Critical analysis of the need for Transient Line Design

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Abstract

This project identified a probabilistic methodology for finding the risk of failure for a transformer when it is subjected to lightning overvoltage. It also did the same for a surge arrester. The methods were then tested using case studies. The first case study found the risk of failure for a transformer without a surge arrester. The second case study had a surge arrester protecting the transformer. The third case study evaluated the risk of failure for a surge arrester which had a low energy rating and also for when it had a higher the energy rating. This project was done to aid electrical engineering consultants in two situations they had faced in the past and expect to face in the future. The first situation involves customers who are reluctant to add a surge arrester to protect their transformer. The probabilistic methodology identified in this project for analysing the risk of failure for a transformer could be used to show the customer the risks of failure for his transformer for with and without a surge arrester. The second situation is for when a surge arrester in the field needs to be analysed for whether it is capable of handling a lightning overvoltage. The risk of failure methodology for a surge arrester could be used in such situations. The project worked on identifying a suitable methodology for the analysis. it also worked on finding a suitable software for modelling the system and running the simulation many times, varying the current level on each run and collecting the peak overvoltage levels at the transformer terminals. Then a probability function was formed out of the collected data for the expected overvoltage levels due to lightning overvoltage at the site. The peak current levels injected in each simulation needs to follow the meteorological data for lightning stroke currents for that area. Then this probability function was multiplied with the probability function for the transformers withstand capability. The result was then integrated within specified limits to find the risk of failure. The case study results showed that when no surge arrester was used, the risk of failure for the transformer was 99.99% and when a surge arrester was added the result was 0.13%. The surge arrester risk of failure analysis showed that when it had a lower energy rating the its risk of failure was high. When the surge arrester's energy rating was increased, the risk of failure reduced. The results indicated that the overall methodology worked and it was ready for use.

Acknowledgements

It is my great pleasure to show my appreciation and gratitude to the people who have made this project a possibility.

First and foremost, I would like to thank both my supervisors, Dr Darren Woodhouse and Professor Sarah Johnson. The technical direction and motivation from Darren and the academic support from Sarah has allowed me to progress this far into my final year project.

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Finally, to a friend who helped understand the statistical concepts surrounding my project. William Jones, I thank you.

Last but not least I would like to thank my wife and children for the love and support that pushed me towards finishing my FYP report.

Contributions

The key contributions of the author of this project are listed below:

- Carried out research on identifying a probabilistic methodology for finding the risk of failure for a transformer and a surge arrester.
- Learnt relevant transmission line theory principles with regards to lightning transients and its impact on transformers and lightning arresters.
- Researched and identified a transient analysis software that were available. PSCAD Free was found to be the most suitable for this project.
- Carried out a case study to show how the risk integral method could be applied.
- Identified ways to achieve the objectives using the cheapest method.
- Identified other ways this project could be used. It could be a training aid for power lines persons to see the values of possible lighting overvoltage in the area they serve. Also, it could be used to demonstrate the need to keep a surge arrester as close as possible to the transformer.

Mr. Maikeli Drose	Sarah Johnson	Dr Darren Woodhouse

Materials that were cited have been acknowledged. All figures that were not produced by the author of this thesis have been cited in the figure's caption.

Table of Contents

Table of Figures

1 Introduction

1.1 History and background

A transient phenomenon in any type of system can be caused by a change of the operating conditions or of the system configuration. Power system transients can be caused by faults, switching operations, lightning strikes or load variations[1]. Lightning strokes to transmission or distribution circuits inject a large amount of energy into the power system in a very short time, which causes overvoltage and overcurrent conditions which are undesirable in a power system. The goal of the power system is to satisfy the energy demand of a variety of users by generating, transmitting and distributing electric energy [1]. Transient conditions can stand in the way of this goal by causing disturbances to system performance or the failures they can cause to power equipment. This problem gives rise to the importance of transient line analysis. One of the objectives of such studies is to determine the potential levels of unwanted overvoltages and currents in the system due to transients and thus mitigation techniques could be applied. An accurate calculation of transients in power systems is a difficult task because of the equipment involved and the interaction between components[1, 2]. The solution of most transients is not easy by hand calculation, even for small size systems. For majority of transients an accurate or even an approximate solution can only be obtained by using a computer. Computer simulations provide a convenient means to characterize transient events, determine resulting problems and evaluate mitigation alternatives[2].

Transients due to lightning strikes (the focus of this project) are classified as electromagnetic transients. This is due to the nature of its physical phenomena. Several techniques have been developed over the years on the computation of electromagnetic transients. Among the time-domain solution methods, the most popular one is the algorithm developed by Dommel [3], which is a combination of the trapezoidal rule and the method of characteristics also known as Bergeron's method. This algorithm was the origin of the Electromagnetic Transients Program (EMTP) [3, 4]. This acronym is nowadays used to designate a family of simulation tools based on Dommel’s scheme. These include electromagnetic transients’ programs, such as EMTP-RV, PSCAD/EMTDC and ATP.

1.2 Objectives

This project worked towards identifying a method that could be used to evaluate the risk of failure for a transformer due to lightning transients or lightning over voltages. The method was used on a case study where a transformer's risk of failure was analysed for when it was not protected and when it was protected by a lightning arrester.

Secondly, the project identified a method to find the risk of failure for a surge arrester which was already in use in a system and it demonstrated the method using a case study. Furthermore, in the course of finding the risk of failure for a transformer and also for a surge arrester, this project found a simple method to demonstrate the reason for why it is important to have the shortest possible distance between a surge arrester and a transformer.

1.3 Motivation

This project came about because of certain situations electrical engineering consultants have faced in the past. There were times when a client with a transformer or about to purchase a transformer was opting to go without a surge arrester. From a business perspective, the consultant needed to convince the client that a surge arrester was a good investment for the purposes of increasing the overall purchase by the customer. In such situations the client would be interested in the extra cost and the overall benefit. This project provides a means to justify the benefits of having a surge arrester by showing a reduced risk of failure for the transformer when it is protected by a surge arrester.

There are times when an electrical consultant is asked to evaluate if a transformer and its surge arrester are compatible and the installation is electrically sound with all the appropriate checks carried out and ticked off. This site visit is normally done without incurring a plant outage. In such situations even though the transformer and its surge arrester meet the protective margin requirements, there is no way of assessing if the energy rating of the surge arrester is appropriate for it to operate reliably at that location. The location could potentially have high lightning current levels compared to other sites. It was for this reason that this project was tasked with finding the surge arrester risk of failure at that particular location.

1.4 Project overview

The risk of failure analysis was done using probabilistic techniques. The author for this project identified the methods of achieving the objective through literature review. A common trend was identified such that the withstand capability of the asset being analysed was compared with the *expected lightning conditions* it could face when a lightning overvoltage occurred on the system. If the assets withstand capability was less than the *expected lightning conditions* then it would fail. For the transformer risk of failure analysis, the cause for transformer failure due to lightning was identified as insulation failure. Therefore, its insulation level was its measure of withstand capability and the expected lightning over voltages reaching at the transformer terminals represented the *expected lighting conditions* it would face. The probabilistic methodology involves finding the probability distribution functions for the withstand capability and the probability distribution function for the expected over voltages, multiplying the functions together and then integrating the result gave the risk of failure for the transformer.

It was found that this methodology could also be used for finding the risk of failure for the surge arrester as well. The only difference was with the surge arrester's cause of failure. It was found that excessive energy passing through the arrester (type of surge arrester - metal oxide surge arrester (MOSA)) was its cause of failure. Therefore, its withstand capability and the *expected lighting conditions* it would face was in terms of energy instead of voltage.

In order to find the *expected lighting conditions* an asset (transformer and surge arrester) would face, transient analysis was used. The software used was a free version of PSCAD/EMTDC which was provided by the vender for the public to download and use. Since it was a free version, it did have limitations in terms of project size and restrictions on some of the features. In the case study, in order to demonstrate the methodology, a single-phase model was created for a system that had a generator, transmission lines, a surge arrester (high frequency model), step down transformer (high frequency model), a load and a lightning current injector. Then a multi run block was initiated in the simulation to generate multiple runs and for each run the peak voltage level at the transformer and the peak energy value passing though the surge arrester were recorded. In each run, the injected lightning current was varied according to the expected current levels for that location. The simulation data was used to formed the probability distribution for the *expected lighting conditions* an asset (transformer and surge arrester) would face. This was then used to find the risk of failure.

2 Review of technical background

This chapter sets out the underlying technical background material needed in discussing this project in the subsequent chapters. This project lighting overvoltage are

2.1 Lightning induced transients on a power line

While overvoltage's can originate from within the system like in the case of switching, it can also have an external cause. Lightening overvoltage in a power system can be classified into three main categories [4].

- Lightning strikes close to the power line but does not make contact,
- The lightning makes direct contact with the power line where it infects a current wave on the line
- The lightning strikes the tower and the grounding wires.

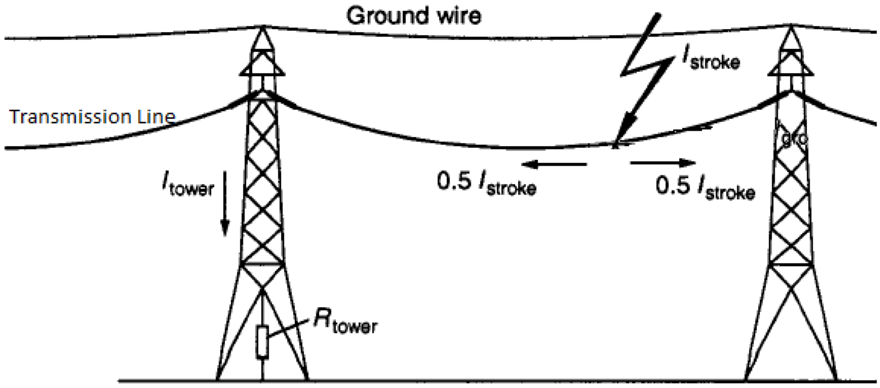


Figure 2.1: Lightning strike on a conductor and the surge current divides into two separate waves that travel away from the strike point [5].

When lightning strikes a phase conductor it injects a current wave, the resulting lightning overvoltage wave is depended on the surge impedance or characteristic impedance of the line (Z_0).

$$V_{peak} = 0.5 \, x \, I \, x \, Z_0$$

Equation 2.1

$$Z_0 = \sqrt{\frac{L}{C}}$$

Equation 2.2

Where

I	is the lightning stroke peak current
Z_0	is the surge impedance
L	line inductance
C	line capacitance

The lightning overvoltage behaves like a traveling wave and travels at speeds close to the speed of light. Another feature of the lightning overvoltage is its fast rise time. Figure 2.2 shows a standardised IEC waveform which can be generated for testing purposes. The rise time is 1.2μs and the tail time is 50μs. This wave is commonly known as the 1.2/50μs lightning wave.

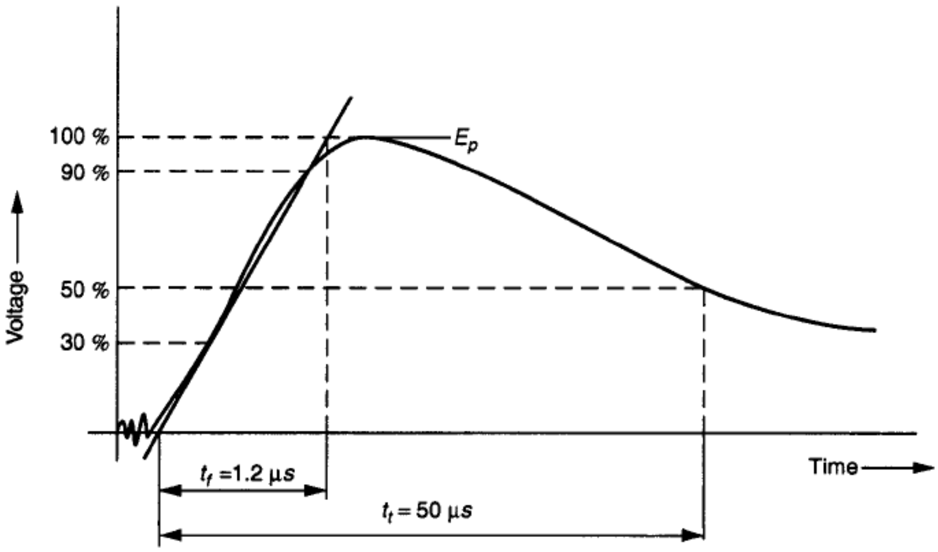


Figure 2.2: Standardised lightning waveform [5]

2.2 Travelling waves

Under normal conditions the wavelength for a 50Hz system is 6000km. The network size is smaller than the wavelength. This allows the use of lumped element representation to carry out steady state analysis. For transients, the frequency is high, and thus the wavelength is smaller. Normal circuit theory cannot be applied. Transmission line theory is used in these cases.

2.2.1 Transmission Line theory

Appendix 1 has the relevant equations associated with transmission line theory. It has been provided to allow the reader to appreciate the depth of the theory and that if required, then further information can be found in [4, 6].

This subsection will cover some of the basic knowledge of what needs to be understood out of transmission line theory to be able to understand and visualise lightning transients, in particular the lightning overvoltage on a line travelling towards a transformer.

In transmission line theory voltage has two parameters; distance and time. Figure 2.1 shows lightning current travelling away from the point of impact. Equation 2.1 finds the magnitude of the resulting lightning overvoltage. This overvoltage will also have the same wave shape and it will travel in the same direction. Figure 2.3 shows a lightning overvoltage propagating towards a transformer. this will be the basis for this project's investigation, which is to find the risk of failure for the transformer with and without a surge arrester when a lightning overvoltage wave travel towards it. In normal circuit theory it is assumed that when a circuit is energised from a source at one end the other end of the circuit instantaneously experiences the voltage. This is not the case in transmission line theory, assume that at time = 0 the voltage at the location of the lightning impact on the line is 2MV. This is not instantaneously experienced at the transformer end. The travel time of the wave needs to be considered in transmission theory. Then after a small fraction of time the surge reaches the transformer. Since all equipment with windings look like an open circuit to a high frequency transient the lightning surge is reflected and it travels back toward the tower. Then it would reflect or refract at another point on the line where it experiences a change in impedance. It will keep on doing this until the line resistance causes it to attenuate or it finds a path to ground.

The voltages at different nodes on the system and with respect to time can be calculated through Equation 2.3, which is commonly known as the telegrapher's equation. The velocity of propagation would ideally be at the speed of light ($v = 150$ m/μs in cables) but in reality, it is slightly slower than that. Some common behaviour of the wave in terms of reflection or refraction are shone in Appendix 2 [50].

