University of Southern Queensland

Faculty of Health, Engineering and Sciences

Operational Characteristics of Surge Arresters within High Voltage Substations

A dissertation submitted by

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ABSTRACT

Surge arresters form a critical component in the safe and reliable operation of electrical zone substations. Overvoltages resulting from a lightning strike pose the greatest risk of damage to substation equipment reaching peak values of over 100 times the nominal line voltage within microseconds. During such overvoltage events, the surge arrester limits the level of voltage that the equipment is subjected to, thus providing protection to very expensive, and specialised electrical infrastructure.

Correct arrester specification is the first step in determining the type of surge arrester required for each installation. A second, but no less important step is determination of its physical location and connection method. The distance a surge arrester is located from equipment is a significant factor in its ability in protecting equipment.

Through the undertaking of this detailed research project, optimum arrester location, connection methods and insulation co-ordination derived from software simulation will be compared to standard design principles utilised by Essential Energy (EE) and verified using equivalent circuit analysis.

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Andrew Close

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GLOSSARY OF TERMS

AAAC	All Aluminium Alloy Conductor
AER	Australian Energy Regulator
AS	Australian Standard
ATP	Alternative Transients Program
BFR	Back Flash Rate
Bi	Bismuth
BIL	Basic Insulation Level
BSL	Basic Switching Level
CCT	Covered Conductor Thick
CDEGS	Current Distribution Electromagnetic fields Grounding and Soil structure analysis
CFO	Critical Flashover
Co	Cobalt
EE	Essential Energy
EMTP	Electromagnetic Transients Program
EPR	Earth Potential Rise
FFT	Fast Fourier Transform
fr	The rated frequency of the power network.
FRP	Fibre Reinforced Plastic
HV	High Voltage
HDBC	Hard Drawn Bare Copper
IEEE	Institute of Electrical and Electronic Engineers
LIPL	Lightning Impulse Protective Level
LIWL	Lightning Impulse Withstand Level
Mn	Manganese
MO	Metal Oxide
MTBF	Mean Time Between Failure
MTBS	Mean Time Between Surge
NSR	Non Self Restoring Insulation
OHEW	Overhead Earth Wire
OPGW	Overhead Pilot Ground Wire
Sb	Antimony
SiC	Silicon Carbide
SR	Self Restoring Insulation
u	Power Frequency Voltage
U_c	Continuous Operating Voltage
U_r	Rated Voltage
Uref	Residual Voltage
V-G	Voltage to Ground
ZnO	Zinc Oxide

NOMENCLATURE

Aluminium Flange	The base on which the arrester housing is secured. Mounting holes in the flange allow the arrester to be fixed to an appropriately designed structure.
Arrester disconnector test	Applicable to surge arresters fitted with disconnectors.
Arrester Housing	Porcelain housings may be either quartz or alumina porcelain. Higher mechanical strength may be achieved with the latter. The housing is designed with sheds to ensure the creepage distance between the active terminal and the base is adequate.
Back Flash Rate	The product of flashover probability and the number of strokes terminating on the OHEW (or OPGW).
Capacitive Coupling	Voltages between long lines that are isolated from earth, and nearby clouds may rise to damaging levels due to capacitance between them.
Cement Joint	Sulphur cement provides superior mechanical properties over Portland cement typically used in insulator construction. Modern techniques allow for cement joints stronger than porcelain housings.
Compression spring	A brace for the column of MO resistors, metallic spacers, supporting rods and holding plates.
Conductive Coupling	(Refer to Residual Voltage)
Continuous Operating Voltage	The voltage that the arrester may be operated at continuously, without any restrictions. $U_c > u$
Effectively Earthed	Where the ratio of zero sequence reactance to positive sequence reactance (X0/X1) is greater than zero and less than three, and, the ratio of zero sequence resistance to positive sequence reactance (R0/X1) is greater than zero and less than one.
External Insulation	The insulation component of equipment that is in direct contact with the surrounding atmosphere. For example porcelain bushing.
Holding Plate	Manufactured from FRP, the holding rods provide additional mechanical strength to the supporting rods, limiting sagging.
Inductive Coupling	A large magnetic field is produced around the lightning strike due to large values of discharge current (thousands of amps). Voltages are induced

	into nearby conductors intersecting the magnetic field
Inductive Voltage Drops	The inductive characteristics of the conductor between the line, surge arrester and the earth result in significant voltage drops. Lead length plays a significant part in the magnitude of this voltage. Example: With an inductance of 1µH/m and a lightning current impulse of 10kA / µs: u=L*di⁄dt=10µH*10kA/µs = 100kV (Hinrichsen 2012)
Insulation withstand test	Determines the surge arrester housings ability to withstands voltage stresses in both wet and dry conditions.
Internal Insulation	The insulation component of equipment which is not in contact with the surrounding atmosphere. For example transformer insulating oil.
Lightning Flash Density	The number of lightning flashes across an area, over a time period (AS1768-2007)
Lightning Impulse Protective Level	(Refer to Residual Voltage)
Lightning Impulse Withstand Level	For non-restoring type arresters, this is the maximum (test) voltage the arrester may experience. This voltage level should never be reached in operation although inductive voltage drops, travelling waves and excessive discharge currents may cause a voltage greater than LIWL to be experienced.
Lightning Protection System	A system used to reduce the probability of danger from direct lightning strikes (AS1768-2007)
Long duration current impulse withstand test	Determines the resistive surge arrester elements ability to withstand dielectric and energy stresses without experiencing flashover.
Mean Time Between Failure	The probability of a surge exceeding a determined level which would result in equipment failure
Mean Time Between Surge	The reciprocal of the number of surges used in the determination of BFR.
Metal Oxide Resistor Column	Comprises of approximately 90% ZnO and the remaining 10% of rare earths; Bi, Sb, Co and Mn. The resister blocks give the arrester its non-linear UI characteristic. A Typical block height is 45 mm with diameters ranging from approximately 30 mm through to 100 mm.

Metallic Spacers	Predominantly aluminium tubes with end covers designed to ensure even contact pressure with the MO resistor.
Multi column arrester current distribution test	Determines the current flowing through each column of parallel resistors.
Non Self Restoring Insulation	Internal insulation which does not contain the ability to recover after a flashover has occurred.
Operating duty test	Determines the surge arresters thermal ability when exposed to pre-defined conditions.
Partial discharge test	Determines partial discharge measured within the surge arrester.
Power Flow Current	The current which continues to flow following the discharge of the arrester.
Power Frequency Voltage	The highest phase-to-earth voltage of the system.
Pressure relief test	Applicable to surge arrester fitted with pressure relief devices, determines the arresters ability to withstand short circuit conditions without failure to the housing.
Rated Voltage	The highest voltage the arrester may temporarily handle. The ratio between U_c & U_r is generally 1.25.
Residual Voltage	The voltage dropped across the surge arrester terminals when nominal discharge current flows through the arrester.
Residual voltage test	Determines the protective levels of the surge arrester.
Resistive Coupling	A cloud to ground lightning strike raises the earth potential of all bonded equipment and conductors. Separately earthed equipment may still be subjected to resistively coupled transients when separated by short distances
Seal test	Determines the integrity of the surge arrester seals.
Sealing Ring and Pressure Relief Diaphragm	Appearing at both the top and bottom of the arrester, these integral components deter water ingress, provide a mechanism for pressure relief allow the build-up of high-pressure gasses before failure of the housing is reached and maintain an electrical path through to the MO resister column.
Self Restoring Insulation	External insulation which consists of the ability to return to pre fault condition after a flashover has occurred.

Single Impulse Energy Handling Capability	The ability of the arrester to withstand the initial energy causing initial sudden temperature rises. The arrester will experience mechanical tensile and compressive forces that may cause physical damage such as cracking or shattering of porcelain type units.
Supporting Rods	Surrounding cage manufactured from FRP for the MO resister blocks.
Thermal Energy Handling Capability	The maximum energy an arrester can handle and return to normal operating temperature.
Venting Outlet	Mechanism within an arrester to allow the venting of pressurised hot gasses.
Verification of spark production	Determines the surge arrester ability to limit sparks produced during the operation of pressure relief devices. This test is applicable to distribution type arresters.

1 INTRODUCTION

Essential Energy is a NSW state owned corporation that owns and operates the electricity network supplying power to over 800,000 residences and businesses across 95% of the state. The network consists of approximately 350 zone substations at operating voltages ranging from 132kV to 11kV (Essential Energy 2015a). When construction work is to be undertaken at any one of these sites or when a new substation is required, standard design practices and templates have been created. Delivering consistent, safe and cost effective designs through the use of templates ensures conformance to relevant Australian standards, corporate guidelines, policies and procedures.

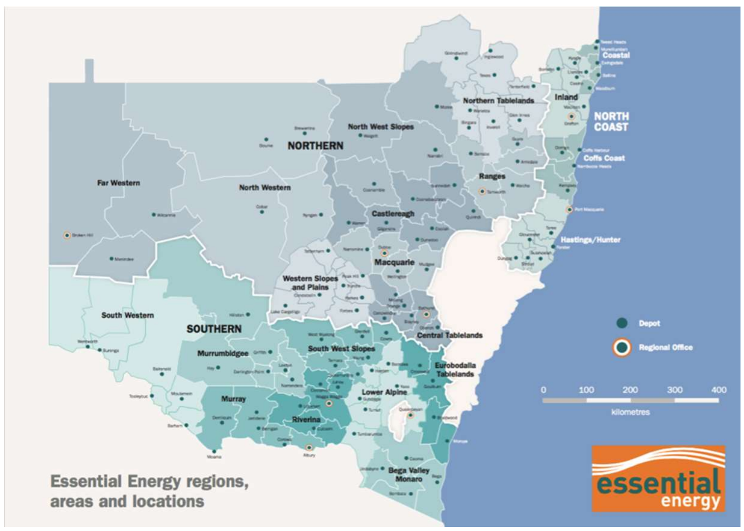

Figure 1-1 Essential Energy Regional Area (Essential Energy 2015b)

The Australian Energy Regulator (AER) provides Essential Energy financial incentives for maintaining and improving reliability of the electricity network. Electricity outages as a result of damage to electrical infrastructure caused by overvoltages have the potential to disrupt many thousands of Essential Energy's customers and significantly contribute to loss of income to businesses across a wide area simultaneously. The three most common types of overvoltages are lightning, switching and temporary. Lightning is the most commonly experienced overvoltage across Essential Energy's network and has the potential to inflict the most damage both physically and financially.

1.1 Background

To date, there has been no recorded investigation by Essential Energy into the operational performance of surge arresters installed within their zone substations. Additionally, no consistent approach towards the assessment on surge arrester performance arising from modifications to electrical connections or equipment positions within the zone substation exists. This effectively leads to uncertainty, and excessive safety margins are factored into the template designs in an attempt to mitigate any increased risk of damage, loss of supply or injury to people. Such increased safety margins have the tendency to add unnecessary costs to projects, without quantifiable or measurable benefits.

The majority of studies into the performance of electrical networks during overvoltage events such as lightning or switching surges have been undertaken using software such as EMTP/ATP. This project presents an opportunity to investigate the viability of using the existing Essential Energy corporate approved software package known as Current Distribution Electromagnetic fields Grounding and Soil structure analysis (CDEGS) to determine if overvoltages are present within zone substations during the transient. Such suitability would present significant cost savings to the business, reduce staff training requirements applicable to new software and present an alternative simulation method for engineers within the industry.

1.2 Research Objectives

There are Four main objectives to this research.

The first objective is to adopt a suitable computer software package to complete the network modelling and lightning simulation. Research into frequency domain (CDEGS) and time domain (ATP) methods shall be undertaken to make this determination.

The second objective is to determine:

a) The effectiveness of the existing surge arrester protective zones whilst maintaining the surge arresters in their present locations.
b) What impacts the surge arrester location and connection methods have in maintaining overvoltage levels below equipment BIL ratings when subjected lightning surges.

The third objective shall identify any improvements to zone substation designs that may be achieved through changes to Essential Energy's contract surge arrester specification.

The fourth objective will present recommendations to Essential Energy design engineers relating to the results obtained in the second and third objectives detailed above.

Objectives two, three and four shall be achieved through the undertaking of two case studies. The first is to incorporate Essential Energy's standard 66/11kV zone substation whilst the second shall be the rural 66/11kV zone substation located at Kywong in the New South Wales Riverina region. Results are to be obtained through detailed computer simulations and validated against analytical calculations derived from the application of simplified equivalent circuits.

2 LITERATURE REVIEW

2.1 Introduction

This chapter aims to:

a) Describe the various transient overvoltages that result in disturbances to electrical networks.
b) Distinguish between the various types of lightning and the properties relating to each, to allow an accurate representation during the computer simulation.
c) Document the history of surge arrester technology and research the electrical and physical characteristics of surge arresters influencing their operation during both real world and computer-simulated events.
d) Identify the differences between surge arrester classes and establish the influence the surge arrester protective zone has on the equipment.
e) Introduce insulation co-ordination and the factors affecting performance of equipment insulation.
f) Provide background into relevant Australian standards relating to both surge arresters, and the design of zone substations and transmission lines they are installed to protect.
g) Determine a suitable computer program to perform the simulation of the network during a transient lightning overvoltage.

2.2 Surge Voltages

2.2.1 Lightning Overvoltages

Overvoltages resulting from a lightning strike pose the greatest risk of damage to substation equipment reaching a peak value over 100 times the nominal line voltage within microseconds (Hinrichsen 2012). The lightning overvoltage may arise due to either backflash or shielding failure with each resulting in slightly differing wave fronts. Such waveshape variations are a result of a number of key factors such as magnitude, polarity and shape of the lightning stroke current, line and tower surge impedances, tower footing impedance and the critical flashover rating of the line insulation (IEEE 1998).

There are two scenarios by which a lightning overvoltage may be inflicted upon the High Voltage (HV) electricity network. The first, and most damaging, is through a direct strike to the network infrastructure. The second, less severe surge, is when an adjacent strike is conducted onto the equipment through the ground.

Lightning overvoltages are transient in nature and are also referred to as fast front transients covering a frequency range 10kHz to 1MHz (Imece et al. 1996). Waveshapes generally consist of a steep front and a long decaying tail. The unpredictability and random nature exhibited by lightning results in many variations to the overvoltage waveshape. AS1768-2007 details the most common waveshapes to represent transients are the 1.2/50µs voltage and the 8/20µs current waveforms.

2.2.2 Switching Overvoltages

There are a number of factors that may initiate a switching overvoltage of up to double the nominal line voltage. These high magnitude events pose a risk to insulation breakdown of equipment and include:

a) Circuit breaker operation to clear network faults
b) Switching of HV capacitor banks

Switching overvoltages tend to present more of a problem at voltages above 345kV (Hileman 1999). The maximum voltage of Essential Energy's network is 132kV. Additionally, this dissertation is primarily focused on surge arrester performance on the 66kV subtransmission network, and therefore switching surges will not be included within this report.

2.2.3 Temporary Overvoltages

Lasting for short durations in the order of tenth of seconds, through to a number of hours, temporary overvoltages may occur due to earth connection faults, energisation of unloaded lines, resonance or during load rejection. The system temporary overvoltage rating must be equal to or less than that of the surge arrester (Hileman 1999).

2.2.4 Travelling Wave

A transient disturbance to an overhead transmission line, such as lightning or switching surge will propagate throughout the electrical network in the form of a travelling (or incident) wave. The velocity at which the wave travels is proportional to the impedance of the conductor and is inversely proportional to the permittivity of the medium.

2.2.4.1 Reflection and Transmission of Travelling Waves

The incident wave may approach a junction within the network that appears as either open circuit, short circuit or a change in surge impedance. In each of these cases a fraction of the incident wave is either reflected back toward the source, or transmitted through to the adjacent section of line. The reflection and transmission factors of the incident wave are defined in section 2.2.4.2.

2.2.4.2 Bewley Lattice Diagram

The Bewley lattice diagram provides a convenient method to represent the position and direction of each incident, reflected and transmitted wave at each network junction. The lattice diagram is to be used in the validation of computer simulation results and an illustrative example containing two differing surge impedances (Z_1 & Z_2) connected in series along with a resistive load (R) at the end of the line is shown in Figure 2-1.

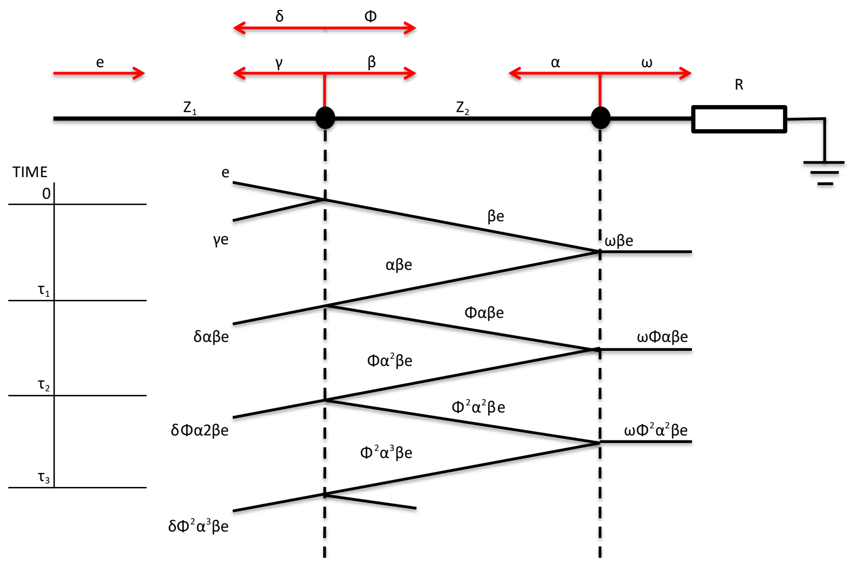

Figure 2-1 Bewley Lattice diagram

Where transmission factors:

$$\Phi = (Z_1 - Z_2)/(Z_1 + Z_2) \tag{2-1}$$

$$\beta = 2(Z_2)/(Z_1 + Z_2) \tag{2-2}$$

$$\omega = 2R/(R + Z_2\ ) \tag{2-3}$$

and reflection factors:

$$\delta = 2(Z_1)/(Z_1 + Z_2) \tag{2-4}$$

$$\gamma = (Z_2 - Z_1)/(Z_1 + Z_2) \tag{2-5}$$

$$\alpha = (R - Z_2)/(R + Z_2) \tag{2-6}$$

2.2.5 Surge Impedance and Velocity

The speed at which the voltage and current travelling waves propagates due to a transient event (such as lightning or switching overvoltages) is proportional to the cable or conductors surge impedance. The surge impedance is purely resistive meaning the voltage and current waveforms have the same shape.

The surge impedance and velocity is described within may be derived from the line inductance and capacitance as follows:

Surge Impedance:

$$Z = \sqrt{L * C}\ \Omega \tag{2-7}$$

$$v = 1/\sqrt{L * C}\ m/s \tag{2-8}$$

Where:

L is the inductance measured in μH/m.

C is the capacitance measured in μF/m.

2.2.5.1 Overhead Lines

The inductance and capacitance of overhead conductors may be defined as:

$$L = (2 * 10^{-7}) * \ln(2h/r)\ \mu\text{H/m} \tag{2-9}$$

$$C = (10^{-3}/18) * \ln(2h/r)\ \mu\text{F/m} \tag{2-10}$$

Where:

h is the conductor height above the ground measured in m.

r is the radius of the conductor measured in m.

The surge impedance and velocity therefore equates to:

$$Z = 60 * \ln(2h/r)\ \Omega \tag{2-11}$$

$$v = 300\ m/\mu s\ (speed\ of\ light) \tag{2-12}$$

2.2.5.2 Cables

The permittivity of the cables insulation medium significantly influences the resultant surge impedance and velocity. The inductance and capacitance of cable may be defined as:

$$L = (2 * 10^{-7}) * \ln(r_2/r_1)/\sqrt{k}\ \mu\text{H/m} \tag{2-13}$$

$$C = (10^{-3}/18) * \ln(r_2/r_1)\ \mu\text{F/m} \tag{2-14}$$

Where:

r_1 is the radius of the current carrying conductors measured in m.

r_2 is the radius of the outside cable insulation measured in m.

k is permittivity of the medium which varies from 2.4 to 4.

The surge impedance and velocity therefore equates to:

$$Z = 60/\sqrt{k} * \ln(2h/r)\ \Omega \tag{2-15}$$

$$v = 300/\sqrt{k}\ m/\mu s \tag{2-16}$$

2.2.6 Sequence Components

In normal (steady state) operation, an electrical power system operates in a balanced state. During a transient event such as lightning strike, the system becomes unbalanced and the displacement between each phase is no longer equal.

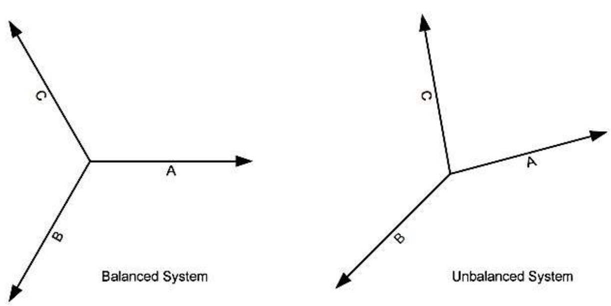

Figure 2-2 Balanced and Unbalance System (Marx & Bender 2013)

The method to solve unbalanced systems is by means of transforming the three phase voltages or currents into three sets of balanced vectors also referred to as positive, negative and zero sequence components (Figure 2-3).

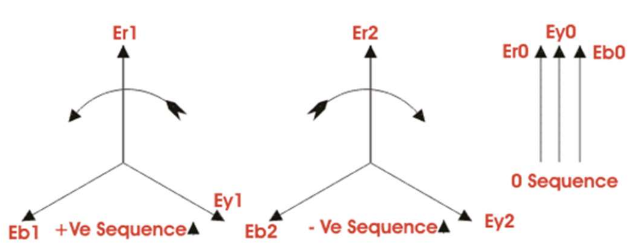

Figure 2-3 Sequence Components (Electrical4u 2011)

The complex operator ‘a’ is often utilised in the definition of symmetrical components and represents a unit phasor with a magnitude of 1 and an angle of 120°. The relationship between phase and sequence components is therefore:

$$\mathrm{E}_r = \mathrm{E}_{r0} + \mathrm{E}_{r1} + \mathrm{E}_{r2} \tag{2-17}$$

$$\mathrm{E}_y = \mathrm{E}_{y0} + \mathrm{E}_{y1} + \mathrm{E}_{y2} = \mathrm{E}_{r0} + a^2\mathrm{E}_{r1} + a\mathrm{E}_{r2} \tag{2-18}$$

$$\mathrm{E}_b = \mathrm{E}_{b0} + \mathrm{E}_{b1} + \mathrm{E}_{b2} = \mathrm{E}_{r0} + a\mathrm{E}_{r1} + a^2\mathrm{E}_{r2} \tag{2-19}$$

$$\mathrm{E}_{r0} = \frac{1}{3}(\mathrm{E}_r + \mathrm{E}_y + \mathrm{E}_b) \tag{2-20}$$

$$\mathrm{E}_{r1} = \frac{1}{3}(\mathrm{E}_r + r\mathrm{E}_y + r^2\mathrm{E}_b) \tag{2-21}$$

$$\mathrm{E}_{r2} = \frac{1}{3}(\mathrm{E}_r + r^2\mathrm{E}_y + r\mathrm{E}_b) \tag{2-22}$$

Positive (Z_1) and negative (Z_2) sequence impedances are equal in power system components such as transformers and overhead lines. For rotating machines they are different. Zero sequence (Z_0) impedance value may vary significantly depending on the physical arrangement of the circuit (Electrical4u 2011).

A lightning strike to overhead conductors is essentially either a phase to earth fault, or in some instances a double phase to earth fault. The equations to calculate sequence currents for earth faults are as follows:

Phase to Earth Fault Current (Electrical4u 2011)

$$\mathrm{I}_{r0} = I_{r1} = I_{r2}\left(\frac{E}{Z_0 + Z_1 + Z_2}\right) \tag{2-23}$$

Double Phase to Earth Fault Current (Electrical4u 2011)

$$\mathrm{I}_{r1} = \frac{E}{(\mathrm{Z}_1 + \frac{Z_2 Z_0}{Z_2 + Z_0})} \tag{2-24}$$

$$\mathrm{I}_{r2} = \mathrm{I}_{r1}\left(\frac{Z_0}{Z_2 + Z_0}\right) \tag{2-25}$$

$$\mathrm{I}_{r0} = \mathrm{I}_{r2}\left(\frac{Z_2}{Z_2 + Z_0}\right) \tag{2-26}$$

2.2.7 Steepness of Incoming Surge

The steepness of the incoming surge refers to the rate at which the surge reaches the peak or crest value.

Two different methods for deriving the steepness of the incoming surge have been presented:

$$S = K_c/d \ \mu s \tag{2-27}$$

(Hileman 1999)

$$S = 1/((1/S_0) \ + K_c * d \ \ kV/\mu s \tag{2-28}$$

(ABB high voltage technologies 1999)

Where:

K_c is the co-ordination factor.

S_0 is the initial surge steepness.

d is the incoming line length

Hileman's method uses assumed surge impedance values as shown in Table 2-1 for K_c (expressed in pF/kV-m) and calculates the length of the incoming line using the following:

$$d = 1/(BFR * MTBF) \ + x \ km \tag{2-29}$$

Where:

BFR is the backflash rate measured in flashovers/100km-years.

$MTBF$ is the mean time between failures measured in years.

x is an additional length added to align with the designed span length measured in km.

Table 2-1 Assumed Z_0 and K_c (Hileman 1999)

No. of conductors	Z_0 (Assumed)	K_c (Suggested)
1	450	700
2	350	1000
3 or 4	320	1700
6 or 8	300	2500

ABB approximates the value for K_c as $5 * 10^{-6}$ μs/kV-m and requires the incoming length of the line to be expressed in meters.

2.3 Lightning

There are around 2000 thunderstorms occurring simultaneously across the globe. This equates to an estimated 100 lightning flashes to ground every second, or 8 million per day (Hileman 1999). Despite this, the likelihood of a fatality due to being struck by lightning is in the order of 1 in 2,000,000 (AS1768 2007).

Average lightning density throughout Australia is highest across the northern coast of Western Australia and Northern Territory with 12 flashes per km^2, per year. In contrast, the New South Wales maximum is between 3 and 4 flashes per km^2, per year, coincidently located within Essential Energy's franchise area.

Electrical infrastructure is more susceptible to lightning strikes, which, when subjected to a lightning strike, results in a sudden disturbance to the system. Such transient events are akin to "closing a big switch" (Abdulwadood 2013) between the power line and a current source.

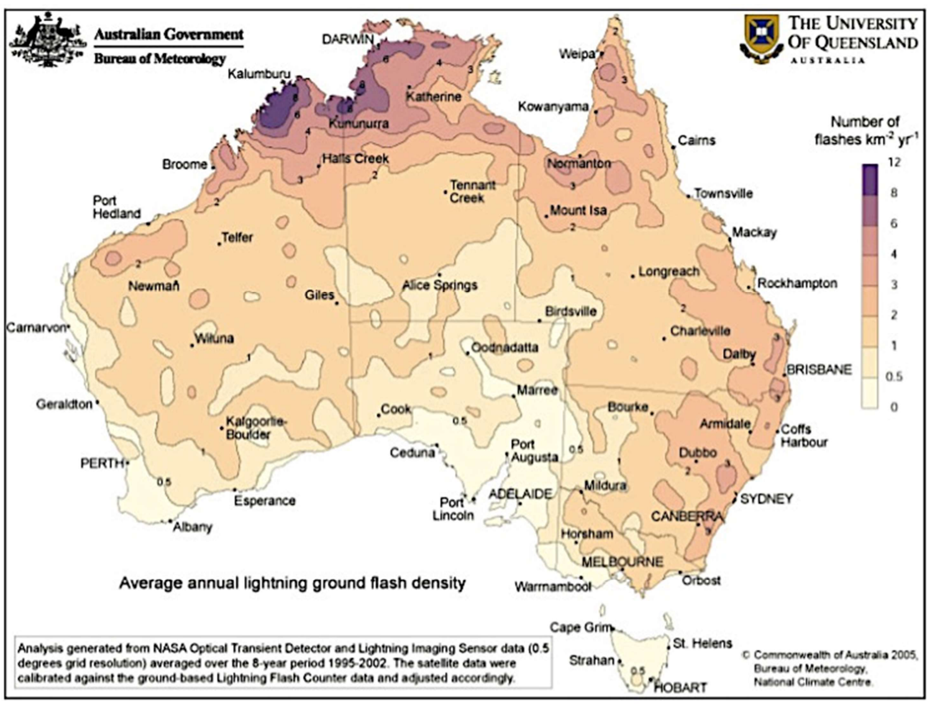

Figure 2-4 Lightning Density Map of Australia (AS1768 2007)

2.3.1 Lightning Process

As warm air close to the earth's surface rises into the atmosphere a resulting cloud formation develops with regions of positive and negatively charged particles. With the positive charged particles residing at the top of the cloud, and the negative charged particles at the bottom, both charges continue to increases until the air gap breaks down and a subsequent lightning strike develops.

The formation of a lightning strike may be categorized into two stages. The first stage begins with what is known as the stepped leader. Progressing slowly from the cloud towards the earth in intermittent steps of around 50m, this leader is not visible to the naked eye and contains comparatively small current between 50-200 amperes. The final stage involves an upward leader meeting the stepped downward leader resulting in the visible flash. Shockwaves produced as a result of the rapid rise of temperature in the upward leader (exceeding 25,000 degrees Celsius). The upward leader typically averages 5-6km in length and may discharge hundreds of thousands of amps. The extreme temperature rise as a result of this discharge current produces shockwaves that is heard as thunder. It is common for subsequent strikes to follow with the average being three per flash. Typically, the first strike is higher in magnitude than subsequent strokes.

2.3.2 Lightning Categories

Intra-cloud, cloud to cloud, and cloud to ground, are three common categories of lightning.

2.3.2.1 Intra-Cloud Lightning

Intra-cloud lighting, or IC lightning, is the most common category of lightning. The lightning discharge occurs between areas of differing potential within a single cloud with the corresponding lightning flash illuminating the night sky with a "sheet" of light, thus leading to intra-cloud lightning commonly referred to as sheet lightning.

2.3.2.2 Cloud to Cloud Lightning

The least common category of lightning is cloud-to-cloud or CC lightning. It occurs when there is an electrical discharge between two or more individual clouds.

2.3.2.3 Cloud to Ground Lightning

The lightning discharge in cloud to ground, or CG lightning, is defined by two terms. First is the lightning direction, which may be either downward (cloud to ground), or upward (ground to cloud) and secondly, the polarity of the charge, which may also be positive or negative in nature.

It wasn't until 1975, when Karl Berger undertook a study to record the parameters of lightning strokes. The data was analysed and initially, three types of lightning strokes were discovered; negative downward, negative upward and positive downward. A fourth type, positive upward was identified after Berger's initial study (Hileman 1999).

2.3.2.4 Negative Downward Stroke

Exhibiting a high median current value of around 33kA, the negative downward flash has been recorded as the most predominant type of lightning stroke, accounting for approximately 85-95% of flashes to structures less than 100m (Berger, Anderson & Kroninger 1975).

2.3.2.5 Negative Upward Stroke

More frequently observed with taller structures. In 1975, Berger found the negative upward stroke to have contributed to approximately 75% of the 1196 recorded lightning strikes upon both 70m and 80m masts installed at the summit of the 650m Mt San Salvadore in Switzerland. A lower median current value of less than 25kA is typical for this type of stroke (Berger, Anderson & Kroninger 1975).

2.3.2.6 Positive Upward Stroke

Known also as a "Super Flash", the positive upward stroke exhibits current magnitudes approximately 1.2 to 2.2 times those found during a negative downward stroke. More prolific during the winter season, and found over oceans, positive upward strokes generally exhibit a greater time from crest to half value (Berger, Anderson & Kroninger 1975).

2.3.2.7 Positive Downward stroke

Further analysis of Berger's study resulted in reclassification of positive upward stokes to a positive downward type. It is therefore taken that a positive stroke may be either upward or downward in nature (Hileman 1999).

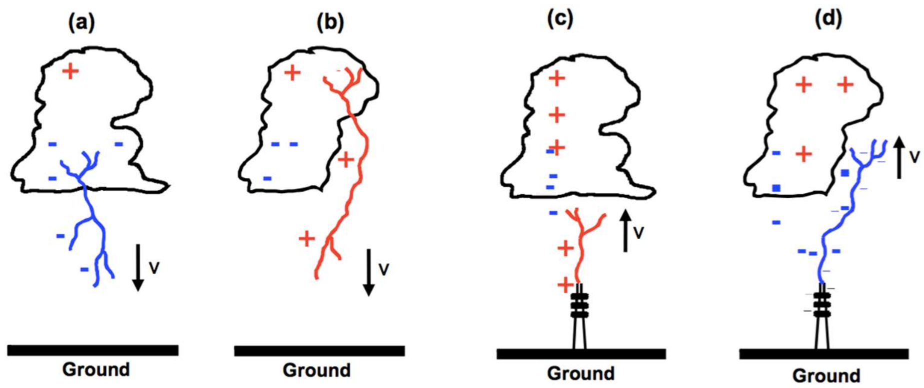

Figure 2-5 Lightning Strokes (a) Negative Downward (b) Positive Downward (c) Positive Upward (d) Negative Upward (Heidler et al. 2008)

2.3.3 Back Flashover

When lightning strikes the overhead earth wire, the discharge current flows through to earth, during which a voltage builds up across the line insulation. At the point this voltage exceeds (or equals) the line's critical flash over voltage, back flashover will occur (Hileman 1999).

2.3.4 Direct Lightning Strike

A direct lightning strike onto electrical equipment or overhead conductors will conduct to earth through the lightning protection system, or along any other metallic path, often resulting in unpredictable back flashovers (Thompson 2008). For 66kV systems, significant overvoltages are produced only by direct strikes (AS1824.2 1985). Such overvoltages may occur between the conductor and ground (V_{CG}) and conductor to conductor (V_{CC}).

The maximum overvoltages may be calculated by (Darveniza 2006):

$$V_{CG} = 0.5(I_p Z)\ V \qquad \text{2-30}$$

And

$$V_{CC} = 0.5(I_p Z)(1 - CF)\ V \qquad \text{2-31}$$

Where:

Z is the surge impedance.

I_p is the peak lightning current.

CF is the coupling factor between conductors.

2.3.5 Indirect Lightning Strike

Transient overvoltages induced onto adjacent or nearby conductors may result from resistive, inductive and capacitive coupling (Thompson 2008).

The maximum induced voltage may be expressed as (Darveniza 2006):

$$U_m = Z * K_p * I_p * (h + 0.15\sqrt{\rho})/d \;\; V \qquad \text{2-32}$$

Where:

Z is the surge impedance.

K_v is the return stroke velocity factor.

I_p is the peak lightning current.

ρ is the ground resistivity.

d is the distance from the line.

h is the height of the line.

It is universally agreed that induced overvoltages above 200kV are rare (Darveniza 2006), and as such would be of concern only to overhead lines and equipment less than 33kV.

2.3.6 Lightning Parameters

The geography across Essential Energy’s network varies from low lying coastal areas to mountainous regions above 1000m. Positive strokes have been discounted from this study on the basis that they are predominantly found over oceans, during winter and at the beginning and end of storms (Hileman 1999). Of the remaining negative polarity strokes, negative downward type is chosen due the higher median discharge current and the proven higher likelihood for striking structures less than 100m in height (typical of substation equipment).

2.3.6.1 Crest Current

The median crest (or peak) current for negative downward strokes has been recorded at 34kA (Hileman 1999). This value was derived through analysis of lightning strikes to structures below 60m in height across seven countries; Czechoslovakia (123), Australia (18), Poland (3), United States of America (44), Sweden (14), South Africa (11) and Switzerland (125).

Published lightning currents across Australia were not widely available. A more accurate representation of peak lightning current in south-eastern Australia is proposed. Reviewing Kuleshov (2012) identified a positive relationship between rainfall and cloud to ground lightning, with lightning activity across south-eastern Australia to be most prevalent between the six months from October to March.

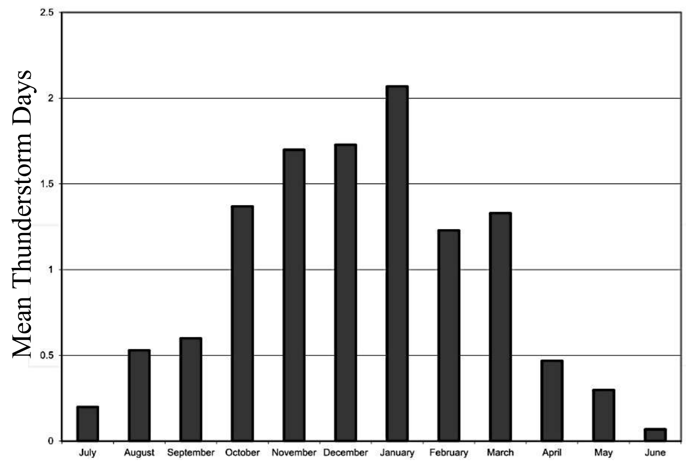

Figure 2-6 Seasonal Distribution of Monthly Mean Thunderstorm Days – Melbourne (Kuleshov 2012)

To derive a lightning magnitude value which represents an average of what would be expected across Essential Energy's network area, data on all recorded negative polarity, cloud to ground lightning strikes within an 800km radius of the regional city of Dubbo New South Wales, between October 2015 and March 2016 was obtained using Essential Energy's licence from Weather Zone online. The regional city of Dubbo was chosen as the location due to the geographical proximity to the centre of New South Wales, and ensured Essential Energy's entire network was captured.

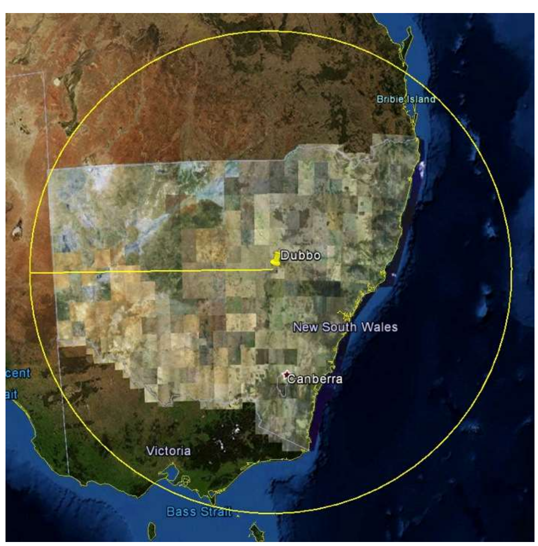

Figure 2-7 Lightning Capture Area (Google Earth 2013a)

The results found a total of 2,670,262 negative polarity cloud to ground strikes were recorded. The maximum magnitude was recorded at -383.5 kA, whilst the minimum was -0.1 kA. The average (mean) magnitude was calculated at -13.7 kA. This value shall be rounded to -14 kA for inclusion in simulations. Figure 2-8 below provides a probability density plot of the recorded lightning magnitudes from 0 kA to -46.5 kA (3 standard deviations from the mean).

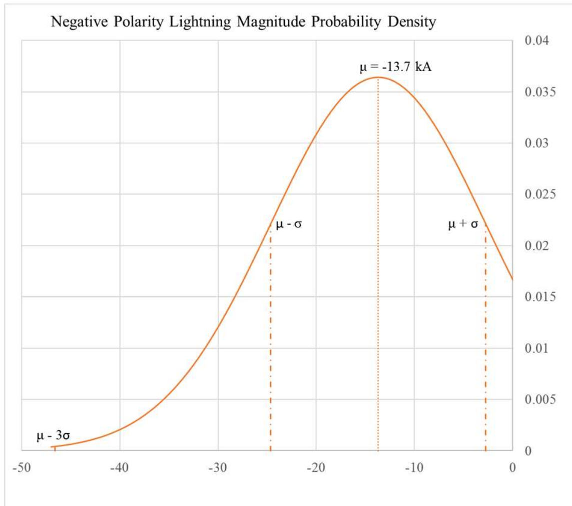

Figure 2-8 Negative Polarity Lightning Magnitude Probability Density Plot

2.3.6.2 Current Waveshape

As shown in Figure 2-9, the industry accepted lightning current waveshape is represented by the 8/20μs curve (AS1768 2007). This curve represents the lightning current increasing from 10% to 90% of its peak (crest) value in 8μs, and decaying to 50% of the crest value after 20μs.

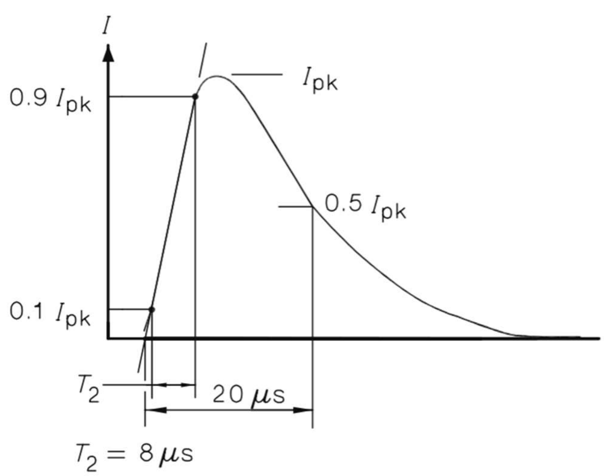

Figure 2-9 Discharge Current Waveshape (AS1768 2007)

2.3.6.3 Voltage Waveshape

As shown in Figure 2-10, the industry accepted lightning voltage waveshape is represented by the 1.2/50µs curve (AS1768 2007). This curve represents the lightning voltage increasing from 30% to 90% of its peak (crest) value in 1.2µs, and then decaying to 50% of the crest value after 50µs.

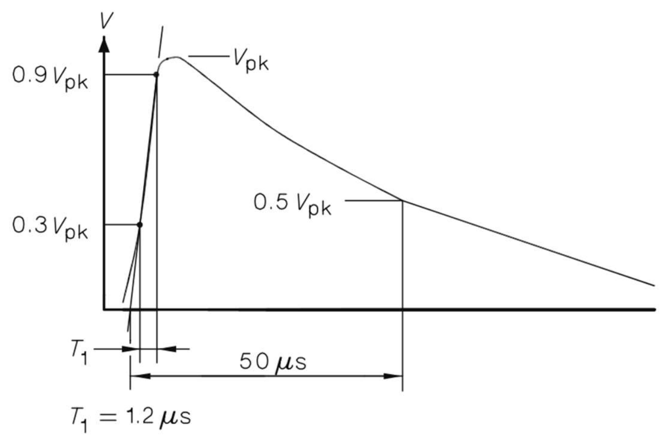

Figure 2-10 Open-Circuit Voltage Waveshape (AS1768 2007)

2.3.6.4 Number of Strokes per Flash

For positive lightning strokes, it is uncommon for more than a single stroke per flash (Hileman 1999). For negative polarity lightning strokes, Anderson and Eriksson (1980) have deduced from Berger's initial study that the average number of strokes is three. The time between each strike is between 40 to 50ms (Uman 1986)

2.3.6.5 Flash Incidence

Also known as Lightning Flash Density. It is used primarily to ascertain the level of risk lightning may pose to people and equipment. AS1768-2007 describes a risk analysis method, the need for lightning protection and protection levels applicable to structure types.

2.4 History of Surge Arresters

The first surge arresters (also known as lightning arresters) were developed over 100 years ago. They included a simple air gap between the line and the ground and provided excellent lightning protection, but could not clear power follow current without a large enough linear resistance connected in series (Sakshaug 1991). A surge arrester or fuse was therefore needed to break this current.

From the early 1900's through till around 1930, the first 'non-linear resister' type arrester was used. It comprised of an array of aluminium cells (inverted cones), each rated at 300V, separated by approximately 0.3 inches of electrolyte and placed in a tank of oil, which is connected in series to a sphere or horn gap (Sakshaug 1991). This type of arrester was very large, and required continual maintenance, but exhibited good current limitation properties.

Prior to the superseding of aluminium cell type arresters, 1920 to 1930 saw 'Oxide Film Arresters' introduced, with a modified version remaining in service until approximately 1954. An array of cells that contained lead peroxide and coated in an insulating film made up the internals of the arrester. Once subjected to a voltage surge, the resistance lowered allowing current to flow. This type of arrester allowed for many operations to be performed before reduction of the performance characteristics was experienced. Unlike the nonlinear resister type arresters of the early 1900's, the ability to handle power follow currents was achieved with the oxide film arrester (Sakshaug 1991).

The introduction of SiC arresters in 1954 heralded a major improvement in arrester design. Improvements to heating and erosion characteristics resulted in a reduction to the BIL of substation equipment protected by the arrester. The use of a porous gap plate material resulted in an arrester that was capable of withstanding high fault current (Sakshaug 1991) and significant reductions in the size of the arresters led to further economic benefits.

Modern day arresters are typically ZnO type units. They were introduced around 1976 and are also known as MO type without gaps (Hinrichsen 2012). ZnO arresters exhibit improved handling characteristics for switching surges as compared to SiC types. Improvements have been made in the reduction of arrester currents where SiC arresters would once have equalled 300 A, are now in the order of 1mA in MO type arresters. Arrester lead lengths have subsequently been reduced by approximately 10% (Sakshaug 1991).

2.5 Surge Arrester Design

There are a number of basic parameters that influence the design and operation of metal oxide surge arresters. Split into two categories, Electrical and Construction, they are listed below:

2.5.1 Electrical Characteristics

Defined by Australian Standards AS1842.1-1995 and AS1307.2-1996, key characteristics include:

a. Power Frequency Voltage (u)
b. Continuous Operating Voltage (U_c) Note: $U_c > u$
c. Rated Voltage (U_t)
d. Rated Frequency (f_r)
e. Lightning Impulse Protective Level (U_{ref})
f. Lightning Impulse Withstand Level (LIWL)
g. Single Impulse Energy Handling Capability
h. Thermal Energy Handling Capability

2.5.2 Construction Characteristics

The construction of MO surge arresters has been simplified significantly since the silicon carbide types used prior to the mid 1970's. Modern surge arresters tend to be of either porcelain or polymer construction.

The active components of both porcelain and polymer arresters operate in a similar fashion. The main difference is in the outer housing. The silicone rubber housing of polymer type surge arresters exhibit much improved hydrophobicity (Hinrichsen 2012). Suppression of contaminants forming a conductive path along the outer sheds is greatly reduced. Porcelain housed surge arresters are prone to explosive damage. In the event of failure to the outer housing, polymer surge arresters reduce the risk of damage to nearby equipment and injury to persons in close proximity.

Weight savings are achieved with utilising polymer type arresters when compared to porcelain. This of course will lead to more efficient handling and transportation along with reduced production and delivery costs.

2.5.2.1 Porcelain Construction

Components include:

a. Metallic Spacers
b. MO Resistor Column
c. Supporting Rods
d. Holding Plate
e. Compression spring
f. Cement Joint
g. Arrester Housing
h. Sealing Ring
i. Pressure Relief Diaphragm
j. Venting Outlet
k. Aluminium Flange

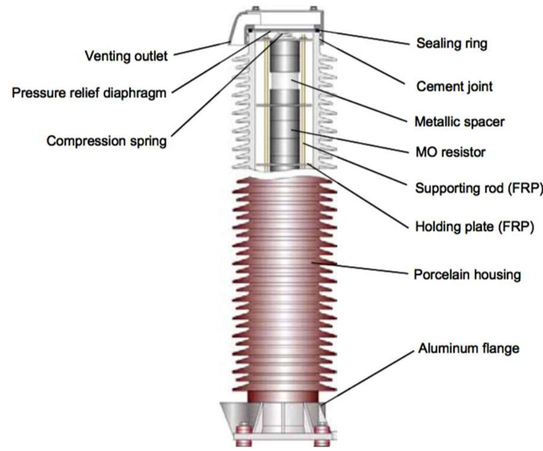

Figure 2-11 Porcelain MO arrester cross section (Hinrichsen 2012)

2.5.2.2 Polymer Construction

Key components include:

a. End Fitting
b. Outer housing
c. Metal Oxide resister stack
d. Fibre reinforced plastic support rods.

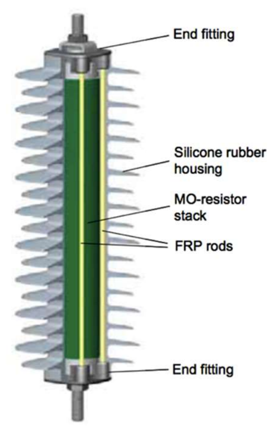

Figure 2-12 Polymer MO arrester cross section (Hinrichsen 2012)

2.5.3 Energy Handling Capability

The energy handling capability of surge arresters are related to the line discharge class of the arrester. There are five line discharge classes defined with AS1307.2-1996. Figure 2-13 shows the energy handling of each line discharge against the ratio of switching impulse to rated voltage of the arrester.

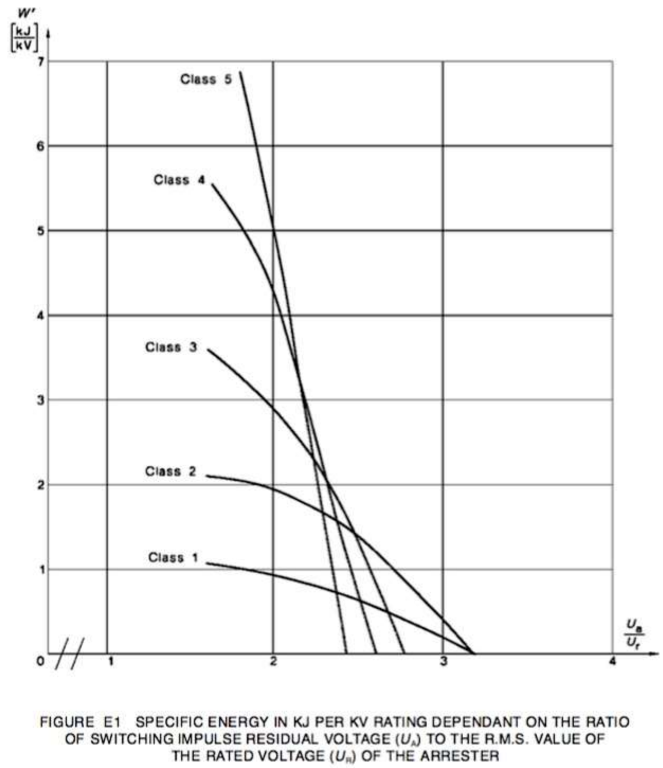

Figure 2-13 Surge Arrester Line Discharge Class (AS1307.2 1996)

2.5.4 Surge Arrester Models

The application of accurate surge arrester models is dependent on the chosen software package. For common software such as ATP/EMTP and Matlab, there are numerous papers comparing the V-I characteristics and accuracy of surge arresters through simulated models. The IEEE, Pincetti-Gianettoni, Fernando-Diaz and the Alternative Transients Program (ATP) developed model are four of the more common types that have been included for comparison in this report.

The following surge arrester models are relevant only to programs which derive solutions using time domain methods (for example ATP).

2.5.4.1 IEEE Model

Developed by the IEEE WG 3.4.11, this surge arrester model is often known as the 'conventional, or non-linear resistor' model for MOV type surge arresters (Bayadi et al. 2003).

As shown in Figure 2-14, the circuit consists of two non-linear resistances designated by A_0 and A_1 that are separated by an RL low pass filter. The values for A_0 and A_1 are given in Table 2-2. When subjected to fast rising transients, the RL circuit impedance becomes significant. Matching the dynamic characteristics of MOV type surge arresters, inductor L_1 derives greater current through A_0, and subsequently, a larger voltage across the arrester terminals. It is important to note that the value of L_1 will require adjustment until measured voltages match manufacturers data.

For slow transients, the two resistances are in parallel simulating arrester behaviour during normal system operation. Additionally, R_0 eliminates numerical oscillations, which may arise when using computer simulation, and C is the surge arrester external capacitance (Zadeh, Abniki & Akmal 2009).

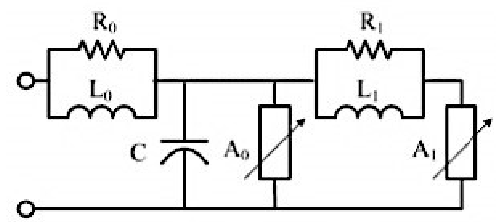

Figure 2-14 IEEE 'Conventional' Model (Abdulwadood 2013)

$$L_0 = 0.2 * (d/n)\ \mu H \quad \text{2-33}$$

$$R_0 = 100 * (d/n)\ \Omega \quad \text{2-34}$$

$$L_1 = 15 * (d/n)\ \mu H \quad \text{2-35}$$

$$R_1 = 65 * (d/n)\ \Omega \quad \text{2-36}$$

$$C = 100 * \left(\frac{n}{d}\right) pF \quad \text{2-37}$$

Where:

d is the surge arrester height.

n is the number of parallel metal oxide columns within the surge arrester.

2.5.5 Pincetti-Gianettoni Model

A variation to the IEEE model, R_0 and R_1 are replaced with a single shunt resistance R_0. As per the IEEE model, R_0 is included to eliminate numerical oscillations when running computer simulations. One advantage the Pincetti-Gianettoni model has when compared to the IEEE model is that the physical characteristics of the arrester are not required, simply manufacturers electrical data only (Christodoulou et al. 2008).

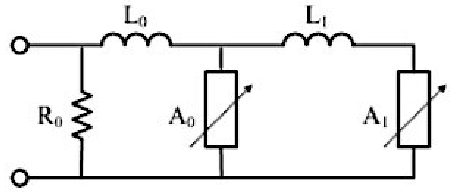

Figure 2-15 Pincetti-Gianettoni Model (Abdulwadood 2013)

$$L_0 = \frac{1}{12}\left(\frac{U_{r1/2} - U_{r8/20}}{U_{r8/20}}\right) * U_r \ \mu H \qquad 2\text{-}38$$

$$L_1 = \frac{1}{4}\left(\frac{U_{r1/2} - U_{r8/20}}{U_{r8/20}}\right) * U_r \ \mu H \qquad 2\text{-}39$$

$$R_0 = 1 \ M\Omega \qquad 2\text{-}40$$

Where:

$U_{r1/2}$ is the residual voltage at 10kA for a 1/2 μs fast front current surge in kV.

$U_{r8/20}$ is the residual voltage at 10kA for a 8/20 μs fast front current surge in kV.

U_r is the rated voltage.

2.5.6 Fernandez-Diaz Model

A variation of both IEEE and Pincetti-Gianettoni models, the Fernandez-Diaz model has been developed to simulate arrester characteristics when subjected to time to crest values 8μs and greater (Bayadi et al. 2003). Two non-linear resistances designated by A_0 and A_1 are separated by a single inductance L_1 whilst a single resistance R_0, and capacitance C_0 are connected across the arrester terminals. Again R_0 is included to eliminate numerical oscillations when running computer simulations, and C is the surge arrester external capacitance (Christodoulou et al. 2008).

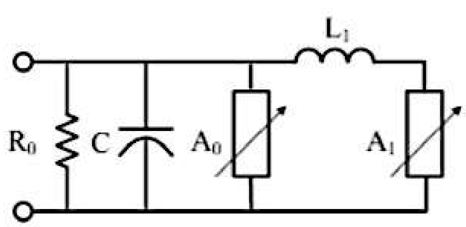

Figure 2-16 Fernandez-Diaz (Abdulwadood 2013)

$$L_0 = \frac{2}{5}\left(\frac{U_{r1/2} - U_{SS}}{U_{r8/20}}\right) * U_r\ \mu H \quad 2\text{-}41$$

$$C = \frac{1}{55}\left(\frac{U_{r1/2} - U_{SS}}{U_{r8/20}}\right) * U_r\ pF \quad 2\text{-}42$$

$$R_0 = 1\ M\Omega \quad 2\text{-}43$$

Where:

U_{SS} is the residual voltage at 500A for a 60/2000 µs current surge or 30/70 µs in kV .

$U_{r1/2}$ is the residual voltage at 10kA for a 1/2 µs fast front current surge in kV.

$U_{r8/20}$ is the residual voltage at 10kA for a 8/20 µs fast front current surge

U_r is the rated voltage in kV.

2.5.7 ATP Model

Utilised with computer software package ATP, the model consists of a number exponential, non-linear devices defined as:

$$I = p\left(\frac{v}{v_{ref}}\right)^q A \quad 2\text{-}44$$

(Meister, Shayani & de Oliveira 2011)

Where:

p is a coefficient.

q is the exponent defining the shape of the V-I characteristic.

v is the residual voltage

v_{ref} is an arbitrary voltage to normalize the equation.

A true representation of the surge arrester's non-linear V-I characteristic is given with this model however the arresters dynamic characteristic is not included (Abdulwadood 2013) The crest current and voltage are therefore calculated by the software as occurring at the same time.

2.5.8 Model Parameters

The values for non-linear devices A_0 and A_1 have been derived from experiments conducted by the IEEE WG 3.4.11. Their non-linear characteristics are shown in Table 2-2.

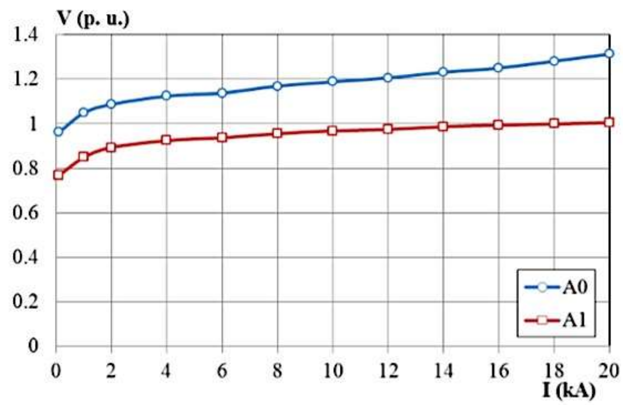

Figure 2-17 A_0 and A_1 V-I Characteristics (Abdulwadood 2013)

Table 2-2 A_0 and A_1 V-I Characteristics (Abdulwadood 2013)

I (kA)	V^* (p.u)	
	A_0	A_1
0.1	0.963	0.769
1	1.05	0.85
2	1.088	0.894
4	1.125	0.925
6	1.138	0.938
8	1.169	0.956
10	1.188	0.969
12	1.206	0.975
14	1.231	0.988
16	1.25	0.994
18	1.281	1
20	1.313	1.006

* The per unit voltage values are based on the 8.20 µs residual voltage of the arrester.

2.5.9 Model Accuracy

The recorded accuracy between the abovementioned surge arrester models is presented in Table 2-3. These results have been compared against measured results from actual surge arrester units within each respective reference.

Table 2-3 Surge Arrester Model Errors using 20kA 8/20μs surge

***I* = 20kA (8/20μs)**	***IEEE***	***Pincetti-Gianettoni***	***Fernandez-Diaz***	***ATP***
Zadeh, Abniki and Akmal (2009)	6.21%	10.92%	0.008%	-
Bayadi et al. (2003)	2.56%	2.89%	0.89%	0.56%
Christodoulou et al. (2008)	1.38%	0.87%	2.04%	-
Meister, Shayani and de Oliveira (2011)	0.84%	0.25%	1.6%	1.3%
Average Error	***2.75%***	***3.73%***	***1.13%***	***0.93%***

2.6 Surge Arrester Operation

A typical lightning strike may consist of one or more lightning strikes (or discharge) over a period of up to 1/3 of a second (Woodworth 2008). Surge arresters do not operate any differently between any of the four types of lightning described in section 2.3.2.

The surge arrester limits the surge magnitude seen by the equipment by 'dropping' voltage across its terminal to ground. This is known as its lightning impulse protective level or arrester discharge voltage. Figure 2-18 has been adapted from ABB high voltage technologies (1999) and provides a simple diagram to show the voltage drop across the arrester (E_d) and the remaining voltage (E_{eq}) that will be seen by downstream equipment.

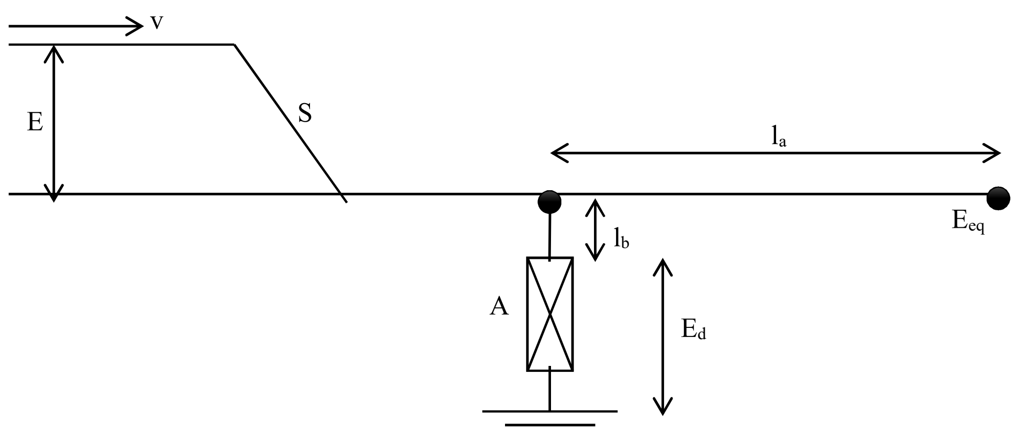

Figure 2-18 Simplified overvoltage diagram (ABB high voltage technologies 1999)

Where:

E is the crest voltage of the incoming surge.

v is the velocity of the incoming surge.

S is the steepness of the incoming surge.

A is the surge arrester.

l_a and l_b are the connecting line lengths between the equipment and the surge arrester.

E_d is the voltage drop across the arrester.

E_{eq} is the overvoltage seen at the downstream equipment.

2.7 Insulation Co-ordination

2.7.1 Insulation Types

Insulation types may be classified as Internal or External, and be either self-restoring or non-self-restoring in nature.

2.7.2 Basic Lightning Impulse Insulation Level (BIL)

Insulation co-ordination is critical to the reliability, longevity and effective operation of zone substation equipment and overhead power lines. The BIL rating of equipment defines "*the electrical strength of insulation expressed in terms of the crest value of a standard lightning impulse*" (Hileman 1999). It is also referred to as the equipment's Lightning Impulse Withstand Voltage. Effective co-ordination ensures the chosen surge arrester will adequately protect equipment. An example is shown in Figure 2-18 where if the overvoltage at point E_{eq} is greater than the equipment BIL rating, then damage to the equipment, network outages and inconvenience to large numbers of customers may result.

