

EMFCOMP-02-E-2023-2

**EMC Assessment Report for:
Secondary (6.6/ 0.4 kV) Substation, Phase 2 Office
Development, New Victoria, Manchester**

20 February 2023

Contract Report

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EMC Study: Secondary (6.6/ 0.4 kV) Substation, Phase 2 Office Development, New Victoria, Manchester

Executive Summary

EMFcomp Limited was contracted to carry out an electromagnetic compatibility (EMC) / interference (EMI) safety assessment of a new substation, associated with the Phase 2 Office Development, to be constructed on the New Victoria site in Manchester. The primary purpose of this study was to assess if electromagnetic emissions presented any potential interference hazards to rail equipment, workers and infrastructure located within the nearby TFGM MetroLink tram line. The substation is a facility incorporating a 6.6/0.4 kV substation, located to the side of the Office Development on the New Victoria site. There are no unshielded electrical conductors associated with the development that would propagate into the tram line region, therefore there are no significant sources of low frequency electric fields presented. There are no significant antennas associated with the substation, so no sources of strong radiofrequency fields are present. Hence, the focus of the study was primarily related to low frequency magnetic field emissions. A source of low frequency magnetic fields within the proposed development would be produced by the various HV and LV electrical conductors associated with the substation. These 50 Hz magnetic fields will propagate impeded through most building materials including masonry, glass, trench fill material etc.

Calculations to predict magnetic fields produced by high current electrical equipment and associated conductors within and around the substation have been carried out. The relevant EMI guidance and standards is contained in BS EN 50121-4:2016 Railway applications. Electromagnetic compatibility. Emission and immunity of the signalling and telecommunications apparatus, IEC 6100-4-8:2009 Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test, the EMC Regulations 2016, BS EN 61000-6-4 - Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments, the Council Recommendations 1999/519/EC, and the Control of Electromagnetic Fields at Work Regulations 2016. These guidelines, regulations and standards are intended to avoid established hazards related to electromagnetic interference.

The work demonstrates that the predicted field values produced by the Phase 2 Office Development substation transformer and associated conductors will not be higher than limits presented in BS EN 50121-4:2016, IEC 6100-4-8:2009, the EMC Regulations 2016, BS EN 61000-6-4, the Council Recommendations 1999/519/EC, and the EMF Regulations 2016, beyond the New Victoria development site boundary. That is, the limits stated in these documents for EMC/EMI would not be exceeded at any relevant distance outside of the facility when the substation is operating under an estimated full electrical load. Therefore, electromagnetic emissions from the proposed substation design do not present a hazard to rail equipment, rail workers or rail infrastructure located within the nearby TFGM MetroLink tram line, and no mitigation actions are anticipated to be required.

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1 Introduction

1.1 Background

This electromagnetic compatibility (EMC) study was commissioned to assess potential electromagnetic interference (EMI) sources to rail infrastructure and equipment from a new substation. The substation is a 6.6/0.4 kV facility as part of the Stage 2- Office Development on the New Victoria site, Manchester. There was a concern related to interference from electromagnetic fields (EMFs) produced by the facility. The substation is to be constructed relatively close to an existing TFGM Metrolink tram line. To address this concern, an EMI assessment of fields produced by cabling to/from the substation and electrical equipment within the substation was carried out. By comparing these predicted field levels to UK guidance and standards on EMI, a view can be formed on whether these EMF emissions are potentially problematic.

It is likely that there will be unshielded electrical conductors associated with the substation, but these would not propagate through solid materials, hence there will be no electric field hazards presented to the rail equipment and infrastructure within the TFGM Metrolink tram line region. Similarly, there were no antennas, hence no radiofrequency (RF) fields related to the application. Therefore, the focus of this assessment was low frequency magnetic fields produced by power frequency electrical equipment and associated cabling.

In particular, the objectives of this EMC assessment of the new substation were to:

- (i) Calculate the magnetic fields produced by the 6.6 kV and 400 V cabling associated with the substation.
- (ii) Calculate the magnetic fields produced by the Schneider Electric (Oil Level) transformer, rated at 1500 kVA, associated with the substation.
- (iii) Compare these field values to relevant limits in EMF/EMI/EMC standards and guidance.

The calculations on which this assessment is based were carried out in February 2023. As far as possible, data were used for electrical equipment and supplies operating under maximum load, or to the electrical current rating of typical electrical cables, subject to the constraints of estimating maximum load for substations such as the new facility to be constructed.

1.2 EMC/EMI Guidance and Standards

1.2.1 EMC/EMI and Electrical Equipment

- (i) Background to EMC, the EMC Directive & EMC Regulations

Electromagnetic fields can present interference hazards to electrical equipment. Electromagnetic compatibility is the engineering discipline that deals with ensuring that electrical and electronic equipment:

- does not emit such high levels of electromagnetic disturbances that they cause too much electromagnetic interference (EMI) to other equipment.
- functions well enough despite the electromagnetic field disturbances in its environment.

The European Union (EU) has a Directive on EMC, 2014/30/EU, which has been transposed into the legislation in the UK, the EMC Regulations 2016. However, of course the financial and safety risks associated with inadequate EMC can be more important than complying with any Directive. This is true for all EMC issues - the techniques that are required to make them work in real-life are not described in EMC Directive or the UK's associated 2016 EMC Regulations. The documents describe what techniques are required, but they do not describe how to do them. The situation is made more difficult by the fact that many of the practical EMC engineering techniques that are now required, are not yet commonly used in electrical installations, and there tend to be no tradition of EMC engineering amongst some trades.

The EMC Directive 2014/30/EU applies to equipment that is placed on the market or put into service. Apparatus is not within the scope of this project, so its requirements are not described here. Fixed installations are defined as 'apparatus intended for use in a specified fixed installation and not otherwise commercially available to an end user as a single commercial item'. All fixed installations in the must comply fully with the EMC Directive 2014/30/EU in the European Union and the subsequent UK's EMC Regulations 2016.

Low frequency magnetic fields from power distribution systems and cabling can interfere with a variety of electrical and electronic devices, equipment, and systems. Therefore, electronic products are generally tested to ensure that they work correctly in their intended operating environment.

Electronic products in the UK are often assessed against the IEC 61000-4-8 power-frequency magnetic field immunity test method (IEC 2009). This has been adopted as the harmonised European standard EN 61000-4-8, which is called up as a basic test method by immunity standards listed under the Electromagnetic Compatibility (EMC) Directive (EC 2014).

The EMC Directive's generic and product-family immunity standards that call up EN 61000-4-8 apply to a product group that includes magnetically sensitive components, such as cathode-ray tubes (CRTs - large, non-flat screen computer monitors or TVs), electron-multiplier tubes, moving-coil microphones, microphone transformers, hall-effect sensors and so on.

Where problems occur, magnetic field shielding is an option, but using ordinary materials can be impractical. 'Mu-metal' and other exotic/expensive high-permeability metals can be used to achieve better shielding of power-frequency magnetic fields, however due to its high cost it is rarely used in non-specialist shielding applications.

Where magnetic susceptibility may be a problem, products are often tested using EN/IEC 61000-4-8 at a test level of 30 A m⁻¹ or 37.6 µT (microtesla).