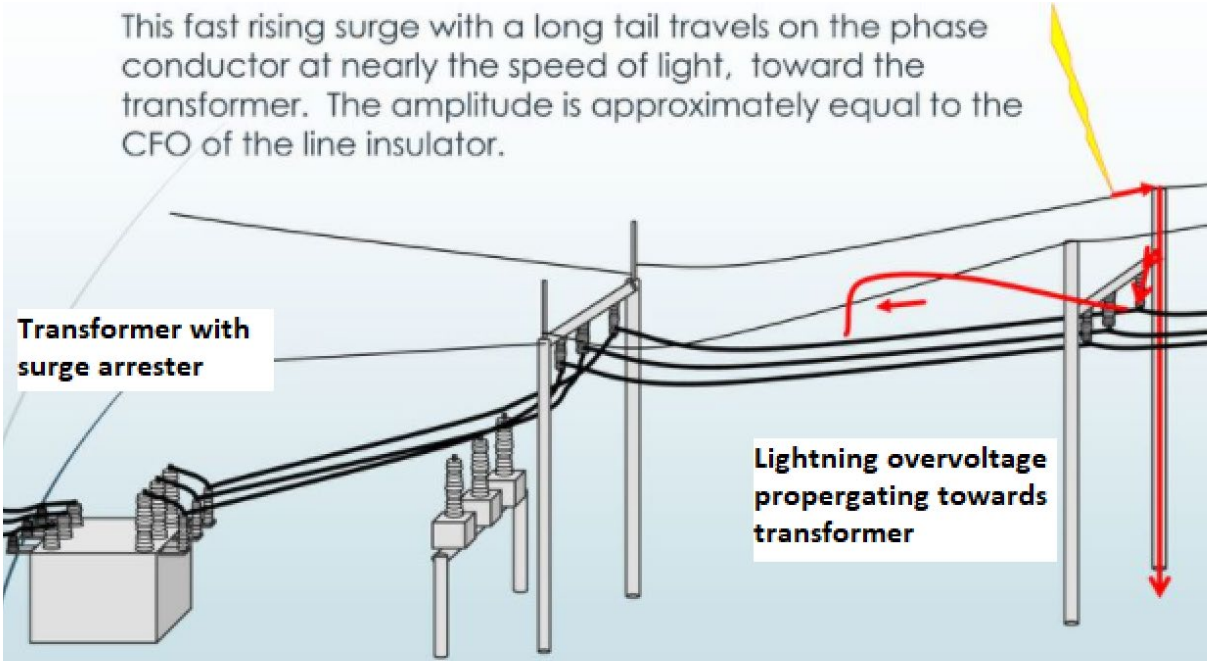


Figure 2.3: Illustration of a lightning overvoltage travveling towards a transformer [7].

$$
\begin{aligned}
u(x,t) &= f_1\left(t+\frac{x}{v}\right)+f_2\left(t-\frac{x}{v}\right)\\
i(x,t) &= -\frac{1}{Z_0}\left[f_1\left(t+\frac{x}{v}\right)-f_2\left(t-\frac{x}{v}\right)\right]
\end{aligned}
$$

Equation 2.3

2.3 How lightning causes a transformer to fail

Transient overvoltage generated by lightning strikes or switching operations represent a significant risk to bushings and windings of power transformers. They cause stress on the insulation system and can, over time, cause dielectric failure and damage to power transformers[8]. Many transformer failures are reported as dielectric failures and they are not necessarily linked to any particular event when they occur but may be the result of prior damage from transient overvoltage events. Lightning and switching overvoltage waveforms appearing at transformer terminals in real operating conditions may significantly differ from standard impulse voltage waveforms used during laboratory testing. The number and amplitudes of overvoltage which stress the insulation depend on various parameters such as the lightning current levels in the considered area, since it determines the amount of stress imposed on the transformer [8].

2.4 Surge Arrestor

An ideal surge arrestor protection device should maintain the system voltage to its nominal value, when an overvoltage condition arises. It should maintain the voltage being applied to the asset being protected within safe values. An arrest or works like a non-liner resistor or a varistor and it has a VI characteristics curve like the one in Figure 2.4.

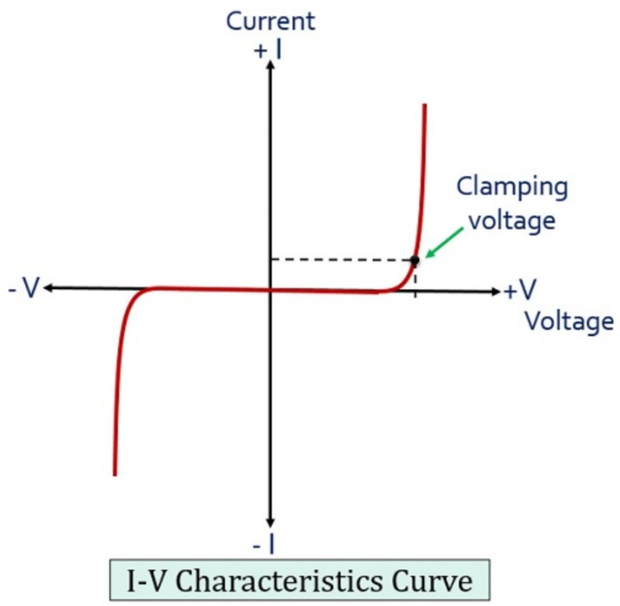


Figure 2.4 VI characteristics for a lightning arrestor [6]

Surge arrestors are used to protect power systems components from the damaging effects of lighting. They are mainly used to protect transformers, cables, transmission tower insulators, switchyard entry and exit, etc. There are a variety of types of lightning arrestors. This project will only focus on Metal surge arresters (MOSA) because they are the most popular, widely used type[9].

2.5 Probability functions.

2.5.1 Normal Distribution

The normal distribution is defined by the following probability density function, where μ is the population mean, σ is the standard deviation and σ^2 is the variance

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]}$$

If a random variable *X* follows the normal distribution, then we write:

$$X \sim N(\mu, \sigma^2)$$

In particular, the normal distribution with $\mu = 0$ and $\sigma = 1$ is called the *standard normal distribution*, and is denoted as $N(0,1)$. It can be graphed as follows:

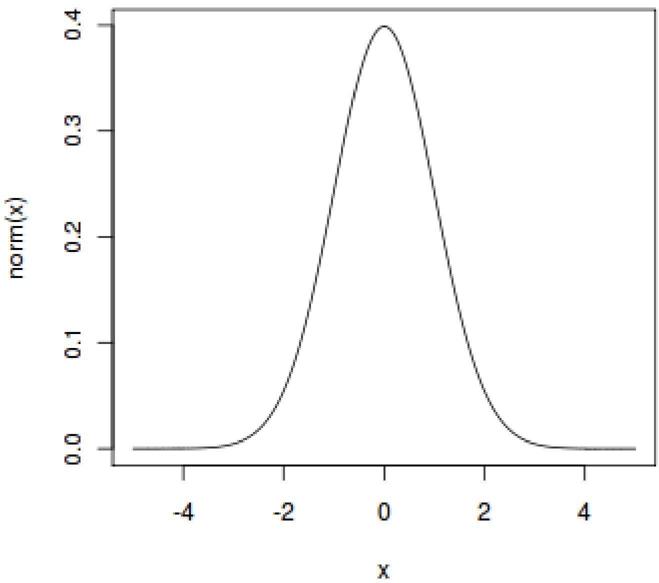


Figure 2.5the standard normal distribution [10]

The normal distribution is important because of the Central Limit Theorem, which states that the population of all possible samples of size *n* from a population with mean μ and variance σ^2 approaches a normal distribution with mean μ and σ^2/n when *n* approaches infinity.

2.5.2 Cumulative Distribution Function

The formula for the cumulative distribution function (CDF) of the standard normal distribution is

$$F(X) = \int_{-\infty}^{X} \frac{e^{-x^2/2}}{\sqrt{2\pi}}$$

Note that this integral does not exist in a simple closed formula [11]. It is computed numerically.

The following is the plot of the normal CDF [11].

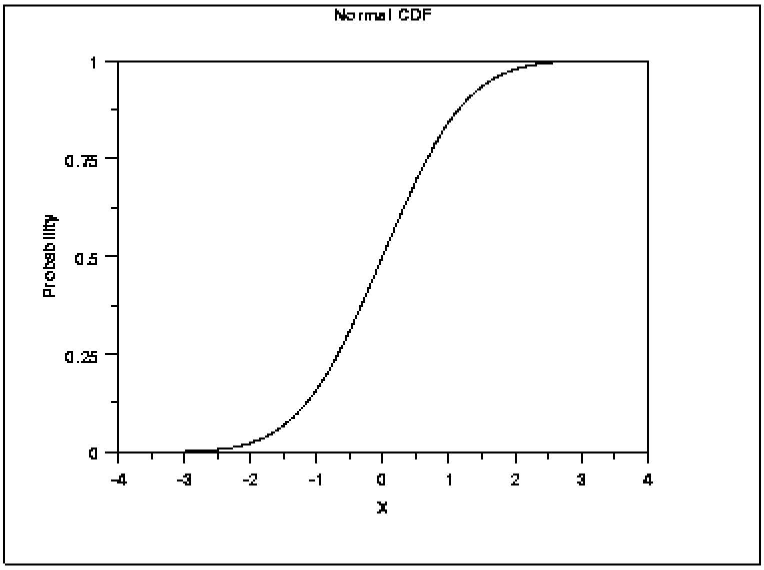


Figure 2.6: A plot of the normal cumulative distribution function (CDF)

2.5.3 Lognormal Distribution

A variable X is lognormally distributed if Y=ln(X) is normally distributed with "LN" denoting the natural logarithm [11]. The general formula for the probability density function (PDF) of the lognormal distribution is:

$$f(x) = \frac{e^{-\frac{\left(ln\frac{x-\theta}{m}\right)^2}{2\sigma^2}}}{(x-\theta)\sigma\sqrt{2\pi}} \qquad x > \theta; m, \sigma > 0$$

where σ is the shape parameter (and is the standard deviation of the log of the distribution), θ is the location parameter and m is the scale parameter (and is also the median of the distribution). If $x = \theta$, then $f(x) = 0$. The case where $\theta = 0$ and $m = 1$ is called the standard lognormal distribution. The case where θ equals zero is called the 2-parameter lognormal distribution.

The equation for the standard lognormal distribution is:

$$f(x) = \frac{e^{-\frac{(\ln x)^2}{2\sigma^2}}}{x\sigma\sqrt{2\pi}} \qquad x >; \sigma > 0$$

Since the general form of probability functions can be expressed in terms of the standard distribution, all subsequent formulas in this section are given for the standard form of the function [11].

Note that the lognormal distribution is commonly parameterized with μ=log(m)

The μ parameter is the mean of the log of the distribution. If the μ parameterization is used, the lognormal pdf is:

$$f(x) = \frac{e^{-\frac{(\ln(x-\theta)-\mu)^2}{2\sigma^2}}}{(x-\ \theta)\sigma\sqrt{2\pi}} \qquad x > 0; \sigma > 0$$

This is preferred because the *m* parameterization since *m* is an explicit scale parameter [11].

The following is the plot of the lognormal probability density function for four values of σ.

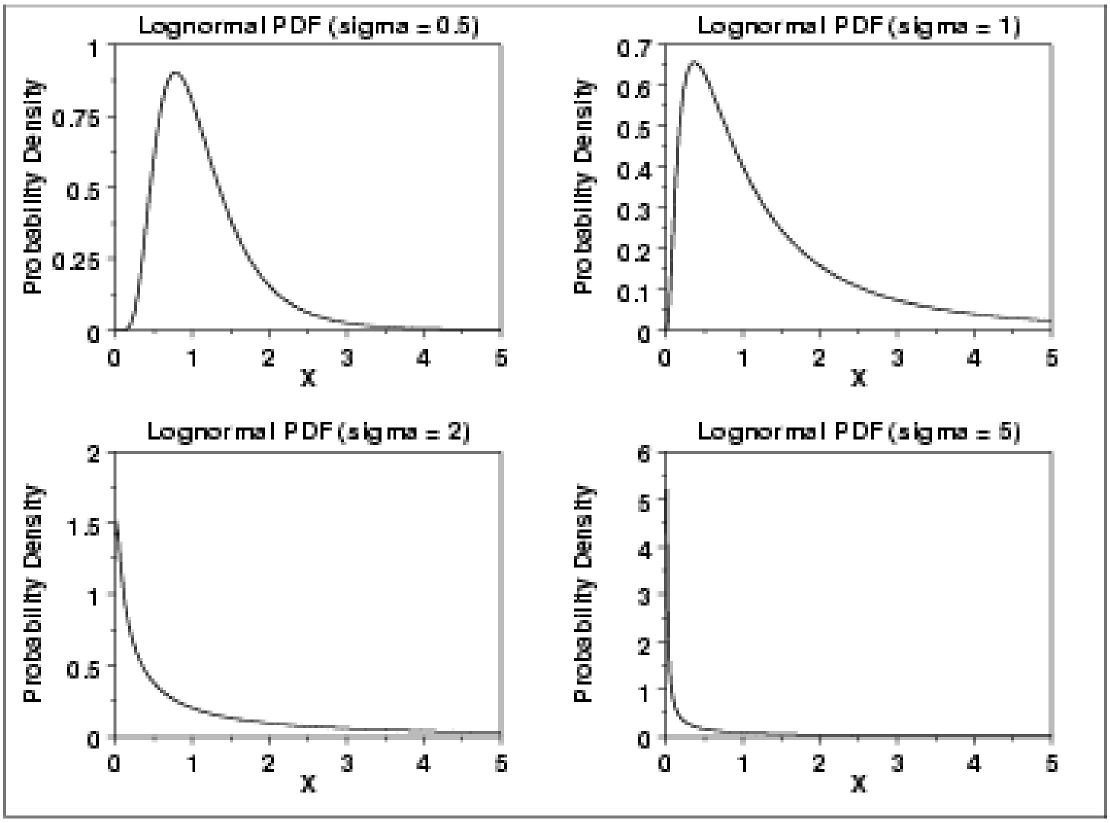


Figure 2.7: Log normal PDF for 4 values for σ

3 Risk analysis for a transformer with and without a surge arrester

This section covers the one of the objectives of the overall scope for this project whereby transient analysis is applied to two scenarios that have been faced by electrical consultants in the past. The first situation/scenario is covered in this section and the second will be covered in section 4. The first situation/scenario is as follows:

When a client wishes to install a privately-owned distribution transformer (for example a mining company), and the electrical engineering consultant advises the client to consider including a lightning arrestor for transformer protection, the most common question asked by the client would be regarding its cost and its benefits. This section aims to show the client the benefit of having a surge arrester through the evaluation of the risk of failure for one lightning event. The risk of failure for a transformer with and without a surge arrester will be found given the variety of lightning magnitudes which that particular site could experience.

The risk of failure for the transformer will be evaluated through probabilistic means. This chapter will cover the theory behind the analysis and will show its application through a case study. the risk of failure for the transformer will be found for a transformer with no surge arrester (Option A) and for the same transformer with a surge arrester (Option B). An illustration for the two options is shown in Figure 3.1.

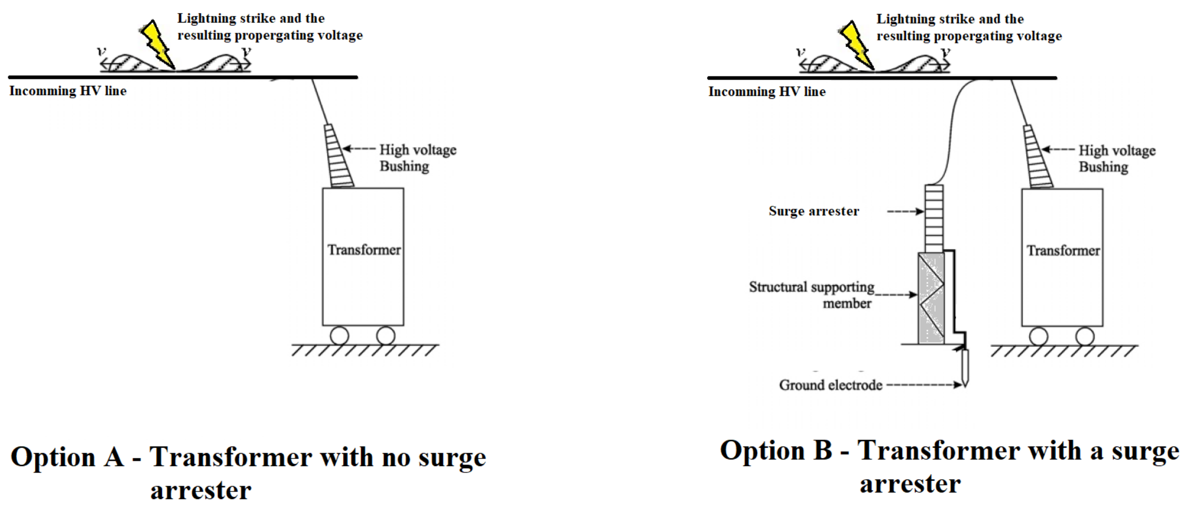


Figure 3.1: Illustration for the two options for the new transformer installation [12]

3.1 Finding the risk of failure for a transformer

With the overall goal in mind to show the benefit of including a lightning arrester to protect a transformer from lightning surges which could enter the substation through its overhead transmission line the risk of failure was found for an unprotected transformer and then the same was done for a transformer with a surge arrester (covered in section 3.3). The differences in the risk of failure should give a measure of the benefits of having a surge arrester. This section explains a statistical method that could be used to find the risk of failure for a transformer and sections 3.2 and 3.3 cover a case study to show its practical application on a transformer without a surge arrester (Option A) and for the same transformer, with a surge arrester (Option B).