BIL may be split into two categories; Statistical and Conventional. Statistical BIL represents the impulse level by which there is a 90% probability of withstand, and 10% probability of failure, whilst Conventional BIL describes the level at which the equipment insulation is not affected after subjection to a number of impulses.

2.7.2.1 Insulation Degradation

The insulating medium in equipment such as transformers (paper, oil) deteriorate over time. Moisture absorption into paper insulation around the windings, contaminants (dirt, moisture, dissolved gasses) and expansion and contraction of the windings due to heat are common factors contributing toward this degradation (modulesdirect.com 2011).

2.7.2.2 Standard BIL Values

Table 3.1 within AS2067 (2016) defines the minimum lightning impulse withstand voltage (BIL) levels for equipment across various voltages. This table is included in APPENDIX B. These values are identical to those specified within IEEE Standard C62.81.1, and the procedure for selection of a suitable BIL rating is included in AS1824.1-1996. The standard BIL level for 66kV equipment is 325kV.

2.7.3 Critical Flash Over

An equipment's Critical Flash Over (CFO) rating is the voltage whereby there is a 50% probability that the insulation may fail. The CFO may be taken from a Gaussian cumulative distribution plot of insulation strength against probability of flashover (Figure 2-19), however calculation of the CFO can also be derived from the statistical BIL equation as shown by Hileman (1999) :

$$BIL = CFO(1 - 1.28(\sigma_f/CFO)\ kV \qquad \text{2-45}$$

Where:

σ_f is the coefficient of variation. For lightning, typical values for σ = 2 - 3% (Hileman 1999)

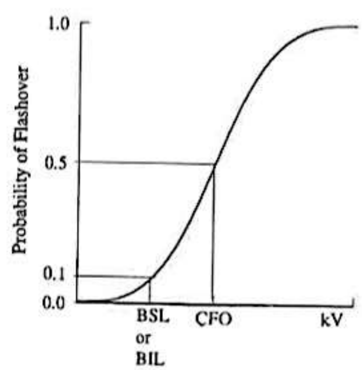

Figure 2-19 Insulation Strength Characteristic (Hileman 1999)

2.7.4 Basic Switching Impulse Level (BSL)

The BSL of equipment may be described similarly to BIL, however with respect to switching impulse in place of lightning. As described in section 2.2.2, switching impulses do not affect the operation of equipment at 66kV and are not included for study under this dissertation of literature review.

2.8 Surge Arrester Classification

The three classes of surge arresters commonly used on electricity networks are Station, Intermediate and Distribution class. Australian standard AS1307.2-1999 defines each arrester class based on standard nominal discharge current.

The minimum information a surge arrester must display on a permanently attached nameplate defined by AS1307.2-1999 is as follows:

a. Continuous operating voltage,
b. Rated voltage,
c. Rated frequency,
d. Nominal discharge current,
e. Pressure relief current (kA r.m.s)
f. Spark production class,
g. Manufacturers name and arrester type identification,
h. Assembling position of the arrester,
i. Year of manufacture,
j. Serial number.

2.8.1 Station Class

Exhibits superior electrical performance due to greater Basic Insulation Level (BIL), higher energy absorption, lower discharge voltages and greater pressure relief (Pryor n.d). Essential Energy utilise station class surge arresters within their zone substations as a standard.

2.8.2 Intermediate Class

Similar to station class, albeit with slightly reduced capabilities, intermediate class arresters are traditionally used within smaller substations, dry type transformers and underground cable protection (Pryor n.d).

2.8.3 Distribution Class

Essential Energy utilise this class of surge arrester on 11/22/33 kV distribution transformers and lines throughout its network.

2.9 Surge Arrester Protective Zone

The protective zone of the surge arrester defines the maximum distance the arrester may be located whilst limiting the residual voltage of the transient event below the BIL or BSL rating of the equipment. The further away the arrester is from the equipment terminals, increases the time that the equipment is subjected to the transient. The velocity, or propagation speed of the travelling wave and the rate at which the travelling wave peak is proportional to the peak value of the overvoltage at the equipment terminals.

Henriksen (2007) provides an example to estimate the protective zone of a surge arrester located near a transformer at the end of a single feeder:

$$x_s = \frac{U_{ref}/(1.15 - U_{pl})}{2 * s} * v\ m \qquad \text{2-46}$$

Where,

x_s = Protective zone in meters.

U_{ref} = Standard Lightning Impulse Withstand Level (BIL) of the equipment in kV.

U_{pl} = Lightning Impulse Protective Level in kV.

s = Front steepness of the overvoltage in kV/µs.

(Typical lightning values = 1000kV/µs for overhead line & 300kV/µs for underground cable (Hinrichsen 2012))

v = Propagation speed of the travelling wave in m/µs.

(Typical overhead line = 300m/µs & Underground cable = 150-210 m/µs (Hinrichsen 2012))

2.10 **Australian and International Standards**

2.10.1 AS1307 Surge Arresters

AS1307 consists of four parts:

Part 1: Silicon Carbide type for a.c. systems

Part 2: Metal-oxide surge arresters without gaps for a.c. systems

Part 3: Distribution type metal-oxide surge arresters with gaps for a.c. systems

Part 4: Application guide

2.10.1.1 AS1307.2-1996 Part 2: Metal-oxide surge arresters without gaps for a.c. systems

This standard is based on, and contains in full, IEC99-4 Surge Arresters, Part 4: Metal-oxide surge arresters without gaps for a.c. systems. It has been modified to suit Australian conditions, the objective of the standard is to detail the minimum requirements for testing gapless metal oxide surge arresters that are applied to a.c. systems (AS1307.2 1996).

Design, routine and acceptance tests described in this standard include:

a. Insulation withstand test
b. Residual voltage test
c. Long duration current impulse withstand test
d. Operating duty test
e. Pressure relief test
f. Arrester disconnector test
g. Partial discharge test
h. Seal test
i. Multi column arrester current distribution test
j. Verification of spark production

2.10.2 AS2067-2016 Substations and High Voltage Installations Exceeding 1kV a.c

Providing the minimum requirements for the design and construction of high voltage installations including zone substations, this standard is used extensively by Essential Energy, and forms the basis for the company's zone substation design guidelines; CEOP8032 – Transmission and Zone Substation Design Guidelines. The objective of this standard, and CEOP8032, is to ensure a consistent approach to the design and construction of installations such as zone substations, whilst also providing minimum safety and electrical clearances, BIL ratings, installation methods, equipment protection, labelling, building requirements, oil containment and earthing systems.

Minimum electrical and safety clearances to which equipment such as surge arresters shall comply (prior to additional dielectric tests) have been derived from AS1842.1-1995 and AS60038-2012 and tabled under table 3.1 of AS2067-2016 (APPENDIX B).

AS1768-2007 is referred to under the section of AS2067-2016 to describe methods for the protection of equipment against lightning strikes.

2.10.3 AS1768-2007 Lightning Protection

This standard defines the “guidelines for the protection of persons and property from hazards arising from exposure to lightning” (AS1768 2007). The standard adopts a risk assessment method for the determination of total risk against a direct lightning strike. Should this total risk be greater than an accepted level of risk, additional lightning protection schemes are required.

The primary method of reducing the risk utilises the rolling sphere technique, whereby an imaginary sphere is brought up to and rolled over the equipment. Any part of the structure that has been in contact, or protrudes through the surface of the sphere, is not protected from a direct lightning strike. The diameter of the sphere is based upon the protection level required to reduce the risk to below or equal to an acceptable level. Surge arresters installed on high voltage systems are included in this standard as additional protection measures against overvoltages and overcurrent’s.

Table 2-4 Protection Level and Rolling Sphere Radius (AS1768 2007)

Protection Level (PL)	Sphere Radius α (m)	Interception Current I_{min} (kA)
I	20	2.9
II	30	5.4
III	45	10.1
IV	60	15.7

2.10.4 AS1824 Insulation Co-ordination

AS1824 Consisting of two parts:

Part 1: Definition, principles and rules

Part 2: Application guide

2.10.4.1 AS1824.1-1995 Part 1: Definitions, Principles and Rules

The definitions and classifications presented in this standard form an integral link with not only part 2 of AS1824, but related standards such as AS1307, AS1931 and AS2067 that refer to terminology defined in AS1824 Part 1. The technical content of this standard has been derived from international standard IEC 71.1-1993 Insulation co-ordination, Part 1: Definitions, principles and rules.

Part 1 of AS1824 allows for the determination of standard insulation levels, and the requirements for testing, of equipment classified between two defined voltage ranges.

Range I: $1kV < U_m \leq 245kV$ Range II: $U_m > 245kV$

2.10.5 AS1824.2-1985 Part 2: Application Guide

Similar to AS1824 Part 1, this standard is derived from international standards IEC 71.2-1976 Insulation co-ordination, Part 2: Application guide, and IEC 71.3-1982 Insulation co-ordination, Part 3: Phase-phase insulation co-ordination, principles, rules and application guide. Three voltage ranges are individually addressed providing guidance on the selection of equipment insulation strengths.

Range A: $Between\ 1\ kV$ & $52\ kV$

Range B: $Between\ 52\ kV$ & $300\ kV$

Range C: $Greater\ than\ 300\ kV$

2.10.6 AS7000-2010 Overhead Line Design

In similar fashion to AS2067, this standard aims to provide an industry standard for new overhead line designs. The standard includes measures to improve the performance of the line against lightning overvoltages and provides guidance on insulation co-ordination between the overhead line and the zone substation. It is important to note however, that for the most part, the standard provides minimum requirements. Essential Energy has used AS7000-2010 as the basis for CEOP8032 Transmission and Zone Substation Design Guidelines. This corporate manual details all electrical, mechanical and civil design criteria for overhead and underground feeders. To cater to site specific, environmental and construction tolerances, Essential Energy guidelines exceed the specifications set out in AS7000-2010 in a number of areas such as electrical clearances to ground.

Table 2-5 Minimum 66kV Conductor Clearances to Ground

Standard	Distance to ground in any direction (m)		
	Over road or carriageway	Over land accessible by vehicles other than road or carriageway	Land not traversable by vehicles
CEOP8032	8.0	7.3	6.0
AS7000	6.7	6.7	5.5

2.11 **Computer Simulation Programs**

There are a number of software packages available to simulate the response of power systems during a high frequency transient event such as lightning. Alternative Transients Program (ATP) and the graphical user interface ATPDraw, Electromagnetic Transients Program (EMTP), Matlab-Simulink and TFlash are examples of the more common programs used extensively within literature documenting the effectiveness and suitability of each.

2.11.1 Simulation Accuracy

Using ATP-EMTP and Matlab-Simulink software, Danyek, Handl and Raisz (2002) simulated a single phase fault on a 60km, 120kV 3phase transmission line, connected to a 40MVA, 10kV load. Comparison of the results found ATP-EMTP performed superior to Matlab in a key areas such as constructability of the models, and in simulation run times. Calculation times took less than a quarter of the time at 15 seconds for ATP-EMTP versus 77 seconds for Matlab-Simulink. Both software packages obtained very similar results with the differences measured at less than 0.15% (Danyek, Handl & Raisz 2002).

Another popular software package used for analysis of lightning surges is TFlash. In order to determine insulator CFO and surge arrester energy discharge on a typical 22kV overhead distribution line 200m total length (four 40m spans), Thanasaksiri (n.d) compared models created in both ATP and TFlash which concluded similar results obtained by both programs.

2.11.2 Alternative Transients Program

Developed in 1984, ATP is a royalty free version of EMTP which provides a mechanism for simulation of electromagnetic and electromechanical system transients (Kizilcoy 2015). Of the common software packages noted in section 0 ATP shall be used as one of the simulation tools in this project.

To solve high frequency transient solutions ATP adopts time domain methods. The time domain method is applicable to solving for any unknown variables. Ordinary and partial differential equations are solved using implicit integration (trapezoidal rule – second order). The resultant simultaneous equations (nodal admittance form) are then solved by means of ordered triangular factorisation to obtain the unknown voltages (University of the Witwatersrand 2015).

2.11.3 ATPDraw

ATPDraw is a add on program providing a more convenient method of creating and working with ATP. The user has the ability to create and edit the ATP model, components and objects via the familiar Windows environment.

2.11.4 CDEGS

CDEGS is a comprehensive software package primarily designed to analyse earthing systems, electromagnetic interference, line and cable parameter computations, cathodic protection, lightning shielding and switching/lightning surges. Presently, Essential Energy utilise CDEGS to perform analysis on network earthing system performance. Several computational models are available within the software:

a) Soil Resistivity Analysis (RESAP)
b) Low Frequency Grounding/Earthing Analysis (MALT)
c) Frequency Domain Grounding/Earthing (MALZ)
d) Line and Cable Constants (TRALIN)
e) Electromagnetic Fields Analysis (HIFREQ)
f) Automated Fast Fourier Transform Analysis (FFTSES)
g) Simplified Fault Current Distribution analysis (FCDIST)
h) Fault Current Distribution and EMI Analysis (SPLITS)

2.11.4.1 Transient Analysis in CDEGS

Analysis of the lightning transient is undertaken over three main computational steps (SES Technologies 2006):

Step 1: Frequency decomposition of the time domain signal.

The lightning current defined by the double exponential type function is selected in the time domain:

$$I(t) = I_m(e^{-\alpha t} - e^{-\beta t})\ A \tag{2-47}$$

where,

I_m = peak current value.

α & β = time constants to determine rise and decay times.

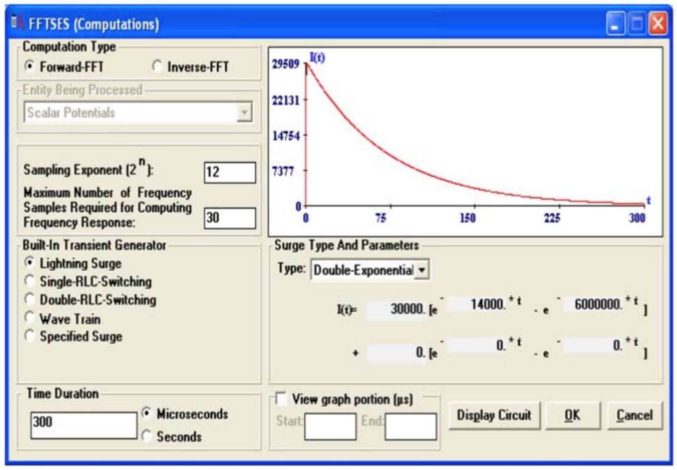

Figure 2-20 Example of Double Exponential Lightning Surge (SES Technologies 2006)

A Fast Fourier Transform (FFT) analysis is performed to represent the lightning source in the frequency domain. The recommended computational frequencies are then utilised by the software for the determination of electromagnetic field response in step 2.

Step 2: Computation of the frequency domain electromagnetic field response.

The construction of the physical network model is at the beginning of this step.

Scalar potential, electric and magnetic fields in the time domain are given as:

$$V(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} V_0(\omega)I(\omega)\, e^{i\omega t} d\omega \quad \text{2-48}$$

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} E_0(\omega)I(\omega)\, e^{i\omega t} d\omega \quad \text{2-49}$$

$$H(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} H_0(\omega)I(\omega)\, e^{i\omega t} d\omega \quad \text{2-50}$$

where,

$$I(\omega) = \int_{-\infty}^{+\infty} I(t)\, e^{i\omega t} dt \quad \text{2-51}$$

The physical quantities of the network are solved by fast fourier transform at the frequencies identified in step 1 obtaining:

$V_0(\omega)$ = unmodulated scalar potential

$E_0(\omega)$ = unmodulated electric field

$H_0(\omega)$ = unmodulated magnetic field

Step 3: Computation of the time domain electromagnetic field response.

An inverse fast fourier transform operation is conducted on $V_0(\omega)$, $E_0(\omega)$ and $H_0(\omega)$ to obtain their respective time domain response $V(t)$, $E(t)$ and $H(t)$.

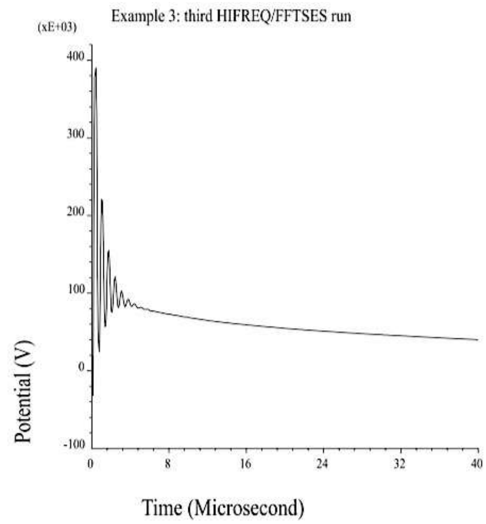

Figure 2-21 Example of Transient Voltage Response using CDEGS (SES Technologies 2006)

2.11.4.2 Analysis of non-linear devices in the frequency domain

Non-linear devices, such as switches and surge arresters, are quite difficult to model by means of frequency based solvers such as the Electromagnetic Fields Analysis (HIFREQ) module within CDEGS

An initial investigation was undertaken using CDEGS to model the system response to a 20kA lightning strike on an overhead line, 10km in length, with a 10mH inductor connected at the end.

The results appeared promising when compared to those calculated using ATP and are shown in Figure 2-22 and Figure 2-23 to validate the CDEGS. There were some minor discrepancies in the peak value of the reflected voltage surge (Dashed blue line in Figure 2-22 and green line in Figure 2-23) but overall the results were similar and considered acceptable.

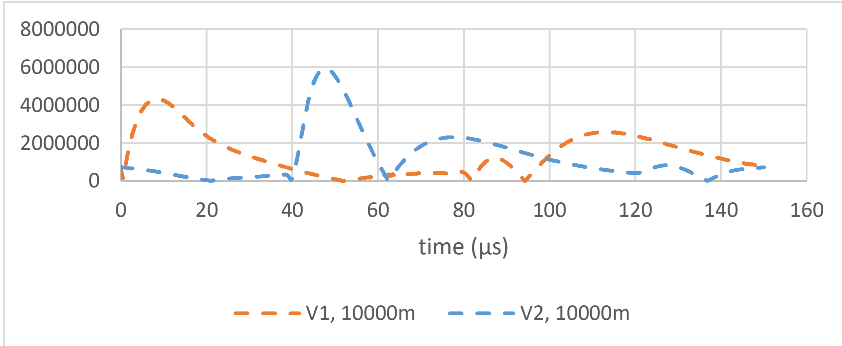

Figure 2-22 CDEGS Results 20kA, 10000m, 10mH Simulation

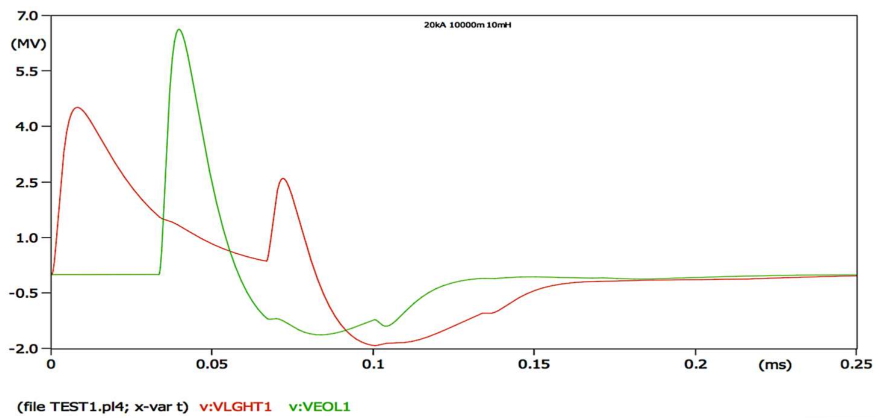

Figure 2-23 ATP Results 20kA, 10000m, 10mH Simulation

In 2001, a technique to model non-linear elements in the frequency domain was developed by W Ruan et al. (2001). This approach, utilising the fixed-point method to derive arrester currents was found to be an effective technique for purely resistive networks, but introducing inductive or capacitive elements often resulted in a failure to obtain a solution. Additionally, the method involved manual input of parameters by the user throughout the process.

In an attempt to address the issues presented by the fixed-point method, Stephane Franiette et al. (2015) applied a stochastic method called Simulated Annealing to the process of modelling non-linear devices.

The simulated annealing method was first developed in 1983 and is essentially an optimisation algorithm that "searches" for the best solution to the problem. The problem when modelling the surge arrester in CDEGS is the nonlinearity of a coefficient α, which is included in equation 2.52 to derive the arrester current, and defines the "squareness" of the V-I curve shown in Figure 2-24:

$$I = i_0 \left(\frac{v}{v_0}\right)^{\alpha} A \qquad \text{2-52}$$

(Stephane Franiette et al. 2015)

Where:

i is the current through the arrester in amps.

v is the voltage across the arrester in volts.

v_0 is the open circuit voltage of the network in volts.

α is the exponent defining the squareness of the arrester V-I characteristic.

The 2015 study by (Stephane Franiette et al. 2015) successfully modelled a network with five surge arresters. The simulated annealing process did however require the use of Matlab software and simulation time took approximately 60 seconds to converge for values of α ranging from 2 to 25.

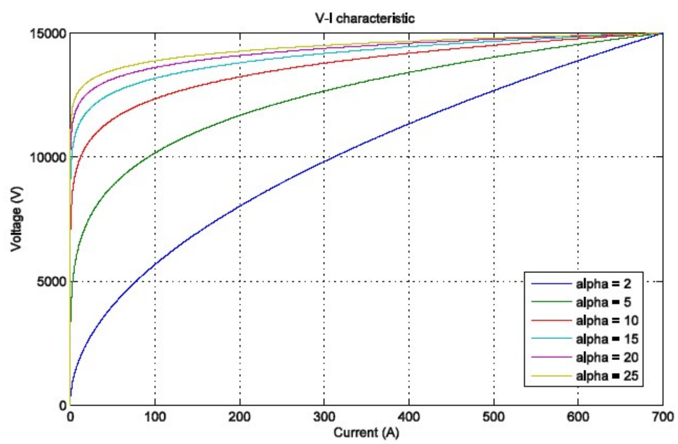

Figure 2-24 Typical MOV arrester V-I characteristics for various values of α (Stephane Franiette et al. 2015)

Further studies into the techniques developed by Stephane Franiette et al. (2015) were continued by Stephane Franiette et al. (2016) and improvements were made which saw solutions for values of α up to 45 achieved. Matlab was still required to perform the simulated annealing.

A promising aspect of this research is based around the improved accuracies of representing the impedances of elements such as poles using the frequency domain methods against time domain methods employed by programs such as ATP. Stephane

Franiette et al. (2016) showed that in their simulation, an inherent inaccuracy might be present when utilising time domain solution methods. For example, when using ATP a 24Ω pole impedance remains constant across a wide frequency range. Frequency domain methods take the physical and electrical characteristics of the pole into account and at low frequencies, calculate the impedance similar to the 24Ω of ATP. At higher frequencies, close to the components resonant frequency ~1.7MHZ, the calculated impedance within CDEGS was 274.3Ω. It was noted that these inaccuracies could extend to all components.

2.11.5 Software Determination

It would appear at this stage that CDEGS has not quite reached a stage where it may be used as an efficient tool in the calculation of peak overvoltages when non linear devices are included in the simulation. The multi-staged approach involving the use of additional software such as Matlab to complete, and limitations of the simulated annealing method which as of today do not have the ability to solve for all typical values of α contribute to the determination that the software used to complete the network simulations in this report shall incorporate time domain solution methods.

ATP/EMTP, Matlab-Simulink and TFlash all possess the capability to be used accurately, but of the three, ATP is free to use and requires no licences to run. This provides cost savings to Essential Energy. Additionally, although training will be required, this is common for all software.

3 CASE STUDIES

3.1 Introduction

Two case studies are presented in this report. The first has been developed from standard design templates both for the incoming 66kV overhead line and the 66/11kV 20/30MVA zone substation. The second case study is an in-service 66/11kV substation, located at Kywong, a rural locality in south-western NSW.

3.2 Case Study 1 - Standard Overhead Line and Zone Substation

3.2.1 Standard Overhead Line

There are approximately 12000 km of subtransmission lines across Essential Energy's franchise area of which 66kV lines contribute to approximately 64% (Essential Energy 2014i). Of the many differing overhead line constructions presently in service across the 66kV subtransmission network, the most common construction types include: Delta, vertical, cross arm and a half, Wishbone, Suspension and H-pole.

Essential Energy utilise a number of standard design templates for 66kV line constructions are included in APPENDIX C. For this report the standard 66kV intermediate delta construction method CEOM7401.24 (including OHEW) is chosen, and included in APPENDIX D. Whilst a single construction has been used in this case study, in reality, a combination of many construction types would be required. This would be based on factors which include the line route, span length, underbuilt distribution circuits, environmental factors including river and railway crossings and, the required line design temperature to name but a few. Typically, surge arresters are not installed along the overhead line. Further detail on the overhead line design methodologies has been included in section 4.2.

3.2.2 Standard Zone Substation

The standard 66/11kV substation arrangement consists of two incoming HV feeder bays, a transverse HV busbar, two HV transformer bays, and two 20/30MVA DYn1 power transformers. Surge arresters are installed at the substation entrance and on the primary and secondary sides of each transformer. A single line diagram, general arrangement and section views of the primary equipment are included in APPENDIX F.

The standard substation design shall be modelled with only a single incoming feeder, and single transformer in service. This arrangement is commonly used in practice and ensures the maximum possible distance between surge arrester sets. Further detail regarding the substation design methodologies has been included in section 4.3.

3.3 Case Study 2 - Kywong Zone Substation

3.3.1 Overhead Line 840/3 and 840/4

Kywong zone substation may be supplied via either the 66kV line *840/3 Lockhart Tee Regulator to Kywong Tee* or line 840/4 *Narrandera to Kywong Tee*. Both feeders are connected one span outside the substation, from which a single line (tee) then extends into the substation.

The line construction primarily utilises cross arm and a half construction with suspension insulators similar to Figure 3-1. No OHEW exists on either feeder 840/3 or 840/4.

Figure 3-1 Typical 66kV Construction Feeder 840/3 & 4

Further detail regarding the overhead line design methodologies has been included in section 4.2.

3.3.2 Zone Substation

The 66/11kV Kywong zone substation is a typical example of a small rural substation within Essential Energy's network. It is located approximately 66km west of the city of Wagga Wagga and 36km east of the town of Narrandera. The substation reaches a peak load of close to 1MVA. It possesses the following characteristics that have contributed to the determination as a viable case study in this report:

- Susceptible to prolonged outage times. Response time for nearest Essential Energy staff is between 30 minutes to one hour.
- Wheat storage silos are located opposite the substation and, in the event of a substation fire, they could be at risk of significant damage.

A single line diagram, general arrangement and section views of the primary equipment are included in APPENDIX F.

Further detail regarding the substation design methodologies has been included in section 4.3.

4 DESIGN METHODOLOGIES

4.1 Introduction

This chapter aims to detail the characteristics and methodologies associated with the overhead transmission line and zone substation designs used in creation of ATP models of both case studies defined in chapter 3.

4.2 66kV Subtransmission Lines

4.2.1 Standard 66kV Intermediate Delta Construction

The standard 66kV intermediate delta construction method detailed in APPENDIX D has been developed from Essential Energy Subtransmission Line Design Manual CEOM7081 (Essential Energy 2015c), which in turn has been based upon specifications contained within AS7000-2010.

The delta configuration allows for greater ground clearance when compared to alternative constructions such as vertical arrangements. Figure 4-1 provides an overview of the pole top arrangement chosen for case study 1.

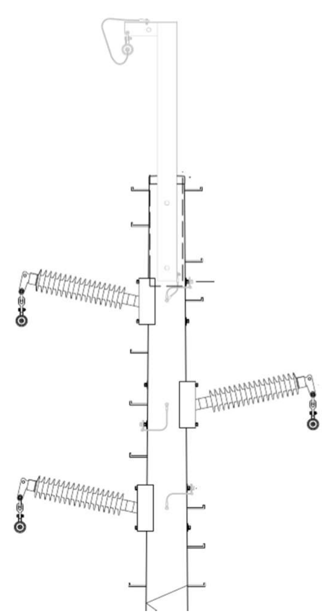

Figure 4-1 66kV Intermediate Delta Construction (Essential Energy 2014h)

With a large number of different pole heights and strengths available to ensure minimum electrical clearances are maintained, Essential Energy has specified two standard pole heights. 21m tall Type 1 poles are used on intermediate structures, and 24m tall type 2 poles for flying angle and strain structures (Essential Energy 2015c).

Prestressed concrete or steel poles have been Essential Energy's preference until late 2015. Ease of transport, installation, lower cost, and proven longevity has changed this preference to timber. The simulation shall be made using 21m tall timber poles. Pole embedment into the ground is calculated using:

$$d = 0.8 + (0.1 * h)\ m \tag{4-1}$$

Where:

d is the pole embedment depth (m)

h is the pole height (m)

Therefore using a 21m tall pole:

$$d = 0.8 + (0.1 * 21)\ m$$
$$d = 2.9\ m$$
$$\therefore d \approx 3\ m$$

With the pole top height aboveground reducing by almost 3 meters, the conductor and OPGW attachment heights become:

A-Phase (Top) = 21-3-1*=17m

B-Phase (Middle) = 21-3-2*=16m

C-Phase (Bottom) = 21-3-3*=15m

OPGW = 21-3+1*=19m

*Dimensions have been estimated from Essential Energy (2014h)

4.2.2 66kV Feeders 840/3 & 840/4 Construction

The 66kV overhead lines supplying Kywong zone substation are made up of several different construction types. The most common type, known as cross arm and a half (Figure 1-1) has been selected as the construction type for the simulation models of case study 2.

Both feeders were initially constructed in the late 1960's and have undergone a number of upgrades such as insulator and cross arm replacements to rectify defects or replacement due to failure. No detailed design or construction drawings exist, therefore the pole height has been estimated to establish simulation model parameters.

An 18.5m pole length is commonly used when replacing condemned poles. This height ensures minimum ground clearances are maintained and applying equation 4.1 the pole embedment is calculated at 2.5m.

There is no OHEW or OPGW on these lines and the phase conductor attachment heights are:

A-Phase (Top) = 18.5-2.5-1*=15m

B-Phase (Bottom Left) = 18.5-2.5-2.5*=13.5m

C-Phase (Bottom Right) = 18.5-2.5-2.5*=13.5m

* Estimated dimensions.

4.2.3 Maximum Operating Temperature

The maximum operating temperature is proportional to the required load capacity of the line. An increase to the operating temperature will cause greater conductor sag, ultimately requiring a reduced span length. Typical operating temperatures for 66kV lines include 50°C, 65°C, 75°C or 85°C (Essential Energy 2015c). 85°C has been chosen for case study 1 and 50°C for case study 2.

4.2.4 Maximum Span Length

An assumed span length of 200m has been used for case study 1. This is typical of average span lengths along semi-rural and rural feeders within Essential Energy's network.

Case study 2 incorporates a span length of 160m. The average span length of the first 10 poles along each of the 840/3 and 840/4 feeders was obtained from Essential Energy's Graphical Information System (GIS), known as Smallworld and is detailed in Table 4-1.

Table 4-1 Feeder 840/3 and 840/4 Span Lengths

Span	Span Length (m)	
	840/3	840/4
1	174	183
2	196	182
3	179	176
4	38	202
5	38	202
6	196	183
7	192	183
8	67	176
9	87	182
10	199	160

4.2.5 Phase Conductors

For transmission lines older than 40 years, common conductor types include 6/0.186 + 7/0.062 Aluminium Conductor Steel Reinforced (ACSR), 7/0.104 Galvanised Steel (SC/GZ), 19/2.00 and 7/0.104 Hard Drawn Bare Copper (HDBC). For new subtransmission lines, Essential Energy specifies two similar conductor types suitable for use as the standard 66kV conductor, 37/3.00 Nitrogen and 37/3.75 Phosphorous All Aluminium Alloy Conductor (AAAC) (Essential Energy 2015c).

Phosphorous is chosen for case study 1 whilst 19/2.00 HDBC is installed on both 840/3 and 840/4 feeders (case study 2).

Physical and electrical properties for both case studies are shown below in Table 4-2 and Table 4-3.

Table 4-2 66kV Phase Conductor Physical Properties

Case Study	Conductor	Strands/Wire Diameter (mm)	Conductor Type	Cross Sectional Area (mm^2)	Diameter (mm)
1	Phosphorous (Essential Energy 2015c)	37/3.75	AAAC/1120	409	26.3
2	19/2.00 (Nexans 2012)	19/2.00	HDBC	59.7	10.0

Table 4-3 66kV Phase Conductor Electrical Properties

Case Study	Conductor	Resistance	Current Rating
		D.C. @ 20°C (Ω/km)	Summer Noon (Amps)
1	Phosphorous (Essential Energy 2015c)	0.090	809
2	19/2.00 (Nexans 2012)	0.303	337

4.2.6 Overhead Earth Wire

Overhead earth wires provide an effective method to shield phase conductors against direct lightning strikes. The shielding angle (α) is the angle between the overhead earth wire, and each outside phase conductor. The determination of the perfect shielding angle has been the subject of many studies. Hileman (1999) deduces the perfect value for α as:

$$\alpha_p = \frac{r_g}{r_c} - \frac{1}{r_c((h+y)/2)} \ degrees \qquad 4\text{-}2$$

Where:

r_g = Height above ground where intersection of arcs of radii r_c is made (Figure 4-3).

$r_c = 0.67y^{0.6}I^{0.74}$ (Phase Conductors)

$r_c = 0.67h^{0.6}I^{0.74}$ (Earth Wire)

I = Maximum shielding failure current.

h = Earth wire height above ground.

y = Phase wire height above ground.

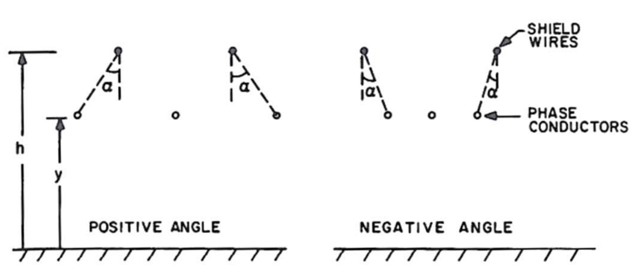

Figure 4-2 Shielding Angle (α) (Hileman 1999)

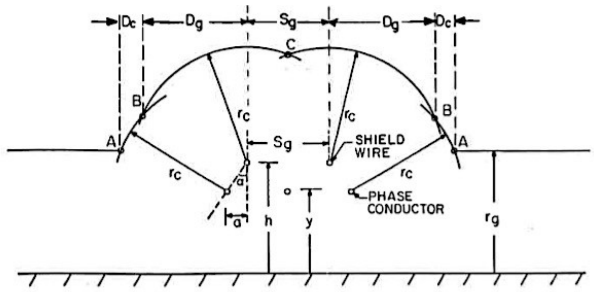

Figure 4-3 Geometric model depicting angle alpha (Hileman 1999)

Conservative values for varying structure heights have been tabulated by Darveniza (2006) and reproduced in Table 4-4. These compare with Essential Energy designs that have resultant shielding angles for Type 1 construction of 25° & 29° (Figure 4-4). Overhead feeders that incorporate effective overhead earth wires achieve lightning outage rates exceeding 1/100km years, essentially becoming “lightning resistant” lines (Darveniza 2006).

Table 4-4 Overhead Earth Wire Shielding Angles (Darveniza 2006)

Height (m)	α(°)
20	35 - 40
30	25 – 30
40	15 – 20
50	5 - 10

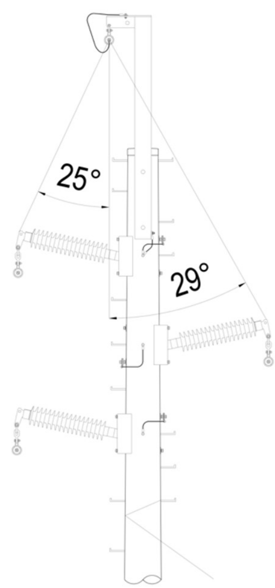

Figure 4-4 Essential Energy Type 1 Construction Shielding Angles

(Essential Energy 2014h)

4.2.7 Optical Fibre Ground Wire

Essential Energy incorporates 48 or 96 core Optical Fibre Ground Wires (OPGW) in lieu of typical overhead earth wires as standard on all new 66kV subtransmission lines. The optical fibre communication path provides additional benefits compared to traditional overhead earth wires through improved unit protection schemes and substation communication paths as per requirements set out by the Australian Energy Market Operator (AEMO). The OPGW conductor consists of an outer, conductive layer used for the transmission of fault current, with the optical fibres contained within an inner, second layer. 96 core OPGW is the most common size installed on new Essential Energy transmission lines and is chosen as the overhead shielding wire for case study 1.

As previously mentioned in Sections 3.3.1 and 4.2.2, no OHEW exists on the 840/3 and 840/4 feeders in case study 2.

Table 4-5 66kV OPGW Conductor Physical Properties

Case Study	Conductor	Strands/Wire Diameter (mm)	Cross Sectional Area (mm^2)	Diameter (mm)
1	96 Fibre OPGW (Essential Energy 2015c)	4/3.35 (Layer 1) 13/3.05 (Layer 2) 2/3.3 (Centre Tube)	139.6	16.25

Table 4-6 66kV OPGW Conductor Electrical Properties

Case Study	Conductor	Resistance
		D.C. @ 20°C (Ω/km)
1	96 Fibre OPGW (Essential Energy 2015c)	0.284

4.2.8 Conductor Sag

The method used to calculate conductor sag has been included in Appendix H. For both case studies this equated to 3 m for phase conductors. The sag on the OPGW conductor of case study 1 was 2 m.

4.2.9 Insulators

The 66kV insulators used for case study 1 have been specified as part of Essential Energy's current period contract. The physical and electrical properties are shown in Table 4-7.

Table 4-7 Case Study 1 - Insulator Properties

Insulator Manufacturer	Apex Insulator Systems
Catalogue Number	H2 90 10 027 MX SS 014
Pos. Critical Impulse flashover (kV)	495
Neg. Critical Impulse flashover (kV)	589
Pos. Minimum Withstand (kV)	443
Neg. Minimum Withstand (kV)	478
Length (L) (mm)	955

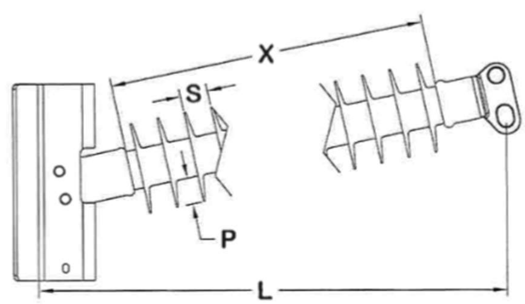

Figure 4-5 Case Study 1 - Insulator Arrangement

A variety of insulators are present along 66kV feeders 840/3 and 840/4. The selected type chosen for inclusion in case study 2 is a porcelain four disc suspension type similar to shown in Figure 4-8Figure 4-8 Case Study 2 - 66kV Insulator. Installed insulator characteristics are unknown, however physical and electrical properties used in simulations have been derived from Preformed Line Products (2014) and shown in Table 4-8.

Table 4-8 Case Study 2 - Insulator Properties (Preformed Line Products 2014)

	Single Disc	Total
Pos. Minimum Withstand (kV)	100	400
Neg. Minimum Withstand (kV)	100	400
Length (L) (mm)	146	585

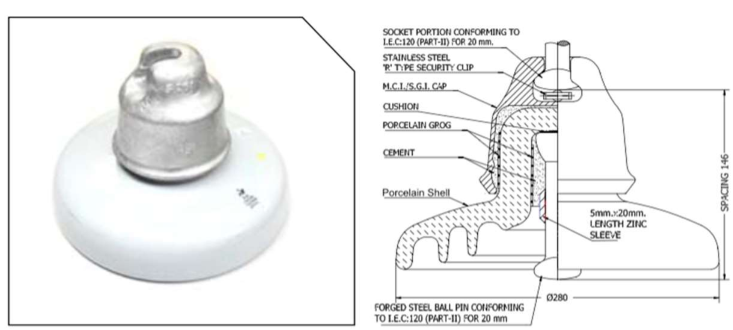

Figure 4-6 Case Study 2 - Insulator Arrangement (Preformed Line Products 2014)

4.3 Template Zone Substation Design

4.3.1 Introduction

The physical layout, equipment specifications, and electrical characteristics such as thevenin impedance values, earth grid resistance and fault levels vary considerably from one zone substation to another. Case study 1 is representative of Essential Energy's most recent standard design for construction and augmentations to zone substations across its network. Case study 2 (Kywong zone substation) is far less complex and represents a typical rural zone substation.

4.3.2 Minimum Electrical Clearances

In both case studies, the minimum electrical clearances for 66kV equipment meet or exceed those set out within AS2067-2010 and are summarised in Table 4-9.

Table 4-9 66kV Minimum Electrical Clearances

Case Study	Nominal Voltage (kV)	Minimum Phase to Earth Clearance (mm)	Minimum Phase to Phase Clearance (mm)
1	66	770	1500
2	66	770	1500
AS2067-2010	66	630	725

4.3.3 Lightning Protection

The substation lightning protection has been determined using the 30m rolling sphere method defined within AS1768-2007 with protection of equipment to a maximum height of 7m is maintained throughout the entire yard (Essential Energy 2014g).

For case study 1 this consists of; 66kV landing span structures for each incoming feeder, a 20m high communication tower and 13m tall galvanised steel lightning masts, (each complete with an additional 1.2m high spire).

With case study 2, the Kywong zone substation does not achieve the minimum standards for lightning protection although two lightning spires provide coverage for the transformer.

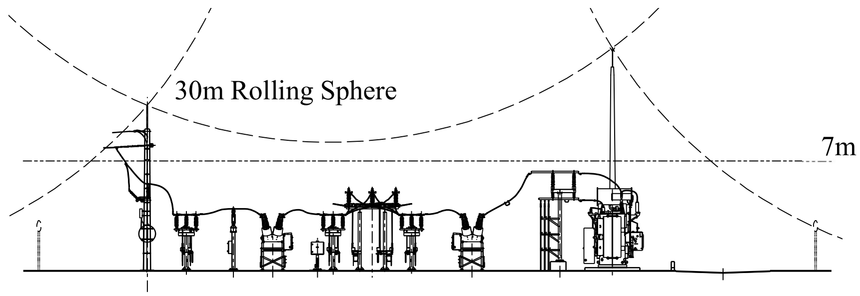

Figure 4-7 Case Study 1 - Lightning Protection Using 30m Rolling Sphere (Essential Energy 2014f)

4.3.4 Lightning Protection Level

AS1768-2007 defines four lightning protection levels against direct lightning strikes. In accordance with AS1768-2007 Table 4.2, Essential Energy's standard substation design provides a protection level of II, and thus a lightning interception current of 5.4 kA. Interception efficiency of protection level II is 97% and, the resulting lightning protection system efficiency becomes 95%.

4.3.5 Insulators

Both case studies utilise the same porcelain post insulators detailed in Table 4-10.

Table 4-10 66kV Zone Substation Post Insulators (AK Power Solutions PTY LTD 2012)

Insulator Manufacturer	NK Power Solutions
Lightning Impulse Withstand Voltage (kVp)	340
Dry Power Frequency Withstand Voltage (kV)	205
Wet Power Frequency Withstand Voltage (kV)	160
Length (L) (mm)	770

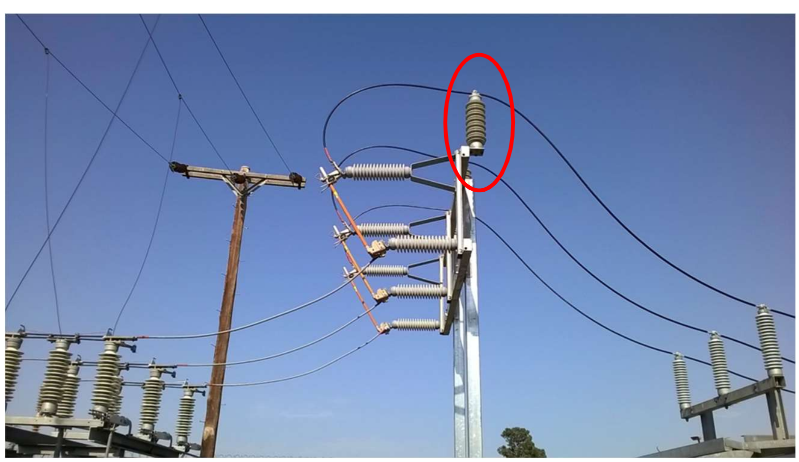

Figure 4-8 Case Study 2 - 66kV Insulator

4.3.6 Equipment

Major equipment included in both case studies consist of air break switches also known as disconnectors, voltage transformers, gas insulated circuit breakers (case study 2 contains a 66kV fuse in lieu of a circuit breaker), power transformers and busbar support structures. The layout of the equipment is included in APPENDIX E (case study 1) and APPENDIX F (case study 2).

4.3.7 Zone Substation Primary Conductors

For spans less than 4 m in length, AAAC/1120 61/3.25 Selenium conductor is used for the zone substation flexible primary conductor of case study 1. Where 4 m spans are exceeded, hollow aluminium (rigid) tubular busbar is used.

No recorded information is available for identification of the conductors used in case study 2. Refurbishment of Kywong zone substation has been completed within the last 10 years and recent photographs indicate CCT used throughout the 66 kV section of the zone substation. 180 mm^2 (19/3.50) 19/33 kV rated CCT is assumed for case study 2. Additionally, no rigid busbar is installed at Kywong zone substation.

Table 4-11 66kV Zone Substation Primary Conductor Physical Characteristics

Case Study	Conductor	Strands/Wire Diameter (mm)	Conductor Type	Cross Sectional Area (mm^2)	Diameter (mm)
1	Selenium (Nexans 2012)	61/3.25	AAAC/1120	506	29.3
1	Tubular Busbar (Preformed Line Products 2012)	100mm OD & 4mm WT	6101 T6 Aluminium Alloy	1206	100
1	Nitrogen (Nexans 2012)	37/3.00	AAAC/1120	262	21.0
2	180 CCT (Nexans 2012)	19/3.50	AAAC/1120 CCT	180	34.2

Table 4-12 66kV Zone Substation Primary Conductor Electrical Characteristics

Case Study	Conductor	D.C. Resistance	Current Rating
		(Ω/km)	Summer Noon (Amps)
1	Selenium (Nexans 2012)	0.0592 (@ 75°C)	912
1	Tubular Busbar (Preformed Line Products 2012)	0.030 (@ 20°C)	2064
1	Nitrogen (Nexans 2012)	0.114 (@ 20°C)	336
2	180 CCT (Nexans 2012)	0.163 (@20°C)	430

4.3.8 Substation Earth Grid

To ensure electrical hazards arising through fault currents to ground are not transferred to people, the substation earth grid is designed to ensure maximum EPR levels and step & touch potentials do not exceed the limits set out within AS1768-2007.

Essential Energy standards recommend 95mm^2 Hard Drawn Bare Conductor (HDBC) buried at a depth of approximately 500mm to be installed throughout the substation and around the perimeter of the security fence to form the earth grid. A number of vertical copper clad steel electrodes are also positioned throughout the grid. Essential Energy's substation earth grid impedances vary from less than one ohm up to 10 ohms. For each case study an earth grid resistance of one ohm is used.

4.3.8.1 Effectively Earthed System

Essential Energy's network has been designed as an effectively earthed system. Positive, negative and zero sequence network impedances at several substation sites have been obtained from Essential Energy's CAPE database and results of R0/X1 and X0/X1 calculations are shown in Table 4-13.

Table 4-13 Zone Substation Effectively Earthed Calculations

Zone Substation	Positive Sequence *Z1 (R1+X1)*	Negative Sequence *Z2 (R2+X2)*	Zero Sequence *Z0 (R0+X0)*	R0/X1	X0/X1
Boronia St	6.769+23.389i	6.768+23.395i	9.74+58.896i	0.416	2.518
Hanwood	12.4+36.7i	12.4+36.7i	19.75+104.3i	0.538	2.842
East Tamworth	1.133+9.885i	1.132+9.894i	1.93+7.846i	0.195	0.794
Grafton North	3.731+16.433i	3.731+16.435i	2.578+12.913i	0.157	0.786
Temora 132	2.746+9.046i	2.748+9.057i	1.208+8.844i	0.134	0.978
Suffolk Park	2.018+8.076i	2.017+8.073i	2.839+15.885i	0.352	1.967
Oberon 132	3.988+12.012i	3.989+12.019i	2.795+15.885i	0.233	1.322

4.3.9 Surge Arrester Locations

Surge arresters are positioned to ensure equipment is protected against overvoltages (Hill 2000). For both case studies surge arresters included in the simulations are located at the landing span of each incoming or outgoing 66kV feeder (station entrance) and the 66kV power transformer bushings. Figure 4-9 through to Figure 4-13 have been taken from Essential Energy designs included for case study 1 (APPENDIX E) and case study 2 (APPENDIX F)

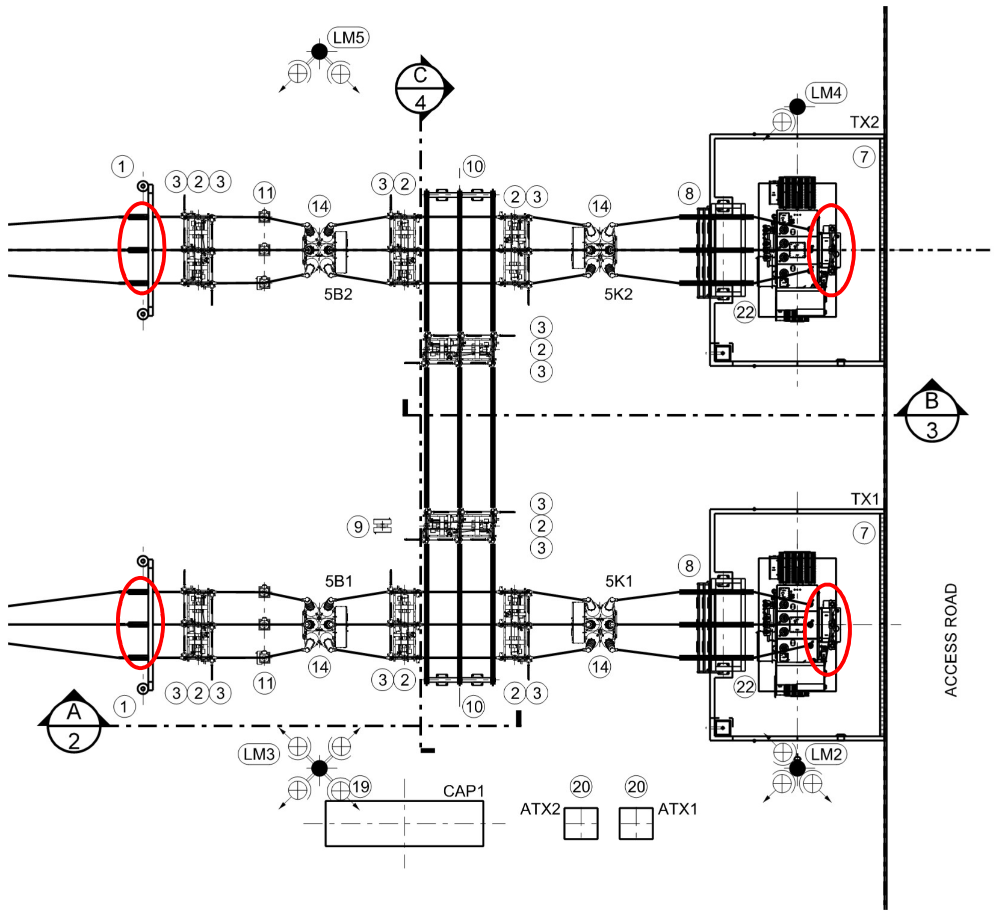

Figure 4-9 Case Study 1 - Surge Arrester Locations (Plan View) (Essential Energy 2014a)

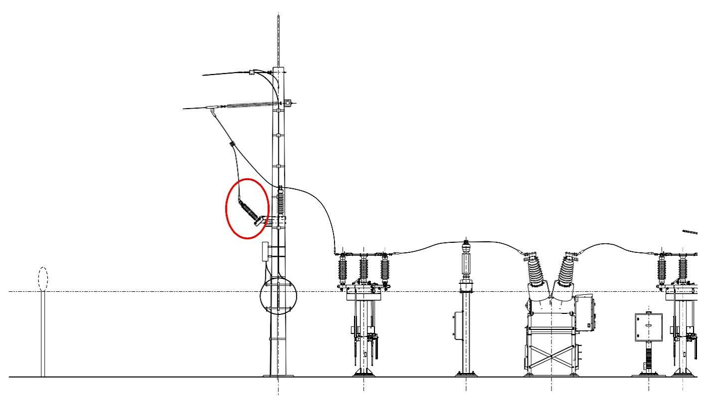

Figure 4-10 Case Study 1 - Surge Arresters Located at Station Entrance (Essential Energy 2014f)

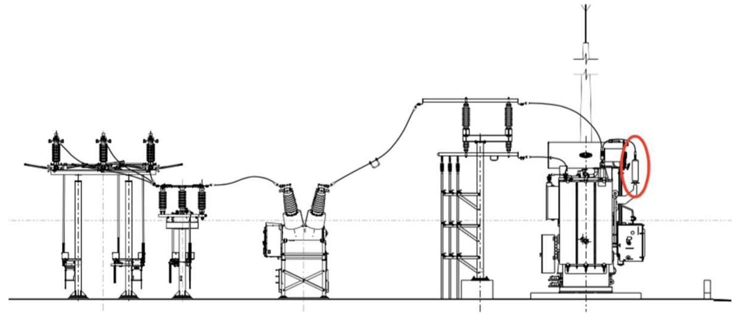

Figure 4-11 Case Study 1 - Surge Arresters at HV Side of Transformer (Essential Energy 2014e)

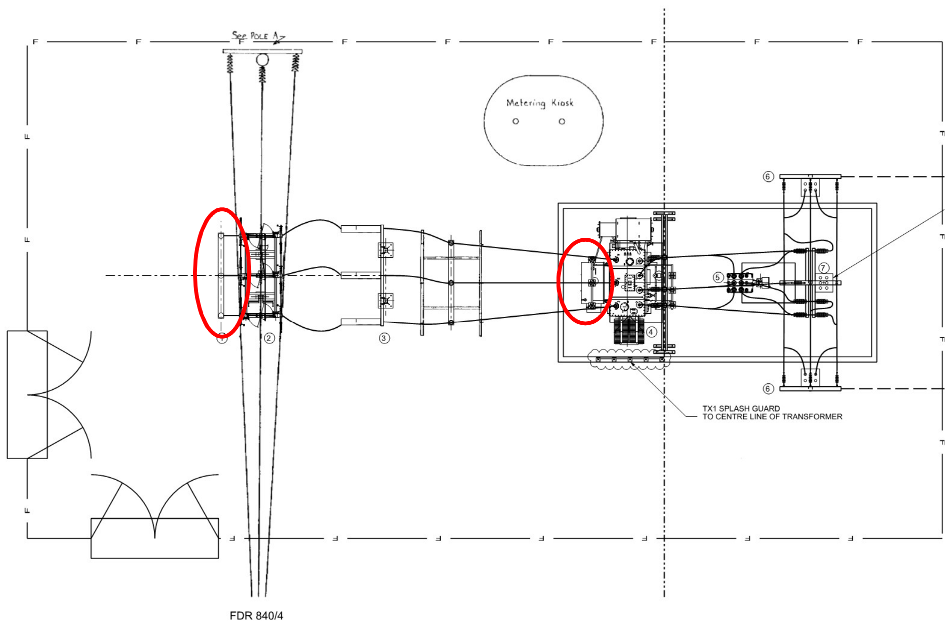

Figure 4-12 Case Study 2 - Surge Arrester Locations (Plan View) (Essential Energy 2016d)

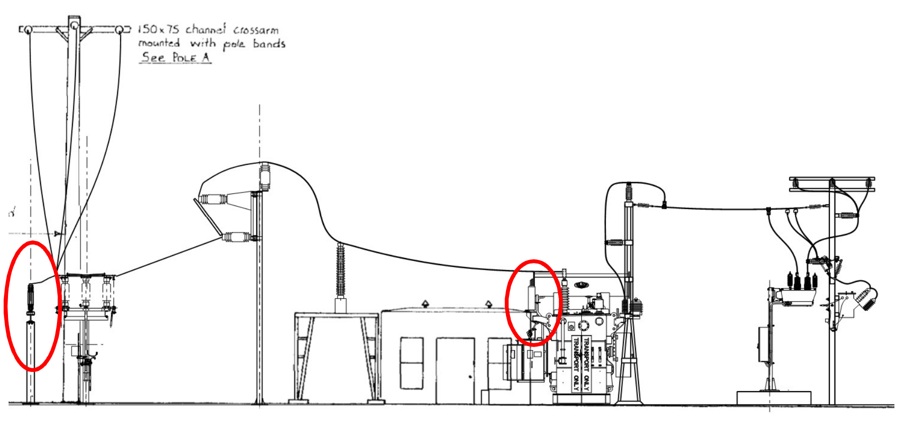

Figure 4-13 Case Study 2 - Surge Arresters Located at Station Entrance and Transformer (Essential Energy 2016c)

4.4 Essential Energy Period Contract Surge Arrester

Essential Energy have four different period contract surge arresters for protection of 66kV zone substation equipment:

Table 4-14 Essential Energy Period Contract 66kV Surge Arresters

Item	Description	Manufacturer	Model Number
1	Effectively Earthed, Regular Strength	Siemens	3EL1 060-1PH21-4XA5
2	Non-Effectively Earthed, Regular Strength	Siemens	3EL1 060-1PK21-4XA5
3	Effectively Earthed, High Strength	Siemens	3EL2 060-2PF31-4KA0
4	Non-Effectively Earthed, High Strength	Siemens	3EQ1 072-2PB31-4KA0

As previously described in section 4.3.8.1, the majority of Essential Energy's network maintains an effectively earthed system, thus eliminating items 2 and 4 as suitable surge arresters for use in simulations. The standard substation design specifies Item 1 as the typical surge arrester installed.

Two types of surge arresters are installed at Kywong zone substation. Bowthorpe 2HSRCP60 type surge arresters are installed at the substation entrance whilst Item 1 above is installed at the transformer.

Table 4-15 Period Contract Surge Arrester Specifications (Siemens 2011), (Tyco Electronics 2001)

Arrester Type		3EL1 060-1PH21-4XA5	3EL2060-2PF21 - 4KA0	BOW-2HSRCP60-xxx
Highest Voltage for Equipment	**U_m kV**	72.5	72.5	72.5
Rated Voltage	**U_r kV**	60	60	60
Continuous Operating Voltage	**U_c kV**	48	48	48
Line Discharge Class	**LD Class**	2	2	2
Maximum Values of Residual Voltages at Discharge currents of the Following Impulses	**8/20µs 5kA (kV)**	142	127	148
	8/20µs 10kA (kV)	153	135	159
	8/20µs 15kA (kV)	164	143	n/a
	8/20µs 20kA (kV)	171	150	175
	8/20µs 40kA (kV)	196	170	199
	Lightning Impulse Withstand Voltage 1.2/50µs kV	365	365	503
	Power Frequency Withstand Voltage 1 min. wet kV	170	170	273
Creepage Distance	**mm**	2050	2340	2650
Flashover Distance	**mm**	630	630	964
Weight	**kg**	12.9	25.4	11.2

5 MODELLING METHODOLOGIES

5.1 ATP

Network models will be developed using the Alternative Transients Program, and version 6.1 of the graphical pre-processor to ATP, ATP-Draw on a laptop with the following specifications:

- Manufacturer - Leader Computers
- Processor – Intel ® Celeron ® CPU N2807 @ 1.58GHz
- RAM – 2Gb
- Operating System – 64 bit, Windows 10

5.1.1 ATP Settings

The following simulation settings were used for all models:

- Minimum Time Step (Delta T) – 1E-9
- Simulation Run Time (T max) – 5E-5
- System Frequency (Freq) – 50
- Simulation type – Time Domain
- Power Frequency – Yes

ATP component settings for scenario one of each case study have been included in APPENDIX H.

5.1.2 IEEE Modelling Guidelines for Fast Front Transients

The Fast Front Transients Task Force of the IEEE Modelling and Analysis of System Transients Working Group (Imece et al. 1996) developed the modelling guidelines for computer simulated lightning studies. These guidelines have formed the basis of the development of all included ATP models in this project. Summaries of key components from the guideline are included below.

5.1.2.1 Overhead Transmission Line, Substation Busbars, Conductors and Cables

All overhead lines (including overhead earth wires), busbars and overhead conductors within the zone substation are to be modelled as a three phase distributed parameter line component. No underground cables are included in either case study model.

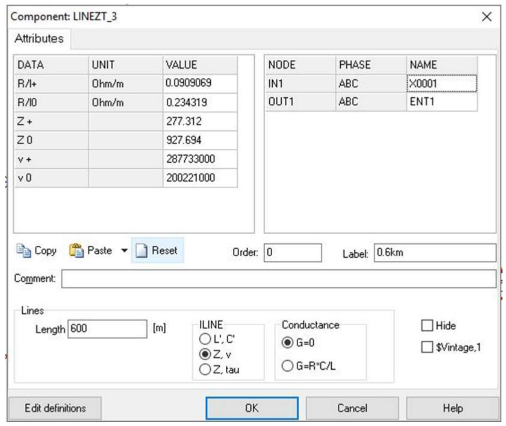

Figure 5-1 ATP-Draw Distributed Parameter Line Component

The positive and zero sequence values for the components resistance per unit length (R/l), surge impedance (Z) and surge velocity (v) are first calculated by entering the physical and electrical characteristics of the section of overhead conductor into an additional component known as LCC or Line Cable Constant before executing ATP. The resistances, surge impedances and surge velocities are displayed within a DOS prompt screen pop-up.Table 5-1 contains an extract of calculated positive and zero sequence values for the case study 1 overhead line. The complete list of ATP calculated figures is included in APPENDIX I.

