University of Southern Queensland

Faculty of Health, Engineering and Sciences

# Measurement of Electromagnetic Fields in DC Traction Substations

A dissertation submitted by

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in fulfilment of the requirements of

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# Abstract

The effects of exposure to electromagnetic fields have been the subject of much research. The current industry consensus is that EMFs of the non-ionizing radiation type (low to mid-frequency typical of electronic devices and power distribution) have no proven connection with harmful effect in human beings. Even with this extensive research global authorities on health such as the World Health Organisation have taken a stance of "prudent avoidance" and classified EMFs as a Group 2B Carcinogen meaning, "Agent is possibly carcinogenic to humans". Because of this stance limits to EMF exposure have been recommend by the Institute of Electrical and Electronic Engineers (IEEE) and are referenced in Australian Standards.

This research project seeks to continue this research concentrating on the specialist area of DC traction substations. To complete this research the dissertation includes a literature review to investigate previous studies into electromagnetic fields and has applied that research to examining the levels of electromagnetic fields that substation worker may be exposed to, in the more unique environment of direct current (DC) traction substations.

DC traction substations have different characteristics to traditional substations in their highly dynamic power loading and uncommon plant such as rectifier transformers and diode units. The possible magnetic field strength exposure levels have been assessed using measurements taken onsite at in-service substations and by modelling for worst case loading conditions.

Research into this specialty area is beneficial to the industry as it promotes health and safety of a controversial and largely unrecognised topic in an already hazardous occupation.

Low-cost recommendations have been made with consideration to reducing EMF exposure for substation workers. Whilst these recommendations are unlikely to show any immediate health improvements, they will show a compliance to a safety culture in-line with the current industry accepted philosophy of pretend avoidance.

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# Glossary of Terms

**AC** – Alternating Current

**Alternating Current Circuit Breaker (ACCB) –** An electrical switch made to interrupt alternating current flow for protection and control.

**Current Transformer (CT)** – Metering device to measure the flow of current through a busbar or electrical conductor.

**DC** – Direct Current

**Direct Current Circuit Breaker (DCCB**) – An electrical switch made to interrupt direct current flow for protection and control.

**Electromagnetic Field (EMF)** – Invisible area of energy often referred to as radiation in the context of this project associated with the use and distribution of electrical power.

**High Voltage (HV) –** Voltages above 1000V AC RMS or 1500V ripple free DC**.**

**International Commission on Non-Ionizing Radiation Protection (ICNIRP)**

**Section Hut** – Installation with the capacity to remotely make or break traction sections for the purpose of altering feeding arrangements.

**Substation -** Installation of electrical plant for the supply and distribution of electrical power

**Traction Substation** – Substation Installation containing rectifiers with the primary purpose of supplying traction power to rail vehicles.

**Voltage Transformer (VT)** - Metering device for the measurement of high voltage.

**World Health Organisation (WHO)**

# Chapter 1 Introduction

## 1.0 Introduction

Electromagnetic fields (EMF) are a by-product of using electricity. In the modern world most people's entire lives are surrounded by electronic devices, and we are constantly being exposed to the electromagnetic field that those devices and their power sources create. The effect of exposure to electromagnetic fields has been the subject of much research with the generally accepted consensus that EMFs of the non-ionizing radiation type (low to mid-frequency typical of electronic devices and power distribution) have no proven connection with harmful effect in human beings. Even with this extensive research global authorities on health such as the World Health Organisation (WHO) have taken a stance of "prudent avoidance" and classified EMFs as a Group 2B Carcinogen meaning, "Agent is possibly carcinogenic to humans". Because of this stance limits to EMF exposure have been recommended by the Institute of Electrical and Electronic Engineers (IEEE) and are referenced in Australian Standards.

Electromagnetic fields are also capable of interfering or damaging electronic devices. This is especially of concern with devices such as medical implants (pacemakers) or devices designed for safe operation of hazardous equipment.

All devices that use electricity will produce a varying level of electromagnetic fields (EMFs), our dependence on these devices has led to the exposure to electromagnetic emissions being unavoidable in modern times. Surveys conducted by the World Health Organization have demonstrated that for the general population exposure to electromagnetic fields is extremely low typically hundreds of times smaller than guideline levels.

Substations are a known source of increased levels EMF and as such the persons and equipment within them can be expected to be exposed to higher-than-average levels of electromagnetic emissions on a more regular basis (Daily & Dawalibi 1994). Because of this there has been considerable interest and research into the level of EMFs in traditional substations.

In Rail Traction power networks such as that of Sydney Trains power is distributed using nominal 1500 Volt Direct Current. This requires specialised electrical plant and equipment to deliver that power. Being aware of how this specialised plant is generating EMFs is essential in assessing the safety of workers and suitability of sensitive electronic devices used in these substations.

## 1.1 Background information

NSW department of planning and the environment predict the Greater Sydney population to grow to approximately 6.1 million people by 2041. To cope with this ever-growing population existing infrastructure needs to be updated. The Sydney Trains rail network is no exception and is currently in the middle of a major overhaul to modernise and boost services to match the growing transport needs of public transport customers. The program is called More Trains, More Services (MTMS) and is expected to cost the government $5.3 billion dollars and is due for completion in 2027 (Transport for NSW, 2022).

The proposed increase to train services has required an update of the electrical distribution network that is necessary to provide auxiliary power to stations, signalling equipment and, its largest load, the traction supply to power the trains. The electrical component of the MTMS program is called the Power Supply Upgrade (PSU) project and is designed to meet the future power requirements of the increased train services and the higher loading of a new fleet of trains. This period of upgrade provides an ideal opportunity to examine and possibly address the controversial issue of electromagnetic fields being produced in the network's substations.

It can be assumed that the increase in power capacity is going to lead to an increase in EMFs generated within the substations (EPA, 2022). To prepare for the MTMS project an external audit was conducted in 2019 by the Middleton Group with an aim to investigate if Sydney Trains design process incorporates a suitable level of Electromagnetic Compatibility and Mitigation. The Audit was based on the following two problem statements:

1) There is currently a lack of evidence to demonstrate EMC compliance on the Sydney Trains Electrical Network
2) There is currently a lack of evidence to demonstrate that EMC requirements are being addressed in new designs to ensure new work will support the safe running of the network.

A risk assessment conducted after the audit identified 11 actions to be considered to better understand electromagnetic hazards in the networks. From these actions the organisation has implemented administrative controls such as a mandatory warning on pre work briefs prior to substation entry to make persons aware of the presence of electromagnetic fields.

However, no research has been undertaken on the levels of exposure and therefore there is no genuine awareness of the level of risk.

Three of these actions that are outstanding from the audit are:

1) Undertake targeted testing of key sites to understand where the risks are on the network.
2) Based on the outcome of testing, determine if further action required.
3) Develop an EMC capability plan, including the training of staff.

At the same time, the organisation has also had a number of Intelligent Electronic Devices (IEDs), primarily protection relays and programmable logic controllers (PLCs), prematurely failing within substations of the distribution network. One of the suspected causes of these failures is Electromagnetic Interference (EMI) but this hypothesis has not yet been proven.

## 1.2 Project aim

The Aim of this dissertation is to develop a greater understanding of the levels of Electromagnetic Fields being produced by DC tractions Substations in the Sydney Trains Network. The intended outcome of the project is to raise awareness within the organisation on the levels and effects of EMI within substations. The benefit of this is the organisation will save expense on prematurely replacing high cost IEDs and improve safety for substation workers, particularly for persons with implanted medical devices.

## 1.3 Project Objectives

This dissertation will deliver upon the following 5 objectives:

1) Research background information relating to exposure to EMFs and the effect on electronic devices, standards, and regulations regarding exposure to EMFs, testing requirements for equipment being installed in substations and how shielding can be used to minimise the negative effects of EMFs.
2) Research testing current methodologies for the measurement of electronic and magnetic fields. Select and acquire a suitable meter for testing.
3) Modify existing testing methodologies to preform my own testing on several key DC traction substations with measurements based around rectifier transformers and traction plant.
4) Develop a Matlab model capable of simulation EMF exposure levels at substation full capacity conditions using base electromagnetic principles and use measured results as a comparison/ verification tool.

5) Present observations on the likely effect of EMF within substations and Make recommendations on improvements that can be made in substation design to limit the effects of EMF on sensitive electronic equipment.

If time and resources permit:

6) Conduct a sensitivity analysis regarding human exposure to EMFs for staff frequently working inside high voltage DC substations by comparison to current safe exposure limit standards.

## 1.4 Consequence and Ethics

Workplaces such as Sydney Trains have a responsibility to their employees to provide a safe workplace environment. Working in High Voltage substations is already recognised as a high-risk workplace. With so many obvious hazards in a High Voltage location it can be easy to become complacent on the not so obvious hazards such as exposure to electromagnetic fields. This research project aims to identify any locations within the substation that present a high exposure risk as per current standards. It was a condition of undertaking this study within the Sydney Trains network that in the unlikely event locations are found to have an immediate risk to health safety it will be reported to the Sydney Trains Engineering and System Integrity division as soon as possible. If there is a low cost mitigation measure that can be implemented within the time frame of this research project, it will be trialled for testing purposes only but will require engineering design approval before becoming permanent.

## 1.5 Limitations

The intention of the dissertation is an educational exercise to fulfill the requirements of a university engineering program. As such the testing is limited to only a small sample of the Sydney Trains Network. Equipment used has been selected within a self-funded budget. It is hoped that this project will form part of a justification to acquire a company funded budget to further testing on a greater sample of the network with equipment more suitable to this level of testing.

# Chapter 2 Literature Review

An important objective of this dissertation is to research the issues related to Electromagnetic Fields. This literature review aims to define what Electromagnetic Fields are and how they may impact on human safety. As studies on medical effects can take many years this dissertation will not present any new information on this topic but rather aims to present reliable research that has been conducted in this field to justify why further study on electromagnetic fields including this dissertation is warranted. The literature review also aims to identify previous testing experiments that have been conducted to measure magnetic field intensity in substation. Building on the work of others test methodologies allows for an experiment to be modified to suit the purposes of this research more efficiently.

## 2.1 What are Electromagnetic Fields

Static magnetic fields are the space surrounding a permanent magnet upon which a magnetic force or magnetic flux is exerted. Magnetic fields are also generated by a moving electric charge such as the flow of electric current through a conductor. When current flows through a conductor the magnetic field will form in concentric circles forming a closed loop perpendicular to that conductor (Strangeway et al 2022). The strength of a magnetic field is expressed in amperes per meter (A/m). Magnetic fields will increase in strength as current through the conductor increases but will decrease in strength as distance from the conductor increases. The symbol used to express magnetic field strength is H. EMF in a simplified model with a uniform straight conductor magnetic field strength can be expressed as (Strangeway et al, 2022):

$$H = \frac{1}{2.\pi.d} \quad \left(\frac{A}{m}\right). \qquad \textit{Equation 1}$$

Magnetic fields may also be express as magnetic flux density which is expressed by the symbol B using the units tesla (T). Magnetic Flux density accounts for how a material interacts with magnetic fields. Magnetic Flux Density is expressed as:

$$B = \mu_0 H \quad (T). \qquad \textit{Equation 2}$$

Where $\mu_0$ is a constant of the magnetic permeability of free space in H/m given as

$$\mu_0 = 4\pi \times 10^{-7} \ (Hm^{-1}). \qquad \textit{Equation 3}$$

Electric Fields are produced around particles that have an electric charge and are defined as the area around that charge where an effect is felt. Electric fields (E) are measured in volts per meter or Newtons per Coulomb(N/C) (1(V/m) = 1(N/C)). Electric fields are vectors, with a field strength magnitude (E) and the conventional direction is the direction in which the positive charges move. The formula for electric fields is shown as:

$$E = \frac{F}{q}\text{ (V/m).} \qquad \textit{Equation 4}$$

The force of attraction (F) between two particles (q1 and q2) of distance ( r ) apart is calculated by applying Coulombs law:

$$F = k\left(\frac{q_1 q_2}{r^2}\right)\text{ (N)} \qquad \textit{Equation 5}$$

where k is Coulomb's constant:

$$k = \frac{1}{4\pi\varepsilon_0} = 8.987552 \times 10^9 \left(\frac{Nm^2}{C^2}\right) \qquad \textit{Equation 6}$$

$\varepsilon_0$ is the value of free space permittivity and is derived by the relationship between magnetic permeability ($\mu_0$) in free space and the speed of light (c):

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}\text{(m/sec)} \qquad \textit{Equation 7}$$

$$\varepsilon_0 = 8.854187817 \times 10^{-12} \left(\frac{F}{m}\right) \qquad \textit{Equation 8}$$

By combing *Equation 4* and *Equation 5* the Electric Field at a given point of charge (q1 from the point q2) can be described as:

$$E = k\left(\frac{q_1}{r^2}\right) \qquad \textit{Equation 9}$$

This equation shows electric field strength increases with increased charge but will rapidly decrease with distance from source. From this equation it can be stated that Electric Fields will be present as soon as a piece of equipment is energised. Equation 4 shows electric fields do not vary according to loading conditions but rather are dependent on Force and distance. It will be Magnetic Field that will be examined in this dissertation.

Electric and Magnetic fields are complementary to each other. A moving electric field will create a magnetic field, and a moving magnetic field will produce an electric field. Electromagnetic fields describe the combination of electric and magnetic fields as shown in Figure 2.1, where an electric field (Ê) and magnetic field (Ĥ) can be visually represented as perpendicular to each other in the same direction of propagation.

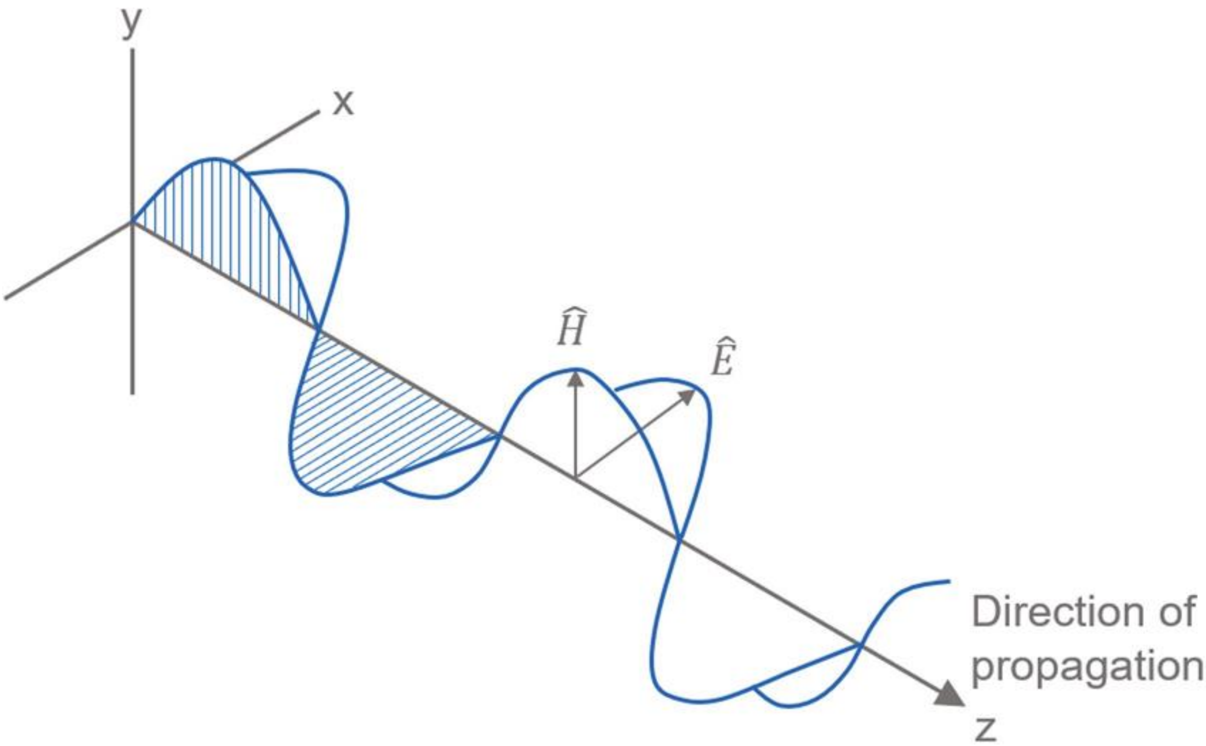


*Figure 2.1 Visual Representation of Complimentary Electric and Magnetic Fields (Keller 2023)*

Electromagnetic fields can be split into different categories depending on frequency. The International Commission on Non-Ionising Radiation Protection (INCRIP) categorises the non-ionisation radiation spectrum as:

*Table 2.1 Categorisation of Electromagnetic Fields by Frequency.*

| Frequency | Designation | Application |
|---|---|---|
| 0 Hz | Static Magnetic fields | Industrial or medical equipment e.g., MRI machines |
| 0 Hz | Static Electric Fields | Energised high voltage Direct current powerlines |
| 1 – 100kHz | Low Frequency | AC electric power supply |
| 100kHz – 300GHz | Radio Frequency | Communication purposes (mobile phones, Wi-Fi radio, tv etc) |

This study is primarily concerned with the extra low frequency electromagnetic fields of the frequency range between 0-3000 Hz, as this encompasses electrical distribution equipment.

Electromagnetic fields will always be present when using electricity, so mitigation rather than elimination is the accepted measure to be taken in adhering to the industry accepted practice of prudent avoidance.

## 2.2 Human Exposure to Electromagnetic Fields

Despite the government bodies world-wide setting classification standards and guidelines, electromagnetic fields continue to be a controversial topic and public concern has been around since the 1960s (Poljak et al., 2003). Public concerns often coincide with uncertainty around new technologies, from Radio Frequency Fields all the way up to most recently the unrolling of the 5G communications network and smart meters, causing enough anxiety and concern within some communities to initiate protesting and even arson attacks on mobile phone towers (Baird, 2022). Because of its controversial nature many studies have been conducted into the medical effect of electromagnetic field exposure on humans with mixed conclusions.

Korbokova's et al. (1972) study in Ukraine's power industry workers reported health effects with symptoms from tiredness, headaches, nausea, to loss of sexual libido affecting the workers. As a result, from this study the Soviet Union implemented guidelines to limit exposure to electric field greater than 5kV/m in the workplace. More recently this study was repeated in Broadbent et al. (1985 to find no correlation between exposure and these symptoms however the effects were more likely linked to the inherent working conditions of power industry workers. There are some people who claim to have a hypersensitivity to EMF's however this cannot be proven.

Whilst some studies suggest there may be links between exposure to low frequency EMFs and increased chance of childhood leukemia (Andolsek, 1998) the World Health Organisation (WHO, 2016) and the International Agency for Research on Cancer have the stance that the studies were inconclusive and require more research. (Mayor, 2011). As the studies do not produce sufficient evidence of a link between EMFs and cancer, EMFs are classified as Group 2B: "Agent is possibly carcinogenic to humans" (Eicholz, 2002). These findings are consistent with Australia's federal government agency responsible for the protection of persons from EMFs, the Australian Radiation Protection and Nuclear Safety Agency (APRANSA). Energy Networks Australia is the national industry body representing Australia's electricity transmission and distribution networks. Their policy statement recommends that energy systems follow an approach of "prudent avoidance" in design and operation of electricity networks to minimise EMF exposure (ENA, 2016).

Modern standards acknowledge the inherent uncertainty in the current scientific data and consequently reduction factor have been applied to acceptable exposure limits that air on the side of caution (ICNIRP, 2010). For the purposes of this dissertation an acceptable level of exposure will be as per ICNIRP recommendations shown in *Table 2.3* and *Table 2.4.*

### 2.2.1 Levels of exposure

In Australia, the accepted exposure limits for electric and magnetic fields are those defined by the international commission on non-ionizing radiation protection. These guidelines were produced to protect human beings from negative short term health effects of electric and magnetic fields. A defining point of the standard is that chronic and long term conditions have not been considered. The ICNIRP point of view is there is no compelling evidence to show a correlation between long term health effects and exposure to electromagnetic fields (ICNIRP, 2010). The Reference levels given by INCRIP are shown below. Table 2.2 shows the reference levels for occupational exposure whilst Table 2.3 shows the reference levels for the general public. Occupational levels of exposure are significantly greater than that of the general public as it is expected that workers in affected industries are trained in the risks and aware of relevant guidelines (APRANSA, 2023). This expectation provides further justification for the current study, as there is a need to improve awareness of electromagnetic fields for the substation workers of Sydney Trains. Identification of gaps in knowledge about occupational exposure to low frequency EMF is listed as a "High Priority" recommendation for further research by the world health organisation.

This report will follow the industry accepted guidelines from ICNIRP reference levels for exposure limitation, therefore, long term health effects is outside the scope of this study.

*TABLE 2.2 Reference levels for occupational exposure to time varying electric and magnetic fields (unperturbed rms values.) (ICNIRP, 2010).*

| Frequency Range $f$ | Electric Field Strength (kV/m) | Magnetic Flux Density B (T) |
|---|---|---|
| 1 Hz - 8 Hz | 20 | $0.2/f^2$ |
| 8 Hz - 25 Hz | 20 | $2.5\ X\ 10^{-2}/f$ |
| 25 Hz - 300 Hz | 5 | $1\ X\ 10^{-3}$ |
| 300 Hz -3 kHz | $5\ X\ 10^2/f$ | $0.3/f$ |
| 3 kHz - 10 MHz | $1.7\ X\ 10^{-1}/f$ | $1\ X\ 10^{-4}$ |

*TABLE 2.3 Reference levels for general public exposure to time varying electric and magnetic fields (unperturbed rms values) (ICNIRP, 2010).*

| Frequency Range $f$ | Electric Field Strength (kV/m) | Magnetic Flux Density B (T) |
|---|---|---|
| 1 Hz - 8 Hz | 5 | $4\ X\ 10^{-2}/f^2$ |
| 8 Hz - 25 Hz | 5 | $5\ X\ 10^{-3}/f$ |
| 25 Hz - 50 Hz | 5 | $2\ X\ 10^{-4}$ |
| 50 Hz - 400 Hz | $2.5\ X\ 10^2/f$ | $2\ X\ 10^{-4}$ |
| 400 Hz -3 kHz | $2.5\ X\ 10^2/f$ | $8\ X\ 10^{-2}/f$ |
| 3 kHz - 10 MHz | $1.7\ X\ 10^{-1}/f$ | $2.7\ X\ 10^{-5}$ |

Additionally, ICNIRP (2009) has made recommendations regarding persons with implanted medical devices such as pacemakers should avoid locations where magnetic flux density exceeds 0.5mT.

There is currently no published standard in Australia for limiting human exposure to Static Electric or Magnetic fields. The AS 62226 series is reproduced from the IEC and describes how to test for exposure, but dose not impose a limit. The Australian standards do however reference international guidelines published by ICNIRP (2009) and endorsed by the world health organisation.

Given the current accepted scientific knowledge could not show any detrimental effect of magnetic field a precautionary restriction of 200mT based on whole of daytime weighted exposure is recommended with a ceiling exposure of 2T as shown in *Table 2.4.*

*Table 2.4. Limits of exposure to static magnetic fields. (ICNIRP, 2010).*

| Exposure Characteristic | Magnetic Flux Density |
|---|---|
| Occupational | |
| Whole workday (time-weighted average) | 200 mT |
| Ceiling Value | 2 T |
| Limbs | 5 T |
| General Public | |
| Continuous exposure | 40 mT |

## 2.3 Electromagnetic Compatibility

The concern of electromagnetic fields is not limited to their effect on humans, interest has also been raised on how they may be detrimental to the normal operation of electrical equipment. Electromagnetic compatibility is the ability for a device to operate unaffected by electromagnetic fields in its working environment. Substation are considered an area prone to a variety of electromagnetic interferences. With modern substation incorporating becoming more dependent on microprocessor base devices, EMF vulnerability is of particular concern. The susceptibility of electronic devices to electromagnetic interference has been well established (Zivic et al 2015) as such, the selection of equipment with appropriate levels of immunity is vital to operating a reliable substation. IEC 61000 (and AS 61000 which is produced as a direct copy of IEC) particularly part 6.5 relates to the immunity requirements of electrical equipment for power station and substation environments. This standard defines the test procedures required to ensure EMC regarding emission and immunity of devices that manufactures must undertake before products are sold.

Figure 2.2 below shows a typical 33kV Bus Section embedded with sensitive electronic devices in the form of numerical protection relays and Programable Logic Controllers used for the critical function of supervision and control of the high voltage switchgear.


*Figure 2.2 Typical Sydney Trains 33kV GIS Bus Section*

## 2.4 Mitigation Measures for Electromagnetic Fields in Substations

In San Sequedo's et al (2007) paper, research was conducted on methods of reducing magnetic field emission levels in substations focusing primarily on optimization of conductor arrangement and magnetic screening. This research examined a scenario where there were three conductors per phase and found by optimizing conductor arrangement shown as arrangement III.3 in figure 2.3 conductor arrangements a reduction of 87% intensity in magnetic fields were measured. This ideal conductor arrangement bunches the conductors in groups of phases whilst also rolling the relative position of phases in each bunch.