3.1.1 Overview of the method for finding risk of failure

The overall methodology for finding the risk of failure for a transformer, can be seen in Figure 3.4 and its associated function in Equation 3.4 [4, 13-15]. The functions *f(V)* and *P(V)* need to be found in order to calculate the risk integral. These are the probability density of overvoltage occurrence and the probability distribution of insulation failure for the transformer. The method for obtaining each function is covered in the two subsequent sections 3.1.2 and 3.1.3.

The truncated version of the risk integral is in Equation 3.5. It removes low voltages that do not cause failure from the risk integral. The same goes for the upper end of the integral where the highest voltages have a very low probability of actualisation and thus these are also not included [4, 14]. The illustration for the risk integral functions shown in Figure 3.7 helps visualise the concept whereby when the two functions are multiplied together they form the small shaded curve in the middle and the integration finds the area for that small shaded curve.

The risk integral can be found for a single-phase circuit, whereby only one out of the three transformer bushings is analysed. This can be done because the this method is following the phase -peak method [14]. Since the equipment being analysed is a transformer, the insulation in the three phases are assumed of be the same. Therefore, the risk of R is only for a single-phase to ground, it needs to be extended to represent the other two phases. Equation 3.1 can be used [14, 16]

$$R_{Total} = 1 - \ (1 - R)^3$$

Equation 3.1

$$R = \int_{0}^{\infty} f(V) \times P(V)\, dV$$

Equation 3.2

$$R = \int_{Vp}^{Vf} f(V) \times P(V)\, dV$$

Equation 3.3

Where:

R risk of failure;

f(V) is a normal PDF function for probability of overvoltage at the transformer terminal.

P(V) is a normal CDF function for probability of insulation failure for the transformer

Vf $\mu_f + (3 * \sigma_f)$

Vp $\mu_P - (4 * \sigma_P)$

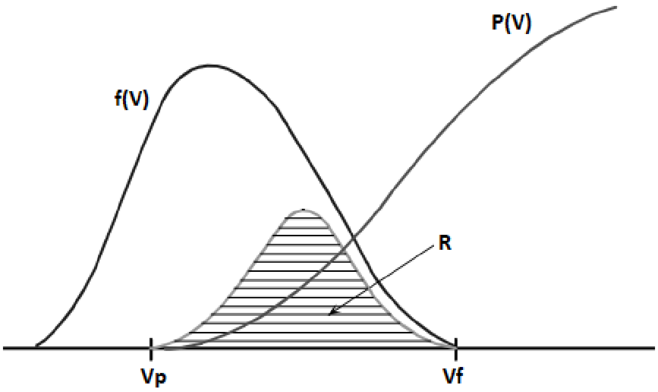


Figure 3.2: Illustration of the product of f(V) and P(V) this is the shaded curve between Vp and Vf and the risk integral finds the area for this product which is the area of the shaded region.

3.1.2 Finding the parameters for the CDF function *P(V)*

P(V) the probability for transformer insulation failure is represented by its cumulative distribution function (CDF) of for which the mean (μ_P) is the critical flashover voltage (CFO) for the transformer and its standard deviation (σ_P) is found through Equation 3.5. These two parameters need to be found in order to form the CDF P(V) which is shown in Equation 3.2. A simplified illustration of the CDF function P(V) is shown in Figure 3.3.

$$P(V) = \frac{1}{\sigma_P \sqrt{2\pi}} \int_{-\infty}^{V} e^{\left[-\frac{(V-\mu_P)^2}{2\sigma_P^2}\right]} dV$$

Equation 3.4

Where:

P(V) is the CDF of the normal probability function representing the probability of insulation failure of the transformer due to lightning overvoltage

μ_P is the mean value of the function P(V). It is also the CFO voltage of the transformer.

σ_P is the standard deviation of the CDF P(V)

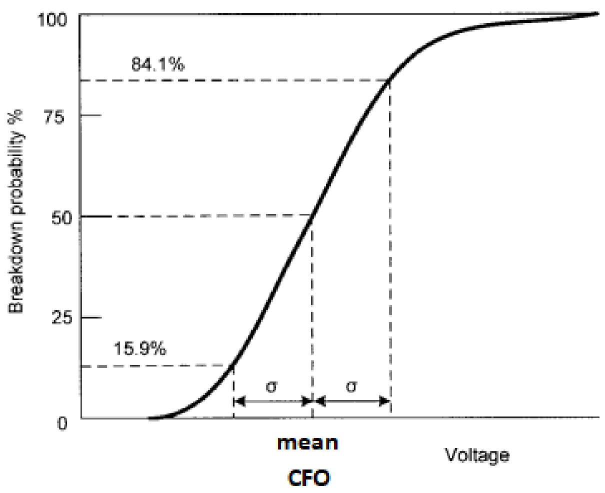


Figure 3.3: Illustration of CDF P(V)

3.1.2.1 Finding the values for the mean and the standard deviation for the normal CDF P(V)

First the BIL and the CFO insulation levels for the transformer need to be found, then Equation 3.5 is used to find the standard deviation. Explanations on the BIL and the CFO are covered below.

$$BIL = \left(1 - 1.28\ \frac{\boldsymbol{\sigma_P}}{\mu_P}\right)$$

Equation 3.5

Where:

BIL the basic impulse level of the transformer provided by the manufacturer
μ_P the CFO is the critical flashover voltage of the transformer, this is a standardized value depending on nominal voltage of the transformer
σ_P the standard deviation of the CFO *P(V)*

- **Basic lightning impulse insulation level (BIL).** Another term for this is the lightning impulse withstand voltage (LIWV)[17]. This may be expressed as conventional BIL or statistical BIL. The *conventional BIL* is the crest value of standardised lightning impulse applied between the terminal and ground for which the insulation does not exhibit disruptive discharge. This is normally done during factory tests using the standardised lightning waveform shown in Figure 2.2. The *statistical BIL* represents the insulation level of the transformer which can withstand a standard lightning impulse with a 10% probability of failure. This project uses the statistical BIL in finding the transformer risk of failure. It is the same as the same voltage as the *conventional BIL*.

- **Critical flashover voltage (CFO) -** The second insulation level which is of interest is the CFO. It represents a peak impulse voltage level that will cause a 50% probability of flashover or disruptive discharge. Transformer datasheets normally display the BIL value. The CFO value is not tested at the factory floor because it could cause a new transformer to fail, and it cannot be sold. For any given transformer there are standardised CFO values for its rated voltage on the HV and LV side and it could be easily accessed on line.

3.1.3 Finding the parameters for the PDF function *f(V)*

The next probability function that is required for risk integral to be evaluated is the statistical distribution of lightning overvoltage at the transformer bushing with respect to ground. This is the PDF *f(V)*. This could be done using transient analysis software like PSCAD. A model is implemented in the software for the system around the transformer and many runs are made (many simulations) each with a randomised lightning current levels injected into the system. For each run the highest voltage at the transformer terminal (phase to ground) recorded. The collected data is assumed to have a normal distribution [4, 15, 17, 18]. This normal distribution is the PDF *f(V)* and it can be expressed as in Equation 3.3. The mean and standard deviation for the equation are from the data accumulated from the many simulation runs.

$$f(V) = \frac{1}{\sigma_f \sqrt{2\pi}} \; e^{\left[-\frac{(V-\mu_f)^2}{2\,\sigma_f^{2}}\right]}$$

Equation 3.6

Where:

f(V) is the probability density function (PDF) of the data accumulated from the multiple runs of the transient analysis software. The data was for the peak voltages experienced at the transformer terminal.

σ_f is the standard deviation of the total data collected through simulations for overvoltage at each node of interest.

μ_f is the mean of the data collected through simulations for overvoltage at each node of interest.

The lighting parameters that are normally varied to give a wide variety of lightning impulse current are shown in table 3.4 [19]. The values in the table were assumed by the authors of [19] to suit a study in Japan. The average values and standard deviation would need to suit the meteorological data for lighting at the location of the transformer of interest. This table shows that the lightning current imposed on the simulation model covers a wide range of lightning current types, which has the overall aim of mimicking the actual lighting currents that could be experienced by the system

Table 3.1: Distributions for lightning current parameters for a case study done by [19].

Lightning impulse waveform parameter	**Probability Distribution**	**Average Values**	**Standard Deviation**
Peak value	Log -normal distribution	26KA	0.33
Front steepness	Log -normal distribution	24kA/µs	0.255
Front duration	Log -normal distribution	1.08µs	0.209
Tail Duration	Log -normal distribution	70µs	0.372

3.1.4 Summary for risk of transformer failure methodology

The method needs statistical data for the area concerned. This data would be used in the simulations in the transient analysis software. The results of the simulations provide a means to obtain the probability function (PDF *f(V)*) for the possible lightning overvoltage levels that the transformer could experience.

The method also needs to form the CDF *P(V)* which is the probability function for the probability of failure of the transformer's insulation. To form this, function the BIL and the CFO for the transformer are needed. Using these two values the standard deviation for the function P(V) can be found. The mean for the function is simply the CFO value.

When these two functions are obtained then the risk integral can be evaluated. The truncated version of the integral uses the mean and standard deviations for the functions f(V) and P(V) as seen in Equation 3.3

Risk of failure also aids in identifying if a transformer design has sufficient insulation withstand capability and thus a higher quality transformer could be bought or a suitable surge arrester could be used. The overall idea behind for this could be seen in Figure 3.5. Where the overall reduction in the risk of failure is achieved by increasing the insulation strength. This could be done by providing surge arrester protection or replacing the equipment with a version that has a higher insulation withstand capability[20].

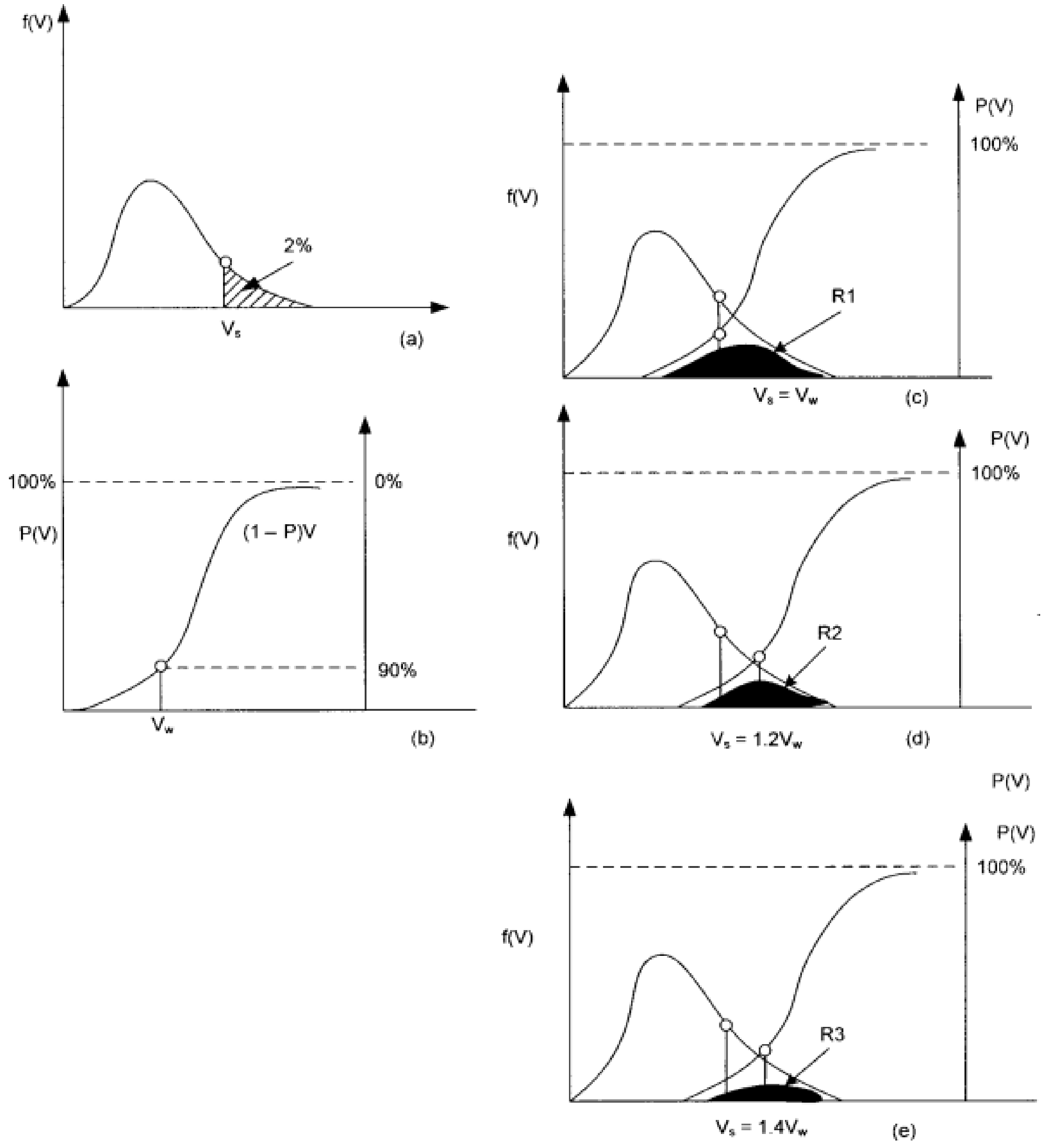


Figure 3.4: An illustration to highlight how risk of failure determination could help in the design process. (a) Overvoltage and (b) insulation strength probability functions. (c), (d), and (e) Reduction of risk of failure factor by increasing insulation strength [4].

3.2 A case study for finding the risk of failure for a transformer without a surge arrester (Option A)

This study assumed that the client already had a transformer and was in the process of deciding whether to install a surge arrester. The simulations were done in PSCAD (free version) and the model created was single phase. There were 7 steps in this study, and they are highlighted in Table 3.5 and the subsections below cover each step

Table 3.2: The actions carried out to find the risk of

Steps	Actions carried out
1	Identify the transformer ratings for this study
2	Selection of transient analysis software.
3	Model the transformer and the system in single phase
4	Set up the lightning parameters as per Table 3.4 using the multirun feature of the system
5	Run the simulation and obtain the mean and standard deviation of the data
6	Use the results from step 5 and transformer BIL and CFO to formulate the functions for *P(V)*, *f(V)* and *R* Equation 3.6 Equation 3.5 Equation 3.4 Equation 3.3
7	Find the risk of failure using Wolfram Alpha an online mathematical calculator. Finally apply Equation 3.1 to get the overall risk of failure for the transformer.

3.2.1 Identify the transformer ratings for this study

For this case study the data in Table 3.6 were assumed. A single-phase representation of the transformer was modelled for

Table 3.3: Transformer Ratings for a 138/13.2kV substation transformer [21]

Power ratings	
Cooling Class	ONAN/ONAF/ONAF
Temp Rise over 40˚C	55˚C
Continuous 55˚C ONAN/ONAF/ONAF Rating	22/26.67/33.33 MVA
Continuous 65˚C ONAN/ONAF/ONAF Rating	22.4/29.87/37.33 MVA
Primary winding ratings:	
Nominal Primary Line Voltage	138kV Single phase = 79.6kV
Maximum Primary Line Voltage	145kV
Primary Winding Connection	Delta
Primary Winding BIL	650kV
Primary Winding Conductor Material	Copper
Secondary winding ratings:	
Nominal Secondary Line Voltage	13.2kV Single phase = 7.62kV
Secondary Winding Connection	Solidly Grounded Wye
Secondary Winding BIL	110kV
Secondary Winding Conductor Material	Copper

3.2.2 Selection of transient analysis software

The positive and negative points were identified for the three transient analysis software that could be used to carry out simulations for this project.

- MATLAB
- EMTP
- PSCAD

Even though EMTP is the most ideal software for transient analysis it did not have a free version. MATLAB would prove challenging since it was not a specialised software for transient analysis and thus there are not many examples and existing models online to help in this project. The best option was PSCAD. There is a free version of this software and there are numerous examples and tutorials available online. Although it has some limitations on the size of projects built and some limitations on model types, it is still usable for this project. Furthermore, it provides its latest version as the free version and thus is a means for a user to learn and practice transient analysis.