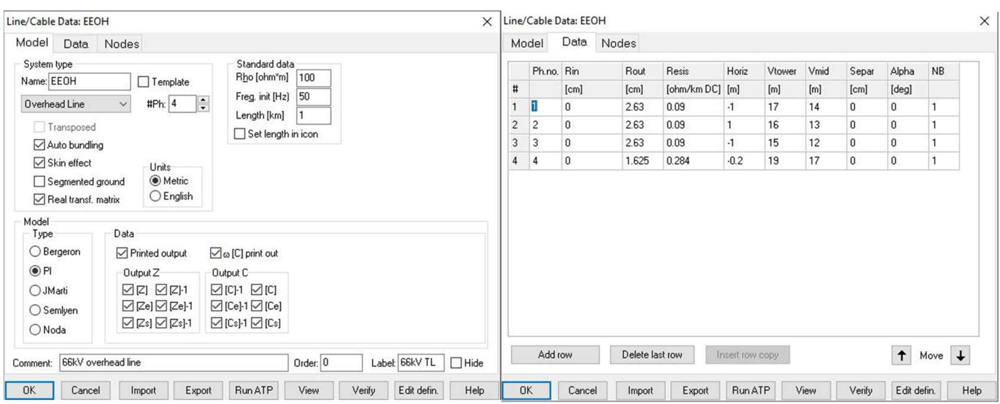

Figure 5-2 ATP-Draw LCC Component

Table 5-1 Conductor Positive and Zero Sequence Values

Sequence	Surge Impedance		Velocity	Resistance
	Magnitude (Ω)	Angle (°)	km/sec	Ω/km
Zero	9.27694E+02	-4.61662E+00	2.00221E+05	2.34319E-01
Positive	2.77312E+02	-8.63386E+00	2.87733E+05	9.09069E-02

5.1.2.2 Substation Equipment

Power transformers may be represented by its surge capacitance that increases in value as the BIL level decreases. The actual surge capacitance of transformers in each case study is calculated using the following equation taken from Hileman (1999):

$$C_T = A(MVA)^B \; nF \quad (5\text{-}1)$$

Where:

MVA = Transformer MVA rating per phase.

Hileman (1999) defines A *and* B as 1.1 and 0.52 respectively. Note these values are given for BIL rating of 350kV. The 350kV values are suitable for use in lieu of 325kV that is not given. For comparison, the next lowest BIL of 250kV is 1.2 (*A*) and 0.56 (*B*).

The calculated transformer surge capacitance for case study 1 equals:

$$C_T = 1.1(20)^{0.52} \; nF$$
$$C_T = 5.22 \; nF$$
$$\therefore C_T \approx 5 \; nF$$

The calculated transformer surge capacitance for case study 2 therefore equals:

$$C_T = 1.1(3)^{0.52} \; nF$$
$$C_T = 1.95 \; nF$$
$$\therefore C_T \approx 2 \; nF$$

Remaining equipment within the substation such as circuit breakers, current transformers, insulators, busbar support structures and outdoor bushings (terminals) are also recommended by Imece et al. (1996) to be represented by surge capacitance values. Equipment included in models used in this report align with the method presented by Hileman (1999) which states that with the exception of very fast transients (surge rise times less than 300nS), surge capacitances may be neglected.

5.1.2.3 Surge Arresters

Imece et al. (1996) state that the arrester may be modelled as a non-linear resistor with 8/20µs V-I characteristics. The accuracy of various methods to represent surge arresters detailed in Table 2-3 concludes that the ATP model allows for very accurate results. As such the non-linear resister component NLRES92 represents each surge arrester in the models. Surge arrester V-I characteristics for all surge arrester types have been sourced from the manufacturers and included in Table 7-13.

The surge arrester ground leads are included as a lumped parameter inductance of 1.0µH/m ensuring the voltage drop across the leads is captured. The surge arrester incoming leads are included as three phase distributed parameter line components similar to 5.1.2.1.

5.1.3 Lightning Surge

5.1.3.1 Lightning Model

The lightning surge is modelled within ATP using source component; Heidler type 15.

As previously defined in section 2.3.6 the lightning is of negative polarity. For clarity, the lightning surge shall be modelled as a positive value. An example of the difference in the presentation of calculated voltages between negative and positive polarity lightning surges is illustrated in Figure 5-3. The magnitude of the surge remains unchanged.

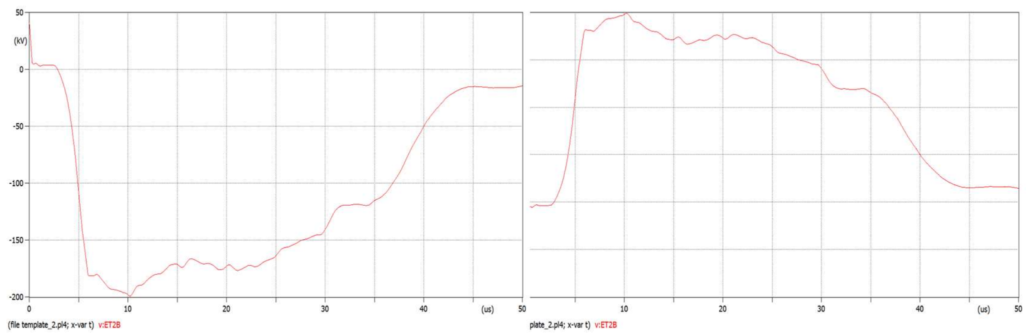

Figure 5-3 Resultant ATP Calculated Voltage Waveform Comparison.
Negative Polarity (Left), Positive Polarity (Right)

5.1.3.2 Model Validation

The lightning surge parameters used in validating the ATP model of both case studies was derived from the analytical calculation of the lightning surge steepness and waveform crest value outlined in APPENDIX K (case study 1) and APPENDIX L (case study 2).

The lightning surge parameters for the validation of case study 1are as follows:

- Amplitude (crest) equivalent to two times the crest voltage of incoming surge or, 2 x 707 kV = 1414 kV (Hileman 1999)
- Rise Time (T_f) of 4 µs
- Decay Time (tau) of 50 µs
- Voltage Source

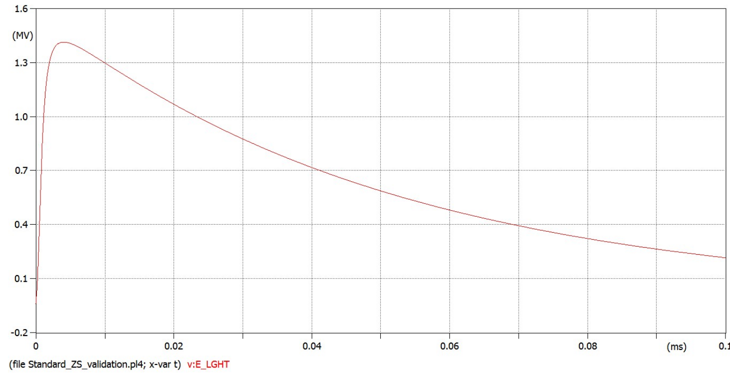

Figure 5-4 Case Study 1 Validation Lightning Waveform

The lightning surge parameters for the validation of case study 2 are as follows:

- Amplitude (crest) equivalent to two times the crest voltage of incoming surge or, 2 x 707 kV = 1414 kV (Hileman 1999)
- Rise Time (T_f) of 3.25 µs
- Decay Time (tau) of 50 µs
- Voltage Source

5.1.3.3 Model Simulations

With the exception of the lightning surge waveforms used in the validation of the ATP models, lightning surges shall conform to the standard 8/20 µs current waveform.

- Amplitude – Scenario dependant.
- Rise Time (T_f) of 14 µs
- Decay Time (tau) of 7.5 µs
- Current Source

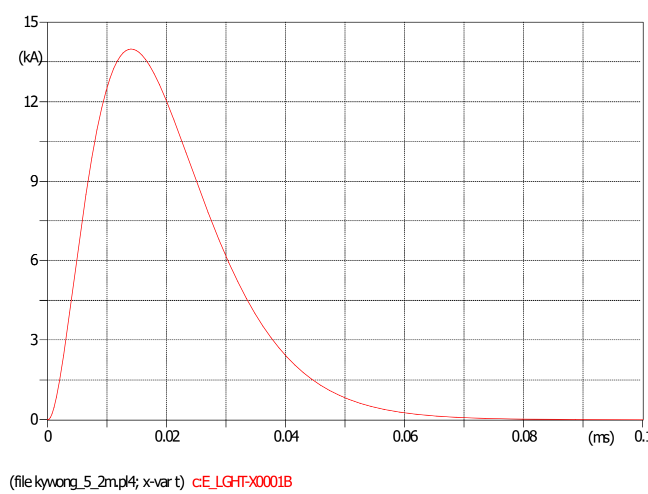

Figure 5-5 14 kA 8/20 µs Lightning Current Waveform

Note. The 14 μs rise time is equal to the time to reach 100% of the peak. The time taken to rise from 10% to 90% of the peak is approximately 8 μs. Similarly, the 7.5 μs decay time results in approximately 20 μs timeframe to rise from 10%, through to the peak value and decay to 50% value.

As detailed in section 2.3.6.1, the mean negative polarity lightning strike magnitude across New South Wales in the six-month period from October 2015 to March 2016 was recorded as -13.7kA. This has been rounded to 14 kA and is the amplitude typically used in each scenario (excludes model validation) unless stated otherwise.

5.1.4 Power Frequency Voltage

The power frequency voltage is defined within Hinrichsen (2012) as “the highest phase-to-earth voltage of the system” and is typically referred to as V_{PF}. Using 72.5 kV as the highest phase-to-phase voltage, V_{PF} equates to 41.86 kV, which is rounded to 40 kV for both case studies.

V_{PF} is added to the resultant voltage to ground values. This represents the worst-case scenario whereby the peak of the power frequency voltage coincides with the peak of the transient overvoltage. The term opposite polarity power frequency voltage relates to the polarity between V_{PF} and the lightning surge. The results taking the opposite polarity power frequency voltage into account shall be referred to as “surge” voltage.

6 MODEL VALIDATION

6.1 Introduction

6.1.1 Aim

This chapter aims to determine the accuracy of the computer models for each case study through a comparison between simulated and analytical calculations.

6.1.2 Objectives

The acceptable variance between simulated and analytical results is to be less than 10%.

6.2 Validation Case Study 1

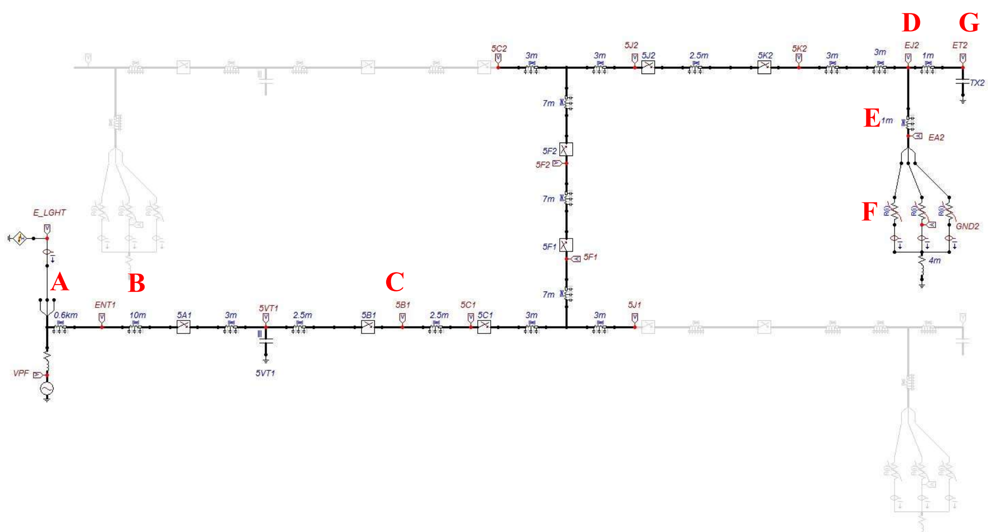

Figure 6-1 Case Study 1, Validation - ATP Model

6.2.1 Methodology

ATP Simulation: Referring to Figure 6-1 a 1414 kV lightning surge is applied to “B” phase of the overhead line (A), three spans or 600m away from the substation entrance – “ENT1” (B). The resultant voltages to ground are calculated at the circuit breaker “5B1” (C), surge arrester 2 junction “EJ2” (D), line terminal of surge arrester 2 “EA2” (E), and the transformer “ET2” (G). The voltage drop across the earth conductor between the surge arrester 2 and the substation earth grid “GND2” (F) is subtracted from “EA2” to determine the surge arrester discharge voltage “ED2”. The lightning surge parameters and the strike distance away from the zone substation have been selected based on the theoretical calculation method detailed in APPENDIX K.

Analytical Calculation: APPENDIX K was compiled using Mathcad software version Prime 3.0 and includes mathematical calculations and process as presented in Hileman (1999) to estimate the voltage to ground and surge voltages at locations B to G in Figure 6-1. A comparison between the calculated and simulated surge voltages are presented in Table 6-1 and Table 6-2.

6.2.2 Case Study 1, Validation Results

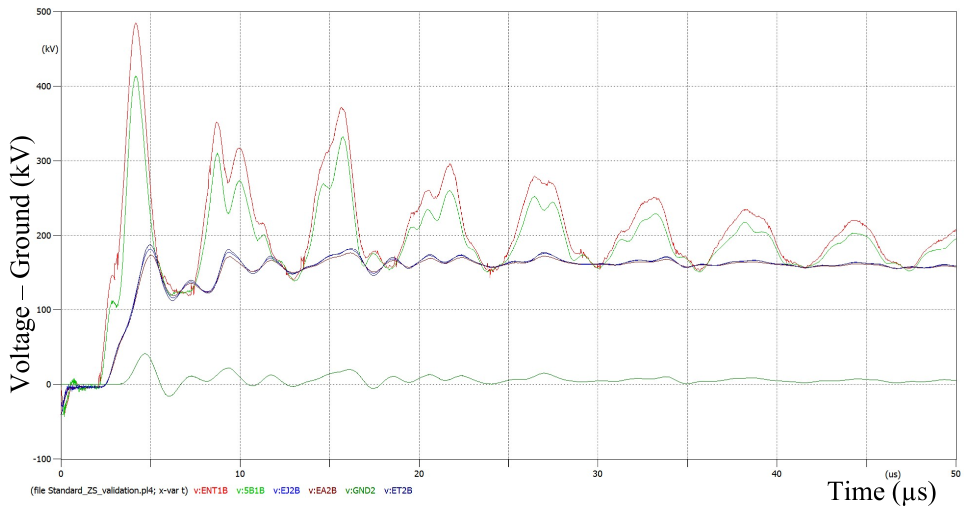

Figure 6-2 Case Study 1, Validation - ATP Voltage to Ground Measurements

Table 6-1 Case Study 1, Validation - Comparison of Simulated and Calculated Voltages to Ground

Circuit Location		Voltage to Ground (kV)		Variance (ATP-Calculated)	
		ATP	Calculated	kV	%
B	Station Entrance *"ENT1"*	484	455.4	28.6	5.9
C	Circuit Breaker *"5B1"*	388	373.4	14.6	3
D	Surge Arrester Junction *"EJ2"*	189	190.5	-1.5	-0.3
E-F	Surge Arrester Discharge Voltage *"ED2"*	158	165	-7	-4.4
G	Transformer 2 *"ET2"*	192	210.3	-18.3	-3.8

Table 6-2 Case Study 1, Validation - Comparison of Simulated and Calculated Surge Voltages

Circuit Location		Surge Voltage (kV)		Variance (ATP-Calculated)	
		ATP	Calculated	kV	%
B	Station Entrance *"ENT1"*	524	495.4	28.6	5.8
C	Circuit Breaker *"5B1"*	428	413.4	14.6	3.5
D	Surge Arrester Junction *"EJ2"*	229	230.5	-1.5	-0.7
E	Surge Arrester *"EA2"*	223	205	18	8.8
F	Surge Arrester Earth Conductor *"GND2"*	66	-	66	-
G	Transformer 2 *"ET2"*	232	250.3	-18.3	-7.3

6.2.3 Case Study 1, Validation Results Discussion

The comparison between the calculated ATP and analytical results reveal the maximum recorded error was the peak surge voltage at the surge arrester terminal with a variation of 8.8%.

The ATP calculated plot shows the travel time for the incoming surge to reach the substation is approximately 2.1 µs. This is consistent with the estimated calculated time of 2.08 µs derived from:

$$T_{surge} = d/v\ \mu s$$
$$T_{surge} = 600/288\ \mu s$$
$$T_{surge} = 2.08\ \mu s$$

Where.

T_{surge} = Surge travel time (µs)

d = Strike distance from substation (m)

v = Surge velocity derived from ATP software (APPENDIX) (m/µs)

Reflections are quite pronounced on the *"ENT1"* and *"5B1"* plots. This may be contributed to the travelling wave reflecting between the power transformer and the strike point as well as effects of the power frequency voltage source.

Additionally, the standard voltage waveshape consisting of a 50 µs decay (tail) time is extending the surge arrester operating time greater than the simulation run time of 50µs.

The arrester discharge voltage is relatively constant throughout the simulation. The initial reflections have a minor influence on the surge arrester discharge voltage which settles to approximately 160 kV. This is consistent with the calculated results.

The aim of this scenario was not to identify any gaps in the substation equipment insulation co-ordination, however it is noted that the both the surge voltage and the voltage to ground at the circuit breaker *"5B1"* and station entrance *"ENT1"* is above the substation's BIL level of 325 kV.

The results therefore validate the accuracy of the ATP model to be utilised with the remaining case study 1 scenarios.

6.3 Validation Case Study 2

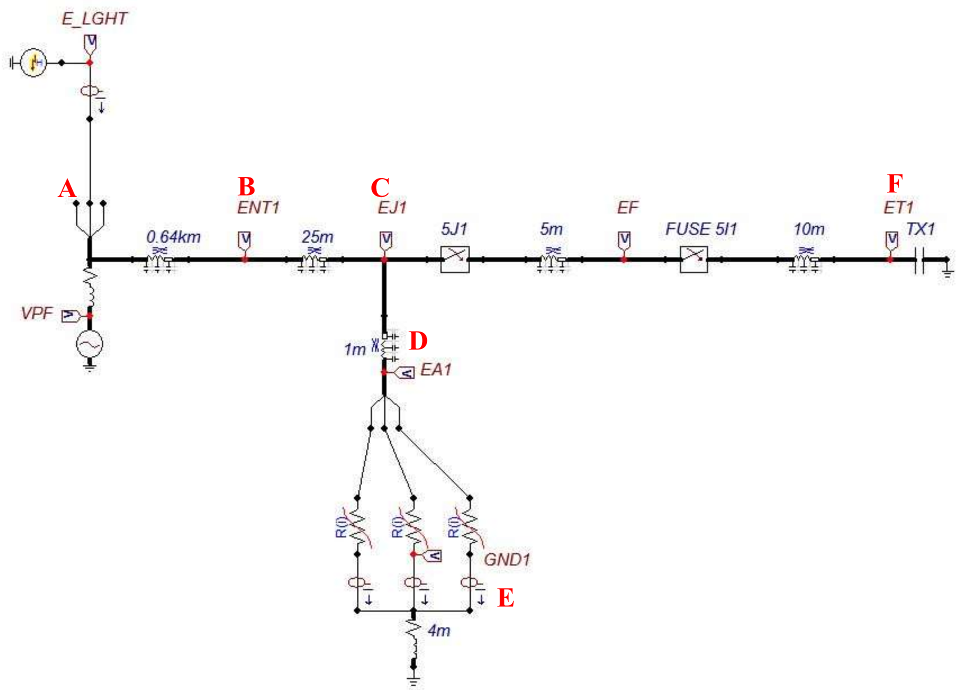

Figure 6-3 Case Study 2, Validation - ATP Model

6.3.1 Methodology

ATP: Referring to Figure 6-3 above, a 1414 kV lightning surge is applied to "B" phase of the overhead line (A), four spans or 640m away from the substation entrance – "ENT1" (B). The resultant voltages to ground are calculated at the surge arrester 1 junction "EJ1" (C), line terminal of surge arrester 1 "EA1" (D), and the power transformer "ET1" (F). The voltage drop across the earth conductor between the surge arrester 1 and the substation earth grid "GND1" (F) is subtracted from "EA1" to determine the surge arrester discharge voltage "ED1". The lightning surge parameters and the strike distance away from the zone substation have been selected based on the theoretical calculation method detailed in APPENDIX L.

Calculated: APPENDIX L was compiled using Mathcad software version Prime 3.0 and includes mathematical calculations and process as presented in Hileman (1999) to estimate the voltage to ground and surge voltages at locations B to F in Figure 6-3. A comparison between the calculated and simulated voltage to ground and surge voltages are presented in Table 6-3 and Table 6-4.

6.3.2 Case Study 2, Validation Results

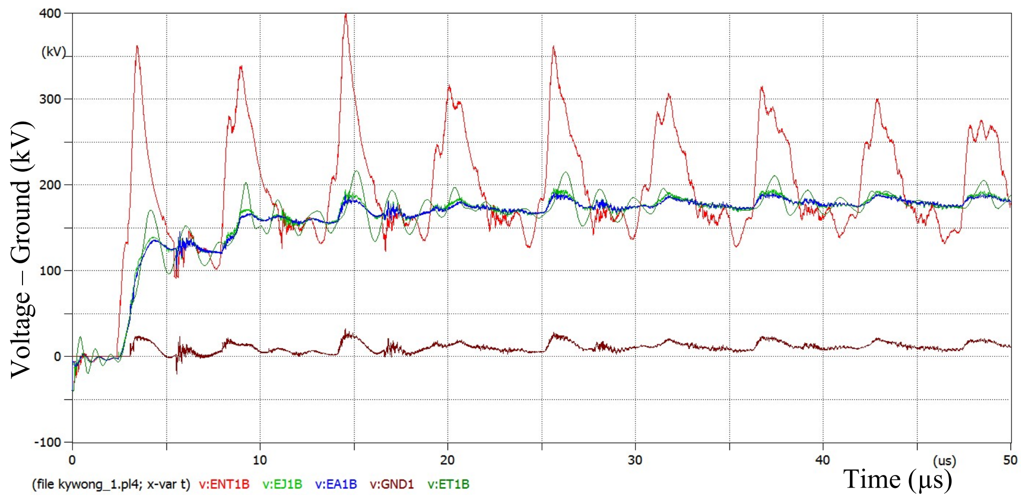

Figure 6-4 Case Study 2, Validation - ATP Voltage to Ground Measurements

Table 6-3 Case Study 2, Validation - Comparison of Simulated and Calculated Voltages to Ground

	Circuit Location	**Voltage to Ground (kV)**		**Variance (ATP-Calculated)**	
		ATP	**Calculated**	**kV**	**%**
B	Station Entrance *"ENT1"*	401	386.5	14.5	3
C	Surge Arrester Junction *"EJ1"*	198	183.9	14.1	2.9
G	Transformer 2 *"ET1"*	226	297.7	-71.7	**-14.7**
D-E	Surge Arrester Discharge Voltage *"ED1"*	155	158.7	-3.7	-0.8

Table 6-4 Case Study 2, Validation - Comparison of Simulated and Calculated Surge Voltages

	Circuit Location	**Surge Voltage (kV)**		**Variance (ATP-Calculated)**	
		ATP	**Calculated**	**kV**	**%**
B	Station Entrance *"ENT1"*	441	426.5	14.5	3.4
C	Surge Arrester Junction *"EJ1"*	238	223.9	14.1	6.3
F	Transformer 2 *"ET1"*	266	337.7	-71.7	**-21.2**
D	Surge Arrester *"EA1"*	217	198.7	18.3	9.2
E	Earth Conductor *"GND1"*	62	-	-	-

6.3.3 Case Study 2, Validation Results Discussion

The comparison between the calculated ATP and analytical results reveal the maximum recorded error was the peak surge voltage at the transformer with a variation of -21.3%. The transformer voltage to ground also varied from the calculated estimate by -14.7%. Investigation into the transformer voltage discrepancy revealed a point of significant discontinuity exists near the surge arrester junction "*EJ1*". It is at this point the overhead line changes from 7/2.00 HDBC to 185mm^2 AAAC1120 covered conductor. The surge impedance decreases from 372.317Ω to 265.454Ω. Application of equation 2.2 (section 2.2.4.2) results in a transmission factor β=0.83. If the voltage to ground result of 297.7kV, derived by calculation, is adjusted by β, then this value becomes 247.1kV. This is within acceptable tolerance with a variance of 8.5% to the ATP calculated result. The subsequent surge voltage is 287.1kV with a variance of 7.4%. That the cause of the discrepancy error was therefore not a result of the ATP model, but inherent within the limitations of the simplified estimate calculations.

The ATP plot shows the travel time for the incoming surge to reach the substation is approximately 2.5µs. This is consistent with the estimated calculated time of 2.37µs derived from:

$$T_{surge} = d/v\ \mu s$$
$$T_{surge} = 640/270\ \mu s$$
$$T_{surge} = 2.37\ \mu s$$

Similar to case study 1 validation, reflections are quite pronounced on the station entrance *"ENT1"* plot and to a lesser extent, the power transformer *"ET1"*. This again may be contributed to the travelling wave reflecting between the power transformer and the strike point and the known point of discontinuity as well as effects of the power frequency voltage source. Additionally, the standard voltage wave shape consisting of a 50µs fall (tail) time is extending the surge arrester operating time greater than the simulation run time of 50µs.

The arrester discharge voltage is relatively constant throughout the simulation. The initial reflections have a minor influence on the response due to the resultant voltage dropping below the arrester discharge voltage after the initial reflection, settling to approximately 160kV.

Similar to case study 1, scenario 1, the aim of this scenario was not to identify any gaps in the substation equipment insulation co-ordination, however it is noted that the both the surge voltage and the voltage to ground at the station entrance *"ENT1"* and the transformer *"ET1"* exceed the substation's BIL level of 325kV.

The results therefore validate the accuracy of the ATP model to be utilised with the remaining case study 2 scenarios.

7 SIMULATION RESULTS

7.1 Introduction

Simulations were run for a number of different scenarios listed below for each case study. These scenarios aim to answer the following points:

a. If standard surge arrester locations provide a suitable zone of protection for major plant.
b. If standard connection methods reduce the surge arrester's operational effectiveness.
c. Identify any improvements to zone substation designs that may be achieved through changes to Essential Energy's standard design or period contract surge arrester specification.

Case Study 1

1. Standard design configuration.
2. Single surge arrester at transformer only.
3. Single surge arrester at station entrance only.
4. Standard design configuration. Comparison of varying incoming lead and earth connection lengths.
5. Comparison of transformer surge arrester connection techniques.
6. Comparison of surge arrester models.
7. Lightning strike onto substation conductors.

Case Study 2

1. In service substation configuration.
2. Recorded lightning strike
3. Lightning strike to substation conductors.

All ATP plots have been included in Appendix N or each scenario listed above.

7.1.1 Surge Arrester Connection Leads

Case study 1, scenario 4 investigates the impact varying the incoming and earth connection lead of each set of surge arresters has on their performance. Figure 7-1 provides a typical overview of these leads and how they connect to the surge arrester.

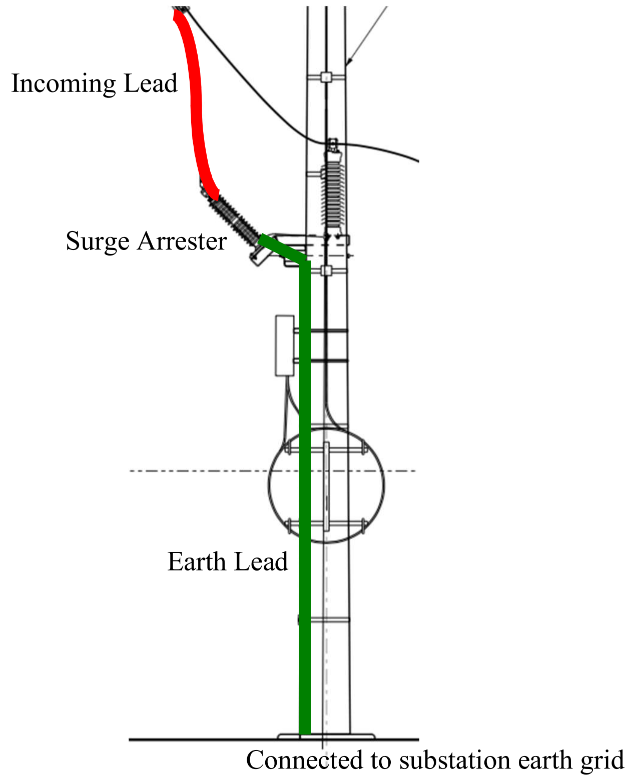

Figure 7-1 Typical Surge Arrester Incoming Lead (Red) and Earth Lead (Green)

7.2 Case Study 1, Scenario 1 – Standard Design Configuration.

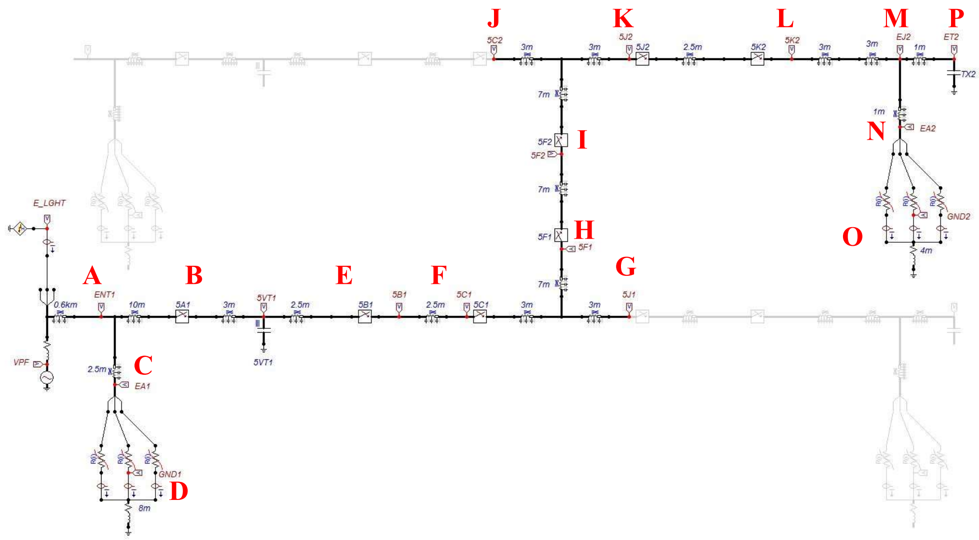

Figure 7-2 Case Study 1, Scenario 1 - ATP Model

7.2.1 Objective

To determine if the placement of surge arresters maintain a suitable zone of protection across all equipment and identify any voltages that exceed 80% of the substation equipment BIL rating of 325 kV (260 kV) at terminals of equipment located as per the standard design for case study 1.

7.2.2 Methodology

ATP: Referring to Figure 7-2 above, a 14 kA, 8/20µs lightning surge is applied to "B" phase of the overhead line (A), three spans or 600 m away from the substation entrance *"ENT1"* (B). The resultant voltages to ground are calculated at the substation entrance and surge arrester 1 junction *"EJ1"* (B), surge arrester 1 *"EA1"* (C), surge arrester 1 ground lead *"GND1"* (D), voltage transformer 1 *"5VT1"* (E), circuit breaker *"5B1"* (F), air break switch *"5J1"* (G), air break switch *"5F1"*(H), air break switch *"5F2"* (I), air break switch *"5C2"* (J), air break switch *"5J2"* (K), circuit breaker *"5K2"* (L), surge arrester 2 junction *"EJ2"* (M), surge arrester 2 *"EA2"* (N), surge arrester 2 ground lead *"GND2"* (O) and power transformer 2 *"ET2"* (P).

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.2.3 Case Study 1, Scenario 1 Results

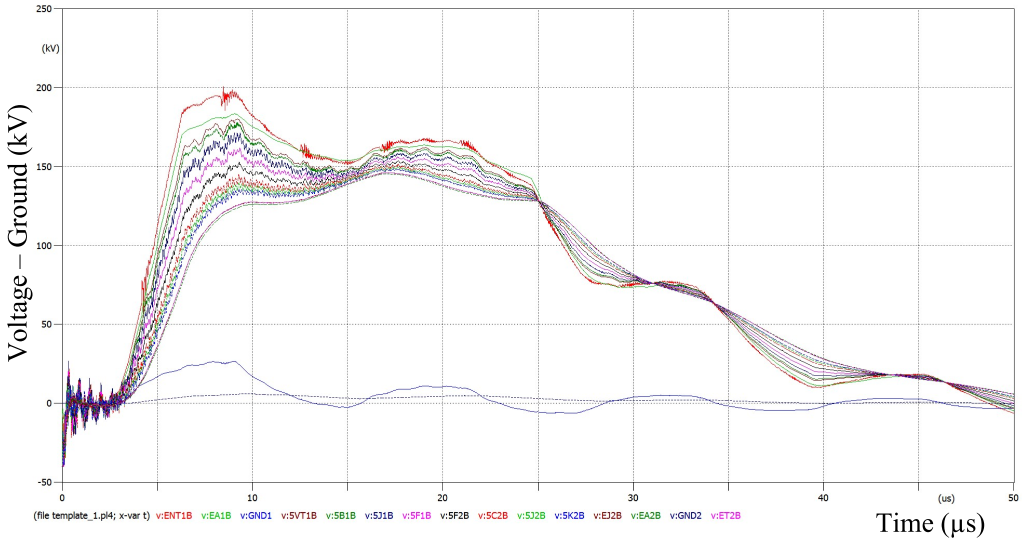

Figure 7-3 Case Study 1, Scenario 1 - ATP Voltage to Ground Measurements

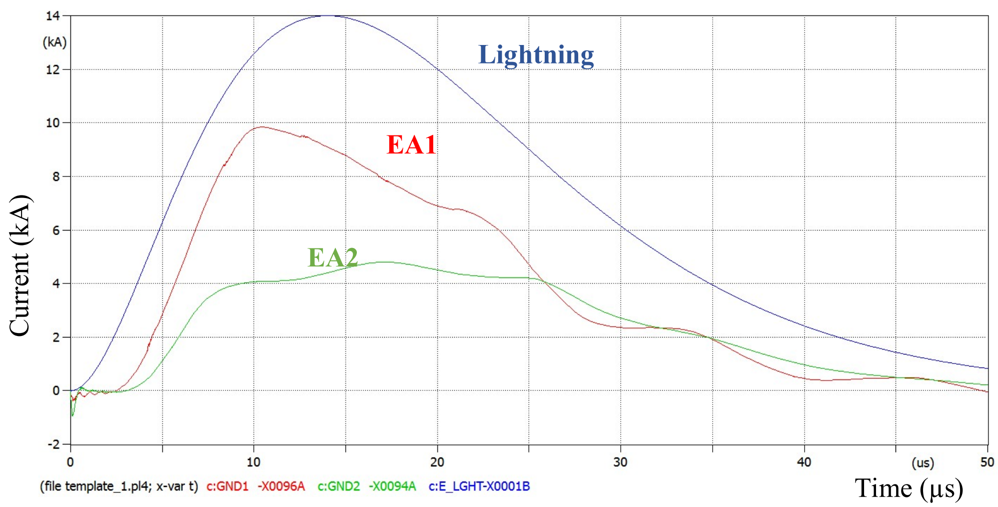

Figure 7-4 Case Study 1, Scenario 1 - ATP Arrester Currents

Table 7-1 Case Study 1, Scenario 1 – ATP Results

Circuit Location		Voltage (kV)	
		V – G	**Surge**
B	Station Entrance *“ENT1”* Surge Arrester 1 Junction *“EJ1”*	195	235
C	Surge Arrester 1 *“EA1”*	183	223
D	Surge Arrester 1 Earth Conductor *“GND1”*	26	66
C-D	Surge Arrester 1 Discharge Voltage *“ED1”*	157	-
E	Voltage Transformer 1 *“5VT1”*	180	220
F	Circuit Breaker *“5B1”*	177	217
G	Air Break Switch *“5J1”*	171	211
H	Air Break Switch *“5F1”*	162	202
I	Air Break Switch *“5F2”*	153	193
J	Air Break Switch *“5C2”*	151	191
K	Air Break Switch *“5J2”*	150	190
L	Circuit Breaker *“5K2”*	149	189
M	Surge Arrester Junction *“EJ2”*	146	186
N	Surge Arrester 2 *“EA2”*	145	185
O	Surge Arrester 2 Earth Conductor *“GND2”*	3	43
N-O	Surge Arrester Discharge Voltage *“ED2”*	142	-
P	Transformer 2 *“ET2”*	146	186

7.2.4 Case Study 1, Scenario 1 Result Discussion

As expected, the comparison between the validation scenario and scenario 1 finds the resultant travel time of the surge is similar to the validation results calculated in section 6.2.3. This is due to no changes to the location of the strike point or the overhead line configuration and surge velocity. The differences in time to reach the peak overvoltage (8 µs v's 4 µs) align with the lightning waveform parameters of each respective scenario. The shorter tail time of the lightning waveform in this scenario results in a faster decay of the overvoltages when compared to the validation scenario.

Effects of the opposite polarity power frequency voltage is present in the voltage oscillations present until the operation of the surge arrester (approximately 2.5 µs) and continue on the station entrance ATP calculated voltage to ground plot (Figure 7-3).

The surge impedances throughout network modelled in case study 1 do not vary by a significant amount. This results in minimisation of reflections at points of discontinuity, and the predicted surge arrester discharge voltages may be estimated and compared against calculated results and manufacturer's data. Referring to the equivalent circuit (Figure 7-5), when all impedances are equal two thirds of the lightning current would flow through the station entrance surge arrester *“EA1”*, whilst the remaining third would be discharged to earth through the transformer 2 surge arrester *“EA2”* (Kirchhoff's Current Law).

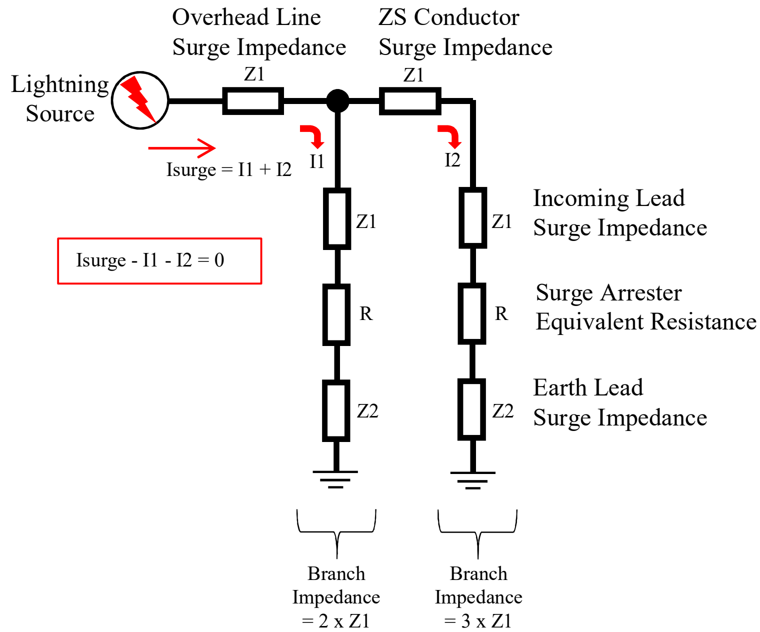

Figure 7-5 Network Equivalent Circuit

With the 14 kA lightning surge this equates to 9.3 kA through *EA1* and 4.7 kA through *EA2*. The ATP calculated current plots Figure 7-4 support this estimate with peaks of 9.9 kA (*EA1*) and 4.1 kA (*EA2*). A comparison of the calculated discharge voltages of 157 kV (*ED1*) and 142 kV (*ED2*), and the respective discharge currents against the manufacturers data in APPENDIX J reveals only a very minor variance of -1% (*ED1*) and -4% (*ED2*)

Estimates of the each surge arrester zone of protection using equation 2.36 equate to approximately 18 m for *ED1* and 20 m for *ED2*. The outcome from this is a gap in the protection zones as the station entrance surge arrester zone of protection extends to circuit breaker 5B1, whilst the transformer 2 surge arresters zone of protection extends to air break switch *5F2*. This would suggest that the elimination of either set of surge arresters will result in damage to substation equipment as will be examined in case study 1, scenario's 2 and 3.

Maintaining the standard design configuration results in a high level of protection against an average magnitude lightning surge with a maximum voltage calculated at surge arrester 1 of 183 kV (V-G) and 223 kV (surge). This represents 70% and 86% of the substation equipment's maximum BIL threshold of 260 kV. The calculated voltages at transformer 2 remained well within the acceptable limit at 146 kV (V-G) and 186 kV (surge).

The results of case study 1, scenario 1 forms a benchmark for all case study 1 scenarios. This shall allow for a determination to be made on the level of surge arrester performance when changes are made to the standard substation design.

7.3 Case Study 1, Scenario 2 – Standard Design, Transformer Surge Arrester Only.

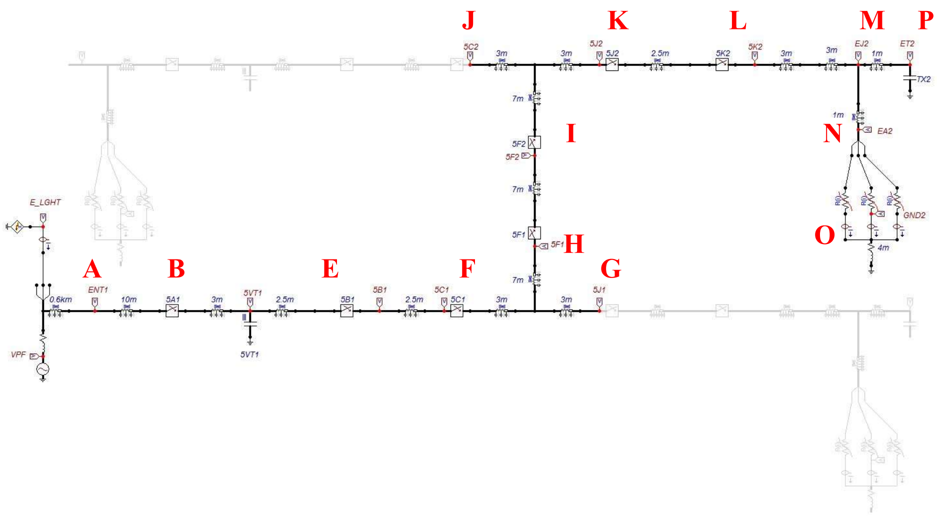

Figure 7-6 Case Study 1, Scenario 2 - ATP Model

7.3.1 Objective

To identify the impact due to the removal of the station entrance surge arresters has on the calculated peak overvoltage levels throughout the substation and identify any voltages exceeding 80% of the substation equipment BIL rating of 325 kV (260 kV) at terminals of equipment located as per the standard design for case study 1.

7.3.2 Methodology

ATP: Referring to Figure 7-6 above, a 14kA, 8/20µs lightning surge is applied to "B" phase of the overhead line (A), three spans or 600m away from the substation entrance *"ENT1"* (B). The resultant voltages to ground are calculated at the substation entrance *"ENT1"* (B), voltage transformer 1 *"5VT1"* (E), circuit breaker *"5B1"* (F), air break switch *"5J1"* (G), air break switch *"5F1"*(H), air break switch *"5F2"* (I), air break switch *"5C2"* (J), air break switch *"5J2"* (K), circuit breaker *"5K2"* (L), surge arrester 2 junction *"EJ2"* (M), surge arrester 2 *"EA2"* (N), surge arrester 2 ground lead *"GND2"* (O) and power transformer 2 *"ET2"* (P).

Changes made to case study 1, scenario 1 include:

- Removal of surge arrester EA1.

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.3.3 Case Study 1, Scenario 2 Results

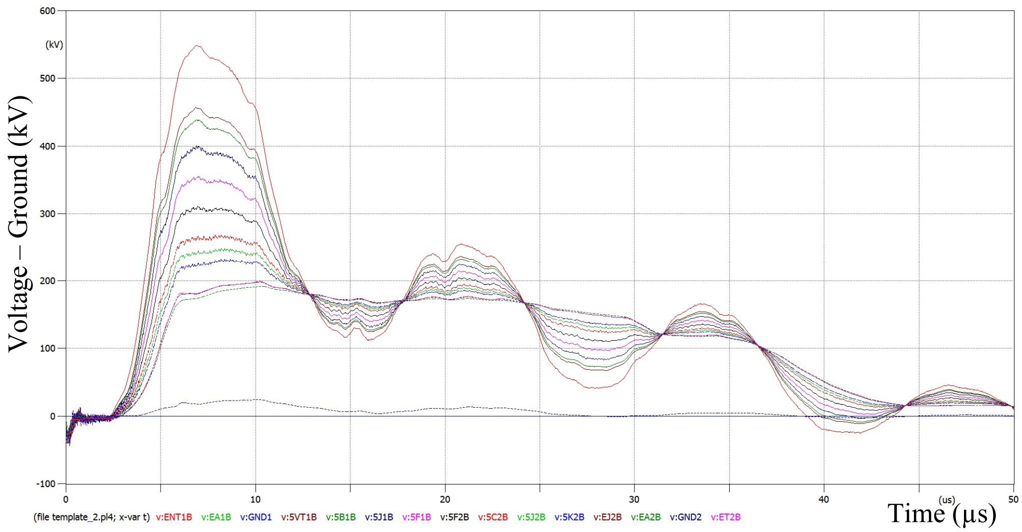

Figure 7-7 Case Study 1, Scenario 2 - ATP Voltage to Ground Measurements

Table 7-2 Case Study 1, Scenario 2 – ATP Results

Circuit Location		Voltage (kV)	
		V – G	Surge
B	Station Entrance *"ENT1"*	***550***	***590***
	Surge Arrester 1 Junction *"EJ1"*		
C	Surge Arrester 1 *"EA1"*	-	-
D	Surge Arrester 1 Earth Conductor *"GND1"*	-	-
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	-	-
E	Voltage Transformer 1 *"5VT1"*	***457***	***497***
F	Circuit Breaker *"5B1"*	***438***	***478***
G	Air Break Switch *"5J1"*	***400***	***440***
H	Air Break Switch *"5F1"*	***355***	***395***
I	Air Break Switch *"5F2"*	***310***	***350***
J	Air Break Switch *"5C2"*	***270***	***310***
K	Air Break Switch *"5J2"*	250	***290***
L	Circuit Breaker *"5K2"*	232	***272***
M	Surge Arrester Junction *"EJ2"*	198	238
N	Surge Arrester 2 *"EA2"*	192	232
O	Surge Arrester 2 Earth Conductor *"GND2"*	24	64
N-O	Surge Arrester Discharge Voltage *"ED2"*	168	-
P	Transformer 2 *"ET2"*	199	239

7.3.4 Case Study 1, Scenario 2 Result Discussion

Removal of the station entrance surge arresters has resulted in the calculated peak voltages at circuit breaker *"5B1"* increasing to 250% (V-G) and 220% (surge) of case study 1, scenario 1 levels. At the transformer terminals, the peak voltages are below the 260kV threshold, but have also increased to 136% (V-G) and 128% (Surge) of those calculated in case study 1, scenario 1.

In a similar fashion to case study 1, scenario 1, the effects of the opposite polarity power frequency voltage are still present, however the significantly larger overvoltage peak makes their influence appear smaller in comparison.

With just the single set of surge arresters installed, the entire lightning current is discharged through the transformer surge arrester (*EA2*). A comparison of the 168 kV calculated discharge voltage (*ED2*), and the respective discharge current of 14 kA against manufacturer data included in APPENDIX J reveal only a very minor variance of -0.1% is present.

The transformer surge arrester zone of protection is estimated at approximately 16 m, which does not provide adequate coverage for all substation equipment. Without the station entrance surge arresters, the substation equipment is therefore subjected to the overvoltage for a greater period of time resulting in the higher calculated overvoltages.

It is clear from these results that the single set of surge arresters at the transformer is not sufficient to protect any of the substation equipment other than the adjacent transformer. The average magnitude lightning surge produced overvoltages greater than the 260kV (80%) equipment BIL limit through to the circuit breaker *"5K1"*. Maximum voltages present at equipment terminals were calculated at the voltage transformer *"5VT1"* and reached 457kV (V-G) and 497kV (Surge). The surge arresters limit the over voltages at the transformer to 199kV (V-G) and 239kV (Surge). This is equivalent to 77% and 92% of the 260kV voltage limit maintaining greater than a 20% BIL protective margin.

7.4 Case Study 1, Scenario 3 – Standard Design, Station Entrance Surge Arrester Only.

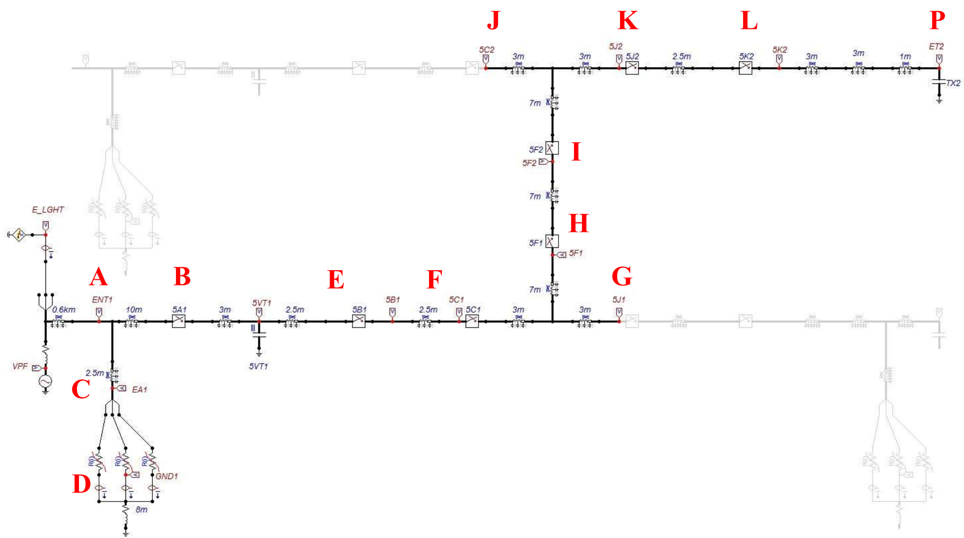

Figure 7-8 Case Study 1, Scenario 3 - ATP Model

7.4.1 Objective

To identify the impact removal of the transformer surge arresters has on the calculated peak overvoltage levels throughout the substation and identify any voltages exceeding 80% of the substation equipment BIL rating of 325Kv (260kV) at terminals of equipment located as per the standard design for case study 1.

7.4.2 Methodology

ATP: Referring to Figure 7-8 above, a 14kA, 8/20µs lightning surge is applied to "B" phase of the overhead line (A), three spans or 600m away from the substation entrance *"ENT1"* (B). The resultant voltages to ground are calculated at the substation entrance and surge arrester 1 junction *"EJ1"* (B), surge arrester 1 *"EA1"* (C), surge arrester 1 ground lead *"GND1"* (D), voltage transformer 1 *"5VT1"* (E), circuit breaker *"5B1"* (F), air break switch *"5J1"* (G), air break switch *"5F1"*(H), air break switch *"5F2"* (I), air break switch *"5C2"* (J), air break switch *"5J2"* (K), circuit breaker *"5K2"* (L) and power transformer 2 *"ET2"* (P).

Changes made to case study 1, scenario 1 include:

- Removal of surge arrester EA2.

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.4.3 Case Study 1, Scenario 3 Results

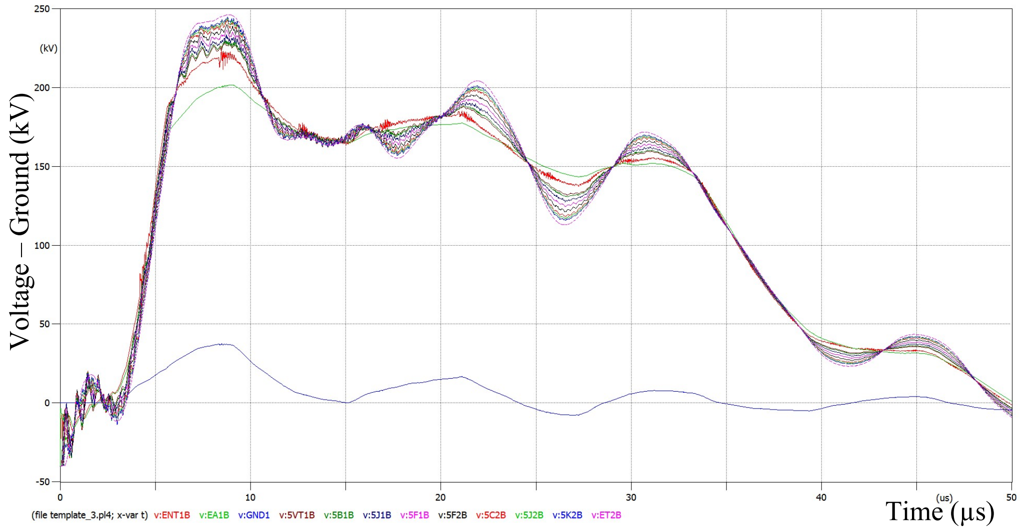

Figure 7-9 Case Study 1, Scenario 3 - ATP Voltage to Ground Measurements

Table 7-3 Case Study 1, Scenario 3 – ATP Results

Circuit Location		Voltage (kV)	
		V – G	**Surge**
B	Station Entrance *"ENT1"*	226	***266***
B	Surge Arrester 1 Junction *"EJ1"*	226	***266***
C	Surge Arrester 1 *"EA1"*	202	242
D	Surge Arrester 1 Earth Conductor *"GND1"*	37	77
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	165	-
E	Voltage Transformer 1 *"5VT1"*	229	***269***
F	Circuit Breaker *"5B1"*	229	***269***
G	Air Break Switch *"5J1"*	233	***273***
H	Air Break Switch *"5F1"*	236	***276***
I	Air Break Switch *"5F2"*	240	***280***
J	Air Break Switch *"5C2"*	243	***283***
K	Air Break Switch *"5J2"*	244	***284***
L	Circuit Breaker *"5K2"*	245	***285***
M	Surge Arrester Junction *"EJ2"*	-	-
N	Surge Arrester 2 *"EA2"*	-	-
O	Surge Arrester 2 Earth Conductor *"GND2"*	-	-
N-O	Surge Arrester Discharge Voltage *"ED2"*	-	-
P	Transformer 2 *"ET2"*	247	***287***

7.4.4 Case Study 1, Scenario 3 Result Discussion

The removal of the transformer surge arresters has resulted in the calculated surge voltage values exceeding the 260kV (80%) BIL limit at all points within the substation except at the terminals of the station entrance surge arrester (*EA1*).

The voltage plots share similar characteristics to scenario 2 with the major difference being higher calculated voltage peaks in scenario 2. This is a result of the increased time for the surge to travel to the surge arrester, and therefore an increased time until the surge arrester operates. With the full lightning surge current flowing through the single arrester, the surge arrester discharge voltage of 165 kV (*ED1*) remained almost constant between scenarios 2 and 3 with a variation of only 1%. The protective zone of the surge arresters is again inadequate to encompass all equipment in the substation with a calculated protective zone of 17 m.

At circuit breaker *"5B1"*, the calculated voltage increased to 129% (V-G) and 124% (surge) of the calculated voltages in case study 1, scenario 2. At the transformer "ET2", this extends to 169% (V-G) and 154% (surge). This highlights that the surge arresters installed at the station entrance has what may be described as the primary, or dominant effect on limiting overvoltages in the substation. This is to be expected considering the station entrance surge arresters would be subjected to the overvoltages for a longer time period.

The single set of surge arresters at the substation entrance do not provide suitable protection to the substation equipment if the protection margin of 80% is to be maintained. The transformer *"ET2"* had the highest calculated surge voltage of 287kV, 110% of the 260kV limit.

7.5 Case Study 1, Scenario 4 – Standard Design Configuration. Comparison of Varying Incoming Lead and Earth Connection Lengths.

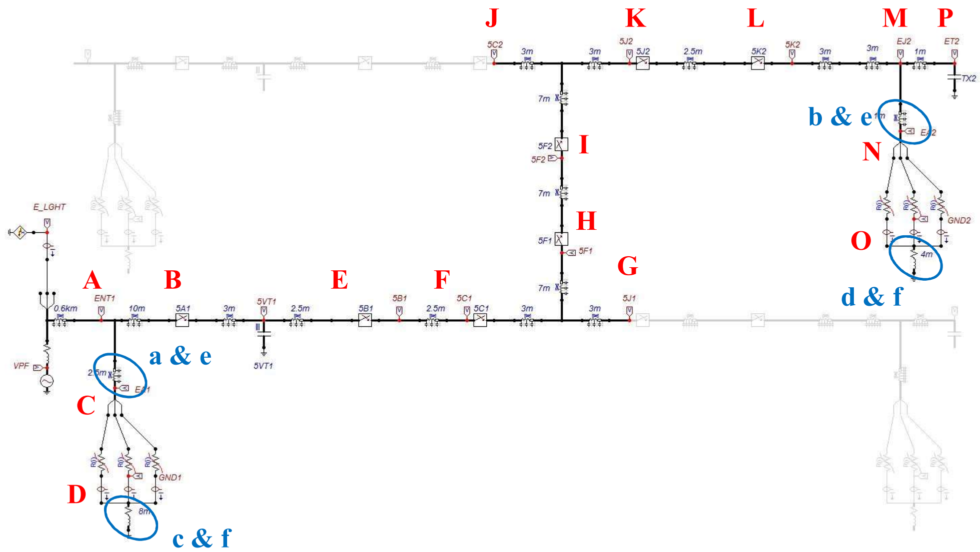

Figure 7-10 Case Study 1, Scenario 4 - ATP Model

7.5.1 Objectives

To establish the impact modifications to the standard design has on the effectiveness of the surge arrester and identify any voltages that exceed 80% of the substation equipment BIL rating of 325Kv (260kV) at terminals of equipment whilst varying the incoming and earth connection leads from the original design for case study 1.

7.5.2 Methodology

ATP: The surge arrester lead lengths are to be modified from case study 1, scenario 1 as follows:

a. Station Entrance surge arrester incoming lead: 1 m, 2.5 m, 5 m, 10 m, 15m
b. Transformer surge arrester incoming connection: 1 m, 2.5 m, 5 m, 10 m, 15 m
c. Station Entrance surge arrester earth lead: 1 m, 2 m, 4 m, 8 m, 15 m, 30 m
d. Transformer surge arrester earth lead: 1 m, 2 m, 4 m, 8 m, 15 m, 30 m
e. Station Entrance and transformer surge arrester incoming lead: 1 m, 2.5 m, 5 m, 10 m, 15 m
f. Station Entrance and transformer surge arrester earth lead: 1 m, 2 m, 4 m, 8 m, 15 m, 30 m

For a to f above, a 14 kA, 8/20µs lightning surge is applied to "B" phase of the overhead line (A), three spans or 600 m away from the substation entrance *"ENT1"* (B). The resultant voltages to ground are calculated at the substation entrance and surge arrester 1 junction *“EJ1”* (B), surge arrester 1 *“EA1”* (C), surge arrester 1 ground lead *“GND1”* (D), voltage transformer 1 *“5VT1”* (E), circuit breaker *“5B1”* (F), air break switch *“5J1”* (G), air break switch *“5F1”*(H), air break switch *“5F2”* (I), air break switch *“5C2”* (J), air break switch *“5J2”* (K), circuit breaker *“5K2”* (L), surge arrester 2 junction *“EJ2”* (M), surge arrester 2 *“EA2”* (N), surge arrester 2 ground lead *“GND2”* (O) and power transformer 2 *“ET2”* (P).

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.5.3 Case Study 1 Scenario 4a Results

Table 7-4 Case Study 1, Scenario 4a – ATP Results

Circuit Location		Voltage (kV)									
		1 m		2.5m		5 m		10 m		15 m	
		V–G	Surge	V-G	Surge	V-G	Surge	V–G	Surge	V–G	Surge
B	**Station Entrance *“ENT1”*** **Surge Arrester 1 Junction *“EJ1”***	194	234	202	242	210	250	235	***275***	250	***290***
C	**Surge Arrester 1 *“EA1”***	183	223	184	224	182	222	180	220	178	218
D	**Surge Arrester 1 Earth Conductor *“GND1”***	27	67	25	65	25	65	24	64	23	63
C-D	**Surge Arrester 1 Discharge Voltage *“ED1”***	156	-	159	-	157	-	156	-	155	-
E	**Voltage Tx 1 *“5VT1”***	175	215	180	220	190	230	209	249	225	***265***
F	**Circuit Breaker *“5B1”***	172	212	177	217	187	227	205	245	220	***260***
G	**Air Break Switch *“5J1”***	165	205	171	211	181	221	198	238	213	253
H	**Air Break Switch *“5F1”***	156	196	162	202	170	210	186	226	200	240
I	**Air Break Switch *“5F2”***	152	192	153	193	160	200	175	215	188	288
J	**Air Break Switch *“5C2”***	150	190	151	191	153	193	165	205	177	217
K	**Air Break Switch *“5J2”***	149	189	150	190	152	192	160	200	172	212
L	**Circuit Breaker *“5K2”***	148	188	149	189	151	191	155	195	167	207
M	**Surge Arrester Junction *“EJ2”***	145	185	146	186	148	188	151	191	158	198
N	**Surge Arrester 2 *“EA2”***	144	184	145	185	147	187	150	190	156	196
O	**Surge Arrester 2 Earth Conductor *“GND2”***	5	45	3	43	4	44	3	43	8	48
N-O	**Surge Arrester Discharge Voltage *“ED2”***	139	-	142	-	143	-	147	-	147	-
P	**Transformer 2 *“ET2”***	145	185	146	186	148	188	151	191	158	198

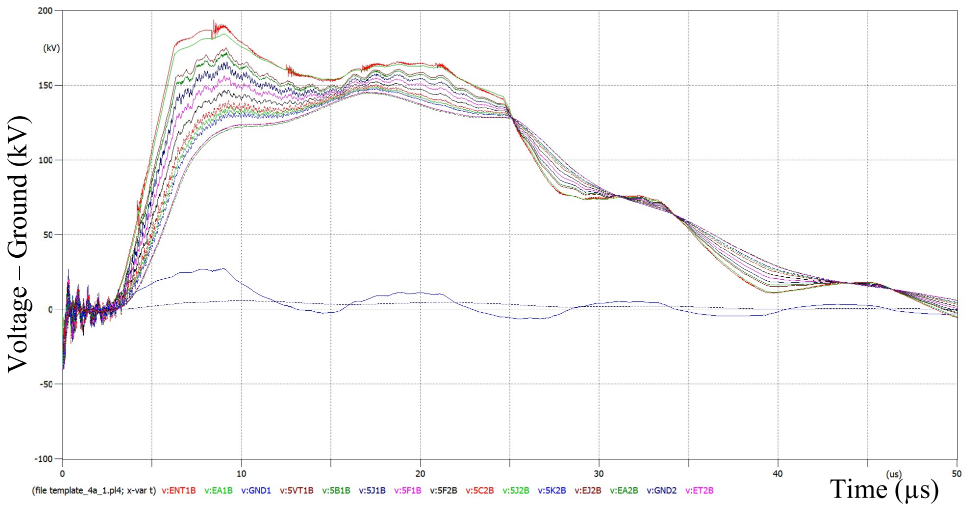

Figure 7-11 Case Study 1, Scenario 4a – 1m ATP Voltage to Ground Measurements

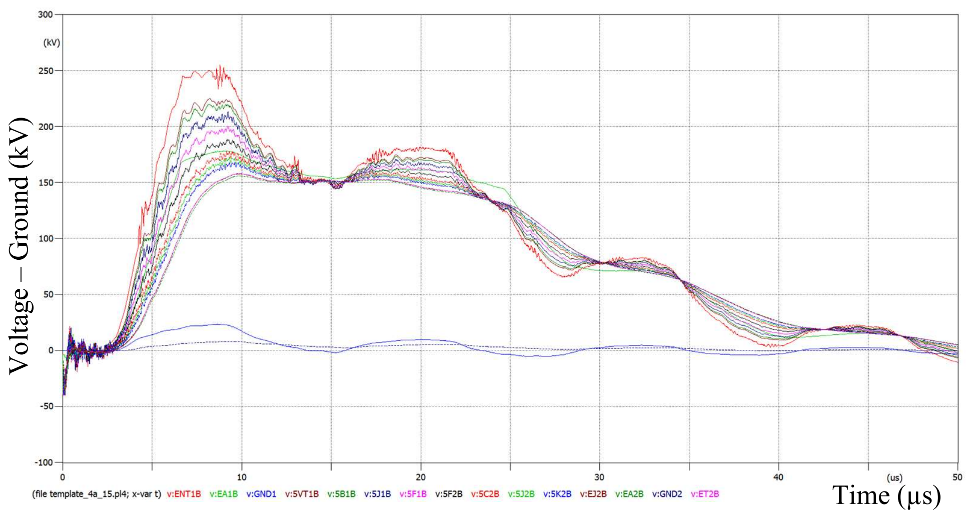

Figure 7-12 Case Study 1, Scenario 4a –15m ATP Voltage to Ground Measurements

7.5.3.1 Case Study 1, Scenario 4a Result Discussion

Reducing the station entrance incoming lead length from 2.5m to 1 m, resulted in almost identical arrester dicharge voltages of 156 kV (*ED1*) and 139 kV (*ED2*) which in turn equates to surge arrester protective zones of 18 m and 21 m respectively. At 15 m, the arrester discharge voltages became 157 kV (*ED1*) and 148 kV (*ED2*). Each respective surge arrester's zone of protection does not change significantly at 18 m (*ED1*) and 19 m (*ED2*).

