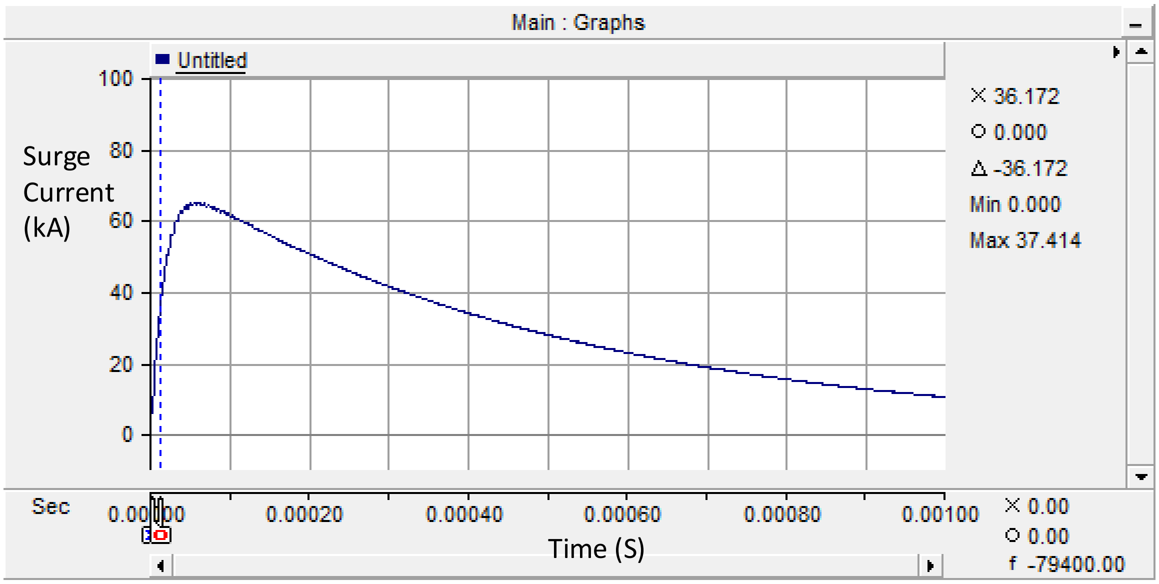


Figure 5. 21 Current through secondary seal

5.8 Results of the PSCAD model for 100kA output and induced surge currents 10/350 µs

Table 5. 8 Tabulated results for 100kA direct lightning surge

Location	Induced surge current (kA)
Ladder Shell Connection	94.493
Primary Seal	86.563
Secondary Seal	49.886