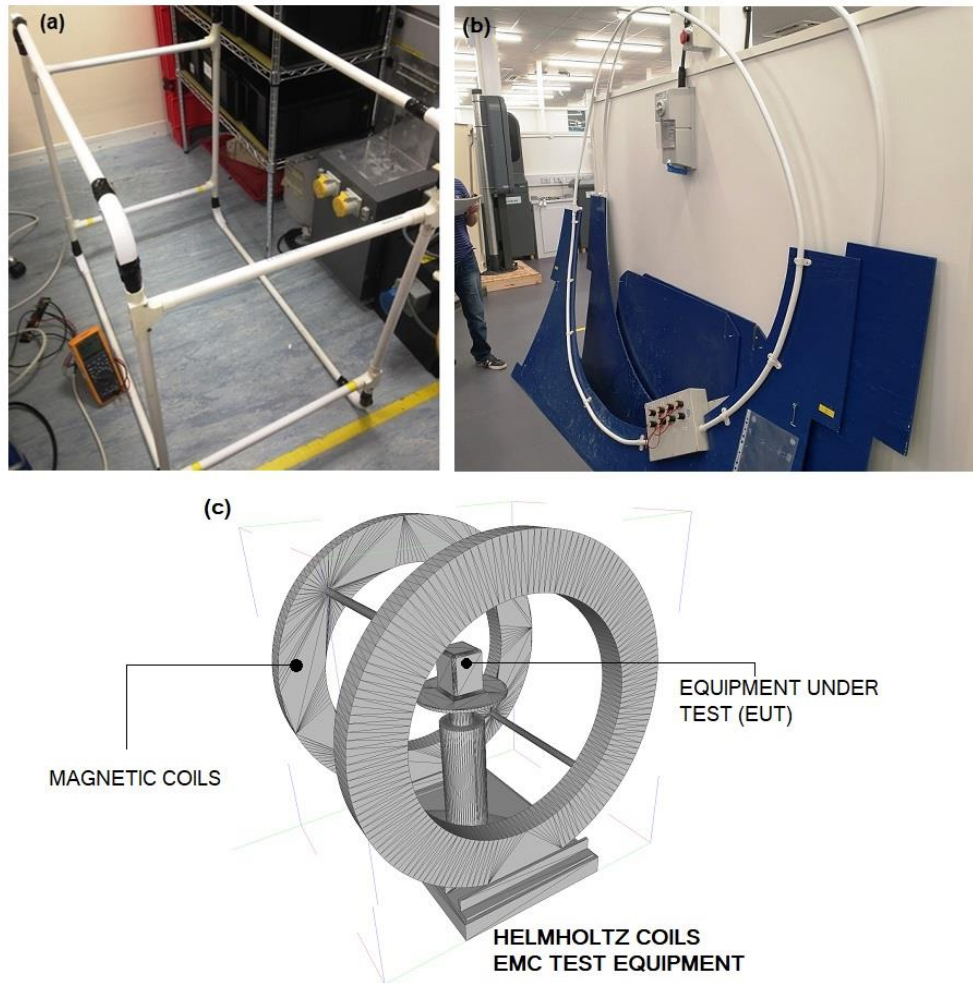


Figure 1.1 (a) An example of a magnetic immunity test rig (b) more substantial coils are required for larger equipment such as trackside cabinets etc. (c) Traditional test setup showing Helmholtz coils and equipment under test (EUT).

The test method exposes the equipment under test (EUT) to a power frequency field created by induction coils. Example test rigs are shown in Figure 1.1. Typically, Helmholtz coils are used, utilising two induction coils spaced apart to create a uniform magnetic field over a volume.

It is recommended in guidance by Members of the IEE's Working Group on EMC and Functional Safety that all products using analogue signals (and maybe some digital products) should be tested using EN/IEC 61000-4-8:2009 in an environment where the magnetic flux density is above $37.6 \mu\text{T}$ (30 A m^{-1}) - as there is a possibility of interference.

Experimental studies have shown that magnetic field levels more than approximately $2 \mu\text{T}$ can cause interference with CRT based VDUs. Although rarely used now in professional environments, it is important to consider legacy or other electrical equipment that may still employ these devices.

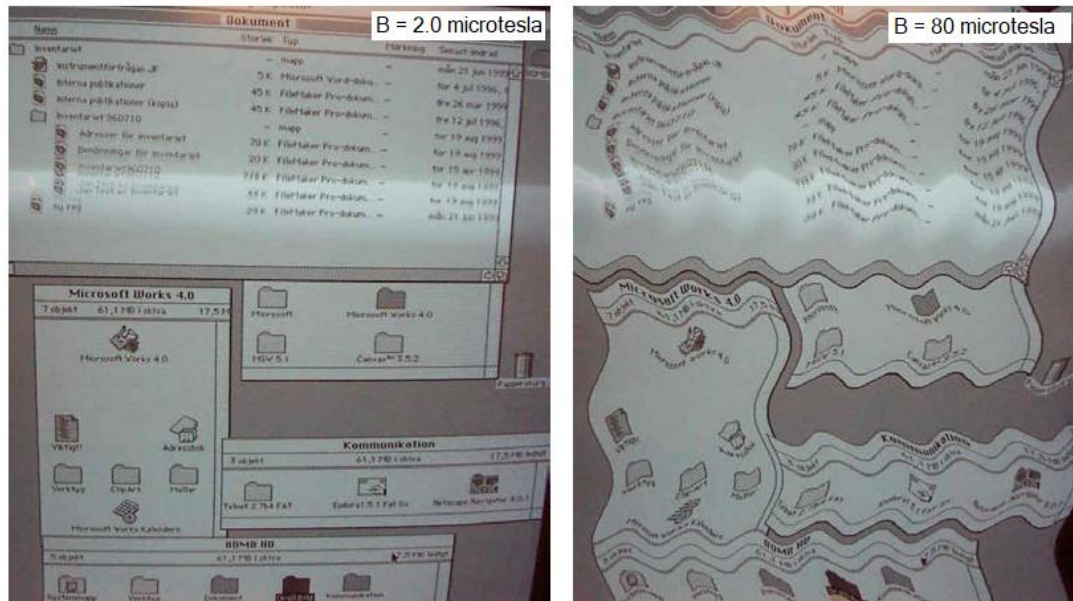


Figure 1.2 Typical distortion of a CRT VDU at magnetic flux densities of (a) 2.0 μT and (b) 80 μT .

1.2.2 EMC/EMI and Workers

Electromagnetic fields can also present health hazards to railway workers. The Control of Electromagnetic Fields at Work (CEMFAW) Regulations were introduced by the HSE in the UK in 2016 to protect workers from EMF exposure. CEMFAW was a result of the transposition of the EMF Directive 2013/35/EU (EU 2013), produced by the European Commission, into UK law.

The Treaty of Rome (now the Treaty on the Functioning of the European Union) set an objective to encourage improvements in the working environment regarding the health and safety of workers. To help achieve this objective it allows for the introduction of Directives to set minimum requirements. In 1989 the Framework Directive 89/391/EEC was introduced as an overarching Directive in this area.

The Framework Directive sets out general requirements for assessing and reducing risks, emergency preparedness, worker information, participation and training, worker obligations, and health surveillance. It also provides for the introduction of individual Directives, which essentially give additional detail on how to achieve the objectives of the Framework Directive in specific situations. The EMF Directive was the twentieth such individual directive.

The CEMFAW Regulations are intended to help employers achieve compliance with their legal obligations for the specific situation of work that involves exposure to EMFs. The main emphasis of the CEMFAW Regulations is to assess risks arising from electromagnetic fields in the workplace and then, if necessary, put in place measures to reduce them. The Regulations seek to introduce minimum requirements for health and safety in relation to work with equipment that produces EMFs.

The first step to creating a safer workplace is to assess the risks that are present. It is important to note that it is not sufficient to simply demonstrate compliance with the limits in the CEMFAW Regulations as this may not be sufficient to adequately protect workers and patients 'at particular risk' or avoid safety risks from indirect effects.

When assessing risks from EMF within a facility, it is necessary to understand the nature of the fields that are present. Hence, the legislation also requires employers to identify and assess EMF in the workplace. However, it allows employers to take account of information provided by others and only requires them to assess fields themselves where it is not possible to demonstrate compliance by any other means.

Where risks have been identified, then appropriate information and training should be provided. However, it is recognised that many workers may be unfamiliar with the nature of the hazards associated with EMF, possible symptoms, or concepts such as EMF limits and so these should be specifically covered in any training. Employees should also be given information about the results of assessments for their specific workplace. It is important that risks are put in perspective. Workers should be aware that many of the sources of electromagnetic fields in the workplace do not present a risk to their health or safety. Indeed many, such as communication devices, may contribute to their welfare or make their work much easier.

The Council Recommendation 1999/519/EC (EC 1999) is a non-binding document that sets out a system of Basic Restrictions (BRs - conceptually equivalent to the CEMFAW Exposure Limit Values (ELVs)) and Reference Levels (RLs - conceptually equivalent to the CEMFAW Action Levels (ALs)). The recommendation sets out guidance to protect people with implanted medical devices and members of the public from established adverse health effects resulting from exposure to EMFs.

The Council Recommendation BRs and RLs are more restrictive than CEMFAW ELVs and ALs. The Council Recommendation system of protection for EMF exposure has been adopted in the UK as a framework for protection of workers at particular risk and the general public.

The RLs specified in the Council Recommendation are used as a basis for managing exposures in publicly accessible areas. Additionally, the RLs have been used to inform the development of standards for the electromagnetic immunity of active implanted medical devices.

The practical EMF guide (EC 2015) and published HSE guidance (HSE 2016b) recommend that the Council Recommendation (EC 1999) Reference Levels, based on the ICNIRP public Reference Levels in their 1998 guidance (ICNIRP 1998), are used for 'workers at particular risk'.

1.2.3 CEMFAW Action Levels and Council Recommendation Reference Levels

As previously described, for workers not at particular risk, the CEMFAW Action Levels apply. For workers at particular risk (workers with active medical devices such as pacemakers, pregnant workers etc.), the more restrictive Council Recommendations 1999/519/EC (EC 1999) Reference Levels (RLs) are applicable instead of CEMFAW Action Levels.

Table 1 - CEMFAW Action Levels and EC Reference Levels at 50 Hz for Magnetic Fields.