3.2.3 Modelling the transformer and a generic system with a source and a load in single phase.

A strategic approach was used to obtain the PSCAD model. An existing model was found and modified to suit the purposes for this project. This idea for modelling was attained from [22]. This approach is quicker for getting results and it allows a user to refer back to the original model when modification results go wrong. A model was found in the PSCAD library that was suitable for this project. The model was modified and unnecessary components were removed. In transient analysis a transformer essentially is an open circuit, because the transformer reactance ($X_L = 2\pi fL$) is very high because the lightning surge has very high frequency. Therefore, the transformer is modelled using its leakage capacitance. The leakage capacitor size was obtained from [16] and is shown in the modified model in Figure 3.8. The model shows a single-phase representation of the transformer data from Table 3.6, along with a single-phase source and load. It also shows the lightning current injection point into the circuit. A multi run block was added to this model and that is covered in section 3.2.4 and in section 3.3.1.2 a surge arrester is added to this model.

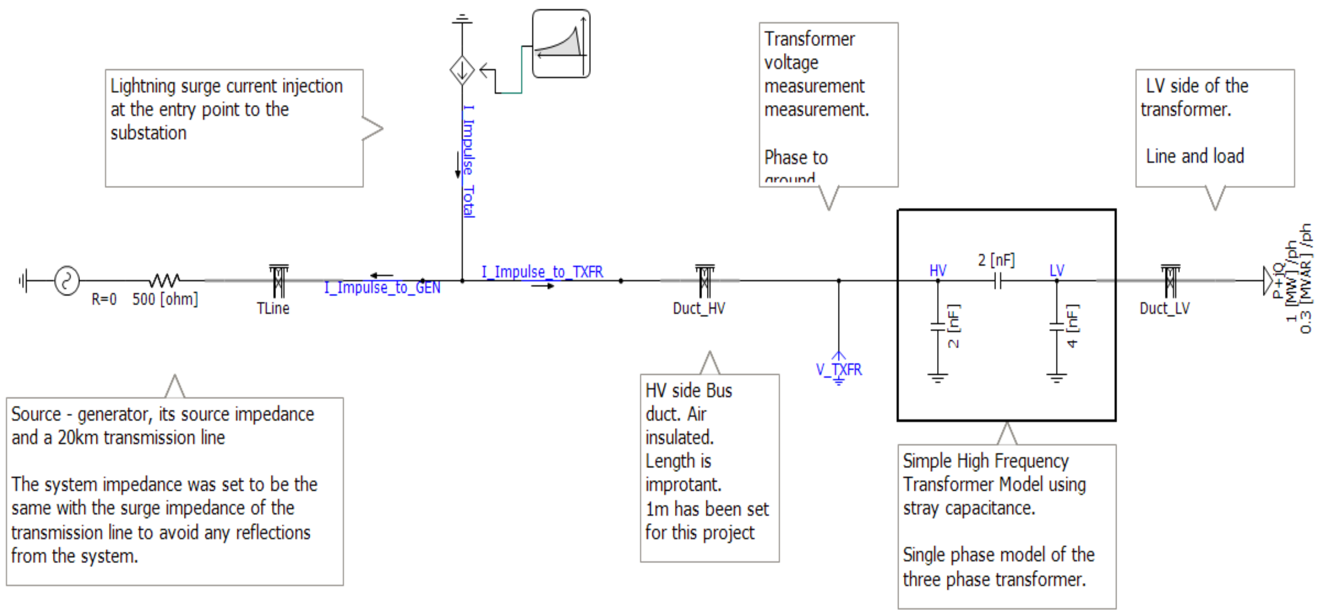
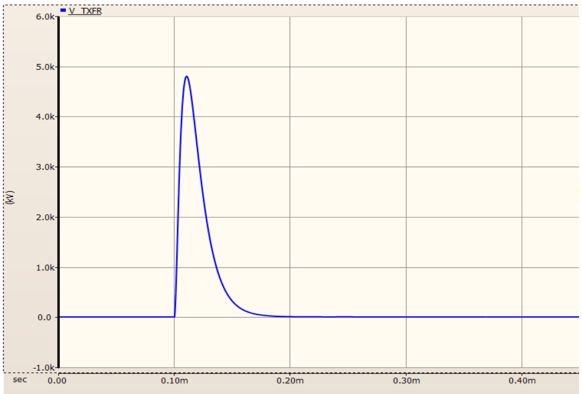


Figure 3.5: PSCAD model used for this case study.

3.2.4 Testing the model

The model in Figure 3.8 was simulated with a 10kA lightning discharge onto the line and Figure 3.9 shows the voltage level experienced at the transformer and the current distribution in the circuit. The voltage level at the transformer reached a peak value of 4.8MV (reasonable value according to [23, 24]) whereas the nominal phase to ground voltage was only 79.6kV which means a 10kA lightning surge, results in an overvoltage of 60 times the nominal voltage This is 7 times the BIL rating and 6 times the CFO rating (CFO value of 805kV [4, 23]). This are the types of voltage levels the transformer experiences when it is without a surge arrester. A key observation was that in theory, the surge current is supposed divided equally upon impacting the line and each travel away from the point of impact[16]. But the current plot shows the blue surge waveform which represents the current surge that went towards the transformer was lower than the current surge going towards the generator (brown waveform). This is because the transformer essentially acts as an open circuit and thus it has a higher impedance path to ground compared to the path provided on the generator side.



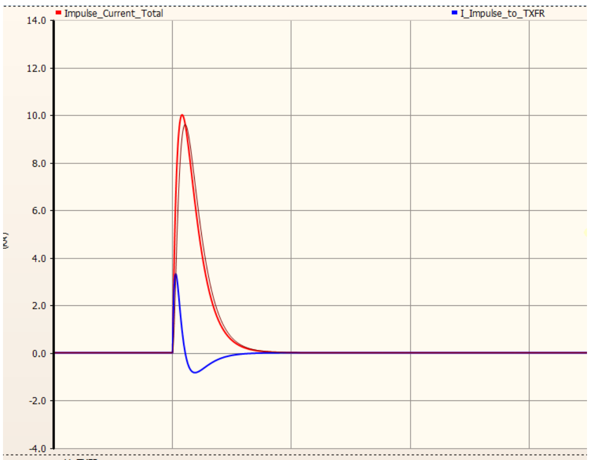


Figure 3.6: A simulation result from the model in Figure 3.8 showing the magnitude of the impulse voltage seen at the transformer terminals (crest value – 4.8MV) and the current plots for the injected lightning surge (10kA).

3.2.5 Setting up a multi-run block in the simulation

The multi run feature in PSCAD allows a set of signals from the model to be varied randomly for as many runs as required and it records the voltage or current at chosen nodes for each run. It then outputs a data file containing all the recorded values and a mean and variance for each data set. The results from this multi run feature would provide the mean and variance needed for the probability function f(V) (Equation 3.2).

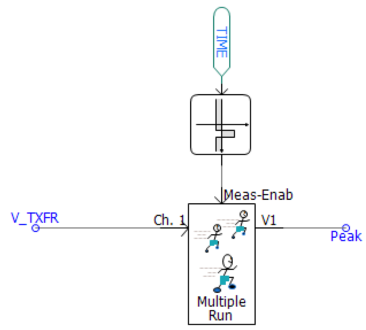


Figure 3.7 The multirun block in PSCAD which can be used for implementing Monte Carlo statistical analysis

The parameters that needed to be varied randomly according to its respective probability distribution are shown in Table 3.4. The values for those parameters need to suit the location for the substation being studied. The parameters were for lightning current peak, rise time, tail time, and rate of rise. When trying to input these parameters into the simulation block for lightning current generator, it was seen that (shown in Figure 3.10) only the peak current was allowed to be varied in the free version of PSCAD. The other parameters that needed to be changing for each simulation were set as constants by default.

One way to get around this is to generate a random number file according to the probability curves (log-normal) for each wave parameter in another software like MATLAB and then use that file in PSCAD.

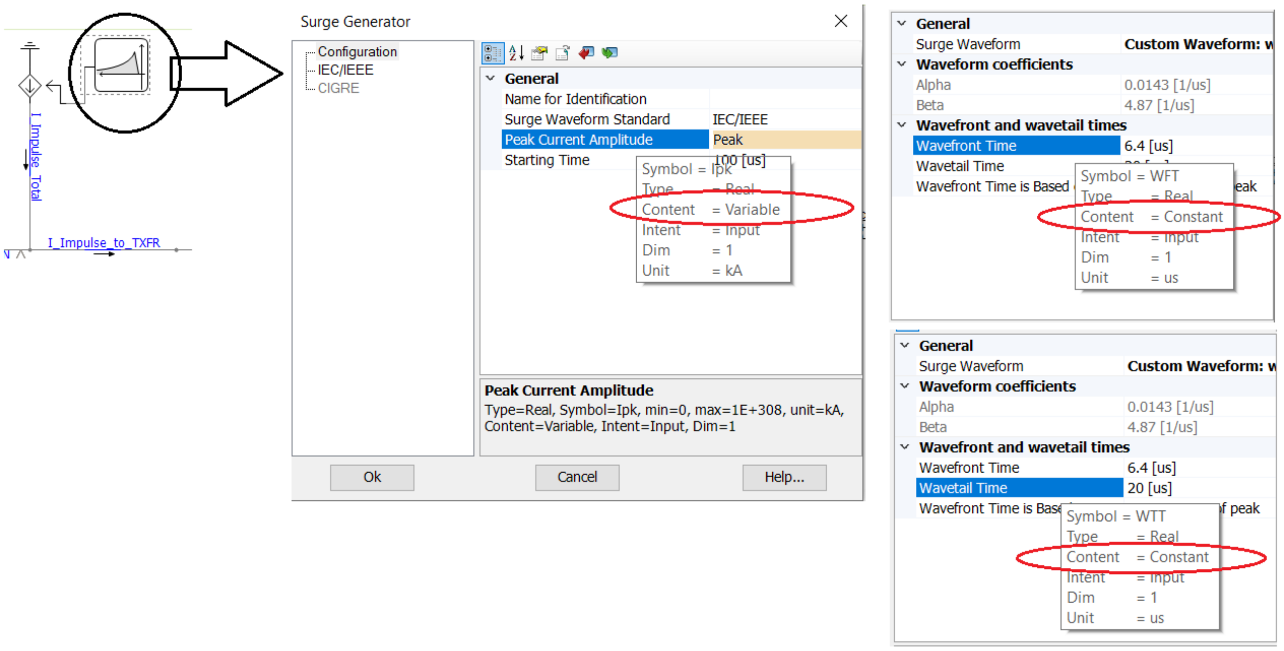


Figure 3.8: the lightning input parameter block is able to take in random variables for peak current only. It is not able to do the same for wavefront time, wave tail time and rate of rise.

However, this project only considered one varying lightning parameter in its multi run simulations. This was the peak current value if the lightning impulse current. The probability distribution for the variable peak current had a mean of 39kA and a standard deviation of 20.4A. The waveform for the probability distribution for the input current peaks is shown in Figure 3.9.

The multirun the simulations for Option B (risk analysis for a transformer with a surge arrester) was also subjected to the same range of peak lightning currents (mean of 41kA and standard deviation of 19kA).

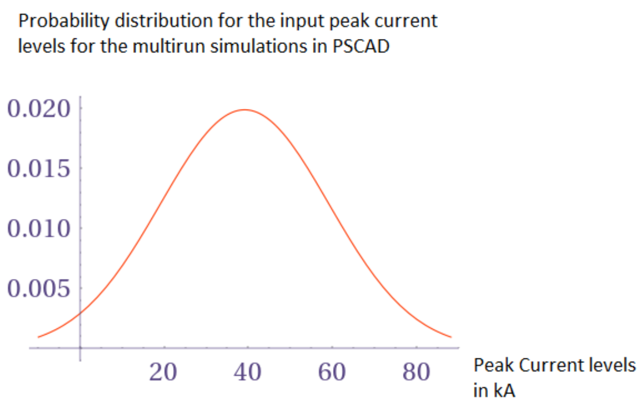


Figure 3.9: Probability distribution for the input current with varying peaks that were implemented in PSCAD in the multirun simulations.

3.2.6 Results from the multi run simulations

A total of 100 runs was implemented in the multirun simulation and the results are shown in Figure 3.10. The parameters of interest were the transformer voltage mean (18.8MV) and the transformer voltage standard deviation (9.8MV). These parameters were then used for form the PDF, *f(V)*.

Statistical Summary Based on 100 Runs:

	Peak_Surge	V_TXFR
Minimum:	2.070773413	993.5040143
Maximum:	79.58679458	38183.64869
Mean:	39.21300359	18813.36748
Std Dev:	20.40471362	9789.643999
2% Level:	-2.693155397	-1292.103517
98% Level:	81.11916257	38918.83848

Figure 3.10: The multirun simulation results from Simulink for a transformer without a surge arrester. The peak lightning current inputs and the transformer terminal voltages are in kilo Amps and kilo Volts respectively.

3.2.7 Setting up the risk of failure function parameters

The mean and standard deviation for the peak voltages recorded at the transformer terminals when different lightning current magnitudes were being impressed on the PSCAD model gives a gaussian distribution for the voltage levels that could be expected at the transformer terminals due to lightning surges. The normal function f(V) represents the probability density function for the expected voltages at the transformer terminals due to lightning surges, and thus the mean and standard deviation obtained from the PSCAD multi run simulation are used as the parameters for f(V). the overall process of finding the risk of failure for the transformer uses the function f(V) in its calculations. The overall collection of functions and its different parameters are shown in Table 3.7

Table 3.4: The values for function parameters that contribute towards finding the risk of failure for the transformer without a surge arrester.

Equation reference	**Functions used for obtaining risk of failure**	**Parameters for each function**
Equation 3.5	$BIL = \left(1 - 1.28\,\frac{\boldsymbol{\sigma_P}}{\mu_P}\right)$	**BIL=650kV** (from Table 3.6 highlighted green) **μ_P = 805kV** (from [4, 23]). **σ_P = 121kV**
Equation 3.4	$P(V) = \frac{1}{\sigma_P\sqrt{2\pi}} \int_{-\infty}^{V} e^{\left[-\frac{(V-\mu_P)^2}{2\,\sigma_P{}^2}\right]}\,dV$	**μ_P = CFO = 805kV** **σ_P = 121kV**
Equation 3.6	$f(V) = \frac{1}{\sigma_f\sqrt{2\pi}}\, e^{\left[-\frac{(V-\mu_f)^2}{2\,\sigma_f{}^2}\right]}$	**μ_f = 18.8MV** (from Figure 3.10) **σ_f = 9.8MV (**from Figure 3.10)
Equation 3.3	$R = \int_{Vp}^{Vf} f(V)\times P(V)\,dV$ Vf = μ_f + (3 * $\boldsymbol{\sigma_f}$**)** Vp = μ_P - (4 * σ_P)	**Vf = 48.2MV** **Vp = 321kV**

3.2.8 risk of failure using Wolfram Alpha an online mathematical calculator.

The risk integral function (Equation 3.13) was calculated using a powerful online calculator, Wolfram Alpha. The results from the calculations are shown in Figure 3.15.

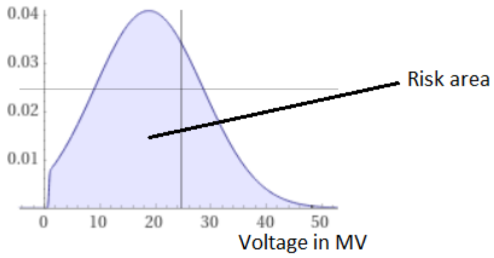
Input	$\int_{0.321}^{48.2} \left(\frac{1}{9.789* \sqrt{2*pi}} \exp\left(-\frac{(v - 18.813)^2}{2*(9.789)^2} \right) \right) * \left(\frac{1}{0.121\sqrt{2*pi}} \int_{0}^{v} \exp\left(-\frac{(v - 0.805)^2}{2*(0.121)^2} \right) d\,v \right) d\,v$
Output	$\int_{0.321}^{48.2} 0.134368\, e^{-0.00521787\,(-18.813+v)^2} (0.151651 - 0.151651\, \mathrm{erf}(4.70431 - 5.84386\, v))\, d\,v \approx \boxed{0.965736475\ldots}$
Plot of area representing risk	

Figure 3.11: Results for risk integral calculation using Wolfram Alpha.