No voltages exceeding the 260 kV (80%) equipment BIL level was recorded after reducing the incoming lead length to 1 m. Increasing the station entrance surge arrester incoming lead length from 2.5 m to 15 m resulted in significant inductive voltage drops across the incoming lead. This was calculated in ATP as the difference in voltage between *EJ1* and *EA1*, and at 5 m produced a 72 kV voltage drop. A 15 m incoming lead length equated to an average peak overvoltage increase of 43 kV recorded at all substation equipment terminals within the station entrance surge arrester zone of protection (*5VT1* through to *5F2*). Using the ATP calculated surge velocity of 287 m/μs and an assumed typical lightning surge voltage surge steepness of 1000 kV/μs, an estimated change in voltage per meter increase to the lead length may be determined as follows:

$$v = 287\ m/\mu s$$

$$\therefore Time\ for\ surge\ to\ travel\ 1m\ = 0.0035\ \mu s$$

$$\therefore Time\ for\ surge\ to\ travel\ additional\ 12.5m = 0.044\ \mu s$$

$$Assuming\ 1000\frac{kV}{\mu s}\ surge\ steepness$$

$$\therefore voltage\ increase = 1000 * 0.044 = 43.75\ kV$$

$$\therefore 3.5\ kV\ voltage\ change\ at\ equipment\ terminals\ per\ meter\ increase\ in\ lead\ length$$

The ATP calculated results in Table 7-4 show at 10 m the maximum peak overvoltage level of 260 kV is exceeded at the station entrance (*ENT1*). Using the method shown above, a theoretical maximum surge arrester incoming lead length may be derived assuming no change to the existing surge arrester earth lead length of 8 m is made. Utilising the highest calculated overvoltage for a 2.5 m lead length (as per case study 1, scenario 1) of 242 kV, the maximum allowable increase in the peak overvoltage is 18 kV. The division of the 18 kV maximum allowable voltage increase by 3.5 kV/m, it may be estimated the maximum allowable incoming station entrance surge arrester lead length is 5.1 m. This aligns with the ATP results at 5 m that calculated a maximum peak overvoltage 250 kV (surge) at the station entrance (*ENT1*).

7.5.4 Case Study 1 Scenario 4b Results

Table 7-5 Case Study 1, Scenario 4b – ATP Results

Circuit Location		Voltage (kV)									
		1 m		2.5m		5 m		10 m		15 m	
		V–G	Surge	V-G	Surge	V–G	Surge	V–G	Surge	V–G	Surge
B	**Station Entrance *“ENT1”*** / **Surge Arrester 1 Junction *“EJ1”***	202	242	200	240	198	138	202	242	202	242
C	**Surge Arrester 1 *“EA1”***	184	224	183	224	184	224	184	224	185	225
D	**Surge Arrester 1 Earth Conductor *“GND1”***	25	65	26	66	27	67	27	67	28	68
C-D	**Surge Arrester 1 Discharge Voltage *“ED1”***	159	-	157	-	157	-	157	-	157	-
E	**Voltage Tx 1 *“5VT1”***	180	220	181	221	183	223	184	224	184	224
F	**Circuit Breaker *“5B1”***	177	217	178	218	179	219	181	221	181	221
G	**Air Break Switch *“5J1”***	171	211	170	210	173	213	174	214	174	214
H	**Air Break Switch *“5F1”***	162	202	162	202	164	204	165	205	165	205
I	**Air Break Switch *“5F2”***	153	193	154	194	154	194	157	197	157	197
J	**Air Break Switch *“5C2”***	151	191	147	187	153	183	154	194	154	194
K	**Air Break Switch *“5J2”***	150	190	151	191	152	192	152	192	152	192
L	**Circuit Breaker *“5K2”***	149	189	150	190	150	190	150	190	150	190
M	**Surge Arrester Junction *“EJ2”***	146	186	146	186	146	186	146	186	146	186
N	**Surge Arrester 2 *“EA2”***	145	185	145	185	143	183	139	179	136	176
O	**Surge Arrester 2 Earth Conductor *“GND2”***	3	43	4	44	4	44	3	43	4	44
N-O	**Surge Arrester Discharge Voltage *“ED2”***	142	-	141	-	139	-	136	-	132	-
P	**Transformer 2 *“ET2”***	146	186	146	186	146	186	146	186	146	186

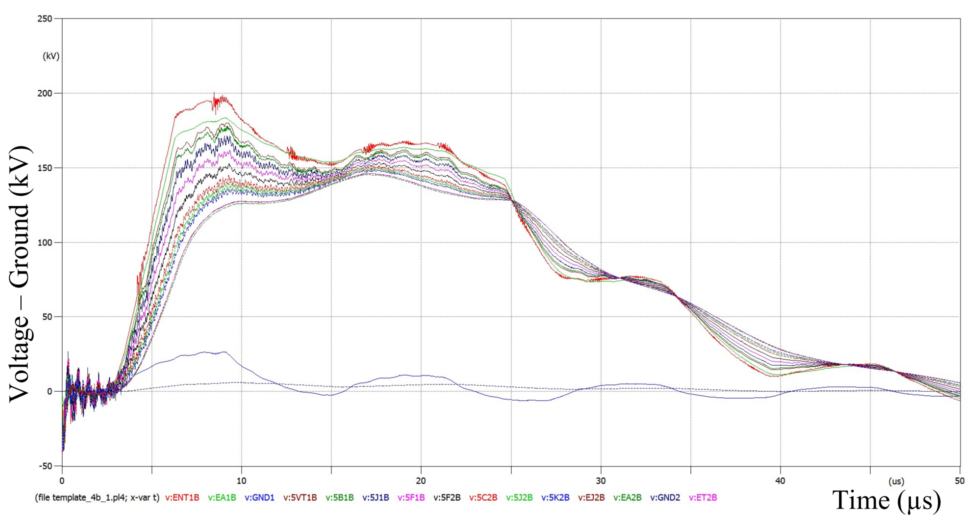

Figure 7-13 Case Study 1, Scenario 4b – 1m ATP Voltage to Ground Measurements

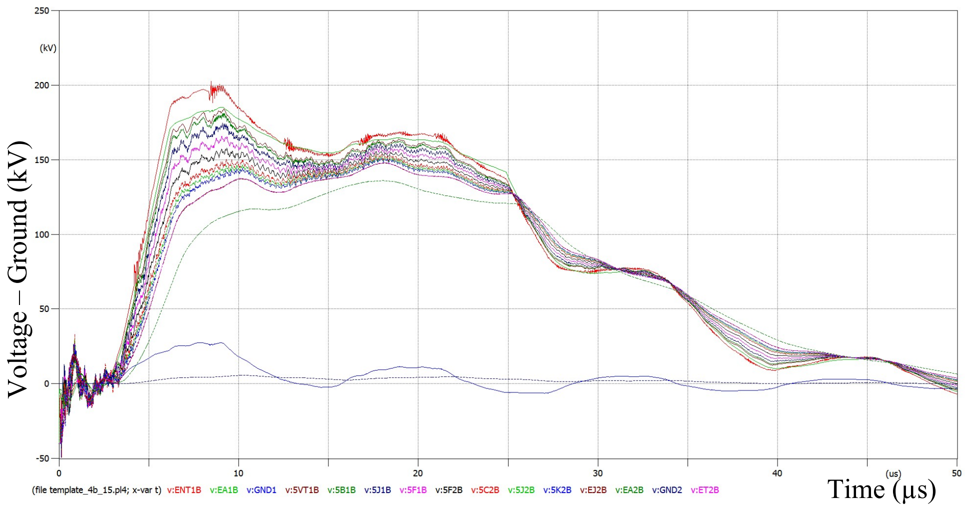

Figure 7-14 Case Study 1, Scenario 4b – 15m ATP Voltage to Ground Measurements

7.5.4.1 Case Study 1, Scenario 4b Result Discussion

As previously discussed in case study 1, scenario 3, it is apparent from the ATP calculated results that the station entrance surge arrester (*EA1*) is the dominant component in supressing the peak incoming surge overvoltage throughout the substation. Consequently, modifications to the transformer surge arrester incoming lead produce very minor variances in the the peak overvoltages at the substation equipment within the protective zone of the transformer surge arrester (*EA2*). A 10 kV reduction in the arrester discharge voltage at *ED2* was observed in the ATP results. This may be contributed to the corrosponding inductive voltage drop across the incoming lead and the susequent lower current discharged through the transformer surge arrester *EA2*. Each surge arrester protective zone becomes 18 m (*EA1*) and 20 m (*EA2*).

No voltages were identified that exceeded the 260 kV (80%) equipment BIL level when the transformer surge arrester incoming lead length was varied between 1 m and 15 m. This is expected based on the previously mentioned dominant attributes of the station entrance surge arrester.

Despite the appearance that the lead lengths may in fact be increased to 15 m or greater, it is recommended that the lead length be increased to no greater than 5 m. This is based on the possibility that the station entrance surge arresters may either fail, or be damaged unknowingly by a previous overvoltage transient. It was demonstrated in case study 1, scenario 2 that insulation coordination was unable to be maintained without the station entrance surge arrester. The peak overvoltage values calculated at transformer 2 was 199 kV (V-G) and 239 kV (surge). Therefore in an effort to maintain insulation coordination with the transformer, a further 21 kV allowable voltage increase at the transformer terminals is possible before the maximum allowable limit is reached. Using the derived 3.5 kV/m voltage rise per meter increase of the arrester lead shown in the result discussion of case study 1, scenario 2, the maximum incoming lead length then becomes 21/3.5 = 6 m. Taking into account there is a 1 m lead from the surge arrester junction (*EJ2*), the maximum incoming lead length for the transformer 2 surge arrester (*EA2*) is 5 m. This is dependant on keeping the earth lead length unchanged at 4 m, Modelling this in ATP produced the following plot of the calculated overvoltage (V-G) at the terminals of transformer 2 (*ET2*).

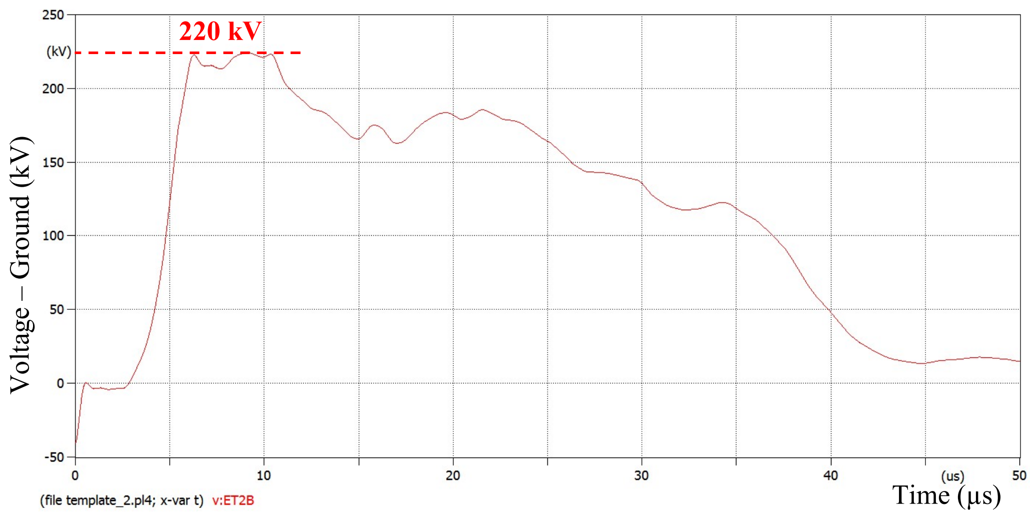

Figure 7-15 Case Study 1, Scenario 2 – 5 m Lead Length at Transformer 2 ATP V - G Measurement

7.5.5 Case Study 1, Scenario 4c Results

Table 7-6 Case Study 1, Scenario 4c – 1 m, 2.5 m & 5 m ATP Results

Circuit Location		Voltage (kV)					
		1 m		2m		4 m	
		V–G	Surge	V–G	Surge	V–G	Surge
B	Station Entrance *"ENT1"* Surge Arrester 1 Junction *"EJ1"*	185	225	190	230	193	233
C	Surge Arrester 1 *"EA1"*	172	212	173	213	176	216
D	Surge Arrester 1 Earth Conductor *"GND1"*	13	53	15	55	19	59
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	159	-	158	-	157	-
E	Voltage Tx 1 *"5VT1"*	170	210	172	212	174	214
F	Circuit Breaker *"5B1"*	167	207	170	210	172	212
G	Air Break Switch *"5J1"*	163	203	164	204	166	206
H	Air Break Switch *"5F1"*	157	197	156	196	156	196
I	Air Break Switch *"5F2"*	155	195	155	195	154	194
J	Air Break Switch *"5C2"*	153	193	153	193	152	192
K	Air Break Switch *"5J2"*	152	192	151	191	151	191
L	Circuit Breaker *"5K2"*	150	190	150	190	150	190
M	Surge Arrester Junction *"EJ2"*	147	187	147	187	147	187
N	Surge Arrester 2 *"EA2"*	147	187	147	187	146	186
O	Surge Arrester 2 Earth Conductor *"GND2"*	3	43	3	43	4	44
N-O	Surge Arrester Discharge Voltage *"ED2"*	144	-	144	-	142	-
P	Transformer 2 *"ET2"*	147	187	147	187	147	187

Table 7-7 Case Study 1, Scenario 4c – 10 m, 15 m & 30 m ATP Results

Circuit Location		Voltage (kV)					
		8 m		15m		30 m	
		V–G	Surge	V–G	Surge	V–G	Surge
B	Station Entrance *"ENT1"* Surge Arrester 1 Junction *"EJ1"*	195	235	210	250	235	***275***
C	Surge Arrester 1 *"EA1"*	183	223	195	235	220	***260***
D	Surge Arrester 1 Earth Conductor *"GND1"*	26	66	38	78	63	103
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	157	-	157	-	157	-
E	Voltage Tx 1 *"5VT1"*	180	220	190	230	210	250
F	Circuit Breaker *"5B1"*	177	217	186	226	205	245
G	Air Break Switch *"5J1"*	171	211	180	220	197	237
H	Air Break Switch *"5F1"*	162	202	170	210	185	225
I	Air Break Switch *"5F2"*	153	193	160	200	175	215
J	Air Break Switch *"5C2"*	151	191	152	192	165	205
K	Air Break Switch *"5J2"*	150	190	147	187	160	200
L	Circuit Breaker *"5K2"*	149	189	148	188	156	196
M	Surge Arrester Junction *"EJ2"*	146	186	145	185	147	187
N	Surge Arrester 2 *"EA2"*	145	185	144	184	145	185
O	Surge Arrester 2 Earth Conductor *"GND2"*	3	43	4	44	7	47
N-O	Surge Arrester Discharge Voltage *"ED2"*	142	-	140	-	138	-
P	Transformer 2 *"ET2"*	146	186	145	185	147	187

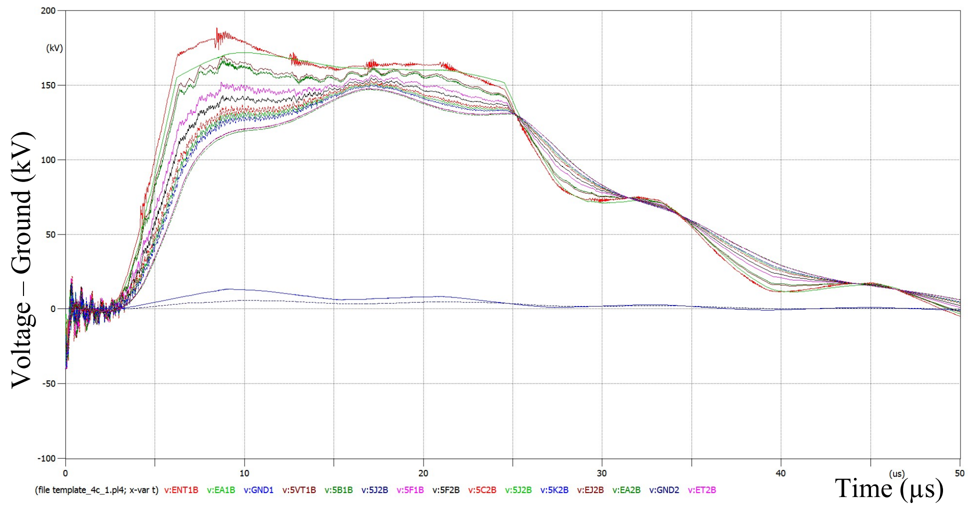

Figure 7-16 Case Study 1, Scenario 4c – 1m ATP Voltage to Ground Measurements

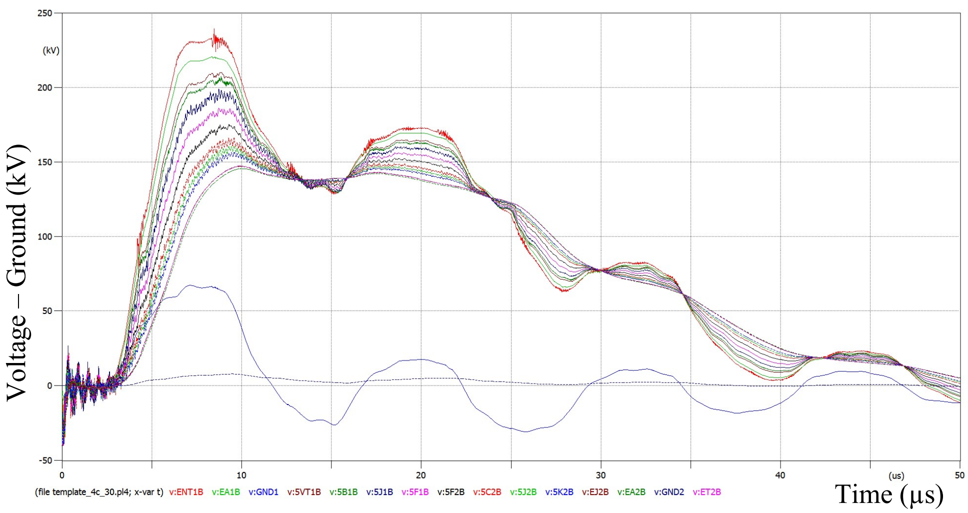

Figure 7-17 Case Study 1, Scenario 4c – 30m ATP Voltage to Ground Measurements

7.5.5.1 Case Study 1, Scenario 4c Result Discussion

It should first be noted that in reality, a reduction of the the station entrance ground lead length from 8 m to 1 m would not be possible without installing the surge arresters below statutory clearances as defined in AS2067. Barriers to maintain clearances from live conductors would be required at additional expense. Despite the results of a 1 m earth lead providing the greatest reduction in peak overvoltages; 20% (V-G) and 16% (Surge) at the station entrance (*ENT1*), 4 m is the recommended minimum length of station entrance earth lead to maintain safe electrical clearances.

No recorded voltages exceeded the 260kV (80%) threshold at any of the modelled earth lead lengths until 15 m was reached. Analysis of the average change in voltage at the station entrance surge arrester terminals (*EA1*) reveals that for every meter in length change to the earth lead, the voltaged varied 1.7 kV. This is not consistant with the voltage change of 3.5 kV per meter for the surge arrester incoming lead derived in case study 1, scenario 2 due to the differences in the electrical properties of each conductor type. The incoming lead is AAAC1120 37/3.00 Nitrogen conductor (Table 4-11) whilst the earth lead is 95 mm^2 covered copper conductor represented as a 0.1 µF/m inductance. There was no significant difference in either surge arrester discharge voltages when compared to Case Study 1, scenario 1.

As is to be expected, increasing the ground lead length from 8m to 30m resulted in the largest peak voltage increases. 20% (V-G) and 17% (Surge) at the terminals of the station entrance surge arrester *"EA1"* were observed in the calculated ATP plots. The only location where the peak surge voltages exceeded the 260 kV (80%) maximum voltage level was at the station entrance (*ENT1*) and the station entrance surge arrester (*EA1*).

The peak surge overvoltage recorded with a 15 m earth connection lead was 250 kV. In an effort to maintain insulation coordination with the station entrance (*ENT1*), a further 10 kV allowable voltage increase at the station entrance is possible before the 260 kV (220 kV V-G) maximum allowable BIL limit is reached. Using the observed 1.7 kV per meter variance of the arrester ground lead, the maximum theoretical ground lead length then becomes 15 + 10/1.7 = 21 m. This is dependant on keeping the incoming lead length unchanged at 2.5 m, Modelling in ATP confirmed these results with the following plot of the calculated overvoltage (V-G) at the terminals of the substation entrance (*ENT1*).

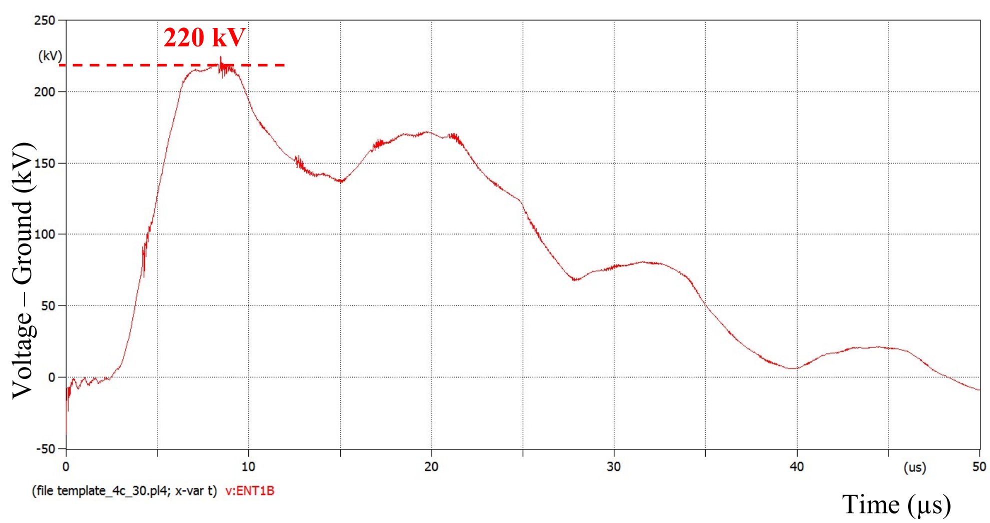

Figure 7-18 Case Study 1, Scenario 4c – 21m ATP Voltage to Ground Measurements

7.5.6 Case Study 1, Scenario 4d Results

Table 7-8 Case Study 1, Scenario 4d – 1 m, 2.5 m & 5 m ATP Results

Circuit Location		Voltage (kV)					
		1 m		2m		4 m	
		V–G	Surge	V-G	Surge	V–G	Surge
B	**Station Entrance *"ENT1"*** **Surge Arrester 1 Junction *"EJ1"***	197	237	197	237	195	235
C	**Surge Arrester 1 *"EA1"***	183	223	183	223	183	223
D	**Surge Arrester 1 Earth Conductor *"GND1"***	26	66	26	66	26	66
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	157	-	157	-	157	-
E	**Voltage Tx 1 *"5VT1"***	180	220	178	218	180	220
F	**Circuit Breaker *"5B1"***	177	217	176	216	177	217
G	**Air Break Switch *"5J1"***	170	210	171	211	171	211
H	**Air Break Switch *"5F1"***	161	201	161	201	162	202
I	**Air Break Switch *"5F2"***	160	200	154	194	153	193
J	**Air Break Switch *"5C2"***	151	191	151	191	151	191
K	**Air Break Switch *"5J2"***	150	190	150	190	150	190
L	**Circuit Breaker *"5K2"***	149	189	149	189	149	189
M	**Surge Arrester Junction *"EJ2"***	147	187	146	186	146	186
N	**Surge Arrester 2 *"EA2"***	146	186	145	185	145	185
O	**Surge Arrester 2 Earth Conductor *"GND2"***	4	44	4	44	3	43
N-O	**Surge Arrester Discharge Voltage *"ED2"***	142	-	141	-	142	-
P	**Transformer 2 *"ET2"***	147	187	146	186	146	186

Table 7-9 Case Study 1, Scenario 4d – 10 m, 15 m & 30 m ATP Results

Circuit Location		Voltage (kV)					
		8 m		15m		30 m	
		V–G	Surge	V-G	Surge	V–G	Surge
B	**Station Entrance *"ENT1"*** **Surge Arrester 1 Junction *"EJ1"***	195	235	195	235	197	237
C	**Surge Arrester 1 *"EA1"***	183	223	183	223	184	223
D	**Surge Arrester 1 Earth Conductor *"GND1"***	26	66	26	66	27	67
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	157	-	157	-	157	-
E	**Voltage Tx 1 *"5VT1"***	180	220	182	222	183	223
F	**Circuit Breaker *"5B1"***	178	218	180	220	181	221
G	**Air Break Switch *"5J1"***	173	213	174	214	175	215
H	**Air Break Switch *"5F1"***	162	202	164	204	166	206
I	**Air Break Switch *"5F2"***	154	194	155	195	157	197
J	**Air Break Switch *"5C2"***	151	191	152	192	153	193
K	**Air Break Switch *"5J2"***	148	188	149	199	150	190
L	**Circuit Breaker *"5K2"***	147	187	148	188	148	188
M	**Surge Arrester Junction *"EJ2"***	146	186	145	185	148	188
N	**Surge Arrester 2 *"EA2"***	145	185	144	184	147	187
O	**Surge Arrester 2 Earth Conductor *"GND2"***	4	44	3	43	7	47
N-O	**Surge Arrester Discharge Voltage *"ED2"***	141	-	141	-	140	-
P	**Transformer 2 *"ET2"***	146	186	145	185	148	188

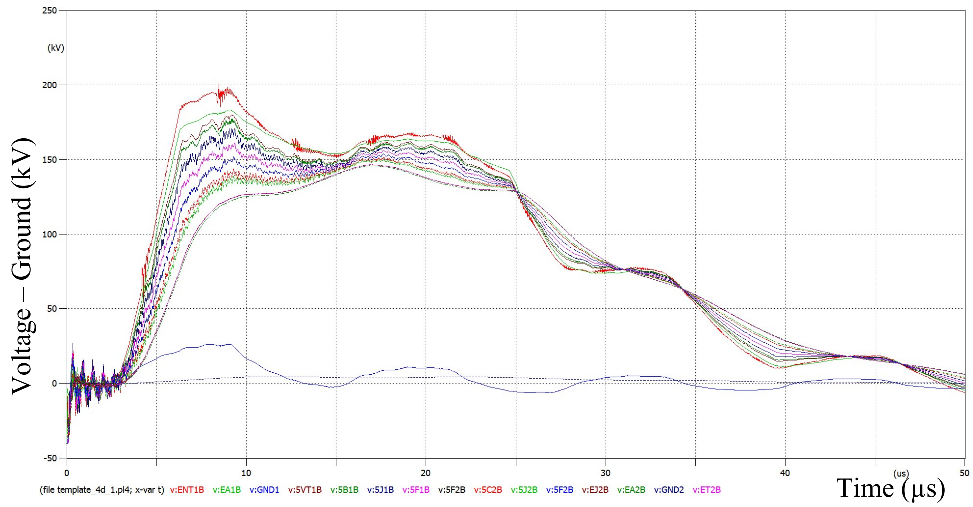

Figure 7-19 Case Study 1, Scenario 4d – 1 m ATP Voltage to Ground Measurements

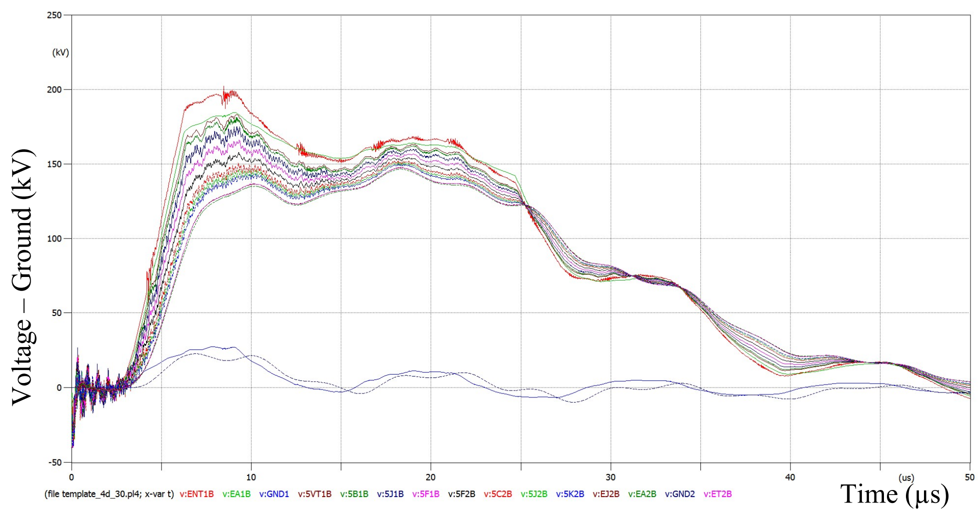

Figure 7-20 Case Study 1, Scenario 4d – 30 m ATP Voltage to Ground Measurements

7.5.7 Case Study 1, Scenario 4d Result Discussion

In similar fashion to case study 1, scenario 4c, a reduction of the the station entrance ground lead length from 4 m to 1 m would not be possible without installing the surge arresters below statutory clearances as defined in AS2067. Barriers to maintain clearances from live conductors would be required at additional expense. A minimum ground lead length of 4 m is again recommended to maintain safe electrical clearances.

No recorded voltages exceeded the 260 kV (80%) threshold at any of the modelled earth lead lengths even at 30 m. This distance is a highly improbable and impractical distance to design the transformer surge arrester ground lead length to. Despite this, the maximum recommended transformer surge arrester (*EA2*) ground lead length shall be such, that a failure to the station entrance surge arresters (*EA1*) the transformer maintains adequate insulation coordination. If the maximum overvoltage at transformer 2 calculated in case study 2, scenario 2 (199 kV V-G) is used as a baseline, a further 21 kV allowable voltage increase at transformer 2 (*ET2*) is possible before the 260 kV (220 kV V-G) maximum allowable BIL limit is reached. Using the observed 1.7 kV per meter variance of the arrester ground lead derived in the case study 1, scenario 4c, the maximum recommended ground lead length then becomes 21/1.7 = 12 m. This is dependant on keeping the incoming lead length and the surge arrester junction (*EJ2*) distance from transformer 2 (*ET2*) each unchanged at 1 m. Modelling this in ATP confirmed these results with the following plot of the calculated overvoltage (V-G) at the terminals of transformer 2 (*ET2*).

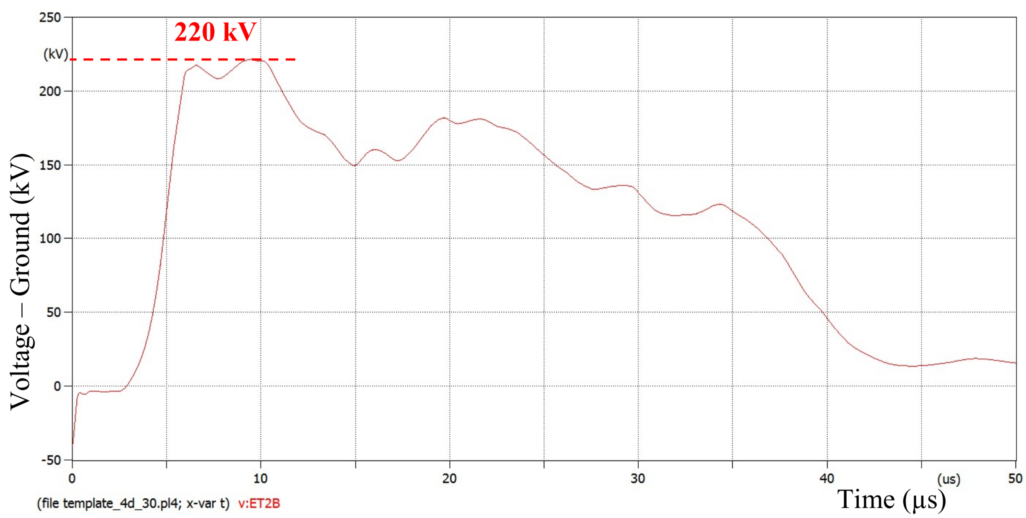

Figure 7-21 Case Study 1, Scenario 4d – 12m ATP Voltage to Ground Measurements

7.5.8 Case Study 1, Scenario 4e Results

Table 7-10 Case Study 1, Scenario 4e – ATP Results

Circuit Location		Voltage (kV)									
		1 m		2.5m		5 m		10 m		15 m	
		V–G	Surge	V-G	Surge	V–G	Surge	V–G	Surge	V–G	Surge
B	**Station Entrance *"ENT1"*** **Surge Arrester 1 Junction *"EJ1"***	190	230	197	237	210	250	233	***273***	255	***295***
C	**Surge Arrester 1 *"EA1"***	184	224	184	224	182	222	181	221	180	220
D	**Surge Arrester 1 Earth Conductor *"GND1"***	27	67	27	67	26	66	25	65	24	64
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	157	-	157	-	156	-	156	-	156	-
E	**Voltage Tx 1 *"5VT1"***	175	215	181	221	192	232	215	255	234	***274***
F	**Circuit Breaker *"5B1"***	172	212	179	219	187	227	210	250	227	***267***
G	**Air Break Switch *"5J1"***	166	206	172	212	183	223	200	240	217	257
H	**Air Break Switch *"5F1"***	156	196	163	203	174	214	191	231	205	245
I	**Air Break Switch *"5F2"***	152	192	154	194	164	204	180	220	197	237
J	**Air Break Switch *"5C2"***	150	190	151	191	156	196	170	210	187	227
K	**Air Break Switch *"5J2"***	149	189	150	190	152	192	165	205	182	222
L	**Circuit Breaker *"5K2"***	148	188	149	189	151	191	161	201	177	217
M	**Surge Arrester Junction *"EJ2"***	145	185	146	186	148	188	154	194	171	210
N	**Surge Arrester 2 *"EA2"***	144	184	144	184	144	184	144	184	145	185
O	**Surge Arrester 2 Earth Conductor *"GND2"***	3	43	3	43	3	43	6	46	7	47
N-O	**Surge Arrester Discharge Voltage *"ED2"***	141	-	141	-	141	-	138	-	138	-
P	**Transformer 2 *"ET2"***	145	185	146	186	148	188	154	194	170	210

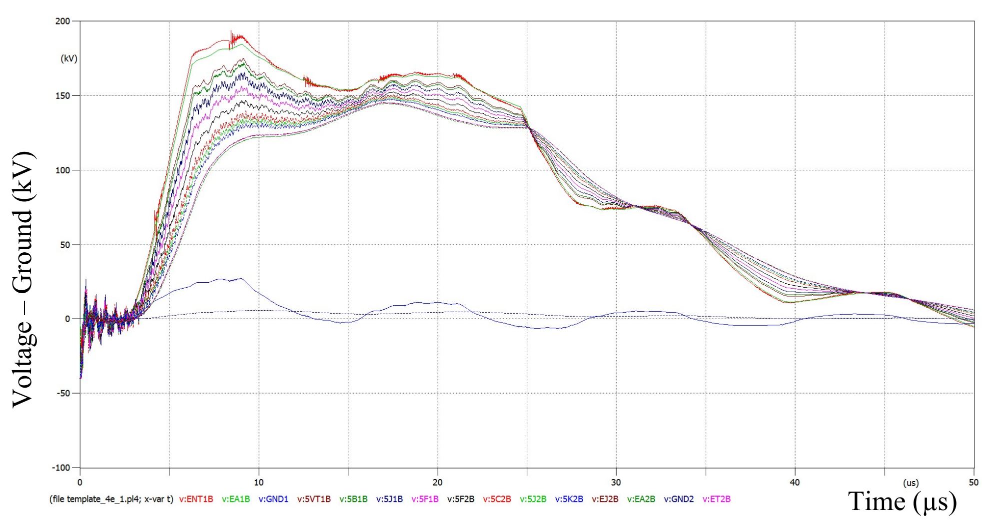

Figure 7-22 Case Study 1, Scenario 4e – 1 m ATP Voltage to Ground Measurements

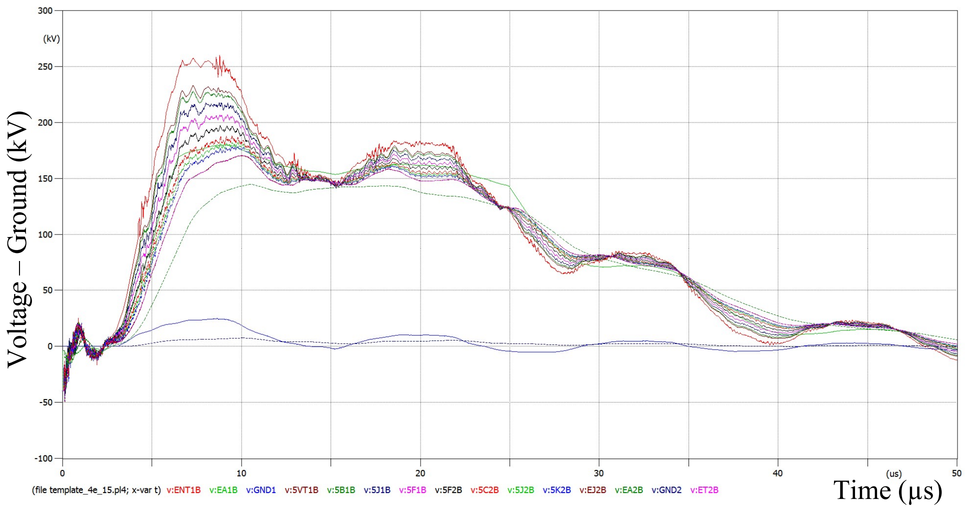

Figure 7-23 Case Study 1, Scenario 4e – 15 m ATP Voltage to Ground Measurements

7.5.9 Case Study 1, Scenario 4e Result Discussion

As expected, the ATP calculated results between case study 1, scenario 4a, and case study 1, scenario 4e are identical. As previously documented in the results for case study 1, scenario 4b, changes to the transformer surge arrester (*EA2*) incoming leads had very little effect on the resultant peak overvoltages throughout the substation. The calculated results align to those of case study 1, scenario 4a are therefore attributed to the dominant effects of the station entrance surge arrester (*EA1*). This dominance is as a result of approximately two-thirds of the lightning current being discharged through the station entrance surge arrester (*EA1*) discussed in case study 1, scenario 1 results.

A maximum of 5 m is recommended for the station entrance surge arrester (*EA1*) incoming leads. This relies on the earth lead length not exceeding the standard design length of 8 m and aligns with the recommendation given for case study 1, scenario 4a to ensure the maximum peak overvoltage level of 260 kV is not exceeded at the station entrance (*ENT1*).

Similarly, the maximum incoming lead length for the transformer surge arrester (*EA2*) is also recommended at 5 m. As discussed in the results of case study 1, scenario 4b, this is dependant on keeping the earth lead length unchanged at 4 m and ensures insulation coordination is maintained with the transformer in the event that the station entrance surge arresters (*EA1*) fail.

7.5.10 Case Study 1, Scenario 4f Results

Table 7-11 Case Study 1, Scenario 4f – 1 m, 2.5 m & 5 m ATP Results

Circuit Location		Voltage (kV)					
		1 m		2.5m		5 m	
		V–G	Surge	V–G	Surge	V–G	Surge
B	Station Entrance *"ENT1"* / Surge Arrester 1 Junction *"EJ1"*	187	227	188	228	193	233
C	Surge Arrester 1 *"EA1"*	171	211	173	213	176	216
D	Surge Arrester 1 Earth Conductor *"GND1"*	13	53	15	55	18	58
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	158	-	158	-	158	-
E	Voltage Tx 1 *"5VT1"*	168	208	170	210	173	213
F	Circuit Breaker *"5B1"*	166	206	168	208	171	211
G	Air Break Switch *"5J1"*	160	200	163	203	165	205
H	Air Break Switch *"5F1"*	157	197	155	195	156	196
I	Air Break Switch *"5F2"*	154	194	154	194	155	195
J	Air Break Switch *"5C2"*	153	193	152	192	152	192
K	Air Break Switch *"5J2"*	152	192	150	190	151	191
L	Circuit Breaker *"5K2"*	151	191	150	190	149	189
M	Surge Arrester Junction *"EJ2"*	148	188	148	188	147	187
N	Surge Arrester 2 *"EA2"*	147	187	147	187	146	186
O	Surge Arrester 2 Earth Conductor *"GND2"*	4	44	4	44	3	43
N-O	Surge Arrester Discharge Voltage *"ED2"*	143	-	143	-	143	-
P	Transformer 2 *"ET2"*	148	188	148	188	147	187

Table 7-12 Case Study 1, Scenario 4f – 10 m, 15 m & 30 m ATP Results

Circuit Location		Voltage (kV)					
		10 m		15m		30 m	
		V–G	Surge	V–G	Surge	V–G	Surge
B	Station Entrance *"ENT1"* / Surge Arrester 1 Junction *"EJ1"*	200	240	210	250	235	***275***
C	Surge Arrester 1 *"EA1"*	183	223	195	235	220	***260***
D	Surge Arrester 1 Earth Conductor *"GND1"*	26	66	40	80	65	105
C-D	Surge Arrester 1 Discharge Voltage *"ED1"*	157	-	155	-	155	-
E	Voltage Tx 1 *"5VT1"*	180	220	189	229	210	250
F	Circuit Breaker *"5B1"*	178	218	185	225	206	246
G	Air Break Switch *"5J1"*	172	212	180	220	197	237
H	Air Break Switch *"5F1"*	162	202	170	210	185	225
I	Air Break Switch *"5F2"*	154	194	160	200	176	216
J	Air Break Switch *"5C2"*	151	191	151	191	182	222
K	Air Break Switch *"5J2"*	149	189	148	188	160	200
L	Circuit Breaker *"5K2"*	148	188	147	187	155	195
M	Surge Arrester Junction *"EJ2"*	146	186	145	185	145	185
N	Surge Arrester 2 *"EA2"*	145	185	144	184	144	184
O	Surge Arrester 2 Earth Conductor *"GND2"*	3	33	4	44	7	47
N-O	Surge Arrester Discharge Voltage *"ED2"*	142	-	140	-	137	-
P	Transformer 2 *"ET2"*	146	186	145	185	145	185

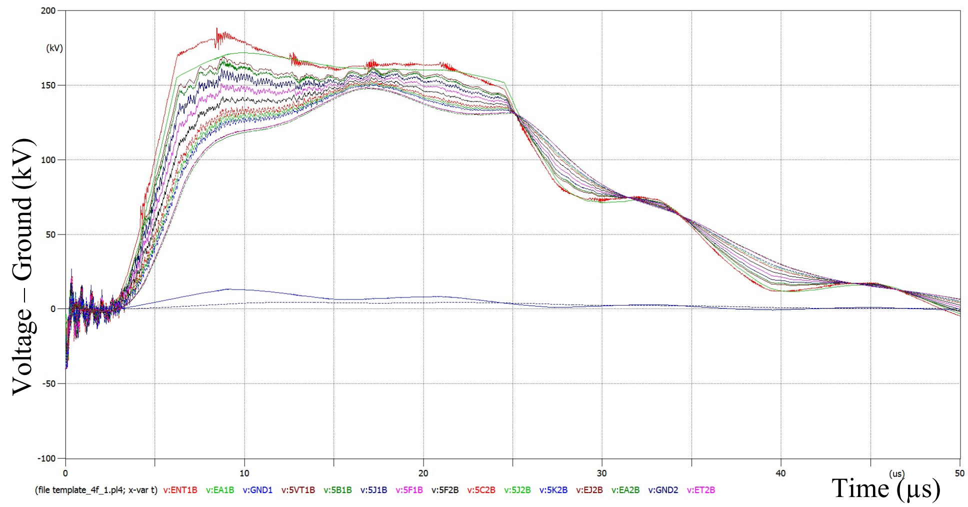

Figure 7-24 Case Study 1, Scenario 4f – 1 m ATP Voltage to Ground Measurements

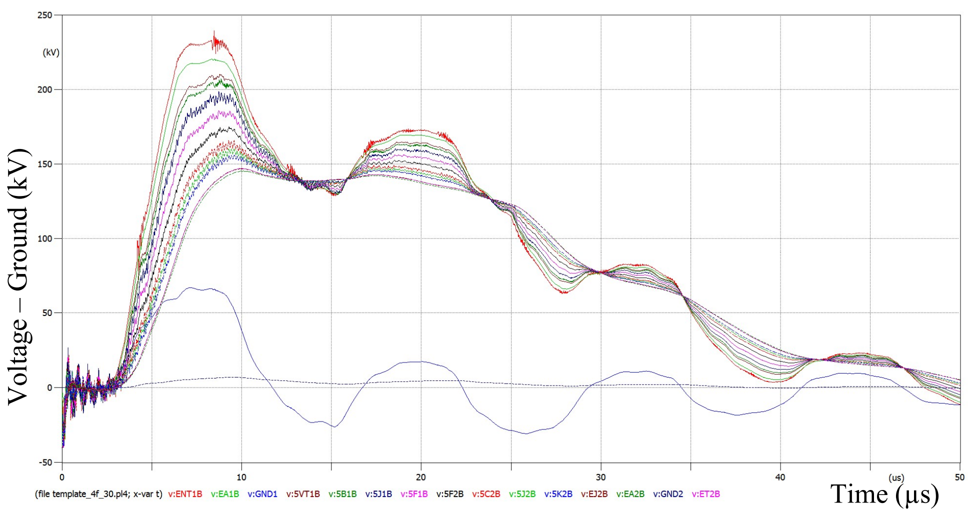

Figure 7-25 Case Study 1, Scenario 4f – 30 m ATP Voltage to Ground Measurements

7.5.11 Case Study 1, Scenario 4f Result Discussion

Identical results have been calculated between case study1, scenario's 4f and 4c. This is the result of the dominance of the station entrance surge arresters (*EA1*).

To maintain safe electrical clearances, the 4 m minimum station entrance surge arrester (*EA1*) earth lead length recommended for case study 1, scenario 4c remains applicable in this scenario. This also applies to the transformer surge arrester (*EA2*) as previously discussed in the results for case study 1, scenario 4d.

To ensure 260 kV (220 kV V-G) maximum allowable BIL limit is not exceeded, the maxmum length for the station entrance surge arrester (*EA1*) earth lead based on the derived voltage increase rate of 1.7 kV/m discussed in case study 1, scenario 4c is equal to 21 m.

To ensure insulation coordination is maintained with the transformer (*ET2*) in the event failure of the station entrance surge arrester (*EA1*), the maximum transformer surge arrester (*EA2*) earth lead length is recommended at 12 m. This is detailed in the result discussion of case study 1, scenario 4d.

Case Study 1, Scenario 5 – Alternate Surge Arrester Connection Arrangement.

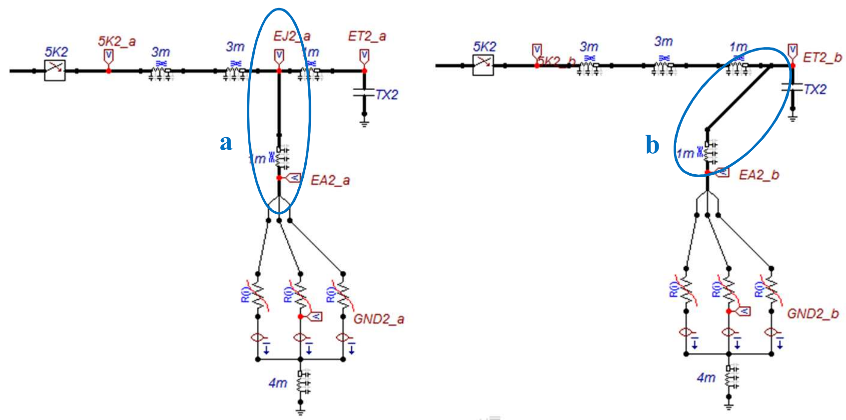

Figure 7-26 Case Study 1, Scenario 5 - ATP Model

7.5.12 Objectives

Modify the transformer surge arrester connection arrangement and identify differences in recorded peak voltages to determine a preferred transformer surge arrester connection arrangement.

7.5.13 Methodology

ATP: Case study 1, scenario 1 is used as the basis of this analysis. An identical lightning surge to scenario 2 is applied and resultant voltages to ground are calculated at the power transformer 2 *"ET2"* (a). This is repeated with the transformer surge arrester incoming lead connected directly to the terminals of the transformer (b).

Changes made to case study 1, scenario 1 include:

- Relocation of the transformer surge arrester (EA2) incoming lead from EJ2, to ET2.

7.5.14 Results

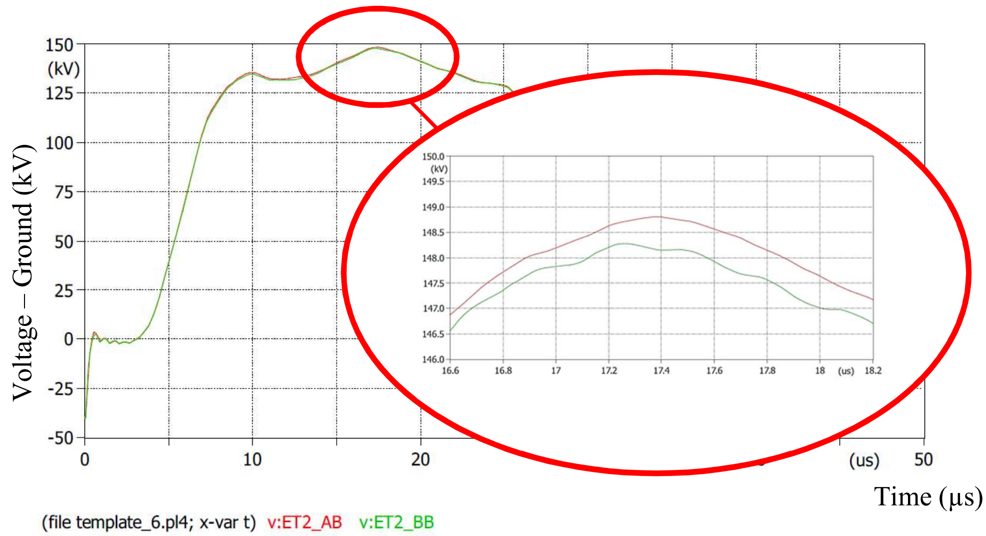

Figure 7-27 Case Study 1, Scenario 5 - ATP Voltage to Ground Measurements

7.5.15 Result Discussion

An examination of the two results in Figure 7-27 reveals a negligible difference between the two different connection arrangements. Connecting the surge arrester lead directly onto the transformer terminals (Type 'b' - Figure 7-26) resulted in a slightly lower peak voltage (149kV versus 148kV). This may be attributed to an additional 1 m separation between the surge arrester and transformer terminals for connection type 'a' (Figure 7-26) due to the distance from transformer terminals to the surge arrester terminals equating to 1m less in this configuration. The simulation was then run with the surge arrester connected to the transformer terminals and the incoming lead length increased to the maximum recommended length as defined in case study 1, scenario 4b (Figure 7-28). This equates to 4m for connection type 'a' and 5 m for connection type 'b'. No discernible difference was calculated leading to the conclusion that at distances up to the maximum recommended in case study 1, scenario 4, the connection arrangement does not influence the effectiveness of the surge arrester.

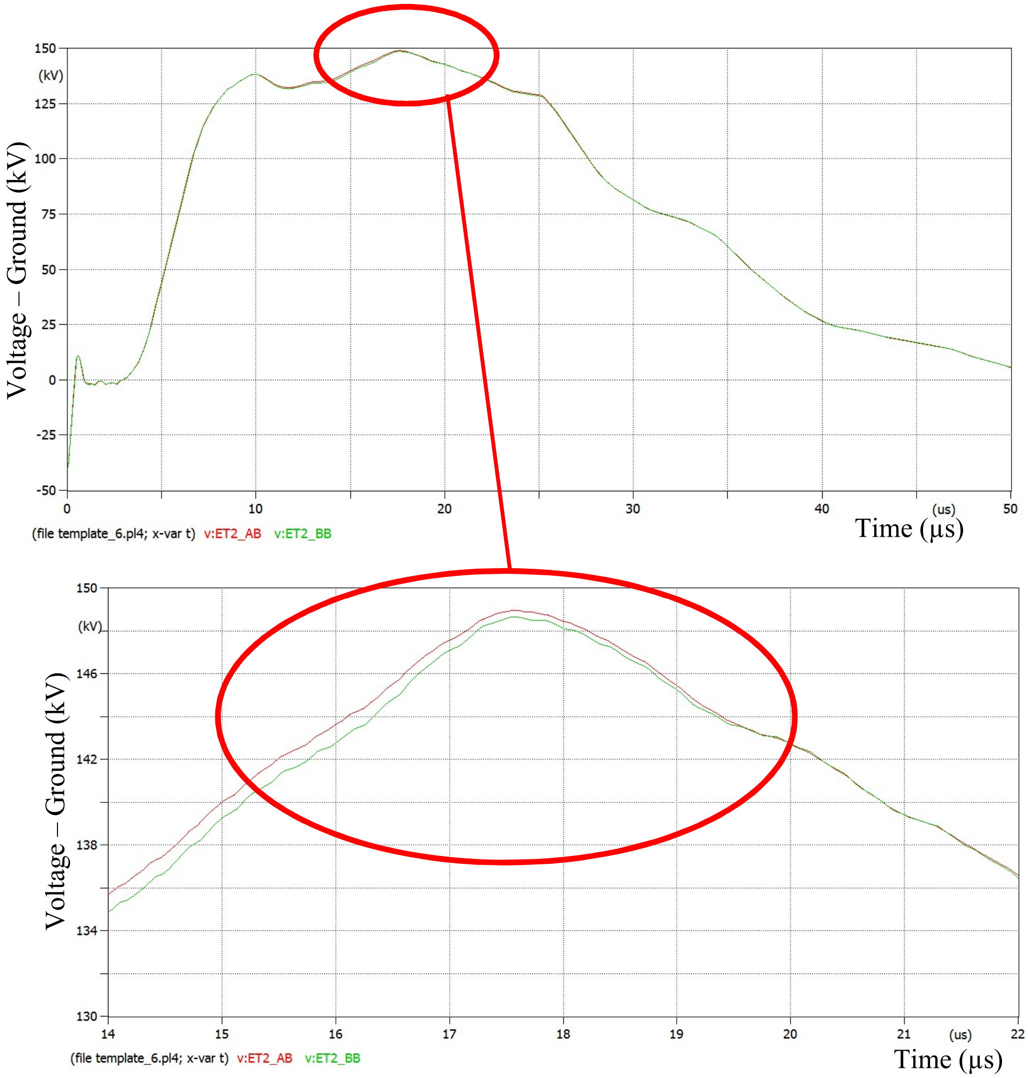

Figure 7-28 Case Study 1, Scenario 5 – Extended Transformer Incoming Lead Length ATP Voltage to Ground Plot

7.6 Case Study 1, Scenario 6 – Comparison of Surge Arrester Models

7.6.1 Objectives

To identify if any areas of deficiency exist with Essential Energy's 66kV effectively earthed period contract surge arresters (Normal and High Strength), a comparison against alternate manufacturers units is proposed.

Identify any improvements to zone substation designs that may be achieved through changes to Essential Energy's standard design or period contract surge arrester specification

7.6.2 Methodology

ATP: Referring to Figure 7-2, case study 1, scenario 1, a 14kA, 8/20 µs lightning surge is applied to "B" phase of the overhead line (A), three spans or 600m away from the substation entrance *"ENT1"* (B).

The resultant voltages to ground are calculated using ATP at surge arrester 1 *"EA1"* (C), surge arrester 1 ground lead *"GND1"* (D), circuit breaker *"5B1"* (F), surge arrester 2 *"EA2"* (N), surge arrester 2 ground lead *"GND2"* (O) and power transformer 2 *"ET2"* (P). Additionally, the discharge currents for each surge arrester are calculated in ATP for comparison against manufacturer data.

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

The five different surge arresters included in this comparison all maintain the following characteristics:

- Maximum Continuous Overvoltage (MVOV) or U_c – 48 kV r.m.s
- Duty Cycle Rating or U_r – 60 kV r.m.s
- Line Discharge Class – 2
- Housing Insulation - Polymer

Manufacturer data for each surge arrester used in the ATP model is included in Table 7-13.

Opposite polarity power frequency voltage is not included in this comparison scenario.

Table 7-13 Case Study 1, Scenario 6 - Surge Arrester Manufacturer Data

ATP Prefix		S	H	B	C	O
Manufacturer		Siemens (Tyree 2015)	Siemens (Siemens 2011)	Bowthorpe (Tyco Electronics 2001)	Cooper Power Systems (Cooper Industries 2012)	Ohio Brass (Hubbell Power Systems 2013)
Arrester Type		3EL1 060-1PH21-4XA5	3EL2 060-2PF21 -4KA0	BOW-2HSRCP60-xxx	UltraSIL VariSTAR Type U2	PVI-LP 30Y648
Rated Voltage		60	60	60	60	60
Continuous Operating Voltage		48	48	48	48	48
Line Discharge Class		2	2	2	2	2
Energy Capability (kJ/kV)		5	5	4.5	3.4	3.4
Residual Voltages (8/20 µs Current Impulse)	**1.5 kA**	-	-	-	131	131
	3 kA	-	-	-	138	138
	5 kA	148	127	148	145	145
	10 kA	159	135	159	156	156
	15 kA	-	143	-	-	-
	20 kA	178	150	175	173	173
	40 kA	204	170	199	196	195

Table 7-14 Case Study 1, Scenario 6 – Calculated Results

Circuit Location		**Voltage to Ground (kV)**				
		Siemens 3EL1 (S)	**Siemens 3EL2 (H)**	**Bowthorpe (B)**	**Cooper (C)**	**Ohio Brass (O)**
C	**Surge Arrester 1 *"EA1"***	186	172	186	187	183
D	**Surge Arrester 1 Earth Conductor *"GND1"***	29	30	29	29	27
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	157	132	157	145	148
F	**Circuit Breaker *"5B1"***	180	169	180	185	172
N	**Surge Arrester 2 *"EA2"***	148	131	148	145	148
O	**Surge Arrester 2 Earth Conductor *"GND2"***	3	4	5	4	4
N-O	**Surge Arrester Discharge Voltage *"ED2"***	145	127	143	141	144
P	**Transformer 2 *"ET2"***	147	132	157	158	156
		Current (kA)				
C	**Surge Arrester 1 *"EA1"***	10.4	10.3	10.3	12.1	11.2
N	**Surge Arrester 2 *"EA2"***	4.9	5.0	4.9	4.0	4.8

7.6.3 Case Study 1 Scenario 6 Results

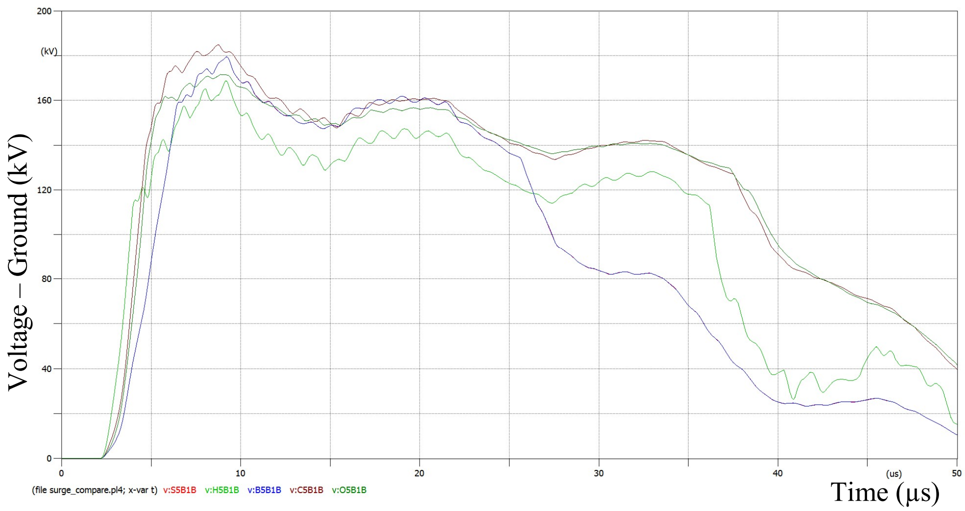

Figure 7-29 Case Study 1, Scenario 6 - CB 5B1 ATP Voltage to Ground Measurements

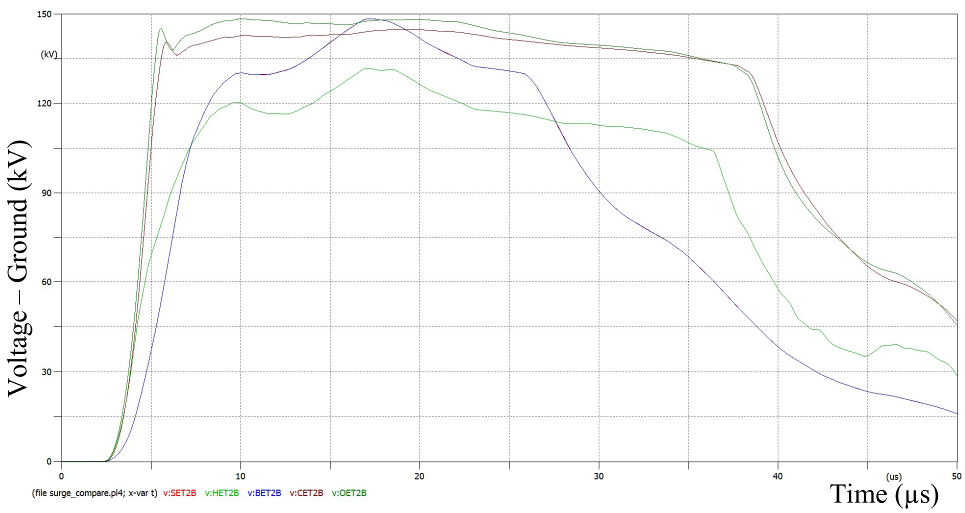

Figure 7-30 Case Study 1, Scenario 6 - Transformer ET2 ATP Voltage to Ground Measurements

7.6.4 Case Study 1, Scenario 6 Result Discussion

Comparing the ATP calculated discharge voltages and arrester currents against manufacturers data, it is found the model accuracy is within 5% for all surge arresters. Station entrance *EA1* (and transformer *EA2*) surge arrester discrepancies are as follows:

- Siemens 3EL1 060-1PH21-4XA5: -1.2% (-1.9%)
- Siemens 3EL2 060-2PF21 - 4KA0: 4.6% (0%)
- Bowthorpe BOW-2HSRCP60-xxx: -1.6% (-3.3%)
- Cooper Power Systems UltraSIL VariSTAR Type U2: -1% (-0.4%)
- Ohio Brass PVI-LP 30Y648: -1.3% (-0.4%)

Examination of the voltage to ground plots at the circuit breaker "5B1" reveal a variance of 9.5% between the highest and lowest calculated voltages (185 kV Cooper Power System and 169 kV Siemens 3EL2). At the transformer the variance increased to 19% (148kV Siemens 3EL1, Bowthorpe & Cooper Power System and 132 kV Siemens 3EL2).