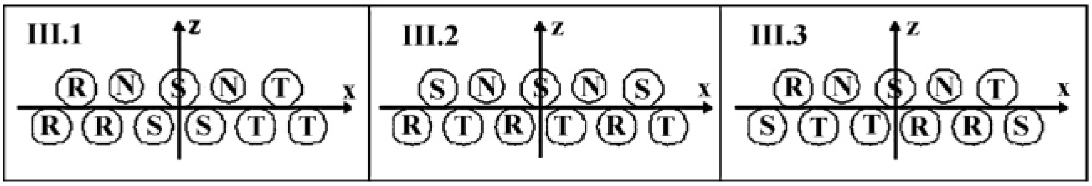


*Figure 2.3 Different Arrangements of Three Phase Conductors for Experimentation (Sequedo, 2007)*

Shielding of conductors has also been proven as an effective mitigation measure to lower magnetic fields in substations. This method is of particular interest as it is relatively low cost and can be easily retrofitted to existing substations. From experimentation with different metal in different configurations Aluminium and Copper screens were found to be the most effective materials for screening magnetic fields. Table 2.5 below shows the results of using different materials as screens.

*Table 2.5 Effectiveness of Different Materials used to screen EMF's (Sequedo, 2007)*

| Material used as screen (thickness) | *B* (μT) | % |
|---|---|---|
| Without shield | 53.53 | 100.0 |
| MuMetal (0.5 mm) | 53.26 | 99.5 |
| FeSi (0.5 mm) | 52.86 | 98.8 |
| MuMetal (0.5 mm) + FeSi (0.5 mm) | 51.06 | 95.4 |
| FeSi (0.5 mm) + MuMetal (0.5 mm) | 50.98 | 95.2 |
| Fe (2 mm) | 36.82 | 68.8 |
| Fe (2 mm) + MuMetal (0.5 mm) | 36.03 | 67.3 |
| Fe (2 mm) + FeSi (0.5 mm) | 35.07 | 65.5 |
| FeSi (0.5 mm) + Fe (2 mm) | 34.65 | 64.7 |
| MuMetal (0.5 mm) + Fe (2 mm) | 34.39 | 64.2 |
| MuMetal (0.5 mm) + Al (2 mm) | 28.55 | 53.3 |
| Al (2 mm) + MuMetal (0.5 mm) | 27.54 | 51.4 |
| Cu (2 mm) + MuMetal (0.5 mm) | 26.85 | 50.2 |
| Al (2 mm) + FeSi (0.5 mm) | 23.16 | 43.3 |
| Al (2 mm) | 22.47 | 42.0 |
| FeSi (0.5 mm) + Al (2 mm) | 21.74 | 40.6 |
| Fe (2 mm) + Al (2 mm) | 21.36 | 39.9 |
| Fe (2 mm) + Cu (2 mm) | 20.72 | 38.7 |
| Al (2 mm) + Fe (2 mm) | 20.11 | 37.6 |
| FeSi (0.5 mm) + Cu (2 mm) | 20.32 | 38.0 |
| Cu (2 mm) | 19.77 | 36.9 |
| Cu (2 mm) + FeSi (0.5 mm) | 19.55 | 36.5 |
| Cu (2 mm) + Fe (2 mm) | 19.52 | 36.5 |
| MuMetal (0.5 mm) + Cu (2 mm) | 18.07 | 33.8 |
| Al (2 mm) + Cu (2 mm) | 16.24 | 30.3 |
| Cu (2 mm) + Al (2 mm) | 17.25 | 32.2 |
| Cu (2 mm) + Fe (perpendicular 10 cm plates) + Al (2 mm) | 14.62 | 27.3 |

This research can be directly applied to the configuration of the low voltage cables between the rectifier transformer and diode unit in typical Sydney Trains traction substations. These cables are configured using multiple conductors per phase in straight lines as per configuration III.1 in Figure 2.3 conductor arrangements. Experimentation showed this to be the worst configuration for mitigation of magnetic fields. Conductors are also currently not shielded in any way, so this presents an ideal opportunity to make improvements pending test results.

## 2.5 TESTING STANDARDS

Australian Standard AS/NZS 61786.1:2021, Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100kHz with regards to exposure of human beings identified crucial elements to testing procedures. Aside from general environmental factors the standard goes into specific details that helped to select the required equipment for this dissertation experiment.

Magnetic fields may be significantly altered by ferrous objects (AS 61786 annex D). During short term measurement a magnetic field meter can be held in the hand without significant impact on the magnetic field. As the desired experiment will require longer readings a non-ferrous support will be required for the meter to not interfere with the readings.

A three-axis instrument is recommended (5.8.1). As magnetic fields exist in a three-dimensional space a three-axis meter is required to detect the field along three mutually orthogonal directions. To obtain the resultant magnetic field ($B_r$) the meter sums the value from the square of each axis (Bx By Bz) and take the square root. As per equation 10 below.

$$B_r = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad \text{Equation 10}$$

Measurements of magnetic fields near power lines should be correlated with load currents (AS6178) for the determination of the largest resultant magnetic field. This theory will also be applicable to the dynamic loading of traction supplies.

A more precise way to assess human exposure to magnetic fields is determined by wearing meter capable of data logging whilst conducting work activities.

## 2.6 Literature Review Conclusion

This literature review has shown that due to the controversial and divisive nature of the topic there has been extensive research into the effects of electromagnetic fields. Some researchers to claim that have the potential to cause long term harm such as cancer to exposed humans but decades of research have failed to produce a direct link or evidence that electromagnetic fields can affect biological processes. The current view does however, accept the uncertain nature of electromagnetic fields, and as such bodies such as ICNRIP have taken a conservative approach when publishing acceptable exposure limits. A clear knowledge gap exists in the unique industry concerning electromagnetic field in traction substation which this dissertation endeavours to address.

# Chapter 3 Methodology

## 3.0 Overview

Objective three of this dissertation is to develop a testing procedure for the measurement of Electromagnetic fields based around the traction equipment. This has been chosen as literature review has shown there is already extensive testing of the more common AC equipment found in the majority of power networks. A knowledge gap exists in how equipment used in traction supply rectification produces EMFs is a potential hazard to persons and equipment in the Sydney Trains network.

The aim of this experiment component is to design and implement a repeatable measurement process to take similar reading at a minimum of three different substations throughout the network. It is expected that the biggest contributing factor to EMF levels will be the power loading of the rectifiers. This will be a limiting factor on measurements as the power drawn on rectifiers is defined by trains running in the system at the time. As train running will not be within the control of the experiment the project will endeavour to overcome this limitation by developing a mathematical based model using Matlab Simscape environment in later parts of this dissertation.

Energy Network Associations EMF management handbook recommend that calculation and modelling are the preferred method for the assessment of magnetic fields involving simple elements, however due to the complex nature of DC traction substation a measurement based experiment will be more suitable to locate problem areas and results can be extrapolated for maximum loading scenarios.

## 3.1 Background on Sydney Trains Traction network

The Sydney Trains electrical distribution network is broken down into Bulk Supply Points (BSPs), Distribution Feeders, Distribution Transformers, and traction distribution. Power is imported onto the network at BSPs by various network providers. The network has BSPs at 132 kilovolts (kV), 66kV, and 33kV. Distribution transformers at situated around the network to transform voltage from 132/33kV, 66/33kv, 66/11kv and 33/11kv. 11kV feeders are used to provide power to stations and signalling locations via pole mounted and pad mount transformers. 66kv and 33kV feeders are used for traction substations where a rectifier transformer is used to covert three phase nominals (i.e., 66kV or 33kV) into six-phase 600-Volt (V) AC. The 600V AC is fed into a diode unit which converts the 12-pulse AC to 1500V DC and is used to power the trains via a DC distribution network.

Traction Substations vary on size and equipment depending on operational needs in the specific location. The simplest of traction substations in suburban Sydney consists of:

The Protection / SCADA / Aux systems required to monitor and control the equipment.

The High Voltage components are show in Figure 3.1.1 consisting of:

- Two 33kV bus sections, including a Bus-Tie.
- Single 33kV feeder into each bus section.
- Single 5MW rectifier off each bus section (one duty/ one back up).

And the 1500V DC components are shown in Figure 3.1.2 consisting of:

- Single or Dual 1500v DC bus sections.
- Incoming rectifier DCCB for each rectifier.
- Four 1500V DC feeder DCCB (one for each track in each direction).
- Negative Reactor
- Harmonic Filter

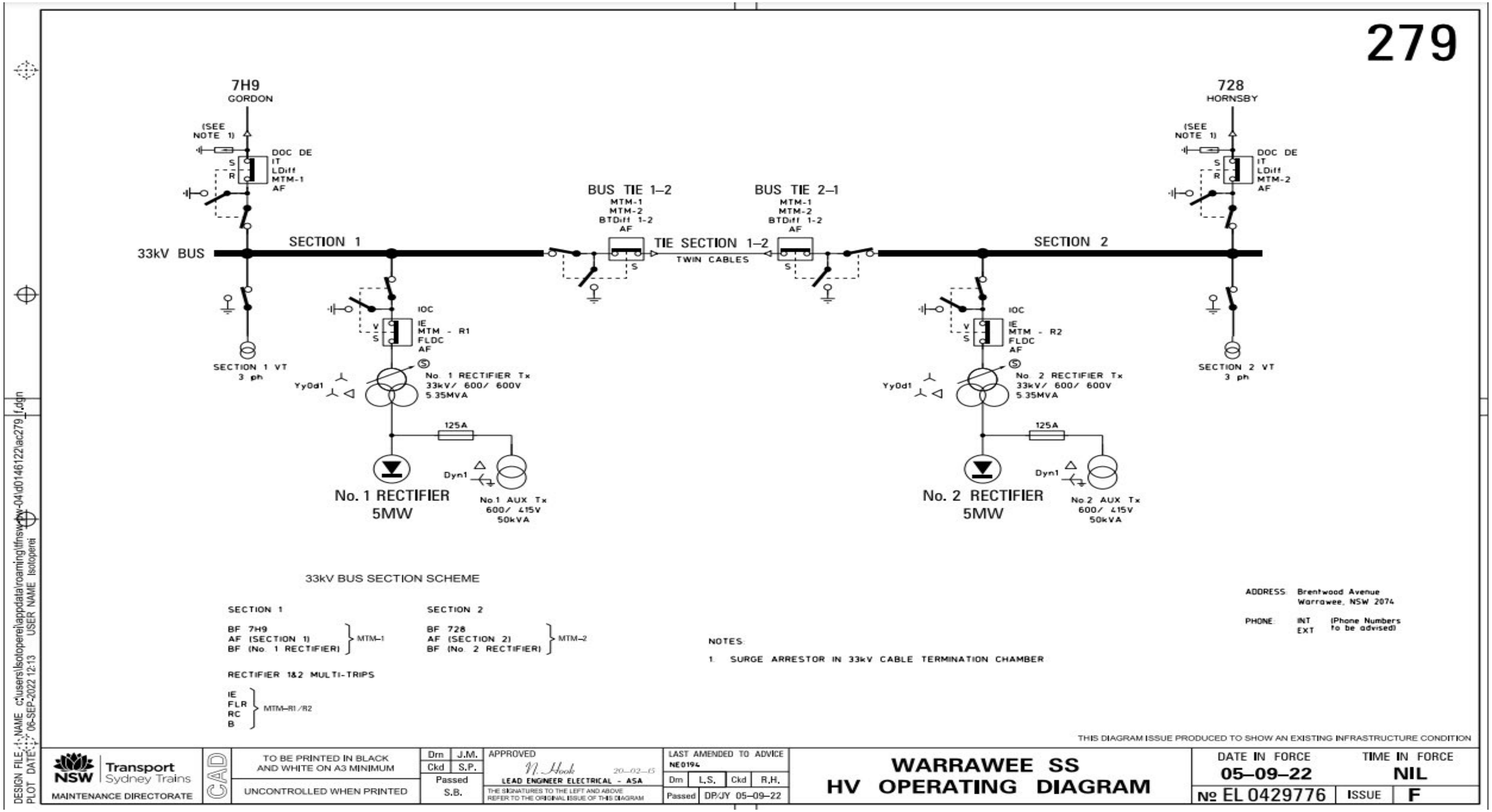


*Figure 3.1.1 Example of Simple Substation HV operating diagram.*

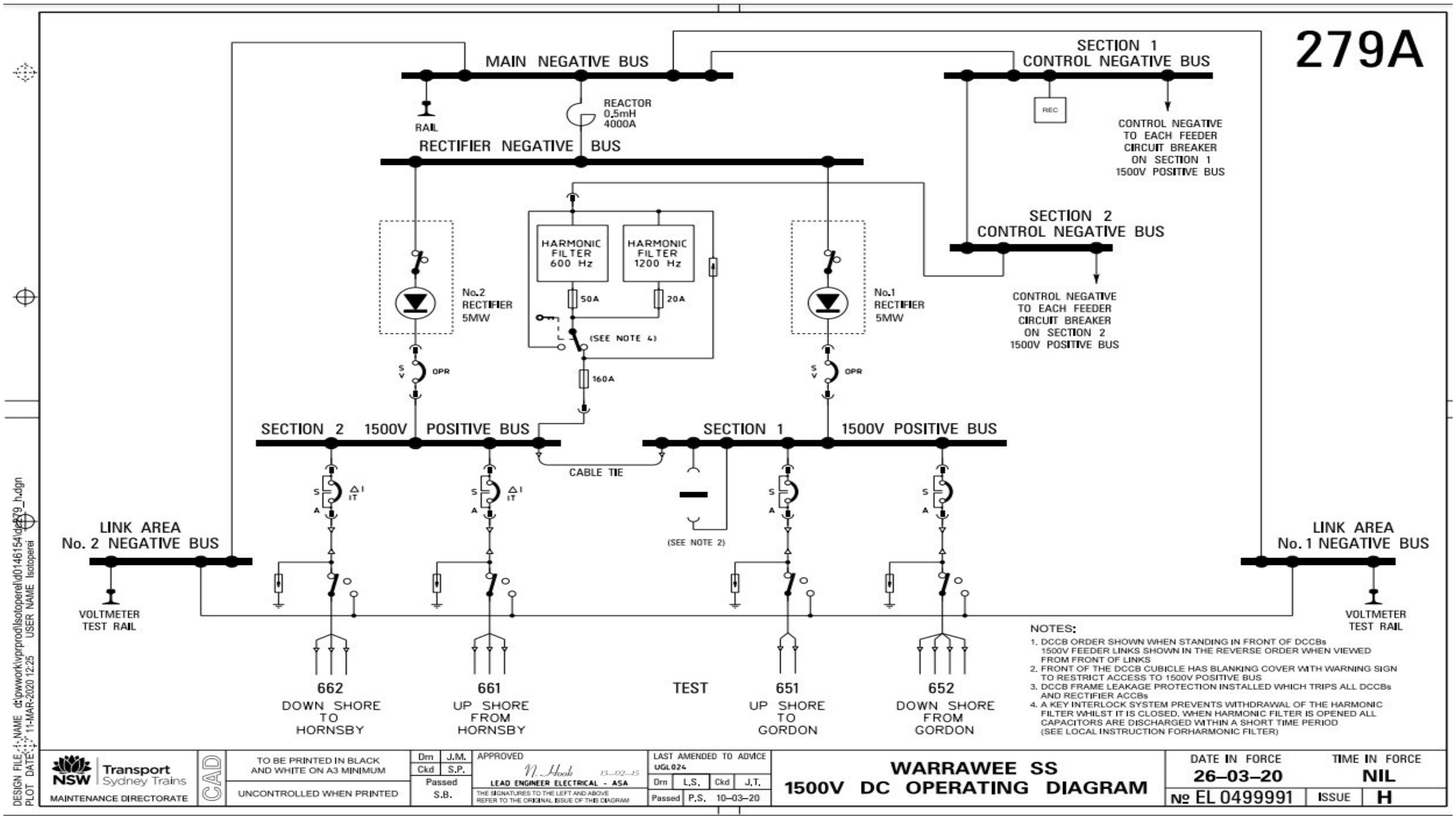


*Figure 3.1.2 Example of Simple Substation HV operating diagram.*

*Jared Saul*

*Student Number:* [redacted]

*OCT 2023*

Maintenance staff are routinely required to work in substations to maintain a reliable network. These maintenance activities are often around the vicinity of in-service equipment due to the nature of maintaining an operational transport network. The only current control for mitigating exposure to Electromagnetic fields in a substation is a mandatory warning as seen below in *Figure 3.1.3*. The warning it to ensure workers are aware of the presence of electromagnetic fields and must be acknowledge by workers before entering a high voltage location. No testing has yet been conducted to quantify the intensity of electromagnetic fields in substations.

**Pre-work Briefing** *cont.*

Participant Acknowledgement

**All incidents and injuries must be reported to the workplace supervisor (Line Manager) and**

*Briefer to tick each item below that is applicable and rule a line through those that are not applicable.*
***NOTE:*** *Workers are to question the Briefer if they don't understand any part of this briefing.*
All workers listed below acknowledge that they:

- ☐ have been inducted to the workplace
- ☐ hold the applicable and current certificates of competency, trade licence and/or induction record e.g. Construction Industry Induction
- ☐ must wear the appropriate Personal Protective Equipment (PPE)
- ☐ have been informed of the requirements of the electrical permit (if required)
- ☐ have been made aware of the Electro Magnetic Field (EMF) hazard(s) to medical implants; pacemaker/implantable cardioverter defibrillator/embedded hearing implant etc. before entering a substation
- ☐ have been briefed on the SWMS/SWIs/documented safe work practice for the job
- ☐ have been instr
- ☐ are free from th
- ☐ have been mad
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*Figure 3.1.3 Extract from Sydney Trains Pre-Work Briefing form.*

## 3.2 Expected outcomes and Benefits

Whilst the substations in the Sydney Trains distribution network are constructed to be similar in electrical design and equipment used, the physical layout and power loading conditions can vary dramatically depending on physical location of each substation. The measurement component of this thesis report will aim to identify possible areas of high EMF exposure. When the areas of high exposure have been located, mitigation measures can be explored and recommended. If a low-cost solution can be implemented in the time frame of this project new measurements will be taken to verify any improvements. With validated evidence of improvement, a future project will be presented to Sydney Trains to implement mitigation measures across the entire network improving safety for staff and equipment.

## 3.3 Data collection by measurements

In the case study completed by Fontgalland et al. (2020), the substation where measurements were taken were under a relatively static power loading. The testing procedure involved taking many measurements from 731 different points in the substation to map out an exposure levels across the entire substation. This method of testing would not be as effective in a rail traction distribution substation as loading is very dynamic fluctuating greatly depending on trains running in the section. In this research project, the aim will be to take magnetic field measurements over a period of time from only a couple of significant points and compare to power consumption of the rectifier at the given time. The outcome of this style of testing will allow for further extrapolation of results in the simulation model phase to estimate exposure levels at substation full loading conditions. As stated in AS/NZS 61786.2:2021 the key to acceptable results in measurements is repeatability, this experiment aims to improve validity of result by having multiple locations of the same measurement carried out under similar conditions.

The locations that have preliminarily been selected for testing as shown in figure 3.3.1 are:

1. Rear of rectifier diode cabinet.
2. Side of rectifier diode cabinet. This location is where the DC positive cables leave the rectifier cubicle to transition onto DC bus via rectifier DC circuit breaker (DCCB).
3. Rear of 33kV AC Gas Insulated Switchgear (GIS).
4. Front of GIS Panels. This is where the protection relays and control IEDs are located.
5. Front of DCCB panels
6. Administration room.
7. Transformer Yard under 600v AC cables.
8. Transformer Yard 33kV Cable entry.

If preliminary results find these locations are not suitable or there is more ideal location the testing positions will be amended for final report.

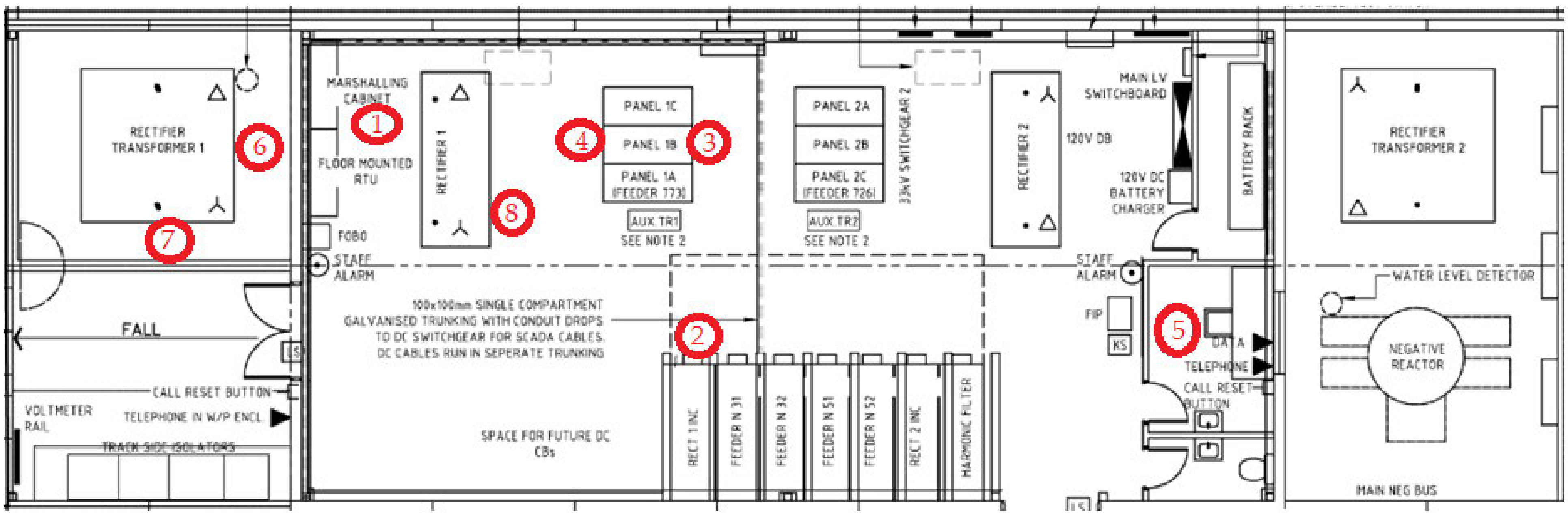


*Figure 3.3.1 Ideal testing locations.*

Locations chosen are centred around the equipment that is more unique to rail distribution substations and hence less research has been carried out.

Location one and six are expected to be the area of highest magnetic field levels. These locations have several of the risk factors associated with magnetic fields identified by the research of Segundo et al. (2007). These locations are where the 6-phase AC cable transition from the transformer output and enter the diode cubicle at 600V AC phase to earth nominal voltage. The low voltage by ohms law directly translates to a higher current flow which as discussed previously intensity of magnetic fields are directly proportional to current flow. These cables are relatively low determined by the diode units cable termination arms and are run in unscreened cables. Phases are spaced close together and run in straight lines from the rectifier transformer (i.e., not twisted in a way in which each phase partially cancel out the other two phases).

Location seven will give an indication of Magnetic Fields produced on the 33kV side of the rectifier transformer. Cables are installed in a manor to minimise the distance where individual phases are not twisted and the inherent shielding of the metal clad switchgear is likely to minimise magnetic fields in this location.

Location three and four have been chosen to show the intensity of magnetic fields in the vicinity of where the protection relays and control IEDs are located. Sensitive electronic equipment can be damaged by electromagnetic fields. Measurements from this location can be used to ensure compliance with manufacturers specifications regarding electromagnetic compatibility of devices.

Location five It is not expected to measure levels of magnetic fields above that of ambient. This is the area designed for workers to spend a significant amount of time it will be included as a control for testing.

Location eight and two have been selected as this location is where the DC positive cables leave the rectifier cubicle to transition onto DC bus via rectifier DC circuit breaker (DCCB). Literature review has shown there has been little research on magnetic fields in regard to high voltage dc equipment. Measurement around these cables will give the highest current path before current is divided between separate feeders via the DC Busbar. As these cables are DC with cable screens earthed on one side it is expected to not have significant magnetic fields in this location.

An important aspect of this research is to relate magnetic field measurements back to power loading of the rectifier. To do this, a power analyser will be installed on the rectifier to measure currents and voltage for comparison. For ease of installation power measurement will be taken off the AC high voltage side of the rectifiers utilising the protection current transformers (CT) for currents and the bus bar voltage transformer (VT) for voltage measurements. The power analyser will have Clamp on CT and magnetic Voltage probes so it can be installed without interfering with existing wiring. An example of meter connections is shown in Figure 3.3.2 below.