5.8.1 Obtained Graphs for Above Tabulated Values

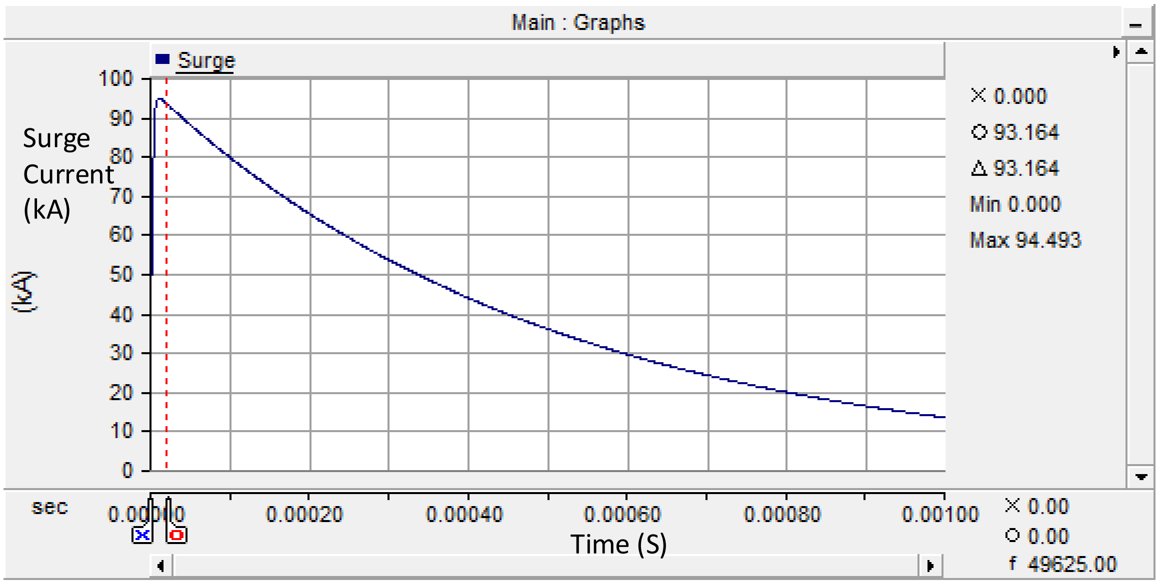


Figure 5. 22 Current through ladder shell connection

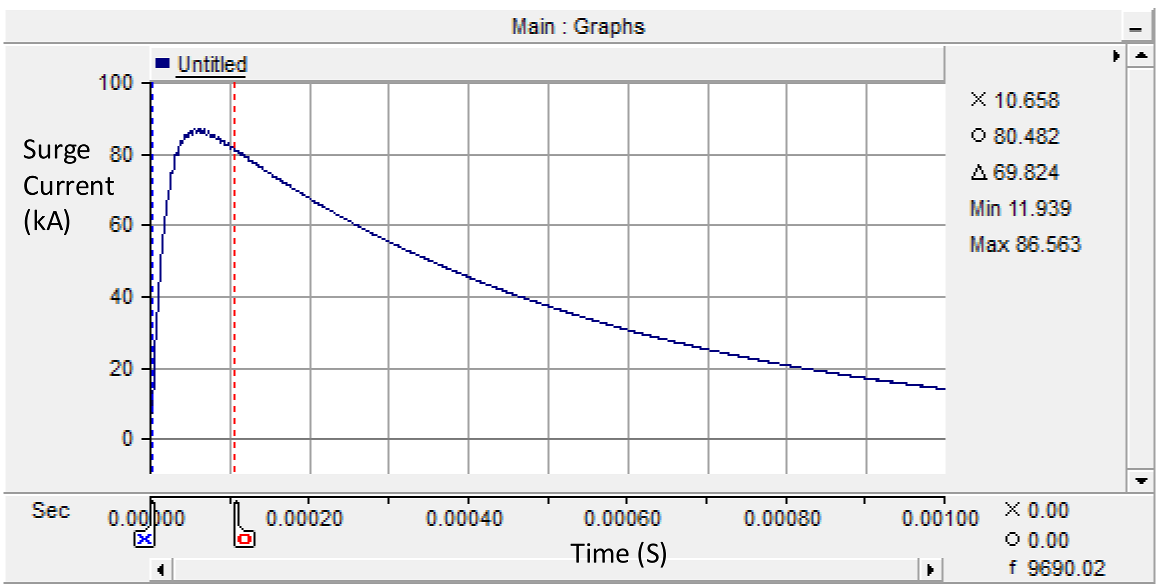


Figure 5. 23 Current through primary seal

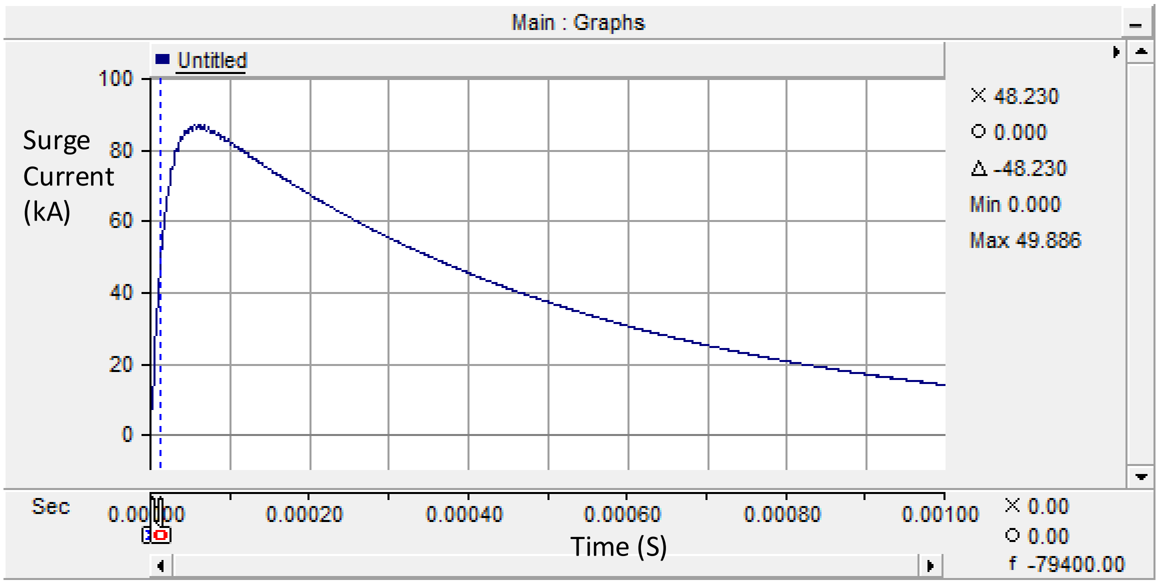


Figure 5. 24 Current through secondary seal

CHAPTER 6

PROPOSED PROTECTION MECHANISM

All floating roof storage tanks are very important to maintain the crude oil allege for proper operability of the Refinery process plant and outage of tanks adversely effect to the country's fuel distribution. To avoid tank fires and large amount of money wastages for lightning strike damages to the tank & apparatus, adopting a reliable protection system is extremely essential.

The research includes analysis of voltage rise due to direct and indirect lightning flashes to the tank moving roof and tank wall. Mainly voltage rises occur due to straight lightning flashes on the moving roof, at the floating roof and ladder interface, Principal seal and the shell, subordinate seal and the shell, ladder and the shell interface which are most prominent locations to propagate a fire due to availability of hazardous vapour in the vicinity. Researches of various lightning strokes' impact to the lighting flash current were simulated for proper selection of the protection mechanism.

6.1 Inductance Calculation for Cu Braded AGC (Adjustable Grounding Conductor)

Since the realistic extent of a 60 000 MT tank is described in paragraph 4.2 as floating roof radius is 66.59 m, tank wall height is 15.8 m, and floating roof of the tank internal can be arrived as maximum height as 14.9 m, and as minimum as 1.8 m. Shell thickness of the tank is 16 mm, and the gap between the tank shell and the floating roof approximately 275 mm. Since the tallness of large oil tank shell is larger than the elevation of maximum level of the floating roof. Actually, the tank shell makes a protective shield effect for the lightning flash current path. Under the protection of the tank shell within 12 meters of circular range from the roof middle was susceptible to lightning flashes [10]. From the research on various locations of the floating roof and the impact of distribution of discharged current, once the tank being stroked by a lightning, it is accurate to consider that the floating roof center was hit by lightning flashes, basically for modelling & calculation.