All surge arresters modelled were specified with a line discharge class of 2 which implies each surge arrester's energy absorption capability has met the requirements set out in AS1307.2-1996 Table 7.2. It can be seen that even with an equal line discharge class, the specified energy handling capability varies amongst the five selected surge arresters from a minimum of 3.4 to 5 kJ/kV. The Essential Energy period contract arresters have the best energy handling capability at 5 kJ/kV.

All of the surge arresters modelled limit the lightning overvoltage to acceptable levels. Both Essential Energy period contract 66 kV surge arresters compare favourably against each of the three alternative surge arresters. Interestingly, a lower discharge voltage was calculated across the Siemens 3EL2 high strength surge arrester compared to the regular strength 3EL1 unit at both sets of surge arresters. Both surge arresters are specified with an energy handling capability of 5 kJ/kV and therefore the difference may be attributed to the construction of the larger construction of the high strength arrester and subsequently the additional MOV discs internal to the arrester. An example of the MOV disc assembly is shown in Figure 2-12. The difference is a somewhat modest 11 kV at CB 5B1, but becomes a rather significant 25 kV at the transformer. Opportunities exist to utilise the 3EL2 units to provide insulation co-ordination where the regular strength units do not. This may extend from increasing the maximum incoming and earth lead lengths recommended in case study 1, scenario 4 to providing greater protection to aged equipment where the BIL rating may have deteriorated over time.

7.7 Case Study 1, Scenario 7 –Lightning Strike Onto Zone Substation

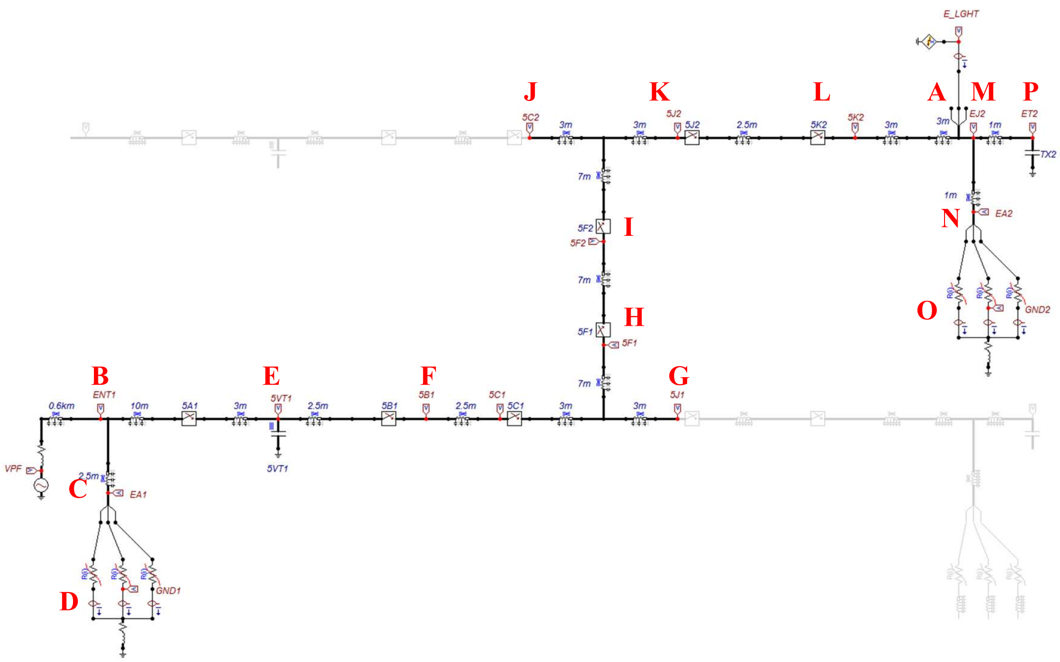

Figure 7-31 Case Study 1, Scenario 7 - ATP Model

7.7.1 Objectives

The simulation of a lightning strike onto the overhead conductors connected to transformer 2 (*ET2*) terminals aims to determine:

a. The level of protection the standard substation design provides by establishing voltages to ground and surge voltages at terminals of equipment.
b. The level of protection station entrance (*EA1*) surge arresters only provide by establishing voltages to ground and surge voltages at terminals of equipment.
c. The level of protection transformer (*EA2*) surge arresters only provide by establishing voltages to ground and surge voltages at terminals of equipment.

7.7.2 Methodology

ATP: As detailed in section 4.3.4, the zone substation lightning protection designed is 97% effective against lightning up to 5.4 kA in magnitude. Referring to Figure 7-2, a 5.4 kA, 8/20µs lightning surge is applied to "B" phase of the zone substation conductor's overhead line (A). The resultant voltages to ground are calculated at the substation entrance and surge arrester 1 junction *"EJ1"* (B), surge arrester 1 *"EA1"* (C), surge arrester 1 ground lead *"GND1"* (D), voltage transformer 1 *"5VT1"* (E), circuit breaker *"5B1"* (F), air break switch *"5J1"* (G), air break switch *"5F1"*(H), air break switch

"5F2" (I), air break switch *"5C2"* (J), air break switch *"5J2"* (K), circuit breaker *"5K2"* (L), surge arrester 2 junction *"EJ2"* (M), surge arrester 2 *"EA2"* (N), surge arrester 2 ground lead *"GND2"* (O) and power transformer 2 *"ET2"* (P).

Changes made to case study 1, scenario 1 include:

- Relocation of the lightning surge to EJ2.
- 5.4 kA lightning surge amplitude.

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.7.3 Case Study 1 Scenario 7 Results

Table 7-15 Case Study 1, Scenario 7 – Calculated Results

Circuit Location		Voltage (kV)					
		Station Entrance & Tx2		Station Entrance Only		Tx2 Only	
		V–G	Surge	V–G	Surge	V–G	Surge
B	**Station Entrance *"ENT1"*** **Surge Arrester 1 Junction *"EJ1"***	72	112	160	200	162	202
C	**Surge Arrester 1 *"EA1"***	70	110	155	195	-	-
D	**Surge Arrester 1 Earth Conductor *"GND1"***	3	43	8	47	-	-
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	67	-	147	-	-	-
E	**Voltage Tx 1 *"5VT1"***	75	115	173	213	161	201
F	**Circuit Breaker *"5B1"***	76	116	175	215	161	201
G	**Air Break Switch *"5J1"***	79	119	181	221	160	200
H	**Air Break Switch *"5F1"***	81	121	187	227	159	199
I	**Air Break Switch *"5F2"***	84	124	192	232	158	198
J	**Air Break Switch *"5C2"***	86	126	200	240	158	198
K	**Air Break Switch *"5J2"***	87	127	203	243	157	197
L	**Circuit Breaker *"5K2"***	88	128	205	245	156	196
M	**Surge Arrester Junction *"EJ2"***	89	129	208	248	155	195
N	**Surge Arrester 2 *"EA2"***	88	128	-	-	153	193
O	**Surge Arrester 2 Earth Conductor *"GND2"***	3	43	-	-	6	46
N-O	**Surge Arrester Discharge Voltage *"ED2"***	85	-	-	-	147	-
P	**Transformer 2 *"ET2"***	89	-	208	248	155	197

7.7.4 Case Study 1, Scenario 7 Result Discussion

The results in Table 7-15 clearly show when two sets of surge arresters are installed, the standard design comfortably handles the 5.4 kA lightning surge. The travel time for the surge is almost instantaneous which is to be expected considering the very short distance between the strike point and the arresters (Figure 23-45). The power frequency voltage is appearing as a dominant transient, but this is somewhat misleading due to the low peak overvoltage levels.

Allowing for peak overvoltage increases at the rate of 3.5 kV/m (incoming lead) and 1.7 kV/m (earth lead), the standard substation design could be modified with surge arrester leads at greater distances than recommended in case study 1, scenario 4. Insulation coordination would not be maintained, however for an average magnitude lightning strike to the incoming overhead line outside the substation.

When only a single set of surge arresters are installed, the results for each (station entrance Figure 23-34 and transformer 2 Figure 23-35) show both configurations protect the substation equipment by limiting the peak overvoltages to below the 260 kV (80%) BIL threshold. Whilst the discharge voltages in each configuration were equal at 147 kV, higher peak overvoltages were calculated as expected in the station entrance surge arresters only example due to the longer time substation equipment is subjected to the lightning surge.

No changes to the recommendations of case study 1, scenario 4 is therefore proposed to maintain insulation co-ordination for higher magnitude surges resulting from strikes to the overhead line, outside the substations lightning protection system.

7.8 Case Study 2, Scenario 1 – In Service Substation Configuration.

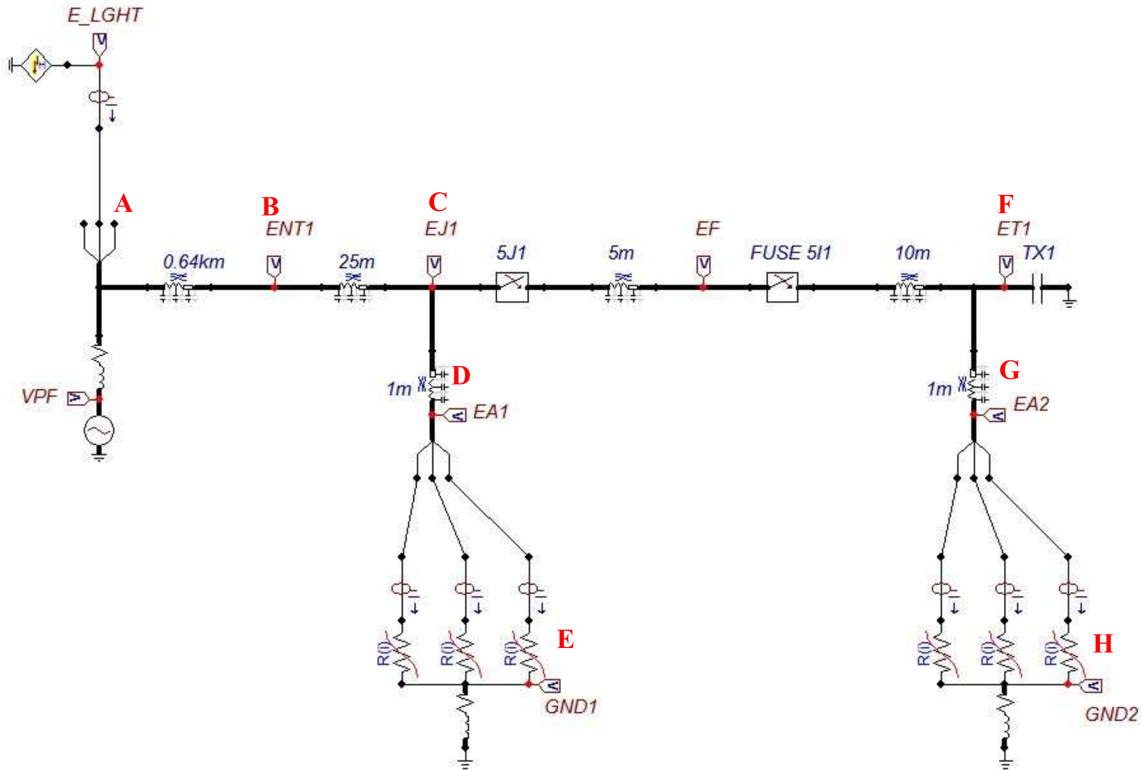

Figure 7-32 Case Study 2, Scenario 1 - ATP Model

7.8.1 Objectives

To determine if the placement of surge arresters within a typical small rural zone substation design maintains a suitable zone of protection across all equipment and identify any voltages that exceed 80% of the substation equipment BIL rating of 325 kV (260 kV) at terminals of equipment located as per the standard design for case study 2.

7.8.2 Methodology

ATP: Referring to Figure 7-32 above, a 14kA, 8/20 µs lightning surge is applied to "B" phase of the overhead line (A), four spans or 640m away from the substation entrance – *"ENT1"* (B). The resultant voltages to ground are calculated at the surge arrester 1 junction *"EJ1"* (C), line terminal of surge arrester 1 *"EA1"* (D), surge arrester 1 ground lead *"GND1"* (E), the power transformer *"ET1"* (F), the line terminal of surge arrester 2 *"EA2"* (G) and surge arrester 2 ground lead *"GND2"* (E).

To determine arrester discharge voltages, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.8.3 Case Study 2, Scenario 1 Results

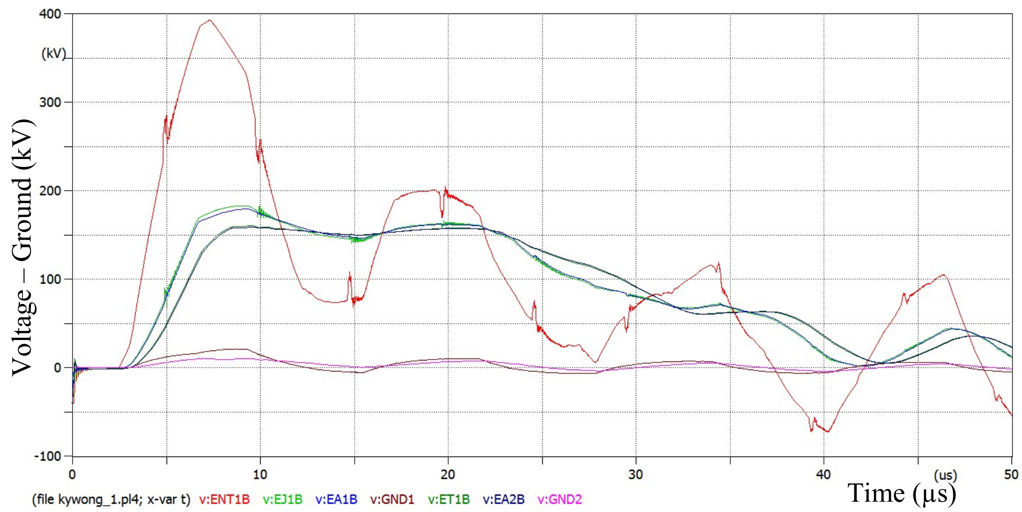

Figure 7-33 Case Study 2, Scenario 1- ATP Voltage to Ground Measurements

Table 7-16 Case Study 2, Scenario 1 – Calculated Results

Circuit Location		Voltage (kV)	
		V – G	Surge
B	Station Entrance *"ENT1"*	466	506
C	Surge Arrester 1 Junction *"EJ1"*	185	225
D	Surge Arrester 1 *"EA1"*	181	221
E	Earth Conductor *"GND1"*	21	61
D-E	Surge Arrester 1 Discharge Voltage *"ED1"*	160	-
F	Transformer 1 *"ET1"*	160	200
G	Surge Arrester 2 *"EA2"*	159	199
H	Earth Conductor *"GND2"*	9	49
G-H	Surge Arrester 2 Discharge Voltage *"ED2"*	150	-

7.8.4 Case Study 2, Scenario 1 Result Discussion

The substation is well protected from the incoming surge. The close proximity of all the substation equipment and the two sets of surge arresters have resulted in relatively constant peak overvoltages at the station entrance (*ENT1*) and the transformer (*ET1*). Such close proximity between each set of surge arrester contributes to similar discharge voltages of 159 kV (*EA1*) and 150 kV (*EA2*). Estimates of the each surge arrester zone of protection using equation 2.36 equate to approximately 18 m for both *EA1* and *EA2*. This indicates that two sets of surge arresters provide no gaps in the zone of protection. If either set of surge arresters was to be removed however, the 14 kA current through the single arrester would result in a discharge voltage similar to that calculated in case study 1, scenario's 2 and 3 of approximately 168 kV. The protective zone would then be reduced to 16 m, still maintaining protection for the transformer.

In Figure 7-34, a comparison of the ATP calculated overvoltage (V-G) plot of the transformer (*ET1*) when the model is modified with only one of the surge arresters only resulted in an identical peak of 205 kV (V-G) and 245 kV (Surge).

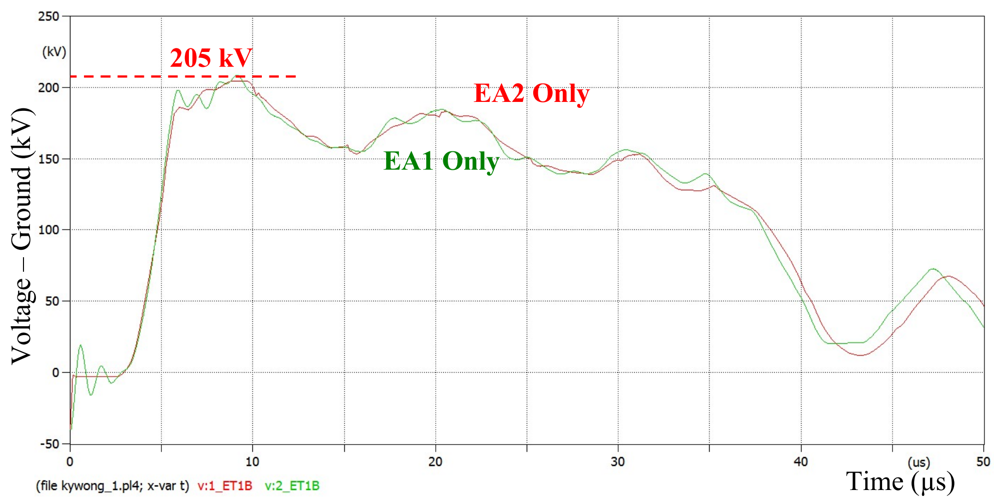

Figure 7-34 Case Study 2, Scenario 1 Station entrance Surge Arrester Only ATP Voltage to Ground Measurements

A reduced number of reflections decaying at a faster rate are also observed when compared with the validation results in section 6.3.2. This is a result of the shorter tail time of the lightning surge waveform. The proximity of power frequency voltage source is resulting in additional reflected voltages transposed onto the resultant station entrance (*ENT1*) and surge arrester 1 junction (*EJ1*) overvoltage plots (Figure 7-33).

For small substations of which case study 2 is representative of, the two sets of surge arresters provide very thorough protection from an average sized lightning surge. A single set of surge arresters at either the station entrance or the transformer still provides suitable protection in this example due to the transformer remaining within the zone of protection.

7.9 Case Study 2, Scenario 2 – Recorded Lightning Strike Onto Overhead Line.

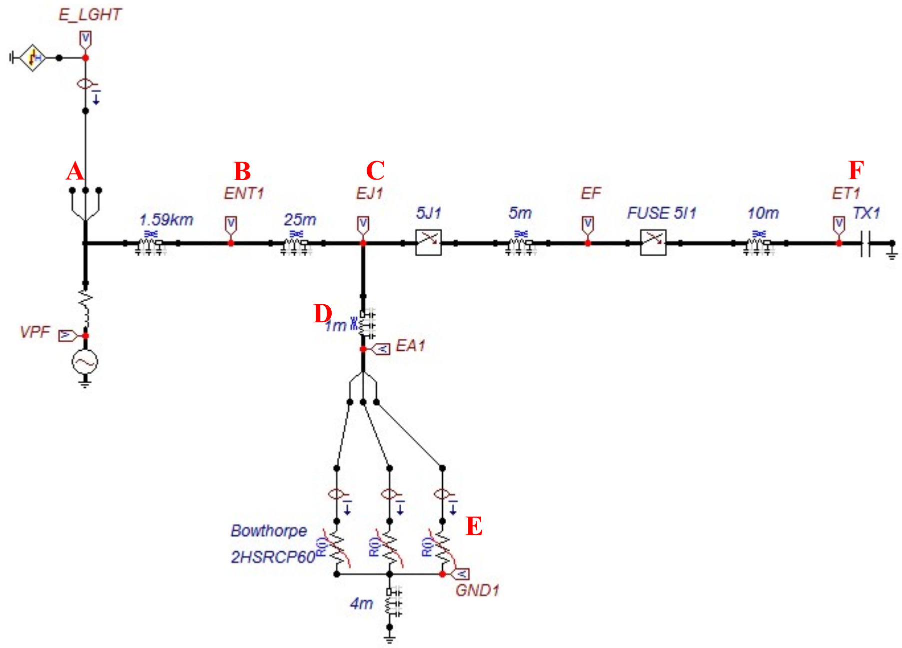

Figure 7-35 Case Study 2, Scenario 2 - ATP Model

7.9.1 Objectives

Simulate the impact an 11.3 kA lightning strike that was recorded 1/11/2015 11:18:45 (APPENDIX N) on the 66kV feeder 840/4 - Narrandera to Kywong Tee had on the Kywong zone substation. Establish voltages to ground and surge voltages at terminals of equipment located as per the arrangement of the substation at the time of strike to determine if voltages exceeded 260 kV (80%) of the substation equipment BIL.

7.9.2 Methodology

ATP: The ATP model has been developed from Case Study 2, scenario 1 with the following modifications:

- Lightning amplitude 11.3kA.
- Strike location 1590 meters from zone substation as measured in Google Earth
- Removal of transformer surge arrester (*EA2*). At time of lightning strike, the substation was fitted with only a single set of surge arresters at the station entrance.

Referring to Figure 7-35 above, an 11.3kA 8/20 µs lightning surge is applied to "B" phase of the overhead line (A), 1590m away from the substation entrance – *"ENT1"* (B). The resultant voltages to ground are calculated at the substation entrance *"ENT1"* (B), surge arrester 1 junction *"EJ1"* (C), line terminal of surge arrester 1 *"EA1"* (D), surge arrester 1 ground lead *"GND1"* (E) and the power transformer *"ET1"* (F).

To determine arrester discharge voltages, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.9.3 Case Study 2, Scenario 2 Results

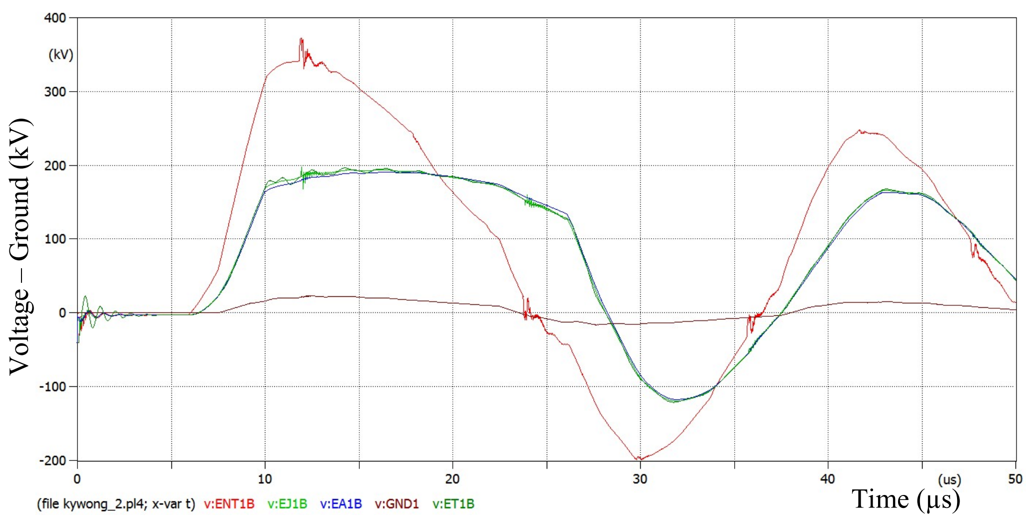

Figure 7-36 Case Study 2, Scenario 2 - ATP Voltage to Ground Measurements

Table 7-17 Case Study 2, Scenario 2 – Calculated Results

Circuit Location		Voltage (kV)	
		V – G	Surge
B	Station Entrance *"ENT1"*	***335***	***375***
C	Surge Arrester 1 Junction *"EJ1"*	195	235
D	Surge Arrester 1 *"EA1"*	190	230
E	Earth Conductor *"GND1"*	20	60
D-E	Surge Arrester 1 Discharge Voltage *"ED1"*	170	-
F	Transformer 1 *"ET1"*	196	236

7.9.4 Case Study 2, Scenario 2 Result Discussion

Referring to the ATP calculated results in Figure 7-36, the time for the lightning surge to reach Kywong zone substation is approximately 7 µs. This is consistent with the ATP calculated surge velocity of 220 m/µs (1590 m / 220 µs = 7.2 µs).

The reduction to the frequency of reflections seen in the calculated results may be attributed to the increased distance to the strike point form the zone substation. In addition, the increased strike distance has had the effect of amplifying the size of the reflected voltage, which now has a peak-to-peak voltage of over 500 kV. Additional reflected voltages transposed onto the resultant overvoltage as a result of the proximity of the power frequency voltage source are still prevalent on the station entrance (*ENT1*) voltage plot. To a lesser extent these reflections may also be seen on the surge arrester junction (*EJ1*) plot.

The calculated results show the station entrance surge arrester has limited the peak overvoltage at the transformer to 196 kV, well below the equipment BIL rating.

Further investigation into reports of power outages at the Kywong zone substation at the time of the recorded lightning strike failed to return any record of such events.

It may therefore be concluded from these results that in this example, the single set of surge arresters provided suitable protection against the below average magnitude lightning strike. Despite this however, it is recommended that a typical small substation such as Kywong have surge arresters installed at the station entrance and the transformer. Comparing the results of case study 2 scenario's 1 and 2, similar peak overvoltages are calculated at the station entrance surge arrester junction (EJ1), with a 15% reduction in the voltage at the transformer observed with the transformer surge arresters installed. With many of this substation type containing transformers in excess of 30 years in age, the added protection the transformer surge arresters provide is justified.

7.10 Case Study 2, Scenario 3 – Lightning Strike Onto Zone

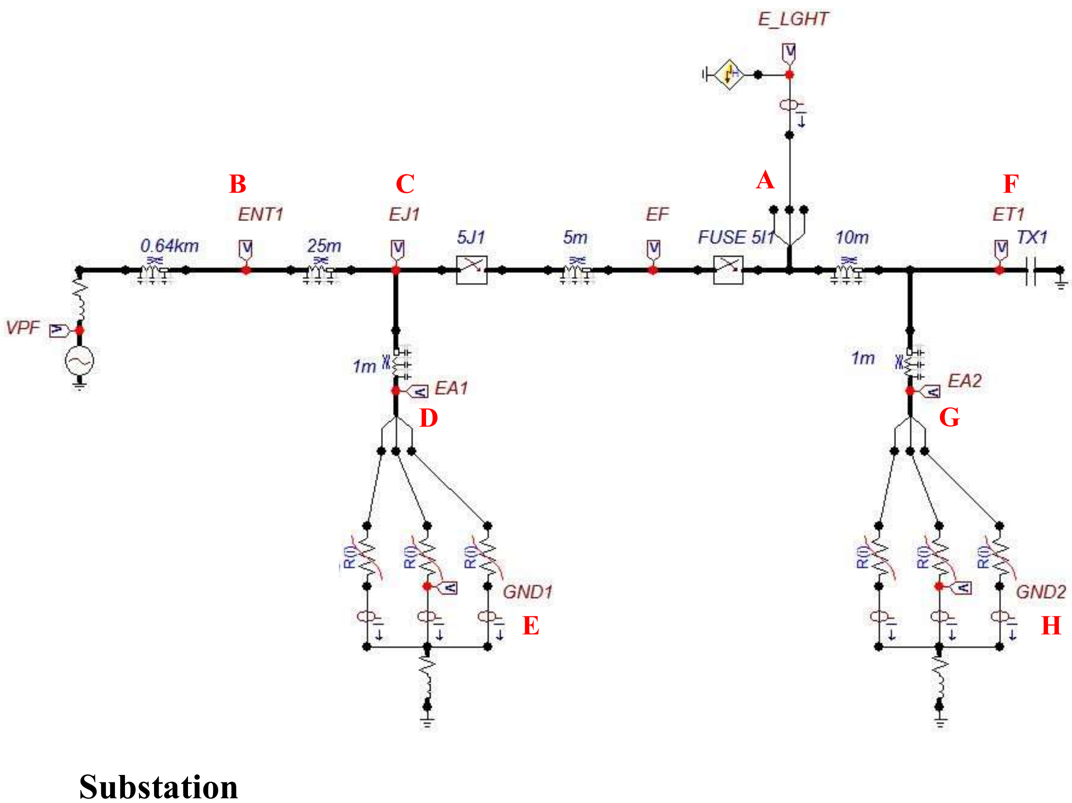

Figure 7-37 Case Study 2, Scenario 3 - ATP Model

7.10.1 Objectives

- Simulation of a lightning strike onto the overhead conductors inside the Kywong zone substation aims to determine The level of protection the Kywong zone substation design provides by establishing voltages to ground and surge voltages at terminals of equipment.

7.10.2 Methodology

ATP: The ATP model has been developed from Case Study 2, scenario 1 with the following modifications:

- Lightning amplitude 38.8 kA.
- Strike location 10 m from transformer.

At the time of the recorded 38.8 kA lightning strike, the substation was fitted with surge arresters at the station entrance only. This scenario will be conducted with:

- Station entrance (*EA1*) and transformer (*EA2*) surge arresters installed.

- Station entrance (*EA1*) surge arresters only installed.
- Transformer (*EA2*) surge arresters only installed.

As previously described in section 4.3.3, Kywong zone substation does not presently have adequate lightning protection. The largest magnitude lightning strike recorded within 2 km of the Kywong zone substation between October 2015 and March 2016 was 38.8 kA (APPENDIX N). Referring to Figure 7-2, a 38.8kA, 8/20 µs lightning surge is applied to "B" phase of the zone substation conductor's overhead line adjacent to 66kV fuse 5I1. (A). The resultant voltages to ground are calculated at the substation entrance (B), and surge arrester 1 junction *"EJ1"* (C), surge arrester 1 *"EA1"* (D), surge arrester 1 ground lead *"GND1"* (E) and transformer *"ET1"* (F).

To determine the arrester discharge voltage, the voltage drop across each earth conductor between the respective surge arrester and the substation earth grid is subtracted from the voltage recorded at the surge arrester.

7.10.3 Case Study 2, Scenario 3 Results

Table 7-18 Case Study 2, Scenario 3 – Calculated Results

Circuit Location		Voltage (kV)					
		Station Entrance & Tx2		Station Entrance Only		Tx2 Only	
		V–G	Surge	V-G	Surge	V–G	Surge
B	**Station Entrance *"ENT1"*** **Surge Arrester 1 Junction *"EJ1"***	230	***270***	255	***295***	***375***	***415***
C	**Surge Arrester 1 *"EA1"***	202	242	240	***280***	-	-
D	**Surge Arrester 1 Earth Conductor *"GND1"***	37	43	41	81	-	-
C-D	**Surge Arrester 1 Discharge Voltage *"ED1"***	165	-	199	-	-	-
F	**Transformer 2 *"ET2"***	177	217	***285***	***325***	250	***290***
G	**Surge Arrester 2 *"EA2"***	173	213	-	-	238	***278***
H	**Surge Arrester 2 Earth Conductor *"GND2"***	15	45	-	-	42	82
G-H	**Surge Arrester Discharge Voltage *"ED2"***	158	-	-	-	196	-

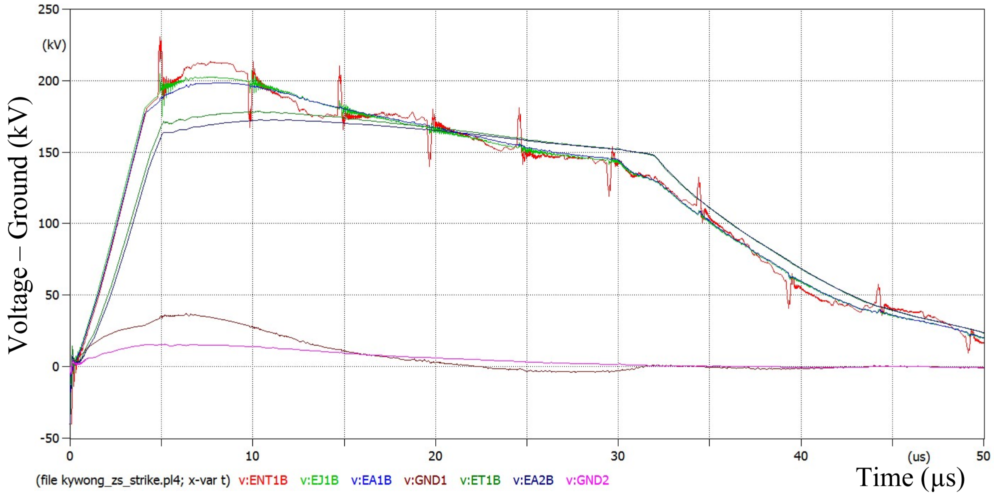

Figure 7-38 Case Study 2, Scenario 3 Station Entrance And Transformer Surge Arrester, ATP Voltage to Ground Measurements

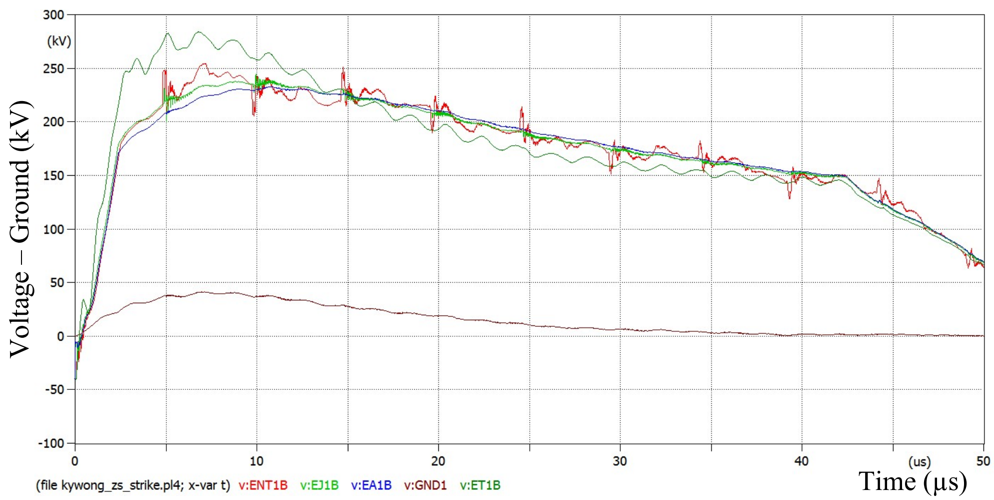

Figure 7-39 Case Study 2, Scenario 3 Station Entrance Surge Arrester Only, ATP Voltage to Ground Measurements

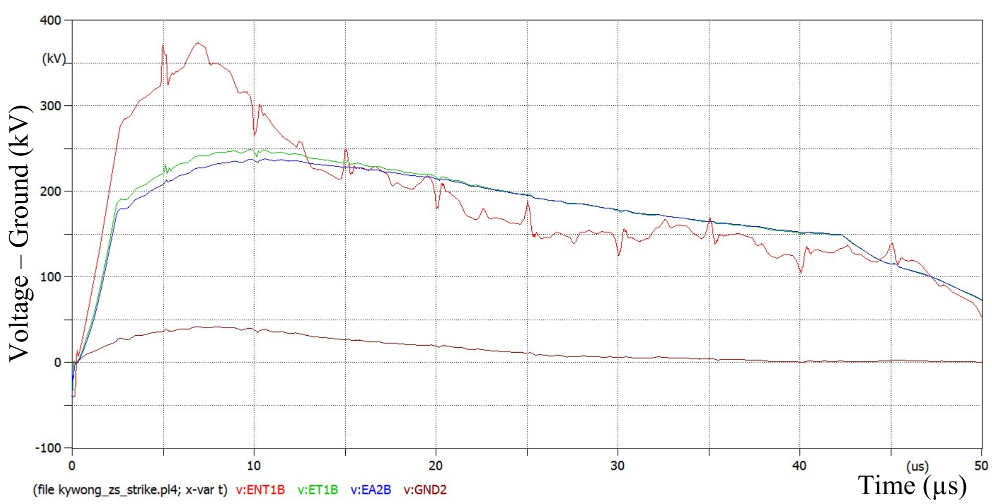

Figure 7-40 Case Study 1, Scenario 7 Transformer Surge Arrester Only, ATP Voltage to Ground Measurements

7.10.4 Case Study 2, Scenario 3 Result Discussion

With two sets of surge arresters installed, the above average magnitude lightning strike limits the peak overvoltage at the transformer to well below the 80% BIL threshold. Taking into account the location of the lightning strike is not equal distance from each surge arrester, the calculated discharge voltages are as expected.

Comparing the calculated results of the station entrance surge arrester (*EA1*) only and transformer surge arrester (EA2) only, the effect of surge arrester separation distance is again highlighted. In the case of station entrance surge arresters only (*EA1*), the additional travel time for the lightning surge to reach the station entrance surge arrester (*EA1*) has resulted in a 35 kV increase in the peak overvoltages which becomes 285 kV (V-G) and 325 kV (surge). It is extremely probable that loss of supply and permanent damage to the transformer would result.

Reflections between the substation and both the lightning and power frequency sources are again observed. Whilst typically most prevalent at the station entrance (*ENT1*), it is clearly visible at the transformer when the station entrance surge arrester (*EA1*) only is installed (Figure 7-39).

These results demonstrate the importance of ensuring transformer surge arresters are installed at a minimum. Prior to early 2016 the Kywong zone substation was reliant on station entrance surge arresters (*EA1*) only. The lack of adequate lightning protection combined with the results for this case study show that this places the substation at considerable risk. Recommendation is for all small rural substations to be upgraded with to include both station entrance and transformer surge arresters.

The importance of adequate zone substation lightning protection is also highlighted in this scenario. If the lightning protection at Kywong were to AS1768-2007, the probability of an above average magnitude lightning strike direct to the substation conductors would be almost zero.

7.10.5 Results Summary

The ten scenarios presented across two case studies have provided a clear report into the effectiveness of surge arresters within Essential Energy standard substation designs, and small, typical, rural substations.

It was found in scenario 1 of each case study, that when the designs remain unmodified, adequate protection of the equipment is maintained. Peak overvoltages were calculated below the 260 kV (80%) BIL threshold. This was despite protective zones of surge arresters in case study 1 found to not encompass the entire zone substation. When removing one set of surge arresters, case study 1 scenario's 2 and 3 showed that satisfactory insulation co-ordination is not possible for an average magnitude lightning strike on the incoming overhead line.

In contrast to case study 1, the surge arrester protective zone calculated for case study 2 incorporated all equipment within the zone substation. As a result of the small distances between the substation entrance and the transformer, removal of either set of surge arresters managed to maintain peak overvoltages to below 260 kV. This was found to be true through the additional simulation of a known recorded strike (case study 2, scenario 2). The results of which showed with the station entrance surge arresters only, no damage to equipment or outages to customers would be encountered. In the case of a strike directly to the substation as shown in case study 2, scenario 3, it was demonstrated that both sets of surge arresters are required to limit the peak overvoltage at the transformer to below 260 kV.

Investigations into the possibility of improvements to zone substation designs were conducted in the following scenarios. Case study 1, scenario 4 (a to f) involved modification to the incoming and earth lead lengths. Case study 1, scenario 5 with a comparison of two connection configurations onto the transformer, and scenario 6, through further comparison between surge arresters from different manufacturers. The calculated results from scenario 4, highlights the inherent limitations of the maximum and minimum surge arrester lead lengths associated with Essential Energy's standard substation design. These lead lengths are given as follows:

Station Entrance Surge Arrester

Incoming Lead Length

- Minimum 1 m
  (Due to physical constraints)
- Maximum 5 m

Earth Lead Length

- Minimum 4 m
  (Maintain min electrical clearances)
- Maximum 21 m

Transformer Surge Arrester

Incoming Lead Length

- Minimum 1 m
  (Due to physical constraints)
- Maximum 5 m

Earth Lead Length

- Minimum 4 m
  (Maintain min electrical clearances)
- Maximum 12 m

Changes to the connection arrangements presented in case study 1, scenario 5 concluded that no discernible differences in calculated peak overvoltages were achieved. It is recommended that either option of connecting the surge arrester incoming lead directly onto the transformer terminals, or teeing off the conductors before the transformer is considered suitable.

The period contract surge arresters utilised by Essential Energy have shown they perform well in comparison to other makes. No changes are recommended to the specifications of the surge arresters. The calculated peak overvoltage's when simulating the high strength period contract surge arresters were considerably lower than all other units modelled. These units are recommended in situations where greater lead lengths are required as well as where increased protective margins to assist in protecting transformers where the internal paper insulation may have deteriorated over time.

8 CONCLUSION

This report provides the first investigation and technical analysis of both Essential Energy standard 66/11 kV zone substation and typical, small rural zone substation designs through network simulation and modelling using industry accepted ATP software. The models have been validated against analytical calculations and it is found that no changes to standard substation designs are required to ensure insulation co-ordination is maintained. Improvements in reduction of peak overvoltages through modification of surge arrester lead lengths have been presented with recommendations made in regards to minimum and maximum arrester lead lengths whilst ensuring insulation co-ordination is maintained. The results presented in chapter 7 provide substation designers answers to common issues surrounding methods of surge arrester connections, maximum lead lengths and preferred surge arrester type. All of which arise when changes are made to standard designs. The use of these validated ATP models provide Essential Energy with a template to aid in the accurate development of future substation designs.

Research into the proposed use of Essential Energy corporate approved CDEGS software in an attempt to simulate network disturbances, such as those resulting from a lightning strike, found the frequency domain methods are unsuitable for accurate modelling. The requirement for additional software to complete complex calculations significantly reduces the efficiency of the simulation process. Secondly, the simulated annealing algorithm required to derive the current flowing through the surge arrester has not yet been refined to a level whereby typical surge arrester V-I characteristics may be replicated.

9 FURTHER WORK

The methodologies and recommendations put forward in Chapter 7 will be presented to Essential Energy's zone substation design group for consideration in future designs. Building on the knowledge obtained whilst developing the 66 kV network models in ATP, there is an opportunity to create ATP models for standard 132/11 kV and 33/11 kV zone substation designs. These would contribute to the continual development of more comprehensive design guidelines an allow for further development of a tool to assist engineers to determine suitable surge arrester or equipment locations on future substation designs.

The continual advancement of CDEGS towards successfully representing non-linear devices without the need for third party software suggests this may be achieved in the not too distant future. Once available, the possibility will exist for Essential Energy to undertake lightning and insulation co-ordination studies for each completed design using an existing corporate software package.

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11 APPENDIX A

ENG4111/ ENG4112 RESEARCH PROJECT

PROJECT SPECIFICATION.

FOR:	Andrew Close Student No. 0061021891
TITLE:	Operational Characteristics of Surge Arresters within High Voltage Zone Substations.
MAJOR:	Bachelor of Engineering (Honours) Power Major
SUPERVISORS:	Assoc Prof Tony Ahfock. (USQ) Luke Clout (Senior Engineer, Essential Energy) Glen Barnes (Network Earthing Manager, Essential Energy)
SPONSORSHIP:	Essential Energy.
ENROLMENT:	Semesters 1 & 2, 2016

PROJECT AIMS:

a) Using equivalent circuits, aided by computer analysis, to determine if surge arresters within Essential Energy design templates and selected in-service substations are:
   a. Positioned so that a suitable zone of protection is provided for major plant.
   b. Connected in a manner that does not reduce their operational effectiveness.

b) Determine if changes to surge arrester specifications improve the protection of equipment and/or provide savings to purchase, installation, and design or construction costs.

PROGRAMME: Issue A 2nd March 2016

1. Research suitable in-service Essential Energy substations to use as case studies.
2. Research Essential Energy period contract, station class surge arresters.
3. Research current standards for protection of substation equipment against voltage surges and compare with Essential Energy design templates.
4. Research into surge arrester operation, construction and insulation co-ordination.
5. Using software such as Alternative Transients Program (ATP) and Current Distribution Electromagnetic Grounding and Soil (CDEGS), develop models of existing and modified Essential Energy's in-service and template substations.
6. Simulate and analyse surge arrester characteristics and identify peak voltage levels at equipment terminals to determine if effective insulation co-ordination is maintained.
7. Validate and interpret simulation results.

If time and resources permit:

8. Develop a tool to assist engineers determine suitable surge arrester or equipment locations on future substation designs.

12 APPENDIX B

TABLE 3.1

ROD TO STRUCTURE/PLATE GEOMETRY (VOLTAGE RANGE I AND VOLTAGE RANGE II)

1	2	3	4	5	6	7	8	9	10	11	12
									Safety clearances for operational purposes and maintenance work		
Nominal voltage (kV r.m.s)	Highest voltage (see note 6) (kV r.m.s)	Rated short duration power frequency withstand voltage (kV r.m.s)	Rated lightning impulse withstand voltage (kV peak)	Rated switching impulse withstand voltage (kV peak)	Minimum phase-to-earth clearance (mm)	Minimum phase-to-phase clearance (mm)	Non-flashover distance (mm)	Ground safety clearance (mm)	Section safety clearance ($N+G$) (mm)	Horizontal work safety clearance ($N+1900$) (mm)	Vertical work safety clearance ($N+1340$) (mm)
U_n	U_m						N	G	S	H	V
Up to 3.3	Up to 3.6	10	40		60	70	65	2440	2505	1965	1405
6.6	7.2	20	60		90	105	100		2540	2000	1440
11	12	28	75		120	140	130		2570	2030	1470
		28	(95)		(160)	185	175		2615	2075	1515
22	24	50	125		220	255	240		2680	2140	1580
		50	(145)		(280)	325	310		2750	2210	1650
33	36	70	170		320	370	350		2790	2250	1690
		70	(200)		(380)	440	420		2860	2320	1760
66	72.5	140	325		630	725	695		3135	2595	2035
110	123	185	450		900	1035	990		3430	2890	2330
		230	550		1100	1265	1210		3650	3110	2550
132	145	230	550		1100	1265	1210		3650	3110	2550
		275	650		1300	1495	1430		3870	3330	2770
220	245	360	850		1700	1955	1800		4240	3700	3140
		395	950		1900	2185	2015		4455	3915	3355
		460	1050		2100	2415	2225		4665	4125	3565
275	300	380	950	750	1900	2185	2015		4455	3915	3355
		450	1050	850	2400	2760	2545		4985	4445	3885
330	362	450	1050	850	2400	2760	2545		4985	4445	3885
		520	1175	950	2900	3335	3075		5515	4975	4415
500	550	620	1425	1050	3400	3910	3605		6045	5505	4945
		680	1550	1175	4100	4715	4345		6785	6245	5685

Figure 12-1 Zone Substation Minimum Electrical Clearances (AS2067 2016)

13 APPENDIX C

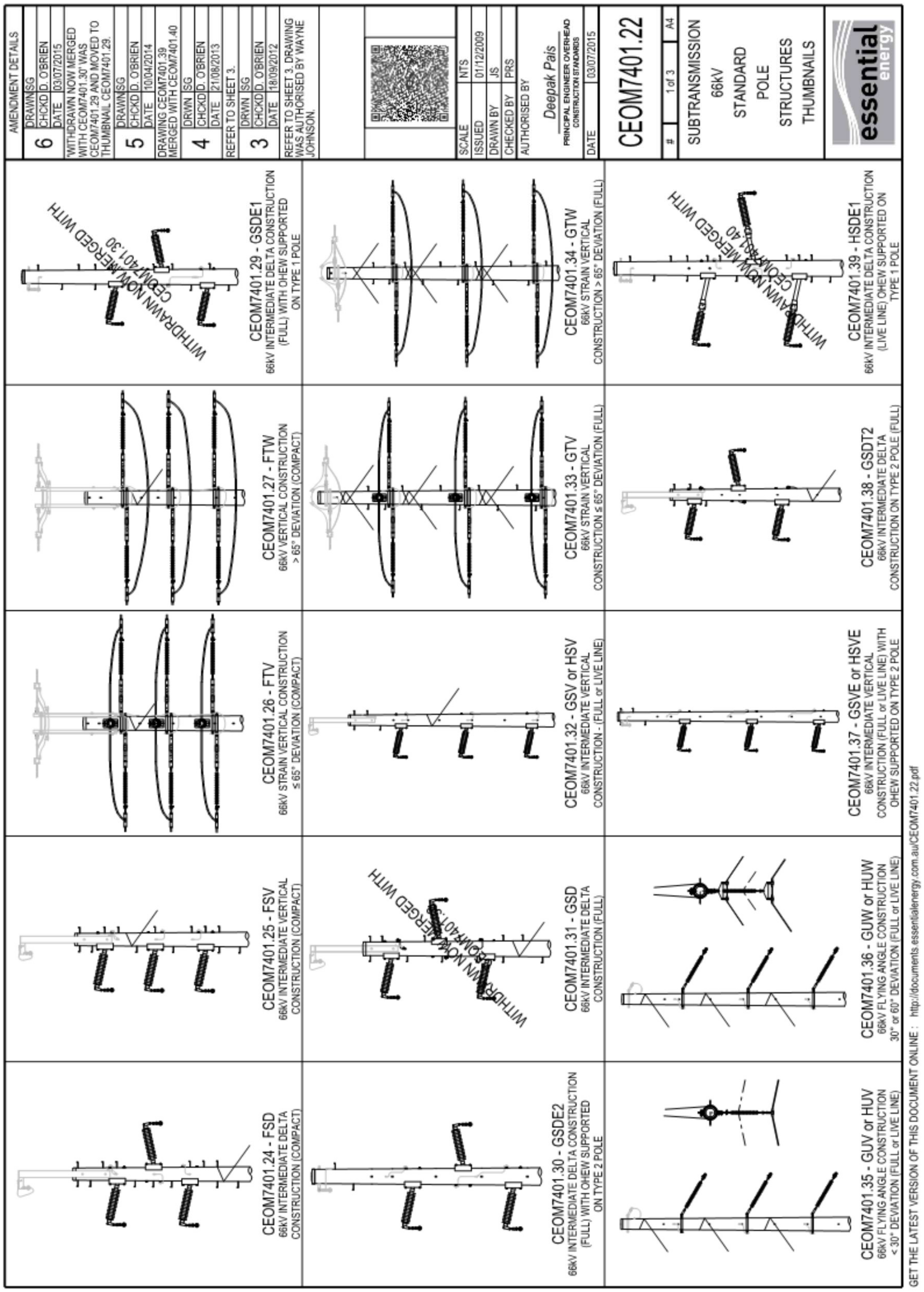
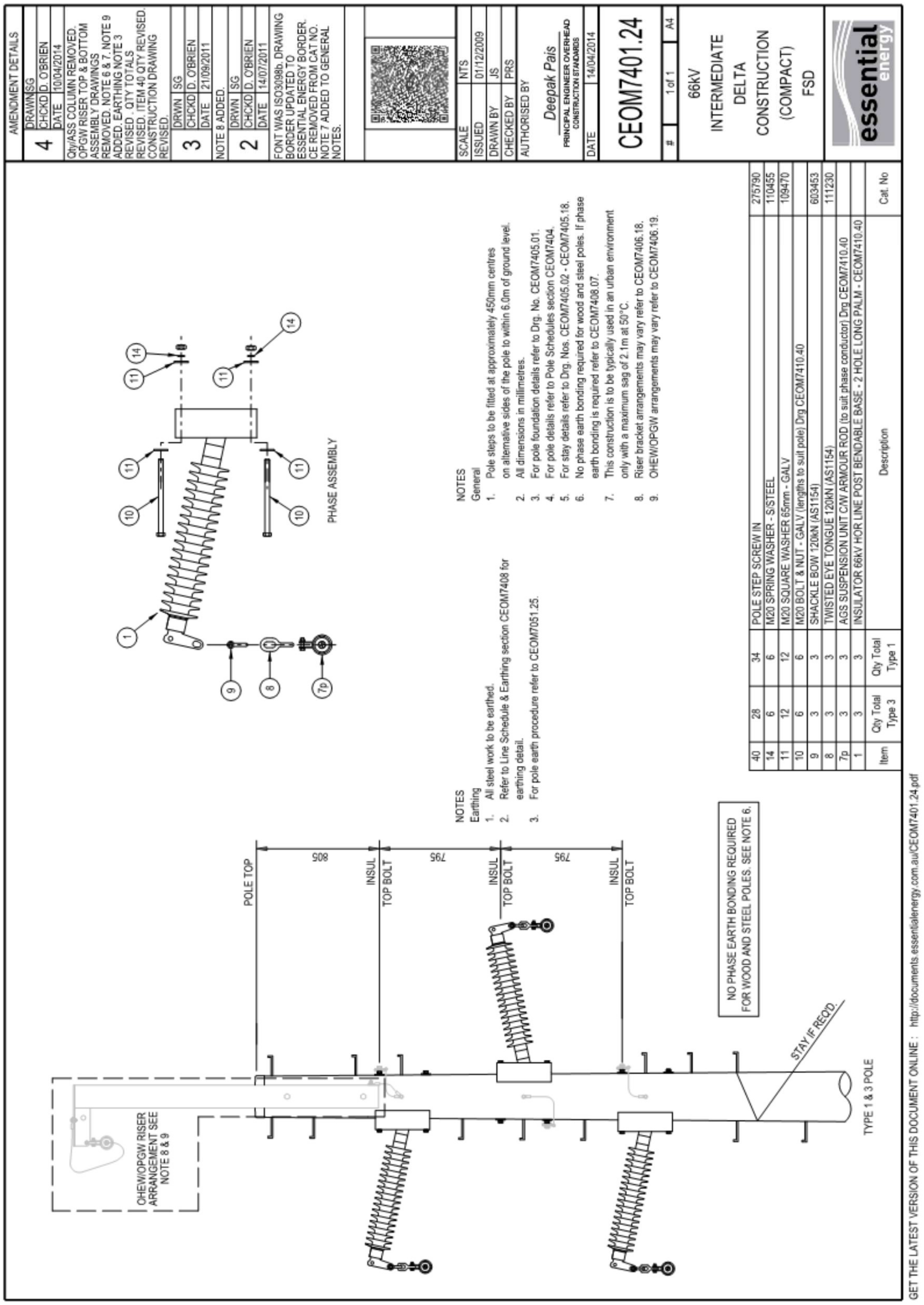


Figure 13-1 Essential Energy Standard 66 kV Pole Constructions (Essential Energy 2014d)

14 APPENDIX D



Item	Qty Total Type 3	Qty Total Type 1	Description	Cat. No
40	28	34	POLE STEP SCREW IN	275790
14	6	6	M20 SPRING WASHER - S/STEEL	110455
11	12	12	M20 SQUARE WASHER 65mm - GALV	109470
10	6	6	M20 BOLT & NUT - GALV (lengths to suit pole) Drg CEOM7410.40	
9	3	3	SHACKLE BOW 120kN (AS1154)	603453
8	3	3	TWISTED EYE TONGUE 120kN (AS1154)	111230
7p	3	3	AGS SUSPENSION UNIT C/W ARMOUR ROD (to suit phase conductor) Drg CEOM7410.40	
1	3	3	INSULATOR 66kV HOR LINE POST BENDABLE BASE - 2 HOLE LONG PALM - CEOM7410.40	

Figure 14-1 Essential Energy 66kV Intermediate Delta Construction (Compact) (Essential Energy 2014h)

15 APPENDIX E

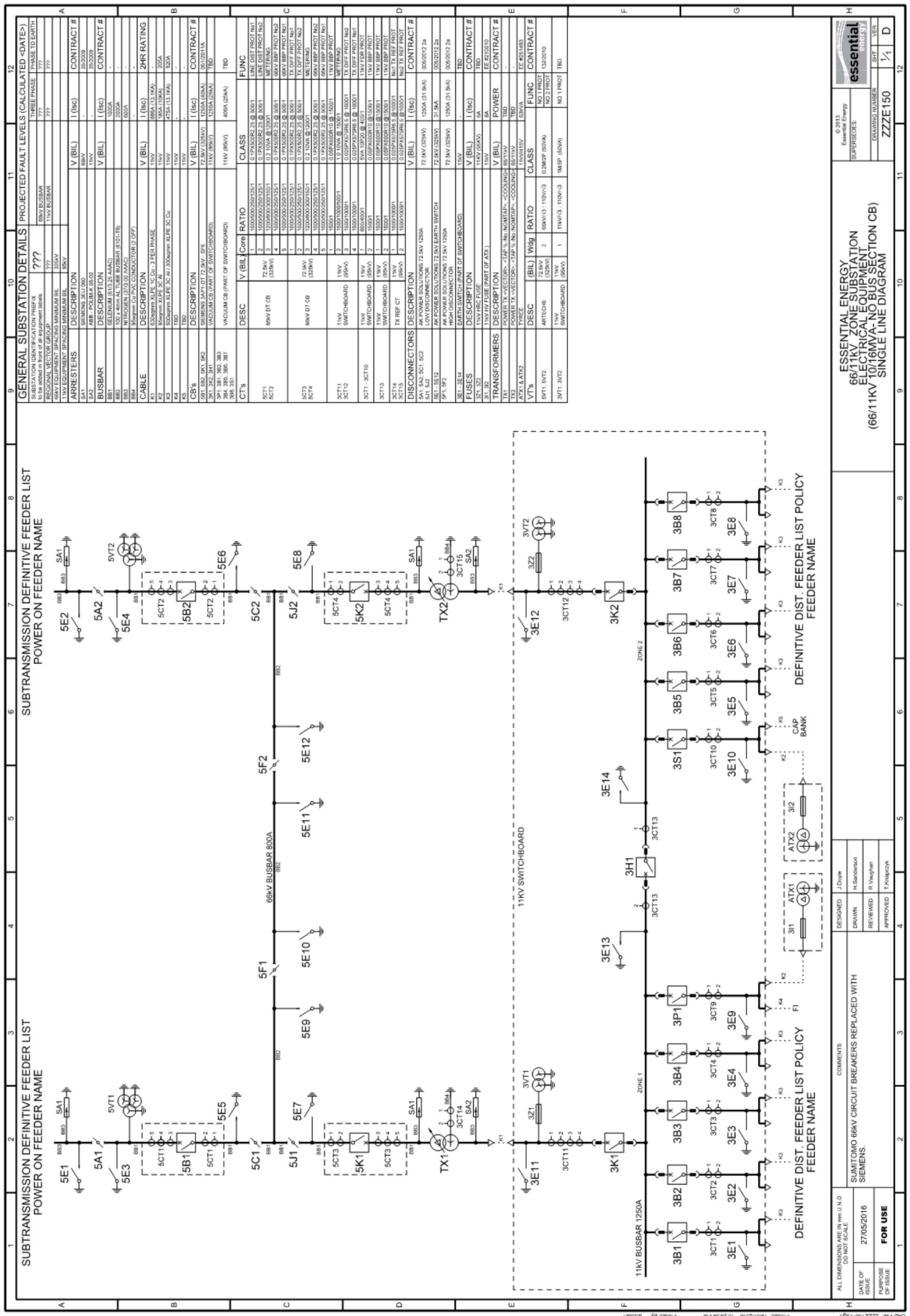


Figure 15-1 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Single Line Diagram (Essential Energy 2016b)