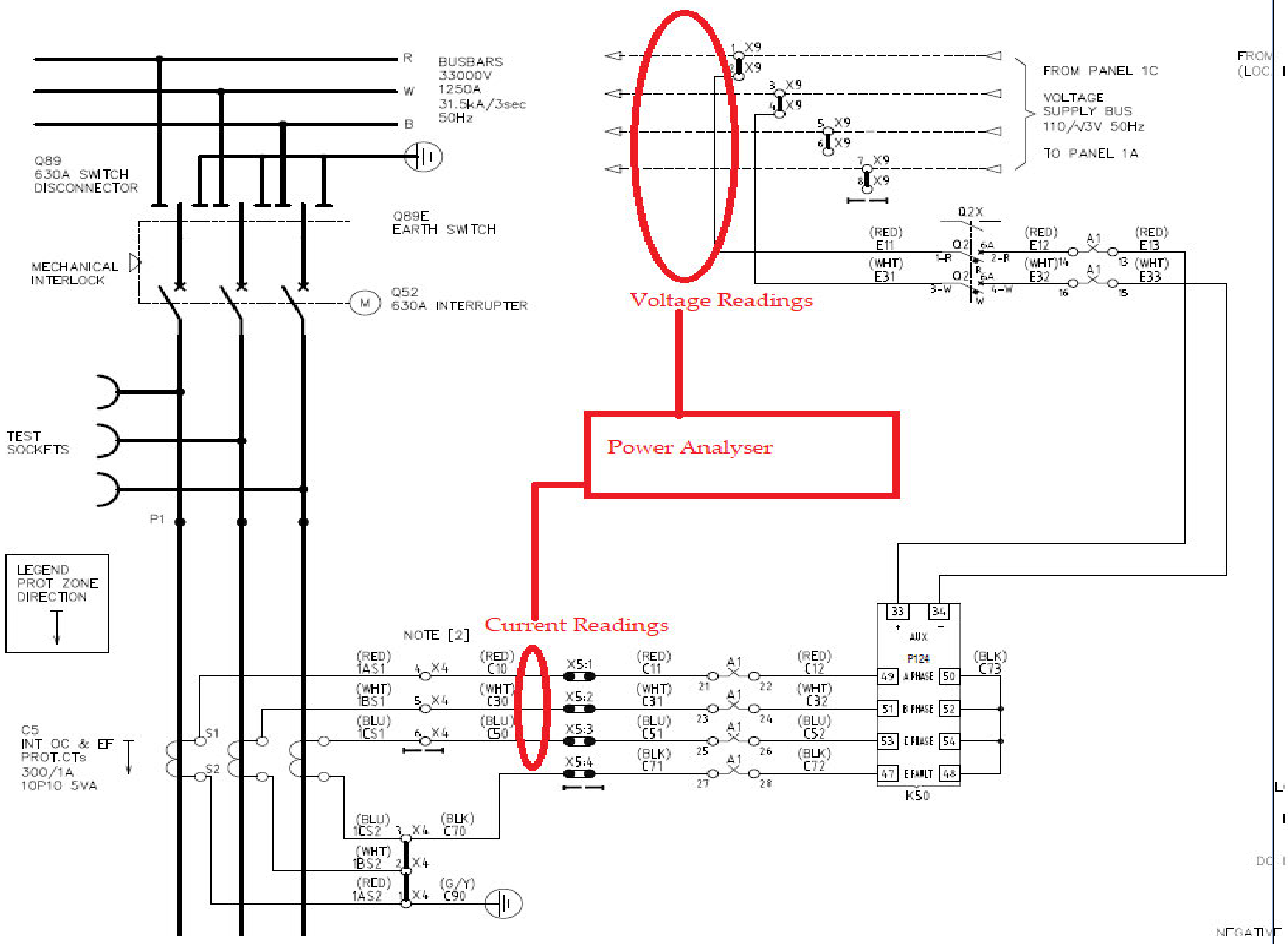


*Figure 3.3.2 Power Analyser Connection.*

It is expected that direct correlation will be evident between the power consumption of the rectifier and the EMFs measured. If feasible, measurements will be taken when energising and de-energising the rectifier as the literature review showed "inrush" conditions to be one of the biggest contributors to EMI in substations. Switching operations will be dependent on operational feasibility.

## 3.4 Meter selection for measurements

To collect data on EMFs being produced in DC Traction Substations an EMF Meter was required to be sourced. As there was a broad selection of commercially available meters the selection was made on the basis of 4 criteria. The criteria were in order of importance:

1) Financial Cost. As this is an educational endeavour funded primarily by myself cost was an important criterion and was limited to a budget of $500.
2) Data logging functionality. The capability to record large amounts of data would allow for the easy comparison to loading conditions. This would be beneficial to the modelling component of this research project.
3) Range. The ICNIRP guidelines for limiting the exposure to time-varying electric and magnetic fields defines the exposure limit at 50Hz as 200µT for general public and 2000 µT Saunders et al, (2010) for occupational exposure.
4) Frequency Response. The meter would be required to measure at the fundamental frequency of 50Hz. The 12-pulse rectifiers used by Sydney Trains also have a strong 11th and $13^{th}$ harmonic component (ASA, 2013) in the acquisition stage it is still unknown what effect this will have on the readings so a frequency response of greater than 650Hz would be ideal.

The three meters compared were the Lutron EMF-828, Hioki Magnetic Field HiTester FT3470-51 and the Tenmars TM-192D as per Table 3.1 below.

The meter selected to carry out field testing in the case study was the Tenmars TM-192D. This meter was able to provide the data logging capability within the full expected frequency response range of AC components, up to the prescribed exposure limit for the general public. For the DC component whilst some smoothing is carried out at the rectification stage there is still expected to be a significant AC component to the "static" magnetic fields. (Doll 2001). The Tenmars TM-192D meter gave the best compromise of features within budget that will allow for the satisfactory completion of the objectives of this research project.

The Hioki was a superior meter and would have allowed for the measurement up to the occupational limits and frequency bandwidth to 0 Hz. The cost of $6530 made it unaffordable for this self-funded case study however this research will be used as a cost justification for the procurement of the Hioki FT3470-51 for further testing in the future.

*Table 3.1* Meter Selection Overview

| Meter | Price ($) | Measurement Range (µT) | Frequency Response (Hz) | Data Logging Capability |
|---|---|---|---|---|
| Lutron EMF828  (Lutron 2023) | 326.20 | 0.01 - 2000 | 30 - 300 | NO |
| Hioki FT3470-51  *(Hioki 2023)* | 6530.00 | 2000 | 0-400k (With additional probes) | YES |
| Tenmars TM-192D  *(Tenmars 2023)* | 429.00 | 0.01-200 | 30-2000 | YES |

## 3.5 Non-Conductive Stand

Previous experiments identified in the literature review brough to light the need for a non-ferrous support to hold the meter during measurements. Whilst there was a large variety of commercially available non-conductive standard available for the purpose of surveying and similar, at a cost of $229 they were out of the financial budget of this experiment.

A low-cost stand was designed and constructed from available insulated materials. Pine timber off cuts were used to make to weighted base. A piece of 25mm PVC conduit was used to increase the height of the stand. A camera mount was repurposed to hold the magnetic field meter and allowed for the height of the measurement to be easily adjusted. Stand was designed to be simple to separate into parts for transport to other locations.

*Figure 3.5.1 Adjustable Non-Conductive Stand for Magnetic Field Meter.*

## 3.6 Bill of Materials

As the majority of materials were available to borrow from Sydney Trains the total cost of extra materials for this project was $419.50. The costing has been detailed in Table 3.2 below.

*Table 3.2 Bill of Materials*

| Item | Cost |
|---|---|
| Hioki PW3198 Power Analyser | $0 On Loan from Employer |
| Tenmars TM-192D Magnetic Field Meter | $399.00 |
| Hioki HiView Software | $0 Licence on loan from employer |
| EMF meter remote control software V1.3 | $0 free download form Tenmars website |
| Conduit 25mm 1 length | $4.50 |
| Pine timbers 1.2m lengths x 2 | $6.00 |
| Cables and Plugs/Accessories | $10.00 |
| Total | $419.50 |

# Chapter 4 On Site Recordings.

## 4.0 Site information

The selected sites for testing were:

- Warrawee Substation
- Beecroft Substation
- Yagoona Substation

These locations were chosen due to their typical Traction Substation arrangement which would allow for the greatest similarity and hence repeatability of experiment for the validation of results.

The standard configuration for Sydney Trains substations is to only have one rectifier (the duty rectifier) energised at any given time with a schedule to swap the duty rectifier each three months. To minimise network disruption from having to switch rectifiers, the in-service duty rectifier on the day of testing was selected for the application of the Power Analyser. With the Power Analyser stationary on the duty rectifier the Magnetic Field Meter was moved between the preselected test positions with a minimum of 30 minutes in each location.

## 4.1 Meter Configurations

Both the Magnetic Field Meter Figure 4.1.1a and the power analyser Figure 4.1.1b were set for a sampling rate of 3 seconds.

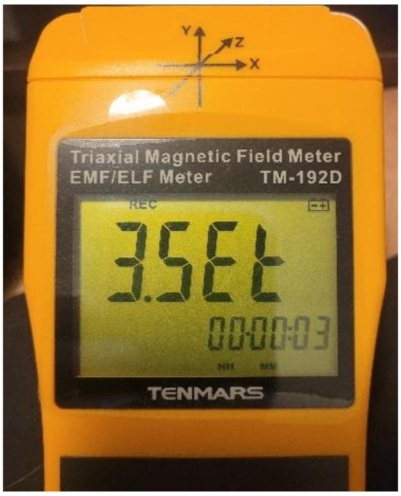


*Figure 4.1.1a EMF Meter set for 3 second recording intervals*


*Figure 4.1.1b Power Analyser set for 3 second recording intervals.*

The power analyser was set as per Figure 4.1.2 for the confirmed correct ratios of CT (300A/1A) and VT (300/1).

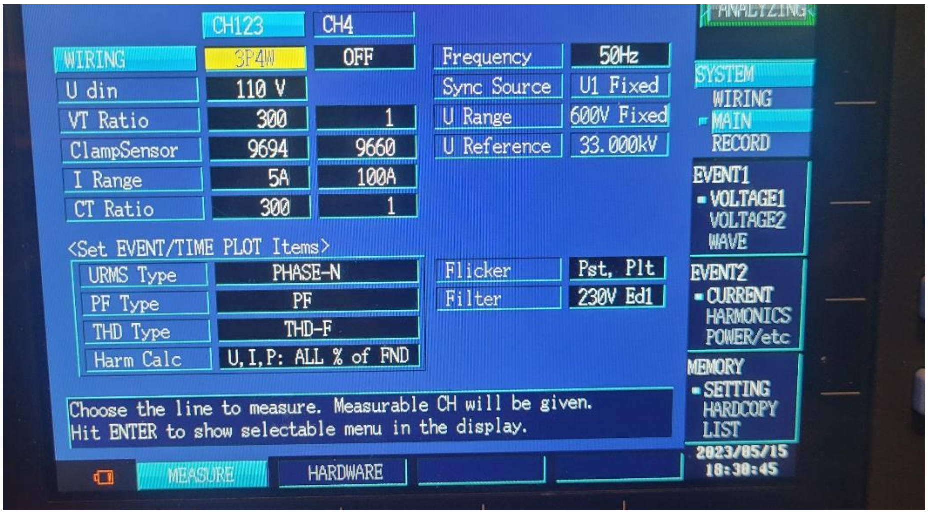


*Figure 4.1.2 Power Analyser set for correct input ratios.*

An un-anticipated complication became apparent in setting up as it was not possible to perfectly synchronise the two separate meters. This lack of synchronisation was minimised by setting each meter to the same time via a "time push" from the software. Figure 4.1.3 shows the meters to be time synchronised prior to testing.

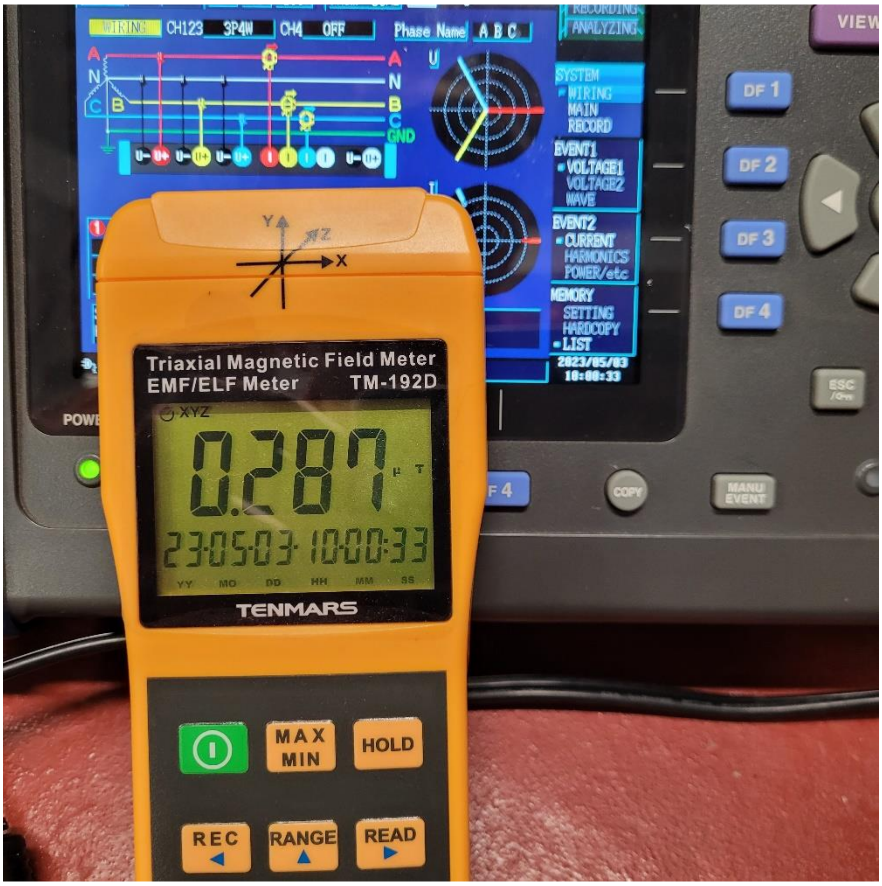


*Figure 4.1.3 Meters Time Synchronised.*

## 4.2 Power Analyser Connection

The Power Analyser inputs were connected as per *Figure 3.3.2* with currents being measured on the inputs to the overcurrent and earth leakage protection relay being the secondary side of a 300/1 current transformer using the Hioki 3694 clamp on current sensor *Figure 4.2.1a*. The voltage was measured at the Bus Bar Voltage Transformer marshalling terminals located in the Rectifier Alternating Current Circuit Breaker (ACCB) protection and control cabinet *Figure 4.2.1b*. Voltage inputs were connected to the power analyser via a Hioki PW9001 wiring adaptor *Figure 4.2.2*.

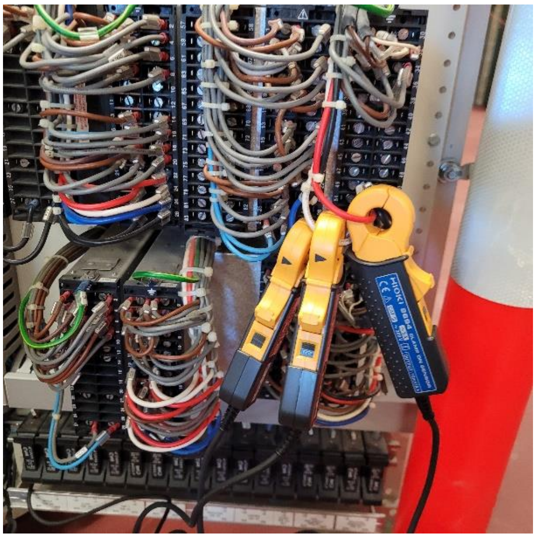

*Figure 4.2.1a Current Input to Analyser*

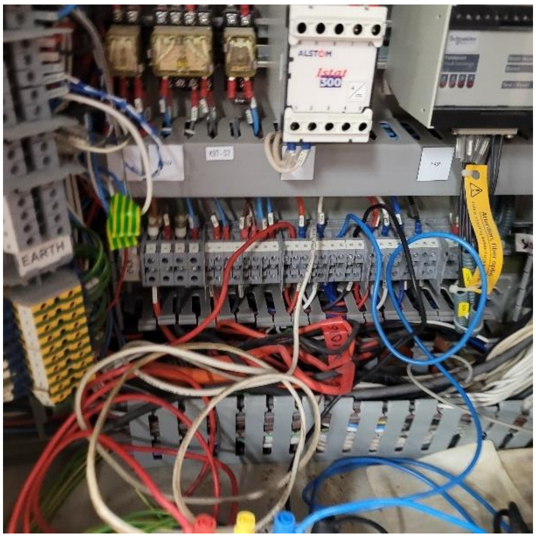


*Figure 4.2.1b Voltage Input to Analyser.*


*Figure 4.2.2 Power Analyser installed location.*

## 4.3 Warrawee Substation

4.3.0 Site Information

Warrawee Substation is a typical Sydney Trains tractions substation located on the upper north shore of metropolitan Sydney supplying power for the T1 line. It is a relatively new substation constructed in January 2015 as part of the Power Supply Upgrade program (Star Group 2023). Warrawee substation was required to support an upgraded fleet of commuter rail vehicles with modern amenities such as air conditioning and CCTV capabilities. Existing substations located at Gordon and Hornsby were not able to provide sufficient load, so Warrawee was constructed to meet the additional power requirements.

Testing of Warrawee Substation was conducted on the 3rd of May 2023 between 1000 and 1540. The power analyser was installed on the No1 Rectifier (duty rectifier at the time of testing) and remained stationary for the duration of testing. Magnetic Field Meter was moved between the preselected test positions with a minimum of 30 minutes in each location.


*Figure 4.3.0 Warrawee Substation Satellite Image (Image Google Maps 20023)*

### 4.3.1 Location 1

The first location where measurements were recorded was underneath the 600 Volt AC cables feeding into the rectifier diode cabinet. Height of the magnetic field meter was set at 1.76 meters above floor level. This value was chosen as the average height of Australian male and would give a standard value for test repetition for exposure to head. Distance measurements were recorded from the axis of the magnetic field meter to centre of each conductor. It is not expected to be able to exactly replicate the position of testing in different substations so the distance from any potential sources of magnetic field will need to be documented each time. *Figure 4.3.1.2* is the graphed results from logging in this location. From the first set of readings this location had the highest recorded values of magnetic flux density with values exceeding 200uT. It is also apparent from the strong correlation that it is the rectifier loading that is having the greatest impact on magnetic field strength.

As can be seen in *Figure 4.3.1a* below this area is used as storage for operating handles and a ladder. This is not in line with a philosophy of prudent avoidance as recommended by governing bodies such as the world health organisation.

This location also showed a very strong correlation between rectifier loading and magnetic flux density proving the theory that magnetic fields need to be considered for the dynamic loading conditions.

*Figure 4.3.1a Rectifier Diode Cubicle*

*Figure 4.3.1b EMF meter positioned under 600V AC cables.*

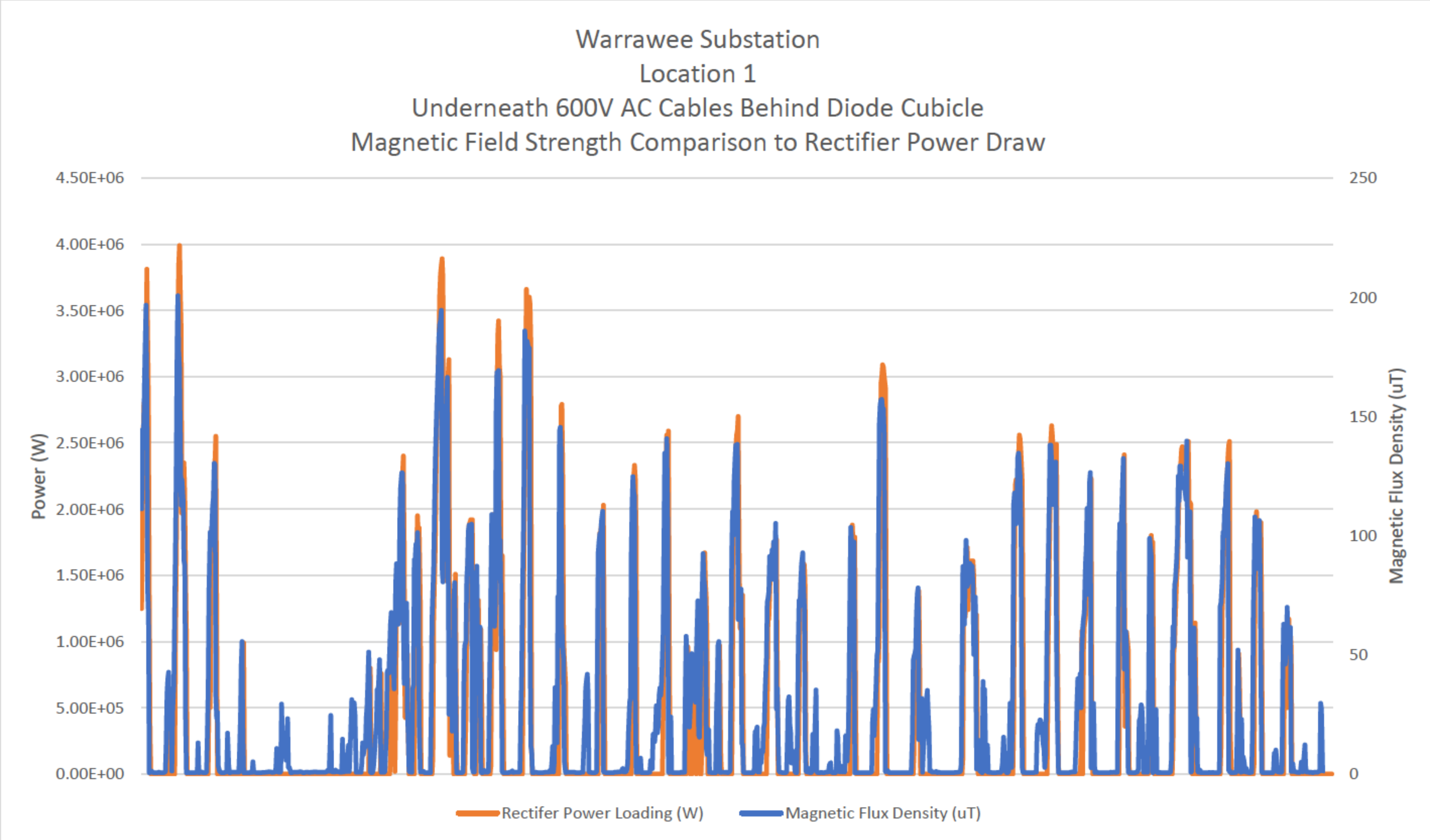


*Figure 4.3.1.2 Warrawee Substation Location 1 Comparison Graph.*

### 4.3.2 Location 2

Measurements were taken from in front of the No 1 Rectifier 1500V DCCB as seen in *Figure 4.3.3*. Height of meter was again set for 1.76 meters. The magnetic field meter was cantered on the DCCB and place as close as possible. No Significant recording were made in this location with a maximum magnetic flux density of 1.7uT despite power loadings on the rectifier exceeding 3kW. As reading were not significant, they will not be further examined in this study.


*Figure 4.3.2 Meter located in front of DCCB.*

### 4.3.3 Location 3

For measurement recording in front of the No1 Rectifier ACCB the height of the Magnetic field meter was adjusted to 1.1 meters. This height was selected to better reflect what the magnetic field exposure is for sensitive electronic devices (protection relays) the rear of which can be seen mounted in the panel door in *figure 4.3.4*. Magnetic Flux density in this location was minimal with a maximum reading of 4.4uT recorded. As reading were not significant, they will not be further examined in this study.

*Figure 4.3.3 Meter located in front of ACCB.*

### 4.3.4 Location 4

Measurements taken behind the ACCB at 33kV cable termination enclosure. Height of meter was 1.1 meters. Meter was centred on the ACCB cubicle and located as close as possible to the panel. The magnetic flux density recorded in this location was again relatively low with a maximum of 10.18uT recorded. As reading were not significant, they will not be further examined in this study. *Figure 4.3.4* shows the meter in position behind the Rectifier ACCB.

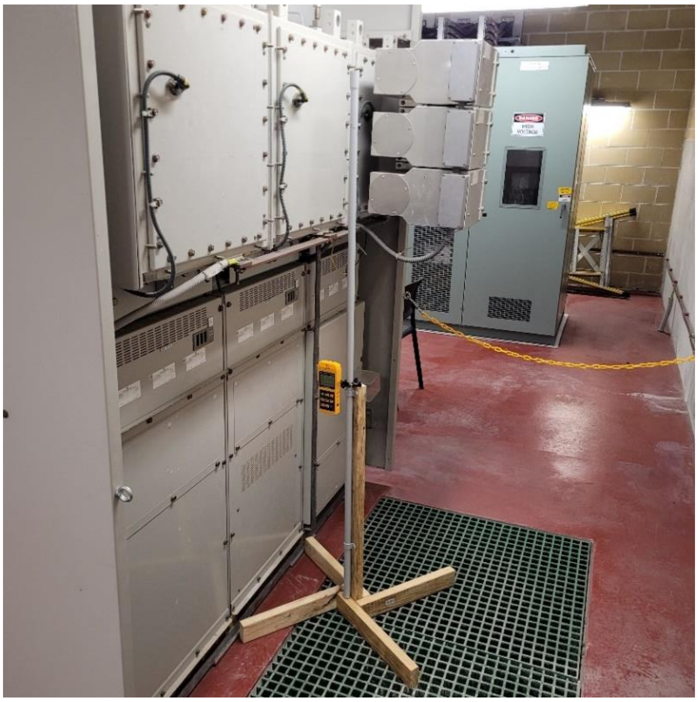

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*Figure 4.3.4 Meter located at cable termination compartment of ACCB.*

### 4.3.5 Location 5

Recordings were taken in the approximate centre of administration room. As the reading are not expected to be significant other than a base line the exact positioning of the meter in further testing is not critical. As expected, readings in this location were very low with a maximum of 0.092uT recorded. As reading were not significant, they will not be further examined in this study.