The cross-section width *b* of proposed Adjustable Grounding Conductor AGC 1 in the calculation was taken as 25 mm, height *c* was 1.8 mm, and the cross-section width b of Adjustable Grounding Conductor AGC 2 utilized in the research was 41 mm, 2.8 mm height *c*, and the span of assembly *l* was varying from 16.4m to 1.8 m, according to the roof levels at different heights. Table 6.1 and figure 6.2 represent the values of AGCs with respect to the roof levels at different heights considering the formula of rectangular cross section straight wire inductor L under the direct current and low frequencies in the inductor handbook [17].

$$L = \frac{\mu_0 \, l}{2\pi} \left(In \frac{2l}{b+c} + \frac{1}{2} \right) \qquad (6.1)$$

6.2 Inductance variance due to size of the AGC

In this research two main sizes of AGCs were selected for the optimum protection from the floating roof lightning strikes are AGC 1- 25.0 mmx1.8 mm and AGC 2- 41.0 mm x 2.8 mm
Voltage rise of the AGC can be calculated as per the equation 6.2,

$$V = R \times i(t) + L \times \frac{di(t)}{dt} \qquad (6.2)$$

The above experimentation represented that the main role of the adjustable grounding conductor (AGC) is to discharge lightning flash current quickly to the ground by minimizing the sparks, when implementation of the acceptable lightning protection procedures on large floating roof tanks. while the large floating roof tanks were hit by lightning strikes, it would boost contact charge release and reduce spurs. Hence to mitigate spark discharge through shunts, other method is to persist conductive path, however to resolve flash discharge problem. The research anticipated to eliminate the conventional conductive path (Shunts) above the secondary seal of floating roof frontier. AGC assembles can be used as the lightning protection mechanism. Following calculations and graphical representations explain the optimum arrangements of the AGCs.

Table 6.1 shows the variance of the inductance values of adjustable grounding conductor (AGC) assembly according to the positions of the floating roof for two available sizes of the rectangular braded copper strips.

Table 6. 1 Inductance variance of two different AGCs

Level of Floating Roof	**Inductance of AGC (μH)**	
	AGC1(25x1.8 mm)	AGC2(41x2.8mm)
Roof at Bottom	24.98	23.37
Roof at 12m	17.53	16.35
Roof at 8m	11.04	10.25
Roof at 4m	4.96	4.57
Roof at top	1.95	1.77

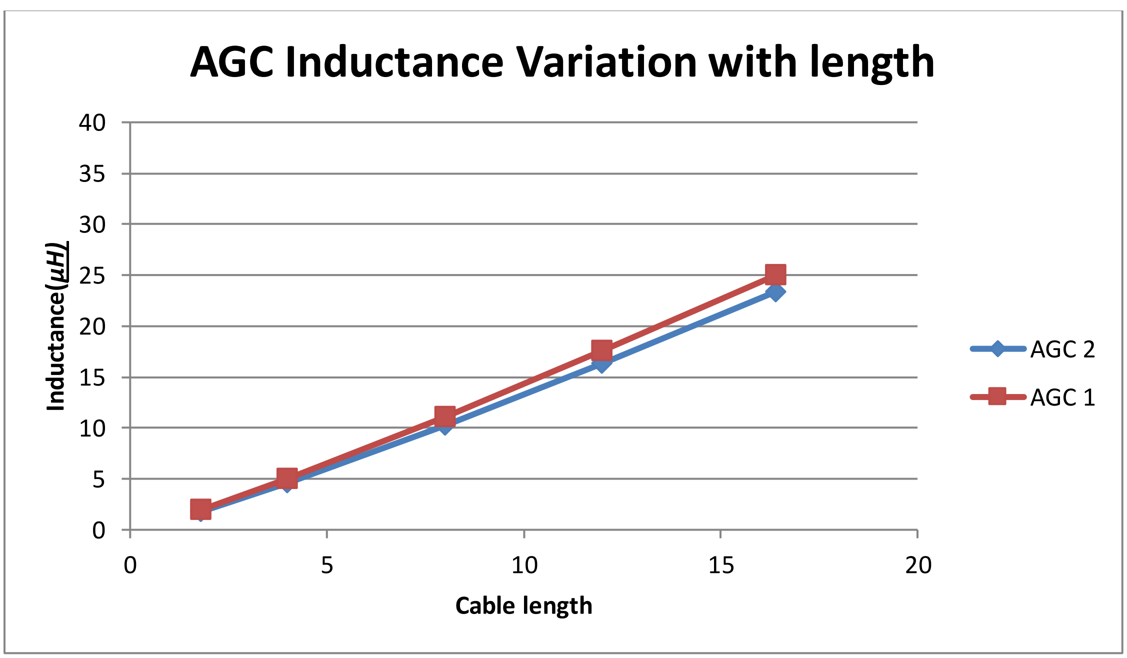


Figure 6. 1 Inductance variance of AGCs for different cable lengths

This shows the cross section of the AGC is not significantly affected the impedances of the grounding conductor path but length of the conductor is a considerable factor for the grounding conductor impedance and hence the voltage-rise due to the lightning strike.

Calculating of collapse voltage for the scaled moving roof tank with various amount of AGCs was calculated using experimental equation, in accordance with connection between lightning flash rod plane-gap failure voltage $u_{50\%}$ considering lightning effect and gap distance d in meter [17].

$$u_{50\%} = 0.537 * d \quad Meg\ V. \tag{6.3}$$

The gap breaks down voltage between floating roof Primary & secondary seals and tank shell are

$$u_{50\%} = 0.537 * 275\ \ kV$$

$$u_{50\%} = 147.68\ \text{kV}$$

Table 6.2 shows the voltage rise due to different magnitudes of lightning strikes and their effects variations due to level of the floating roof at different heights. This research shows that the most vulnerable positions of grounding path, was the floating roof at bottom section of the tank due to high impedance of the grounding path and fortunately at these levels the probability of lightning stroke hits the floating roof is very exceptional.

Table 6. 2 Transient voltage rise with the level variation of floating roof

Level of Floating Roof	**Transient Voltage Rise U (kV)**				
	25kA	50kA	75kA	100kA	200kA
Roof at Bottom	584.19	1168.37	1752.56	2336.74	4673.49
Roof at 12m	408.70	817.39	1226.09	1634.78	3269.57
Roof at 8m	256.23	512.46	768.70	1024.93	2049.86
Roof at 4m	114.24	228.48	342.73	456.97	913.94
Roof at top	44.22	88.43	132.65	176.87	353.73