The overall risk of failure for the three-phase transformer was found from Equation 3.14 and thus the risk of failure due to lightning is very high (0.9999) as shown below. This a very high probability of failure and indicates that the transformer is highly likely to be damaged by a lightning surge. This result can be compared to the risk of failure obtained for the same simulation current inputs, same transformer, same model except a surge arrester is included to protect the transformer 3.3.1.2.1

$$R_{Total} = 1 - (1 - R)^3$$

$$R_{Total} = 0.9999$$

3.3 Transformer installed with a surge arrester (Option B)

The previous section showed the risk of failure for a transformer without a surge arrester. This section includes a surge arrester in the simulation in Figure 3.1. The same analysis is carried out to find the risk of failure for the transformer. Since the theory for the overall method has already been covered in sections 3.1, this section will cover how the surge arrester was selected, the important ratings that need to be considered and how it was modelled in PSCAD.

3.3.1 Selecting and modelling a surge arrester.

A surge arrester must be able to withstand the maximum continuous power-frequency voltage (MCOV) for the system it will be installed in. It must discharge any transient energy from the system and reduce lighting overvoltage levels at its terminations. It must operate in the same environment as the protected equipment[25]. Surge arresters are normally connected between phase and ground and thus most of the ratings associated with surge arresters are scaled versions of the system phase to ground voltage. Metal oxide surge arresters (MOSA) are the most common surge arresters now. Ausgrid network standards require all its surge arresters to be of this type [9]. A MOSA arrester has a series of metal oxide varistor blocks. These blocks are like a voltage-controlled switch, which acts as an insulator under nominal conditions. Once the voltage across the arrester rises above the reference voltage of the arrester, the blocks go into conduction mode. Since the blocks are highly non-linear, once the voltage drops below the reference voltage, the conduction ends [25]. However, there are always some form of leakage current, but it is negligible [16].

3.3.1.1 Selection of surge arrester

The selection of a surge arrester for this project follows a procedure highlighted in [26]. The surge arrester selected is shown in Appendix 3 [40].

There are two main steps involved.

1. Find the maximum continuous operating voltage (MCOV) for the surge arrester and the discharge voltage (also known as the pinch off voltage of residual voltage).
2. Find the temporary overvoltage (TOV) and the energy class

Figure 3.16 shows an overview of the voltage levels related to step 1. Step 2 will not be investigated further because the lightning-based overvoltage study in this report, does not assess TOV however the energy class for the surge arrester is assumed to be of station class low (SL) with a rating of 3kJ/kV.

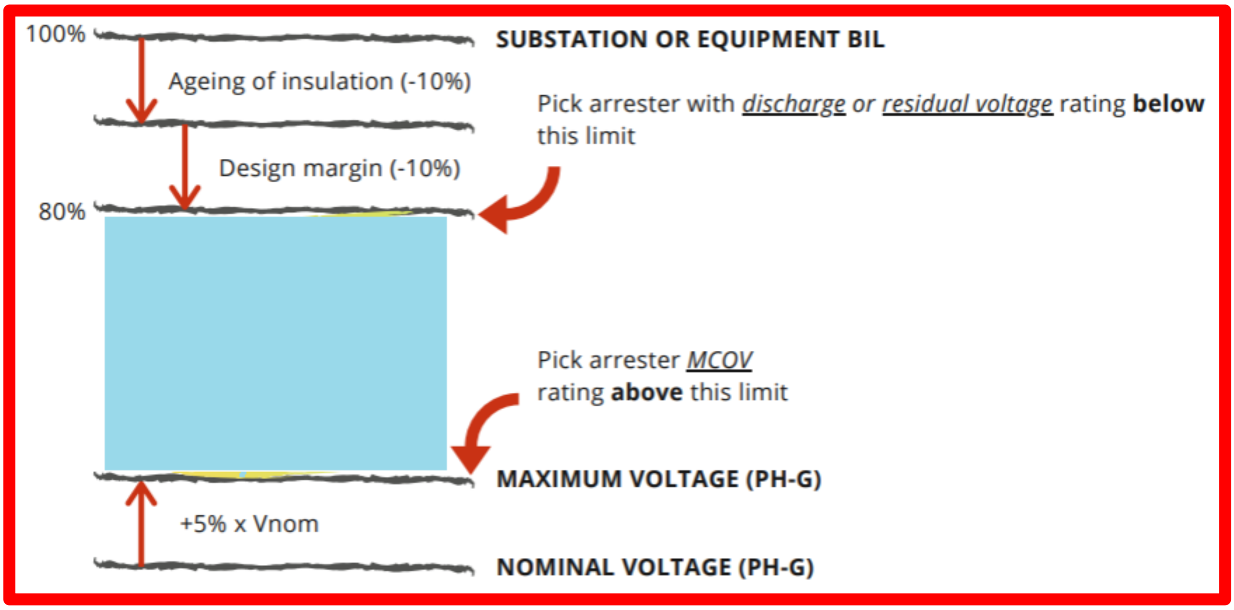


Figure 3.12: A generalised way of selecting a surge arrester for a given voltage system [27]

- The nominal voltage for the case study was 138kV$_{L-L}$, and assuming low grounding impedance.
- 138 kV L-L multi-grounded application with 5% voltage regulation.

  - **MCOV Calculations**
  - Maximum voltage (PH-PH): 138 x 1.05 = 145kV
  - Maximum voltage (PH - G): 145/Sqrt(3) = 84kV
  - Choose MCOV >= 84kV
  - **Discharge voltage calculations**
  - Removing 20% from 650 yields - 520kV BIL
  - Choose discharge voltage <= 520kV
  - Using table, an adequate arrester has
  - 98kV MCOV and 291kV discharge voltage @10kA this is shown in Appendix 3 [40]
  - **Protection Margin**
  - 55.38% which is greater than the standardised minimum value of 25%. Equation 3.7 was used to obtain the protection margin.

$$PM\,\% = \frac{BIL(transforemr) - Residual\,Voltage(surge\ arrester)}{BIL(transformer)} \times 100$$

3.7 [25]

Where:

PM is the protective margin.

3.3.1.2 Modelling the surge arrester in PSCAD

A PSCAD documentation on how to model a high frequency model of a surge arrester was used for this project [28], the model used follows IEEE high frequency model [29]. A comparison of a simple surge arrester model and a fast front model is shown in Figure 3.13 to show the extra components needed for the fast front model.

The procedure identifies the values for resistances, inductances, capacitance (R0, R1, L0, L1, and C) and the V-I characteristics of the individual arresters A0 and A1, so that the overall performance of the high frequency model is as close as possible to the real surge arrester being modelled. The V-I characteristics for the non-linear resistance's A0 and A1 were obtained from a surge arrester model of similar residual voltage levels even though the procedure provided a table for recommended p.u. values. This was done because previous test simulation runs were not producing expected results. The values for L0, R0, L1, R1 and C, were obtained through a set of equations that was provided in the document. These are shown below:

L1 = 15 d/n μH   Lo = 0.2 d/n μH   C = 100 n/d pF

R1 = 65 d/n Ω   Ro = 100 d/n Ω

Where:

d estimated height of the arrester in metres (use the overall dimension from the catalogue data).

n number of parallel columns of metal oxide in the arrester.

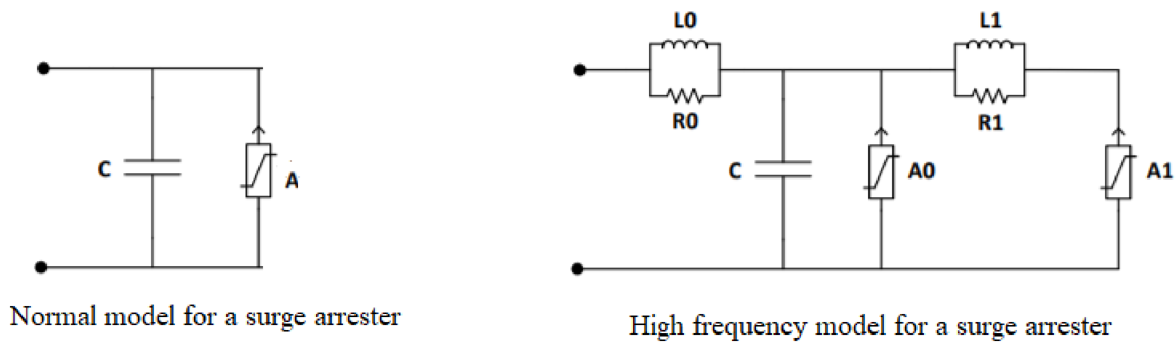


Figure 3.13: High frequency model for a surge arrester and a normal surge arrester model

The model was tested by injecting standardised lightning impulses akin to the tests done to the actual surge arrester on a factory floor to show that its discharge voltage was close to the datasheet value. The simulation schematic is shown in Figure 3.18 ,the resulting plots are shown in Figure 3.19 and the results for peak discharge voltages from the model in comparison with the surge arrester ratings selected for this case study are shown in Table 3.8. The tabulated results indicate that the model comes very close to mirroring the performance of the real surge arrester.

The complete model was then implemented in the simulation for a transformer without a surge arrester which was covered in section 3.2.2.2.3 (Figure 3.9). The complete model for transformer with the surge arrester, modelled as a single-phase system is shown in Figure 3.17

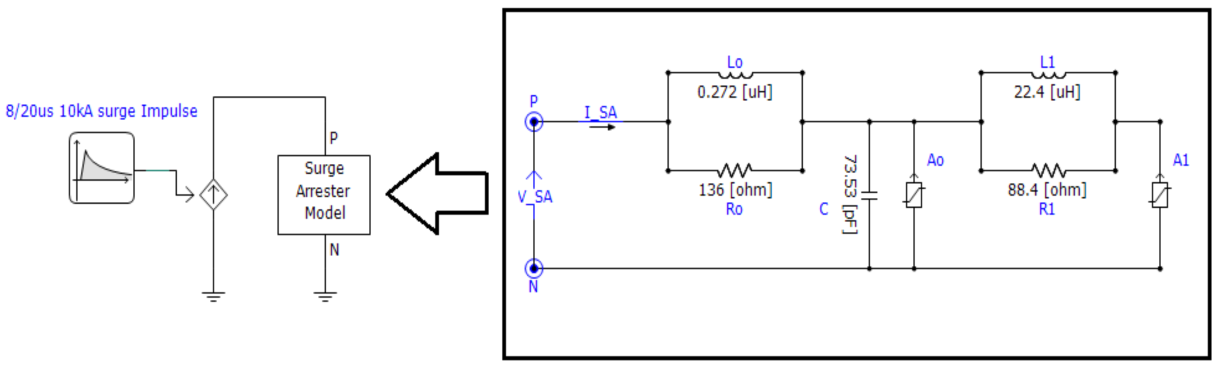


Figure 3.14 Frequency dependent surge arrester showing the values for the circuit components

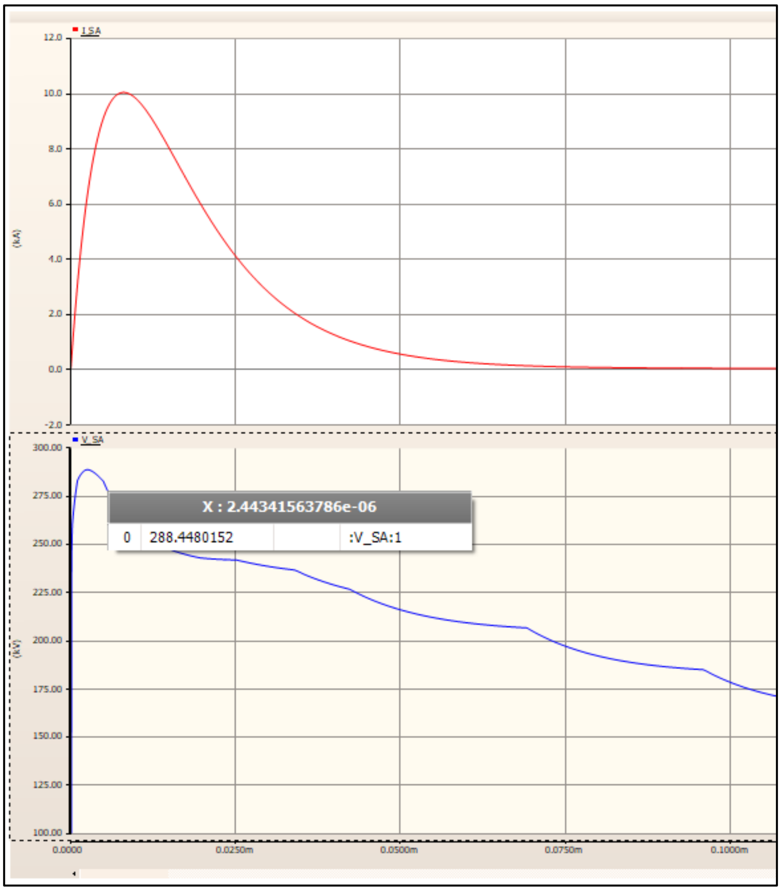


Figure 3.15: PSCAD surge arrester model test results

Table 3.5 Surge arrester discharge voltage comparison between the manufacturer and the model ratings

Current Wave shape	Current Magnitude	Discharge Voltage	
		Manufacture	PSCAD/EMTDC Model
8/20 µs	10kA	291kV	288kV

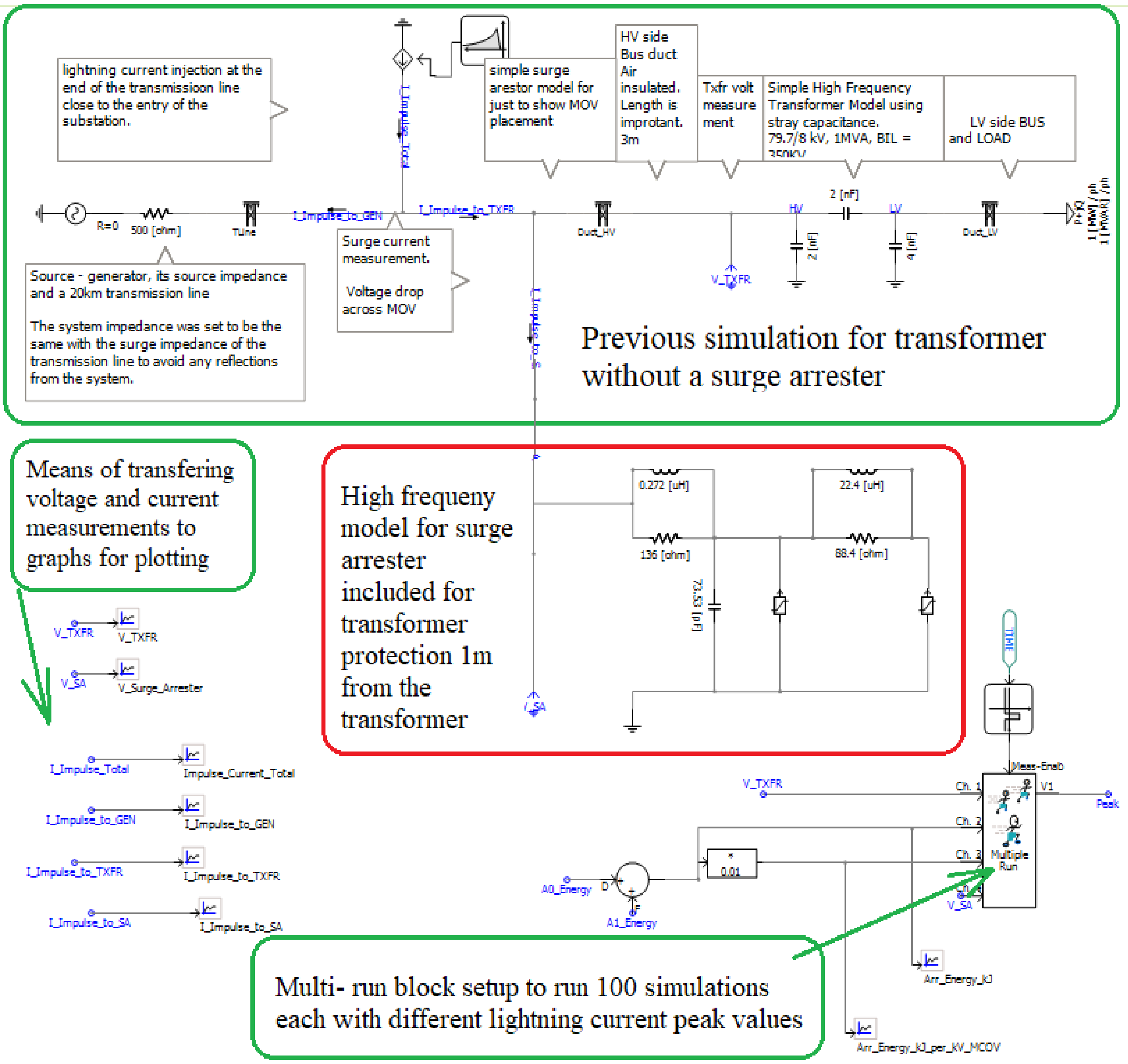


Figure 3.16: This was the simulation model created in PSCAD for obtaining the multirun simulation data needed for forming the PDF f(V).