4.3.6 Location 6

The readings for this location were taken in the No1 Rectifier transformer bay. The standard configuration in the Sydney Trains network is to have the transformer bays outside directly in line with rectifier diode unit. This measurement captures magnetic field emissions from the 600V AC cables transitioning to inside the transformer as well as the transformer itself. *Figure 4.3.6.1* shows the meter in location beneath the 600V AC cables. As with section 4.3.1 distances to each conductor as well as to the transformer were recorded and will be required for further examination of data. Like Location 1 there were substantial magnetic flux density readings were recorded in this location. The maximum reading recorded was 137.3uT seen in *Figure 4.3.6.2*. The lower reading can be attributed to the increased height of the cables. The strong correlation between rectifier loading and magnetic field strength is clearly shown in *Figure 4.3.6.2*.

*Figure 4.3.6.1 Meter located in Transformer Yard under 600V cables.*

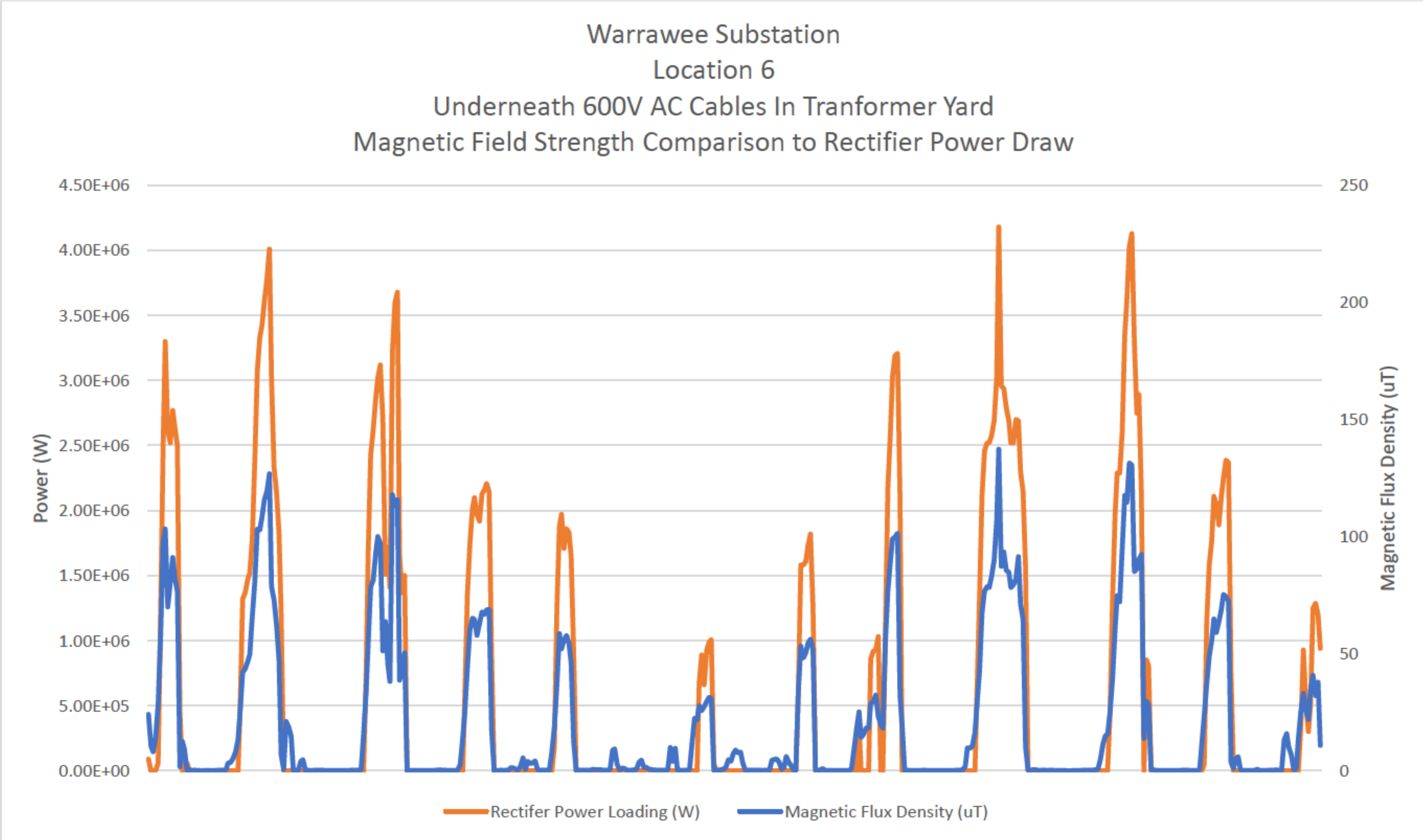


*Figure 4.3.6.2 Warrawee Substation Location 6 Comparison Graph.*

4.3.7 Location 7

This location was again in the No1 Rectifier transformer yard. This reading was centralised around the 33kV input cables to the transformer shown in *Figure 4.3.7.1*. Distances were recorded from the transformer as well as to each phase of the incoming cable.

*Figure 4.3.7.1 Meter located in Transformer Yard close to 33kV Cables.*

Figure4.3.7.2 shows magnetic flux density peaked at 52.3uT in this location. This result was as expected, significantly lower than readings near the low voltage cables. This is due to the proportionately lower current flowing through the high voltage cables.

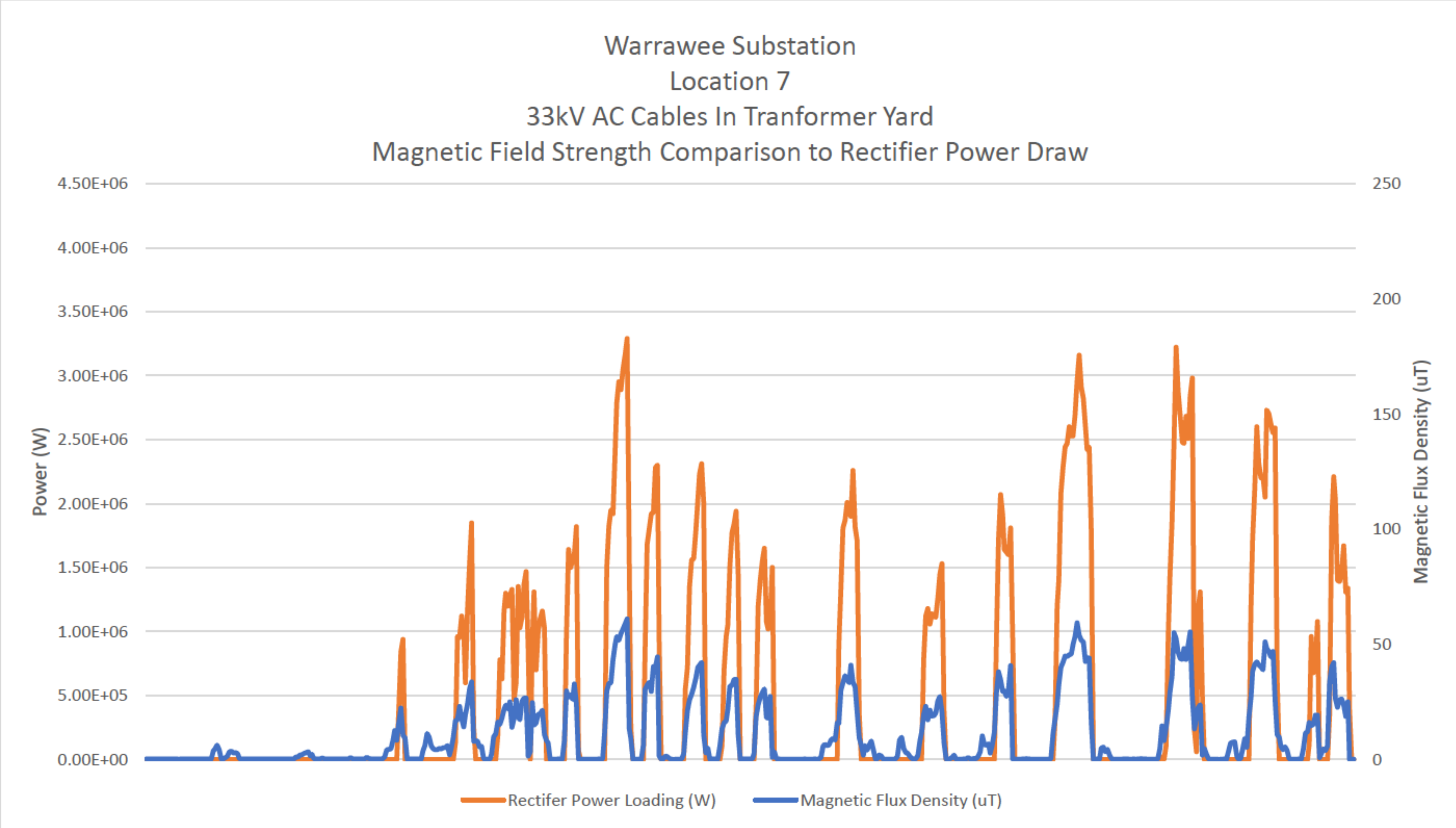


*Figure 4.3.7.2 Warrawee Substation Location 7 Comparison Graph.*

### 4.3.8 Location 8

The final location tested was in front of the Rectifier diode cubicle. The cabinet is fitted with air flow vents for cooling as seen in *Figure 4.3.8.1*. The vents are approximately cantered at a height of 1.1 meters above floor level. It was hypothesised the open vents would provide the least amount of shielding and result in the highest emission of electromagnetic fields. In the interest of recording worst case scenarios, the magnetic field meter was also set to a height centred around the vent.


*Figure 4.3.8.1 Front of Rectifier Diode Unit.*

The logged data in *Figure 4.3.8.2* shows peak levels of magnetic field strength reach 161.4uT. The lower readings in this location confirms the area around the 600V AC cables is the area of greatest concern.

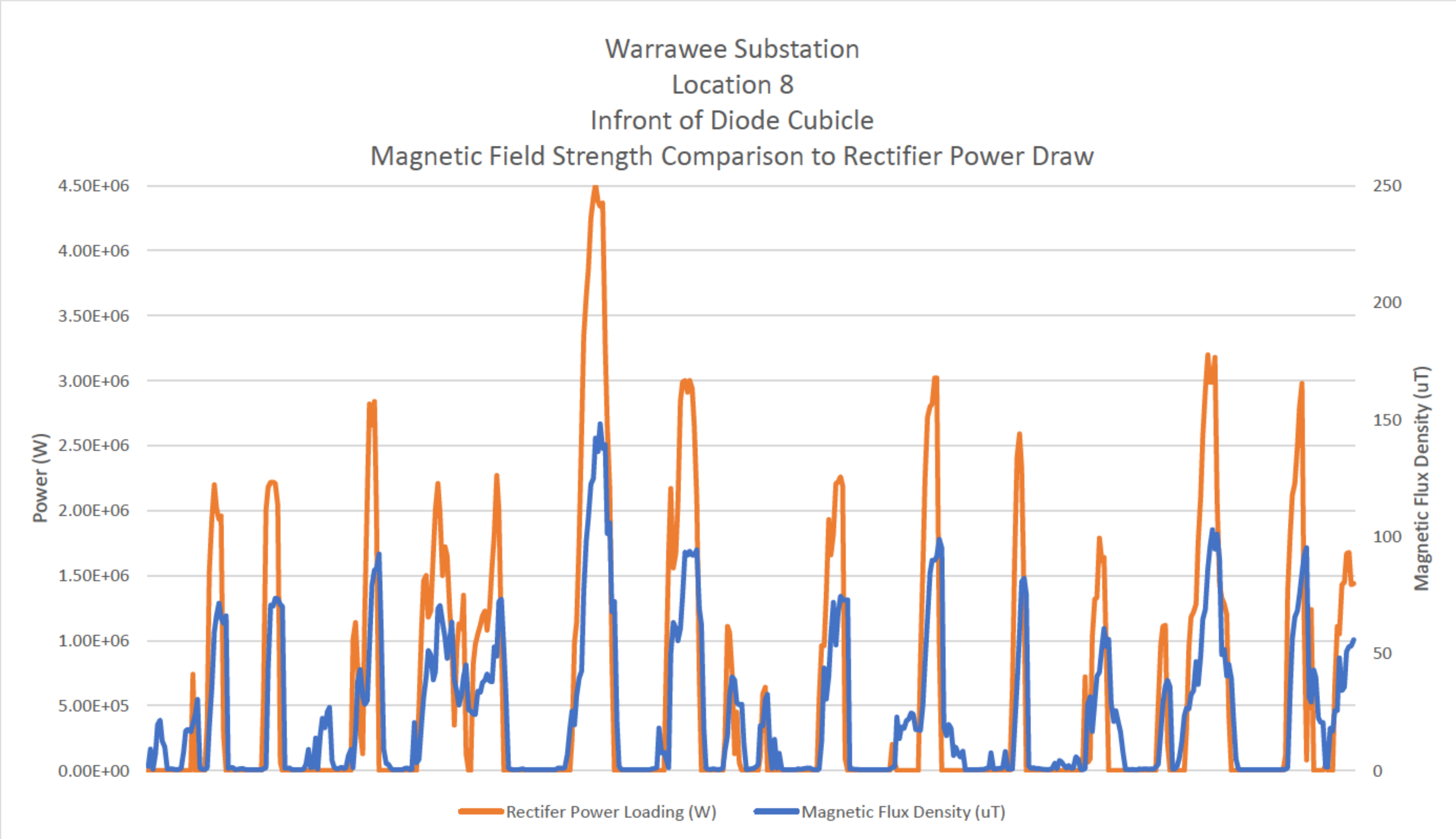


*Figure 4.3.8.2 Warrawee Substation Location 8 Comparison Graph.*

## 4.4 Beecroft Substation

### 4.4.0 Site Information

Beecroft Substation is located on the main northern or T9 line of the Sydney Trains network. The substation was commissioned into service in 2007 to increase traction load capabilities between the existing Hornsby and Epping Substation. This location is the same typical substation layout consisting of two 33kV bus sections each with a single feeder and rectifier supplying two sectional 1500V positive bus bars with two 1500v feeders each.

Because of Beecroft Substations placement in the rail corridor there was only a small allotment of land shown in *Figure 4.4.0.1*. This required the substation design to be physically narrower and shorter than the other substations studied in this research.


*Figure 4.4.0.1 Beecroft Substation Satellite Imagery (Google Maps, 2023).*

The compact design has led to a restricted placement of equipment. Of particular interest to this research is the placement of:

- Supervisory control and data acquisition (SCADA) remote terminal unit (RTU) and marshalling cabinet.
- Fibre optics break out (FOBO) panel.
- Main low voltage (LV) switchboard and 120v Distribution Board (DB).
- 120V DC battery charger.

The equipment layout schematic *Figure 4.4.0.3* shows all these equipment panels have been installed directly beneath the 600v AC cables between the rectifier transformers and diode units. When required to perform maintenance or fault finding any of that equipment workers can be expected to spend extended periods of time in these areas.

The testing program was conducted on 23rd June 2023. As with the previous test the Power Analyser and Magnetic Field Meter needed to be time synced to allow for the correlation of data.

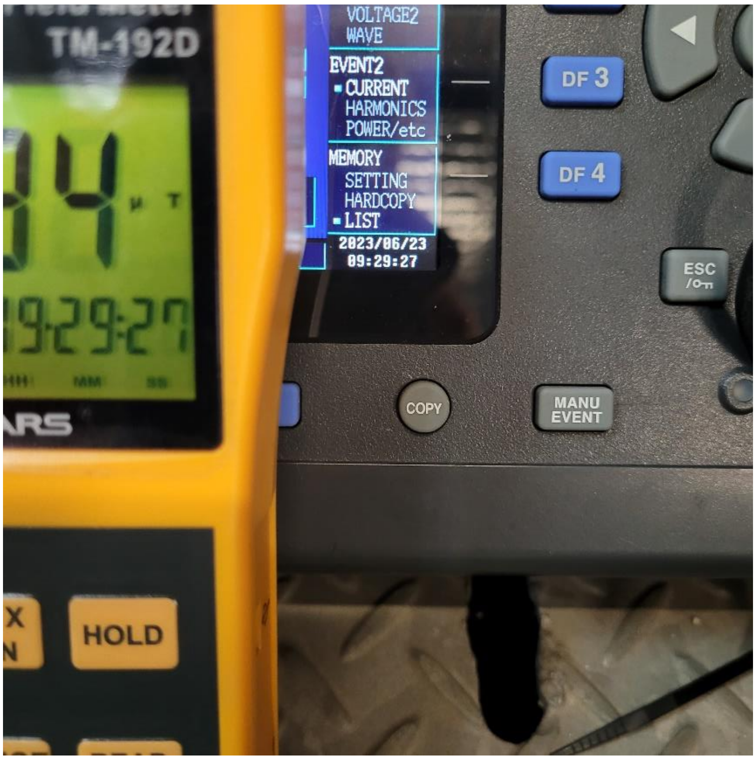


*Figure 4.4.0.2 Confirmation of meter time synchronisation.*

The Hioki Power Analyser was installed on the No1 Rectifier as it was the designated duty rectifier at the time of testing. Current and Voltage connection were made as per *Figure 3.3.2*.

Testing in locations 2, 3, 4 and 5 all confirmed previous findings with no significant levels of magnetic fields in excess of ambient levels. Locations 1,6, 7 and 8 have been examined further.

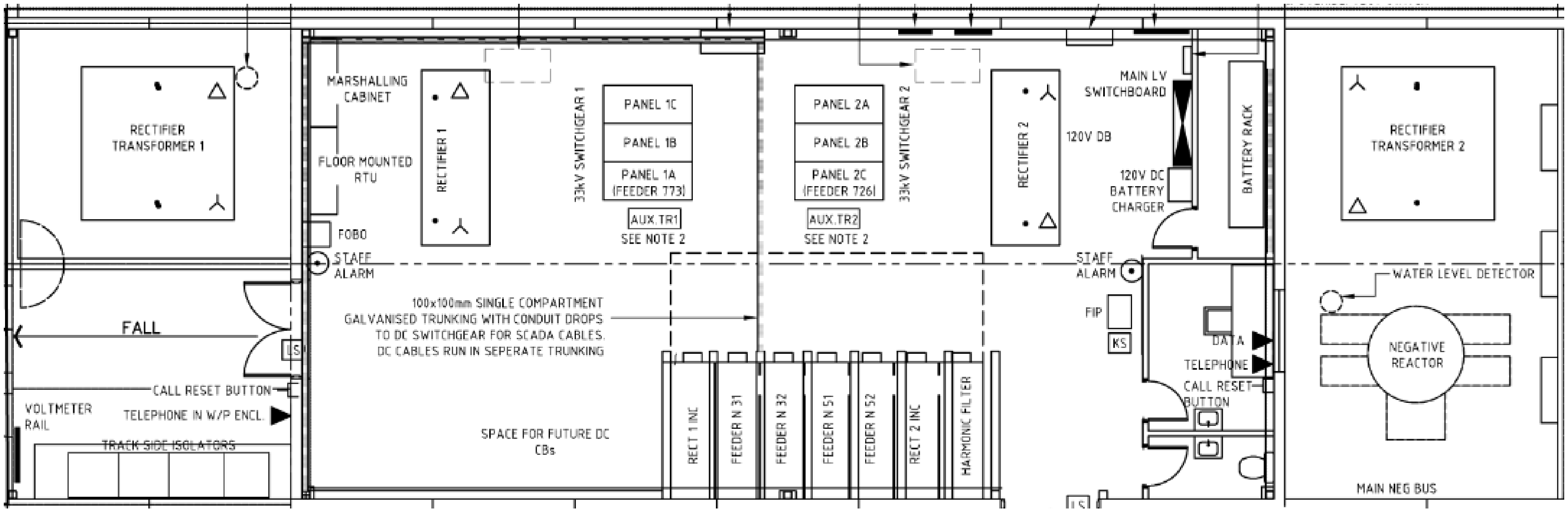


*Figure 4.4.0.3 Beecroft Substation Equipment Layout.*

### 4.4.1 Location 1

Location 1 was underneath the 600v AC cabled inside between the Rectifier diode unit and the Rectifier transformer. This area was of particular interest due to the installation of the SCADA RTU being directly in what would be considered the zone of influence of these cables. *Figure 4.4.1.1* shows the proximity of the RTU panel to the 600V AC cables. The meter was set to a height of 1.76m above the ground.


*Figure 4.4.1.1 Location 1 Underneath 600V AC cables.*

The maximum magnetic flux density recorded in this location was 119.8uT however the rectifier loading also only reached a peak of 1.25MW as shown in *Figure 4.4.1.3*. The differences in these reading to previous in similar locations is due to the height and configuration of the installed cables. The cables at Beecroft are installed at a height of 3.5m which is 40% higher than that of Warrawee and Yagoona Substation. As shown in Equation 1 magnetic field strength is directly proportional to distance away from the source so it was expected that readings here would be significantly less than those of other substations.

*Figure 4.4.1.2 SCADA RTU installed directly beneath cables.*

Figure 4.4.1.1 shows the height of the cables above the meter which was set as per the experiment procedure to the standard height of 1.76m. Figure 4.4.1b show the configuration difference where cables are installed in a 2x4 arrangement, instead of the 4x2 arrangement seen in Figure 4.3.1.2. This configuration gives means there is a wider surface area of cables per a phase on the side that is exposed to persons underneath. This configuration also lowers the overall height of the cables leading to a higher magnetic field strength.

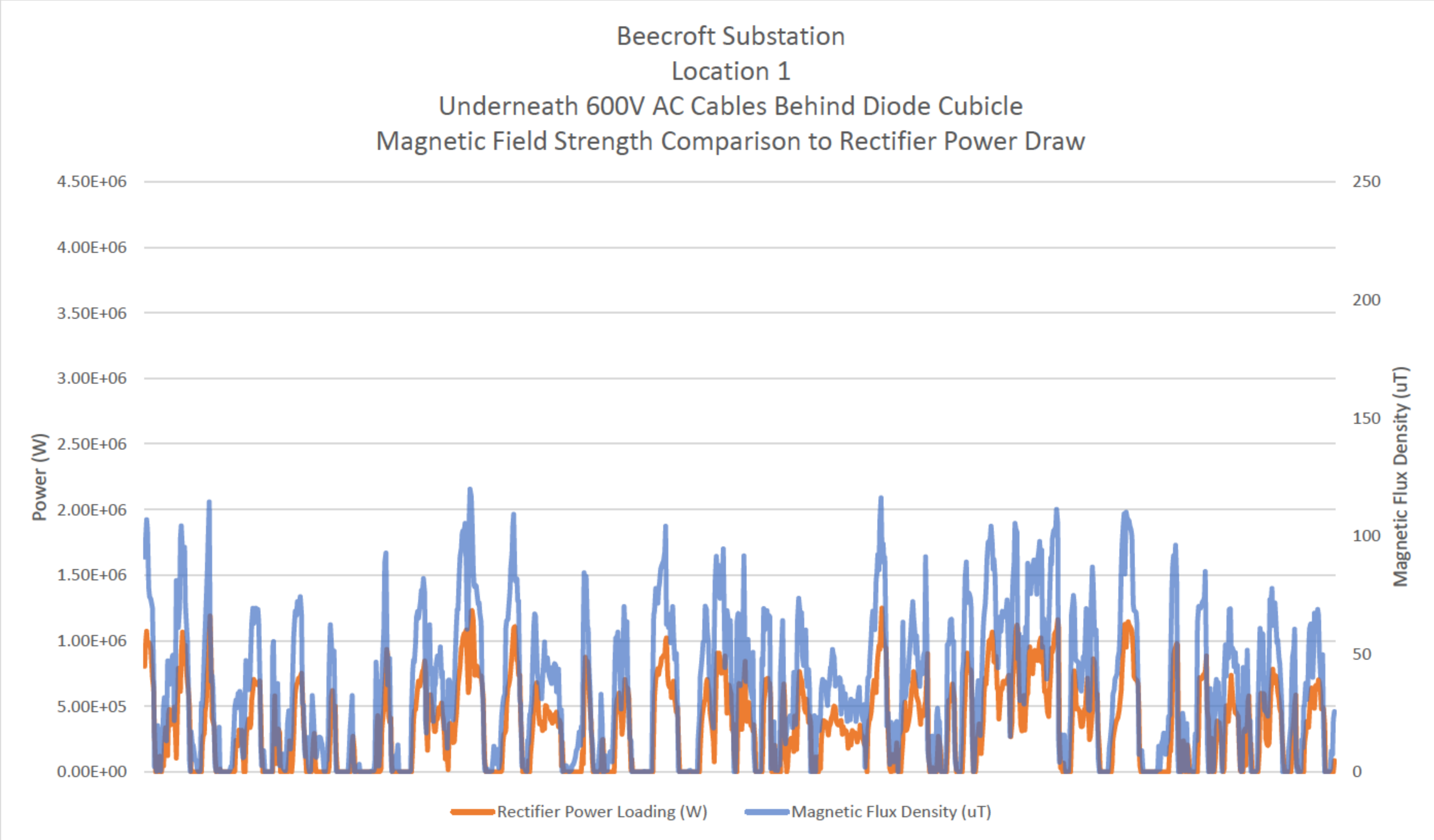


*Figure 4.4.1.3 Beecroft Substation Location 1 Comparison Graph.*

4.4.2 Location 6

The readings for this location were taken under the 600V AC cables in the No1 Rectifier transformer bay. The Beecroft Substation design differs from others testing in that the transformer bay is not fully enclosed by a sealed blast wall. This substation instead has been constructed to have a screen blast wall and metal roof. This enclosed design is not expected to have an influence on testing for the purpose of this study.