Body Region	Magnetic Flux Density (microtesla (μ T))	
	CEMFAW Occupational Action Levels (ALs)	Council Recommendation Public Reference Levels (RLs)
Low Action Level (Head)	1000	100
High Action Level (Trunk)	6000	100
Limb Action Level (Limbs)	18000	100

The CEMFAW Action Levels and Council Recommendation Reference Levels for measured magnetic fields at 50 Hz (power frequency) are shown in Table 1. Action Levels and Reference Levels for electric fields at 50 Hz are shown in Table 2. If field values are below these values, known adverse health effects will be avoided. If the field levels are above these values, further work is required to ensure safety.

Table 2 - CEMFAW Action Levels and EC Reference Levels at 50 Hz for Electric Fields.

	Electric Field (kV m ⁻¹)	
	CEMFAW Occupational Action Level (AL)	Council Recommendation Public Reference Level (RL)
Low Action Level (Head)	10	5
High Action Level (Rest of body)	20	5

1.2.4 BS EN 50121-4:2016 Railway applications - EMC

The standards related to EMC/EMI in a railway environment have adopted the 37.6 μT (30 A m⁻¹) field level for power frequency magnetic field immunity, notably in BS EN 50121-4:2016 Railway applications. Electromagnetic compatibility. Emission and immunity of the signalling and telecommunications apparatus (BS 2016).

The rail sector has also recommended limits on radiofrequency fields, as rail telecommunications and signalling systems can be susceptible to high frequency fields. The radiated immunity limits are 10 V m⁻¹ (80-1000 MHz), 20 V m⁻¹ (800-1000 MHz), 20 V m⁻¹ (1.4 - 2.1 GHz) and 5 V m⁻¹ (2.1 - 2.5 GHz).

1.3 Workplan

Calculations of magnetic flux densities (known as B, unit of measure - tesla or microtesla (μT) and commonly called 'magnetic fields') were performed for relevant areas around the substation. EMFcomp's Dr Richard Findlay carried out this EMI assessment.

A numerical method based on the integral approach was used to compute the quasi-static magnetic field values from a fully loaded electrical scenario. The magnetic flux density was determined in areas around the phase conductors and associated equipment.

1.4 Report Structure

The methods for the calculations are outlined in Section 2. The results of the electromagnetic field assessment are described in Section 3. Section 4 presents a discussion of the results obtained. Conclusions are presented in Section 5 and references are listed in Section 6.

2 Methods

2.1 EMI Assessment Methodology

Risk evaluation is a fundamental requirement of EMC/EMF regulations referred to in this report. The evaluation can be applied to either people or electrical equipment. There are a number of specific matters that should be considered when assessing the risks from electromagnetic fields, however, there are no fixed rules related to undertaking EMF assessments. Structured approaches to the assessment tend to be the most effective as they allow hazards, rail equipment and workers at particular risk to be identified systematically. This helps ensure that risks are not inadvertently missed.

Generally, for EMF assessments, terms and definitions used are recommended by the European Agency for Safety & Health at Work. Specifically:

- Hazard - The intrinsic property or ability of something with the potential to do harm.
- Risk - The likelihood that the potential for harm will be attained under the conditions of use and/or exposure, and the possible extent of the harm.
- Risk Evaluation - The process of evaluating the risk to health and safety of people arising from the circumstances of the occurrence of a hazard at the facility.

What follows is a brief outline of the stages required in the assessment.

(1) Preparation - Developing an overview of the particular assessment you are about to begin and can allow you to further customise the assessment to the specific nature of the facility and equipment.

(2) Identification - Present a series of potential hazards or problems that could exist in and around the facility. By answering the statements/questions with either yes or no, it can be determined if such hazards or problems are present.

(3) Evaluation - Determine the level of risk attached to each of the items identified as 'need to be addressed' in the 'identification' stage.

(4) Action plan - Decide what steps needed to be taken to address the risks identified previously and what resources this might require. Based on this, a plan can be produced.

2.2 Zoning

(i) The Principle of Zoning for EMC/EMI

Electromagnetic field 'zoning' can be used as a mitigation technique. In its simplest form it is a segregation approach to organise electrical systems and installations so neighbouring equipment does not interfere with each other. Electromagnetic mitigation techniques such as shielding, filtering etc. can be applied around the boundaries of each electromagnetic field zone, to attenuate the conducted, induced and radiated field disturbances that would otherwise cross that boundary.

It makes good practical and financial sense to carry out electromagnetic field zoning for the start of the design and construction of any fixed installation, so that field mitigation techniques can be applied easily later, if problems arise.

(ii) EMI Zoning and Rail Infrastructure

EMI zoning can of course also be used as segregation approach to organise electrical systems and installations, so rail infrastructure equipment and neighbouring electrical equipment does not interfere with each other. Applying the EMC standards framework to equipment deployed removes or mitigates any identified hazards. This CENELEC framework will satisfactorily close EMC risks.

The BS EN 50121 series of railway-specific standards defines test limits for equipment placed within the railway boundary. Limits contained within the standards applicable to the railway boundary are generally equivalent to the limits defined for standards relevant to the 'heavy industrial' environment. There are some specific limits for equipment placed within 3 m of the nearest running line. Beyond the 10 m railway boundary, 'light industrial' environment EMC standards apply. In practice, it is more likely that there is a gradual transition from 'heavy industrial' limits to 'light industrial' limits and associated EM environments at 20 m. It is therefore recommended that equipment supplied for the 'Buffer Zone' that extends beyond the 10 m railway boundary is also certified to EMC standards applicable to the 'heavy industrial' environment, or to the requirements in BS EN 50121, to achieve immunity and resilience to known sources of EMI.

Relevant to the low frequency electrical supplies to and from the new substation, the appropriate standard is the power frequency immunity testing, EN 61000-4-8 for 50 Hz fields, discussed previously in this report. Specifically, 100 A m⁻¹ (125 µT) if within a 3-metre zone or 30 A m⁻¹ (37.6 µT).

2.3 EMF Calculations

2.3.1 Background

Sources of power frequency electromagnetic fields in developments such as the new substation are exterior cables, busbars (potentially carrying currents up to a few thousand amps), transformers, and in-house cables. In order to evaluate the risk to people and other electrical equipment, it is important to study the properties, similarities and differences of these sources.

The following theory has been used to calculate fields present in this report.

The magnetic field, or magnetic flux density, produced by the electrical conductors was modelled as a series of straight current-carrying thin wire segments. The magnetic flux density B_θ produced by these conductors was proportional to the electrical current passing through them. The field at separation distance r from each such conductor carrying a current I is calculated using Ampere's law:

$$B_\theta = \frac{\mu_0 I}{2\pi r} \quad (2.1)$$

B and I are frequency dependent quantities. Equation (1) can be rewritten:

$$B(x, y) = \frac{\mu_0 I}{2\pi \sqrt{(x - x_c)^2 + (y - y_c)^2}} \quad (2.2)$$

where x_c, y_c are the conductor centre point coordinates; and

x, y are the coordinates of the point at which the field is to be calculated.

In the case of a three-phase system of conductors with length L , the three segments are parallel and carry currents with different phase angles, the resultant field will be a rotating vector, i.e., an elliptically polarised field. A frequently used measure of the magnitude of B is given by the following expression:

$$B_{resultant} = \sqrt{B_{major}^2 + B_{minor}^2} \quad (2.3)$$

Where B_{major} and B_{minor} are the maximum and minimum magnitudes of B in the ellipse.

Under certain conditions (e.g., if the distance between segments is much smaller than the distance to the plane X-Z), it can be assumed that the polarisation of the magnetic field in the region of interest (the plane X-Z) is approximately linear. The field at the point P is calculated adding the vector-field contribution of each current of the three-busbar system.