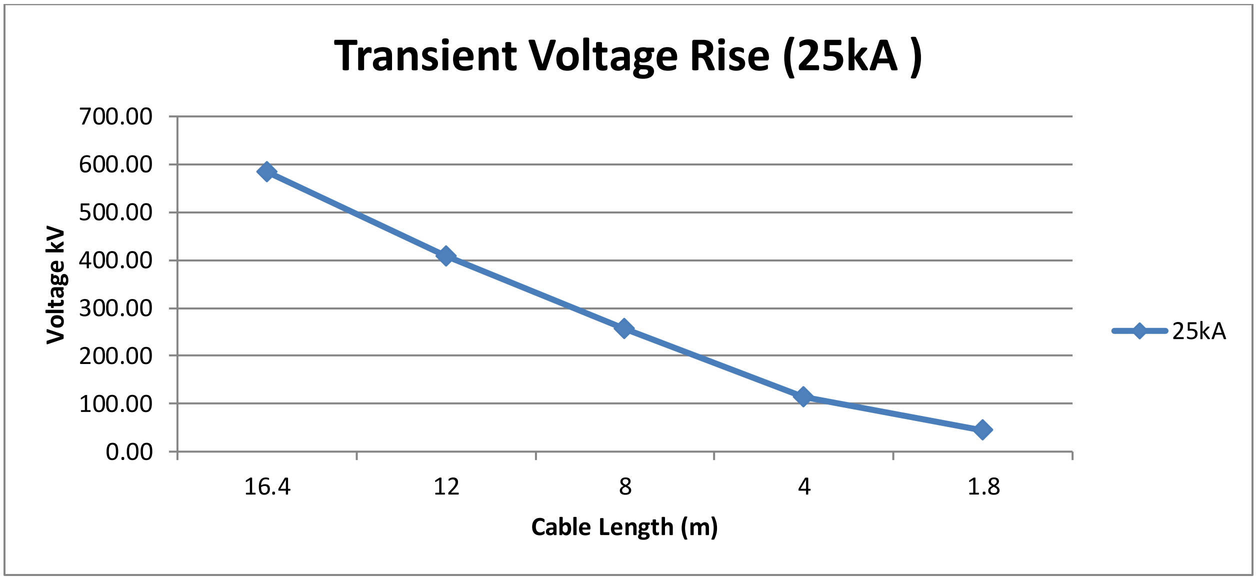


Figure 6. 2 Transient voltage rise of AGC for different cable lengths for 25kA surge

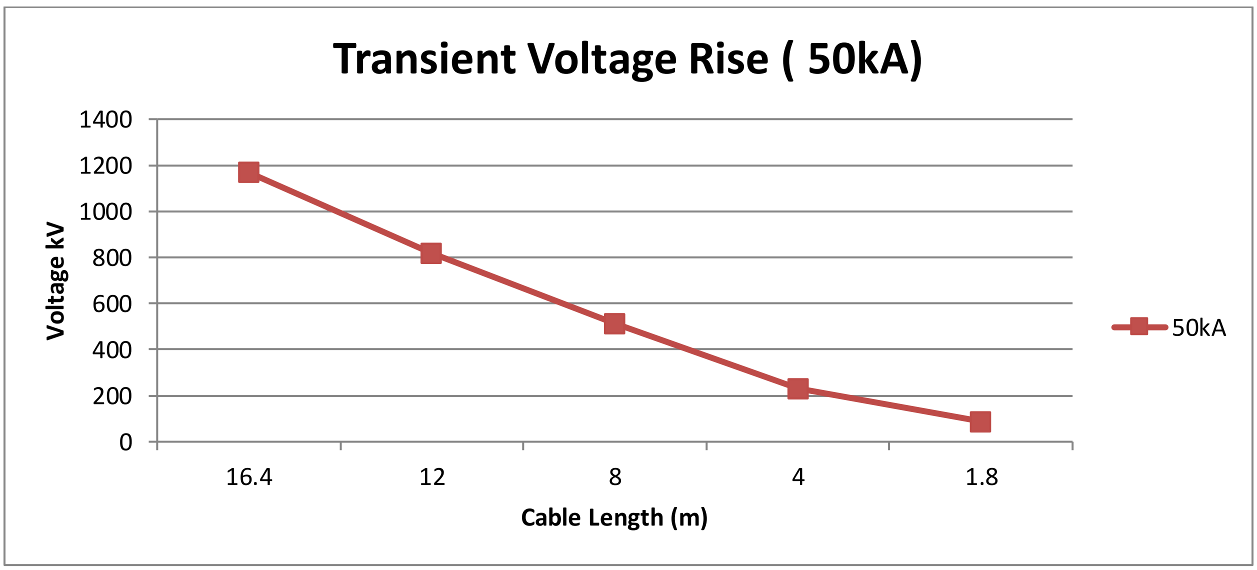


Figure 6. 3 Transient voltage rise of AGC for different cable lengths for 50kA surge