As with Location 1 the cables are installed at a greater height than previous substations to allow for a physical clearance over equipment installed on internal wall. The cables are installed in 2 bunches of four in a horizontal configuration.

Similar to Location 1 there were substantial magnetic flux density readings were recorded in this location. The maximum reading recorded was 108.4uT but again this was limited by the Rectifier loading only reaching a peak of 1.37MW during testing. Figure 4.4.2.2 shows the rectifier loading dose not reach the same levels as other test sites however the magnetic field levels are relatively high.

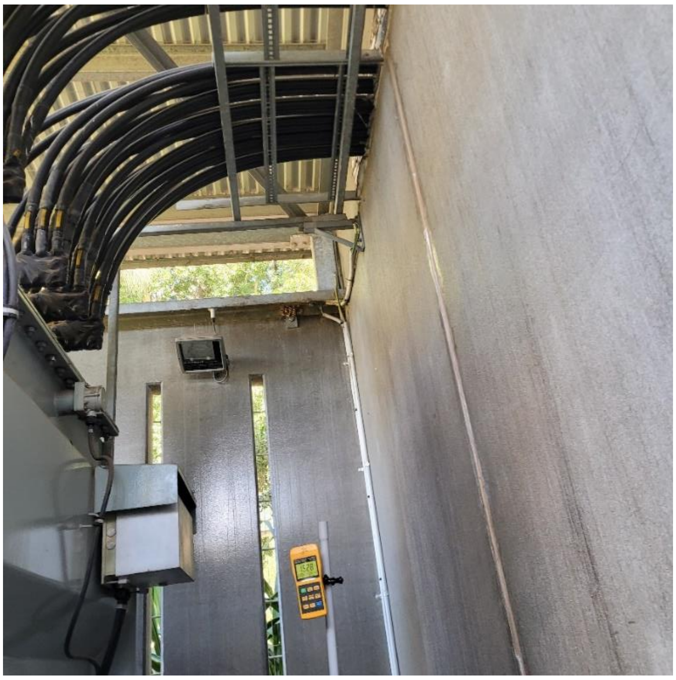.

*Figure 4.4.2.1 Magnetic Field Meter beneath cables in Transformer Yard.*

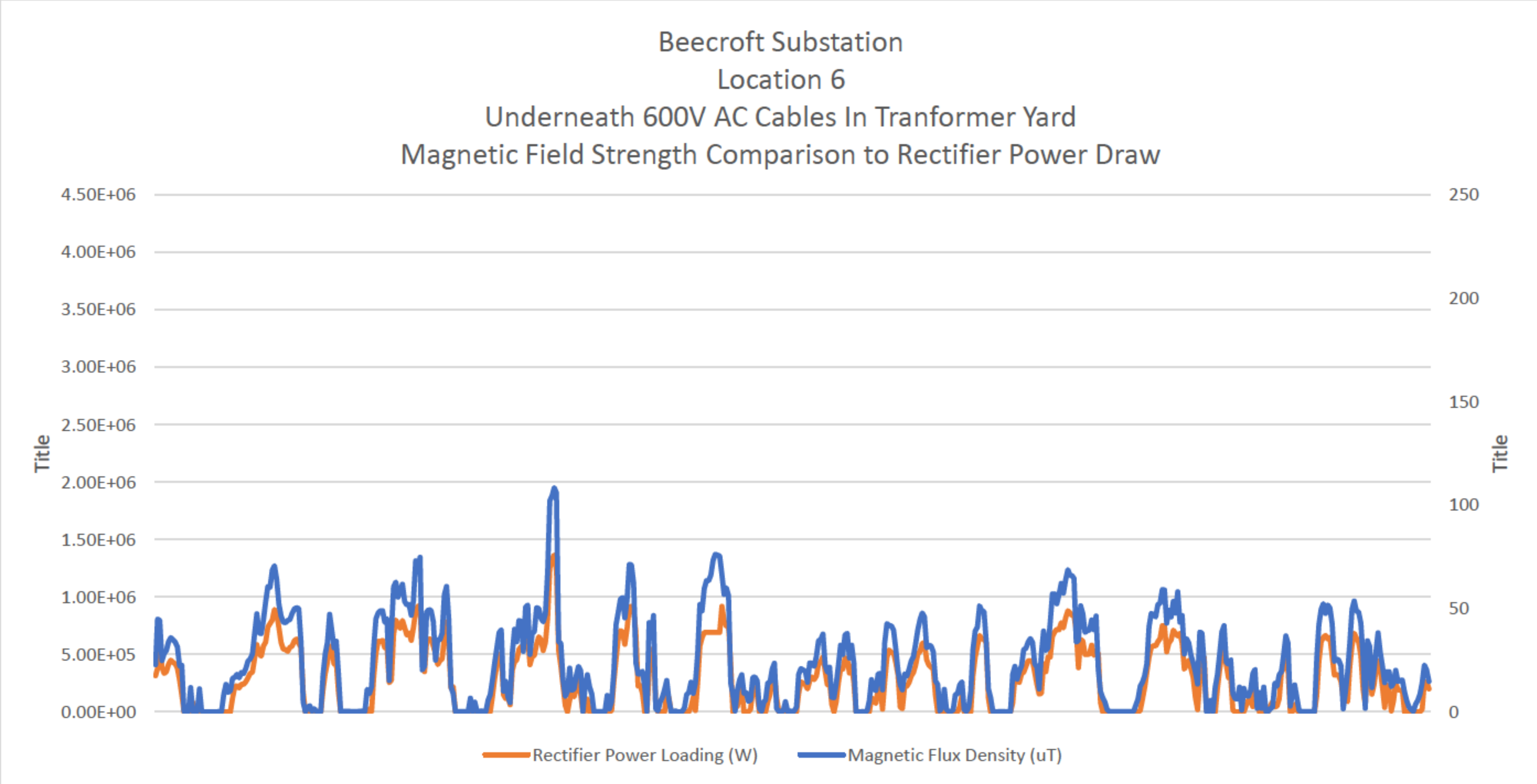


*Figure 4.4.2.2* ***Beecroft Substation Location 6 Comparison Graph.***

### 4.4.3 Location 7

Location 7 was the measurements on the HV cable side of the transformer. These reading were significant at a maximum of 74.7 at a peak rectifier loading of 1.64MW as seen in figure 4.4.3.2. These readings are of relevance as it confirms the previous findings that the 600V AC cables are the biggest contributor to EMFs in this area.


*Figure 4.4.3.1a Magnetic Field Meter next to HV cables*

*Figure 4.4.3.1b Magnetic Field Meter next to HV cables*

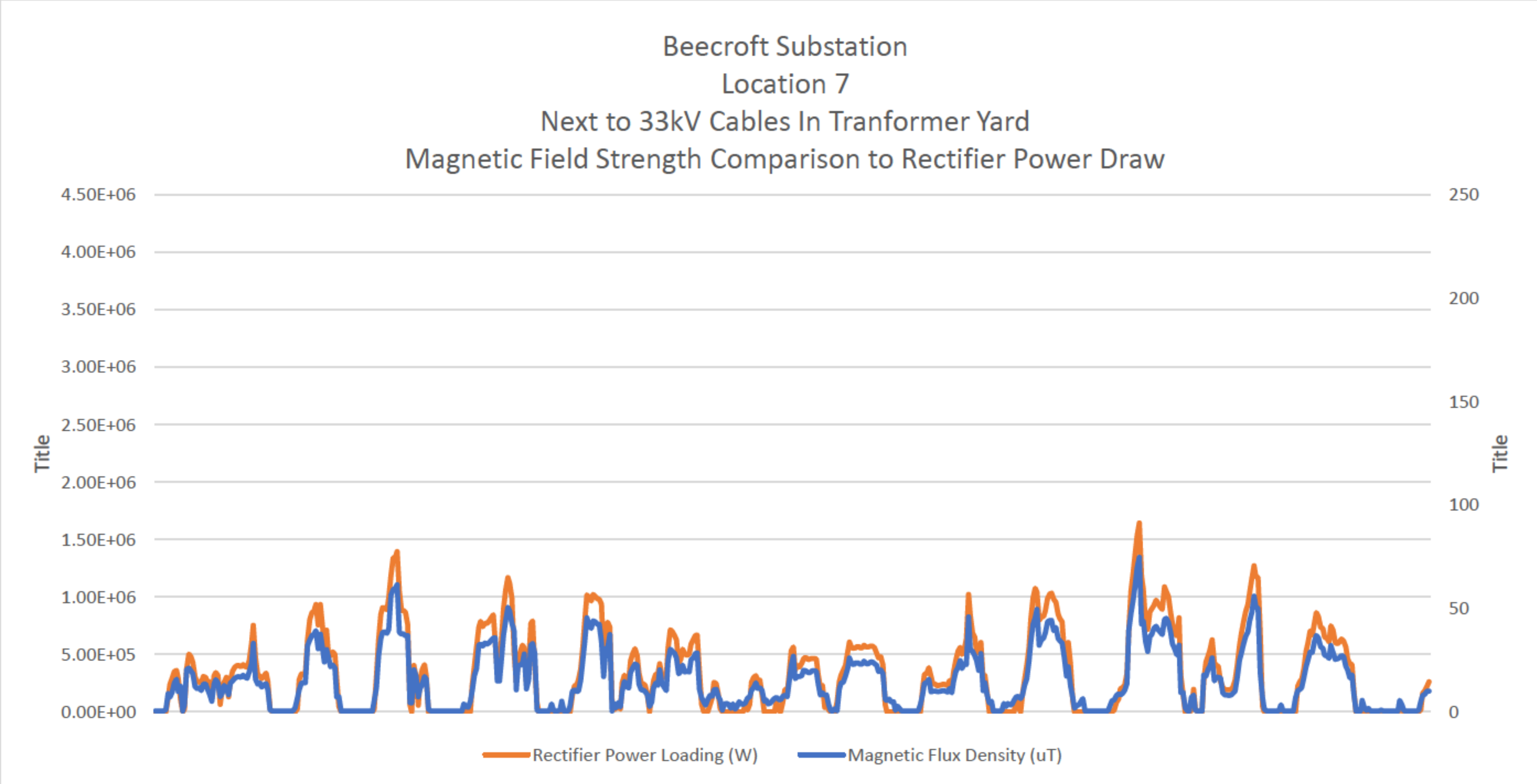


*Figure 4.4.3.2 Beecroft Substation Location 7 Comparison Graph.*

4.4.4 Location 8

Measurements were taken on the front side of Rectifier Diode unit in line with ventilation mesh shown in Figure 4.4.4.1. Confirming the results of previous testing the EMF exposure limits were above significantly above ambient levels but not as high as locations within closer vicinity to the 600V AC cables. The maximum recorded magnetic field strength was 112.3uT at a power loading of 1.08MW as seen in figure 4.4.4.2.


*Figure 4.4.4.1 Magnetic Field Meter Front Side of Diode Unit.*

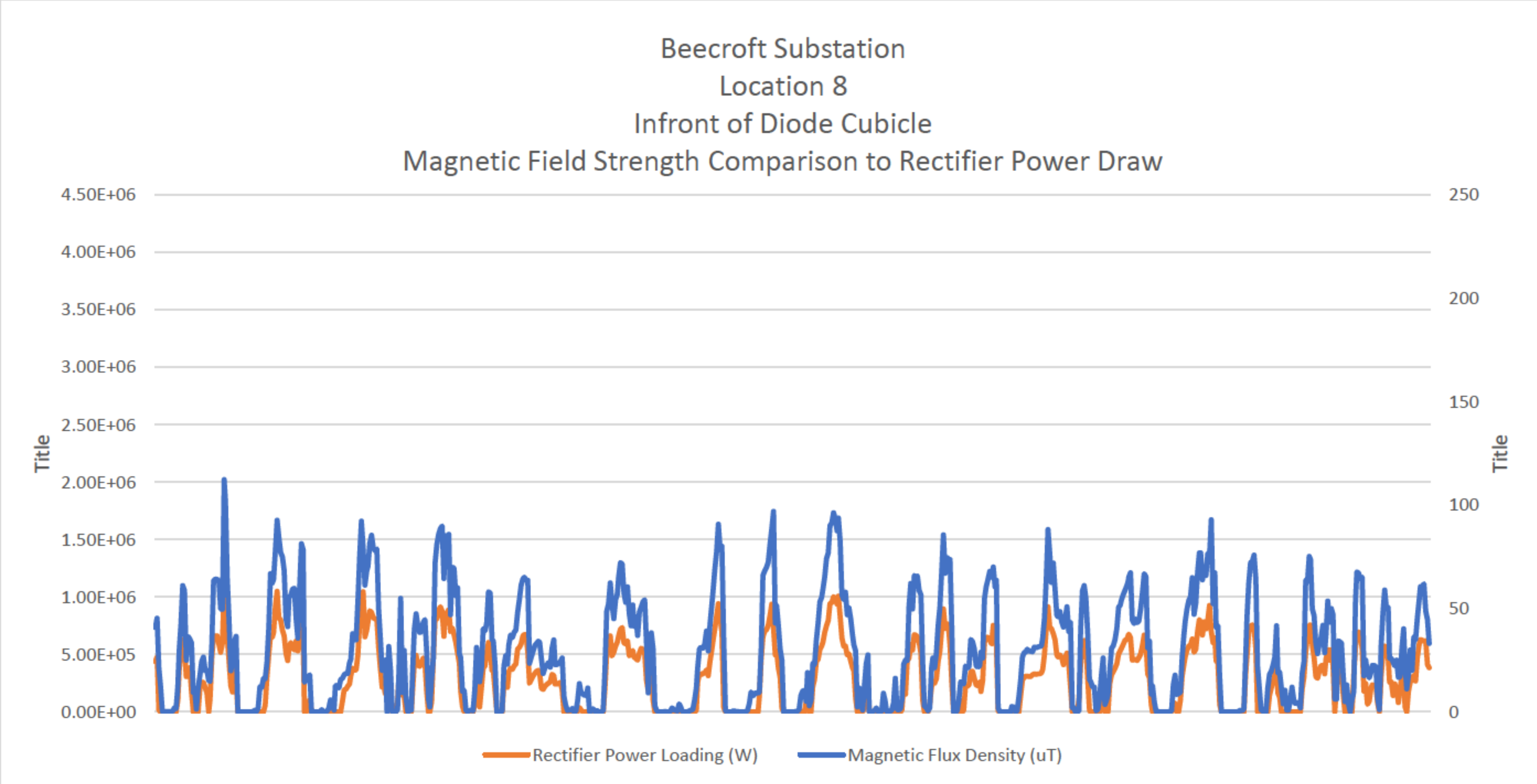


*Figure 4.4.4.2 Beecroft Substation Location 8 Comparison Graph.*

## 4.5 Yagoona Substation

### 4.5.0 Site Information

Yagoona Substation is located on the Bankstown or T3 line of the Sydney Trains network. The substation was commissioned into service in 2012 adding an additional 5MW of 1500V traction capacity in that rail section. This installation replaced the existing Yagoona Section Hut. As with the other sites selected for this testing Yagoona is of the typical substation configuration consisting of two 33kV bus sections each with a single feeder and rectifier supplying two sectional 1500V positive busbars supplying two 1500V feeders each.


*Figure 4.5.0 Yagoona Substation Satellite Imagery (Image Google Maps 2023)*

Testing at Yagoona Substation was carried out on the 18th of July 2023 and was centred around the No2. Rectifier which was the designated duty Rectifier at the time. The results from Yagoona have further proven previous finding in that the areas exposed to the highest magnetic field strength are locations 1,6,7 and 8 due to their proximity to the 600V AC cables.

In line with previous findings locations 2,3,4 and 5 showed EMF levels to be not significantly higher than that of ambient levels. As such detail examinations of these locations have been omitted from this report.

### 4.5.1 Location 1

Testing was conducted in location 1 as per the now established testing procedure. Location 1 beneath the 600V AC cables between diode unit and internal wall yielded the highest recorded magnetic field strength. Figure 4.5.1.2 shows the peak magnetic field strength at 218uT for a rectifier however this was also the highest power loading of all sites tested at 4.6MW. It should be noted that the Tenmar-TM19D Magnetic Field Meter is only rated for 200µT, so this reading was outside of the calibrated bandwidth however this recording is consistent with other readings. The cable configuration was similar to that of Warrawee Substation with 2 horizontal rows and 4 vertical columns of 400mm$^2$ cables per phase. Again, this location has been used for storage as seen in figure 4.5.1.

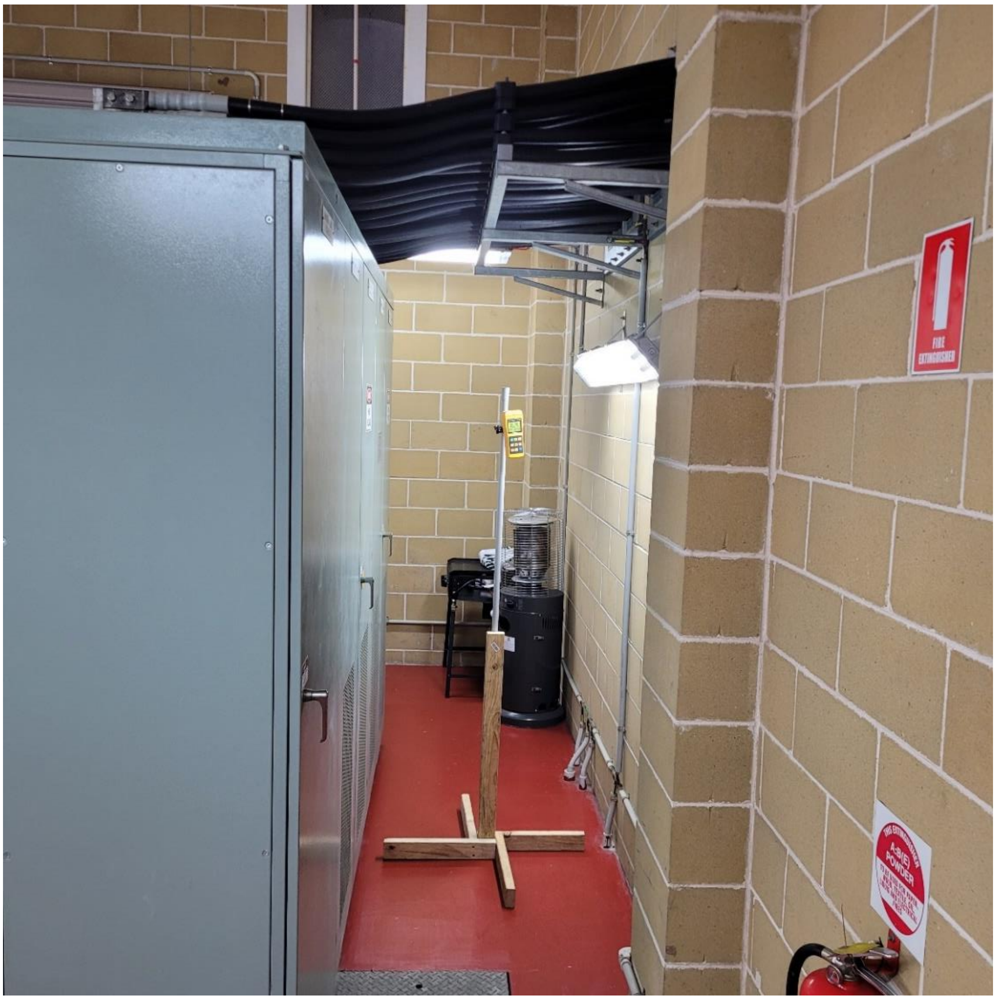

*Figure 4.5.1.1 Yagoona Behind Rectifier Diode Unit.*

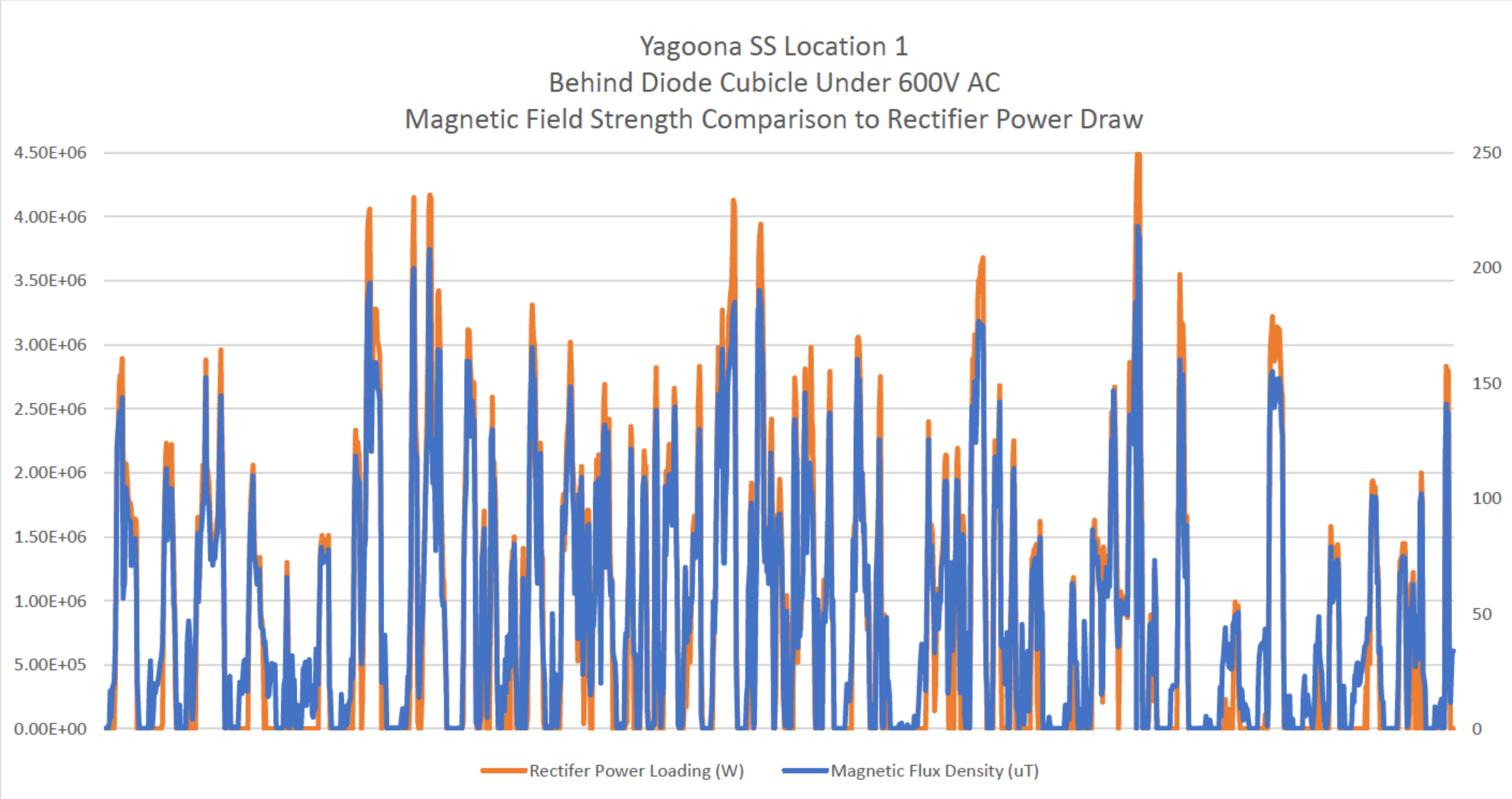


*Figure 4.5.1.2 Yagoona Substation Location 1 Comparison Graph.*

4.5.2 Location 6

The magnetic field meter was positioned approximately centre of all cables shown in figure 4.5.2.1 and measurements confirmed significant magnetic fields. Figure 4.5.2.2 shows the maximum recorded level was 205.9µT at 5.47Mw. As with previous locations this area is sealed from other areas by concrete blast walls and is unlikely to be frequented without a specific purpose.