Starting with the equation for two wires carrying a single-phase current

$$B(x, y, z) = \frac{\mu_0 I}{4\pi} (-ye_x + xe_y) f(x, y, z) \quad (2.4)$$

Where:

$$f(x, y, z) = \frac{1}{(x^2 + y^2)} \left[\frac{L/2 + z}{\sqrt{x^2 + y^2 + (L/2 + z)^2}} + \frac{L/2 - z}{\sqrt{x^2 + y^2 + (L/2 - z)^2}} \right] \quad (2.5)$$

the value of the magnetic field (in microtesla) acquires the following expression:

$$B_{total}(x, y) = \frac{I}{10} \cdot \left\{ \left(A_1 - \frac{A_2}{2} - \frac{A_3}{2} \right) + \left(C_1 - \frac{C_2}{2} - \frac{C_3}{2} \right) + \frac{3}{4} ((A_2 - A_3)^2 + (A_2 - A_3)^2) \right\}^{1/2} \quad (2.6)$$

Where:

$$A_k(x, y) = \frac{x}{x^2 + y_k^2} \left[\frac{L/2 + z}{\sqrt{x^2 + y_k^2 + (L/2 + z)^2}} + \frac{L/2 - z}{\sqrt{x^2 + y_k^2 + (L/2 - z)^2}} \right] \quad (2.7)$$

$$C_k(x, y) = \frac{-y_k}{x^2 + y_k^2} \left[\frac{L/2 + z}{\sqrt{x^2 + y_k^2 + (L/2 + z)^2}} + \frac{L/2 - z}{\sqrt{x^2 + y_k^2 + (L/2 - z)^2}} \right] \quad (2.8)$$

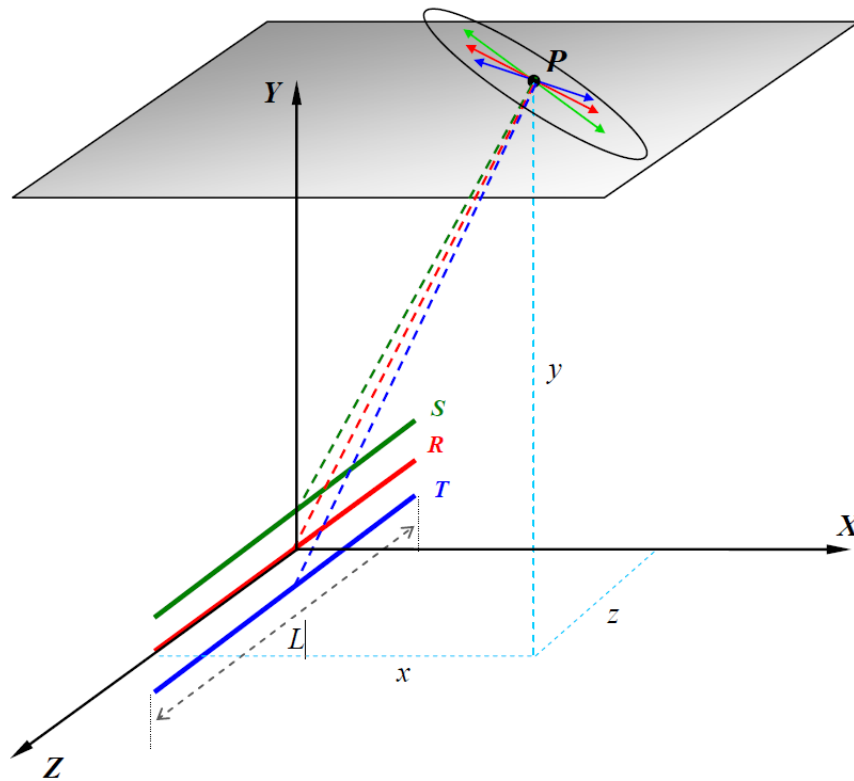


Figure 2.1 The magnetic field of a three-phase system of wires evaluated at the point P. The resulting field is rotating and elliptically polarised.

So, to summarise, the analysis of the magnetic field was made in the phasor domain, meaning that every sinusoidal function of time was represented as a phasor that encodes the magnitude and phase angle of the sinusoid. All magnitudes are assumed to be root-mean-squared or rms. Each phase conductor of a three-phase supply generates its own magnetic field.

The resultant field from all conductors $\vec{B}_T$ is obtained by vector summation of the fields from the individual magnetic field vectors $\vec{B}_A$, $\vec{B}_B$ and $\vec{B}_C$, taking account of the phase of the current in each one, i.e.

$$\vec{B}_T = \vec{B}_A + \vec{B}_B + \vec{B}_C$$

In a three-phase circuit, the currents in the three conductors are equal in magnitude and have phases 120 degrees apart, which can be written in complex notation as:

$$I_A := I$$

$$I_B := I_A \cdot e^{-j.120 \text{ deg}}$$

$$I_C := I_A \cdot e^{-j.240 \text{ deg}}$$

Code was written in FORTRAN and MATLAB to model the way the fields from the different conductors interact. This interaction can be non-intuitive, particularly in planes where phase cancellation occurs - resulting in lower field regions at certain locations amongst a high field area.

There are more complex assessment methods involving numerical methods such as the scalar potential finite difference (SPFD) method and finite element method (FEM), however these were not employed in this work due to time constraints. The methods outlined above were considered appropriate and sufficient for the exposure situations presented in this assessment. Occasionally in the analysis, just the higher

sources of fields are addressed (e.g., the high current busbars from a transformer to a switchboard) rather than a complex three-dimensional analysis of fields from transformer coils, which will often result in lower fields outside of the transformer enclosure.

2.3.2 Power Frequency Fields from Substations

A large body of research exists relating to the generation of power and distribution via power transmission lines etc. However, the final distribution stages have received less attention, despite similar levels of concern encountered as at the transmission stage. This prevails, even though secondary substations and associated cabling have different voltage values (see Figure 2.2).

As electrical power is distributed from high voltage stages to lower stages, the currents are diverted to a multitude of sources. Therefore, if this was the only consideration, lower magnetic fields would be expected at the end points of this distribution network. However, of course when the voltage diminishes (via transformer operation), the electrical current increases.

In addition, the separation distance from field sources to affected areas decreases and the density of population and equipment (sensitive to power frequency electromagnetic fields) increases.

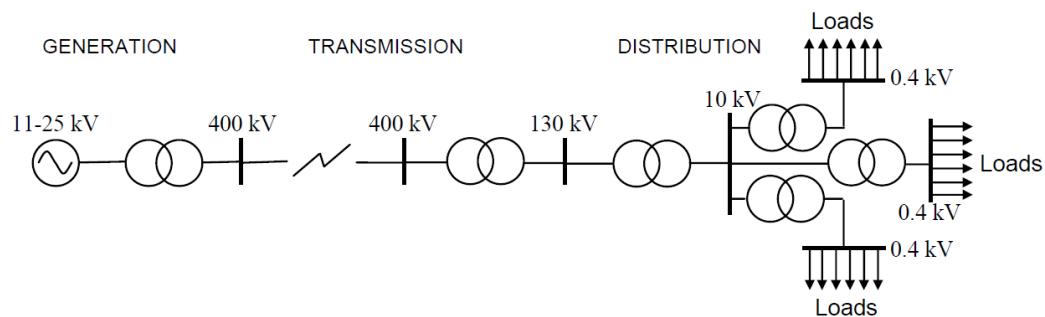


Figure 2.2 Simplified diagram of the distribution of power from the power generation station to client.

The substation analysed in this report contains various three-phase transformers. They also contain high and low voltage switchboards that have covers customarily made of sheet steel, enclosing busbars. However, due to the reduction in voltage, the currents increase with the same factor at the secondary side of the transformers. Therefore cables, and busbars at the low voltage part of the substation also constitute non-trivial sources of magnetic fields. Hence, magnetic fields do need to be assessed and compared with guidance and limits, both for exposure to people and sensitive electrical equipment.

The magnetic field values originating from a substation are the result of complex superposition of the fields from various sources. Is it possible to discriminate in advance the magnitude of the contribution of each source by scanning the field values in the affected area? The answer to this question is yes. There are two reasons for this:

- Analysis of the field gradient on a selected plane can suggest the possible source behaviour.
- Analysis of the variation of the field values with the distance perpendicular to the planar surface investigated can provide a 3-dimensional picture of the field decay, and subsequent source

identification. Moreover, after a simple inspection of the substation itself (this may include a few extra calculations), problems can be solved and mitigation methods, if required, can be put forward.

2.3.3 Phase Arrangements

Cables, wires, power lines and busbars are the carriers of electrical power and sources of low frequency magnetic fields. Hence, the phase configuration and geometrical positioning of these sources are essential factors in the design of electrical installations with low power frequency electromagnetic fields. Fields can be calculated around phase configurations assuming that the relative permeability of the surrounding environment is unity, and the conductivity of the surrounding material is zero. Computations are based on the direct application of the mathematical expressions presented in other parts of this report.

The current of the conductor and the dimensions and geometry of the conductors are the main inputs. To enable these conductors to be oriented in space correctly, local coordinate systems can be used. To reduce the amount of input data when dealing with several conductors, operations such as reflections and translations can be used to replicate any basic shape. The following computation serves as an example of how distances between phase conductors are important, and how phase arrangement can be used as a field mitigation technique.