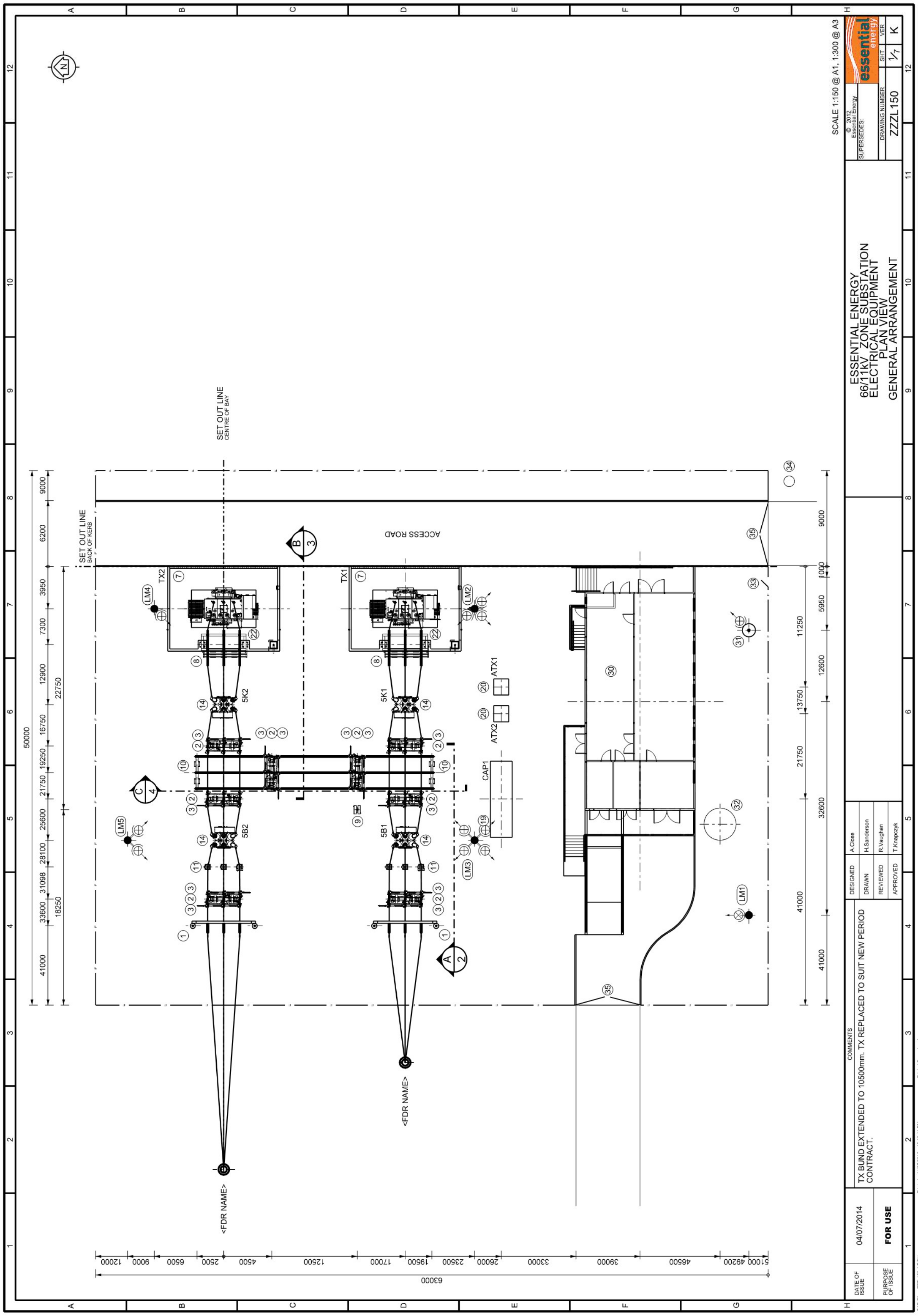


Figure 15-2 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Plan View (Essential Energy 2014a)

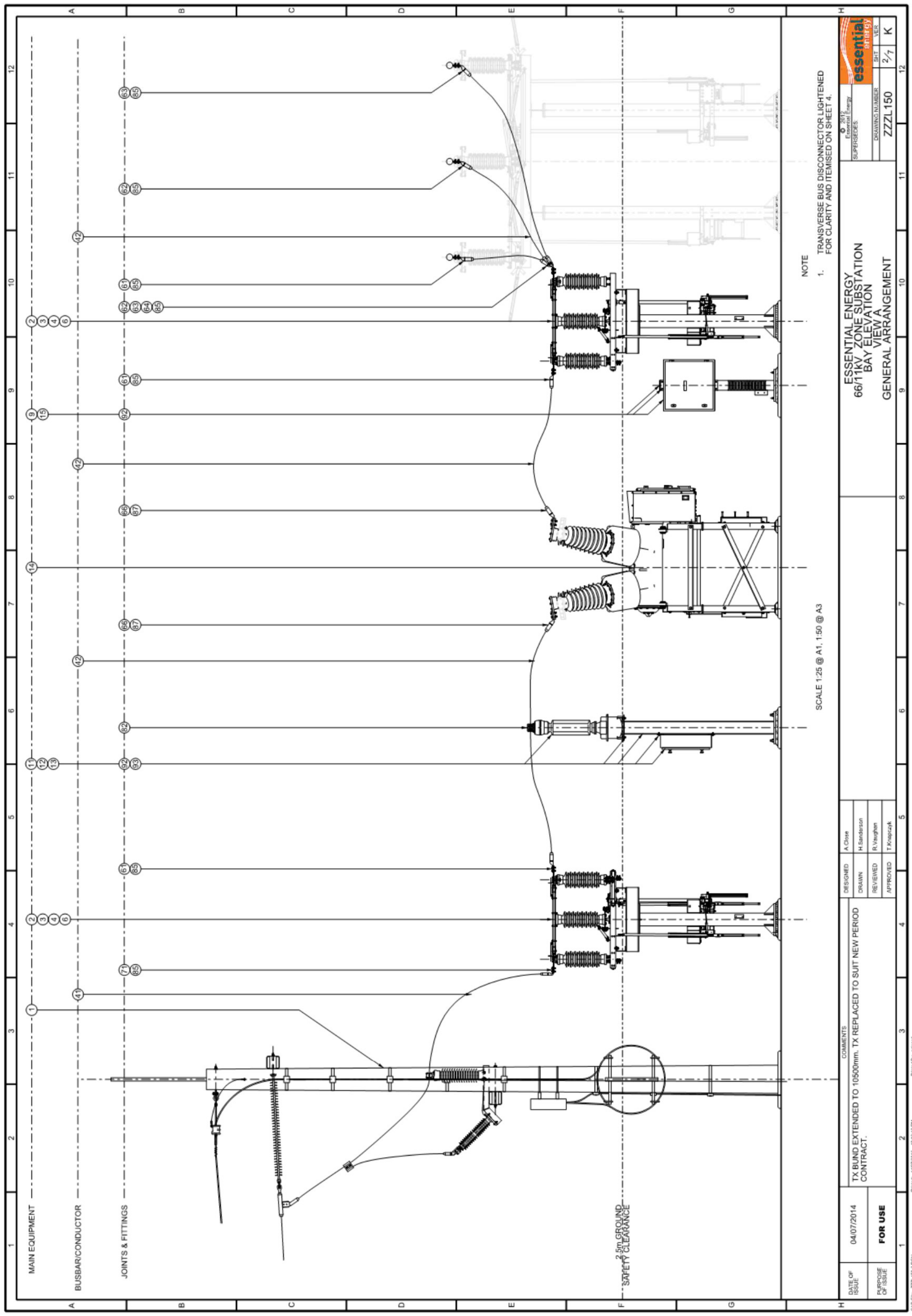


Figure 15-3 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Station Entrance Elevation (Essential Energy 2014f)

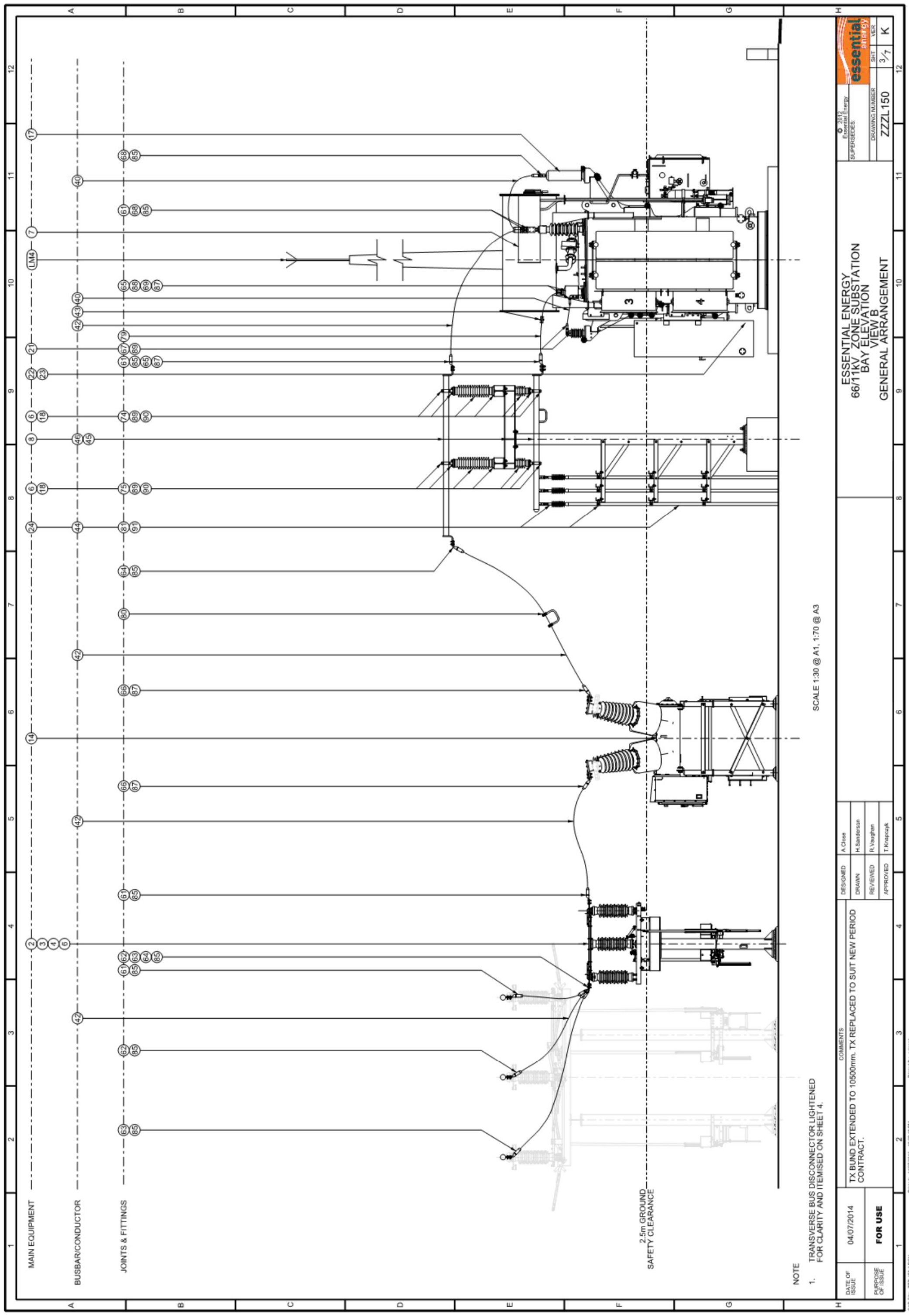


Figure 15-4 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Transformer Elevation (Essential Energy 2014e)

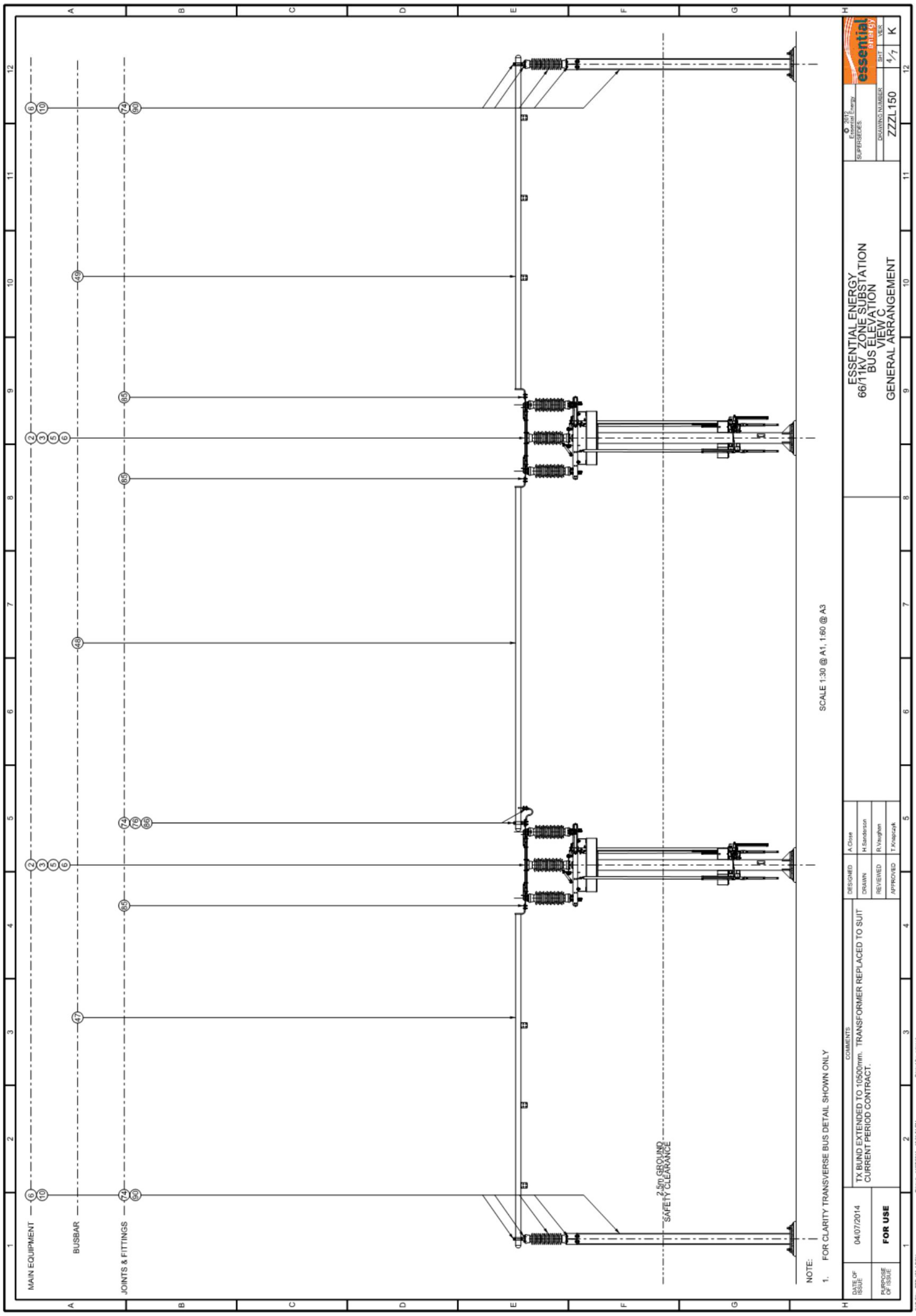


Figure 15-5 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Transverse Busbar Elevation (Essential Energy 2014c)

MAIN EQUIPMENT

ITEM	DESCRIPTION	REMARKS	QTY
1	66kV H LANDING STRUCTURE C/W 3m LIGHTNING SPIKE	REFER DRG. No. ZZZS29	2
2	66kV DISCONNECTOR AK POWER SOLUTIONS 1250A 31.5kA 1 sec		12
3	66kV EARTH SWITCH AK POWER SOLUTIONS 72.5 kV, 31.5 kA/1 sec, 325kV BIL		6
4	66kV DISCONNECTOR STRUCTURE (3.5m HIGH)		6
5	66kV DISCONNECTOR STRUCTURE (5.0m HIGH)		2
6	66kV POST INSULATOR		90
7	66/11kV POWER TRANSFORMER - WILSON		2
8	66kV TRANSFORMER BUS SUPPORT STRUCTURE	REFER DRG. No. ZZZS23	2
9	66KV BBP SUMMATION CUBICLE	REFER DRG. No. ZZZL105	1
10	66kV BUSBAR SUPPORT STRUCTURE (5.0m HIGH)	REFER DRG. No. ZZZS21	2
11	66kV VT ARTECHE		6
12	66kV VT SUPPORT STRUCTURE	REFER DRG. No. ZZZS32	6
13	66kV VT MARSHALLING CUBICLE	REFER DRG. No. ZZZL4	2
14	66kV LIVE TANK CIRCUIT BREAKER MEIDENSHA 72.5KV 1250A 40kA		4
15	BBP SUMMATION CUBICLE STRUCTURE	REFER DRG. No ZZZS34	1
16	66KV SURGE ARRESTOR - SIEMENS SEL1060-1PH21-4XA5		6
17	66kV SURGE ARRESTER - ABB-PEXLIM R054-072	SUPPLIED WITH POWER TX	6
18	33KV POST INSULATOR		12
19	11kV CAPACITOR BANK		1
20	11kV AUXILIARY TRANSFORMER ABB SAFELINK 63KVA		2
21	11 kV SURGE ARRESTER - ABB-POLIM-S10N	SUPPLIED WITH POWER TX	6
22	11 kV TRANSFORMER NEUTRAL CT		4
23	11kV TRANSFORMER NEUTRAL CT SUPPORT STRUCTURE	REFER DRG. No ZZZS40	2
24	11kV CABLE TERMINATION TO SUIT ITEM 44		9
25			
26			
27			
28			
29			
30	CONTROL & SWITCHROOM BUILDING		1
31	COMMUNICATIONS POLE (20m HIGH)		1
32	RAIN WATER TANK		1
33	PERSONAL ENTRY GATE		1
34	FIRE HYDRANT		1
35	VEHICLE ACCESS GATE		1
36			
37			
38			
39			
LM1	LIGHTNING MAST (13m HIGH)		1
LM2	LIGHTNING MAST (13m HIGH)		1
LM3	LIGHTNING MAST (13m HIGH)		1
LM4	LIGHTNING MAST (13m HIGH)		1
LM5	LIGHTNING MAST (13m HIGH)		1
L1	FLOODLIGHT - METAL HALIDE 400W		12
P1	SOCKET OUTLET 3 PHASE 5 PIN IP56 415V/32A		2
P2	SOCKET OUTLET SINGLE PHASE IP56 240V/10A		4
S1	SWITCH OUTDOOR 3 GANG IP56 240/20A		1

BUSBAR/CONDUCTOR

ITEM	DESCRIPTION	REMARKS	QTY
40	CONDUCTOR OVERHEAD HV BARE AAAC/1120 210mm² 19/3.75 AL NEON	REFER TO CABLE SCHEDULE	TBD
41	CONDUCTOR OVERHEAD HV BARE AAAC/1120 262mm² 37/3.00 AL NITROGEN	REFER TO CABLE SCHEDULE	TBD
42	CONDUCTOR OVERHEAD HV BARE AAAC/1120 506mm² 61/3.25 AL SELENIUM	REFER TO CABLE SCHEDULE	TBD
43	CONDUCTOR OVERHEAD HV BARE AAAC/1120 506mm² 61/3.25 AL SELENIUM - 2 PER PHASE	REFER TO CABLE SCHEDULE	TBD
44	CABLE POWER HV 1 CORE SCREENED 630 mm² CU XLPE 11KV - 3 PER PHASE	REFER TO CABLE SCHEDULE	
45	11KV TRANSFORMER BUSBAR - LOW 100mm x 4mm ALUMINIUM ROUND TUBE	REFER DRG. No. ZZZS41	6
46	66KV TRANSFORMER BUSBAR - HIGH 100mm x 4mm ALUMINIUM ROUND TUBE	REFER DRG. No. ZZZS41	6
47	66kV TRANSVERSE BUSBAR END SECTION 100mm x 4mm ALUMINIUM ROUND TUBE	REFER DRG. No. ZZZS41	6
48	66kV TRANSVERSE BUSBAR CENTER SECTION 100mm x 4mm ALUMINIUM ROUND TUBE	REFER DRG. No. ZZZS41	3
49			
50			
51			
52			
53			
54			
55			
56			
57			
58			
59			
60			

JOINTS & FITTINGS

ITEM	DESCRIPTION	REMARKS	QTY
61	LUG COMPRESSION 61/3.25 SELENIUM No.4 PALM 0°/TUBE 0° OFFSET PALM		46
62	LUG COMPRESSION 61/3.25 SELENIUM No.4 PALM 30°/TUBE 0° OFFSET PALM		8
63	LUG COMPRESSION 61/3.25 SELENIUM No.4 PALM 45°/TUBE 0° OFFSET PALM		8
64	LUG COMPRESSION 61/3.25 SELENIUM No.4 PALM 60°/TUBE 0° OFFSET PALM		10
65	LUG COMPRESSION 61/3.25 SELENIUM No.11 PALM 0°/TUBE 0° OFFSET PALM		12
66	LUG COMPRESSION 61/3.25 SELENIUM No.11 PALM 45°/TUBE 0° OFFSET PALM		24
67	LUG COMPRESSION 19/3.75 NEON No.2 PALM 0°/TUBE 0° OFFSET PALM		6
68	LUG COMPRESSION 19/3.75 NEON No.4 PALM 0°/TUBE 0° OFFSET PALM		6
69	LUG COMPRESSION 19/3.75 NEON No.11 PALM 0°/TUBE 90° OFFSET PALM		6
70	LUG COMPRESSION 37/3.00 NITROGEN No.4 PALM 0°/TUBE 0° OFFSET PALM		6
71	LUG COMPRESSION 37/3.00 NITROGEN No.4 PALM 90°/TUBE 0° OFFSET PALM		6
72			
73			
74	BUSBAR SUPPORT ROLLER ASSEMBLY TO SUIT 100mm BUSBAR (UNIVERSAL MTG.)	SUIT 76PCD, 127PCD, AS5 & AS8	21
75	BUSBAR SUPPORT FIXED ASSEMBLY TO SUIT 100mm BUSBAR (UNIVERSAL MTG.)	SUIT 76PCD, 127PCD, AS5 & AS8	12
76	ALUMINIUM FLEXIBLE LAMINATION CONNECTOR		3
77			
78			
79	SPACER PARALLEL DOUBLE 70mm SPACING TO SUIT 61/3.25 SELENIUM (29.3mm DIAM.)		6
80	EARTHING STIRRUP INLINE SINGLE CONDUCTOR 61/3.25 SELENIUM (29.3mm DIAM.)		6
81	CLEAT SINGLE APPLICATION TO 43 - 58mm DIA CABLE S/S GRADE 316		54
82	CONNECTOR PALMLESS APC7 TO SUIT 500-630 SQMM ALUMINIUM C/W MOUNTING BOLTS		6
83			
84			
85	M12 x 50mm BOLT C/W 2 LARGE SERIES FLAT WASHERS, 1 SPRING WASHER & NUT	S/S GRADE 304, NUT GRADE 316	240
86	M12 x 70mm BOLT C/W 2 LARGE SERIES FLAT WASHERS, 1 SPRING WASHER & NUT	S/S GRADE 304, NUT GRADE 316	24
87	M16 x 80mm BOLT C/W 2 LARGE SERIES FLAT WASHERS, 1 SPRING WASHER & NUT	S/S GRADE 304, NUT GRADE 316	84
88	M16 x 90mm BOLT C/W 2 LARGE SERIES FLAT WASHERS, 1 SPRING WASHER & NUT	S/S GRADE 304, NUT GRADE 316	12
89	M12 x 25mm SET SCREW C/W 1 FLAT WASHER & 1 SPRING WASHER	GALVANISED GRADE 8.8	102
90	M16 x 35mm SET SCREW C/W 1 FLAT WASHER & 1 SPRING WASHER	GALVANISED GRADE 8.8	144
91	M12 x 30mm SET SCREW C/W 1 FLAT WASHER & 1 SPRING UNISTRUT NUT	GALVANISED GRADE 8.8	54
92	M12 x 50mm BOLT C/W 2 FLAT WASHERS, 1 SPRING WASHER & NUT	GALVANISED GRADE 8.8	16
93	M16 x 50mm BOLT C/W 2 FLAT WASHERS, 1 SPRING WASHER & NUT	GALVANISED GRADE 8.8	24

DATE OF ISSUE	04/07/2014	COMMENTS: TX BUND EXTENDED TO 10500mm. TRANSFORMER REPLACED TO SUIT NEW PERIOD CONTRACT.	DESIGNED	A.Close
			DRAWN	H.Sanderson
PURPOSE OF ISSUE	FOR USE		REVIEWED	R.Vaughan
			APPROVED	T.Knapczyk

ESSENTIAL ENERGY
66/11kV ZONE SUBSTATION
ELECTRICAL EQUIPMENT
TABLE INFORMATION
GENERAL ARRANGEMENT

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DRAWING NUMBER: ZZZL150 SHT: 7/7 VER: K

Figure 15-6 Case Study 1, Essential Energy Standard 66/11kV Zone Substation Equipment Table (Essential Energy 2014b)

16 APPENDIX F

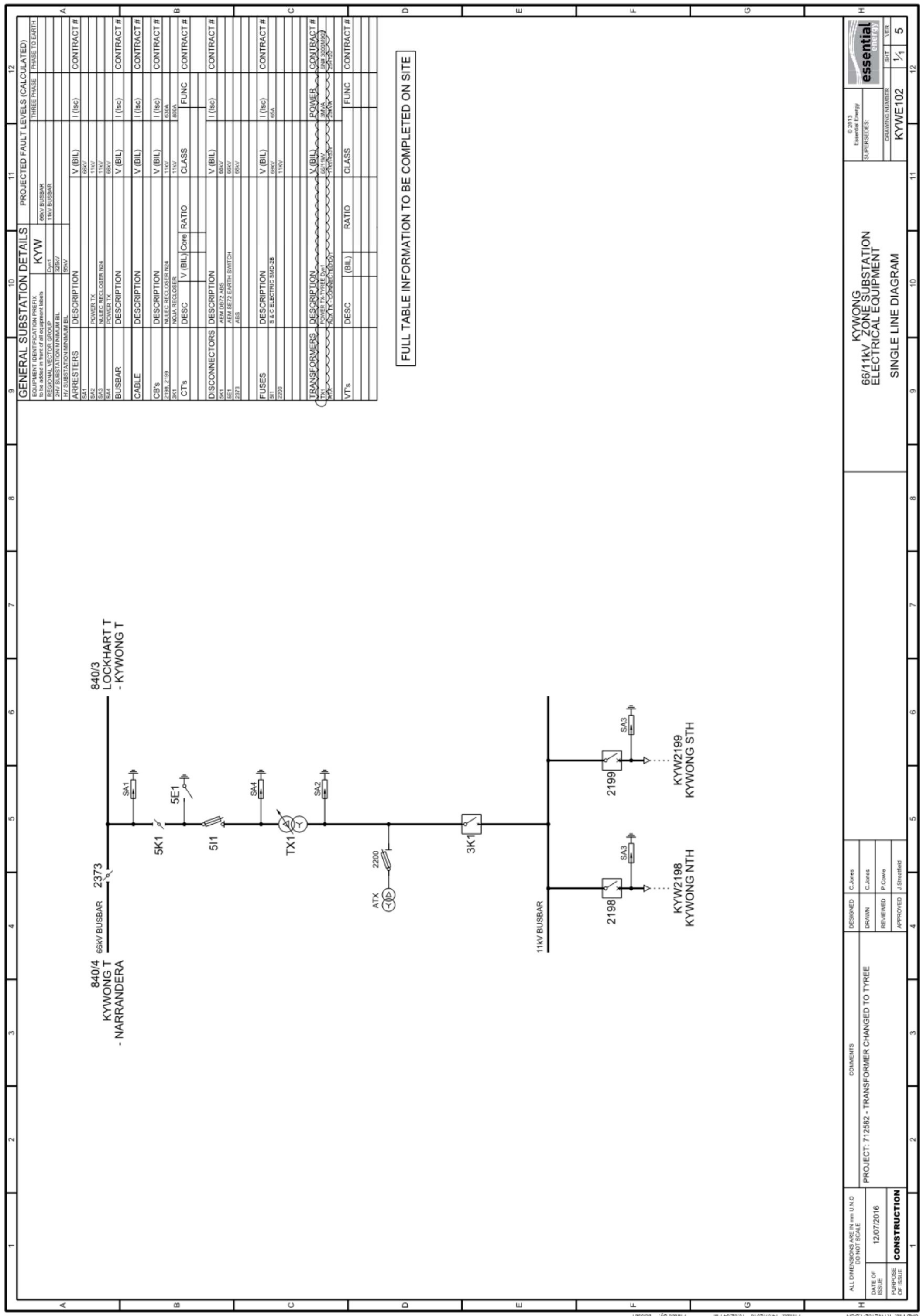


Figure 16-1 Case Study 2, Kywong 66/11kV Zone Substation Single Line Diagram (Essential Energy 2016a)

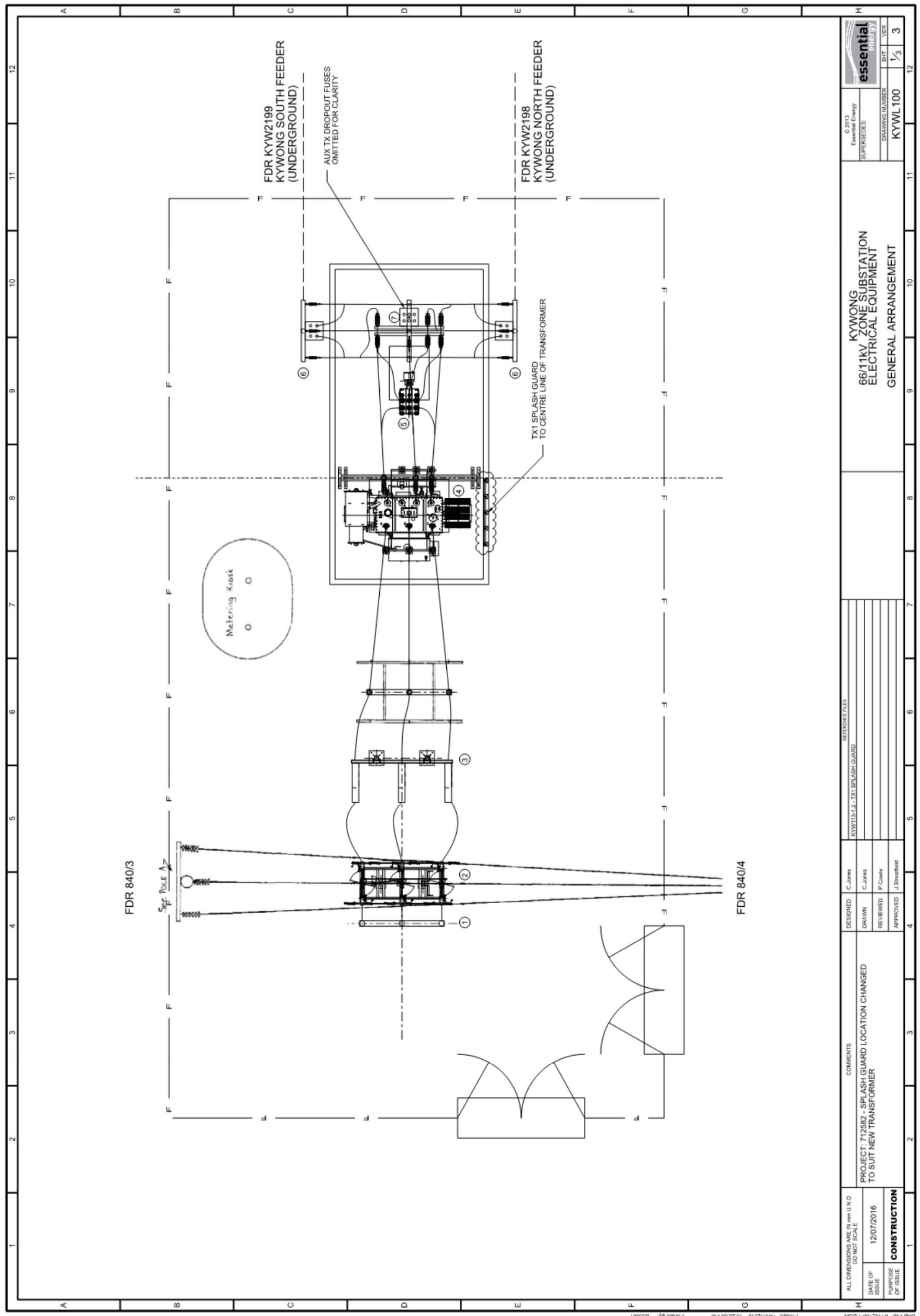


Figure 16-2 Case Study 2, Kywong 66/11kV Zone Substation Plan View (Essential Energy 2016d)

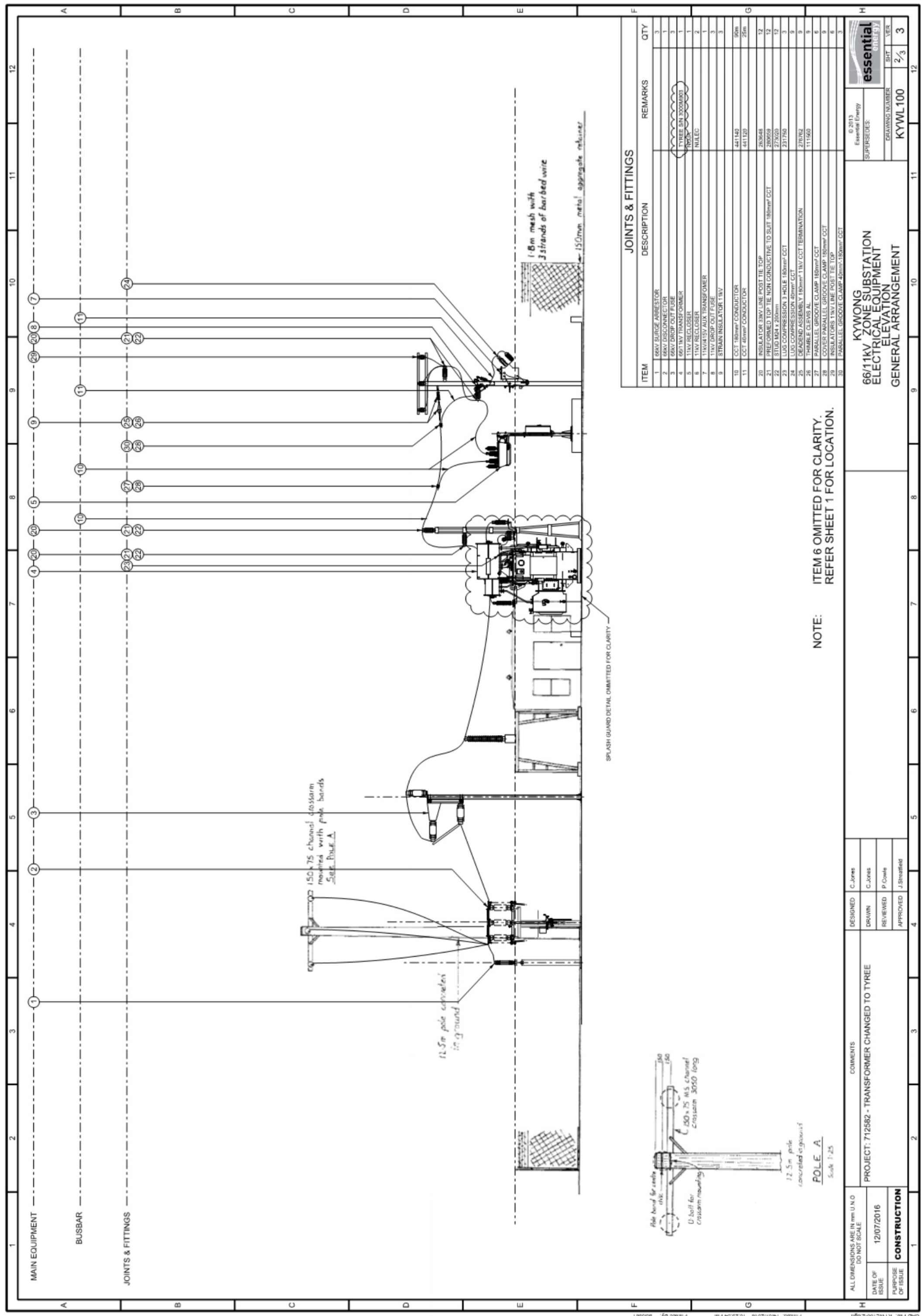


Figure 16-3 Case Study 2, Kywong 66/11kV Zone Substation Elevation (Essential Energy 2016c)

17 APPENDIX G

Conductor sag was calculated using the equation:

$$sag = L^2 / 8 \times c \text{ m}$$

where:

L is the span length (m)

c is the catenary constant equal to:

$$c = Tension / Weight$$

where:

Tension is calculated at a specified percentage of the Conductor Breaking Load (CBL) in Newtons (N)

Weight is the conductor's mass in kg/m converted to N/m

The weight and CBL for conductors of both case studies was obtained from Nexans (2012)

Case Study 1 - Phosphorous Phase Conductor.

$$\begin{aligned} L &= 200 \text{ m} \\ Tension &= 21.5\% \\ CBL &= 93.1 \text{ kN} \\ Weight &= 1.12 \text{ kg/m} \\ &= 1.12\text{kg} \times 9.8 \text{ m/s}^2 \\ &= 10.976 \text{ Nm} \end{aligned}$$

Calculation of the catenary constant:

$$\begin{aligned} c &= (21.5\% \times 93.1 \text{ Nm}) / 10.967 \text{ Nm} \\ &= 20.016 \text{ kN} / 10.976 \text{ Nm} \\ &= 1823.66 \end{aligned}$$

The sag therefore becomes:

$$\begin{aligned} sag &= 200^2 / 8 \times 1823.66 \; m \\ &= 2.727 \text{ m} \\ &\approx 3 \text{ m} \end{aligned}$$

Case Study 1 - 96 Fibre OPGW

$$
\begin{aligned}
L &= 200 \text{ m} \\
Tension &= 21.5\% \\
CBL &= 75.8 \text{ kN} \\
Weight &= 0.575 \text{ kg/m} \\
&= 0.575\text{kg} \times 9.8 \text{ m/s}^2 \\
&= 5.635 \text{ Nm}
\end{aligned}
$$

Calculation of the catenary constant:

$$
\begin{aligned}
c &= (21.5\% \times 75.8 \text{ Nm}) / 5.635 \text{ Nm} \\
&= 16.297 \text{ kN} / 5.635 \text{ Nm} \\
&= 2892.1
\end{aligned}
$$

The sag therefore becomes:

$$
\begin{aligned}
sag &= 200^2 / 8 \times 2892.1 \; m \\
&= 1.73 \text{ m} \\
&\approx 2 \text{ m}
\end{aligned}
$$

Case Study 2 - 7/2.00 HDBC Phase Conductor.

$$
\begin{aligned}
L &= 160 \text{ m} \\
Tension &= 21.5\% \\
CBL &= 8.89 \text{ kN} \\
Weight &= 0.197 \text{ kg/m} \\
&= 0.197\text{kg} \times 9.8 \text{ m/s}^2 \\
&= 1.93 \text{ Nm}
\end{aligned}
$$

Calculation of the catenary constant:

$$
\begin{aligned}
c &= (21.5\% \times 8.89 \text{ kN}) / 1.93 \text{ Nm} \\
&= 1.911\text{kN} / 1.93 \text{ Nm} \\
&= 990.34
\end{aligned}
$$

The sag therefore becomes:

$$
\begin{aligned}
sag &= 160^2 / 8 \times 990.34 \; m \\
&= 3.231 \text{ m} \\
&\approx 3 \text{ m}
\end{aligned}
$$

18 APPENDIX H

Table 18-1 Case Study 1 ATP Conductor Data

Case Study 1 ATP Conductor Data

66kV Overhead Line Conductor Parameters

Component		LCC Template
Name		EEOH
Conductor Type		Overhead Line
#Ph		4
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		66kV Overhead Line
Order		0
Label		66kV TL
Data		
Ph No 1		
Rin	cm	0
Rout	cm	2.63
Resis	ohm/km DC	0.09
Horiz	m	1
Vtower	m	15
Vmid	m	12
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	1
Resis	ohm/km DC	0.09
Horiz	m	-1
Vtower	m	13.5
Vmid	m	10.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	1
Resis	ohm/km DC	0.09
Horiz	m	1
Vtower	m	13.5
Vmid	m	10.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 4		
Rin	cm	0
Rout	cm	1.625
Resis	ohm/km DC	0.284
Horiz	m	-0.2
Vtower	m	19
Vmid	m	17
Separ	cm	0
Alpha	deg	0
NB		1

66kV Zone Substation Conductor ENT1 - 5A1 / 5A1 - 5VT1 / 5VT1- 5B1 / 5B1 - 5C1 / 5J2 - 5K2 Parameters

Component		LCC Template
Name		sel1
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		Selenium - template ZS 3m
Order		0
Label		66kV ZS1
Data		
Ph No 1		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	1.5
Vtower	m	3.5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	0
Vtower	m	3.5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	-1.5
Vtower	m	3.5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1

66kV Zone Substation Conductor 5C1 - Transverse Bus / 5C2 - Transverse Bus / 5J1 - Transverse Bus / 5J2 - Transverse Bus / Tx2 Bus - Tx2 Parameters

Component		LCC Template
Name		sel2
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		Selenium - template ZS 5m
Order		0
Label		66kV ZS2
Data		
Ph No 1		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	1.5
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	0
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	-1.5
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1

Kywong Zone Substation Conductor EJ1 - EF / EJ1 - EA1 / ET1 - EA2 Parameters

Component		LCC Template
Name		Bus1
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		100mm Busbar - template ZS 5m
Order		0
Label		66kV ZS3
Data		
Ph No 1		
Rin	cm	0
Rout	cm	10
Resis	ohm/km DC	0.04
Horiz	m	1.5
Vtower	m	5
Vmid	m	5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	10
Resis	ohm/km DC	0.04
Horiz	m	0
Vtower	m	5
Vmid	m	5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	10
Resis	ohm/km DC	0.04
Horiz	m	-1.5
Vtower	m	5
Vmid	m	5
Separ	cm	0
Alpha	deg	0
NB		1

Kywong Zone Substation Conductor EJ1 - EF / EJ1 - EA1 / ET1 - EA2 Parameters

Component		LCC Template
Name		Tx
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		66kV Overhead Line
Order		0
Label		66kV ZS4
Data		
Ph No 1		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	1.5
Vtower	m	3.5
Vmid	m	6.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	0
Vtower	m	3.5
Vmid	m	6.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	2.93
Resis	ohm/km DC	0.0592
Horiz	m	-1.5
Vtower	m	3.5
Vmid	m	6.5
Separ	cm	0
Alpha	deg	0
NB		1

Kywong Zone Substation Conductor EF - ET Parameters

Component		LCC Template
Name		S/A
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		Template ZS Incoming S/A lead
Order		0
Label		66kV ZS5
Data		
Ph No 1		
Rin	cm	0
Rout	cm	2.1
Resis	ohm/km DC	0.114
Horiz	m	1.5
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	2.1
Resis	ohm/km DC	0.114
Horiz	m	0
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	2.1
Resis	ohm/km DC	0.114
Horiz	m	-1.5
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1

Table 18-2 Case Study 1 Validation, ATP Component Data Part 1

Case Study 1 Validation ATP Component Data

Lightning Source	Component		Heidler
	Amplitude	Volts/Amps	1414000
	T_f	s	4.00E-06
	tau	s	5.00E-05
	n		2
	Tstart	s	0
	Tstop	s	1000
	Name		E_LGHT
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Current Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Opposite Polarity Power Frequenc Voltage	Amplitude	Volts/Amps	80000
	f	Hz	50
	pha	Deg/Rad	0
	A1		0
	Tstart	s	-1
	Tstop	s	1
	Name		VPF
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		VPF
	# Phases		3
	Monitor		B-2
RLC Component	R	Ohs	1
	L	Ohm	50
	C	µF	0
	Name	In1	X0001
		Out1	VPF
	Order		0
	Output		0-No
Overhead Line	Component		LINEZT_3
	R/l+	Ohm/m	0.0909069
	R/l0	Ohm/m	0.234319
	Z+		277.312
	Z0		927.694
	v+		287733000
	v0		200221000
	IN1	Name	X0001
	OUT1	Name	ENT1
	Order		0
	Label		0.6km
	ILINE		Z,v
	Conductance		G=0
	Length	m	600
	Output		No
Voltage Probe	Name		ENT1
	# Phases		3
	Monitor		B-2

Standard ZS Conductor ENT1 - 5A1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	ENT1
	To	Name	X0095
	Order		0
	Label		10m
	ILINE		Z,v
	Conductance		G=0
	Length	m	10
	Output		No
Air Break Switch 5A1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5A1
	Order		0
	Output		0-No
Standard ZS Conductor 5A1 - 5VT1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	X0099
	To	Name	5VT1
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Transformer 5VT1 Surge Capacitance	Component		RLC3
	R_1	Ohms	0
	L_1	mH	0
	C_1	µF	0.0005
	R_2	Ohms	0
	L_2	mH	0
	C_2	µF	0.0005
	R_3	Ohms	0
	L_3	mH	0
	C_3	µF	0.0005
	Order		0
	Label		5VT1
	Comment		
Voltage Probe	Name		5VT1
	# Phases		3
	Monitor		B-2

Standard ZS Conductor 5VT1 - 5B1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	IN1	Name	5VT1
	OUT1	Name	X0097
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No
Circuit Breaker 5B1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5B1
	Order		0
	Output		0-No
Voltage Probe	Name		5B1
	# Phases		3
	Monitor		B-2
Standard ZS Conductor 5B1 - 5C1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	IN1	Name	5B1
	OUT1	Name	5C1
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No
Voltage Probe	Name		5C1
	# Phases		3
	Monitor		B-2
Air Break Switch 5C1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5C1
	Order		0
	Output		0-No

Standard ZS Conductor 5C1 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0098
	OUT1	Name	X0102
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		5J1
	# Phases		3
	Monitor		B-2
Standard ZS Conductor Transverse Bus - 5J1	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0102
	OUT1	Name	5J1
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Rigid Busbar Transverse Bus - 5F1	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0105
	OUT1	Name	5F1
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5F1
	# Phases		3
	Monitor		B-2

Air Break Switch 5F1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5F1
	Order		0
	Output		0-No
Air Break Switch 5F2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5F2
	Order		0
	Output		0-No
Rigid Busbar 5F1 - 5F2	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0104
	OUT1	Name	5F2
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5F2
	# Phases		3
	Monitor		B-2
Rigid Busbar 5F2 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0103
	OUT1	Name	X0102
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5C2
	# Phases		3
	Monitor		B-2

Table 18-3 Case Study 1 Validation, ATP Component Data Part 2

Case Study 1 Validation ATP Component Data

Standard ZS Conductor 5C2 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	5C2
	OUT1	Name	X0102
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Standard ZS Conductor Transverse Bus - 5J2	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0102
	OUT1	Name	5J2
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		5J2
	# Phases		3
	Monitor		B-2
Air Break Switch 5J2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5J2
	Order		0
	Output		0-No
Standard ZS Conductor 5J2 - 5K2	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	X0113
	To	Name	X0115
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No

Circuit Breaker 5K2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5K2
	Order		0
	Output		0-No
Voltage Probe	Name		5K2
	# Phases		3
	Monitor		B-2
Standard ZS Conductor 5K2 - Transformer Busbar	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.883
	Z0		889.808
	v+		287062000
	v0		180528000
	From	Name	5K2
	To	Name	X0114
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Rigid Busbar Transformer	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0114
	OUT1	Name	EJ2
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		EJ2
	# Phases		3
	Monitor		B-2

Standard ZS Conductor EJ2 - EA2	Component		LINEZT_3
	R/l+	Ohm/m	0.114781
	R/l0	Ohm/m	0.261381
	Z+		284.292
	Z0		870.201
	v+		284155000
	v0		183986000
	IN1	Name	EA2
	OUT1	Name	EJ2
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		No
Voltage Probe	Name		EA2
	# Phases		3
	Monitor		B-2
Splitter Component	IN	ABC	EA2
	OUTA	A	EA2
	OUTB	B	EA2
	OUTC	C	EA2
	Order		
	Label		
A- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0044
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000

B- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0039
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
C- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0030
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000

Voltage Probe	Name		GND2
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"C"	1
	Monitor		A-1
EA2 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	µF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No
Standard ZS Conductor EJ2 - ET2	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	From	Name	EJ2
	To	Name	ET2
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		No
Voltage Probe	Name		ET2
	# Phases		1
	Monitor		A-1
Transformer ET2 Surge Capacitance	Component		RLC_3
	R	Ohms	0
	L	Ohms	0
	C	µF	0.002
	Name	In1	
		Out1	ET2
	Order		0
	Output		0-No

Table 18-4 Case Study 1 Scenario 1, ATP Component Data Part 1

Case Study 1 Scenario 1 ATP Component Data

Lightning Source	Component		Heidler
	Amplitude	Volts/Amps	1414000
	T_f	s	4.00E-06
	tau	s	5.00E-05
	n		2
	Tstart	s	0
	Tstop	s	1000
	Name		E_LGHT
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Current Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Opposite Polarity Power Frequenc Voltage	Amplitude	Volts/Amps	80000
	f	Hz	50
	pha	Deg/Rad	0
	A1		0
	Tstart	s	-1
	Tstop	s	1
	Name		VPF
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		VPF
	# Phases		3
	Monitor		B-2
RLC Component	R	Ohs	1
	L	Ohm	50
	C	µF	0
	Name	In1	X0001
		Out1	VPF
	Order		0
	Output		0-No
Overhead Line	Component		LINEZT_3
	R/l+	Ohm/m	0.0909069
	R/l0	Ohm/m	0.234319
	Z+		277.312
	Z0		927.694
	v+		287733000
	v0		200221000
	IN1	Name	X0001
	OUT1	Name	ENT1
	Order		0
	Label		0.6km
	ILINE		Z,v
	Conductance		G=0
	Length	m	600
	Output		No

Voltage Probe	Name		ENT1
	# Phases		3
	Monitor		B-2
Standard ZS Conductor EJ2 - EA2	Component		LINEZT_3
	R/l+	Ohm/m	0.114781
	R/l0	Ohm/m	0.261381
	Z+		284.292
	Z0		870.201
	v+		284155000
	v0		183986000
	IN1	Name	EA2
	OUT1	Name	EJ2
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No
Voltage Probe	Name		EA1
	# Phases		3
	Monitor		B-2
Splitter Component	IN	ABC	EA1
	OUTA	A	EA1
	OUTB	B	EA1
	OUTC	C	EA1
	Order		
	Label		
A- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	XX0082
	To	Name	EA1
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000

B- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	EA1
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
C- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	XX0081
	To	Name	EA1
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
Voltage Probe	Name		GND1
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"C"	1
	Monitor		A-1

EA1 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	µF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No
Voltage Probe	Name		5VT1
	# Phases		3
	Monitor		B-2
Voltage Transformer 5VT1 Surge Capacitance	Component		RLC3
	R_1	Ohms	0
	L_1	mH	0
	C_1	µF	0.0005
	R_2	Ohms	0
	L_2	mH	0
	C_2	µF	0.0005
	R_3	Ohms	0
	L_3	mH	0
	C_3	µF	0.0005
	Order		0
	Label		5VT1
	Comment		
Standard ZS Conductor 5VT1 - 5B1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	IN1	Name	5VT1
	OUT1	Name	X0097
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No
Standard ZS Conductor ENT1 - 5A1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	ENT1
	To	Name	X0095
	Order		0
	Label		10m
	ILINE		Z,v
	Conductance		G=0
	Length	m	10
	Output		No

Air Break Switch 5A1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5A1
	Order		0
	Output		0-No
Standard ZS Conductor 5A1 - 5VT1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	X0099
	To	Name	5VT1
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Circuit Breaker 5B1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5B1
	Order		0
	Output		0-No
Voltage Probe	Name		5B1
	# Phases		3
	Monitor		B-2
Standard ZS Conductor 5B1 - 5C1	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	IN1	Name	5B1
	OUT1	Name	5C1
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No
Voltage Probe	Name		5C1
	# Phases		3
	Monitor		B-2

Air Break Switch 5C1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5C1
	Order		0
	Output		0-No
Standard ZS Conductor 5C1 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0098
	OUT1	Name	X0102
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Standard ZS Conductor Transverse Bus - 5J1	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0102
	OUT1	Name	5J1
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		5J1
	# Phases		3
	Monitor		B-2
Rigid Busbar Transverse Bus - 5F1	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0105
	OUT1	Name	5F1
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5F1
	# Phases		3
	Monitor		B-2

Table 18-5 Case Study 1 scenario 1, ATP Component Data Part 2

Case Study 1 Scenario 1 ATP Component Data

Air Break Switch 5F1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5F1
	Order		0
	Output		0-No
Rigid Busbar 5F1 - 5F2	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0104
	OUT1	Name	5F2
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5F2
	# Phases		3
	Monitor		B-2
Air Break Switch 5F2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5F2
	Order		0
	Output		0-No
Rigid Busbar 5F2 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0103
	OUT1	Name	X0102
	Order		0
	Label		7m
	ILINE		Z,v
	Conductance		G=0
	Length	m	7
	Output		No
Voltage Probe	Name		5C2
	# Phases		3
	Monitor		B-2

Standard ZS Conductor 5C2 - Transverse Bus	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	5C2
	OUT1	Name	X0102
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Standard ZS Conductor Transverse Bus - 5J2	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	IN1	Name	X0102
	OUT1	Name	5J2
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		5J2
	# Phases		3
	Monitor		B-2
Air Break Switch 5J2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5J2
	Order		0
	Output		0-No
Standard ZS Conductor 5J2 - 5K2	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.235
	Z0		826.078
	v+		286341000
	v0		177945000
	From	Name	X0113
	To	Name	X0115
	Order		0
	Label		2.5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	2.5
	Output		No

Circuit Breaker 5K2	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5K2
	Order		0
	Output		0-No
Voltage Probe	Name		5K2
	# Phases		3
	Monitor		B-2
Standard ZS Conductor 5K2 - Transformer Busbar	Component		LINEZT_3
	R/l+	Ohm/m	0.0605643
	R/l0	Ohm/m	0.207397
	Z+		257.883
	Z0		889.808
	v+		287062000
	v0		180528000
	From	Name	5K2
	To	Name	X0114
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Rigid Busbar Transformer	Component		LINEZT_3
	R/l+	Ohm/m	0.0419758
	R/l0	Ohm/m	0.188302
	Z+		182.308
	Z0		792.85
	v+		281782000
	v0		180469000
	IN1	Name	X0114
	OUT1	Name	EJ2
	Order		0
	Label		3m
	ILINE		Z,v
	Conductance		G=0
	Length	m	3
	Output		No
Voltage Probe	Name		EJ2
	# Phases		3
	Monitor		B-2
Standard ZS Conductor EJ2 - EA2	Component		LINEZT_3
	R/l+	Ohm/m	0.114781
	R/l0	Ohm/m	0.261381
	Z+		284.292
	Z0		870.201
	v+		284155000
	v0		183986000
	IN1	Name	EA2
	OUT1	Name	EJ2
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		No

Voltage Probe	Name		EA2
	# Phases		3
	Monitor		B-2
Splitter Component	IN	ABC	EA2
	OUTA	A	EA2
	OUTB	B	EA2
	OUTC	C	EA2
	Order		
	Label		
A- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0044
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
B- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0039
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000

C- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0030
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
	I(A) / U(V)		-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
Voltage Probe	Name		GND2
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"C"	1
	Monitor		A-1
EA2 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	µF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No
Standard ZS Conductor EJ2 - ET2	Component		LINEZT_3
	R/l+	Ohm/m	0.0606543
	R/l0	Ohm/m	0.207227
	Z+		257.484
	Z0		845.16
	v+		286169000
	v0		182036000
	From	Name	EJ2
	To	Name	ET2
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		No
Voltage Probe	Name		ET2
	# Phases		1
	Monitor		A-1
Transformer ET2 Surge Capacitance	Component		RLC_3
	R	Ohms	0
	L	Ohms	0
	C	µF	0.002
	Name	In1	
		Out1	ET2
	Order		0
	Output		0-No

Table 18-6 Case Study 2 ATP Conductor Data

Case Study 2 ATP Conductor Data

66kV Overhead Line Conductor Parameters

Component		LCC Template
Name		KWGOH
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		66kV Overhead Line
Order		0
Label		66kV TL
Data		
Ph No 1		
Rin	cm	0
Rout	cm	1
Resis	ohm/km DC	0.303
Horiz	m	1
Vtower	m	15
Vmid	m	12
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	1
Resis	ohm/km DC	0.303
Horiz	m	-1
Vtower	m	13.5
Vmid	m	10.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	1
Resis	ohm/km DC	0.303
Horiz	m	1
Vtower	m	13.5
Vmid	m	10.5
Separ	cm	0
Alpha	deg	0
NB		1

Kywong Zone Substation Conductor EJ1 - EF / EJ1 - EA1 / ET1 - EA2 Parameters

Component		LCC Template
Name		KYZS1
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		66kV Overhead Line
Order		0
Label		66kV TL
Data		
Ph No 1		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	1.5
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	0
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	-1.5
Vtower	m	5
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1

Kywong Zone Substation Conductor EF - ET Parameters

Component		LCC Template
Name		KYZS2
Conductor Type		Overhead Line
#Ph		3
Auto Bundling		Yes
Skin Effect		Yes
Segmented Ground		No
Real Transfo. Matrix		Yes
Units		Metric
Rho	(ohm*m)	100
Freq init	(Hz)	50
Length	(km)	1
Model Type		PI
Printed Output		Yes
ω (C) Print out		Yes
Output Z		Yes (All)
Output C		Yes (All)
Comment		66kV Overhead Line
Order		0
Label		66kV TL
Data		
Ph No 1		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	1.5
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 2		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	0
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1
Ph No 3		
Rin	cm	0
Rout	cm	3.42
Resis	ohm/km DC	0.163
Horiz	m	-1.5
Vtower	m	7
Vmid	m	3.5
Separ	cm	0
Alpha	deg	0
NB		1

Table 18-7 Case Study 2 Validation, ATP Component Data

Case Study 2 Validation ATP Component Data

Lightning Source	Component		Heidler
	Amplitude	Volts/Amps	1414000
	T_f	s	3.25E-06
	tau	s	5.00E-05
	n		2
	Tstart	s	0
	Tstop	s	1000
	Name		E_LGHT
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Current Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Opposite Polarity Power Frequenc Voltage	Amplitude	Volts/Amps	80000
	f	Hz	50
	pha	Deg/Rad	0
	A1		0
	Tstart	s	-1
	Tstop	s	1
	Name		VPF
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		VPF
	# Phases		3
	Monitor		B-2
RLC Component	R	Ohms	1
	L	Ohms	50
	C	µF	0
	Name	In1	X0001
		Out1	VPF
	Order		0
	Output		0-No
Overhead Line	Component		LINEZT_3
	R/l+	Ohm/m	0.0303272
	R/l0	Ohm/m	0.0447315
	Z+		372.317
	Z0		1074.66
	v+		270972000
	v0		216133000
	IN1	Name	X0001
	OUT1	Name	ENT1
	Order		0
	Label		0.64km
	ILINE		Z,v
	Conductance		G=0
	Length	m	640
	Output		0-No

Voltage Probe	Name		ENT1
	# Phases		3
	Monitor		B-2
Kywong ZS Conductor ENT1 - EJ1	Component		LINEZT_3
	R/l+	Ohm/m	0.0303271
	R/l0	Ohm/m	0.0447474
	Z+		351.874
	Z0		1114.63
	v+		267693000
	v0		217960000
	From	Name	ENT1
	To	Name	EJI
	Order		0
	Label		25m
	ILINE		Z,v
	Conductance		G=0
	Length	m	25
	Output		0-No
Voltage Probe	Name		EJ1
	# Phases		3
	Monitor		B-2
Kywong ZS Conductor EJ1 - EA1	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	EA1
	OUT1	Name	EJ1
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		0-No
Kywong ZS Conductor EJ1 - EA1	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	EA1
	OUT1	Name	EJ1
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		0-No

A- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0012
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000
B- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0012
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000
Voltage Probe	Name		GND1
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"C"	1
	Monitor		A-1

C- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0004
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
	I(A) / U (V)		-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
			0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000
EA1 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	µF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No
Station Air Break Switch 5J1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5J1
	Order		0
	Output		0-No
Kywong ZS Conductor EJ1 - EF	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	XX0045
	OUT1	Name	EF
	Order		0
	Label		5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	5
	Output		No

Fuse 5I1 (EF)	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5A1
	Order		0
	Output		0-No
Kywong ZS Conductor EF - ET1	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	XX0046
	OUT1	Name	ET1
	Order		0
	Label		10m
	ILINE		Z,v
	Conductance		G=0
	Length	m	10
	Output		0-No
Voltage Probe	Name		ET1
	# Phases		3
	Monitor		B-2
RLC Component	R	Ohms	0
	L	Ohms	0
	C	µF	0.002
	Name	In1	
		Out1	ET1
	Order		0
	Output		TX1

Table 18-8 Case Study 2 Scenario 1, ATP Component Data

Case Study 2 Scenario 1 ATP Component Data

Lightning Source	Component		Heidler
	Amplitude	Volts/Amps	14000
	T_f	s	1.40E-05
	tau	s	7.50E-06
	n		2
	Tstart	s	0
	Tstop	s	1000
	Name		E_LGHT
	Source		Current
	Order		0
	Label		
Voltage Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Current Probe	Name		E_LGHT
	# Phases		1
	Monitor		A-1
Opposite Polarity Power Frequenc Voltage	Amplitude	Volts/Amps	80000
	f	Hz	50
	pha	Deg/Rad	0
	A1		0
	Tstart	s	-1
	Tstop	s	1
	Name		VPF
	Source		Voltage
	Order		0
	Label		
Voltage Probe	Name		VPF
	# Phases		3
	Monitor		B-2
RLC Component	R	Ohs	1
	L	Ohm	50
	C	μF	0
	Name	In1	X0001
		Out1	VPF
	Order		0
	Output		0-No
Overhead Line	Component		LINEZT_3
	R/l+	Ohm/m	0.0303272
	R/l0	Ohm/m	0.0447315
	Z+		372.317
	Z0		1074.66
	v+		270972000
	v0		216133000
	IN1	Name	X0001
	OUT1	Name	ENT1
	Order		0
	Label		0.64km
	ILINE		Z,v
	Conductance		G=0
	Length	m	640
	Output		0-No
Voltage Probe	Name		ENT1
	# Phases		3
	Monitor		B-2

Kywong ZS Conductor ENT1 - EJ1	Component		LINEZT_3
	R/l+	Ohm/m	0.0303271
	R/l0	Ohm/m	0.0447474
	Z+		351.874
	Z0		1114.63
	v+		267693000
	v0		217960000
	From	Name	ENT1
	To	Name	EJI
	Order		0
	Label		25m
	ILINE		Z,v
	Conductance		G=0
	Length	m	25
	Output		0-No
Voltage Probe	Name		EJ1
	# Phases		3
	Monitor		B-2
Kywong ZS Conductor EJ1 - EA1	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	EA1
	OUT1	Name	EJ1
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		No
A- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0012
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
			-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000

B- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0012
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
			-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000
C- Phase Station Entrance Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND1
	To	Name	XX0004
	Order		0
	Label		
	Comment		Bowthorpe 2HSRCP60
	Output		0-No
	Characteristic		
			-40000 / -199000
			-20000 / -175000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 175000
			40000 / 199000
Voltage Probe	Name		GND1
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND1
	# Phases	"C"	1
	Monitor		A-1

EA1 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	μF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No
Station Air Break Switch 5J1	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5J1
	Order		0
	Output		0-No
Kywong ZS Conductor EJ1 - EF	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	XX0045
	OUT1	Name	EF
	Order		0
	Label		5m
	ILINE		Z,v
	Conductance		G=0
	Length	m	5
	Output		0-No
Fuse 5I1 (EF)	Component		SWIT_3XT
	T-cl_1	s	-1
	T-op_1	s	1000
	T-cl_2	s	-1
	T-op_2	s	1000
	T-cl_3	s	-1
	T-op_3	s	1000
	Label		5A1
	Order		0
	Output		0-No
Voltage Probe	Name		ET1
	# Phases		3
	Monitor		B-2
Voltage Probe	Name		EA2
	# Phases		3
	Monitor		B-2

Kywong ZS Conductor ET1 - EA2	Component		LINEZT_3
	R/l+	Ohm/m	0.063504
	R/l0	Ohm/m	0.0310167
	Z+		265.454
	Z0		839.919
	v+		276115000
	v0		180393000
	IN1	Name	EA2
	OUT1	Name	ET1
	Order		0
	Label		1m
	ILINE		Z,v
	Conductance		G=0
	Length	m	1
	Output		0-No
A- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0044
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
			-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
B- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0039
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
			-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000

C- Phase Transformer Surge Arrester	Component		NLRES92
	Nflash	-1,0,+1	0
	RLIN	ohms	0
	Vflash	Volts	-1
	Vzero		0
	From	Name	GND2
	To	Name	XX0030
	Order		0
	Label		
	Comment		Siemens 3EL1 060-1PH21-4XA5
	Output		0-No
	Characteristic		
			-40000 / -204000
			-20000 / -178000
			-10000 / -159000
			-5000 / -148000
	I(A) / U (V)		0 / 0
			5000 / 148000
			10000 / 159000
			20000 / 178000
			40000 / 204000
Voltage Probe	Name		GND2
	# Phases		1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"A"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"B"	1
	Monitor		A-1
Current Probe	Name		GND2
	# Phases	"C"	1
	Monitor		A-1
EA2 Earth Lead & ZS Earthgrid	R	Ohms	1
	L	Ohms	0.004
	C	μF	0
	Name	In1	
		Out1	
	Order		0
	Output		0-No

19 APPENDIX I

Table 19-1 Case Study 1 Conductor Sequence Component Attributes

66kV Overhead Transmission Line

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	927.694	-4.617	0.0011005	200221	4004.420	0.234	1.441	0.000001697
Positive	277.312	-8.634	0.0014400	287733	5754.660	0.091	0.292	0.000003982

ZS Conductor (ENT1-5A1, 5A1-5VT1, 5VT1-5B1, 5B1-5C1, 5J2-5K2)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	826.078	-4.077	0.0010931	177945	3558.900	0.207	1.447	0.000002143
Positive	257.235	-6.160	0.0010285	286341	5726.830	0.061	0.277	0.000004290

ZS Conductor (5C1-Transverse Bus, 5C2-Transverse Bus, 5J1-Transverse Bus, 5J2-Transverse Bus, ET2 Bus-ET2)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	845.160	-4.074	0.0010676	182036	3640.720	0.207	1.448	0.000002047
Positive	257.484	-6.160	0.0010275	286619	5732.370	0.061	0.277	0.000004282

Tubular Busbar (Tranverse Bus-5F1, 5F1-5F2, Transverse Bus-5F2, ET2 Bus)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	792.850	-3.912	0.0010339	180469	3609.380	0.188	1.371	0.000002201
Positive	182.308	-5.927	0.0010053	281782	5635.640	0.042	0.200	0.000006148

ZS Conductor (5K2-ET2 Bus)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	889.808	-4.062	0.0010115	191591	3831.820	0.207	1.448	0.000001847
Positive	257.883	-6.160	0.0010259	287062	5741.240	0.061	0.277	0.000004268

Surge Arrester Incoming Lead (EA1, EA2)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	918.565	-5.033	0.001238	194146	3882.930	0.261	1.469	0.000001768
Positive	284.732	-10.515	0.001780	284594	5691.890	0.115	0.298	0.000003943

Table 19-2 Case Study 1 Conductor Sequence Component Attributes

66kV Overhead Transmission Line

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	1074.660	-8.232	0.0018265	216133	4322.650	0.447	1.514	0.000001367
Positive	372.317	-20.566	0.0037784	270972	5419.440	0.303	0.347	0.000003326

ZS Conductor (ENT1-EJ1)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	1114.630	-8.005	0.0017607	217960	4359.210	0.447	1.559	0.000001306
Positive	351.874	-21.543	0.0040242	267693	5353.850	0.303	0.324	0.000003586

ZS Conductor (EJ1-5I1, EJ1-EA1))

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	839.919	-6.086	0.0016129	180393	3607.860	0.310	1.438	0.000002085
Positive	265.454	-15.705	0.0027787	276115	5522.300	0.164	0.268	0.000004452

ZS Conductor (5I1-ET1)

Sequence	Surge magnitude(Ohm)	impedance angle(degr.)	Attenuation db/km	velocity km/sec	Wavelength km	Resistance Ohm/km	Reactance Ohm/km	Susceptance mho/km
Zero	861.949	-6.081	0.0015705	185100	3702.000	0.310	1.438	0.000001980
Positive	265.690	-15.705	0.0027763	276361	5527.210	0.164	0.268	0.000004444

20 APPENDIX J

TITLE:
SURGE ARRESTER, 66kV, 10kA, 3EL1

TYREE

DESCRIPTION: SURGE ARRESTER, 66kV, 10kA, 3EL1

SPECIFICATIONS:

MATERIAL: SILICONE HOUSING, METAL OXIDE SURGE ARRESTER
COLOUR: GREY
RATED VOLTAGE, Ur (kV): 60.0
CONTINUOUS OPERATING VOLTAGE, Uc (kV): 48.0
FREQUENCY: 50Hz
DISCHARGE CURRENT In (kA): 10
Is (kA): 65

MECHANICAL:
ARRESTORS ARE DESIGNED AND CONSTRUCTED FOR OUTDOOR APPLICATION WITH FULL UV EXPOSURE. MOUNTING AND TERMINAL HARDWARE SHALL BE SUITABLY CONDUCTIVE AND CORROSION RESISTANT

APPROVED SUPPLIER: MV TECHNOLOGY
MANUFACTURER: SIEMENS
TYPE: 3EL1 060-1PH21-4XA5

RMQC (TYREE):
- PHYSICAL INSPECTION
- VISUAL AND MECHANICAL DEFECT NOTICE

BY: AR		**DWG No: 0515-3058**	**REV: A**
DATE: 4/11/2015			**SHEET:** 1 **of** 3

Figure 20-1 Essential Energy 66 kV Period Contract Surge Arrester Specification Part 1 (Tyree 2015)

TITLE:
SURGE ARRESTER, 66kV, 10kA, 3EL1

TYREE

SIEMENS

Technical Datasheet Offer number: 27036337 Attachment

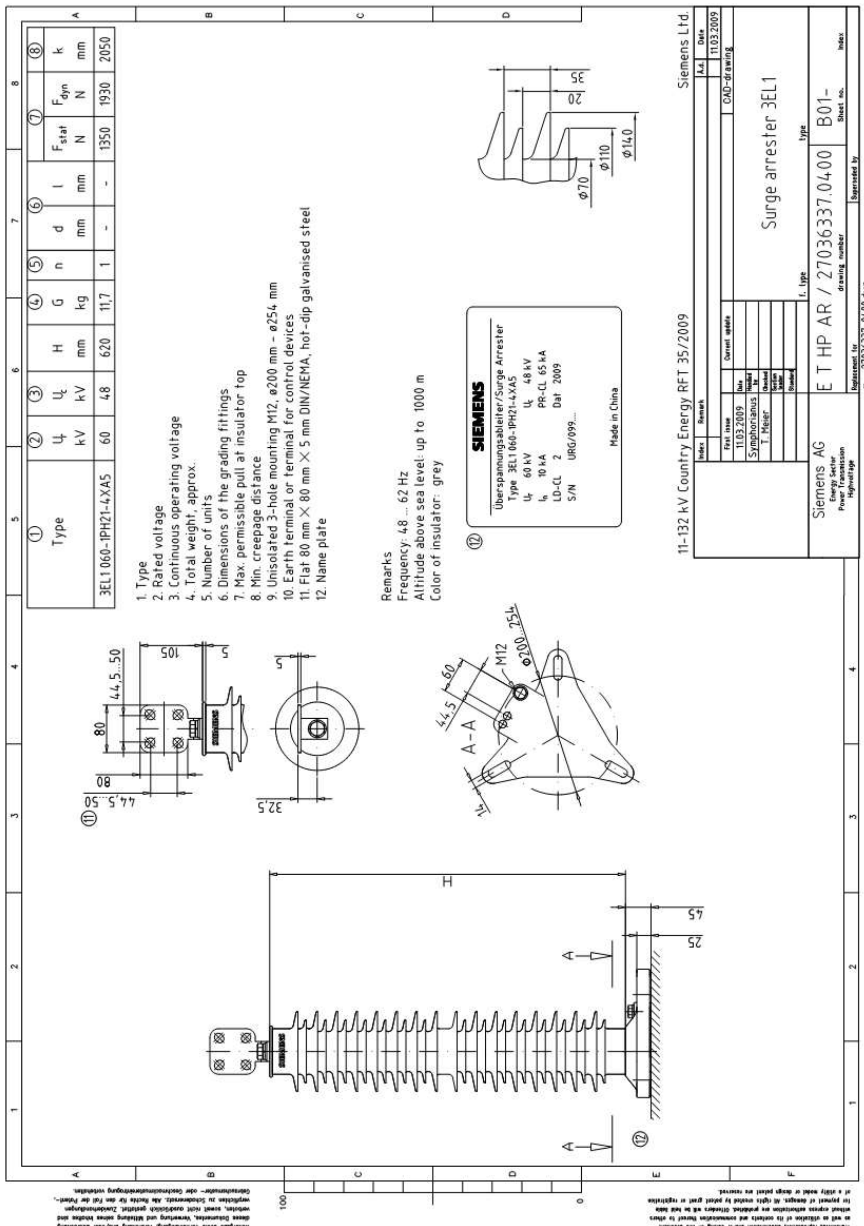
Siemens H-Pos: 400; 3EL1 060-1PH21-4XA5

System Information		
Highest Voltage of Equipment (Um)	72,5	kV
Basic Insulation Level (BIL)	325	kV
Maximum altitude of installation (a.s.l.)	1000	m
Neutral system earthing	solid	
Power Frequency	48 ... 62	Hz
Electrical data		
Applied Standard	IEC 60099-4	
Rated voltage (Ur)	60	kV
Maximum continuous operating voltage (Uc / MCOV)	48	kV
Nominal discharge current (In, 8/20 µs)	10	kA
Line discharge class	2	
Long duration impulse current withstand (2 ms)	500	A
High current impulse withstand (4/10 µs)	100	kA
Rated short circuit current (0,2 s)	65,0	kA
Maximum residual voltage at :		
10 kA 1/2 µs	169	kV
5 kA 8/20 µs	148	kV
10 kA 8/20 µs	159	kV
20 kA 8/20 µs	178	kV
40 kA 8/20 µs	204	kV
500 A 30/60 µs	123	kV
1 kA 30/60 µs	127	kV
2 kA 30/60 µs	134	kV
Temporary overvoltage for 1 s	69,0	kV
Temporary overvoltage for 10 s	64,5	kV
Energy discharge capability - thermal	5,00	kJ/kV_r
Energy discharge capability - impulse	2,60	kJ/kV_r
Power Frequency withstand voltage (1min, wet)	170	kV
Lightning Impulse withstand voltage (1,2/50 µs)	365	kV
Mechanical data		
Height (H)	620	mm
Minimum creepage distance	2 050	mm
Number of units	1	
Weight (G)	11,7	kg
Color of housing	grey	
Cantilever load, static (Fstat)	1350	N
Cantilever load, dynamic (Fdyn)	1930	N
Drawing number	E T HP AR 27036337.0400	
Accessories		
Line terminal	Flat terminal 80 x 80 mm DIN/NEMA, hot dip galvanized	
Ground terminal	3-hole, PCD 200 - 254 mm (7.87" - 10"), not insulated, hot dip galvanized	

BY: AR		DWG No: 0515-3058	REV: A
DATE: 4/11/2015			SHEET: 2 of 3

Figure 20-2 Essential Energy 66 kV Period Contract Surge Arrester Specification Part 2 (Tyree 2015)

TITLE:
SURGE ARRESTER, 66kV, 10kA, 3EL1



BY: AR		DWG No: 0515-3058	REV: A
DATE: 4/11/2015			SHEET: 3 of 3

Figure 20-3 Essential Energy 66 kV Period Contract Surge Arrester Specification Part 3 (Tyree 2015)

21 APPENDIX K

Template Substation Validation Calculations

Incoming Surge & Overhead line Parameters

Maximum Continuous Over Voltage $MCOV := 48 \ kV$

Mean Time Between Failures $MTBF := 35 \ yrs$

Nominal System Voltage (kV)	BIL, kV	BFR FO/100, km-yrs	K_c, km-kV/μs	Span Length, meters	MTBF, years
500	1800	0.6	1000	300	390 x 10^6
345	1300	0.6	1000	300	3 x 10^6
230	900	1	700	300	29000
115	550	3	700	250	470
69	350	5	700	150	35
34.5	150	10	700	150	3

MTBF - Ch11, Table 9, pg 490 "Insulation Coordination for Power Systems" (Hileman 1999)

Number of lines into substation $n := 1$

Mean Time Between Surges $MTBS := n \cdot MTBF = 35 \ yrs$

Back Flashover Rate $BFR := \frac{5}{100} = 0.05$ *Flashovers/100km-yrs*

System Voltage (kV)	S_L, meters	BFR FO/100, km-yrs	MTBS, years	K_c, km-kV/μs	d_m, km	S, kV/μs
500	300	0.6	200	1000	0.9	1110
345	300	0.6	200	1000	0.9	1110
230	300	1	150	700	0.6	1170
138	250	3	100	700	0.5	1400
69	100	5	100	700	0.4	3500

BFR - Ch11, Table 6, pg 483 "Insulation Coordination for Power Systems" (Hileman 1999)

Incoming line span length $l_{span} := 0.2 \ km$

Therefore minimum distance between substation entrance and lightning strike to determine steepness of the incoming surge becomes: $d_m := \frac{1}{BFR \cdot MTBS} = 0.57 \ km$

Extending d_m *to a multiple of the span length:* $d_m := 3 \cdot l_{span} = 0.6 \ km$

This assumes any midspan flashover is very unlikely and therefore flashovers will only occur at the overhead line structures. Ch11, pg 471 "Insulation Coordination for Power Systems" (Hileman 1999)

Corona constant $K_c := 700 \ km\text{-}kV/\mu s$

Conductor	K_c, km-kV/μs
Single	700
Two-cond. bundle	1000
Three or four cond. Bundle	1700
Six or eight cond. Bundle	2500

Kc - Ch11, Table26, pg 470 "Insulation Coordination for Power Systems" (Hileman 1999)

Surge steepness $S := \frac{K_c}{d_m} = 1167\ kV/\mu s$

Critical Flashover Voltage $CFO := 589\ kV$

Crest voltage of incoming surge $E := 1.2 \cdot CFO = 707\ kV$

Power frequency voltage $V_{pf} := 40\ kV$

Surge Velocity $v := 287\ m/\mu s$

Surge Impedance $Z_s := 277\ \Omega$

Time to crest of the incoming surge $t_f := \frac{E}{S} = 0.606\ \mu s$

Zone Substation Parameters

Transformer surge capacitance $C_{tx} := 5 \cdot 10^{-9}$

Transformer surge capacitance time constant $\tau := C_{tx} \cdot Z_s \cdot 10^6 = 1.385\ \mu s$

Separation Distances

Station Entrance to Circuit Breaker $l_1 := 15.5m$

Circuit Breaker to Arrester Junction $l_2 := 40m$

Arrester Junction to Arrester $l_3 := 1\ m$

Arrester Junction to Transformer $l_4 := 1\ m$

Surge Propagation Times

Station Entrance to Circuit Breaker $T_1 := \frac{l_1}{v} = 0.054\ \mu s$

Circuit Breaker to Arrester Junction $T_2 := \frac{l_2}{v} = 0.139\ \mu s$

Arrester Junction to Arrester $T_3 := \frac{l_3}{v} = 0.003\ \mu s$

Arrester Junction to Transformer $T_4 := \frac{l_4}{v} = 0.003\ \mu s$

Surge Arrester Data (From Manufacturer Datasheet)

Rated Voltage $U_r := 60\ kV$

Discharge Voltage (1/20 μs @10kA) $U_{d0.5} := 171\ kV$

Discharge Voltage (8/20 μs @5kA) $U_{d5} := 148\ kV$

Discharge Voltage (8/20 μs @10kA) $U_{d10} := 159\ kV$

Discharge Voltage (8/20 μs @20kA) $U_{d20} := 175\ kV$

Discharge Voltage (8/20 μs @40kA) $U_{d40} := 204\ kV$

Surge Arrester Discharge Current and Voltage

Multiplying factor $K := \frac{U_{d0.5}}{U_{d10}} = 1.08$ *(applied to 8/20μs voltages to calculate apparent arrester resistance)*

Discharge Voltage (8/20 μs @5kA) $U_{d5} := U_{d5} \cdot K = 159.17\ kV$

Discharge Voltage (8/20 μs @10kA) $U_{d10} := U_{d10} \cdot K = 171\ \ kV$

Apparent arrester resistance $R_A := \frac{(U_{d10} - U_{d5})}{10 - 5} = 2.37\ \Omega$

Minimum arrester discharge voltage $E_0 := U_{d5} - (U_{d10} - U_{d5}) = 147.34\ kV$

Arrester current $$I_A := 1.6 \cdot \left(\frac{\left(\left(2 \cdot \frac{E}{n} \right) - (E_0 - V_{pf}) \right)}{\left(\left(\frac{Z_s}{n} \right) + R_A \right)} \right) = 7.48\ \ kA$$

Arrester discharge voltage $E_d := E_0 + (R_A \cdot I_A) = 165\ \ kV$

Surge voltage at arrester $E_A := E_d + V_{pf} = 205\ \ kV$

Transformer Surge Voltage to Ground

Time to crest of the voltage at the transformer $t_T := \pi \cdot \sqrt{(T_3 + T_4) \cdot (\tau + T_3 + T_4)} + \frac{E_A}{S} = 0.485\ \ \mu s$

$$K_I := \frac{S \cdot (T_3 + T_4)}{E_A} = 0.04$$

Constants for E_T / E_A & E_J / E_A $A := 1$ $B := 0.14$ *Given in Table 6 (Ch13, pg 568) in "Insulation Coordination for Power Systems" (Hileman 1999)*

E_T / E_A $$E_{T\_A} := 1 + \left(\frac{A}{1 + \frac{B}{K_I}} \right) = 1.22$$

Surge voltage at transformer $E_T := E_{T\_A} \cdot E_A = 250.3\ \ kV$

Surge voltage at transformer minus power frequency voltage $E_t := E_T - V_{pf} = 210.3\ \ kV$

Arrester Junction Surge Voltage to Ground

$$K_I := \frac{S \cdot (T_3)}{E_A} = 0.02$$

E_J / E_A $$E_{J\_A} := 1 + \left(\frac{A}{1 + \frac{B}{K_I}} \right) = 1.12$$

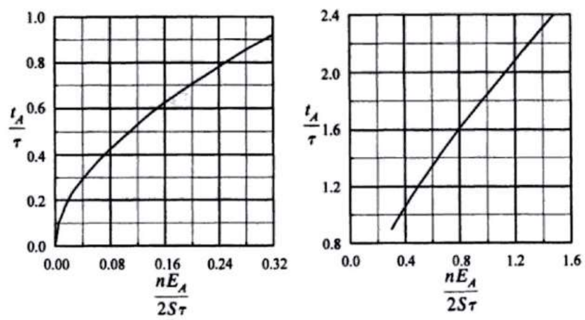
Surge voltage at arrester junction $E_J := E_{J\_A} \cdot E_A = 230.5\ \ kV$

Surge voltage at arrester junction minus power frequency voltage $E_j := E_J - V_{pf} = 190.5\ \ kV$

Circuit Breaker Surge Voltage to Ground

$$\frac{n \cdot E_A}{2 \cdot S \cdot \tau} = 0.06$$

Arrester operating time T_A / τ $\quad T_{A\_\tau} := 0.35 \ \mu s$



T_A / τ - *Ch13, Figure 9, pg 575 "Insulation Coordination for Power Systems" (Hileman 1999)*

Time to reach crest voltage minus two times the propagation time between the circuit breaker and arrester $\quad t_f - 2 \cdot (T_2 + T_3) = 0.32 \ \mu s$

Is $T_A / \tau \leq t_f - 2(T_2 + T_3)$? **NO**

If "Yes":

Surge voltage at circuit breaker $\quad E_B := E_J + 2 \cdot (S \cdot T_2) = 555.7 \ kV$

If "No":

Surge voltage at circuit breaker $\quad E_B := (2 \cdot E) - (2 \cdot S \cdot (T_2 + T_3)) - \left(2 \cdot \tau \cdot S \cdot \left(1 - e^{\frac{-(t_f - 2 \cdot (T_2 + T_3))}{\tau}}\right)\right) = 413.4 \ kV$

Surge voltage at circuit breaker minus power frequency voltage $\quad E_b := E_B - V_{pf} = 373.4 \ kV$

Station Entrance Surge Voltage to Ground

$$\frac{n \cdot E_A}{2 \cdot S \cdot \tau} = 0.063$$

Arrester operating time T_A / τ $\quad T_{A\_\tau} := 0.55 \ \mu s$ $\quad$ *Estimated using Figure 9 (Ch13, pg 575) in "Insulation Coordination for Power Systems"*

Time to reach crest voltage minus two times the propagation time between the circuit breaker and arrester $\quad t_f - 2 \cdot (T_1 + T_2 + T_3) = 0.21 \ \mu s$

Is $T_A / \tau \leq t_f - 2(T_2 + T_3)$? **NO**

If "Yes":

Surge voltage at station entrance $\quad E_{B1} := E_J + 2 \cdot (S \cdot T_1) = 356 \ kV$

If "No":

Surge voltage at station entrance $\quad E_{B1} := (2 \cdot E) - (2 \cdot S \cdot (T_1 + T_2 + T_3)) - \left(2 \cdot \tau \cdot S \cdot \left(1 - e^{\frac{-(t_f - 2 \cdot (T_1 + T_2 + T_3))}{\tau}}\right)\right) = 495.4 \ kV$

Surge voltage at station entrance minus power frequency voltage $\quad E_{b1} := E_{B1} - V_{pf} = 455.4 \ kV$

22 APPENDIX L

Kywong Substation Validation Calculations

Incoming Surge & Overhead line Parameters

Maximum Continuous Over Voltage $MCOV := 48 \ kV$

Mean Time Between Failures $MTBF := 35 \ yrs$

Nominal System Voltage (kV)	BIL, kV	BFR FO/100, km-yrs	K_c, km-kV/µs	Span Length, meters	MTBF, years
500	1800	0.6	1000	300	390 x 10^6
345	1300	0.6	1000	300	3 x 10^6
230	900	1	700	300	29000
115	550	3	700	250	470
69	350	5	700	150	35
34.5	150	10	700	150	3

MTBF - Ch11, Table 9, pg 490 "Insulation Coordination for Power Systems" (Hileman 1999)

Number of lines into substation $n := 1$

Mean Time Between Surges $MTBS := n \cdot MTBF = 35 \ yrs$

Back Flashover Rate $BFR := \frac{5}{100} = 0.05$ *Flashovers/100km-yrs*

System Voltage (kV)	S_L, meters	BFR FO/100, km-yrs	MTBS, years	K_c, km-kV/µs	d_m, km	S, kV/µs
500	300	0.6	200	1000	0.9	1110
345	300	0.6	200	1000	0.9	1110
230	300	1	150	700	0.6	1170
138	250	3	100	700	0.5	1400
69	100	5	100	700	0.4	3500

BFR - Ch11, Table 6, pg 483 "Insulation Coordination for Power Systems" (Hileman 1999)

Incoming line span length $l_{span} := 0.16 \ km$

Therefore minimum distance between substation entrance and lightning strike to determine steepness of the incoming surge becomes:

$$d_m := \frac{1}{BFR \cdot MTBS} = 0.57 \ km$$

Extending d_m *to a multiple of the span length:* $d_m := 4 \cdot l_{span} = 0.64 \ km$

This assumes any midspan flashover is very unlikely and therefore flashovers will only occur at the overhead line structures. Ch11, pg 471 "Insulation Coordination for Power Systems" (Hileman 1999)

Corona constant $K_c := 700 \ km\text{-}kV/\mu s$

Conductor	K_c, km-kV/µs
Single	700
Two-cond. bundle	1000
Three or four cond. Bundle	1700
Six or eight cond. Bundle	2500

Kc - Ch11, Table 2, pg 470 "Insulation Coordination for Power Systems" (Hileman 1999)

Surge steepness $S := \frac{K_c}{d_m} = 1094\ kV/\mu s$

Critical Flashover Voltage $CFO := 589\ kV$

Crest voltage of incoming surge $E := 1.2 \cdot CFO = 707\ kV$

Power frequency voltage $V_{pf} := 40\ kV$

Surge Velocity $v := 270\ m/\mu s$

Surge Impedance $Z_s := 372\ \Omega$

Time to crest of the incoming surge $t_f := \frac{E}{S} = 0.646\ \mu s$

<u>Zone Substation Parameters</u>

Transformer surge capacitance $C_{tx} := 2 \cdot 10^{-9}$

Transformer surge capacitance time constant $\tau := C_{tx} \cdot Z_s \cdot 10^6 = 0.744\ \mu s$

<u>Seperation Distances</u>

Station Entrance to Arrester Junction $l_1 := 25\ m$

Arrester Junction to Arrester $l_{2a} := 1\ m$

Arrester Junction to Transformer $l_{3a} := 15\ m$

<u>Surge Propagation Times</u>

Station Entrance to Arrester Junction $T_1 := \frac{l_1}{v} = 0.093\ \mu s$

Arrester Junction to Arrester $T_{2a} := \frac{l_{2a}}{v} = 0.004\ \mu s$

Arrester Junction to Transformer $T_{3a} := \frac{l_{3a}}{v} = 0.056\ \mu s$

<u>Surge Arrester Data (From Manufacturer Datasheet)</u>

Rated Voltage $U_r := 60\ kV$

Discharge Voltage (1/20 μs @10kA) $U_{d0.5} := 169\ kV$

Discharge Voltage (8/20 μs @5kA) $U_{d5} := 148\ kV$

Discharge Voltage (8/20 μs @10kA) $U_{d10} := 159\ kV$

Discharge Voltage (8/20 μs @20kA) $U_{d20} := 175\ kV$

Discharge Voltage (8/20 μs @40kA) $U_{d40} := 199\ kV$

Surge Arrester Discharge Current and Voltage

Multiplying factor $K := \frac{U_{d0.5}}{U_{d10}} = 1.06$ *(applied to 8/20 μs voltages to calculate apparent arrester resistance)*

Discharge Voltage (8/20 μs @5kA) $U_{d5} := U_{d5} \cdot K = 157 \ kV$

Discharge Voltage (8/20 μs @10kA) $U_{d10} := U_{d10} \cdot K = 169 \ kV$

Apparent arrester resistance $R_A := \frac{(U_{d10} - U_{d5})}{10 - 5} = 2.34 \ \Omega$

Minimum arrester discharge voltage $E_0 := U_{d5} - (U_{d10} - U_{d5}) = 146 \ kV$

Arrester current $I_A := 1.6 \cdot \left(\frac{\left(\left(2 \cdot \frac{E}{n}\right) - (E_0 - V_{pf})\right)}{\left(\left(\frac{Z_s}{n}\right) + R_A\right)} \right) = 5.59 \ kA$

Arrester discharge voltage $E_d := E_0 + (R_A \cdot I_A) = 158.7 \ kV$

Surge voltage at arrester $E_A := E_d + V_{pf} = 198.7 \ kV$

Transformer Surge Voltage to Ground

Time to crest of the voltage at the transformer $t_T := \pi \cdot \sqrt{(T_{2a} + T_{3a}) \cdot (\tau + T_{2a} + T_{3a})} + \frac{E_A}{S} = 0.87 \ \mu s$

$K_I := \frac{S \cdot (T_{2a} + T_{3a})}{E_A} = 0.33$

Constants for E_T / E_A & E_J / E_A $A := 1$, $B := 0.14$ *Given in Table 6 (Ch13, pg 568) in "Insulation Coordination for Power Systems" (Hileman 1999)*

E_T / E_A $E_{T\_A} := 1 + \left(\frac{A}{1 + \frac{B}{K_I}} \right) = 1.7$

Surge voltage at transformer $E_T := E_{T\_A} \cdot E_A = 337.7 \ kV$

Surge voltage at transformer minus power frequency voltage $E_t := E_T - V_{pf} = 297.7 \ kV$

Arrester Junction Surge Voltage to Ground

$K_I := \frac{S \cdot (T_{2a})}{E_A} = 0.02$

E_J / E_A $E_{J\_A} := 1 + \left(\frac{A}{1 + \frac{B}{K_I}} \right) = 1.13$

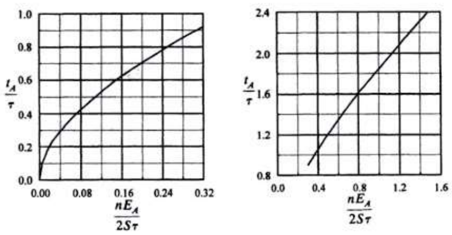
Surge voltage at arrester junction $E_J := E_{J\_A} \cdot E_A = 223.9 \ kV$

Surge voltage at arrester junction minus power frequency voltage $E_j := E_J - V_{pf} = 183.9 \ kV$

Station Entrance Surge Voltage to Ground

$$\frac{n \cdot E_A}{2 \cdot S \cdot \tau} = 0.122$$

Arrester operating time T_A / τ $T_{A\_\tau} := 0.55 \mu s$



T_A / τ - Ch13, Figure 9, pg 575 "Insulation Coordination for Power Systems" (Hileman 1999)

Time to reach crest voltage minus two times the propagation time between the circuit breaker and arrester $t_f - 2 \cdot (T_1 + T_{2a}) = 0.45 \mu s$

Is $T_A / \tau \leq t_f$-2(T_2 T_3)? ***YES***

If "Yes":

Surge voltage at station entrance $E_{B1} := E_J + 2 \cdot (S \cdot T_1) = 426.5$ *kV*

Surge voltage at station entrance minus power frequency voltage $E_b := E_{B1} - V_{pf} = 386.5$ *kV*

If "No":

Surge voltage at circuit breaker $E_{ENT} := (2 \cdot E) - (2 \cdot S \cdot (T_1 + T_{2a})) - \left(2 \cdot \tau \cdot S \cdot \left(1 - e^{\frac{-(t_f - 2 \cdot (T_1 + T_{2a}))}{\tau}}\right)\right) = 460.012$ *kV*

23 APPENDIX M

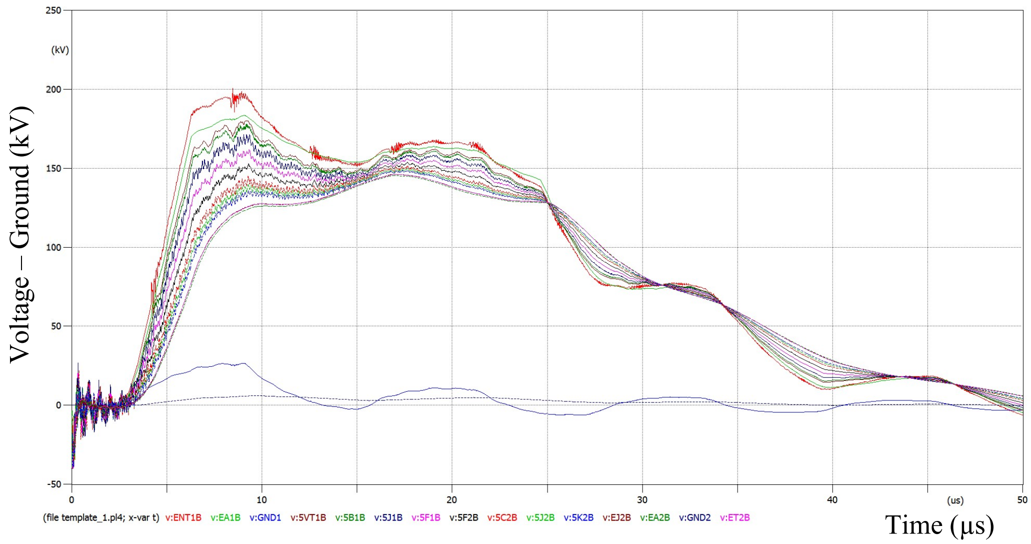


Figure 23-1 Case Study 1, Scenario 1 - ATP Voltage to Ground Plot

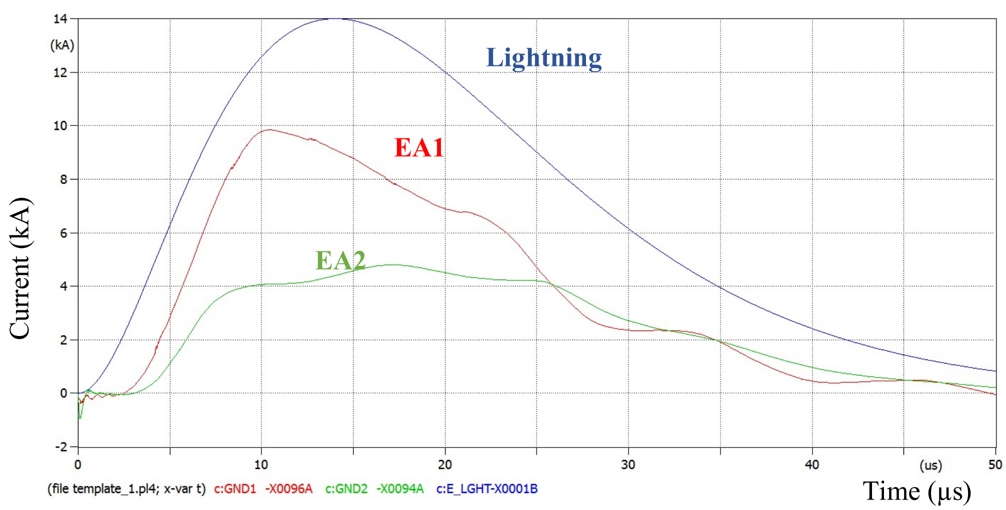


Figure 23-2 Case Study 1, Scenario 1 - ATP Surge Arrester & Lightning Current Plot