3.3.1.3 *Evaluating the risk of failure for the transformer with surge arrester protection*

The following analysis for ascertaining risk integral for a transformer with a surge arrester, follows the steps previously carried in Option A (sections 3.2.6, 3.2.7, and 3.2.8). The results from the multi-run simulations in PSCAD are shown in Figure 3.17. The voltages at the transformer terminals had a mean of 377kV and a standard deviation of 44kV. These are normal distribution parameters and were used as parameters for the function f(V). This function and its parameters are shown in Table 3.6 along with the parameters for other functions used in the risk calculation. With all the function parameters identified the online calculator Wolfram Alpha was used to find the risk integral. The overall results for the two options are discussed in section 3.4

Statistical Summary Based on 100 Runs:

	Peak_Surge	V_TXFR	Arr_Energy_kJ	Arr_Energy_kJ_p	V_SA
Minimum:	1.744931829	238.4202893	4.785882786	0.4785882786E-01	237.6585489
Maximum:	79.37263330	446.7050680	554.0190886	5.540190886	441.9926314
Mean:	41.00682093	377.1005176	261.9147092	2.619147092	353.5719634
Std Dev:	19.01351252	44.99997503	134.7981821	1.347981821	43.98658882
2% Level:	1.957839731	284.6818665	-14.92691461	-.1492691461	263.2345532
98% Level:	80.05580214	469.5191686	538.7563331	5.387563331	443.9093736

Figure 3.17: The multirun simulation results from Simulink for a transformer without a surge arrester. The peak lightning current inputs and the transformer terminal voltages are in kilo Amps and kilo Volts respectively.

Table 3.6: The values for function parameters that contribute towards finding the risk of failure for the transformer with a surge arrester.

Equation reference	**Functions used for obtaining risk of failure**	**Parameters for each function**
Equation 3.9	$BIL = \left(1 - 1.28\ \frac{\boldsymbol{\sigma_P}}{\mu_P}\right)$	**BIL=650kV** (from Table 3.6 highlighted green) **μ_P = 805kV** = CFO (from [4, 23]). **σ_P = 121kV**
Equation 3.10	$P(V) = \frac{1}{\sigma_P\ \sqrt{2\pi}} \int_{-\infty}^{V} e^{\left[-\ \frac{(V-\ \mu_P)^2}{2\ \sigma_P{}^2}\right]}\ dV$	**μ_P = CFO = 805kV** **σ_P = 121kV**
Equation 3.11	$f(V) = \frac{1}{\sigma_f\ \sqrt{2\pi}}\ e^{\left[-\ \frac{\left(V-\ \mu_f\right)^2}{2\ \sigma_f{}^2}\right]}$	**μ_f = 377kV** (from Figure 3.14) **σ_f = 45kV (**from Figure 3.14)
Equation 3.13	$R = \int_{Vp}^{Vf} f(V)\ \times\ P(V)\ dV$ Vf = μ_f + (3 * $\boldsymbol{\sigma_f}$**)** Vp = μ_P - (4 * σ_P)	**Vf = 48.2MV** **Vp = 321kV**

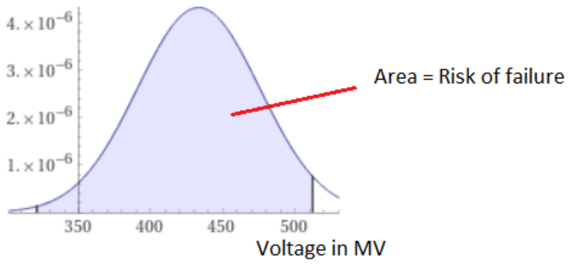
Input	$\int_{321}^{512} \left(\frac{1}{45\sqrt{2*pi}} \exp\left(-\frac{(v-377)^2}{2*45^2} \right) \right) * \left(\frac{1}{121\sqrt{2*pi}} \int_0^v \exp\left(-\frac{(v-805)^2}{2*121^2} \right) dv \right) dv$
Output	$\int_{321}^{512} \frac{e^{-(-377+v)^2/4050} \left(\text{erf}\left(\frac{805}{121\sqrt{2}}\right) + \text{erf}\left(\frac{-805+v}{121\sqrt{2}}\right) \right)}{90\sqrt{2\pi}} \, dv = \boxed{0.000441474}$
Plot of area representing risk	

Figure 3.18: Results for risk integral calculation for a transformer with a surge arrester using Wolfram Alpha.

The overall risk of failure for the three-phase transformer was found from Equation 3.1. The risk of failure due to lightning is very low (0.0013) as shown below. This a very low probability of failure and indicates that the transformer is highly unlikely to be damaged by a lightning surge. This result is further discussed in the discussion below (section 3.4)

$$R_{Total} = 1 - (1 - R)^3$$

$$R_{Total} = 0.00132$$

3.4 Discussion of overall results from the Option A and Option B for risk of failure

The main difference between the two risk of failure calculations was the reduction in peak voltages experienced at the transformer terminals. When there is no surge arrester the voltages reached magnitudes averaging 18MV but when a surge arrester was included the voltages at the transformer terminals averaged 377kV. The reduction in the level of overvoltage was because the surge arrestor discharges surge energy/current to ground resulting in a reduction in the voltage of the travelling wave going past the surge arrester towards the transformer. The voltage is being reduced according to the surge arrestors residual voltage rating. However, the residual voltage rating was for a 10kA surge (10kA gives 291kV residual voltage). The residual voltage increases as the surge current increases. The mean surge current for the simulations was higher than 10kA, it was 41kA. Therefore, the mean overvoltage for the simulations (377kV) with a surge arrester was higher than the residual voltage (291kV). For current levels higher than that, the residual voltage also goes higher. The surge current levels for the location of a project is thus very important in the selection of a surge arrester or two or more surge arresters could be used in parallel.

The overall risk of failure for the two options differ significantly. For option A, whereby no surge arrester is used the probability of failure (0.9999 or 99.99%) is almost certain if a lightning hits a conductor. This is understandable because the BIL for the transformer is only 650kV and its CFO or critical flashover voltage was 805kV but, the travelling wave voltages reaching the transformer terminals ranged from a minimum of 993kV to 38MV, which are all above the critical flashover voltage. Furthermore, the CFO rating statistically has a 50% chance of having a flashover, and 1.2MV (1.5 * CFO) of surge impulse voltage has a 100% chance of flashover. 1.2MV is on the lower end range of all the simulated overvoltage's, therefore nearly all the surge voltages (from 1.2MV to 38MV) had a 100% chance of causing a flashover. Therefore, it is understandable that the risk of failure had a very high probability.

Option B, where a surge arrester was included, had a very low risk or probability of failure (0.00132 or 0.13%). This indicates that there is a very low chance of the transformer failing due to a lightning strike on a conductor. One of the main reasons for this is the protective margin the surge arrester that was selected provided (PM 55.38%). The protective margin is a measure of how further away the surge arrestors discharge voltage is from the BIL level of the transformer. if the surge arrestors discharge level was equal to the BIL then the protective margin would be 0% meaning there is no protection provided by the surge arrestor. The further away the surge arrester discharge voltage is from the transformer BIL the better the protective margin. The minimum protective margin level according to standard is 25%.

The surge arrester in the model had a protective margin that was more than the minimum requirement and this it had a good buffer zone (between 290kV to 650kV) for lightning overvoltage that are caused by lightning currents higher than10kA the surge arrester would have a higher discharge voltage in those cases. The buffer provides room for the surge arrestor's increase in discharge voltage. As long as the increased discharge voltage does not exceed the transformer BIL the transformer is considered safe.

Another reason contributing to the low probability of failure in option B is because the distance between the surge arrester and the transformer was within the recommended distance of 3m (1m was used). the shorter the distance between the surge arrester and the transformer the better it is for the overall transformer protection against overvoltage. The transformer can be subjected to no more than double the arrester discharge voltage plus lead voltage rise. The voltage stresses the equipment is subjected to is determined by the separation distance between the surge arrester and the equipment. This can be seen in Figure 3.23 (and a PSCAD simulation example is shown in Appendix 4) where the duration the transformer has to withstand double the discharge voltage is related to the separation distance. The doubling effect comes from transmission line theory where an incident voltage surge waveform reflects with a coefficient of 1. Therefore, a full wave reflection at the transformer terminals causes the reflected wave to add on to the incoming wave and thus doubles. The period the transformer is subjected to such conditions depends on the separation distance. If a longer distance was assumed in the simulations the risk of failure would have been slightly higher.

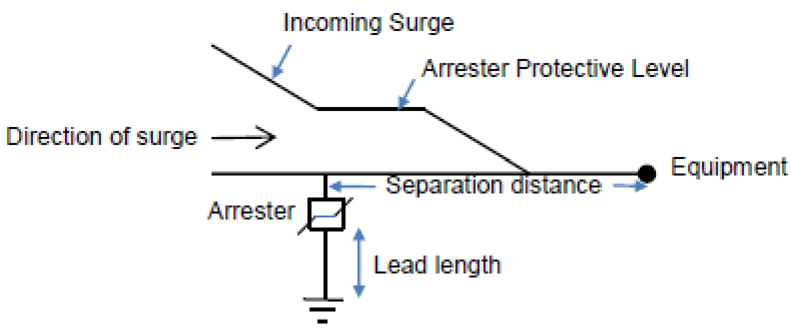


Figure 3.19: illustration for the importance of having a short separation distance.

Overall the risk of failure gives an indication of what could happen if a lightning surge, terminated on the transmission line near the transformer. This could be used to help make decisions on whether or not to invest in a surge arrester. However, the lightning stroke rate in the area also needs to be considered. If an area has a very low strike rate on a line then there is little support for installing a surge arrester.

There are limitations to this method and these are mentioned in the further improvements section of this report. The method can be applied to the analysis of any transformers risk of failure given the lightning stroke current peak levels are known and the transformer BIL and CFO along with the surge arresters MCOV and discharge voltage (residual voltage). This project also shows a probabilistic method an electrical consultant could use to perform risk of failure analysis on a transformer using a free version of PSCAD and Wolfram Alpha reducing the cost of producing a report for a customer. The only costs incurred would be the attaining of the lightning current levels for the area from relevant authorities.

4 Analyzing the risk of failure for a surge arrester

This section has an overall objective of finding out if a surge arrester protecting a transformer has sufficient energy rating. Situations have been identified whereby surge arresters are not capable of handling surge current levels and thus fail instantly when a lightning surge occurs, leaving the transformer unprotected. This leaves engineers hired to do a reliability compliance check on a transformer and a surge arrester, reluctant on signing off with the assurance of the protective margin alone. If the plant cannot incur an outage to remove the surge arrester for testing then a probabilistic approach could be used. The statistical risk of failure analysis is a way of finding a probability of failure for the surge arrester and thus gives a measure of whether the surge arrester is sufficiently rated to handle lightning energy levels.

4.1 Reasons for surge arrester failure

Surge arresters are exposed to switching overvoltage, temporary system over voltages (TOV), and lightning overvoltage. All these stresses, as well as the environ-mental pollution and manufacturing defects, may lead to arrester failure. This project specifically looks at lightning overvoltage as the cause for surge arrester failure specifically on metal oxide surge arresters. Metal oxide surge arresters are the most common surge arresters in industry, and other types of surge arresters are being phased out [9].

Metal oxide surge arresters are able to protect the transformer from high voltage surges by absorbing energy from the surge. When the arrester is energized under normal conditions it absorbs energy resulting in an increase in its internal temperature and there is a balance between heat generated and heat dissipated through heat transfer to the arrester housing and onwards to the surrounding atmosphere resulting in a stable operating condition[30]. When overvoltage occurs, the stability is disturbed and the increased amount of energy absorbed (for a period) thus there is an increase in its temperature. If the temperature rise is too high the arrester can be driven into a state of thermal runaway where heat is not dissipated fast enough causing further increase internal temperature. This could reach a point where the internal discs of the surge arrester are damaged leading to electrical breakdown and arrester failure[14].

The energy level the arrester can absorb without causing itself damage after a high voltage event is called the energy withstand capability of the MOSA and is expressed in terms of kilojoules per kilovolt of arrester MCOV[30]. Therefore, arrester failure due to lightning can be considered by looking at the energy it absorbs and comparing it to its energy withstand rating.

4.2 Probabilistic method for assessing surge arrester risk of failure

The concept behind finding the risk of failure of a surge arrester is similar to that of transformers, whereby the stress experienced is compared to the strength of the equipment. A failure occurs when the stress experienced is more than the strength of the equipment [15]. This can be evaluated through the risk integral similar to Equation 3.12 and its illustration in Figure 3.7, except instead of voltage being the variable for the functions this time it is energy [15, 31-33][15, 31-33][15, 31-33]

$$R_{SA} = \int_0^\infty f(E) \times P(E) \ dE$$

Equation 4.1

Where:

R_{SA}	is the risk of failure for a surge arrester
f(E)	is the probability distribution function (PDF) of the energy absorbed by the surge arrester
P(E)	is the cumulative distribution function (CDF) of the arrester failure (although it is counter intuitive but this is the measure of the lightning arrester strength).

Therefore, the steps for finding the risk of surge arrester failure can be summarized as follows:

A. Generate the PDF for the energy the surge arrester absorbs over a range of different lightning current peak injected into the line.
B. Find the CDF function of the arrester failure.
C. Evaluate the risk integral.

There are a number of different methods published in literature on how to calculate the risk [15, 31-34]

This report however will follow the energy method because it aligns well with the PSCAD software capabilities which can output PDF parameters for the energy absorbed by the surge arrester.

4.3 Finding the risk of failure of the surge arrester used in the case study in section 3.3 (Option B)

In section 3.3 a case study to illustrate the need for a for transformer to be protected by a surge arrester was shown. That scenario was brought forward into this section to form a new scenario/case study for analyzing the risk of failure for a surge arrester that is already protecting a transformer. This is a simple way to illustrate the use of the methodology for finding the risk of failure for a surge arrester that is already in the field and cannot be removed from service so its fitness for duty could be tested using standardized stress tests.

The following subsections follow the three steps (A, B, and C) highlighted in section 4.2 in order to find the risk of failure for the surge arrester.