*Figure 4.5.2.1 Yagoona Under 600V AC Cables in Transformer Yard.*

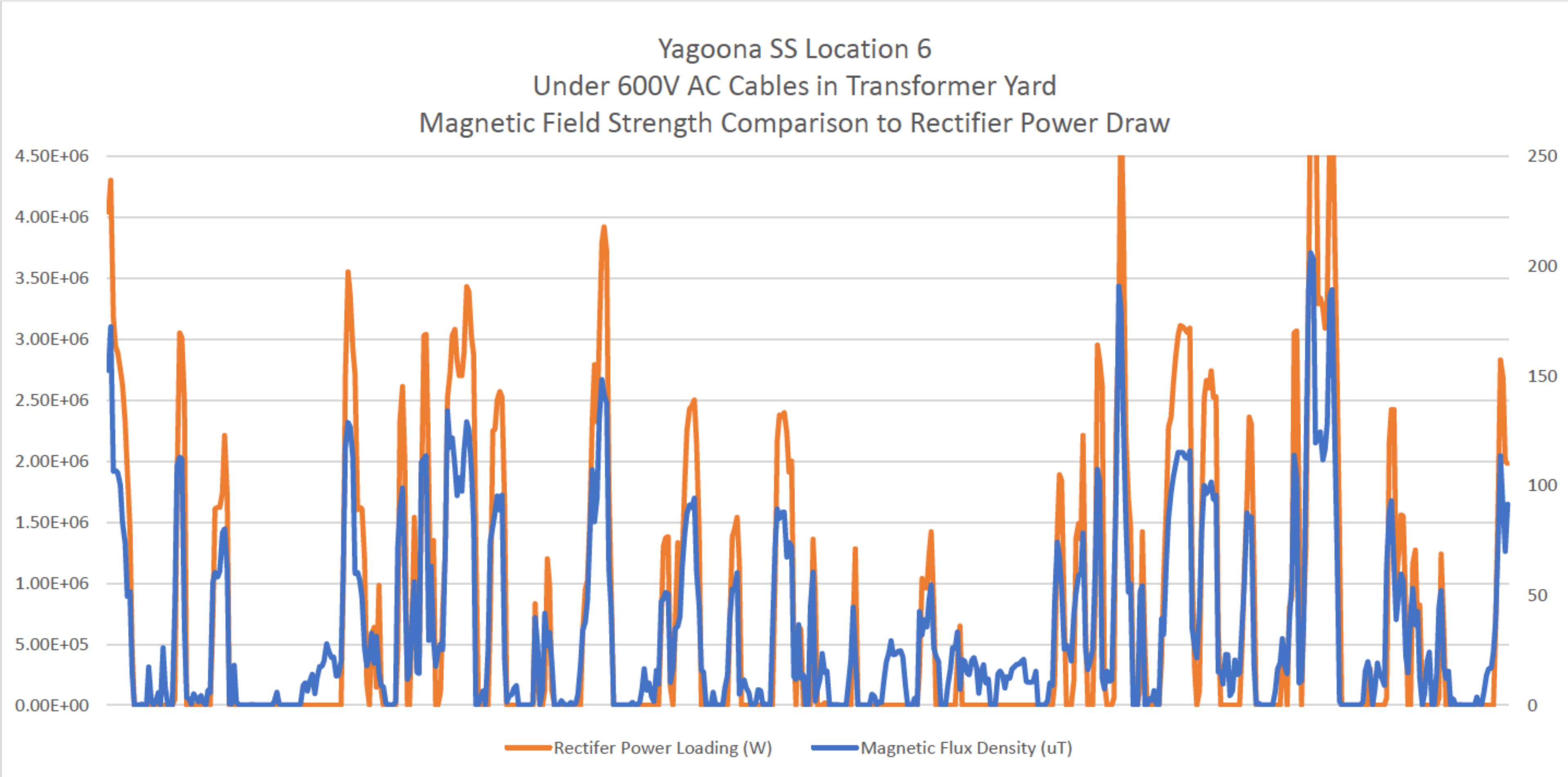


*Figure 4.5.2.2 Yagoona Substation Location 6 Comparison Graph.*

### 4.5.3 Location 7

The HV cable side of the rectifier transformer (Figure 4.5.3.1) showed EMF exposure levels above that of ambient but not as high as readings closer to the 600V AC cables. As shown in Figure 4.5.3.2 the highest recorded magnetic field strength during testing was 66.0μT at a power loading of 4.08MW.


*Figure 4.5.3.1 Yagoona Next to HV Cables in Transformer Yard.*

### 4.5.4 Location 8

Whilst testing the front of diode unit the highest recorded magnetic field strength was 124.5μT. this result again confirms that the locations of greatest concern are those in close proximity to the 600V AC cables. The result from this location is presented in Figure 4.5.4.

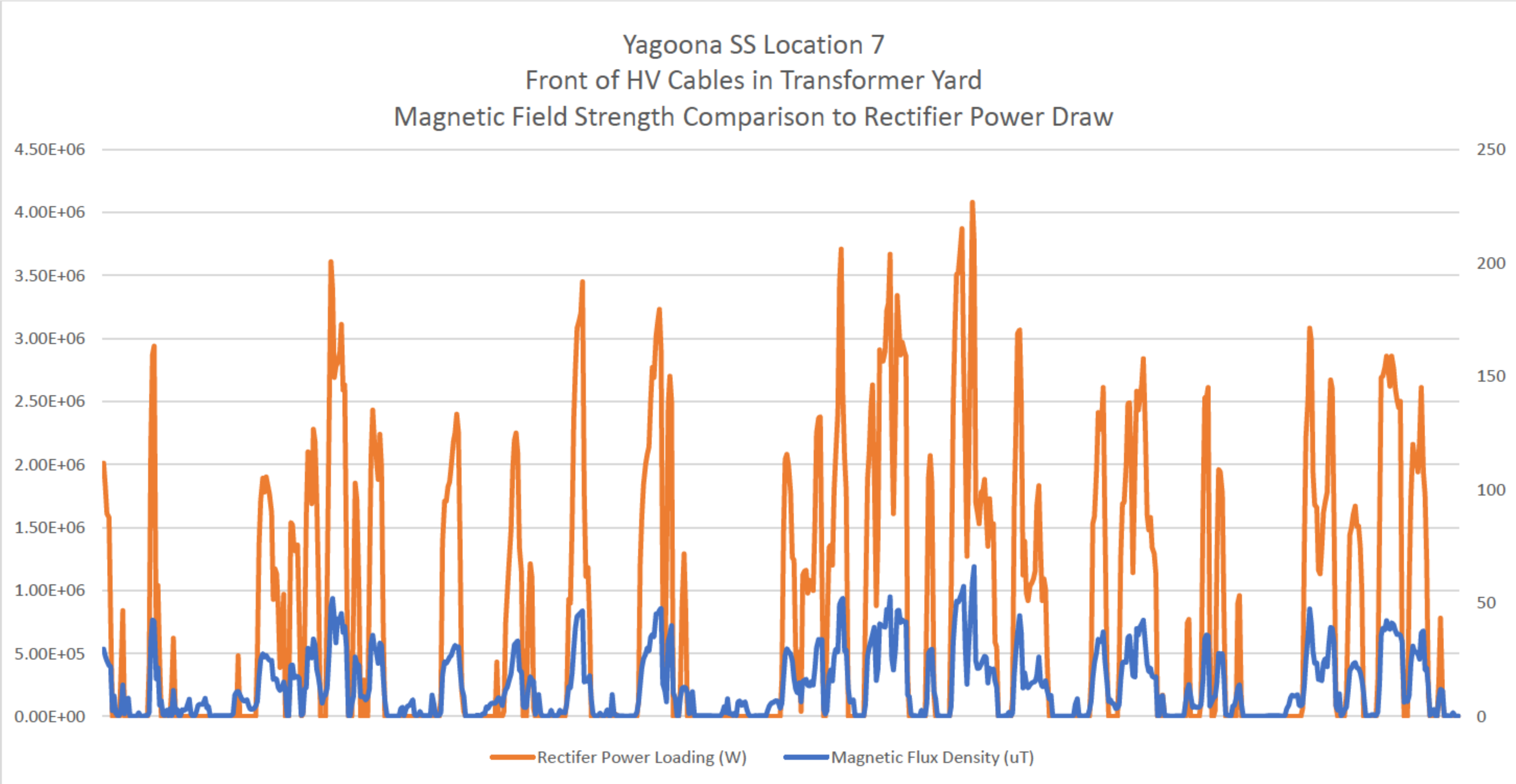


*Figure 4.5.3.2 Yagoona Substation Location 7 Comparison Graph.*

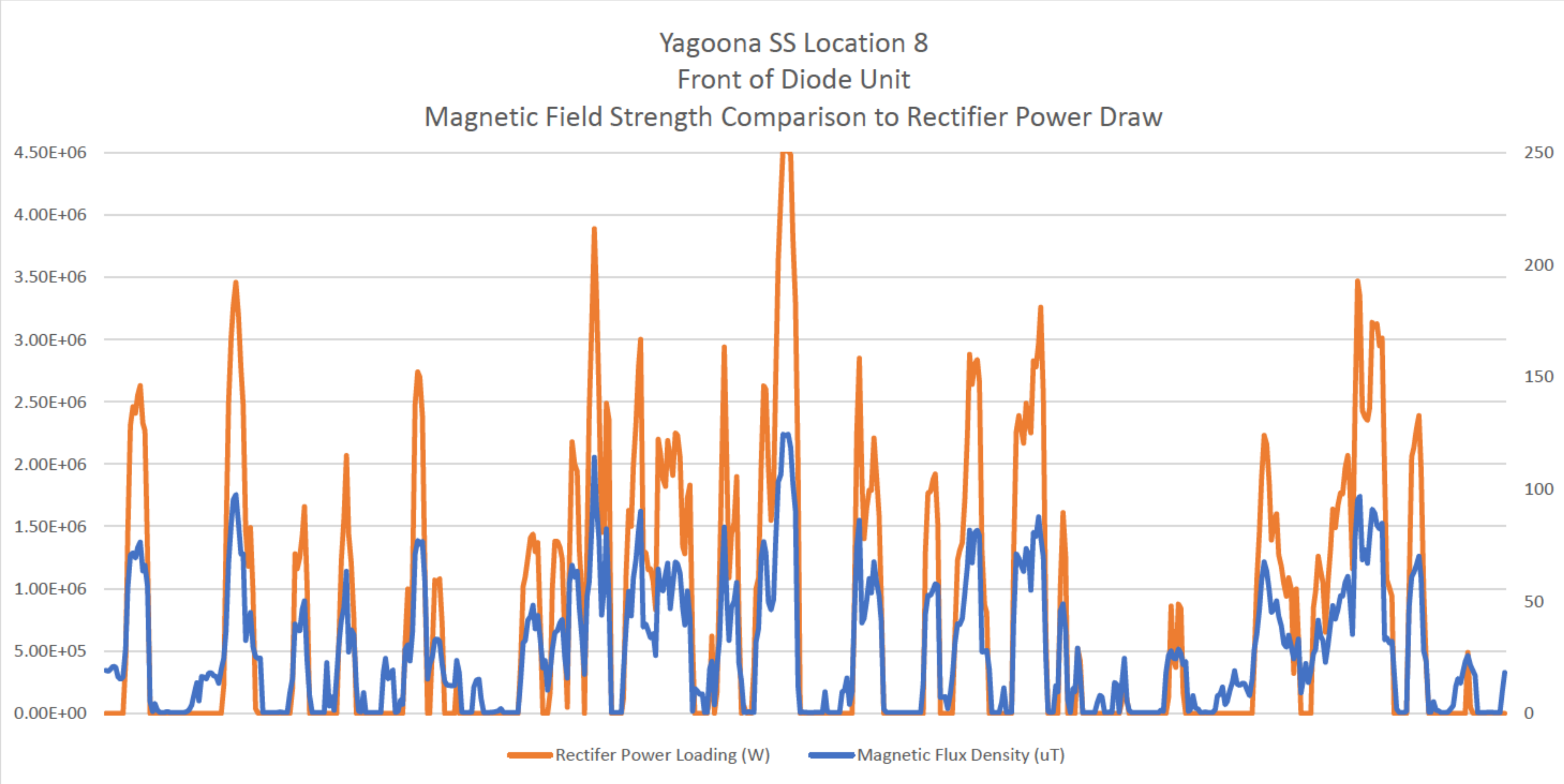


*Figure 4.5.4 Yagoona Substation Location 8 Comparison Graph*

## 4.6 Measurements Summary of Finding

As depicted in all the graphed results there is an extremely strong correlation between magnetic field strength and rectifier power loading. This conclusively proves that the observed magnetic fields can be attributed to the Traction supply and not another external source.

Preliminary findings show that there are specific locations within the substation that had a magnetic flux density greater than 200uT. This is a significant finding as it is above the exposure limit allowable by INCRIP guidelines for general public.

These values are significantly less than the exposure limits allowed for industrial exposure (1000uT) however as discussed in Chapter 2 the increased exposure limits come with an expectation of training and risk mitigation of the inherent hazards presented by exposure to electromagnetic fields.

By extrapolating the result and forming a trend line as shown in *Table 4.6.1* it can be seen that Warrawee Substation and Yagoona Substation are very similar this was expected as they are constructed from very similar designs.

Beecroft Substation show vastly different results. In Beecroft the cables have been installed at a height of 3.5m (1m higher than that of Warrawee and Yagoona). With the cables installed at a greater height initial assessment expected the Beecroft magnetic field strength levels to be lower than other substations however the extrapolated results shown in Figure 4.6.2 show that for the same power loading the magnetic field strength is greater.

The difference can be accounted for by the conductor configurations as seen in *Figure 4.6.1a & b.* At Beecroft, having more horizontal rows of cables per phase, presents a larger surface area of cables with the same phase hence a larger combined magnetic field strength.

*Figure 4.6.1a Beecroft 4 horizontal rows, 2 vertical columns.*

*Figure 4.6.1b Yagoona 2 horizontal rows, 4 vertical columns.*

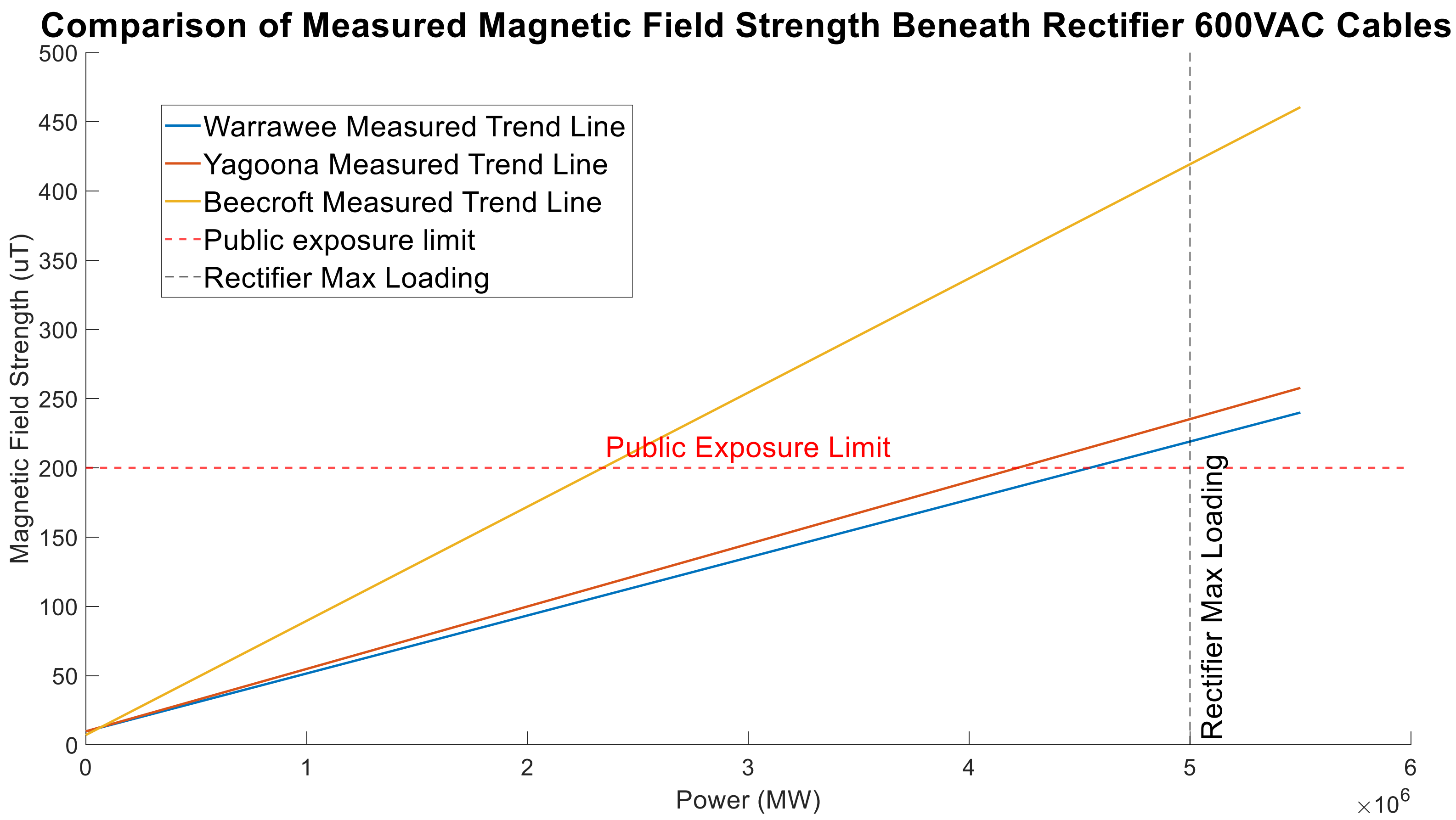


*Figure 4.6.2 Comparison of Measurement Trend Lines.*

A visual observation found whilst conducting testing was the common practice of the storage of materials and equipment in the area behind the rectifier diode unit. This implies that these areas would be commonly frequented by staff to access this equipment. This finding is of concern as this was the location that was found to have the highest levels of magnetic field strength.

*Figure 4.6.3 Storage of operating handles and ladders under 600V AC cables*

Because of the high magnetic field strength readings combined with the likelihood to be trafficked by workers, location 1 has been selected as the area of highest concern and the subject of further investigation with modelling simulations.

# Chapter 5 Simulink Modelling.

## 5.0 Justification for Modelling

Modelling is an important tool for engineering it allows an engineer to quickly and cost effectively test a concept for important factors before implementing the final design. Measurements such as the ones taken in Chapter 4 are useful but are very time-consuming requiring planning, access, expensive test equipment, certain qualifications for applying that test equipment, and produce large amounts of data to process. The on-site recording found in chapter 4 of this report have identified that there are areas in the traction substations where workers may be exposed to levels of EMF's that exceed the recommendations of the ICNRIP guidelines for general public. These findings have validated the need to further research into this topic. Whilst a continued on-site testing program would have benefits, modelling provides an alternative method to predict EMF exposure levels with significant time and financial benefits. The on-site recordings give a good depiction of the current real-world conditions, but they were however, limited by the current loading of the system at the time of testing. Objective 4 of this dissertation was to use modelling to overcome this loading limitation and be able to predict expected EMF exposure levels at worst case scenarios.

For this study it was decided to focus on testing location 1, the area underneath the 600V AC cables between the Rectifier Transformer and the Diode unit. This location was chosen as testing has show this location to have the highest levels of EMF exposure. This area is also likely to be trafficked by personnel on a regular basis as site investigations showed it to be commonly used for storage.

The two goals of developing this model were:

1) Correlate modelled results to on-site testing results to ensure a level of accuracy in modelling.
2) A simple model with three adjustable inputs to quickly see the effect of vertical position, horizontal position and loading may have on levels of EMF exposure.

All modelling in this study was completed with the specifications of the Warrawee Substation and Yagoona Substation designs however the Matlab script was coded to allow for simple adjustment of the parameters to correspond with any location. Beecroft Substation results were excluded from the modelling comparison due to the different configuration of cables.

## 5.1 Verification of Matlab Script

To confirm the modelling could produce an acceptable level of accuracy a Matlab script was coded applying the mathematical principles described in section 2.1.

Specification for dimension were taken from Sydney Trains standard configuration design drawing number EL0283610 – "SUBSTATIONS – UNITED GROUP 5MW 1500V DC RECTIFIER CUBICLE". It is likely that there is some variation between design and installation, but the impact is deemed to be negligible.

Initial testing showed a large variance in calculated results compared to measured results. This variance was identified to be due to the formula being derived from conductors being of infinite length (National Grid, 2023). To overcome this large variation a correction factor was applied to account for the short length of the cables between the rectifier and diode unit.

An array of currents was generated to simulate the loading conditions from 0 to 110% of Rectifier Full-Load. The horizontal X position of the point of interest was assumed to be centre of all cables. This could be improved by taking more accurate measurements in the testing procedure.

The logged data from Warrawee Substation and Yagoona measurements was imported into Matlab. *Figure 5.1* show the plotted comparison between the measured and modelled data. At Rectifier full loading the Trend of measured data from Warrawee Substation suggests a magnetic field strength of 220.1uT. At the same loading the modelled data calculates the magnetic field strength to a value of 229.8uT. This is a variance of 4.2% between measured and calculated data at full loading.

Comparing Yagoona Substation extrapolated from measurement trend result of 234.5uT at 5MW there is a variance of 2%.

This level of variance is determined to be acceptable given the inherent complicating factors of the measured results.

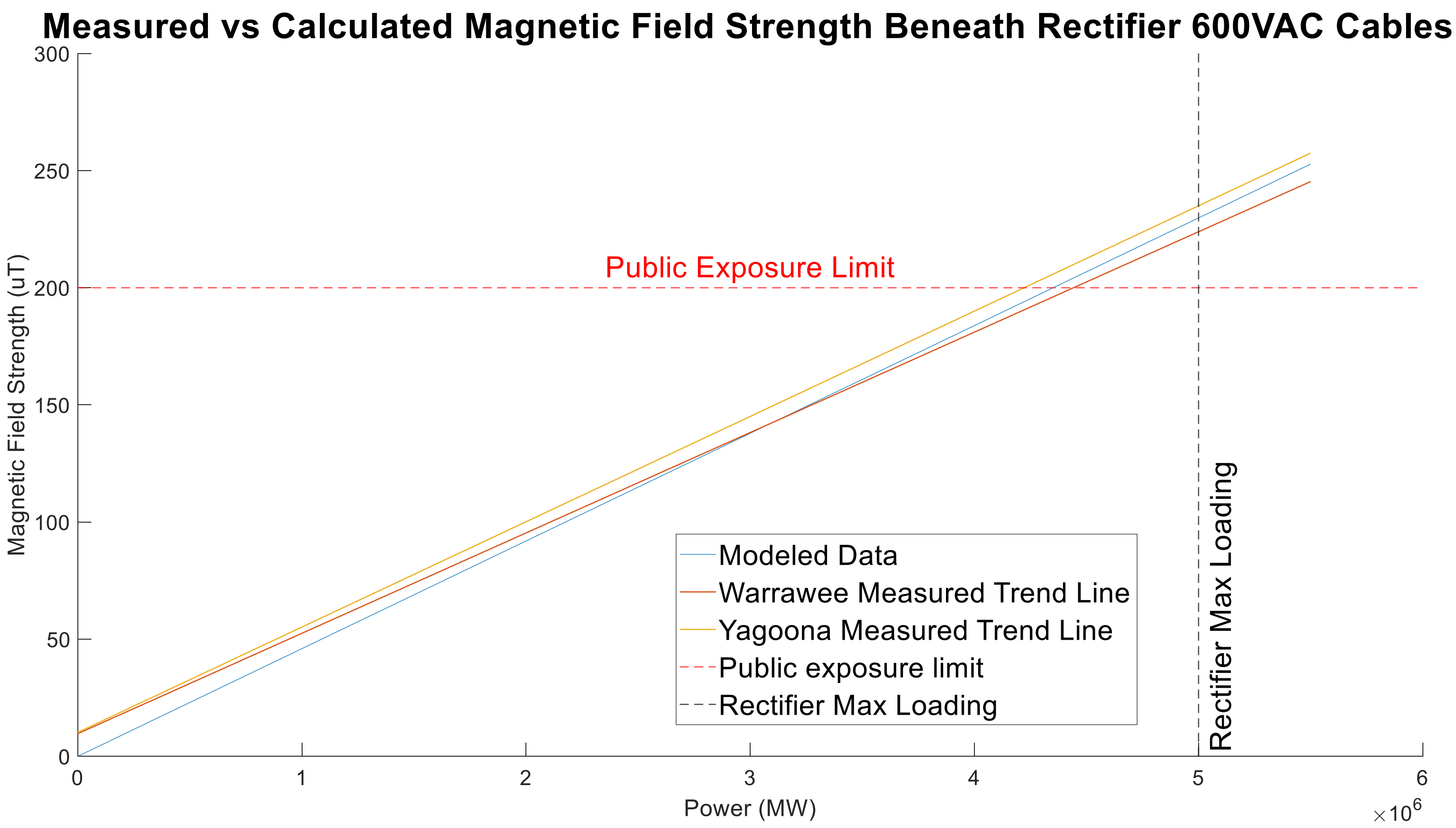


*Figure 5.1 Comparison of Measured and Calculated Results.*

## 5.2 Simulink Model

Running the Matlab script was successful in validating the calculated results compared to measured results. It was however complex and would not likely be able to be used by someone unconfident in Matlab coding. A Simulink model was decided on to allow for a simpler user interface that could be easily used by most people.

The design is modelled directly from the Sydney Trains standard configuration design drawing number EL0283610 – "SUBSTATIONS – UNITED GROUP 5MW 1500V DC RECTIFIER CUBICLE".

The model was designed to be as simple as possible to be able to deliver an accurate estimation of EMF exposure limits with three variable inputs. The model is comprised of six major components including:

- Three phase ideal 33kV 50hz AC supply input
- Three winding 5MW Rectifier Transformer. Primary side Star winding rated at 33kV. Dual 600V secondary windings, one as Star configuration and the other as a Delta with 30-degree phase shift.
- Custom designed block for Rectifier Diode Unit from Sydney Trains Design specifications
- Simulated variable traction load.
- Displayed measurements for High Voltage input current and loading.
- Displayed Magnetic Field Strength in µT.