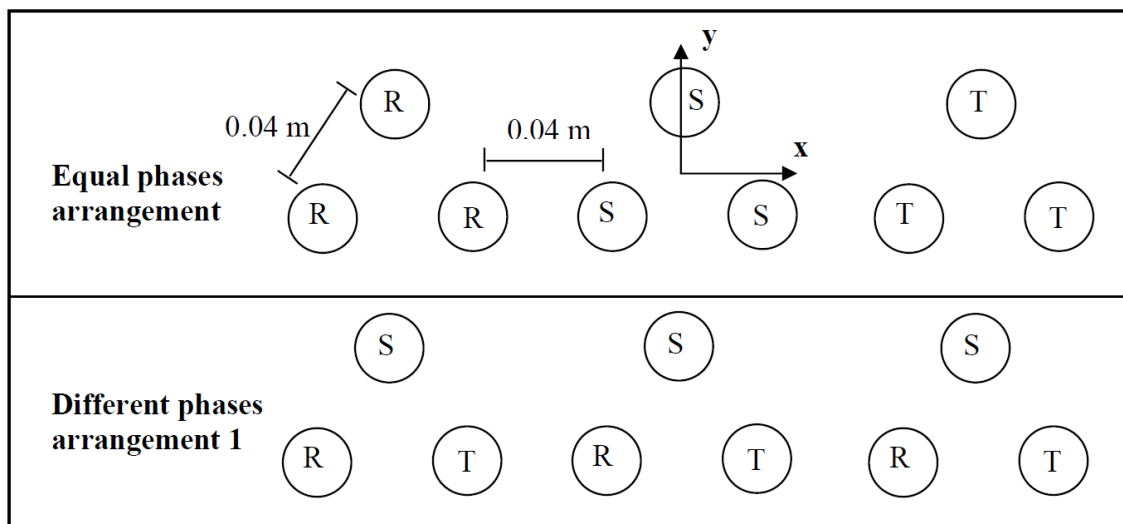


Figure 2.3 Different phase arrangements for a system of nine conductors, each conductor diameter is 0.02 m, insulation thickness 0.01 m, and the current per phase is $I = 100$ A.

Three bundles of three-phase conductors R (0°), S (120°) and T (240°) carrying a 50 Hz current of 100 A (rms) are grouped in different phase arrangements as shown in Figure 2.3. How does the arrangement affect the magnetic fields produced?

The magnetic fields produced are shown in Figure 2.4. The contour plots are on the same scale, the field values are plotted within the range: 0.1 to 1 μ T, and the interval between lines is 0.05 μ T. It can be observed that the arrangement of different phases results in significantly reduced magnetic fields.

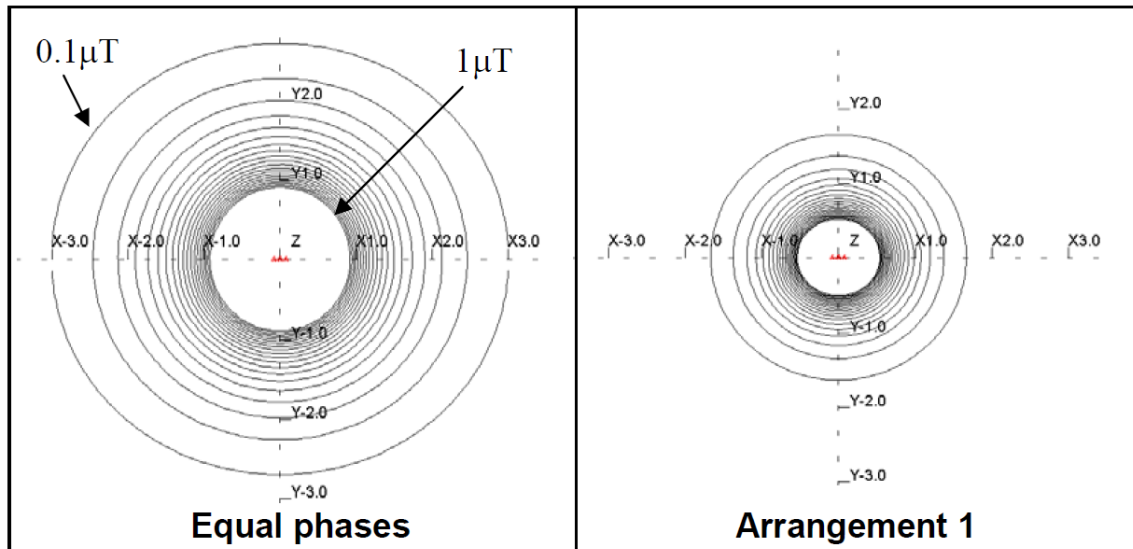


Figure 2.4 Contour plots for the different phase configurations of Figure 2.3. The plots are all on the same scale, the field values are plotted within the range $[0.1 - 1] \mu\text{T}$, and the interval between lines is $0.05 \mu\text{T}$. The scales are in metres.

2.4 Calculation Assumptions

The following assumptions and approximations are accepted as appropriate and as not introducing any unacceptable errors:

- That the field is not significantly altered by the electrical properties of the surroundings.
- That, for three-phase sources, all three currents are equal and exactly 120° apart (alternatively expressed by saying that the field is calculated from positive-phase-sequence currents only, ignoring negative- and zero-phase-sequence currents); and
- That sheath currents are negligible.

3 Results

3.1 Exposure Situation

(i) General

The new substation to be installed is a Schneider Electric (Oil Level) transformer rated at 1500 kVA. The frequency of the field utilised is 50 Hz, and it steps down 6.6 kV (HV) to 0.4 kV (LV) electric supplies. Both the HV and LV flanges are located on the same side of the transformer tank. The location of the substation housing this transformer is denoted in Figure 3.1 as a red square, attached to the Phase 2 Office Development for the site. The TFGM - MetroLink tram lines can be seen to the left of the development.



Figure 3.1 The location of the substation, as well as its proximity to the nearby tram line.

The HV electrical conductors are shown in a detail from the electrical drawing in Figure 3.2, denoted by a dotted green line. Also shown in yellow is the Schneider Electric 1500 kVA transformer, within the Phase 2 Office Development substation.

Once routed into the switchroom for the Phase 2 Office Development, understood to be in the basement, the electrical conductors from the transformer are then directed to supplies within the development via the various distribution cabinets/ boards. These conductors will be of a lower power, and more significantly a lower current - while being a large distance away from the tram line. The magnitude of a magnetic field reduces considerably with separation distance. Hence, the magnetic fields produced by these will have no effect on rail infrastructure and equipment. The focus of this study is related to the previously described conductors, and the region between the proposed substation and the tram line.

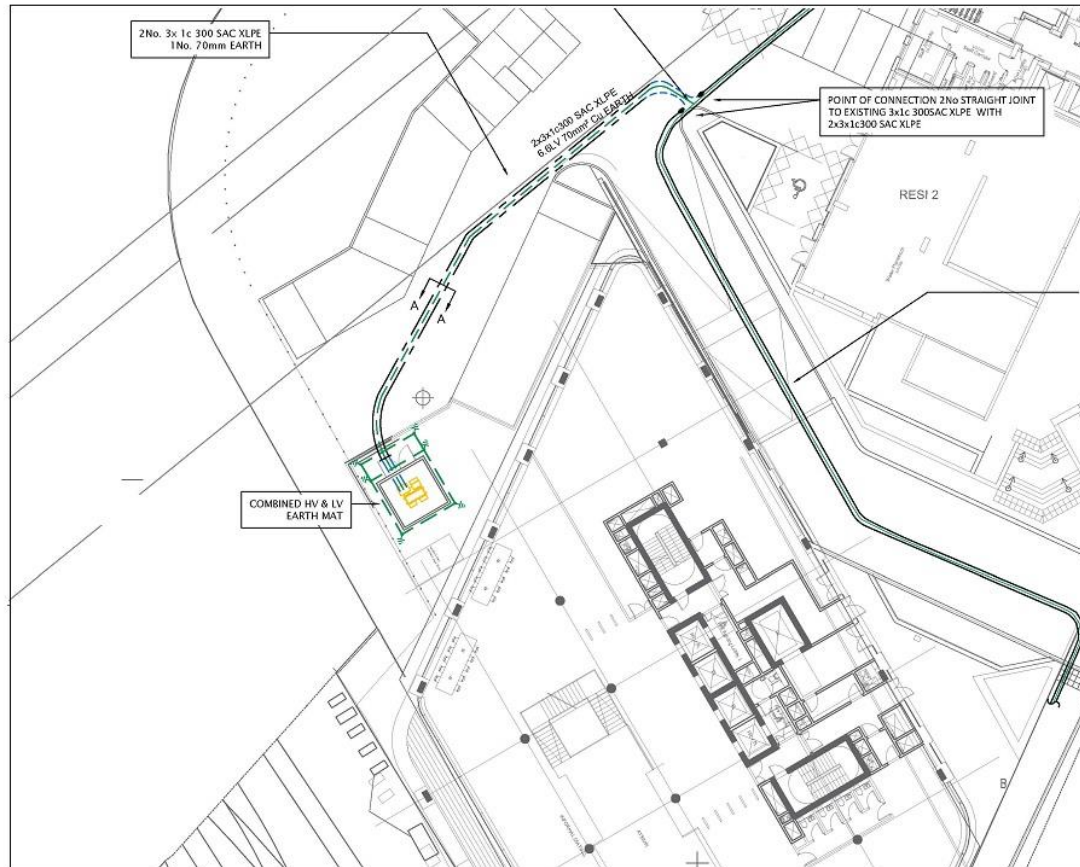


Figure 3.2 Detail from sketch showing the new substation adjacent to the TFGM MetroLink assets and proximity of 6.6 kV cables to the tram line.