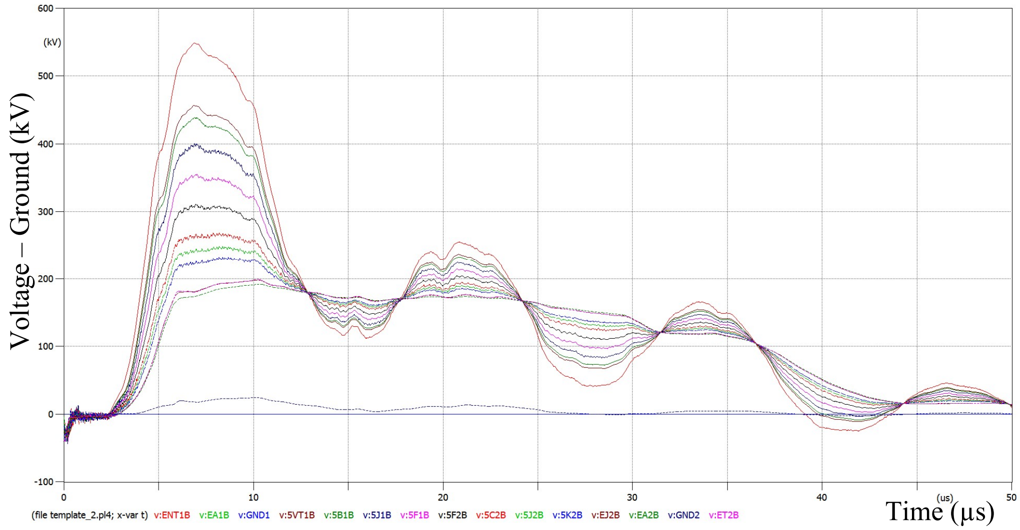


Figure 23-3 Case Study 1, Scenario 2 - ATP Voltage to Ground Plot

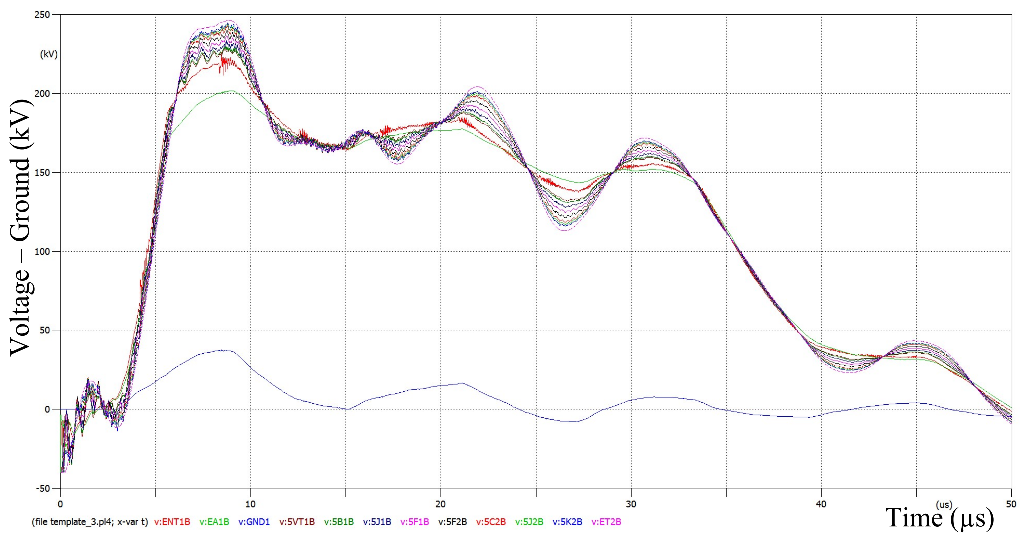


Figure 23-4 Case Study 1, Scenario 3 - ATP Voltage to Ground Plot

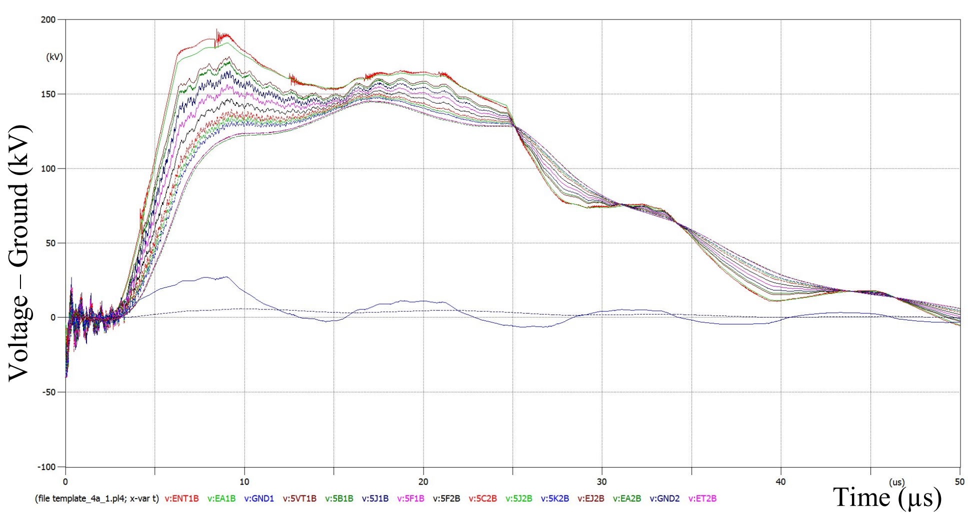


Figure 23-5 Case Study 1, Scenario 4a – 1m ATP Voltage to Ground Plot

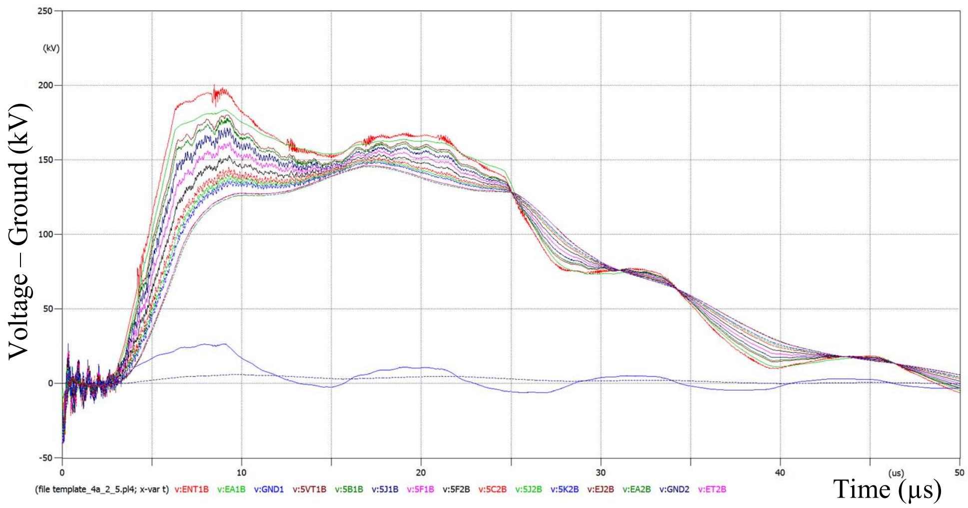


Figure 23-6 Case Study 1, Scenario 4a – 2.5m ATP Voltage to Ground Plot

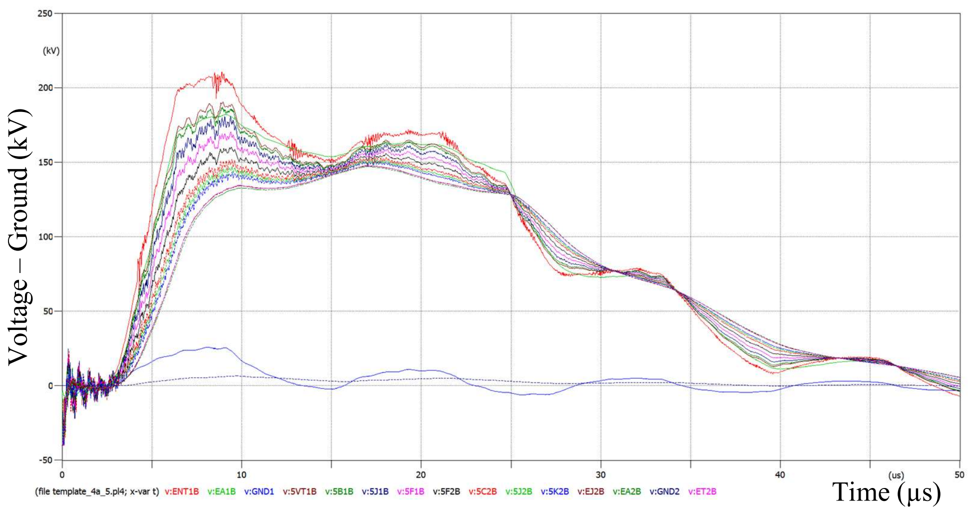


Figure 23-7 Case Study 1, Scenario 4a – 5m ATP Voltage to Ground Plot

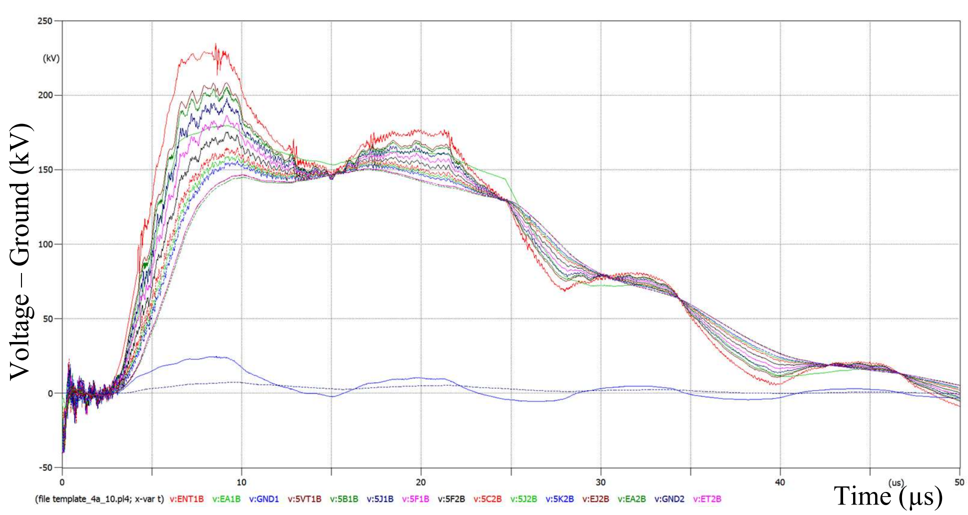


Figure 23-8 Case Study 1, Scenario 4a – 10m ATP Voltage to Ground Plot

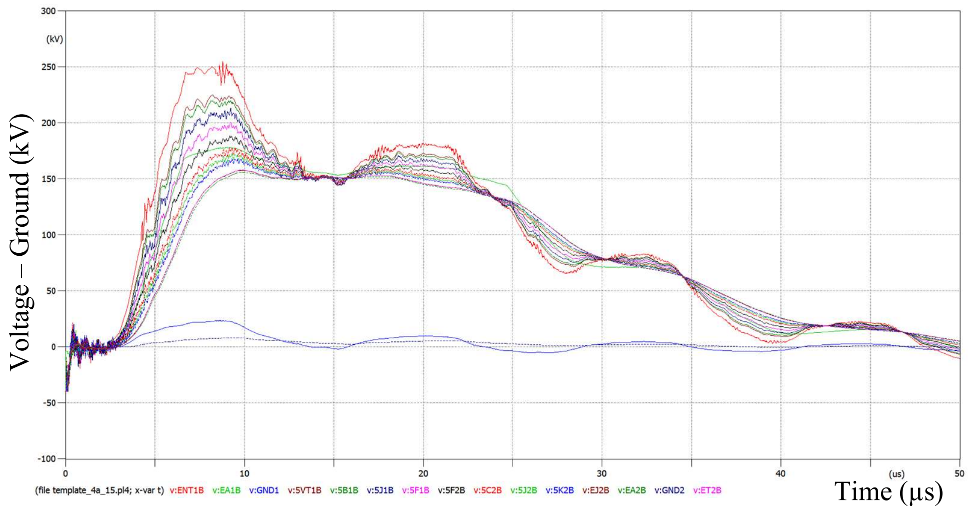


Figure 23-9 Case Study 1, Scenario 4a –15m ATP Voltage to Ground Plot

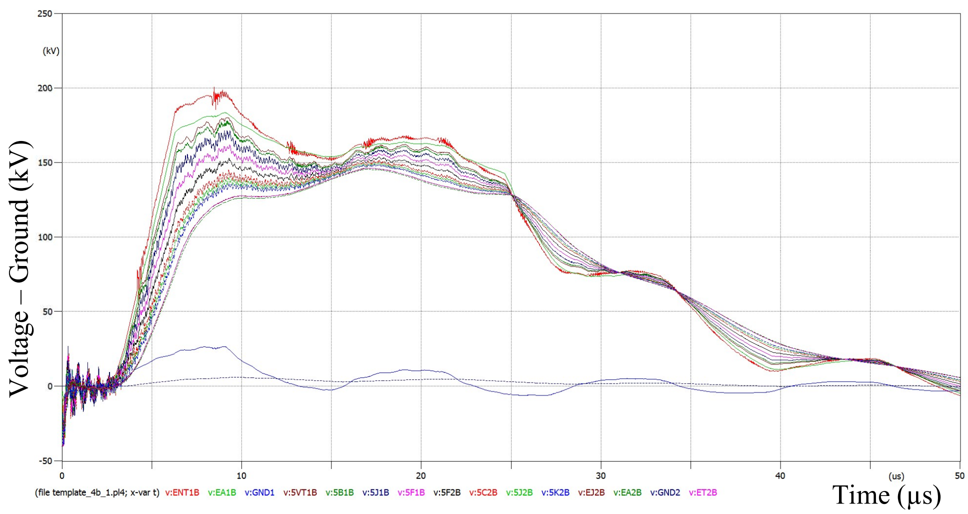


Figure 23-10 Case Study 1, Scenario 4b – 1m ATP Voltage to Ground Plot

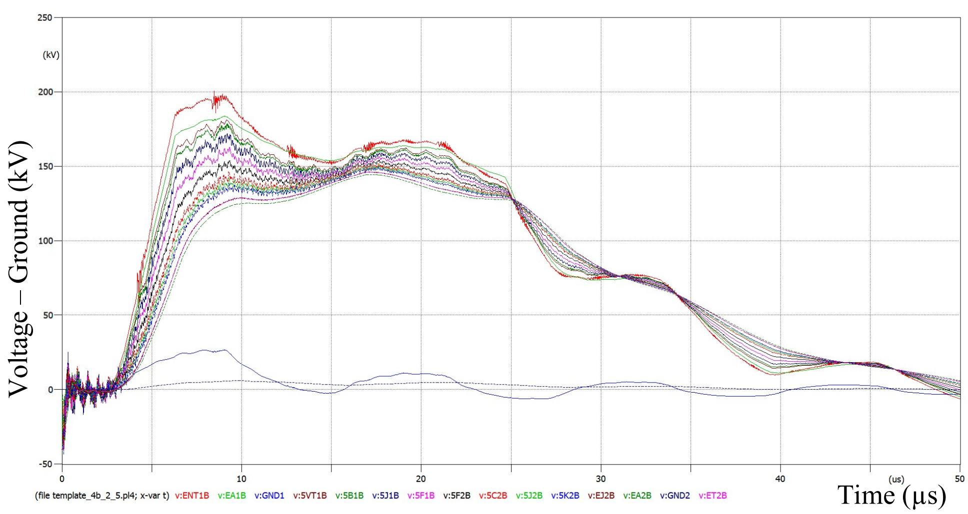


Figure 23-11 Case Study 1, Scenario 4b – 2.5m ATP Voltage to Ground Plot

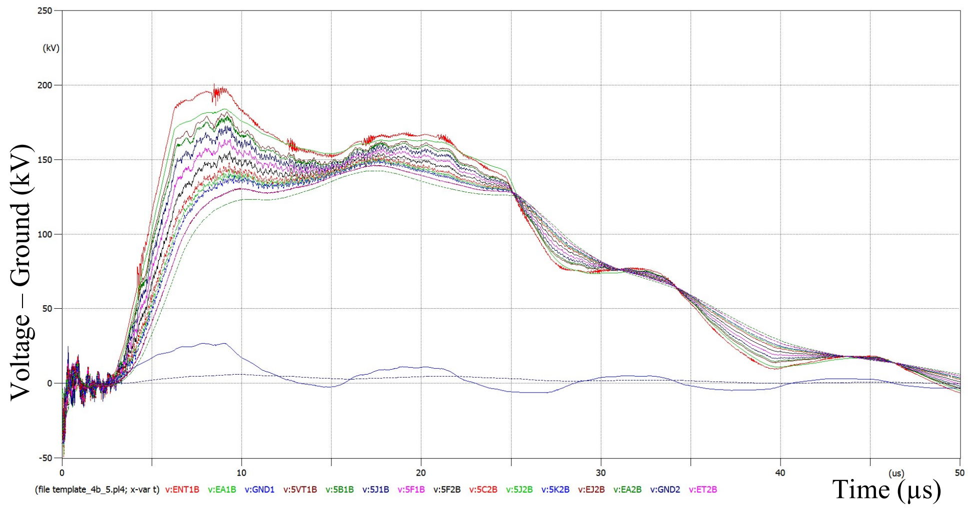


Figure 23-12 Case Study 1, Scenario 4b – 5m ATP Voltage to Ground Plot

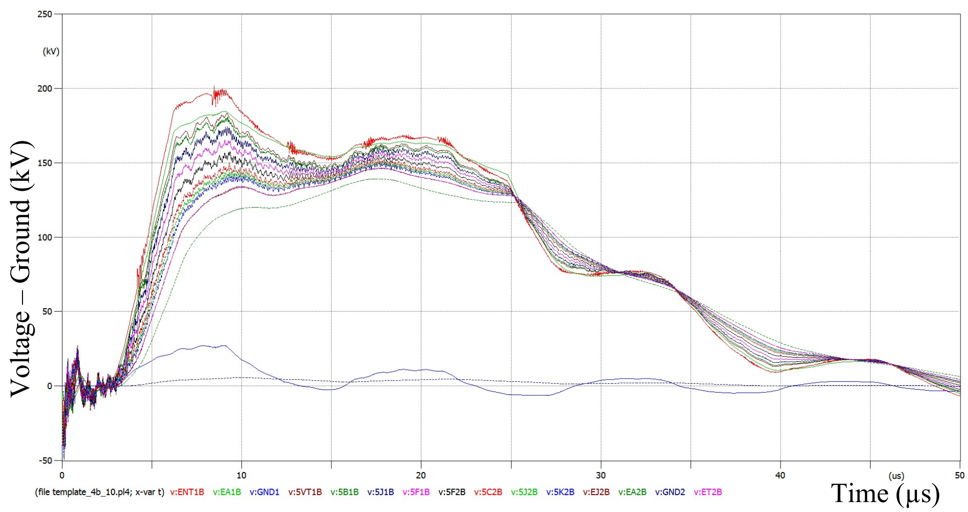


Figure 23-13 Case Study 1, Scenario 4b – 10m ATP Voltage to Ground Plot

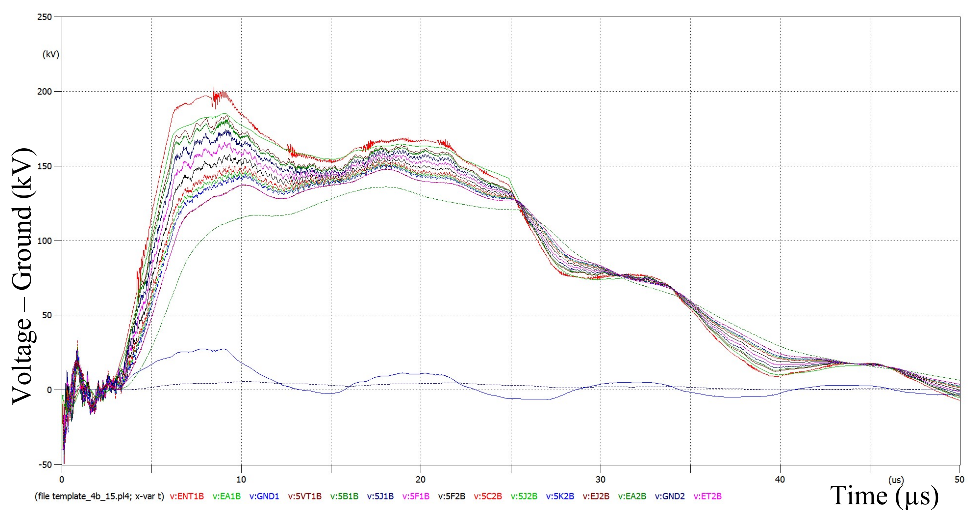


Figure 23-14 Case Study 1, Scenario 4b – 15m ATP Voltage to Ground Plot

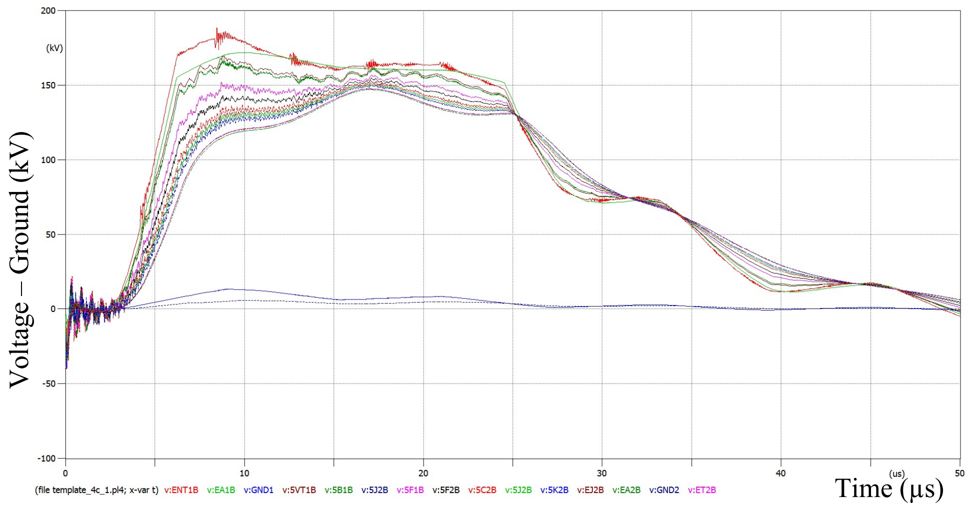


Figure 23-15 Case Study 1, Scenario 4c – 1m ATP Voltage to Ground Plot

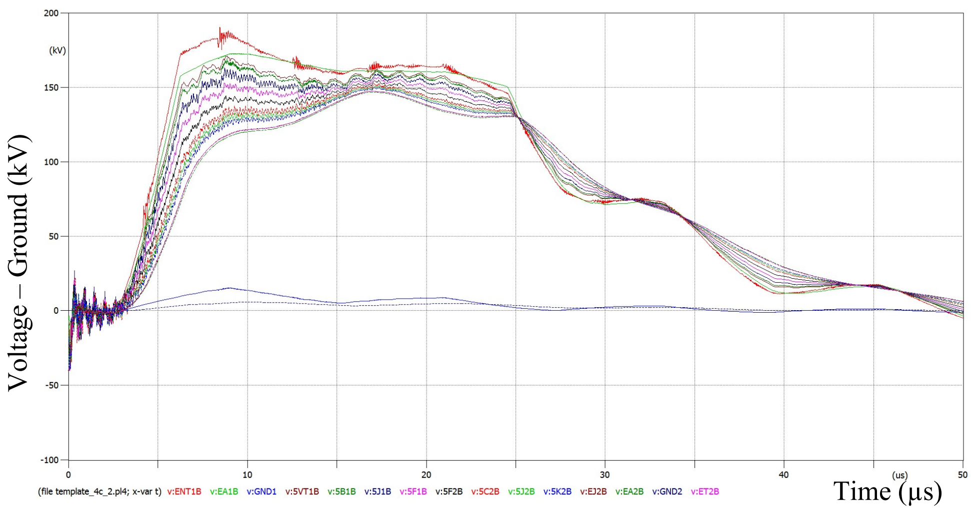


Figure 23-16 Case Study 1, Scenario 4c – 2m ATP Voltage to Ground Plot

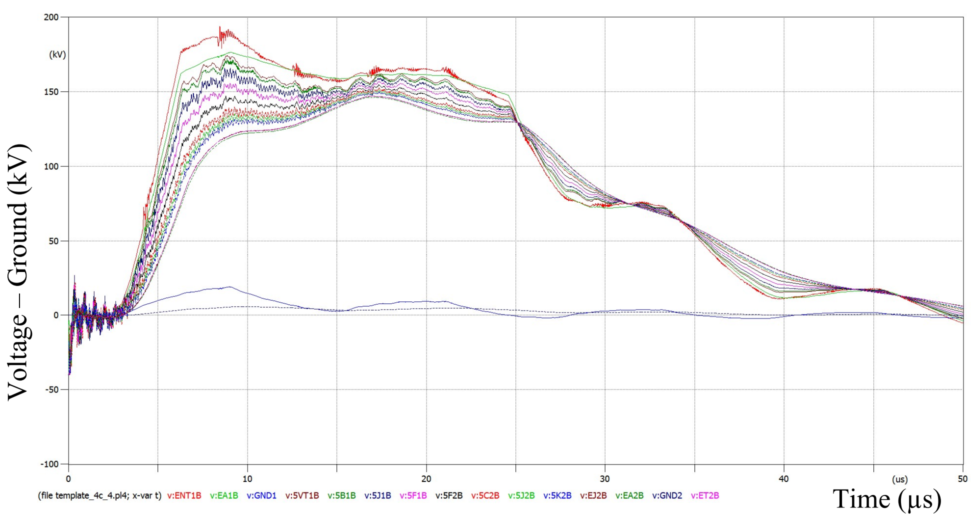


Figure 23-17 Case Study 1, Scenario 4c – 4m ATP Voltage to Ground Plot

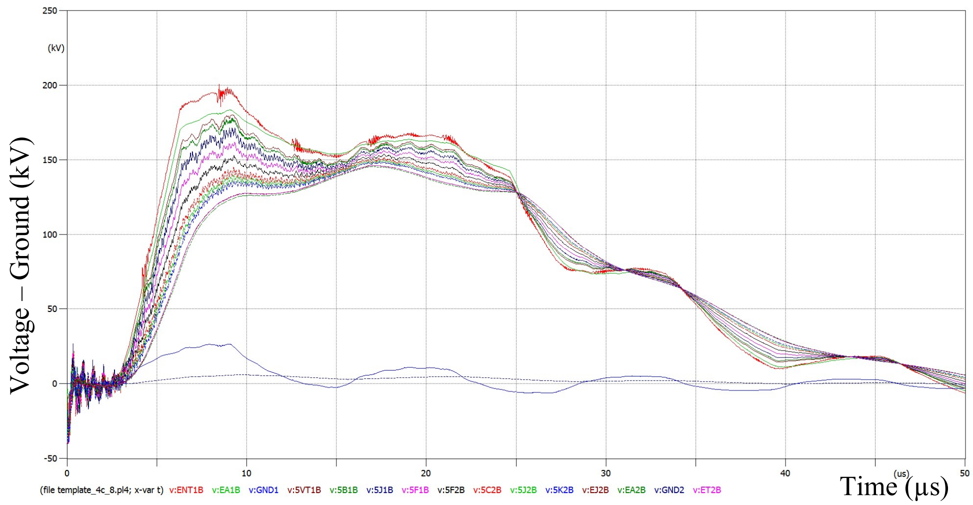


Figure 23-18 Case Study 1, Scenario 4c – 8m ATP Voltage to Ground Plot

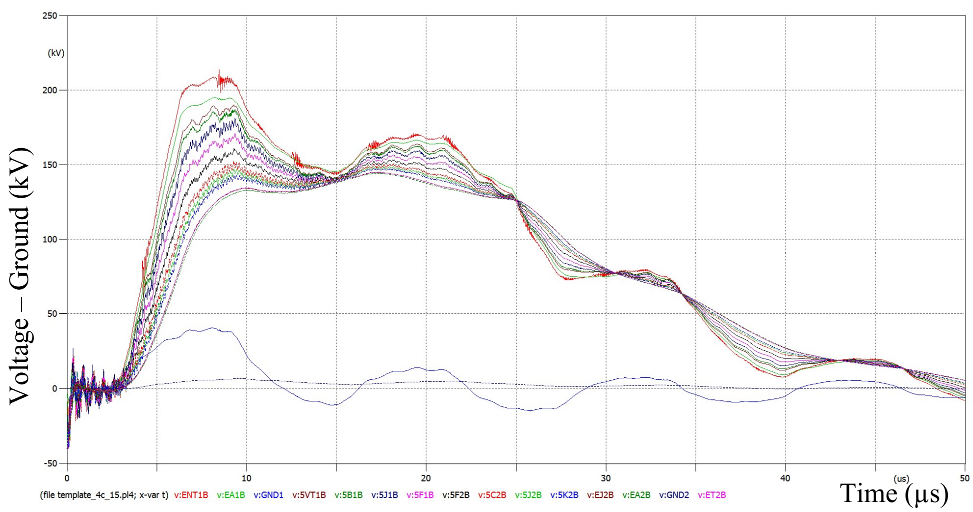


Figure 23-19 Case Study 1, Scenario 4c – 15m ATP Voltage to Ground Plot

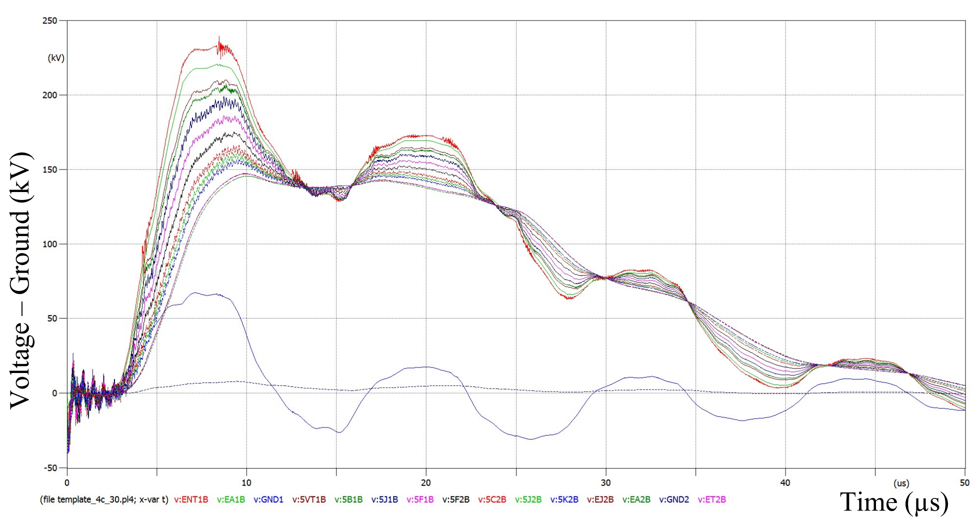


Figure 23-20 Case Study 1, Scenario 4c – 30m ATP Voltage to Ground Plot

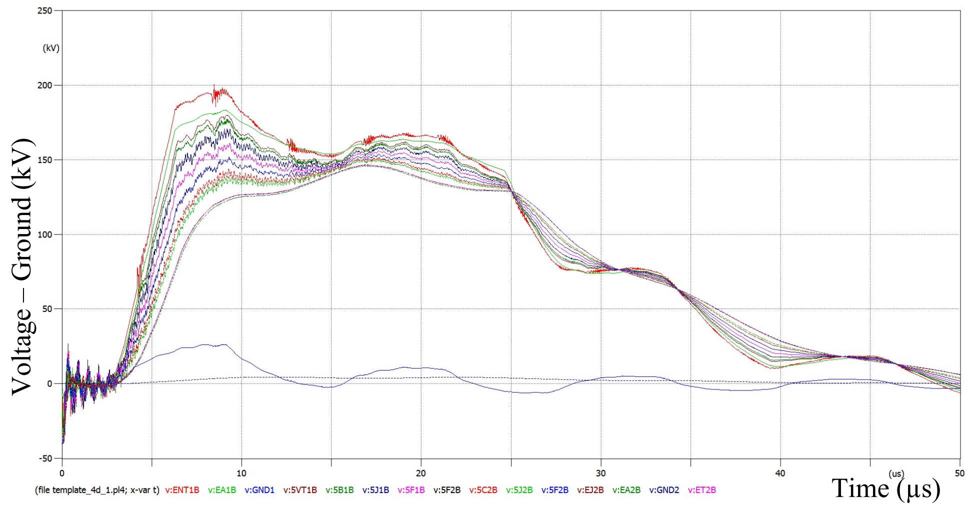


Figure 23-21 Case Study 1, Scenario 4d – 1 m ATP Voltage to Ground Plot

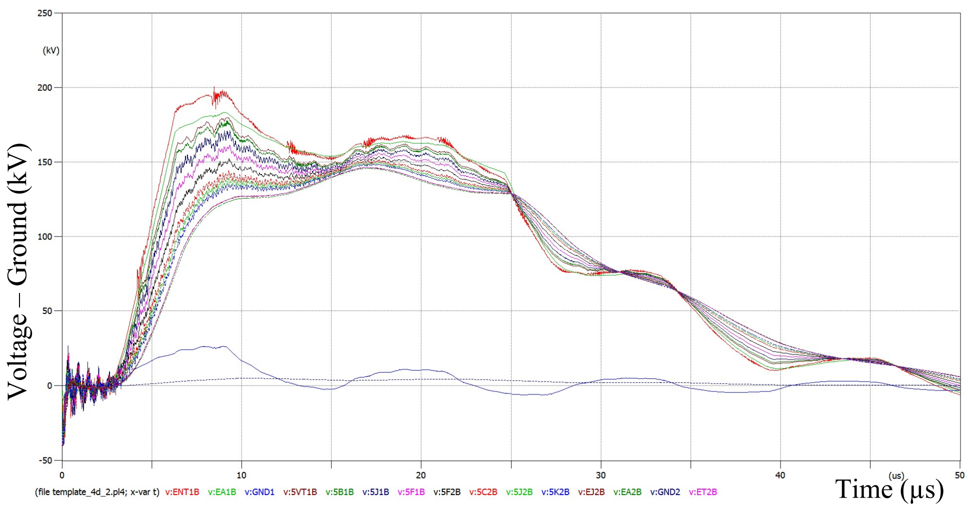


Figure 23-22 Case Study 1, Scenario 4d – 2 m ATP Voltage to Ground Plot

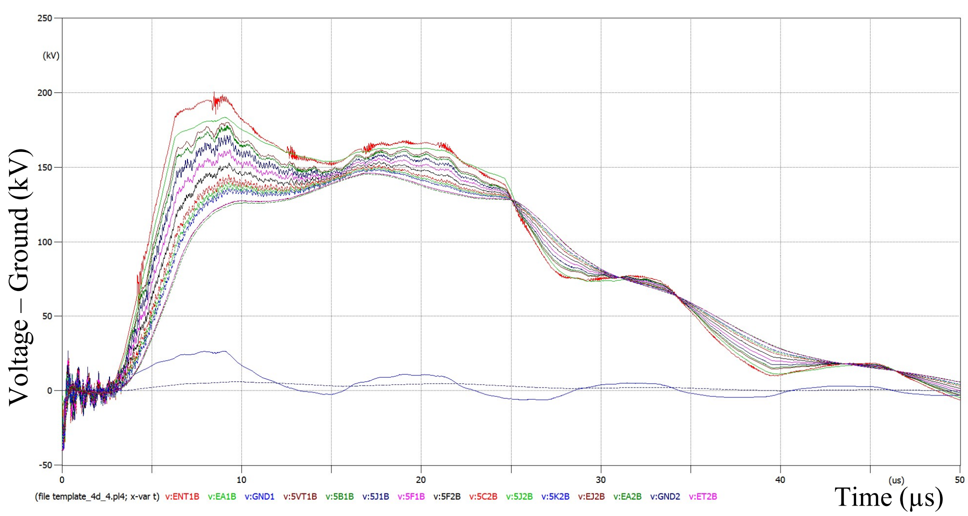


Figure 23-23 Case Study 1, Scenario 4d – 4 m ATP Voltage to Ground Plot

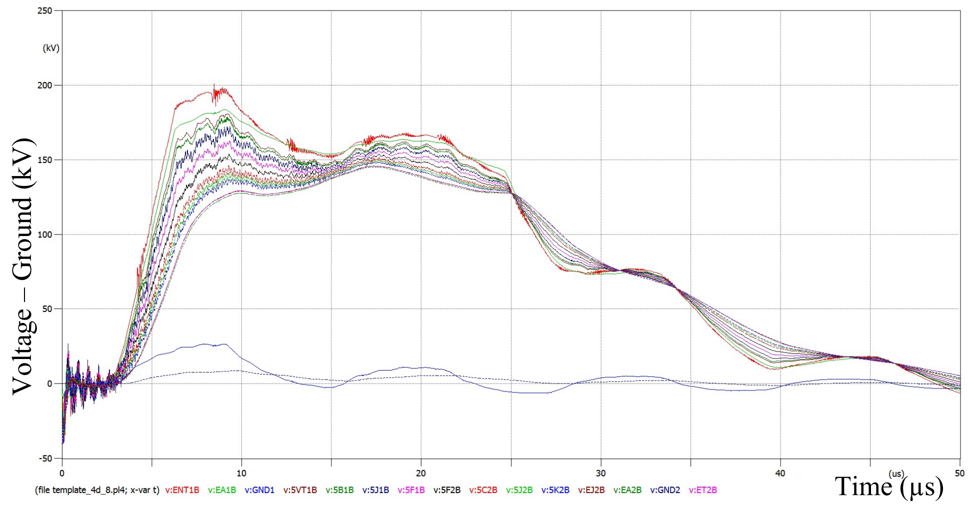


Figure 23-24 Case Study 1, Scenario 4d – 8 m ATP Voltage to Ground Plot

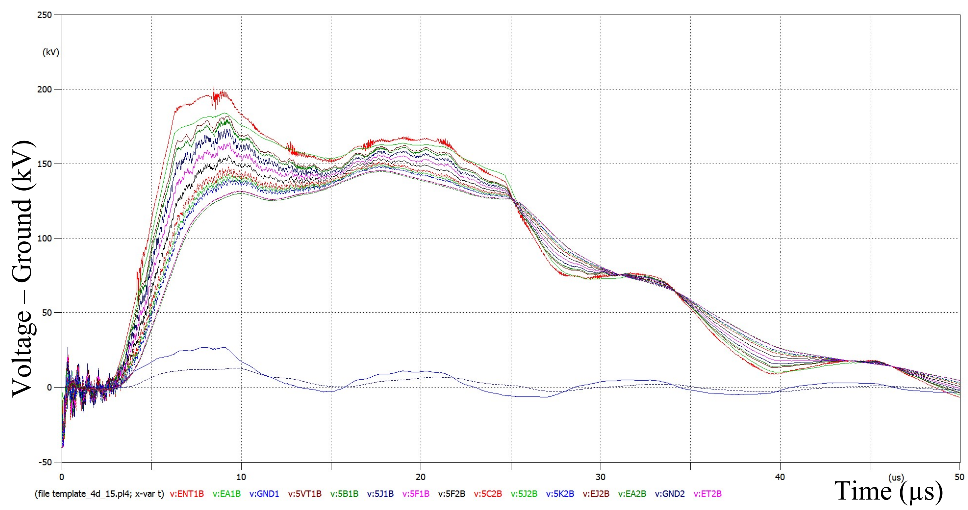


Figure 23-25 Case Study 1, Scenario 4d – 15 m ATP Voltage to Ground Plot

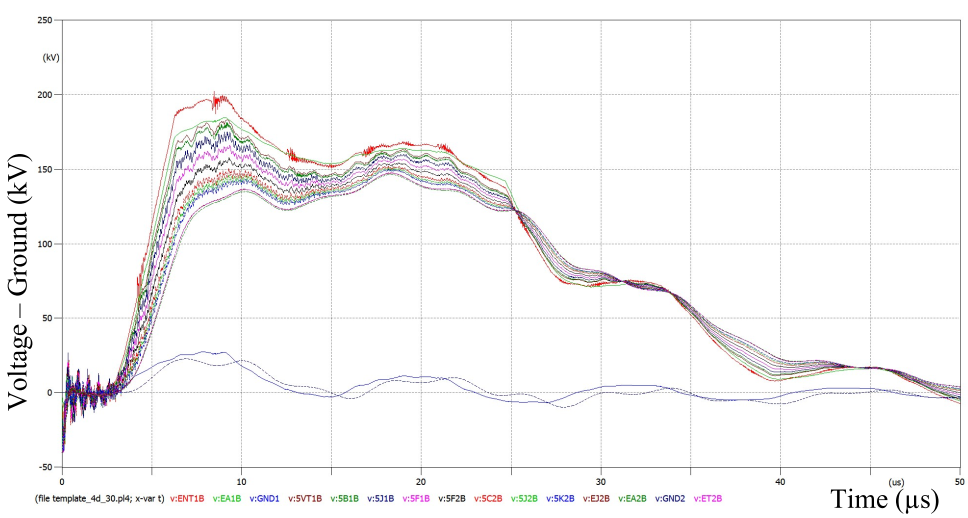


Figure 23-26 Case Study 1, Scenario 4d – 30 m ATP Voltage to Ground Plot

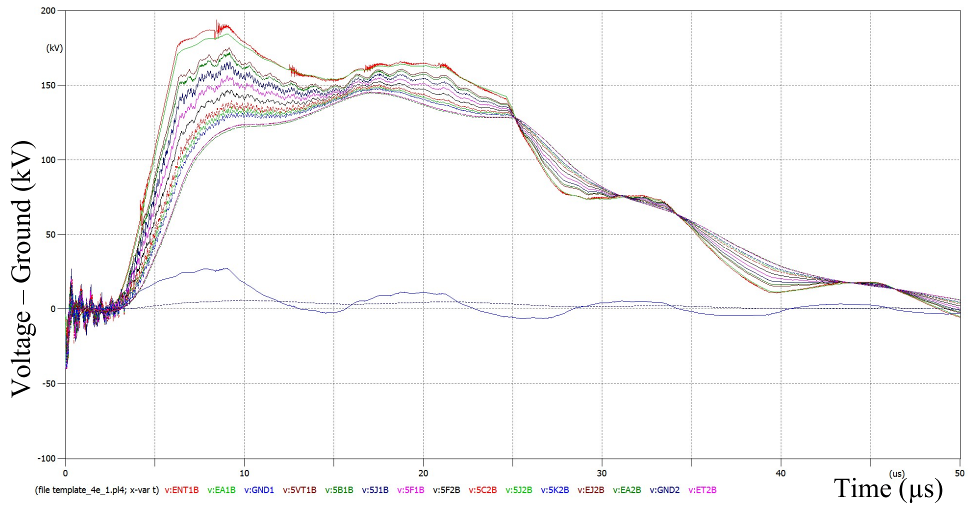


Figure 23-27 Case Study 1, Scenario 4e – 1 m ATP Voltage to Ground Plot

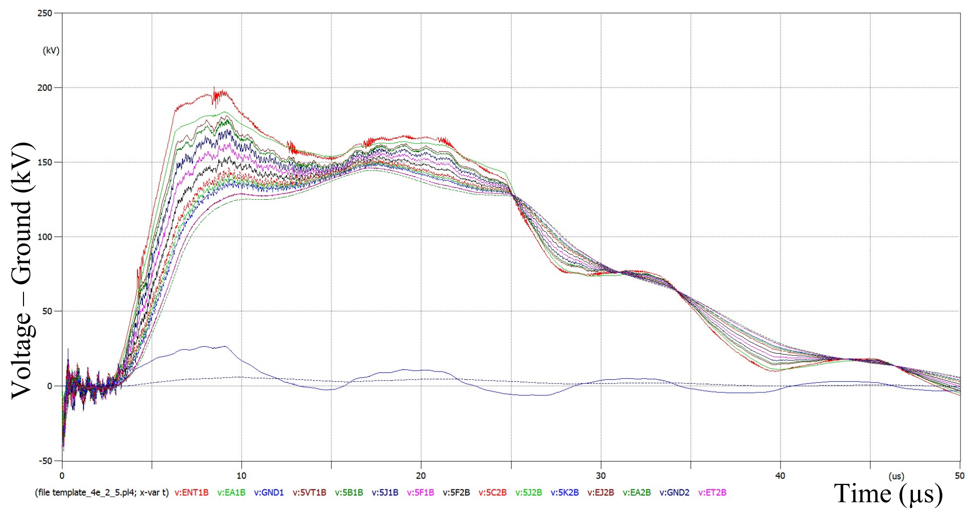


Figure 23-28 Case Study 1, Scenario 4e – 2.5 m ATP Voltage to Ground Plot

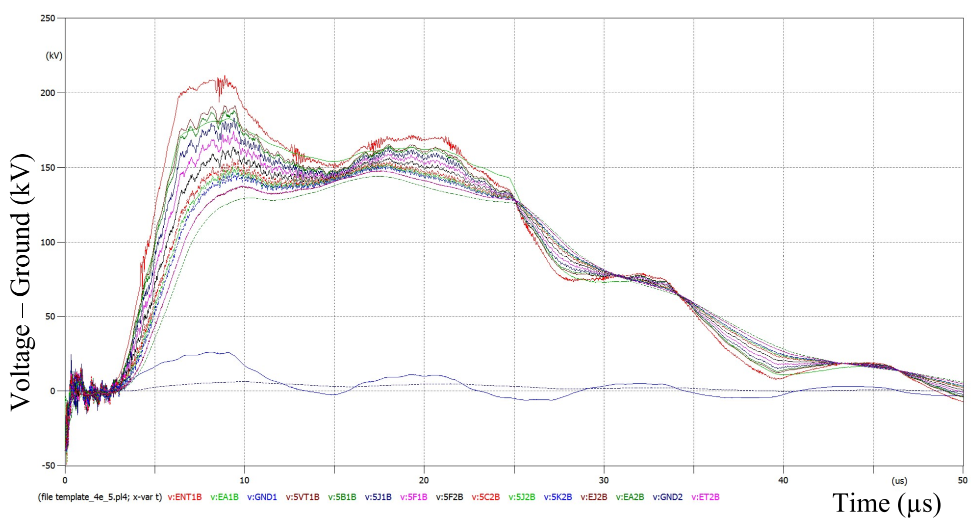


Figure 23-29 Case Study 1, Scenario 4e– 5 m ATP Voltage to Ground Plot

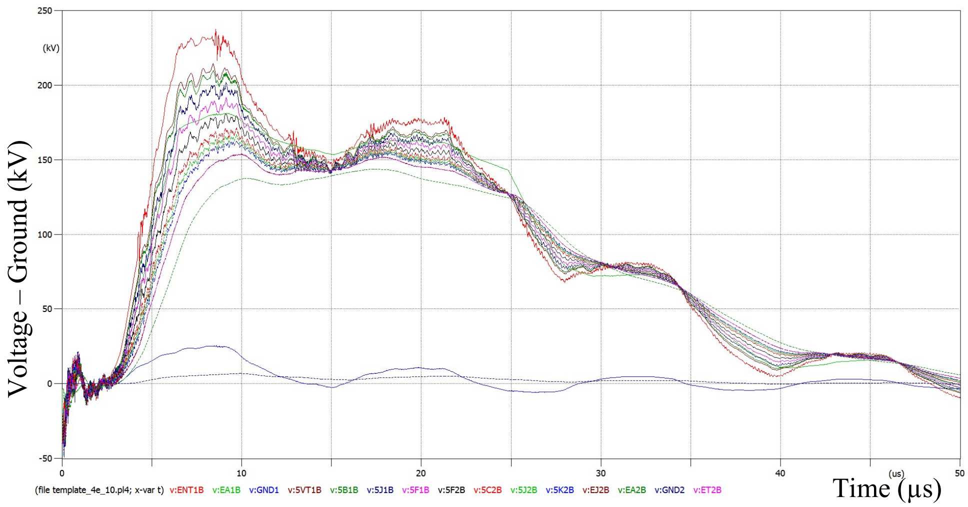


Figure 23-30 Case Study 1, Scenario 4e – 10 m ATP Voltage to Ground Plot

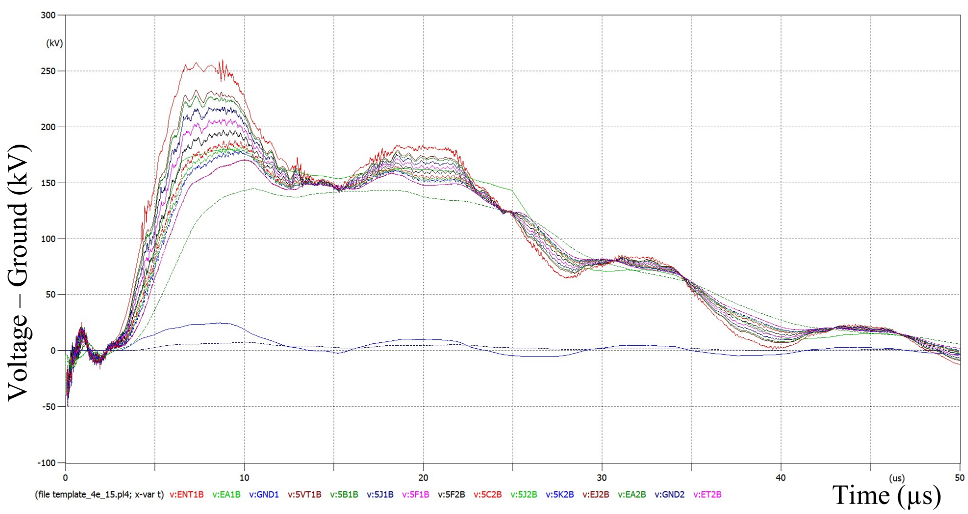


Figure 23-31 Case Study 1, Scenario 4e – 15 m ATP Voltage to Ground Plot

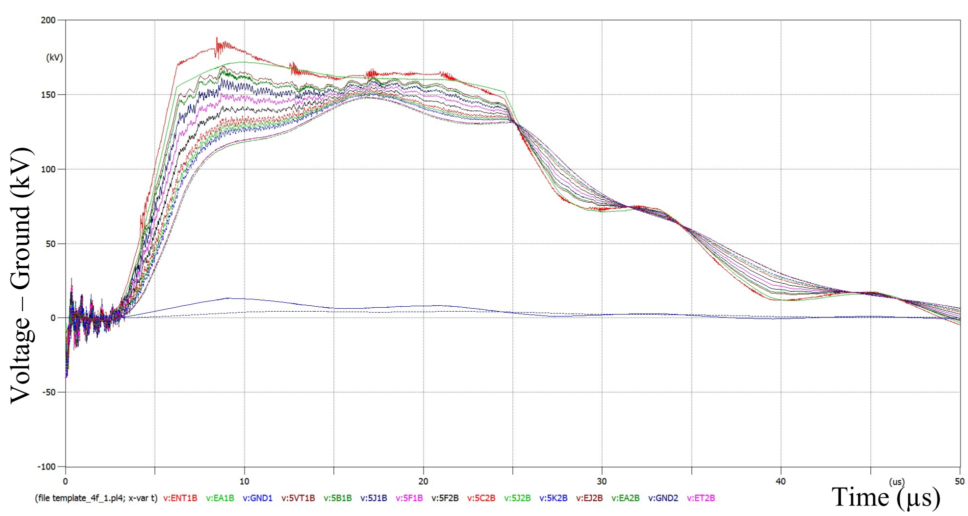


Figure 23-32 Case Study 1, Scenario 4f – 1 m ATP Voltage to Ground Plot

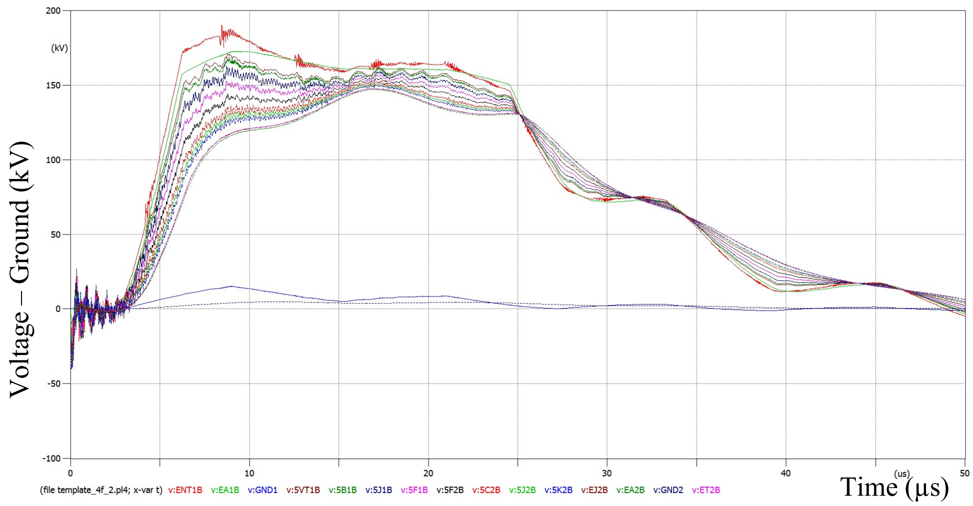


Figure 23-33 Case Study 1, Scenario 4f – 2 m ATP Voltage to Ground Plot

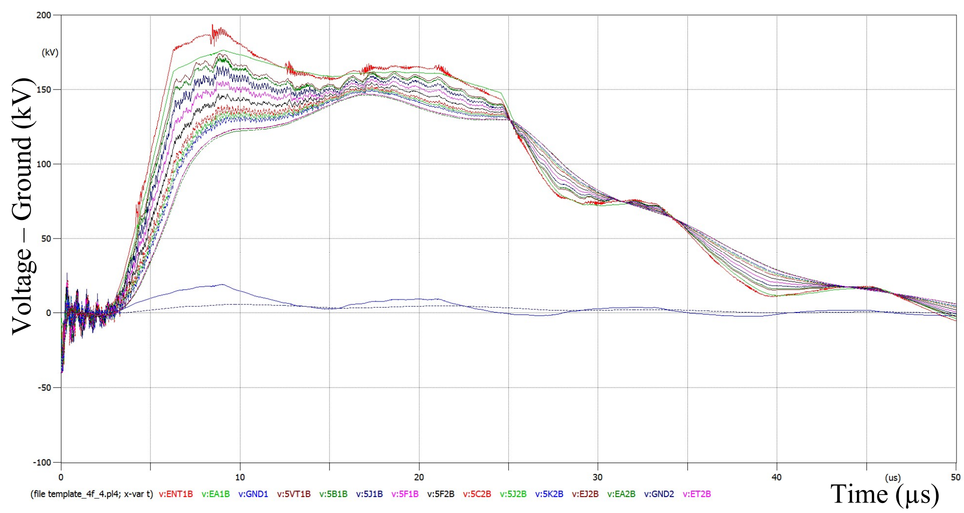


Figure 23-34 Case Study 1, Scenario 4f – 4 m ATP Voltage to Ground Plot

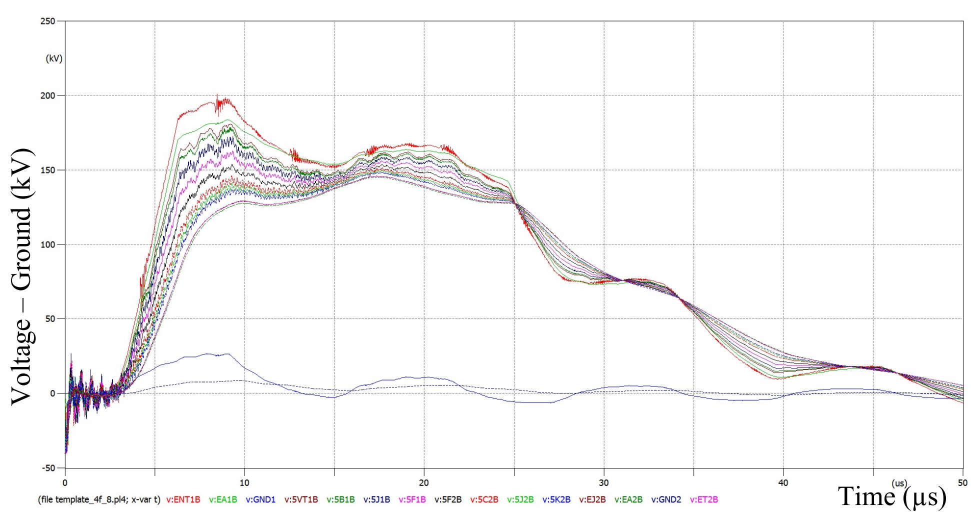


Figure 23-35 Case Study 1, Scenario 4f – 8 m ATP Voltage to Ground Plot

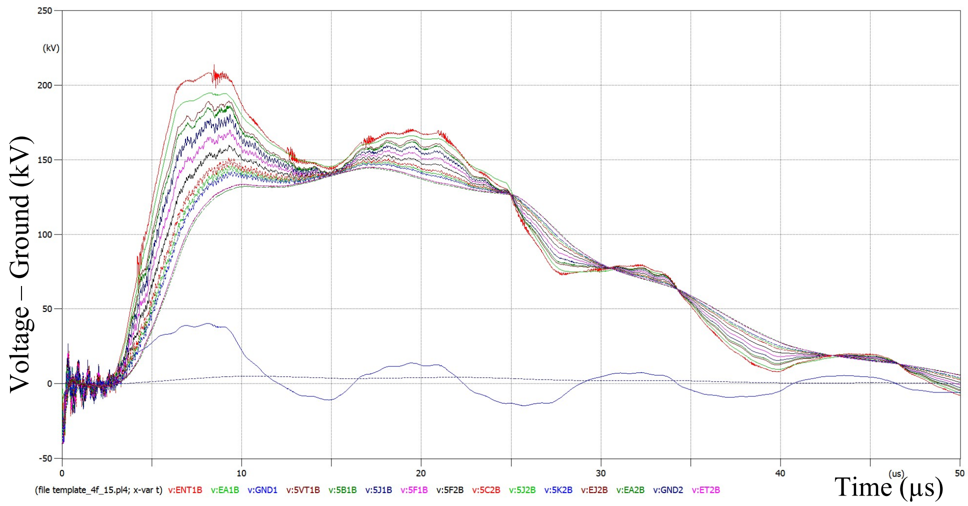


Figure 23-36 Case Study 1, Scenario 4f – 15 m ATP Voltage to Ground Plot

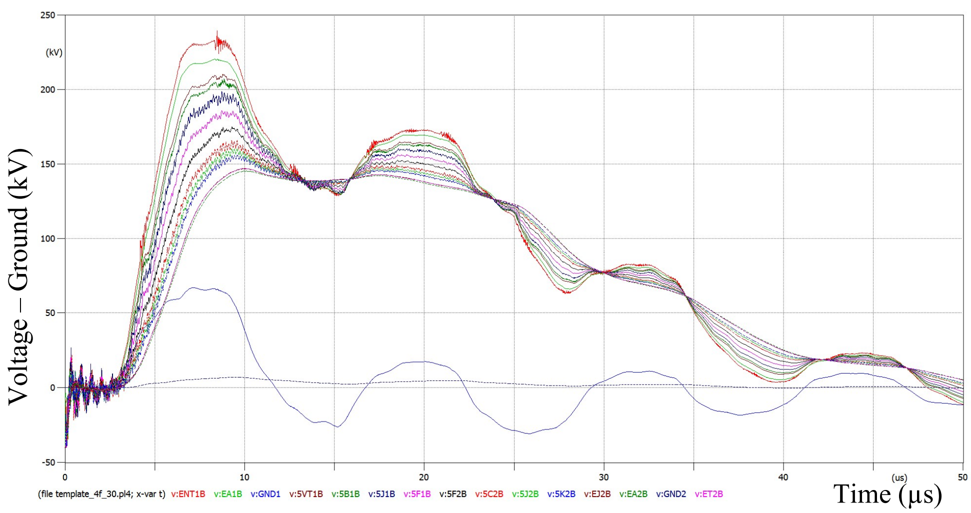


Figure 23-37 Case Study 1, Scenario 4f – 30 m ATP Voltage to Ground Plot

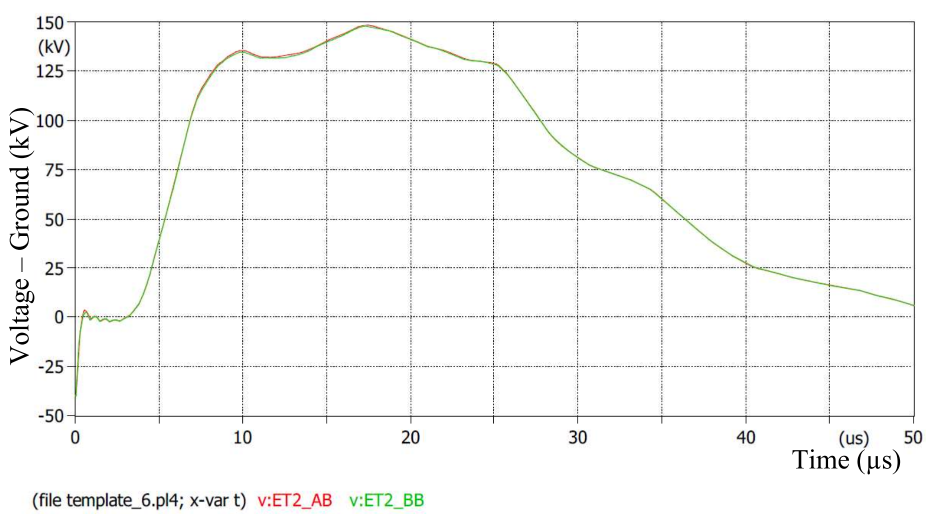


Figure 23-38 Case Study 1, Scenario 5 - ATP Voltage to Ground Plot

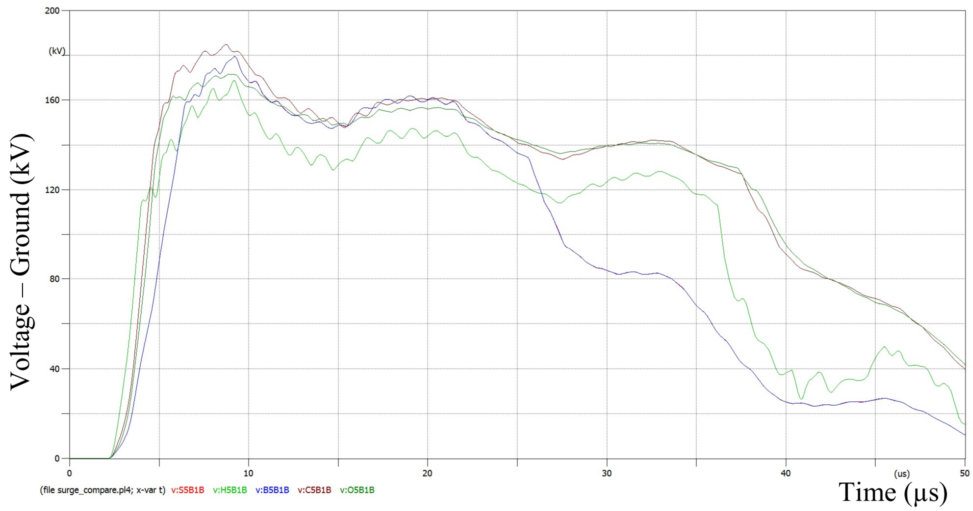


Figure 23-39 Case Study 1, Scenario 6 - CB 5B1 ATP Voltage to Ground Plot

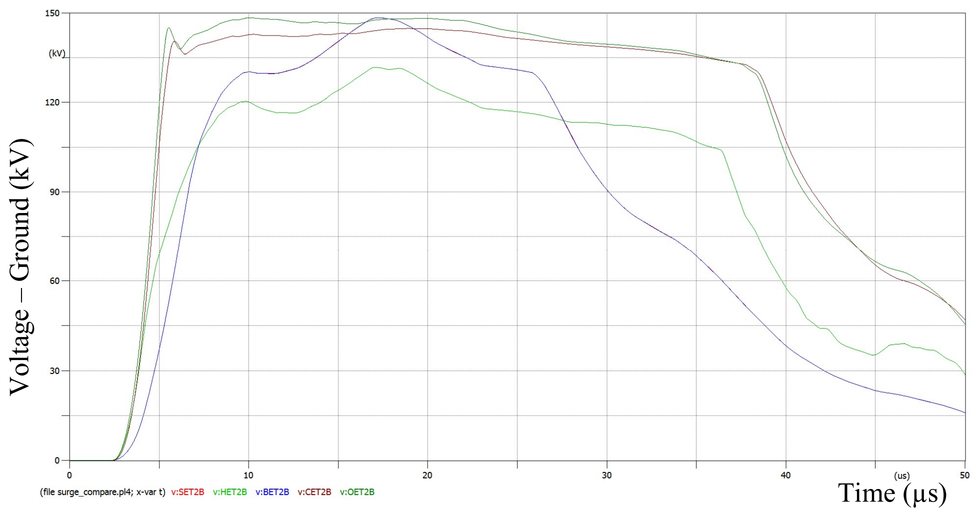


Figure 23-40 Case Study 1, Scenario 6 - Transformer ET2 ATP Voltage to Ground Plot

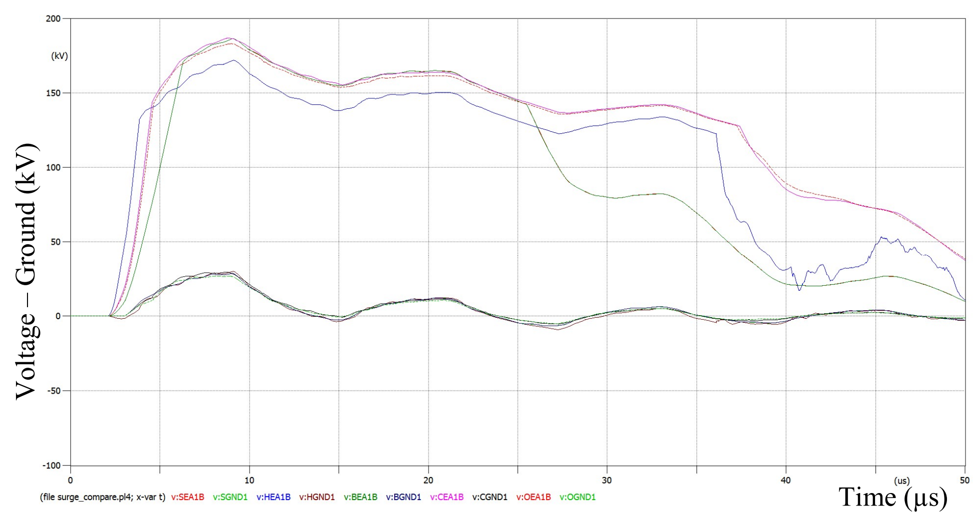


Figure 23-41 Case Study 1, Scenario 6 – Surge Arrester 1 (Station Entrance) ATP Discharge Voltage Plot

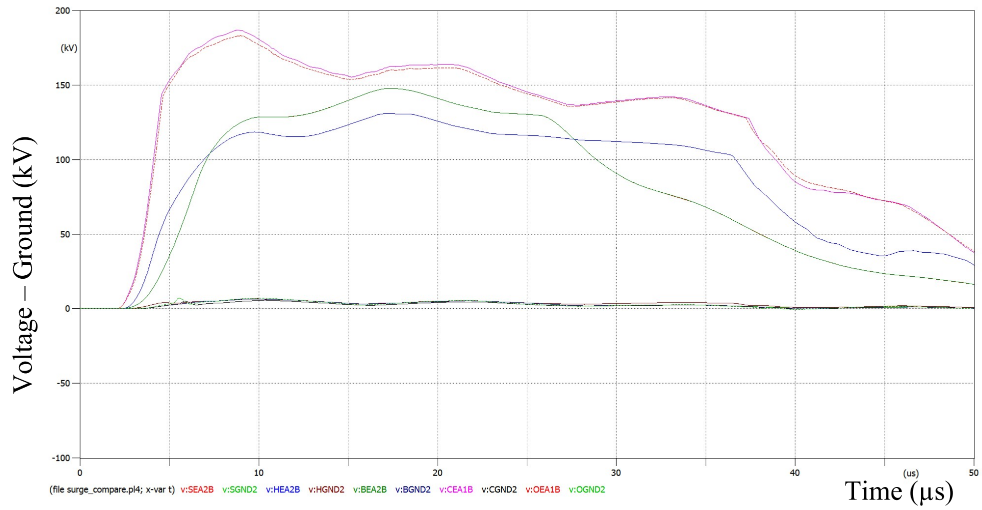


Figure 23-42 Case Study 1, Scenario 6 – Surge Arrester 2 (Transformer 2) ATP Discharge Voltage Plot

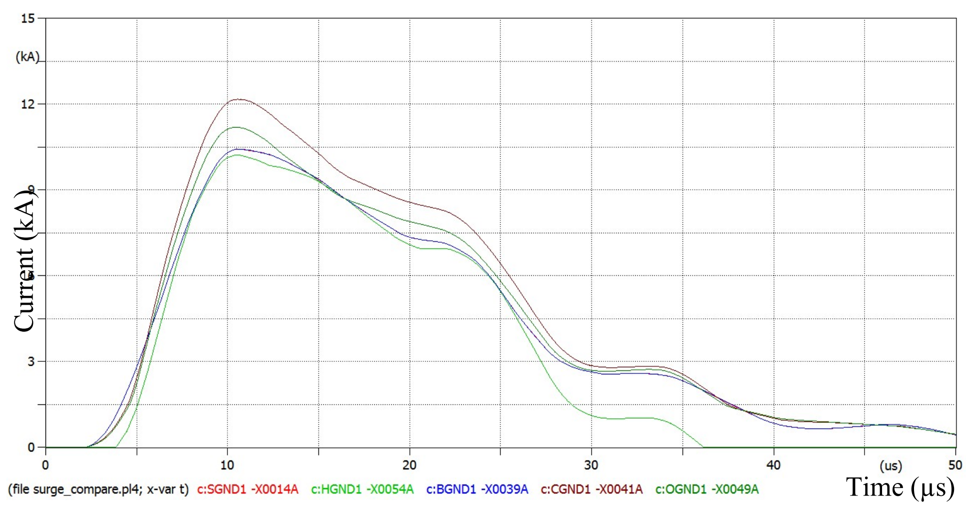


Figure 23-43 Case Study 1, Scenario 6 – Surge Arrester 1 (Station Entrance) ATP Arrester Current Plot

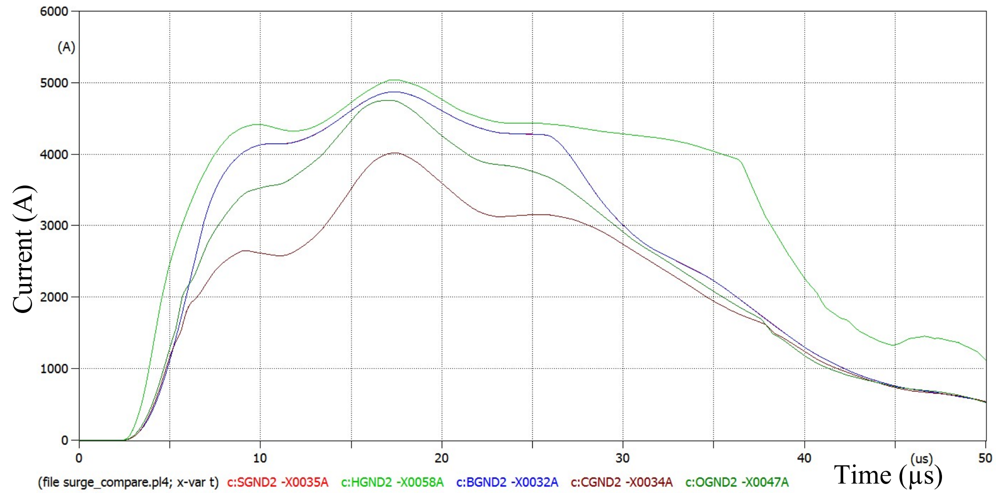


Figure 23-44 Case Study 1, Scenario 6 – Surge Arrester 2 (Transformer 2) ATP Arrester Current Plot

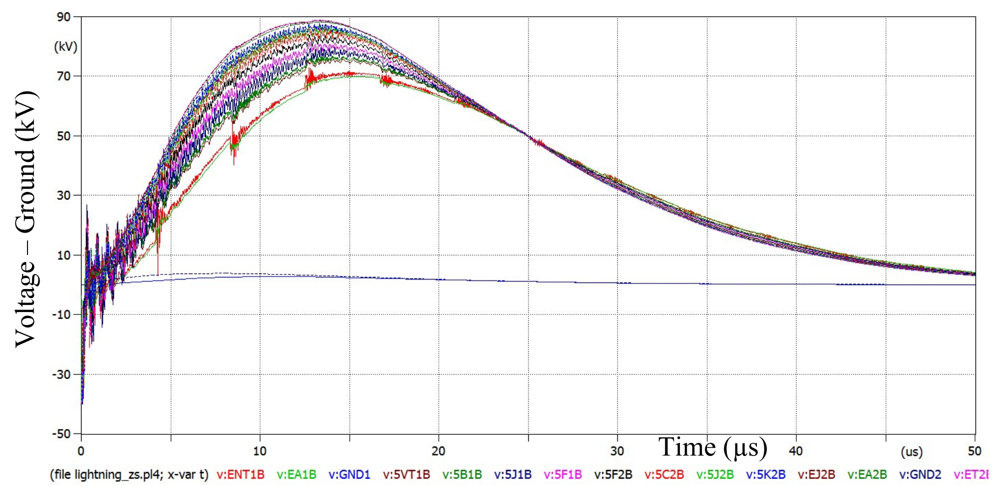


Figure 23-45 Case Study 1, Scenario 7 Station Entrance And Transformer Surge Arrester, ATP Voltage to Ground Plot

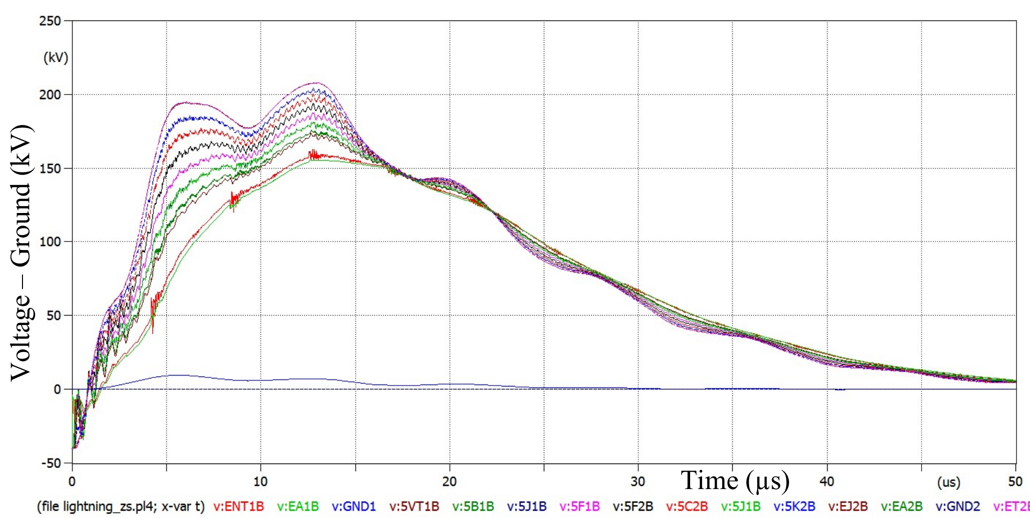


Figure 23-46 Case Study 1, Scenario 7 Station Entrance Surge Arrester Only, ATP Voltage to Ground Plot

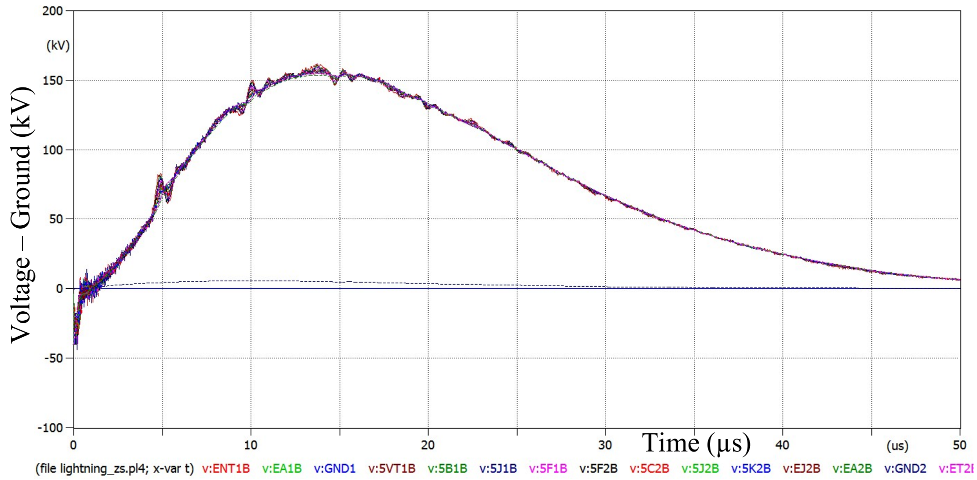


Figure 23-47 Case Study 1, Scenario 7 Transformer Surge Arrester Only, ATP Voltage to Ground Plot

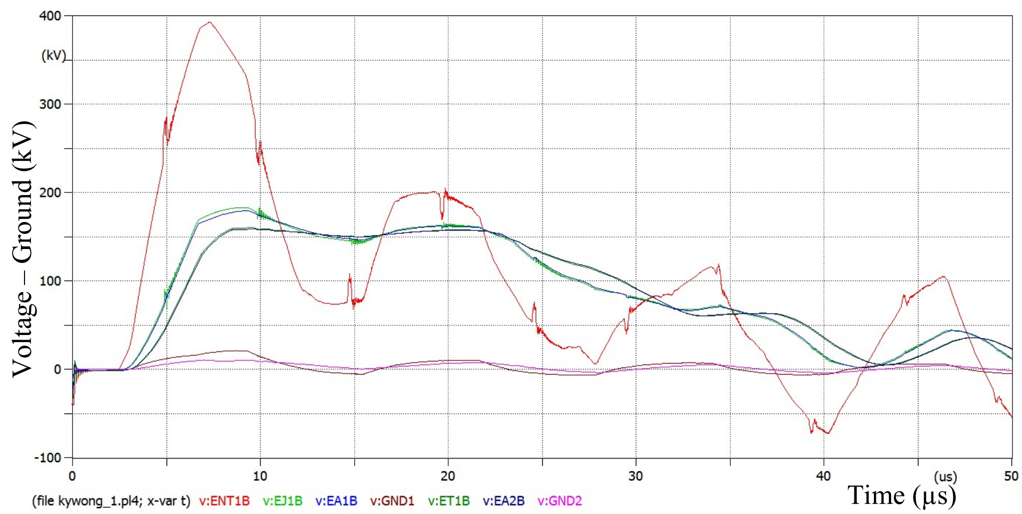


Figure 23-48 Case Study 2, Scenario 1- ATP Voltage to Ground Plot

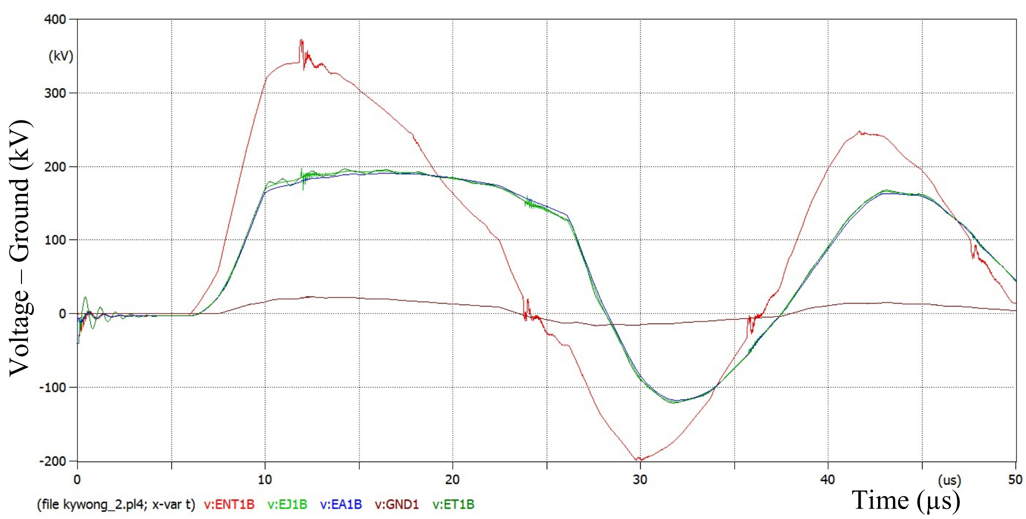


Figure 23-49 Case Study 2, Scenario 2 - ATP Voltage to Ground Plot

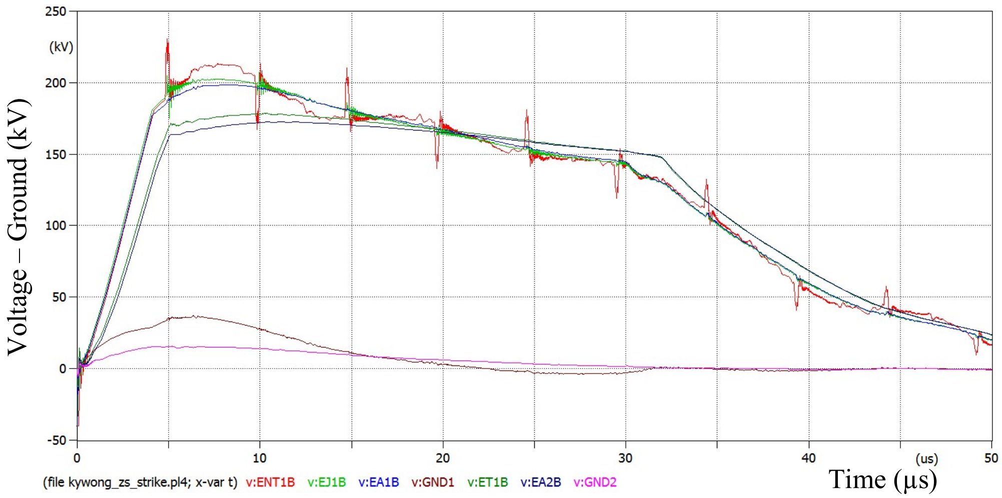


Figure 23-50 Case Study 2, Scenario 3 Station Entrance And Transformer Surge Arrester, ATP Voltage to Ground Plot

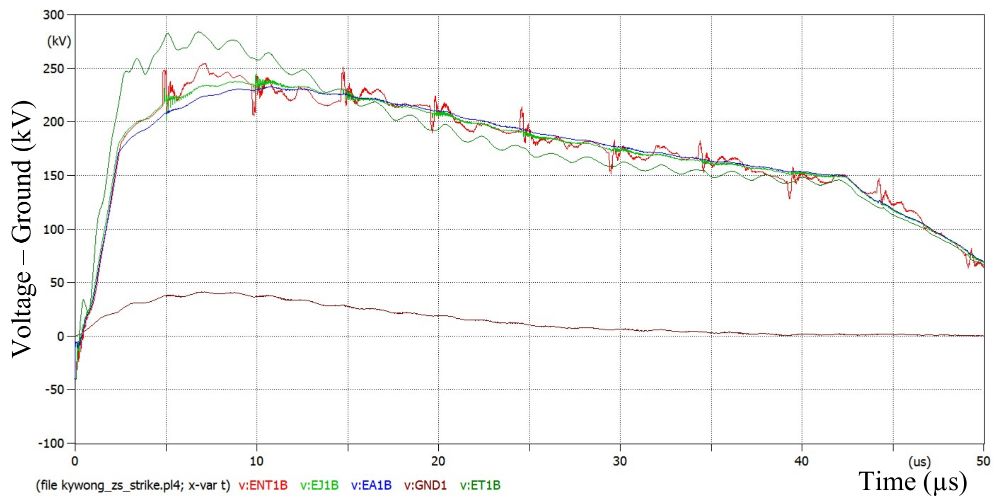


Figure 23-51 Case Study 2, Scenario 3 Station Entrance Surge Arrester Only, ATP Voltage to Ground Plot

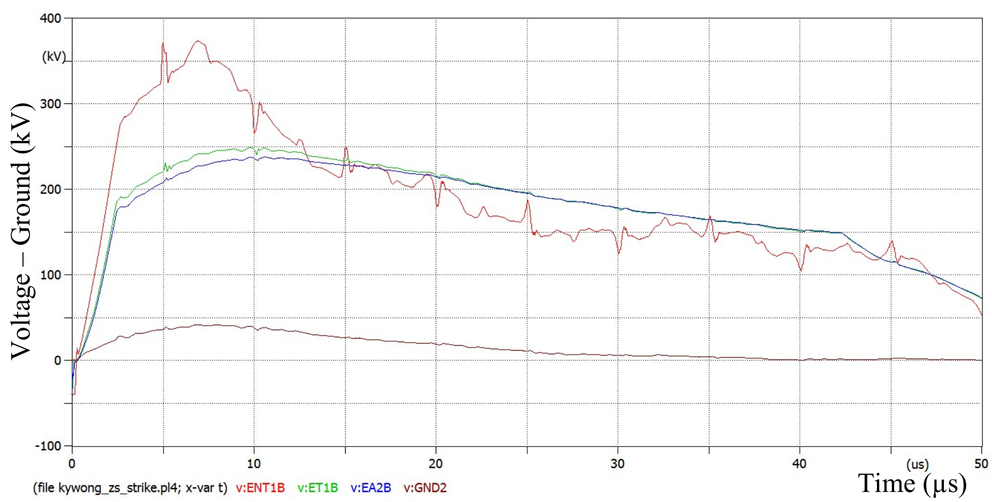


Figure 23-52 Case Study 2, Scenario 3 Transformer Surge Arrester Only, ATP Voltage to Ground Plot

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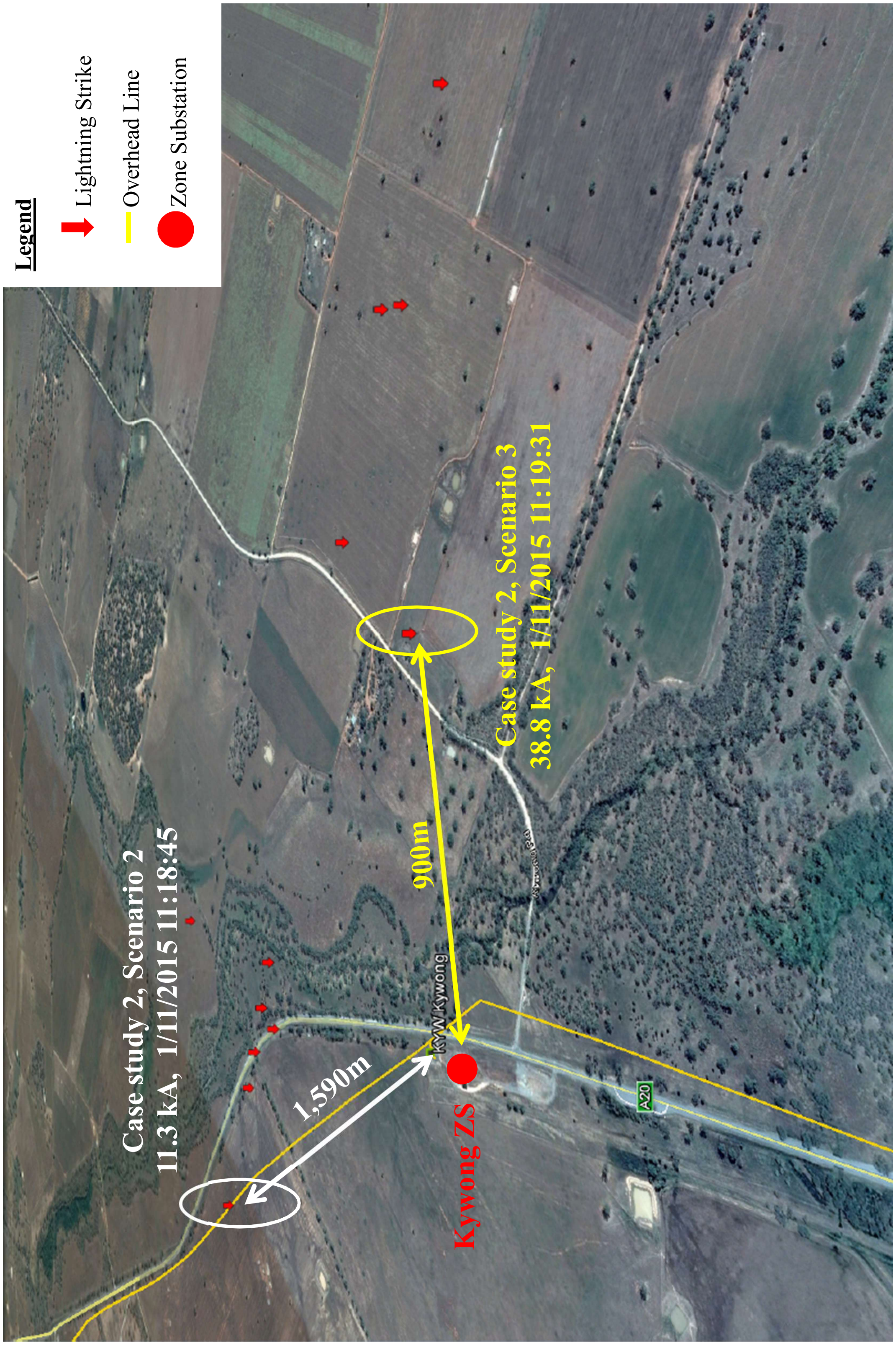

Figure 24-1 Kywong ZS Recorded Lightning Strikes (Google Earth 2013b)