The model works by inputting the calculated low voltage current into a modified version of the Matlab script used in section 5.1. Loading can be easily adjusted using "Traction Load" slider to view a loading range from 0 to 110% of Rectifier capacity. The height of the position of interest can be adjusted using the "Y Position" slider to adjust from floor level to the height of the cables. The horizontal position along the axis of the diode unit can be adjusted using the "X Position Slider". The Z-axis (position between transformer and diode unit was excluded from the model as the length of cable between the rectifier diode unit and transformer is very small for the formulas applied.

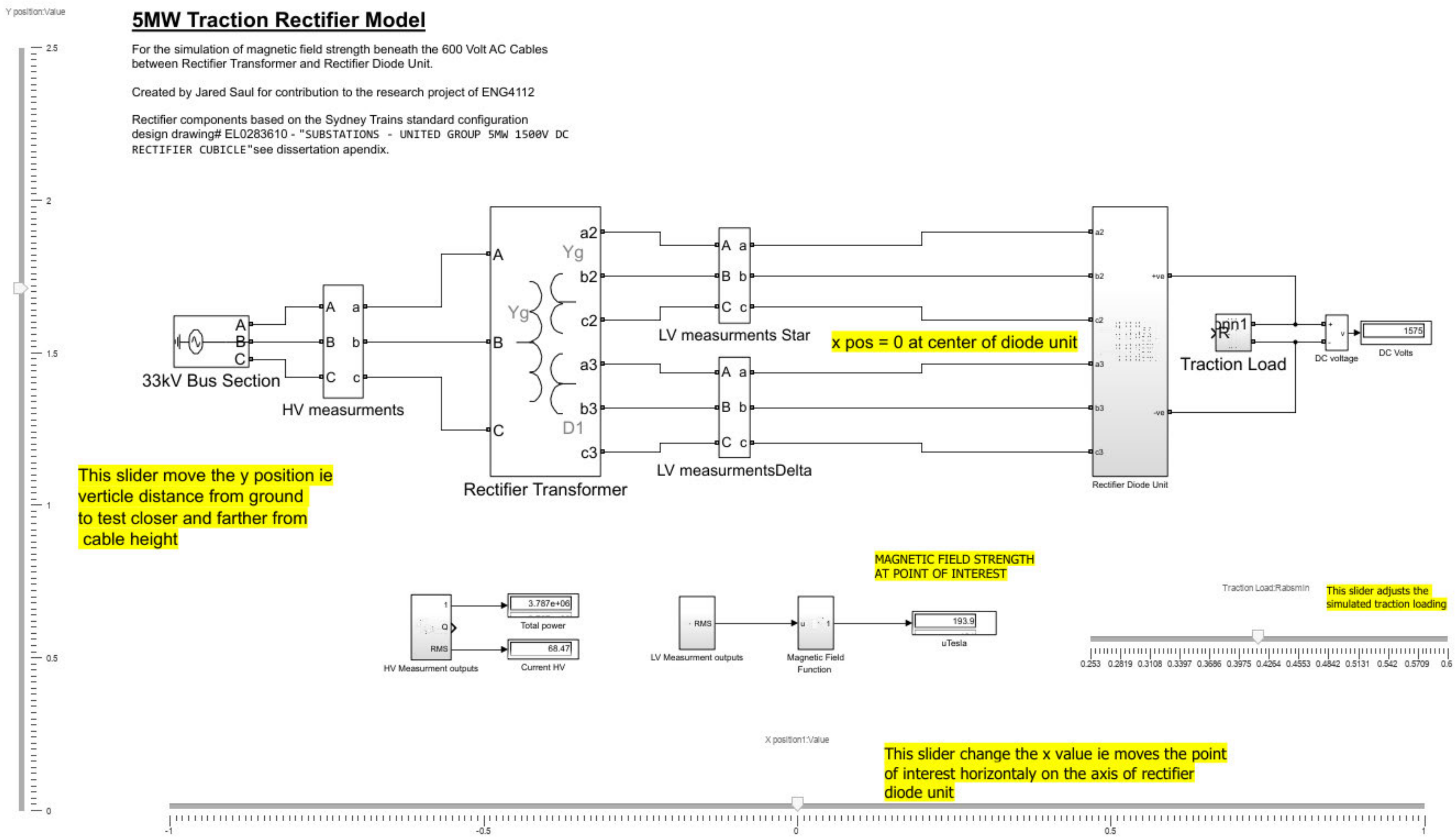


*Figure 5.2.1 Simulink Model.*

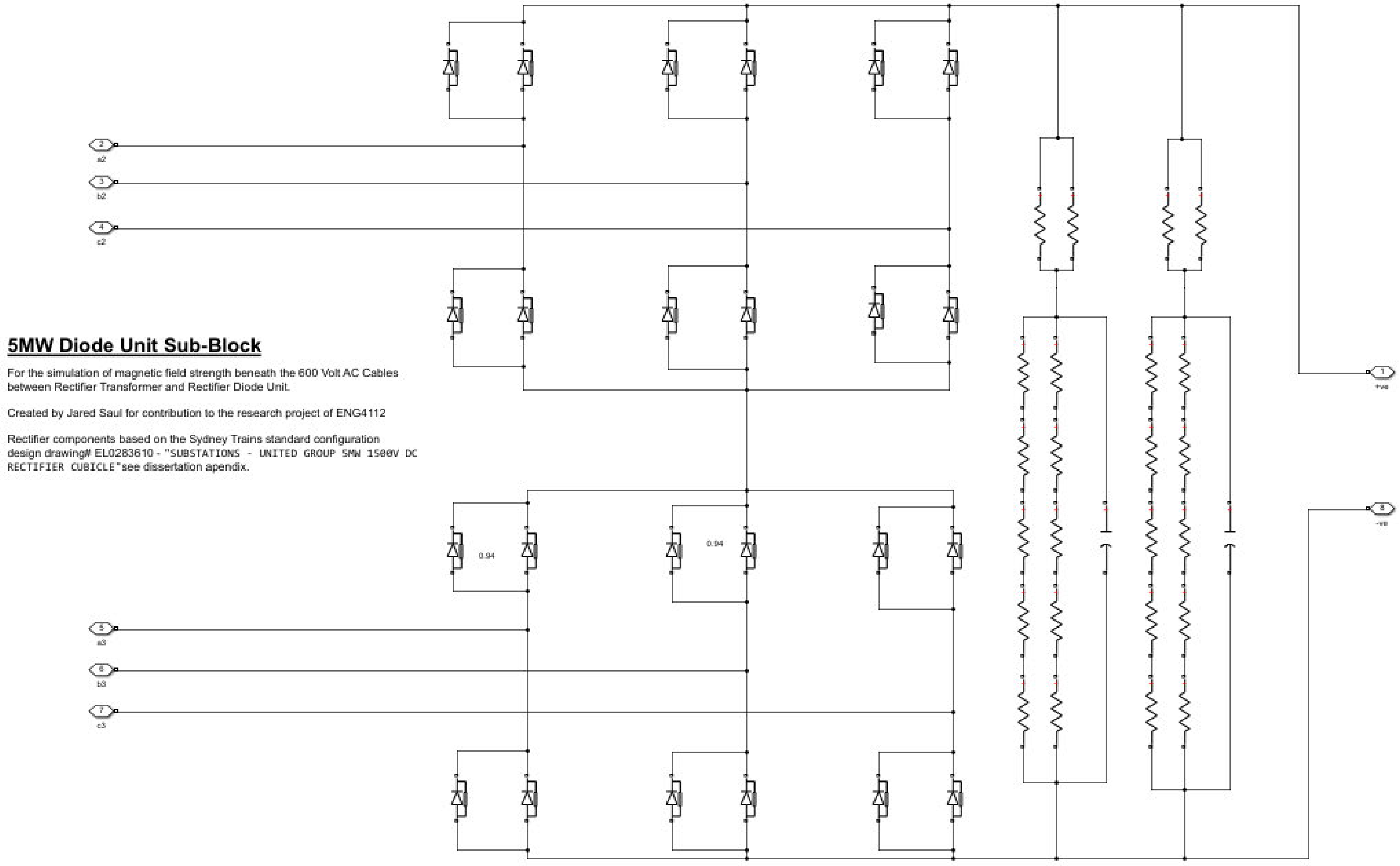


*Figure 5.2.2 Simulink Model Diode Unit Sub Block.*

Findings from using the adjustable parameters have been as expected with the Magnetic field levels increasing as the distance from the cables decreases. The centre of all cables has been identified as the area of highest exposure levels.

Simulating different parameters with the model has been useful to show the effect of change of height of the conductors as depicted in Figure 5.2.3. As all on-site testing was done at 1.76m (average height of Australian male) this model was able to show the expected exposure levels for taller individuals without having to conduct testing again on site.

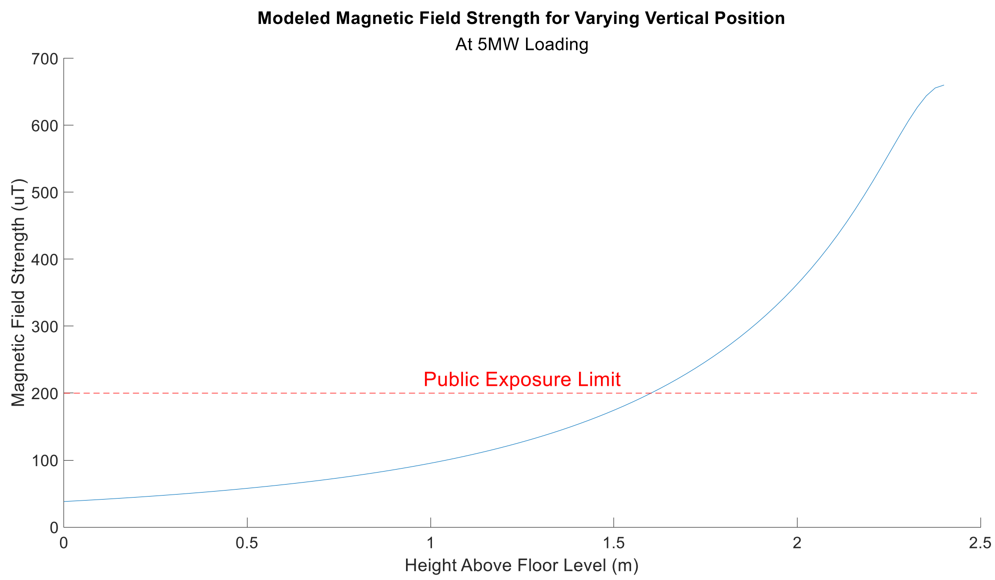


*Figure 5.2.3 Modelled Magnetic Field Strength for Variations in Height.*

Having the adjustable horizontal position has also aided in the ability to make recommendations on the installations of equipment in these locations when it is necessary to do so. *Figure 5.2.4* shows the changing magnetic field strength with varying horizontal position with a steady rectifier load of 5MW. Equipment installed on the outer flanks of the cables would be expected to see 10% less EMF exposure than if installed in the centre of the cables.

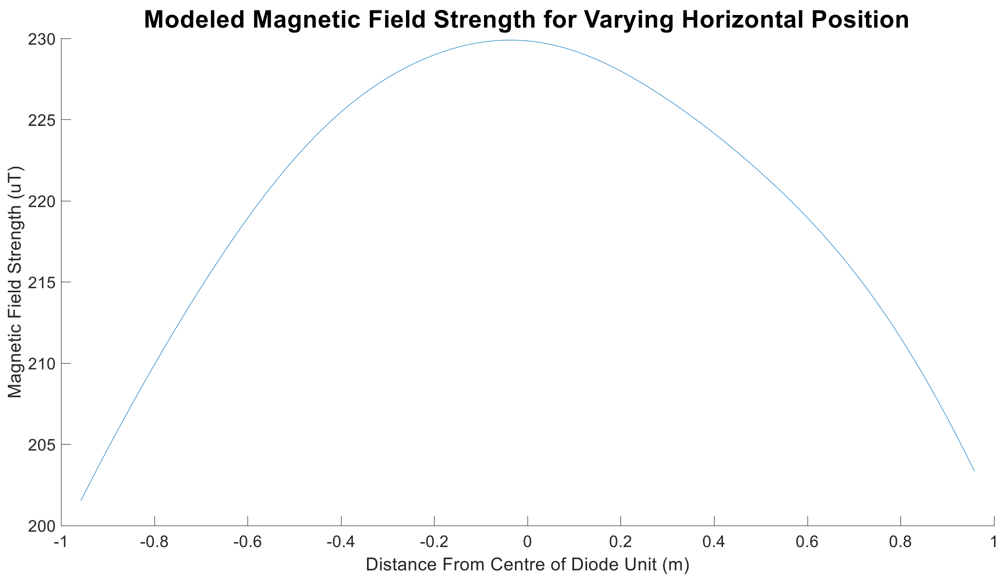


*Figure 5.2.4 Modelled Magnetic Field Strength for Variations in Horizontal Position.*

# Chapter 6: Recommendations and Conclusion

## 6.1 Recommendations

The WHO has stated that "Even when allowing for the legitimate desire for society to err on the side of safety, it is likely that it will be difficult to justify more than very low-cost measures to reduce exposure to ELF fields" (WHO, 2007). In line with this philosophy the following recommendations have only been considered due to their expected genuine improvements at low financial cost.

Recommendations have also been ranked aligned with the engineering hierarchy of controls (WorkSafetyQLD 2022) as seen in *Figure 6.1*.

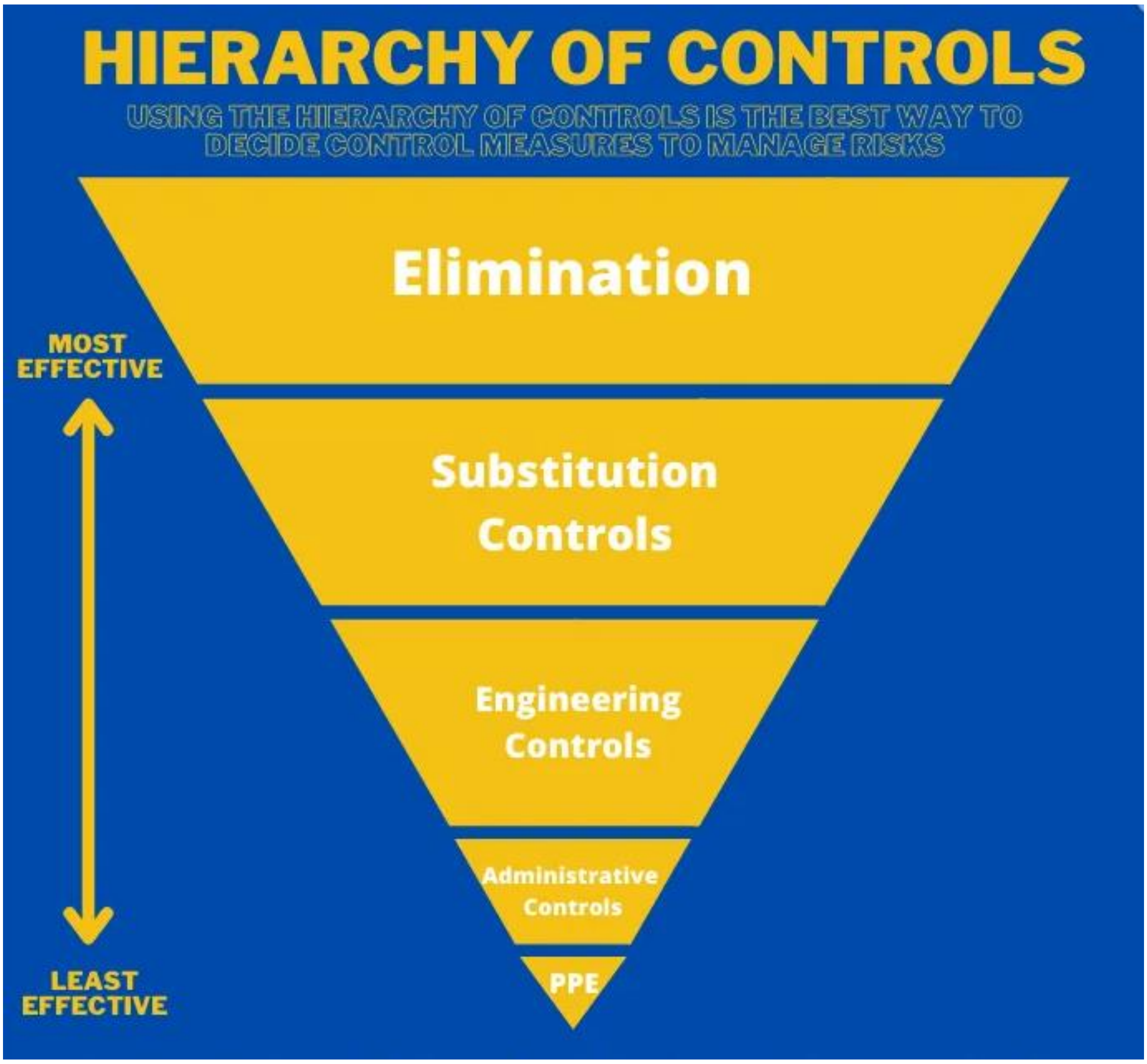


*Figure 6.1 Hierarchy of Controls (image WorkSafetyQLD, 2022).*

The preference of the hierarchy of controls is to eliminate the hazards. Recommendations 1 and 2 would be the most effective at reducing EMF exposure but these recommendations can only be cost effective in the early design stage of a substation and is unlikely to be practical for existing builds.

The next level of control that can be applied is engineering controls as seen in recommendation 3 and 4. These recommendations are the most likely to suitable for existing locations.

Recommendations 5 and 6 are administrative controls and will require significant ongoing effort from workers and management but will ensure all necessary parties are informed of any hazards and any changes in regulations to controls them.

In line with this philosophy and the finding of this study the following recommendations have been made.

1) EQUIPTMENT LOCATION. New substation designs must account for the high levels of EMF's underneath the 600V AC cables between the Rectifier Transformer and Diode unit. Installation of equipment in this location should be avoided. If installation of equipment in this location cannot be avoided due to space limitations priority must be given to installation on the side rather than centred. As shown in modelling installation of equipment on the sides can have significant decrease in EMF exposure.
2) CABLE CONFIGURATIONS. As discussed in section 2.4 optimised conductor arrangements can have a drastic affect in the mitigation of EMF's. As the run between rectifier transformer and diode unit is very short there is not an opportunity to twist phase cabling to cancel each other out. Of the two configurations seen during testing the configuration of 2 horizontal 4 vertical conductors (seen at Warrawee Substation and Yagoona Substation was significantly better at minimizing EMF exposure when compared to the 4 horizontal 2 vertical conductor configuration (seen at Beecroft Substation).
3) SHEILDING. A shielding plate should be installed on cable mounting brackets beneath the 600V AC cables between the rectifier diode unit and the transition to the outdoor area. From table 2.5 a shielding plate layered by a sheet of 2mm thickness steel and a sheet of 2mm thickness aluminium could reduce EMF strength by up to 60%. Sheild would be a simple and cost-effective way to mitigate EMF exposure in all substations however, existing Substations where equipment has already been installed underneath the 600V AC cables such as Beecroft Substation should be prioritised for trials first.

4) RESTRICT ACCESS. Access should be restricted to areas identified as high exposure. This can be achieved easily through sign posting and controlled locking systems for the outdoor areas. Indoor areas again can be sign posted and fenced off similar to the plastic chain link used to exclude access behind ACCB seen in *Figure 4.4.1.1*
5) AWARENESS OF STAFF. Staff that are working in Substations need to be educated to be aware of the presence and levels of Electromagnetic Hazards in the workplace. Having a greater understanding of the levels of exposure would allow them to make informed decisions about working in those areas and would improve the safety culture overall.
6) CONTINUAL MONITORING OF UP-TO-DATE INFORMATION. As research continues into the effects of EMFs on person and equipment there will undoubtedly be update to recommendation regarding the management of EMF hazards in the workplace. By designating an individual responsible for maintaining membership in a professional organisation technical society such as Engineering Australia EMC committee is a good way to stay informed of any updates regarding this topic.

Recommendations have also been ranked aligned with the engineering hierarchy of controls. The preference of the hierarchy of controls is to eliminate the hazards. Recommendations 1 and 2 would be the most effective at reducing EMF exposure but these recommendations can only be cost effective in the early design stage of a substation and is unlikely to be practical for existing builds.

The next level of control that can be applied is engineering controls as seen in recommendation 3 and 4. These recommendations are the most likely to suitable for existing locations.

Recommendations 5 and 6 are administrative controls and will require significant ongoing effort from workers and management but will ensure all necessary parties are informed of any hazards and any changes in regulations to controls them.

## 6.2 Conclusion

Exposure to electromagnetic fields has been a controversial issue within the power industry for many years and continues to be a point of research to this day. A literature review has shown that whilst there has been much research into the possibility of negative health impacts from the exposure to electromagnetic fields there has not been any documented link to prove this. Even without any current evidence to show a link to between exposure to electromagnetic fields and negative health effects, standard making authorities have acknowledge there is only a limited understanding and have implemented a policy of prudent avoidance. Companies such as Sydney Trains have a responsibility to provide their staff with a safe workplace by understanding and controlling the limits of exposure to staff in their work activities.

The primary objective of this study was to gain a better understanding of current industry practices for testing electromagnetic fields and how they can be applied to the unique conditions of DC traction substations. This has been achieved by adapting some of the more position-based AC substation testing to the developed EMF/loading comparison-based testing carried out that is more suited to the dynamic loading of a Traction environment. The testing conducted at typical Sydney Trains substations have shown that magnetic field levels are within the limits of industrial exposure but certain locations within the substation can exceed the recommended limits for public exposure. The findings indicate that it is the unique DC components of a rail traction substation that have the highest-level electromagnetic field emissions which validated the need for further research.

Whilst on-site measurements have provided an insight into the EMF exposure levels of current conditions, they are limited to the current network loading conditions. The developed Matlab Simulation has provided an alternate method of estimating EMF exposure levels in future heavy loading conditions. Testing with the modelling simulation has shown that even at full rated loading the exposure levels will not exceed the recommended occupational limits of ICNIRP.

The circumstances allowing the higher exposure limits for an industrial setting is that in industrial environments there is an expectation of understanding and implementation of controls for the hazard. As part of the final objective of this dissertation, recommendations have been made to mitigate EMF exposure levels in the areas of highest concern. As the recommendations have only been considered if they are of low financial expense they can be implemented easily and provide evidence of Sydney Trains compliance to the industry philosophy of prudent avoidance and overall safety culture.

Overall completion of the dissertation has achieved the project aim by developing a greater understanding of electromagnetic fields in the unique environment of DC traction substations. If the suggested recommendations can be adopted this research will benefit the industry by improving worker safety in line with current recommendations and mandated guidelines.

## 6.3: Further Work

1) This dissertation has shown that Rail Traction equipment is capable of producing electromagnetic fields above the recommended exposure limits for the general public set by Australian Standards. Whilst the levels are considerably less than that of occupational exposure pursuing all or some of the recommendations made in section 6.2 would provide evidence of adherence to policy of electromagnetic mitigation.

2) After any EMF mitigation recommendations are trialled, new on-site measurements should be taken to ascertain the new EMF exposure levels. The new comparison data can be used to present a cost/benefit analysis of the mitigation measure to determine if it should continue to be implemented.

3) An investigation should be conducted for the entire Sydney Trains Network to identify any variations in rectifier designs that are currently in place that may cause a difference in exposure limits such as the cable configurations of Beecroft Substation. Once identified these areas should be logged and data be used for further development of the simulation model.

4) The testing and simulations that have been conducted in this report have been centred around the power source being the Traction Substations. Testing in traction substations was selected as it was identified as a knowledge gap in the literature review but since presenting the finding of this study to industry peers within Sydney Trains there has been considerable interest in extending the study into more publicly accessible areas including on the rolling stock itself. To perform this testing at an acceptable level new more suitable equipment with certifiable calibration would need to be acquired.

5) Whilst the testing of this dissertation has identified areas of concern for EMF exposure it is still unclear how often worker will be in these locations to be exposed. By conducting a sensitivity analysis for staff frequenting traction substation would allow for the analysis of EMF exposure levels of a worker carrying out their normal duties over a period of time.

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# Appendix A Risk Assessment

UniSQ

## Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

| | | | |
|---|---|---|---|
| **Name** | **ENG4111/ENG4112 Measurements of EMFs** | **Current Rating** | **Residual Rating** |
| **Location** | **Off Campus: Various Substations within the Sydney Trains Network** | Low | Very Low |
| **Business Unit** | | **Last Review Date** | **Risk Owner** |
| USQ Council | | 20/03/2023 | Jared Saul |
| **Risk Assessment Team** | | **Risk Approver** | |
| Jared Saul | | Marilia Menezes De Oliveira | |
| **Additional Notes** | | | |
| | | | |
| **Describe task / use** | | | |
| Research into EMFs produced in DC traction substations to fulfil the requirements of ENG4111 and ENG4112 Research Project. | | | |

UniSQ

# Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

## Risk Factors

| **Risk Factor** | Electrical |
|---|---|

**Description**

Measurements taken in HV Substations

- Does the work involve:
  - Low Voltage Electricity -- Yes
  - Electromagnetic fields -- Yes
  - High Voltage Electricity, Electrical Substations, Overhead powerlines -- Yes
- Could hazards be caused by:
  - Exposed electrical parts? -- Yes
- Will the work be affected by the loss of power? -- No
- Will electricity be used in wet or potentially wet conditions? -- No

UniSQ

# Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

| Low | Very Low | | |
|---|---|---|---|
| **Existing Controls** | **Proposed Controls** | | |
| • 5 - Administration: Qualified and trained person conducting testing | Description | Responsibility | Target Date |
| | Isolation required no work on live equiptment | | 20/06/2023 |

UniSQ

# Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

| Risk Factor | Ergonomics and Manual Handling |
|---|---|

**Description**

Injury such as slip trips, falls or back starins.