(ii) Zoning

Segregation and the principles of electromagnetic field 'zoning' to reduce EMI was discussed in the previous section. The electrical design of the substation has applied these principles well to mitigate EMI as far as reasonably practicable.

Segregation, that is the placement of strong magnetic field emitters, and their associated cables as far away physically as can be practically achieved from sensitive equipment and their cables, has been considered in this design.

3.2 Identification of Potential Hazards for EMI

The electric fields from the unshielded electrical conductors within the substation associated with the development would not penetrate through to the tram line, therefore there are no significant sources of low frequency electric fields that will impinge on rail equipment or infrastructure. There are no antennas associated with the substation, hence there are no significant sources of radiofrequency fields present.

Strong electromagnetic fields produced by the substation will be limited to power frequency magnetic fields, associated with electrical conductors in and around the development. Particular elements, as outlined in the previous section, would be the HV and LV supplies.

3.3 EMI Assessment Details

EMI assessments of identified sources of strong electromagnetic fields in and around the substation development, positioned near the boundary with the railway, are presented in this section. Taking each in turn:

(i) 6.6 kV Conductors

Fields have been calculated for the 6.6 kV conductor arrangement shown in Figure 3.2, under an estimated full load (i.e., worst-case exposure condition). Electrical currents within these conductors will produce an associated magnetic field. To calculate these magnetic fields, the methods described in the previous section were used. Code was written in FORTRAN and MATLAB to model the way the fields from different conductors interact. This interaction can be non-intuitive, particularly in planes where there are conductors at the same phase and phase cancellation occurs - resulting in lower field regions at certain locations amongst higher field areas. Figure 3.4 shows the spatial distribution of the magnetic fields in a two-dimensional x-z plane produced by typical 6.6 kV conductors.

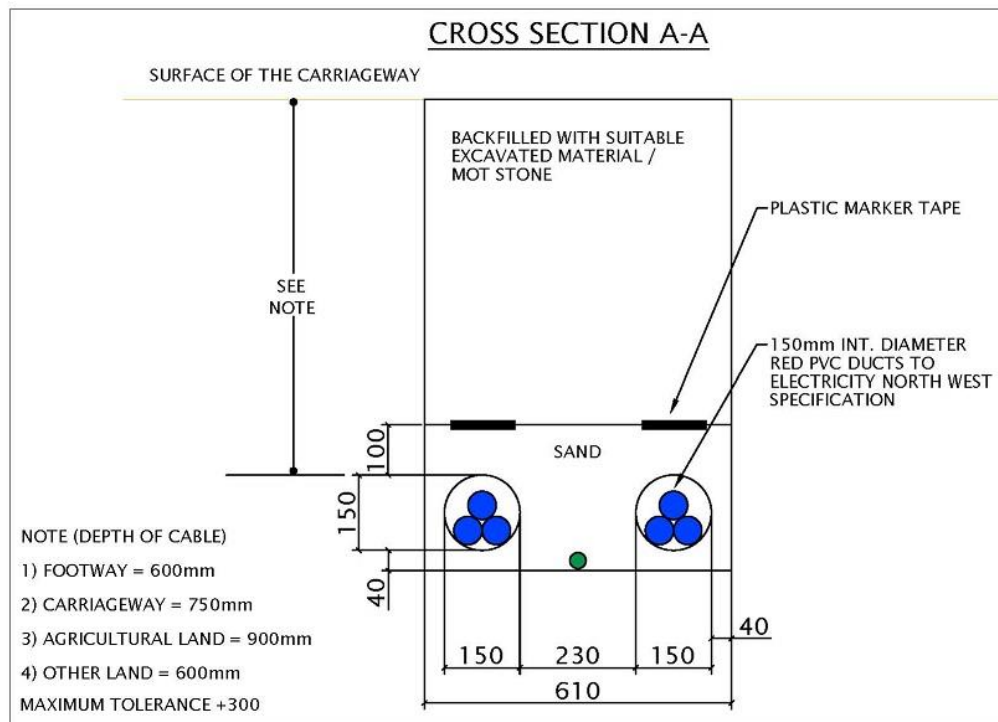


Figure 3.3 - Cross section showing depth and arrangement of HV conductors beneath surface.

The intensity of the magnetic field is represented by a colour map, a high field is denoted by a dark red colour and a low field is denoted by a dark blue colour. For Figure 3.4 and subsequent figures, the scale for the colour map is set to 100 μT to represent the field limit for implanted active medical devices and magnetic field susceptibility for electrical devices. Therefore, within the dark red region the field is in excess of 100 μT . It can be seen from the plot that the exclusion zone for the 100 μT field level is a radius of approximately 0.60 m and the exclusion zone for the 37.6 μT field level is a radius of approximately 1.11 m.

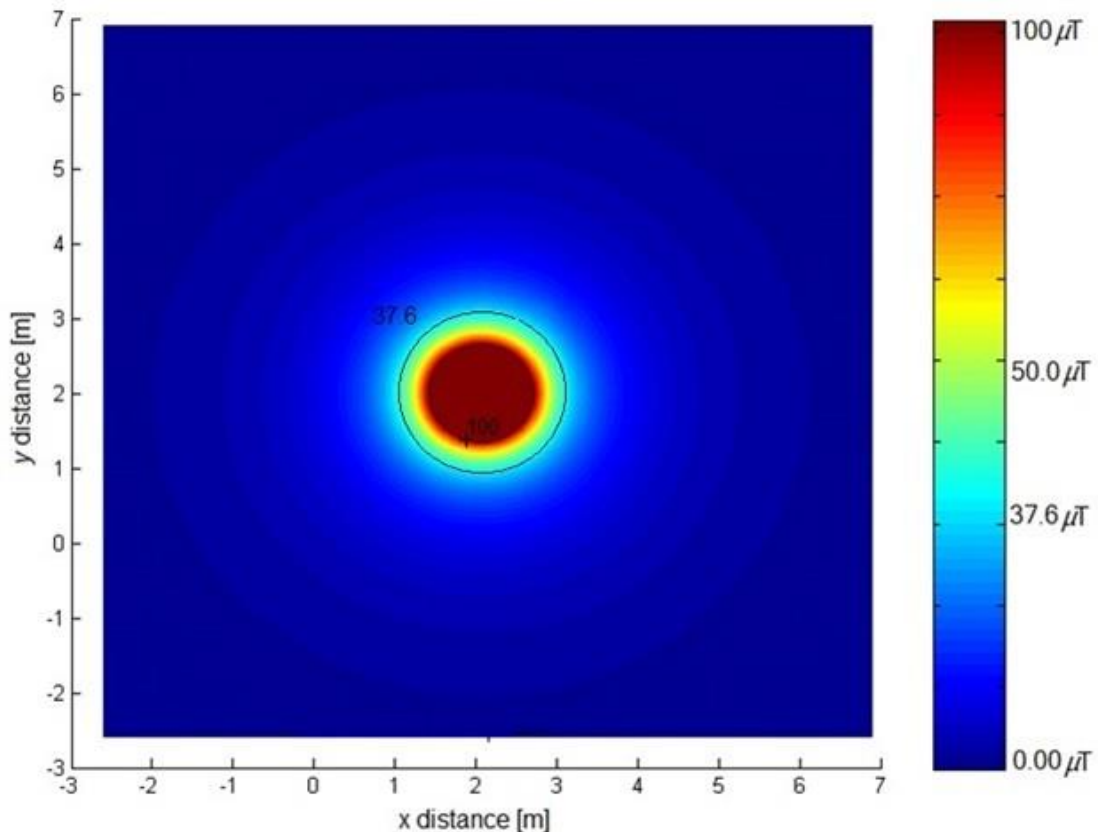


Figure 3.4 Predicted spatial distribution of the magnetic fields in the x-y plane for the 6.6 kV conductors of the new substation operating under full load. The contours show the regions where the field is 100 μT (exclusion zone radius 0.60 m) and 37.6 μT (exclusion zone radius 1.11 m).

As previously stated, the magnitude of the magnetic field does decrease very quickly with distance. For single conductors and a separation distance d , the magnetic flux density tends to be proportional to one-over- d . The magnetic fields produced can be reduced by running send and return conductors, carrying equal and opposite currents, as close together as possible. For three-phase (or three-phase and neutral) power conductors, the currents (and hence their fields) are all at 120 degrees to each other and running them together in a single bundle helps reduce fields in exactly the same way. Where there are a number of conductors that have the potential to balance out (e.g., send and return currents to a DC motor, three-phase or three-phase-plus-neutral power), the magnetic flux density tends to be proportional to one-over- d^2 . For transformers, solenoids and the coils of induction heaters, the magnetic flux density tends to be proportional to one-over- d^3 .