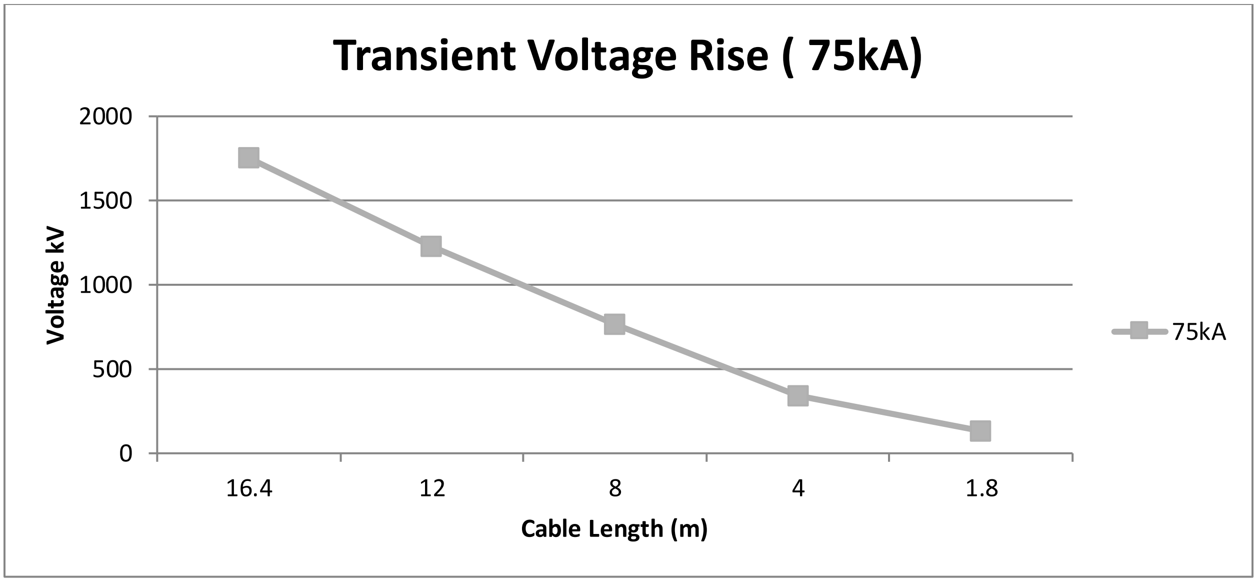


Figure 6. 4 Transient voltage rise of AGC for different cable lengths for 75kA surge

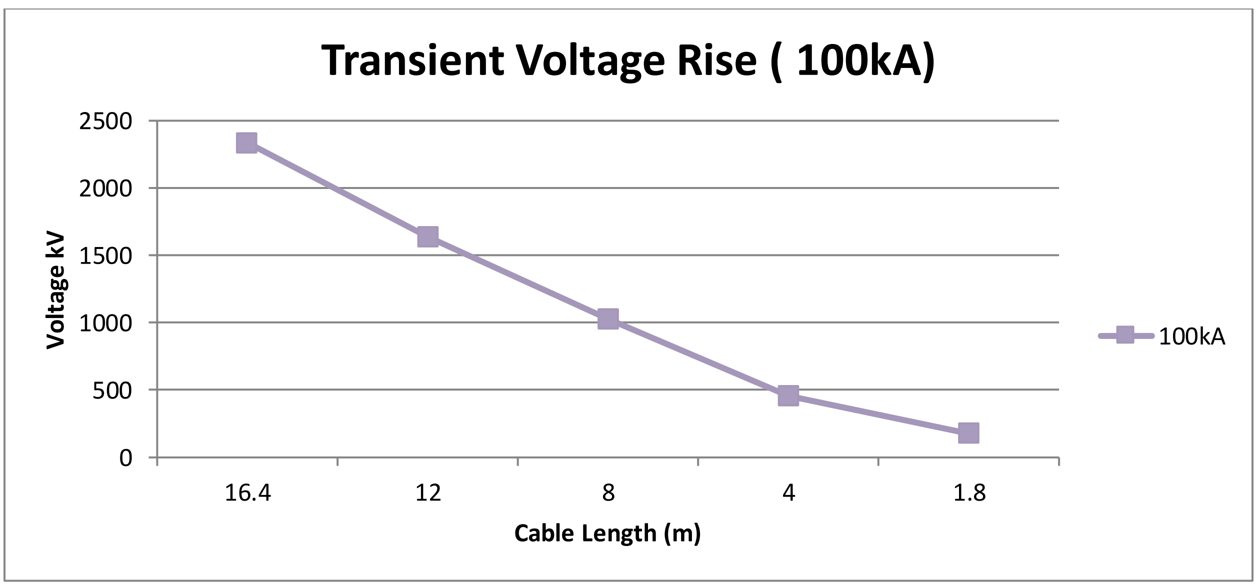


Figure 6. 5 Transient voltage rise of AGC for different cable lengths for 100kA surge

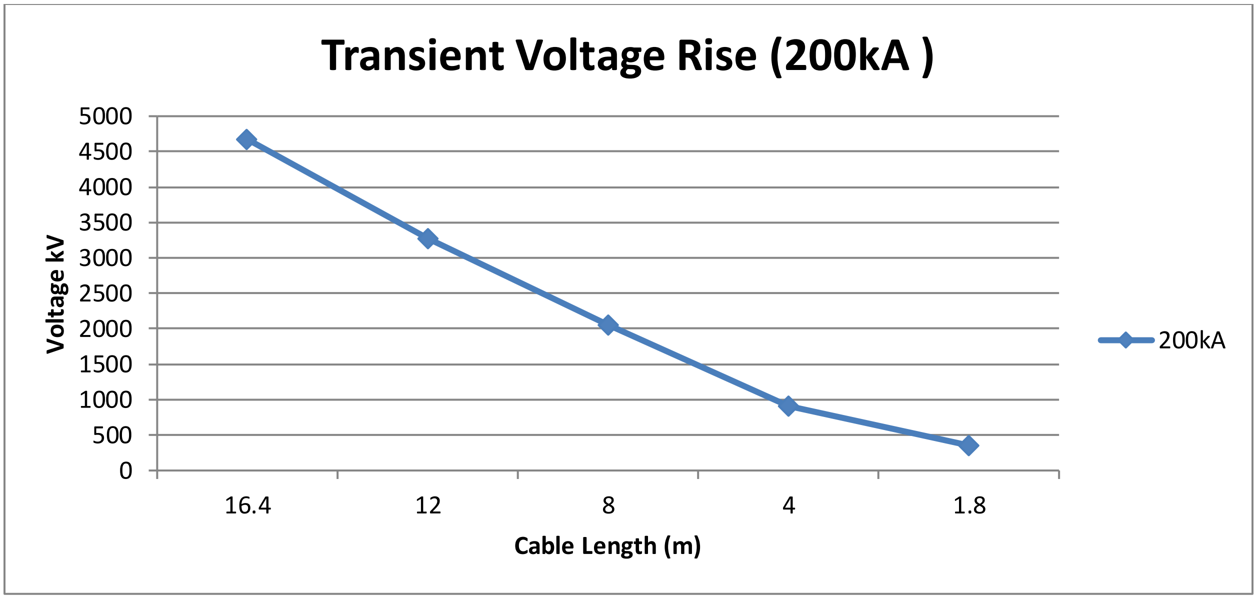


Figure 6. 6 Transient voltage rise of AGC for different cable lengths for 200kA surge

The maximum value of U is 2336.4 kV for 100kA surge. In this research 100kA is considered as the most prominent surge affected to refinery large oil storage tanks by considering the probability curve of the lightning behavior (*Figure 2.4*) and the data received for around the refinery area. Calculated in-rushed voltage values against number of AGCs fixing to crude oil floating roof pontoon and tank shell are tabulated in Table 6.3.