- Does the activity involve manual tasks: -- No
- Does the work involve:
- Lifting, carrying and walking? -- Yes
- Does the work involve sustaining static postures for long periods of time e.g. sitting or standing? -- No
- Are there egonomic hazards related to:

UniSQ

# Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

| Very Low | Very Low | | |
|---|---|---|---|
| **Existing Controls** | **Proposed Controls** | | |
| • 6 - PPE: maintain clean worksites | Description | Responsibility | Target Date |
| | maintain clean worksites. Use handrails. Correct lifting techniques. | | |

UniSQ

# Risk Assessment [Ref Number: 2169]

Date Printed: Friday, 19 May 2023

## Appendix

| Risk Matrix Level | |
|---|---|
| Very Low | Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate |
| Low | Task can proceed upon approval of the risk assessment by the relevant supervisor, manager or higher delegate |
| Medium | Task can proceed upon approval of the risk assessment by a Category 4 or higher delegate |
| High | Task can only proceed in extraordinary circumstances provided there is authorisation by the Vice Chancellor |
| Extreme | Task must not proceed. Appropriate and prompt action must be taken to reduce the risk to as low as reasonable practicable |

| ATTACHMENTS |
|---|
| |

# Appendix B Project Specification

ENG4111/4112 Research Project

Project Specification

For: Jared Saul [redacted] Major: BENH Power Engineering

Title: Measurement and Simulation of Electromagnetic Fields in High Voltage Direct Current Traction Substations

Supervisors: Dr Marilia Menezes de Oliveira

Enrolment: ENG4111 – EXT S1, 2023 ENG4112 – EXT S2, 2023

Project Aim: Develop a greater understanding of the levels of electromagnetic fields (EMF) currently being produced by a sample group of DC traction substations in the Sydney Trains network.

Objectives: 1. Design a simulation model to calculate EMF levels at full loading conditions.
2. Apply research to review and make recommendations on the suitability of risk mitigation measures taken to minimize potential hazardous EMF exposure to persons and sensitive electronic equipment in substations within a sample of Sydney Trains network.

**Program: Version 1, 6th March 2023**

1. Research background information relating to exposure to EMFs and the effect on electronic devices, standards, and regulations regarding exposure to EMFs, testing requirements for equipment being installed in substations and how shielding can be used to minimise the negative effects of EMFs.
2. Research testing current methodologies for the measurement of electronic and magnetic fields. Select and acquire a suitable meter for testing.
3. Modify existing testing methodologies to preform my own testing on several DC traction substations with measurements cantered around rectifier transformers.
4. Develop a Matlab model capable of predicting EMF exposure levels at substation full capacity conditions using base electromagnetic principles and use measured results as a comparison/ verification tool.
5. Present observations on the likely effect of EMF within substations and Make recommendations on improvements that can be made in substation design to limit the effects of EMF on sensitive electronic equipment.

*If time and resource permit:*

6. Conduct a sensitivity analysis regarding human exposure to EMFs for staff frequently working inside high voltage DC substations by comparison to current safe exposure limit standards.

# Appendix C Matlab Simulation Script

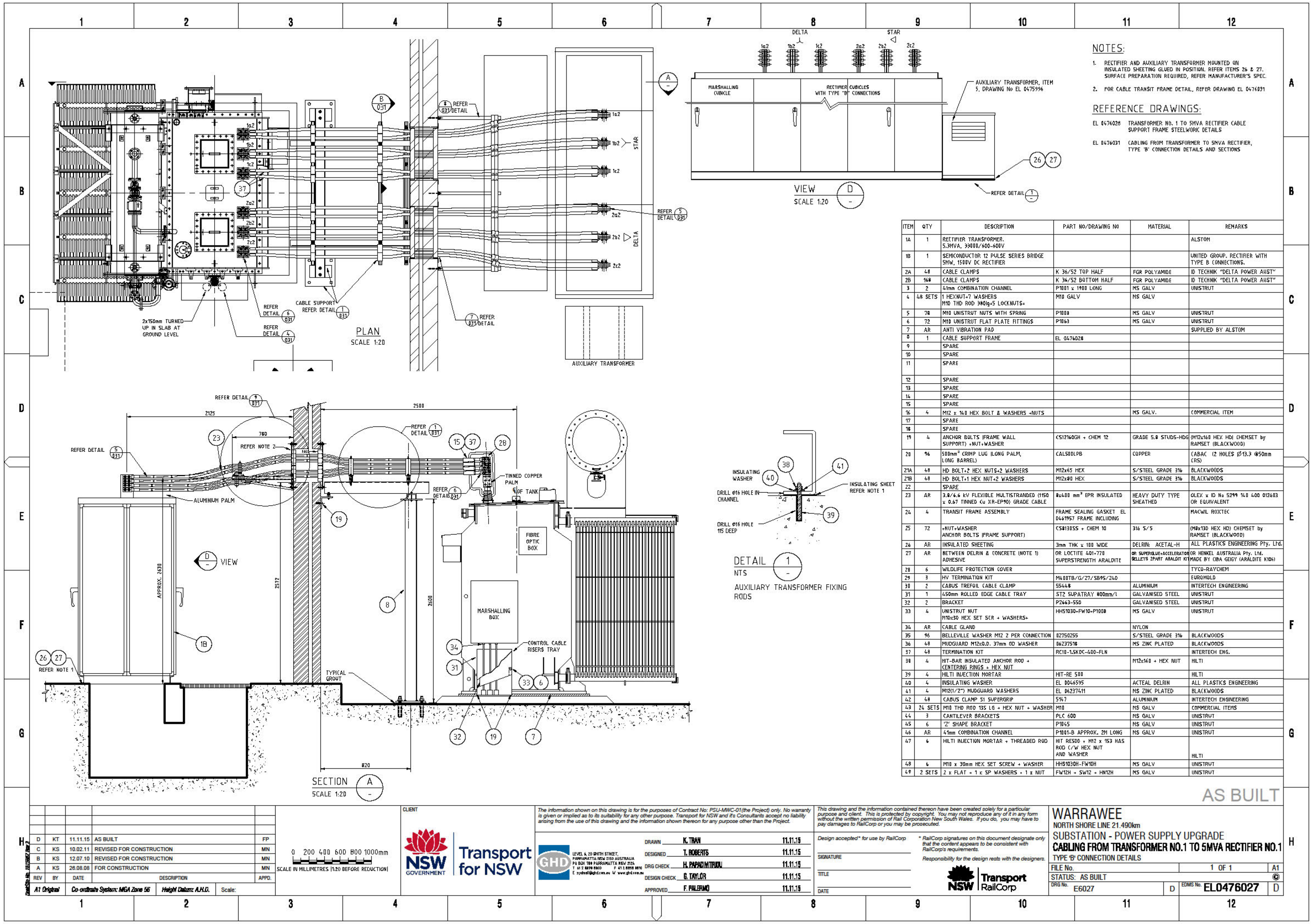
```
%%######################################################################
%                                                                      %
%             Calculations of Magnetic Field Strength in               %
%                                DC Substations                        %
%                                                                      %
%**********************************************************************
%                                                                      %
% Author:                 Jared Saul                                   %
% Student Number:         [redacted]                                   %
% Created:                26/07/2023                                   %
%                                                                      %
% Modified:                                                            %
%    method adapted from National Grid UK                              %
%         https://www.emfs.info/wp-content/uploads/2014/07/....        %
% Howtocalculatethemagneticfieldfromathree.pdf                         %
%         https://www.emfs.info/what/measuring/finite/                 %
%######################################################################

%%
close all;         %clears variables and closes opened figures
%clc;                       %clears control screen
%clear all;

u0=4*pi*(10^-7); % magnetic permeability of free space

% input the location of conductors in two dimensional coordinate system.
% cordinate are derived from measurments taken in drawing# EL0283610
% "SUBSTATIONS - UNITED GROUP 5MW 1500V DC RECTIFIER CUBICLE"
% Variable must be adjusted for any alternate deigns

V1= 33e3;  %voltage primary
V2 = 600;  %voltage secondary
MVA = 5e6; %transformer power rating

Conductor_height=2.505;

Star_Ax = -(.358+.358+(.484/2));
Star_Ay = Conductor_height;

Star_Bx = -(.358+(.484/2));
Star_By = Conductor_height;

Star_Cx = -(.484/2);
Star_Cy = Conductor_height;

Delta_Cx = (.358+.358+(.484/2));
Delta_Cy = Conductor_height;

Delta_Bx = (.358+(.484/2));
Delta_By = Conductor_height;

Delta_Ax = (.484/2);
Delta_Ay = Conductor_height;
```

```
%input the position of interest
% height of 1.76m used as average height of Australian male
Py= 1.76;
%centered on conductor
Px = 0;


%input length of cable
L=2.125/2; %taken form drawing EL0476027

FLC = MVA/(sqrt(3)*V1); %Full load current


%input primary (33kV) current
I1= linspace(0,FLC*1.1,100); %A array of currents ranginging
% from 0 to %110 loading

%convert primary current into secondary

turnsratio = V1/V2; %primary / secondary voltage
I2 = I1 * turnsratio /2;  %dual winding transformer


%%

f=50; %frequency [Hz]
t=(0:1/(f*100):(1/f)*2);


w=2*pi*f;

for i = 1:100

    I =I2(i);
%magnetic field contribution from A phase in Star Winding
pshift=0;  %phase
R_StarA =  sqrt((Star_Ay - Py)^2+(Star_Ax-Px)^2);
BStarAx=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarA)))*((Star_Ay - Py)/R_StarA);
BStarAy=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarA)))*((Star_Ax - Px)/R_StarA);

%magnetic field contribution from B phase in Star Winding

pshift=-120;  %phase
R_StarB =  sqrt((Star_By - Py)^2+(Star_Bx-Px)^2);
BStarBx=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarB)))*((Star_By - Py)/R_StarB);
BStarBy=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarB)))*((Star_Bx - Px)/R_StarB);

%magnetic field contribution from C phase in Star Winding

pshift=120;  %phase
R_StarC =  sqrt((Star_Cy - Py)^2+(Star_Cx-Px)^2);
BStarCx=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarC)))*((Star_Cy - Py)/R_StarC);
BStarCy=u0*((I*sin(w*t+pshift))/(2*pi*(R_StarC)))*((Star_Cx - Px)/R_StarC);

%magnetic field contribution from A phase in Delta Winding

pshift=30;  %phase
R_DeltaA =  sqrt((Delta_Ay - Py)^2+(Delta_Ax-Px)^2);
```

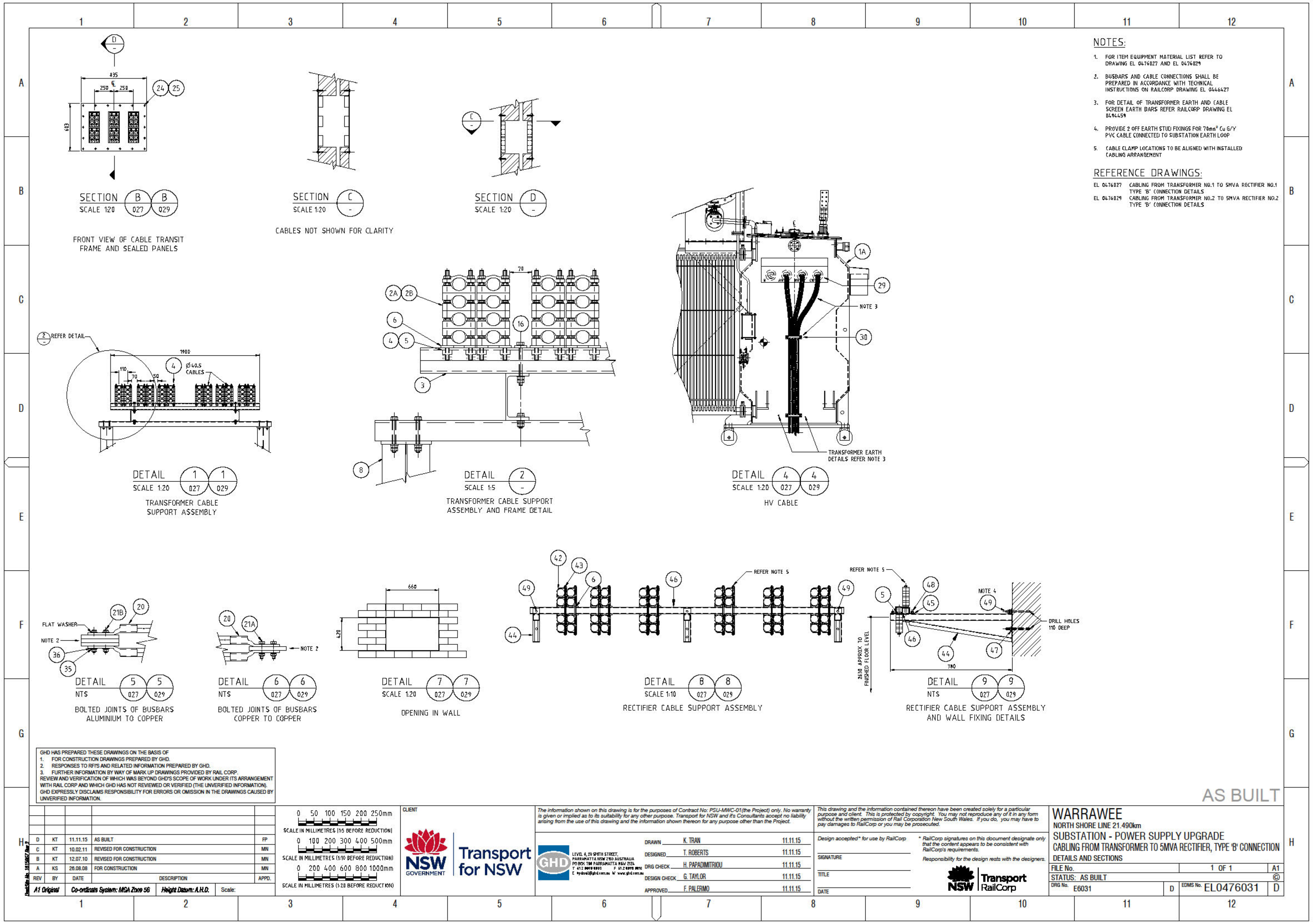
```
BDeltaAx=u0*((I*sin(w*t+pshift))/(2*pi*(R_DeltaA)))...
    *((Delta_Ay - Py)/R_DeltaA);
BDeltaAy=u0*-((I*sin(w*t+pshift))/(2*pi*(R_DeltaA)))...
    *((Delta_Ax - Px)/R_DeltaA);


%magnetic field contribution from B phase in Delta Winding

pshift=-90;  %phase
R_DeltaB =  sqrt((Delta_By - Py)^2+(Delta_Bx-Px)^2);
BDeltaBx=u0*((I*sin(w*t+pshift))/(2*pi*(R_DeltaB)))...
    *((Delta_By - Py)/R_DeltaB);
BDeltaBy=u0*-((I*sin(w*t+pshift))/(2*pi*(R_DeltaB)))...
    *((Delta_Bx - Px)/R_DeltaB);


%magnetic field contribution from C phase in Star Winding

pshift=150;  %phase
R_DeltaC =  sqrt((Delta_Cy - Py)^2+(Delta_Cx-Px)^2);
BDeltaCx=u0*((I*sin(w*t+pshift))/(2*pi*(R_DeltaC)))...
    *((Delta_Cy - Py)/R_DeltaC);
BDeltaCy=u0*-((I*sin(w*t+pshift))/(2*pi*(R_DeltaC)))...
    *((Delta_Cx - Px)/R_DeltaC);
%figure, plot(t,BDeltaCy)
%hold on
%plot(t,BDeltaCx)
%xlabel('time(s)')
%ylabel('magnetic field(t)')


%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%
%  Sum of all components  normalised                                        %
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%


Bx_total = sqrt(BDeltaAx.^2+BDeltaBx.^2+BDeltaCx.^2 ...
        +BStarAx.^2+BStarBx.^2+BStarCx.^2);

By_total = sqrt(BDeltaAy.^2+BDeltaBy.^2+BDeltaCy.^2 ...
        +BStarAy.^2+BStarBy.^2+BStarCy.^2);


%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%
% Sum of X and Y                                                            %
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%
HRMS =Bx_total+By_total;



%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%
% As this formula is for a line of infinite length Need a correction   %
% factor to account for the short lenghth of cable                      %
%reduce it by the sin of the angle subtended from worse case            %
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%

C_Factor = L/sqrt(((Conductor_height - Py)^2 + L^2))/4;
HRMS = HRMS*C_Factor;
```

```
G = rms(HRMS);

uT(i) = G*10^6;
loading(i) = (I2(i)*V2*sqrt(3)*2);

end


%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%
% Plot Results                                                          %
%                                                                       %
%                                                                       %
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$%

hold on
plot(loading,uT,'DisplayName',"Modeled Data");



yline(200,"--r",'Public Exposure Limit',LineWidth=1, FontSize=25,...
    LabelHorizontalAlignment='center',DisplayName="Public exposure limit")
xline(5e6,"--k",'Rectifier Max Loading', LineWidth=1, FontSize=25,...
    LabelVerticalAlignment='bottom',DisplayName="Rectifier Max Loading")

ylabel("Magnetic Field Strength (uT)",FontSize=25)
xlabel('Power (MW)',FontSize=25)
title('Calculated Magnetic Field Strength'...
    ,'Beneath Rectifier 600VAC Cables',FontSize = 30 )

legend(FontSize=25)
 ax.FontSize = 20
```

# Appendix D Warrawee Rectifier Design




| ITEM | QTY | DESCRIPTION | PART NO/DRAWING NO | MATERIAL | REMARKS |
|---|---|---|---|---|---|
| 1A | 1 | RECTIFIER TRANSFORMER, 5.3MVA, 33000/600-600V | | | ALSTOM |
| 1B | 1 | SEMICONDUCTOR 12 PULSE SERIES BRIDGE 5MW, 1500V DC RECTIFIER | | | UNITED GROUP, RECTIFIER WITH TYPE B CONNECTIONS. |
| 2A | 48 | CABLE CLAMPS | K 36/52 TOP HALF | FGR POLYAMIDE | ID TECHNIK "DELTA POWER AUST" |
| 2B | 168 | CABLE CLAMPS | K 36/52 BOTTOM HALF | FGR POLYAMIDE | ID TECHNIK "DELTA POWER AUST" |
| 3 | 2 | 41mm COMBINATION CHANNEL | P1001 x 1900 LONG | MS GALV | UNISTRUT |
| 4 | 48 SETS | 1 HEXNUT+7 WASHERS M10 THD ROD 380lg+5 LOCKNUTS+ | M10 GALV | MS GALV | |
| 5 | 78 | M10 UNISTRUT NUTS WITH SPRING | P1008 | MS GALV | UNISTRUT |
| 6 | 72 | M10 UNISTRUT FLAT PLATE FITTINGS | P1063 | MS GALV | UNISTRUT |
| 7 | AR | ANTI VIBRATION PAD | | | SUPPLIED BY ALSTOM |
| 8 | 1 | CABLE SUPPORT FRAME | EL 0476028 | | |
| 9 | | SPARE | | | |
| 10 | | SPARE | | | |
| 11 | | SPARE | | | |
| 12 | | SPARE | | | |
| 13 | | SPARE | | | |
| 14 | | SPARE | | | |
| 15 | | SPARE | | | |
| 16 | 4 | M12 x 140 HEX BOLT & WASHERS +NUTS | | MS GALV. | COMMERCIAL ITEM |
| 17 | | SPARE | | | |
| 18 | | SPARE | | | |
| 19 | 4 | ANCHOR BOLTS (FRAME WALL SUPPORT) +NUT+WASHER | CS12160GH + CHEM 12 | GRADE 5.8 STUDS-HDG | (M12x160 HEX HD) CHEMSET by RAMSET (BLACKWOOD) |
| 20 | 96 | 500mm² CRIMP LUG (LONG PALM, LONG BARREL) | CAL500LPB | COPPER | CABAC (2 HOLES Ø13.3 @50mm CRS) |
| 21A | 48 | HD BOLT+2 HEX NUTS+2 WASHERS | M12x65 HEX | S/STEEL GRADE 316 | BLACKWOODS |
| 21B | 48 | HD BOLT+1 HEX NUT+2 WASHERS | M12x80 HEX | S/STEEL GRADE 316 | BLACKWOODS |
| 22 | | SPARE | | | |
| 23 | AR | 3.8/6.6 kV FLEXIBLE MULTISTRANDED (1150 x 0.67 TINNED Cu XR-EP90) GRADE CABLE | 8x400 mm² EPR INSULATED | HEAVY DUTY TYPE SHEATHED | OLEX x ID No 5299 140 400 012603 OR EQUIVALENT |
| 24 | 4 | TRANSIT FRAME ASSEMBLY | FRAME SEALING GASKET EL 0461957 FRAME INCLUDING | | MACWIL ROXTEC |
| 25 | 72 | +NUT+WASHER ANCHOR BOLTS (FRAME SUPPORT) | CS8130SS + CHEM 10 | 316 S/S | (M8x130 HEX HD) CHEMSET by RAMSET (BLACKWOOD) |
| 26 | AR | INSULATED SHEETING | 3mm THK x 100 WIDE | DELRIN: ACETAL-H | ALL PLASTICS ENGINEERING Pty. Ltd. |
| 27 | AR | BETWEEN DELRIN & CONCRETE (NOTE 1) ADHESIVE | OR LOCTITE 401+770 SUPERSTRENGTH ARALDITE | OR SUPERGLUE+ACCELERATOR SELLEYS 2PART ARALDIT KIT | OR HENKEL AUSTRALIA Pty. Ltd. MADE BY CIBA GEIGY (ARALDITE K106) |
| 28 | 6 | WILDLIFE PROTECTION COVER | | | TYCO-RAYCHEM |
| 29 | 3 | HV TERMINATION KIT | M400TB/G/27/SB95/240 | | EUROMOLD |
| 30 | 2 | CABUS TREFOIL CABLE CLAMP | 55448 | ALUMINIUM | INTERTECH ENGINEERING |
| 31 | 1 | 450mm ROLLED EDGE CABLE TRAY | ST2 SUPATRAY 800mm/l | GALVANISED STEEL | UNISTRUT |
| 32 | 2 | BRACKET | P2663-550 | GALVANISED STEEL | UNISTRUT |
| 33 | 4 | UNISTRUT NUT M10x30 HEX SET SCR + WASHERS+ | HHS1030+FW10+P1008 | MS GALV | UNISTRUT |
| 34 | AR | CABLE GLAND | | NYLON | |
| 35 | 96 | BELLEVILLE WASHER M12 2 PER CONNECTION | 02750255 | S/STEEL GRADE 316 | BLACKWOODS |
| 36 | 48 | MUDGUARD M12xO.D. 37mm OD WASHER | 06237518 | MS ZINC PLATED | BLACKWOODS |
| 37 | 48 | TERMINATION KIT | RC10-1.5KDC-400-FLN | | INTERTECH ENG. |
| 38 | 4 | HIT-BAR INSULATED ANCHOR ROD + CENTERING RINGS + HEX NUT | | M12x160 + HEX NUT | HILTI |
| 39 | 4 | HILTI INJECTION MORTAR | HIT-RE 500 | | HILTI |
| 40 | 4 | INSULATING WASHER | EL 0046595 | ACTEAL DELRIN | ALL PLASTICS ENGINEERING |
| 41 | 4 | M12(1/2") MUDGUARD WASHERS | EL 06237411 | MS ZINC PLATED | BLACKWOODS |
| 42 | 48 | CABUS CLAMP 51 SUPERGRIP | 5147 | ALUMINIUM | INTERTECH ENGINEERING |
| 43 | 24 SETS | M10 THD ROD 135 LG + HEX NUT + WASHER | M10 | MS GALV | COMMERCIAL ITEMS |
| 44 | 3 | CANTILEVER BRACKETS | PLC 600 | MS GALV | UNISTRUT |
| 45 | 6 | 'Z' SHAPE BRACKET | P1045 | MS GALV | UNISTRUT |
| 46 | AR | 41mm COMBINATION CHANNEL | P1001-B APPROX. 2M LONG | MS GALV | UNISTRUT |
| 47 | 6 | HILTI INJECTION MORTAR + THREADED ROD | HIT RE500 + M12 x 153 HAS ROD C/W HEX NUT AND WASHER | | HILTI |
| 48 | 6 | M10 x 30mm HEX SET SCREW + WASHER | HHS1030H-FW10H | MS GALV | UNISTRUT |
| 49 | 2 SETS | 2 x FLAT + 1 x SP WASHERS + 1 x NUT | FW12H + SW12 + HN12H | MS GALV | UNISTRUT |




Jared Saul
Student Number: [redacted]
OCT 2023