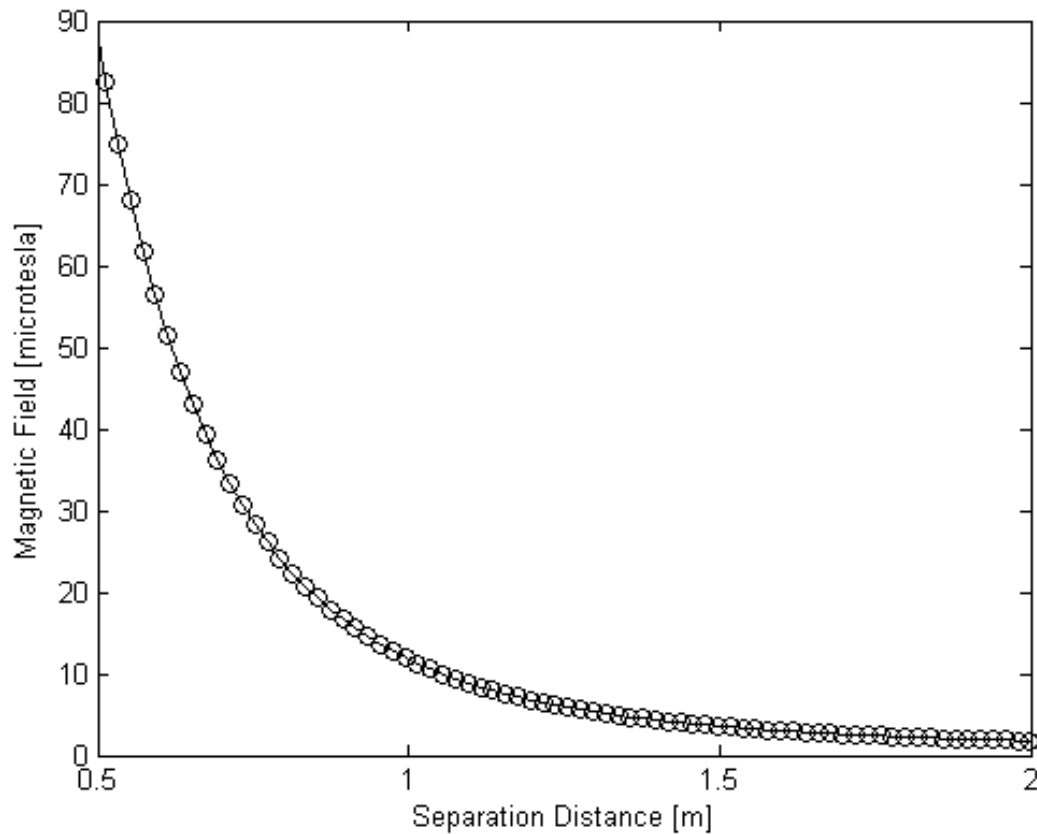


Figure 3.5 - Reduction of the magnetic field for the 6.6 kV conductors related to the new substation under a representative load. The detail shows the change field in field for a separation distance between 9 and 10 metres.

Figure 3.5 shows the predicted reduction of the field from the 6.6 kV conductors under a representative electrical load, at separation distances between 0.5 metres and 1.5 metres.

The significant field reduction in such a small distance is clear. The magnitude reduces from just below 90 microteslas at 0.5 metres to a few microteslas in just a one metre distance.

(ii) 400 V Conductors

Finally, the LV conductors at 400 V have been examined for a predicted worst-case load. The spatial distribution of the magnetic fields for these calculations is shown in Figure 3.7. It can be seen from the plot that the exclusion zone for the 100 μT field level is a radius of approximately 0.28 m and the exclusion zone for the 37.6 μT field level is a radius of approximately 0.54 m.

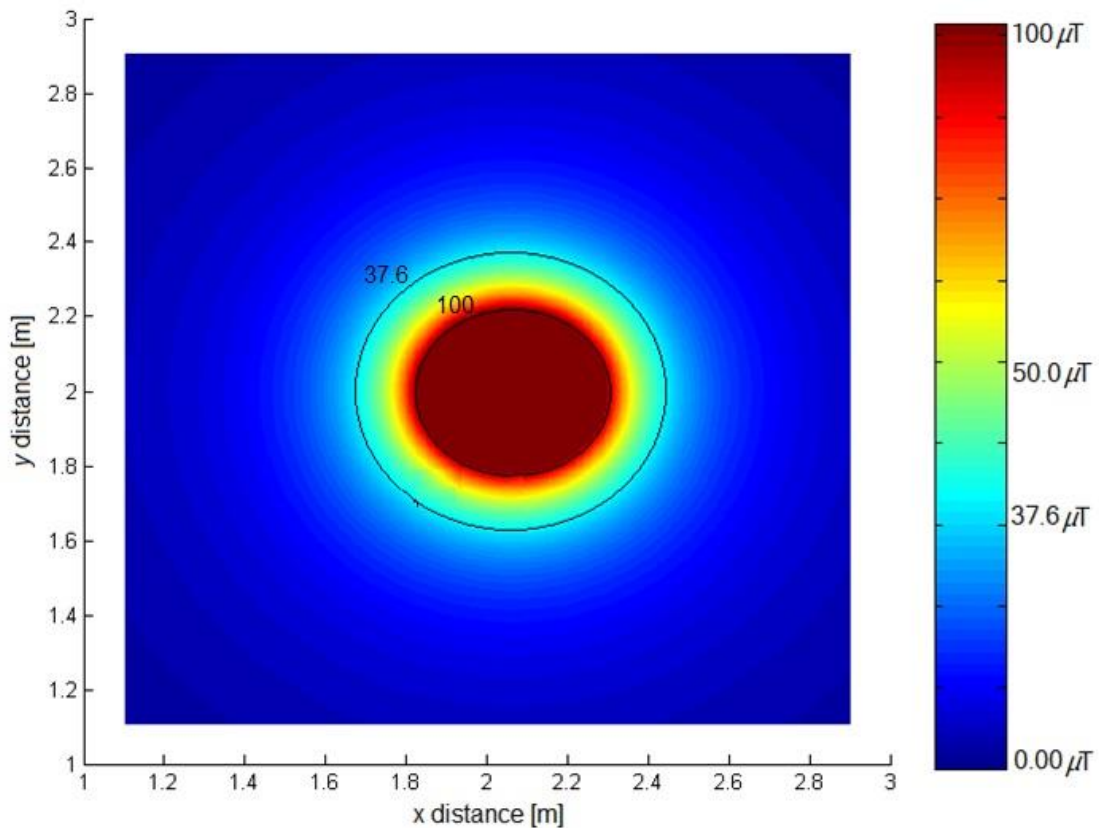


Figure 3.6 Predicted spatial distribution of the magnetic fields in the x-y plane for the 400 V LV conductors of the new substation operating under full load. The contours show the regions where the field is 100 μT (exclusion zone radius 0.28 m) and 37.6 μT (exclusion zone radius 0.54 m).

(iii) RF Emissions

The standard BS EN 61000-6-4 'Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments' is applicable to rail environments. Compliance with this standard is therefore of interest to TFGM - MetroLink. This is predominantly an intermediate/ high or radiofrequency field standard as it is concerned with frequencies from 9 kHz to 400 GHz. The emissions from substations such as the one associated with the Phase 2 Office Development are predominantly low frequency (50 Hz) fields. However, for completeness, RF fields have been examined as part of this work. Radiofrequency fields have been measured on site in a variety of positions, and are presented in Table 3.1, along with a comparison with BS EN 50121/ BS EN 61000-6-4 radiofrequency field limits for EMC, along with the Council Recommendation 1999/519/EC public Reference Levels for human exposure.

For potential interference with electrical equipment from RF fields, BS EN 61000-6-4, BS EN 50121, and their related standards present some of the most restrictive RF limits for particularly sensitive equipment, e.g., telecommunications, IT, and rail infrastructure. The value of 0.066 W m^{-2} (5 V m^{-1}) has been chosen as this is the most conservative electric field limit presented, generally applied between 2.1 and 2.5 GHz (other limits are 10 V m^{-1} (80-1000 MHz), 20 V m^{-1} (800-1000 MHz), 20 V m^{-1} (1.4 - 2.1 GHz)). For potential adverse health effects in people, the value of 3.5 W m^{-2} has been chosen as this is the Reference Level (at 10 MHz to 400 MHz - the most restrictive in the frequency range seen at the site) for members of the public. Again, if fields are below this value for radiofrequency field exposure, authoritative bodies such as ICNIRP state that known adverse health effects will be avoided.