Table 6. 3 Transient voltage rise with the variation of AGC assembly count

Number of AGC	**Transient Voltage Rise (kV)**				
	25kA	50kA	75kA	100kA	200kA
4	146.0465	292.0929	438.1394	584.1858	
6	97.36431	194.7286	292.0929	389.4572	778.9145
8	73.02323	146.0465	219.0697	292.0929	584.1858
10	58.41858	116.8372	175.2558	233.6743	467.3487
12	48.68215	97.36431	***146.0465***	194.7286	389.4572
16	36.51162	73.02323	109.5348	***146.0465***	292.0929
20	29.20929	58.41858	87.62788	116.8372	233.6743
21				111.2735	222.547
22				106.2156	212.4312

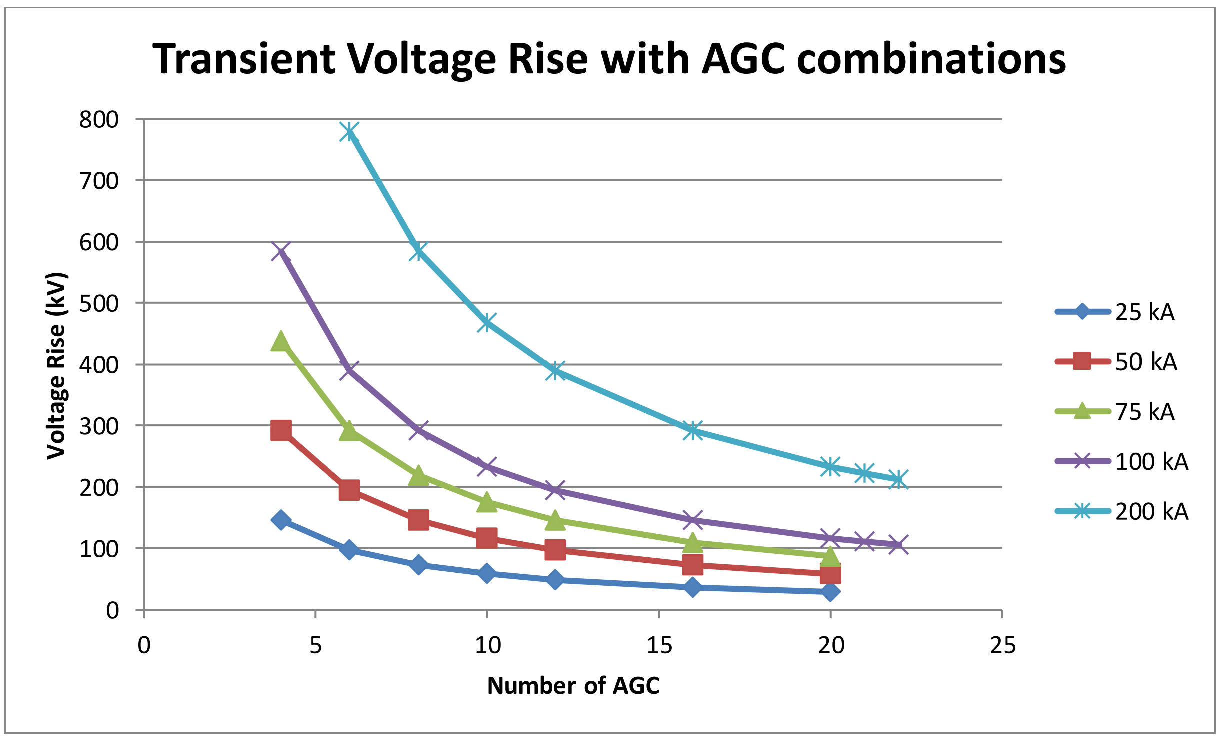


Figure 6. 7 Transient voltage rise for different count of AGC assembly

CHAPTER 7

DISCUSSION

7.1 Discussion

The more common tanks fires in petroleum industry are lightning related fires than other fires at petroleum refinery storage facilities. Floating roof tanks (FRT's) are especially vulnerable to lightning strikes & fires. According to an analysis of petroleum storage tank fires, the amount of tank fires published in the international media at the range of 16 to 24 incidents annually. The level of the oil tank fire occurrences differs considerably, extending from a roof seal fire to multiple avalanched complete destructive tank fires.

Earthing systems acts as the path for the huge discharge current flow between the cloud and the planet earth to achieve the purpose of neutralizing. The objective of the effective earthing system is to distribute the neutralizing charge stream to the ground as fast as possible in an efficient way by maintaining the gap sparks of the grounding path at a minimal level. Therefore, the performance of the grounding system is very important for the effectiveness of the lightning protection system of any equipment, building or structure.

Petroleum products such as crude oil, gasoline, diesel fuel, etc., are commonly stored in Floating Roof Tanks (FRTs). A floating roof tank is a type of tank where the roof floats on top of the product being stored. The roof, although it is made of steel, rests on pontoons that float on the product being stored. Consequently, as the tank is filled or drained, the roof journeys up and down correspondingly within the operational shell height of the tank. Floating roof tanks are commonly used to reduce oil evaporation effectively nowadays.