4.3.1 Generate the PDF for the energy the surge arrester absorbs over a range of different lightning current peak injected into the line

This step requires a transient analysis software like PSCAD to have a model of the system being analyzed implemented and many simulations are run. Each simulation has a different magnitude of lightning current incident on the line. These magnitudes need to be related to the actual magnitudes of lightning current for the area in question. It can be purchased from relevant sources either from government meteorological services or from private firms. Each simulation would output data on the amount of energy the surge arrester absorbed. This data is recorded and analyzed to produce a PDF of the amount of energy the surge arrester absorbs. The PDF is assumed to have a normal distribution [4, 15, 17-19, 32, 33] The function for is shown in Equation 4.2

$$f(E) = \frac{1}{\sigma_{fE}\sqrt{2\pi}}\ e^{\left[-\frac{(V-\mu_{fE})^2}{2\ \sigma_{fE}^2}\right]}$$

Equation 4.2

Where:

f(E) is the probability distribution function (PDF) of the energy absorbed by the surge arrester

μ_{fE} is the mean of the gaussian PDF *f(E)*

σ_{fE} is the standard deviation of the gaussian PDF *f(E)*

The simulations carried out in section 3.3 were also recording the energy being absorbed by the MOSA. The analysis for surge arrester failure covered in [32] stated that the energy can be evaluate in its kJ/kV form. This result outputted from the simulation can be seen in Figure 3.17 indicated by a green box. Therefore, the probability distribution function (PDF) of the energy absorbed by the surge arrester (*f(E)*) for this case study has been found. It follows a normal distribution curve and its mean and standard deviation are 2.62kJ/kV MCOV and 1.35kJ/kV MCOV respectively. The overall calculation showing this function is covered in section 4.3.3.

4.3.2 Finding the CDF function for the probability of failure of the arrester.

The probability function for surge arrester failure is an inherent property of the surge arrester. It depends on its quality and its ratings. This should be provided by manufacturers or through lab experiments. However, this data is hard to come by and thus litterateur has shown that previous researches have formulated a function to represent the CDF *P(E) [13, 31-33]*. The function is shown in Equation 4.3. The energy rating (E_R) assumed for this case study is of the station class category as per section 3.3 surge arrester ratings and these have a general value of 3 to 5 kJ/kV MCOV.

- A value of 3kJ/kV MCOV was used for this case study
- As a demonstration to show what the risk of failure would look like if a lower energy capability rating was used, a rating of 1 kJ/kV MCOV was used in a second calculation. This would show how a lower energy rating for a surge arrester would increase the risk of failure for a given area (different places have different lightning current and frequency levels).

$$P(E) = 1 - 0.5^{\left(\frac{\left(E/E_R\right) - 2.5/0.375}{4} + 1\right)^5}$$

Equation 4.3

Where:

P(E) is the cumulative distribution function (CDF) of the arrester failure

E_R is the energy rating for the surge arrester in kJ/kV MCOV.

4.3.3 Evaluating the risk integral for the case study

Table 4.1 shows the summary of formulae and the parameters that were used in the risk of failure calculations. There were two calculations performed, each had a different energy capability rating for the surge arrester. The first one was with the energy rating for the surge arrester used in the case study, and the second was for surge arrester of a lower energy capability rating to show how the risk of failure would increase for inappropriately rated surge arresters.

Table 4.1:The three functions needed for calculating the surge arrester risk of failure and the parameters for each one.

Equation reference	Functions used for obtaining risk of failure	Parameters for each function
Equation 4.2	$f(E) = \frac{1}{\sigma_{fE}\sqrt{2\pi}} \; e^{\left[-\frac{(E-\mu_{fE})^2}{2\,\sigma_f{}^2}\right]}$	μ_{fE} = 2.62 kJ/kV MCOV (from Figure 3.14) σ_{fE} = 1.35 kJ/kV MCOV (from Figure 3.14)
Equation 4.3	$P(E) = 1 - 0.5^{\left(\frac{\left(E/E_R\right) - 2.5/0.375}{4} + 1\right)^5}$	$\boldsymbol{E_{R1}}$ = 3kJ/kV MCOV $\boldsymbol{E_{R2}}$ = 1kJ/kV MCOV **Two calculations were done.** The first used E_{R1} which is the rating for the surge arrester in the case study. The second used E_{R2} to show how a lower energy rating for a surge arrester would increase the risk of failure for a given area (different places have different lightning current and frequency levels).
Equation 4.1	$R_{SA} = \int_0^{\infty} f(E) \times P(E)\, dV$	

4.3.4 Results from the risk of failure case study

Figure 4.1 shows the results from the risk of failure evaluation carried out for the case study. The risk of failure probability was found to be 0.16%. This indicates that the surge arrester in the case study has an energy rating which was large enough to handle the energy level deposited by the different types of lightning currents expected for that area.

Figure 4.2 shows the results for risk of failure, if a surge arrester with a lower energy rating was used instead of the one in the case study. An energy rating of 1kJ/kV MCOV was chosen because it was lower than the average energy level (2.6kJ/kV MCOV) that was expected for the surge arrester to absorb at that site. This is not an actual surge arrester rating for a station class surge arrester but it helps in understanding the overall concept. The results did show that there was a significant increase in risk of failure (54%). Therefore, given a specific site where a transformer and a surge arrester installed, the surge arrester chosen has have an energy rating sufficient enough to handle the lightning surge levels for that site.

Input	$\int_0^\infty \left(\left(\frac{1}{1.35\sqrt{2pi}}\exp\left(-\frac{(x-2.6)^2}{2(1.35)^2}\right)\right)\left(1-(0.5)^{\left(1+\frac{\frac{\frac{x}{3}-2.5}{0.375}}{4}\right)^5}\right)\right)dx$ Energy rating for surge arrester = 3 kJ/kV MCOV
Output	$\int_0^\infty\left(\frac{1}{1.35\sqrt{2\pi}}\exp\left(-\frac{(x-2.6)^2}{2\times1.35^2}\right)\right)\left(1-0.5^{\left(1+\frac{\frac{x}{3}-2.5}{0.375}/4\right)^5}\right)dx = \boxed{0.00155067}$

Figure 4.1: Results from the surge arrester risk of failure analysis for the surge arrester discussed in the case study for in section 3 and section 4 of this project. The online calculator Wolfram Alpha was used for this calculation.

Input	$\int_0^\infty \left(\left(\frac{1}{1.35\sqrt{2pi}}\exp\left(-\frac{(x-2.6)^2}{2(1.35)^2}\right)\right)\left(1-(0.5)^{\left(1+\frac{\frac{\frac{x}{1}-2.5}{0.375}}{4}\right)^5}\right)\right)dx$ Energy rating for surge arrester = 1 kJ/kV MCOV
Output	$\int_0^\infty\left(\frac{1}{1.35\sqrt{2\pi}}\exp\left(-\frac{(x-2.62)^2}{2\times1.35^2}\right)\right)\left(1-0.5^{\left(1+\frac{x\frac{1}{1}-2.5}{0.375}/4\right)^5}\right)dx = \boxed{0.538374}$

Figure 4.2: Results from the surge arrester risk of failure analysis for a surge arrester with a lower energy rating than the one for the case study. This was done to show that the risk of failure increases

when a surge arrester with suboptimal energy rating is used. The online calculator Wolfram Alpha was used for this calculation.

4.3.5 Discussion and limitations

The results from this section does show that risk of failure analysis carried out on a surge arrester gives an indication of whether it has a sufficient energy rating to withstand the energy levels introduced by lightning in that particular area. The case study shows a practical methodology that could be easily implemented to carry out such an analysis. The data required to carry out this analysis is listed below:

- The lightning current magnitudes for that area sourced from relevant databases. Mostly this has to be purchased or some licencing agreement is needed.
- A power systems transient analysis software like PSCAD or EMTP
- The data for the system being analysed so that a high frequency model could be implemented in the software. This includes transformer data like its leakage capacitance, its BIL and CFO also surge arrester data like its (discharge voltage), MCOV, surge arrester energy rating.

There are some limitations to consider in this method and these are listed below:

- Earth resistance was not considered in the case study. It assumed that there was good conduction between the surge arrester and ground. A better representation of the risk of failure could be found by including a true measurement of the sites grounding resistance in the simulations.
- The lightning surge current parameter that was being varied in each simulation was only for the peak current levels, the other parameters in Table 3.4 like the front time of the surge or the tail time. These were not included in the case study simulations because there were limitations in the free version of the software (PSCAD free was used in this project). For a more complete analysis these lightning current parameters need to be varied in order to mimic the probabilistic nature of lightning fully.
- The surge arrester fails due to excessive energy absorption leading to thermal runaway, therefore the subsequent strokes that follow after the first stroke needs to be modelled in the simulation because these other strokes also deposit lightning energy onto a line and thus there is more heat generated in the surge arrester.

5 Conclusion

This project set out to find a method of finding the risk of failure due to lightning overvoltage for a transformer and a surge arrester and to demonstrate the method using a case study. The project goals were achieved and a method for finding risk of failure due to lightning overvoltage was identified and tested.

Since this project was associated with transient analysis a suitable software needed to be found to carry out lightning overvoltage transient analysis. PSCAD was found to have a lot more advantages compared to MATLAB and EMTP. MATLAB Simulink was the main option because it was readily available but scholarly articles for past works in transient analysis on power systems were very few and example models on transient analyses were not found. Researchers on this topic preferred the mainstream electromagnetic transients' programs like EMTP and PSCAD and there were many papers showing past works on lightning transients. Furthermore, there were many YouTube video tutorials available on PSCAD and EMTP. EMTP required a licence to gain access to its free version (ATP) required an association with a user group. Australia only had one person listed and there was no reply when emails were sent. Therefore, the best option was the free version of PSCAD. This free software has made it possible for this project to demonstrate a practical application of the methodology for finding risk of failure due to lightning.

The method chosen for evaluating the risk of failure due to lightning overvoltage was found to be the most compatible with the limitations and constraints of the free software. Even though the Monte Carlo method was a lot simpler, implementing it in PSCAD Free and extracting the data for processing was a challenge.

Close to the project's completion, a final step in the risk analysis was omitted because more time would have been needed to verify if the calculation method used by a number of papers concurred with statistics theory. The common trend found was to take the risk of failure which was classified in research papers as a probability and multiply it with a rate. The rate was for the number of lightning strikes terminated on a line for a given area per year. Since it was done in four research papers, the author assumed that that was industry practice. When the realisation was made that the method was not correct, it was dropped from this report. It was an easy step, just a multiplying and inverting the result would have given a mean time between failures and thus would carry greater weight when convincing a customer to purchase a surge arrester. This author felt it was better not to include that final step in this report because it was not verified and any misleading data given to a client could have legal consequences. This has been mentioned in the extensions section so that the next researcher may verify if the method is mathematically and statistically correct.

The risk integral method was successfully implemented in the case study and the results for Option A which was the risk of failure for a transformer without a surge arrester was found to be 99.99%. This was not surprising given that the lightning overvoltage it was experiencing had a mean value of 18MV but it had a CFO of only 805kV. When a surge arrester was included, the risk of failure dropped to 0.13%, which was a significant reduction. This showed that for 1 lightning overvoltage event if no surge arrester was used then the transformer would very likely fail but if it was included then there was a very high chance it would be safe.

The report also found a methodology for finding the risk of failure for a surge arrester. It clearly demonstrated that if a surge arrester had a lower energy rating than the expected energy levels for a particular location, then it had a higher risk of failure.

During the research phase for this project, it was found that a surge arrester needed to be as close as possible to the transformer terminals. According to regulations, it was recommended to have this distance less than 3m. The simulation model for this project was used to prove this. The simulation results clearly showed that there was indeed an increase in the transformer terminal voltage when this distance was increased.

There are a few limitations to this methodology. The process of generating multiple runs in the simulation needs a wide variety of impulse currents. This includes varying the wave front times, tail times, rate of rise and peak current values. Only the peak current was allowed by PSCAD Free to be manipulated, the rest were fixed values. Furthermore, multiple strokes were not modelled but lightning strikes do have a high chance of having multiple strokes. When the first stroke has contacted ground, a conducting path would have been formed. The remainder of charges in the cloud now have an easy path to ground, thus forming subsequent strokes. Given these limitations the method proposed can be said that there is much room for improvement in terms of trying to mimic actual lightning wave shapes in the simulations

A point to make with regards to this project is that it had a sense of novelty in that it tried to make use of the cheapest means to carry out an analysis which professionals in the field are charging clients for.

This project could be used as a learning aid in technical schools, especially in undeveloped countries where access to licenced software for such studies is scarce. It could also be used as a demonstration tool for trainee lines persons to show the importance of having a short lead length for the cable used to connect a surge arrester to a transformer. This project has many practical applications in the commercial and educational fields. Thus, it forms a positive argument for the posit the title for this project poses.

5.1 Extensions

This project could be further improved as follows:

- Research and identify ways to combine the risk of failure of a transformer (which is a probability) with the rate of lightning strikes terminating on a line.
- Compare this methodology to a different technique of finding risk of failure or probability of failure
- Write a program to carry out this analysis in a more efficient way
- Improve the variability of the lightning impulse current in the simulation to include front time, tail time, rate of rise and multiple current strokes.
- Improve the model to make it a three-phase model
- Use MATLAB Simulink since it is readily available to students and it generate random variable according to any probability function. It can also handle large data sets very easily.
- Repeat this project using a licenced EMT software and make improvements.

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APPENDIX 1 [35]

Transmission Line Equations

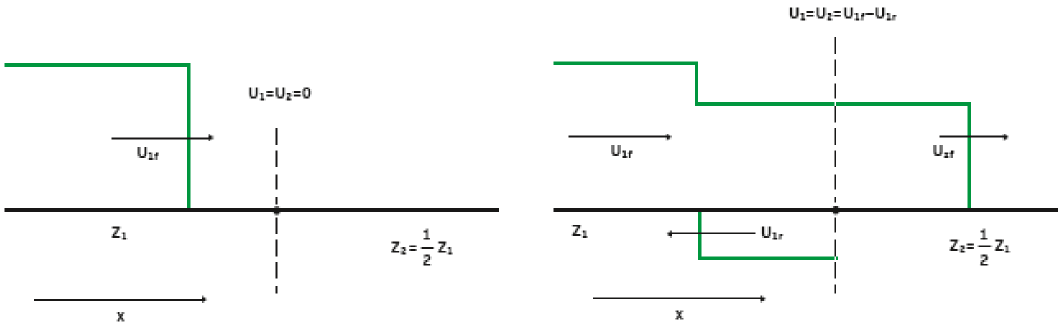
		Voltage	Current
Telegrapher's Equations (Time Domain) Describe voltage and current along the T-line in terms of position and time.	Lossy	$\frac{\partial v(z,t)}{\partial z} = -\frac{\partial i(z,t)}{\partial t}L - i(z,t)R$	$\frac{\partial i(z,t)}{\partial z} = -\frac{\partial v(z,t)}{\partial t}C - v(z,t)G$
	Lossless	$\frac{\partial v(z,t)}{\partial z} = -\frac{\partial i(z,t)}{\partial t}L$	$\frac{\partial i(z,t)}{\partial z} = -\frac{\partial v(z,t)}{\partial t}C$
Telegrapher's Equations (Steady State) Describe voltage and current along the T-line in terms of position.	Lossy	$\frac{dV(z)}{dz} = -(R + jwL)\, I(z)$	$\frac{dI(z)}{dz} = -(G + jwC)\, V(z)$
	Lossless	$\frac{dV(z)}{dz} = -(jwL)\, I(z)$	$\frac{dI(z)}{dz} = -(jwC)\, V(z)$
Wave Equations (Time Domain) Solution to Telegrapher's equations. Shows rate of change of property WRT distance as a function of a property changing WRT time.		$\frac{\partial^2 v(z,t)}{\partial z^2} = LC\frac{\partial^2 v(z,t)}{\partial t^2} + (RC + LG)\frac{\partial v(z,t)}{\partial t} + RG\, v(z,t)$	$\frac{\partial^2 i(z,t)}{\partial z^2} = LC\frac{\partial^2 i(z,t)}{\partial t^2} + (RC + LG)\frac{\partial i(z,t)}{\partial t} + RG\, i(z,t)$
Wave Equations (Steady State) General solution to Telegrapher's equations.		$\frac{d^2V(z)}{dz^2} = [(RG - w^2LC) + jw(RC + LG)]\, V(z)$ $\frac{d^2V(z)}{dz^2} = \gamma^2\, V(z)$	$\frac{d^2I(z)}{dz^2} = [(RG - w^2LC) + jw(RC + LG)]\, I(z)$ $\frac{d^2I(z)}{dz^2} = \gamma^2\, I(z)$
Traveling Wave Equations Non-differential equations, allowing us to find V & I anywhere on line. Indicates that they are traveling waves, not constants.		$V(z) = V_0^+ e^{-\gamma z} + V_0^- e^{+\gamma z}$	$I(z) = I_0^+ e^{-\gamma z} + I_0^- e^{+\gamma z}$