Seals with more flexibility are fixed round the perimeter of the roof to avoid product vaporization. These flexible seals are made out of a material with low conductivity, such as neoprene rubber, canvas etc. Several different seal types designs are used as main two rim seals, called prime and secondary seals which are mounted along the floating roof & shell boundary. Since the seal are manufactured in non-conductive materials, it separates the roof from the tank shell electrically. Inappropriately, these primary and secondary seals are not perfectly contacted to the shell. They developed scratches, split and/or become defective over time. Furthermore, the tank wall repeatedly makes distorted and bulged shape due to recurrent filling, emptying, thermal expansions etc. The internal surface of the tank wall can be formed as irregular shapes due to weathering or Petro-chemical deposits, e.g. sludge, bitumen and paraffin. Because of this type deficiencies around the roof and shell boundary interface, leaks of the product vapor sometimes take place adjacent to the seals and combines with the atmosphere. Since, this vapor can be tremendously flammable, the location over the roof inside of the floating roof become a classified area as a Class I Division I according to IEC standard. This hazardous classification sometimes spreads up from the pontoon to the topmost level of the tank wall. Most probably the floating roof and tank wall are not at the equal potential, and when the voltage gap between the two surfaces becomes adequate, an arc flash will generate among these two sides due to lightning strikes. This is the vulnerable location for the arc flash. As combustible fumes might be existing from deficient roof seals and this preparation creates a hazardous situation during lightning strikes for the floating roof storage tanks.

To decrease the oil evaporation effectively, floating roof tanks are frequently used nowadays. The size of tanks is extended progressively with the growth of crude oil exploration in the world. And also, the hazard of lightning strikes to the floating roof storage tanks rises as well due to global climate changes and extreme weather situations in the world nowadays.

In this study, main concern given to large floating roof crude oil storage tank facility. The utmost overall technique to mitigate the possible damage to floating roof crude oil storage tank is using good conductive paths to ground. An easiest electrical path is created by the earthing system up to the ground and performance of the grounding mechanism gets better as the ground loop impedance becomes lower.

Grounding systems for hydrocarbon processing plants and storage tank farms should be designed carefully for continuous and reliable services, ease of operation and maintenance, safety to people and equipment and protection of the equipment. Refinery grounding network was designed as a mesh type grounding system connected each & every earth pit (Node) by forming a very low grounding impedance of the network. This earthing network is measured individually by removing other connection to the said earth pit and maintain in a healthy manner to maintain the grounding impedance at a minimal value. The grounding impedance of the network is maintained in the range of milli ohm.

Thus, lightning is a natural phenomenon with a considerable amount of potential harm. It is a scientific fact which can be predicted upon a careful study of its empirical properties and methods of impacts for mitigating. In order to minimize the damages, suitable lightning protection system (LPS) should be installed at appropriate locations.

Most of the references were based on the industrial environments and few of them were described about the tank structures and their properties related to mechanical strength of the tanks. All lightning protection systems were based on the buildings and towers and not for the petroleum oil storage tanks. Therefore, it has to made more effort to select suitable literature for this aspect and have made lot of assumptions to the actual tank parameters due to non-availability of previous researches regarding this topic in tropical region.

Analyzing the effects of lightning strikes on oil tanks offers alternative options to reduce flashovers caused by lightning on floating roof oil storage tanks. In addition, this information can be applied for the purposes of giving information about proper grounding system installation to meet reliability criteria. This practical method can be easily applied by planning and design engineers to evaluate lightning performance of the floating roof tanks in the tank farm. It depends on the location and may be unique for the location.

CHAPTER 8

CONCLUSION & FUTURE WORK

8.1 Conclusion and Recommendations

According to this research outcome the most optimal solution is for lightning flash protection system for large floating roof storage tank facility is Adjustable Grounding Conductors (AGC) which is always maintain the minimum length between tank shell and the floating roof.

The AGC consists of a spring tensioned flat cable that connects amongst the floating roof pontoon and tank wall. The connecting cable of the AGC is made using flat braided copper strip. The AGC assembly housing should be stainless steel alloy (Monel) with high conductivity for better protection for the corrosion due to high corrosive environment at the refinery surroundings. The flat conductor is tinned for additional corrosion protection and better contactability. Figure 8.1 illustrate the AGC assembly installation.

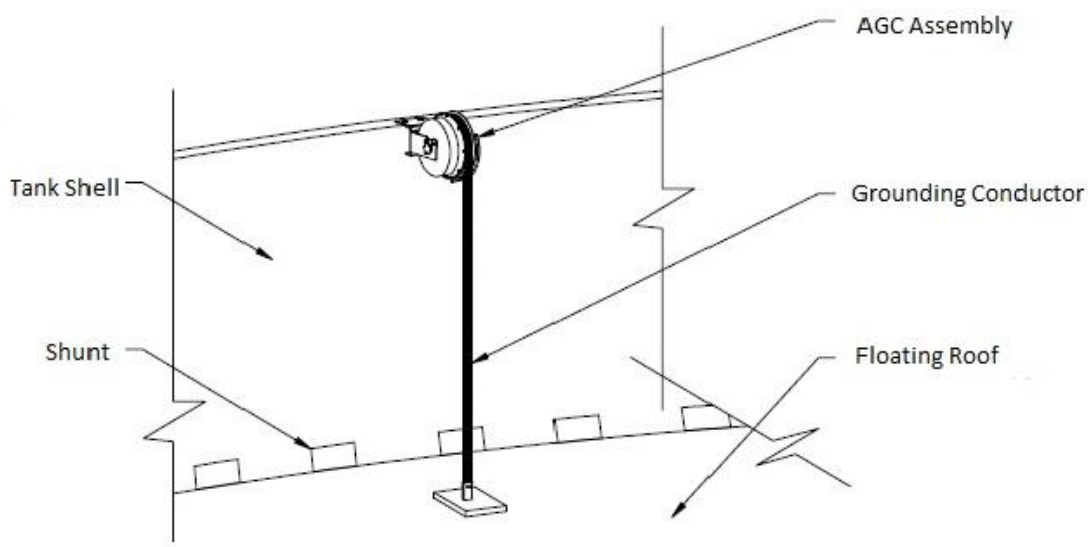


Figure 8. 1 proposed Adjustable Grounding Conductor Assembly

The braded flat conductor of the AGC is spring-tensioned for the automatic retraction arranged in the rotating wheel once it is not experiencing a tightness. Thus, the strip is continually maintaining its length as minimum as possible (i.e low impedance), regardless of the position of the floating roof. Further this is also non-dependent of the tank shell wall pureness and any existence of shunts. Furthermore, it provides better grounding linking amongst tank floating roof and tank wall, even no shunts are present.