	Lossy T.L.	Lossless T.L.
Propagation Constant Simplifies wave equations.	$\gamma = \sqrt{(R + jwL)\,(G + jwC)}$	$\gamma = jw\sqrt{LC}$
Characteristic Impedance Property of T.L, regardless of length.	$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}}$	$Z_0 = \sqrt{\frac{L}{C}}$
Traveling Wave Equations w/ Z₀	$V(z) = V_0^+ e^{-\gamma z} + V_0^- e^{+\gamma z}$	$I(z) = \frac{V_0^+}{Z_0} e^{-\gamma z} - \frac{V_0^-}{Z_0} e^{+\gamma z}$
Line Impedance Relationship between V & I anywhere on line.	$Z(z) = Z_0 \frac{(e^{-\gamma z} + \Gamma_0 e^{+\gamma z})}{(e^{-\gamma z} - \Gamma_0 e^{+\gamma z})}$	$Z(z) = Z_0 \frac{(e^{-j\beta z} + \Gamma_0 e^{+j\beta z})}{(e^{-j\beta z} - \Gamma_0 e^{+j\beta z})}$ $\beta = w\sqrt{LC}$

	Along Line	At Z=0
Reflection Coefficient Characterizes mismatch between T.L. and attached load.	$\Gamma(z) = \frac{V_0^- e^{+\gamma z}}{V_0^+ e^{-\gamma z}} = \frac{V_0^-}{V_0^+}\, e^{+2\gamma z}$	$\Gamma_0 = \frac{V_0^-}{V_0^+} = \frac{1\text{-}Z_0}{1\text{+}Z_0}$

Appendix 2 [35]

Figure 3: Reflection and transmission at points of discontinuity (principle depiction)



a: Before the voltage impulse reaches the point of discontinuity

b: After the voltage impulse reached the point of discontinuity

Figure 4a: Line with an open end ($Z_E \to \infty$)

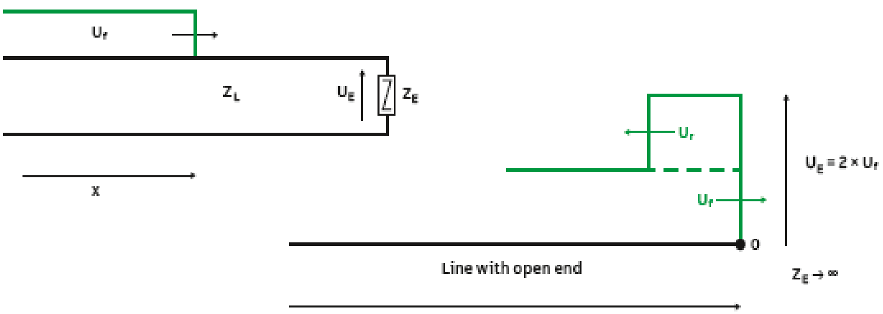
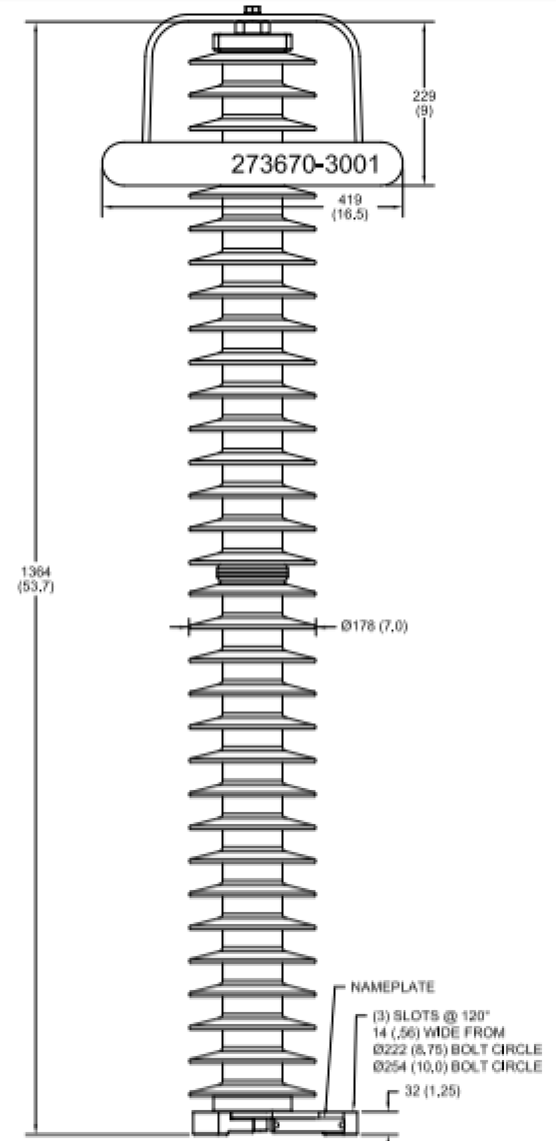
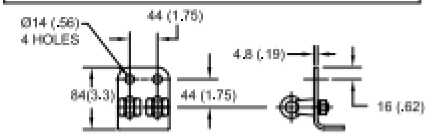


Figure 4b: Line terminated with a matched impedance ($Z_E = Z_L$)

Appendix 3 [36]

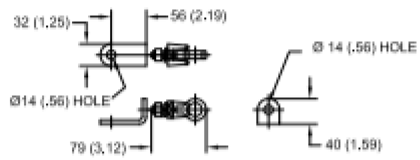


LINE TERMINAL DETAIL



HDG 4-HOLE TERMINAL PAD, PART No. 274914-4002
TWO HDG TERMINALS, PART No. 271414-3001
SUITABLE FOR COPPER OR ALUMINUM CONDUCTOR SIZE
Ø 7 (.25) - Ø 21 (.81)
25 - 240 sq mm
AWG#4 - 500 MCM

GROUND TERMINAL DETAIL



HDG TERMINAL BRACKET, PART No. 89606-4001
ONE HDG TERMINAL, PART No. 271414-3001
SUITABLE FOR COPPER OR ALUMINUM CONDUCTOR SIZE
Ø 7 (.25) - Ø 21 (.81)
25 - 240 sq mm
AWG#4 - 500 MCM

Ø = DIAMETER
HDG = HOT DIP GALVANIZED

CHARACTERISTICS	
RATED VOLTAGE (Ur)	120 kVrms
MCOV (Uc)	98 kVrms
MASS	33.2 kg (73.1 lb)
COG ABOVE BASE	713 (28.1)
CREEPAGE DISTANCE	3654 (143.9)
STRIKE DISTANCE	1135 (44.7)
LIGHTNING IMP W/S	652 kVpk
SWITCHING IMP WET W/S	546 kVpk
POWER FREQ WET W/S	283 kVrms
TOV 1s NO PRIOR DUTY	139 kVrms
TOV 10s NO PRIOR DUTY	133 kVrms
TOV 1s W/PRIOR DUTY	133 kVrms
TOV 10s W/PRIOR DUTY	125 kVrms

CANTILEVER FORCE	
MAXIMUM CONTINUOUS	781 N (176 lbf)
ULTIMATE (max pk)	1562 N (351 lbf)

RECOMMENDED CLEARANCE (METAL - METAL)	
PHASE TO GROUND	564.9 (22.2)
PHASE TO PHASE	652.2 (25.7)

NOTES:
1. DIMENSIONS IN millimeters(inches) SUBJECT TO ±3% TOLERANCE
2. CLEARANCE AND INSULATION W/S VOLTAGE APPLY AT SEA LEVEL
3. ARRESTER SUITABLE FOR OPERATION AT ALTITUDES UP TO 4380 m (14370 ft)
4. PACKAGED IN A CORRUGATED BOX.

.5μSEC 10kA IR kV	SWITCHING SURGE IR kV		MAXIMUM 8/20 DISCHARGE VOLTAGE - kV AT					
	500 A	1 KA	1.5 kA	3.0 kA	5 kA	10 kA	20 kA	40 kA
322	231	241	246	259	271	291	315	359

IEEE C62.11
STATION-CLASS SURGE ARRESTER
Program Revision 2015.07.30.08.09.10
REV DATE 05/03/11

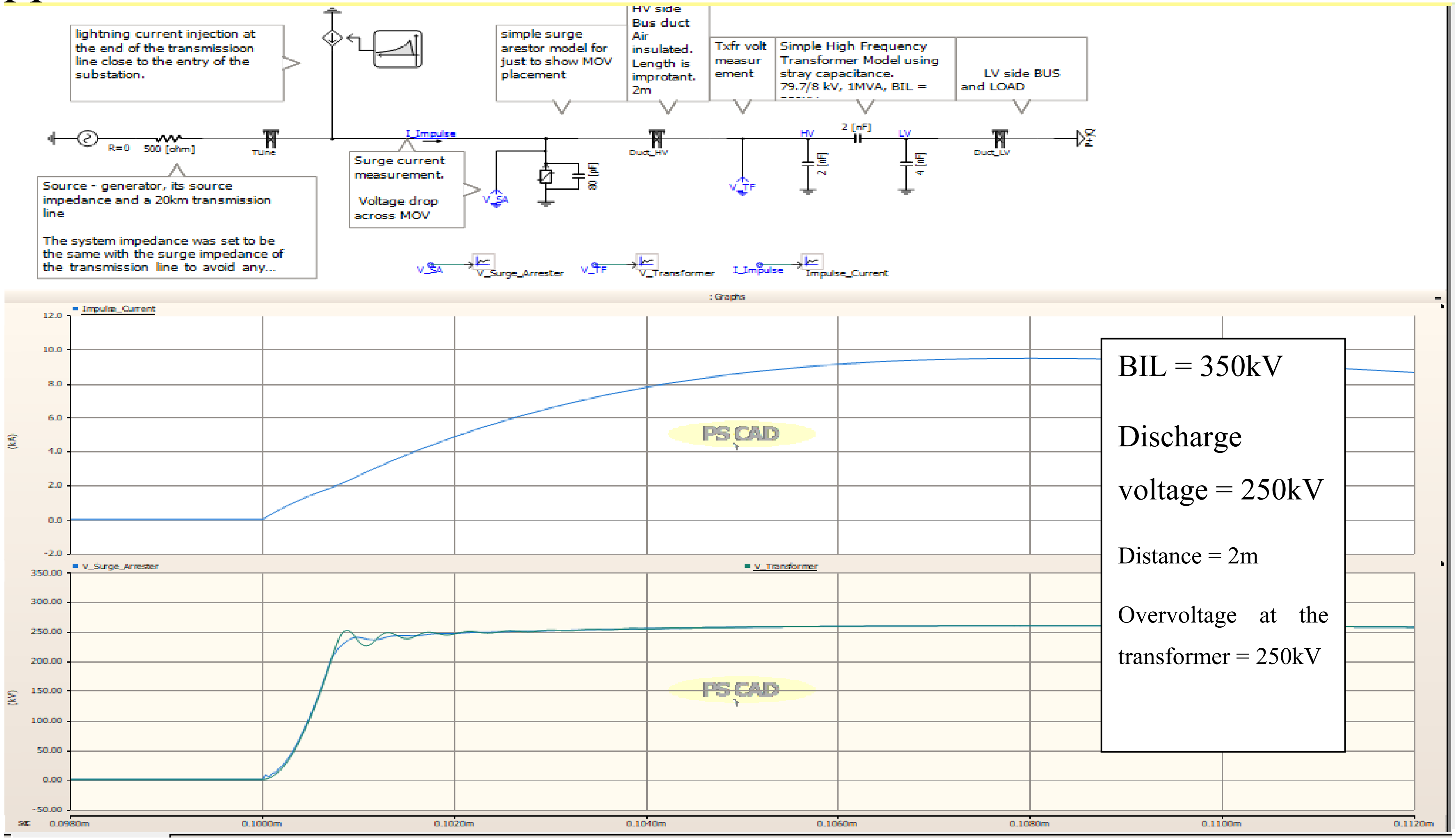
TITLE EVP ARRESTER 98 KV MCOV

SIZE	DWG NO.	CAT / PART / ASSY NO.	REV
S	181962399	EVP0098003001	1

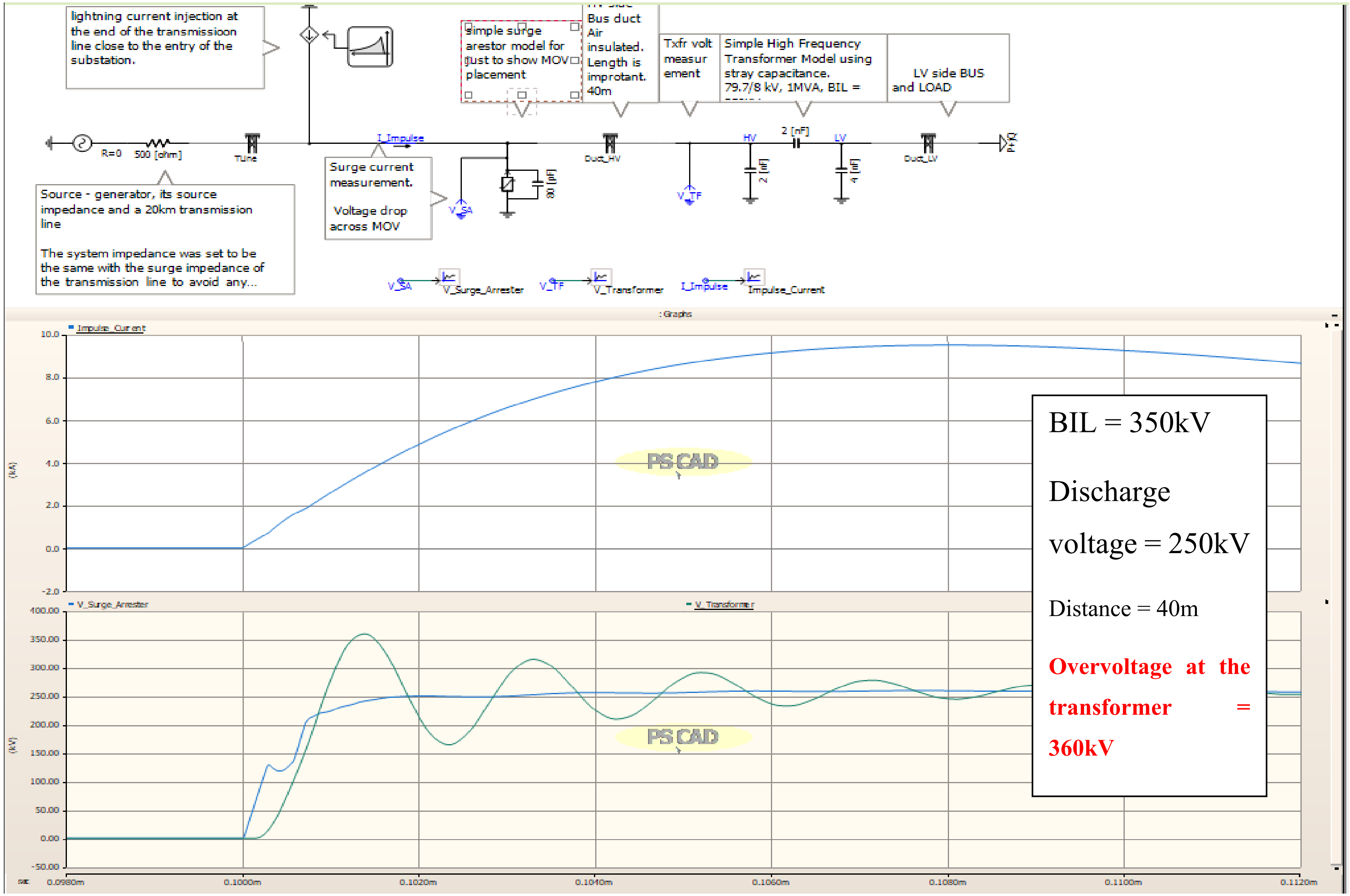
DO NOT SCALE THIS DRAWING | DRN BY NON | DATE 05/03/11 | SHEET 1 OF 1

HUBBELL® POWER SYSTEMS

Appendix 4



Situation 1 – Separation distance = 1m



Situation 2 – Separation distance = 40m