Since floating roof tanks have of enormous size in diameter, it is significant to maintain the floating roof and tank wall impedance to minimize the arc flashes during the lightning strikes, by installing multiple AGCs. The final outcome of this research is selecting the number of AGCs for better protection of the floating roof tank from lightning strikes. According the data shown in table 6.3, when the numbers of AGCs are increased, voltage rise at the gap ($u_{50\%}$) between floating roof and primary seal, shell and secondary seal assemblies would be lower than the gap collapse voltage ($u_{50\%}$). This describes that it is needed to be optimum no of AGCs to reduce the sparks at these critical locations. By considering the investigation results, probability of lightning strikes more than 100kA (Fig. 2.4) and other practical aspects and economic impacts on floating roof oil storage tank installations, the number of proposed Adjustable Grounding Conductors (AGCs) for the better lightning protection up to 100 kA surge for Large Oil Storage tanks at the refinery is as follows,

1. The optimum number of AGCs required for a 67 m diameter floating roof tank is **12 Nos.**
2. The practical size of the AGC shall be of 40 mm (W) & 3 mm (T) and total length of the AGC shall be 18 m

The installation of proposed adjustable grounding probes is comparatively easier task and low-cost, on both prevailing tanks and newly constructing tanks. Present tanks can be arranged to retrofit proposed AGCs even though they are in service, irrespective of the location of the floating roof. Since they installed externally, AGCs are easy to test the conductivity and sustain in healthy condition by measuring the lead impedances of the conductor frequently.

8.2 Following are the difficulties associate with the Research

1. Any design of lightning strike flash protection behaves as the probabilistic pattern of lightning characteristics.
2. Lack of data due to infrequency of lightning strokes in the refinery area considered
3. It is needed to test the tank to check flash over value for different impulse level. There are technical barriers & finances involved in investigating scaled model with further details
4. 100% shielding is not identified practically for providing of lightning strikes protection.
5. Ecological shielding cannot be evaluated correctly due to lack of data
6. There are number of other variables, involved in the process of construction of lightning protection system for the tanks.
7. Maximum possible resistance for grounding system depend on
    - Ground Flash Density of the location
    - Tank configuration (Method of construction)
    - Earth Resistivity
    - Earth lead length
    - Number of earth electrodes

This analysis allowed to understand the behavior of the grounding path impedance and the connecting cables to evaluate the lightning effects in the floating roof tank. PSCAD package is based on more comprehensive representations of floating roof tank and AGCs illustration. In this research, the effect of lightning over voltages on floating roof and associated connections, and also the energy diverted to ground have been simulated by using the PSCAD program.

References

[1] http: //www.the map of sri lanka.com

[2] J. R. Lucas, "*High Voltage Engineering*", Dept. Elect. Eng., University of Moratuwa, Colombo, Sri Lanka, [2001].

[3] W.A.K.T. Indrajith, "*Designing of distribution substation lightning protection system to minimize damage due to lightning*", Msc. dissertation, Dept. Elect. Eng., University of Moratuwa, Colombo, Sri Lanka, 2014.

[4] J. R. Lucas and D. A. J. Nanayakkara, "*Lightning protection of pole-mounted Transformers and its applications in Sri Lanka*", Trans. IEE Sri Lanka, April 2001.

[5] A. J. Eriksson et al. "*Lightning performance and overvoltage surge studies on a rural distribution line*", IEE Proc. Vol. 129 Pt. C, No2 March 1982.

[6] F. Heidler et al. "*Parameters of Lightning Current Given"* in IEC 62305

[7] IEC INTERNATIONAL STANDARD 62305, "Protection against lightning (Part 1 -5)" Edition 2.0, 2010-12

[8] NFPA 780 Standard for the Installation of "Lightning Protection Systems", 2008 Edition

[9] API/EI Research Report 545 "*A Verification of lightning protection requirements for above ground hydrocarbon storage tanks*", First Edition, October 2009, Summary

[10] API RP 545 "*Recommended Practice for Lightning Protection of Above Ground Storage Tanks for Flammable or Combustible Liquids*", First Edition, October 2009

[11] M.A. Uman, Martin, "*All About Lightning*" 1993

[12] IEEE Transactions on "*Experimental study of Ionizing Air Terminal Performance*"

[13] IEEE Transactions on "*Lightning Protection Systems, Advantages and Disadvantages*"

[14] Hu Hai-Yan and Liu Quan-Zhen, "*Research on Lightning Sparks Discharge and Protection Measures of Large Floating Roof Tank*" -2012 ICLP

[15] WANG Zhen-guo, "*The reason and counter method of oil gas space explode and fire in the first and second seal of oil floating roof tank*" – 2007

[16] Diaz, Luis and Miry "*Calculation of Lightning Transient Voltages in Cables considering a Large Industrial site using a FDTD Thin Wire Model*"-2015

[17] "*Inductance calculation manual*", Beijing, China: China Machine Press, 1992.

[18] Zhang renyu, Chen changyu, Wang changchang. "*High voltage test techniques*", Beijing, China: Tsinghua University Press, 2003.

[19] G. Diendorfer, and W. Schulz "*Ground Flash Density and Lightning Exposure of Power Transmission Lines*", Paper accepted for presentation at IEEE Bolonga Power Tech Conference 2003.

[20] "Protection of structures against lightning", BS 6651:1992, Dec 1992.

[21] Introduction to the PSCAD/EMTDC Version3, Manitoba HVDC Research Center 2001.

[22] Applications of PSCAD™ / EMTDC™, Manitoba HVDC Research Centre 2001.

[23] W. Ireshani Jayatunga, "*Modelling of lightning surge propagation in railway track and propose a cost-effective protection system*", MSc. Dissertation, Department of Electrical Engineering, University of Moratuwa, Sri Lanka 2018