Table 3.1 - Radiofrequency (700 MHz - 2.5 GHz) field levels for various measurement positions P1 to P10 across the New Victoria site.

Location	Power Density (W m^{-2})	% Of EN/IEC 61000-6-4 Test Level (0.066 W m^{-2})	% Of Public Reference Level (3.5 W m^{-2})
P1	0.0004	0.61%	0.011%
P2	0.0003	0.45%	0.009%
P3	0.0002	0.30%	0.006%
P4	0.0004	0.61%	0.011%
P5	0.0004	0.61%	0.011%
P6	0.0004	0.61%	0.011%
P7	0.0005	0.76%	0.014%
P8	0.0004	0.61%	0.011%
P9	0.0003	0.45%	0.009%
P10	0.0006	0.91%	0.017%

The radiofrequency fields measured were very low. The highest radiofrequency field, measured at position P10 was recorded as 0.9% of BS EN 61000-6-4 Level (0.066 W m^{-2}) and 0.017% of the 3.5 W m^{-2} Reference Level (recall that, below 100% of the RLs, the fields are in compliance with the Council Recommendation Reference Levels, used as limits in this instance for members of the public etc.).

There are no significant radiofrequency field emitters associated with the transformer and associated electrical equipment to be situated in the Phase 2 Office Development substation. Therefore, the radiofrequency field levels presented in Table 3.1 are not expected to increase once this equipment has been installed.

4 Discussion

4.1 Evaluation

If rail equipment and infrastructure are subjected to very strong electromagnetic fields, these can adversely affect the reliable operation of this equipment. As stated in the previous section, there are no significant broadcast antennas within the proposed development, therefore no sources of strong radiofrequency fields. There are also no unshielded electrical conductors within the substation that would penetrate through to the tram line, hence no significant sources of low frequency electric fields. Hence, the focus of the assessment was low frequency magnetic field emissions.

Electrical conductors produce these low frequency magnetic fields. If rail equipment and infrastructure is subjected to very strong magnetic fields, the type that can be generated by these power frequency electrical supplies to, from and around large substations, this may influence the reliable operation of these items of rail infrastructure and systems.

Magnetic field levels have been calculated for the substation in the previous section. To assess any potential impact on sensitive railway apparatus, the procedures described in relevant legislation, guidance and standards have been followed. Key documents for this exposure situation, as previously described, include:

- The Control of Electromagnetic Fields at Work Regulations 2016
- The Council Recommendation 1999/519/EC
- The EMC Regulations 2016 Schedule 1
- BS EN 50121-4 Railway applications - Electromagnetic compatibility - Part 4: Emission and immunity of the signalling and telecommunications apparatus
- BS EN 61000-6-4 (high freq - 9 kHz to 400 GHz) - Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
- IEC 61000-6-8:2020 (low and high freq - 0 Hz to 400 GHz) - Electromagnetic compatibility (EMC) - Part 6-8: Generic standards - Emission standard for professional equipment in commercial and light-industrial locations.
- BS EN 61000-4-8 Electromagnetic compatibility (EMC) Testing and measurement techniques - power frequency magnetic immunity test

The Control of Electromagnetic Fields at Work Regulations 2016 contain a limit of 1000 μT for power frequency fields for workers 'not at particular risk' (i.e., 'standard' workers) - Section 4.1.1. The Council Recommendation 1999/519/EC Reference Levels are used for workers 'at particular risk' (i.e., pacemaker/defibrillator wearers etc). These contain a limit of 100 μT for power frequency fields.

The European Standard BS EN 61000-4-8 Electromagnetic compatibility (EMC) Testing and measurement techniques - power frequency magnetic immunity test (as referenced in BS EN 50121-4 Railway applications - Electromagnetic compatibility - Part 4: Emission and immunity of the signalling and telecommunications apparatus) is intended to demonstrate the immunity of equipment when subjected to power frequency magnetic fields related to the specific location and installation condition of the equipment (e.g. the proximity of the equipment to the disturbance source).

The continuous magnetic field test documented in this standard applies to all types of electrical equipment intended for public or industrial HV/LV distribution networks, electrical plants etc. as in the electrical conductors for the substation development. The waveform tested is that of power frequency (50 Hz) as it can be assumed that in many cases (substations, power plants, households, and office buildings etc.) that the magnetic fields produced by harmonics are negligible.

BS EN 61000-4-8 gives a range of Test Levels and associated magnetic fields, these are Level 1: 1 A/m (1.25 μT), Level 2: 3 A/m (3.76 μT), Level 3: 10 A/m (12.5 μT), Level 4: 30 A/m (37.6 μT) and Level 5: 100 A/m (125 μT).

The standard declares that the test levels should be selected in accordance with the most realistic installation and environmental conditions for the particular exposure situation. So, depending on where the equipment is due to operate, in this case a railway environment, the class is derived from the following levels as defined in Annex C of BS EN 61000-4-8:

Class 1: Environment where sensitive devices using electron beams can be used. CRT monitors, electron microscopes etc. are representative of these devices.

Class 2: Well protected environment, characterised by the following attributes: absence of electrical equipment like power transformers that may give rise to leakage fluxes and areas not subjected to the

influence of HV busbars. Households, offices, hospital protected areas far away from earth protection conductors, areas of industrial installations and HV substations may be representative of these environments.

Class 3: Protected environment, characterised by the following attributes: electrical equipment and cables that may give rise to leakage fluxes or magnetic fields, proximity of earth conductors of protection systems, MV and HV busbars far away (a few hundred metres) from equipment concerned. Commercial areas, control building, field of not heavy industrial plants, computer rooms of HV substations may be representative of this environment.

Class 4: Typical industrial environment, characterised by the following attributes: short branch power lines as busbars etc, high power electrical equipment that may give rise to leakage fluxes, ground conductors of protection system, MV and HV busbars at relative distance (a few tens of metres) from equipment concerned. Fields of heavy industrial and power plants and the control room of HV substations may be representative on this environment.

Class 5: Severe industrial environment, characterised by the following attributes: conductors, busbars or MV, HV lines carrying tens of kA, ground conductors of the protection system, proximity of MV and HV busbars, proximity of high-power electrical equipment. Switchyard areas of heavy industrial plants, MV, HV and power stations may be representative of this environment.

The European Standard BS EN 50121-4 Railway applications - Electromagnetic compatibility - Part 4: Emission and immunity of the signalling and telecommunications apparatus, defines the immunity and emission test requirements for apparatus defined in the scope in relation to electromagnetic disturbances likely to be experienced in the railway.

The test requirements represent the essential immunity requirements and have been selected to ensure an adequate level of immunity for apparatus installed in railway environments.

The standard defines two zones, a 3-metre zone and a 10 metre zone. More specifically, the 3 m zone represents an area along the railway line within a distance of 3 m from the centreline of the nearest track at both sides of the track. The 10-metre zone is an area along the railway line within a distance of 10 m from the centreline of the nearest track at both sides of the track.

It specifies limits for emission and immunity and provides performance criteria for signalling and telecommunications apparatus (including power supply systems belonging to this). As previously mentioned, it references BS EN 61000-4-8 Electromagnetic compatibility (EMC) Testing and measurement techniques - power frequency magnetic immunity test and has limits of 30 A/m within the 10-metre zone and 100 A/m within the 3-metre zone. Therefore, it regards the 3-metre zone as Class 5 - a 'severe industrial environment' and the 10-metre zone as Class 4 - a 'typical industrial environment'.

It states that whilst the standard cannot cover all possible configurations of apparatus, these test levels are sufficient to achieve satisfactory EMC in most cases. Furthermore, compliance with the test levels will in most cases allow the railway apparatus to perform as intended inside the rail environment.

4.1.1 1000 μ T 50 Hz Magnetic Field Limit for Workers not at Particular Risk

The 1000 μ T magnetic field limit, applicable to workers not at particular risk, is not exceeded for any substation electrical conductors beyond a few tens of centimetres of high-power cables/busbars, therefore does not present a hazard to 'standard' rail workers within the boundaries of the adjacent railway tram line.

4.1.2 100 μ T 50 Hz Magnetic Field Limit for Workers at Particular Risk

(i) 6.6 kV conductors

For the 6.6 kV conductors associated with the new substation, a magnetic field of 100 μ T is predicted to be produced within a radius of 0.60 m of these cables. The closest 6.6 kV conductor is several metres away from the tram lines. Therefore, these 6.6 kV cables present no hazard from an EMF exposure point of view to workers at particular risk associated with the railway, within the tram line.

(ii) 400 V Conductors

Similarly, the LV 400 V conductors will not present a hazard to rail workers at particular risk within the tram lines. Figure 4.1 shows these predicted zones for the substation within which the 100 μ T limit for AIMD (pacemaker/defibrillator etc) wearers could be exceeded (displayed as a red mesh).

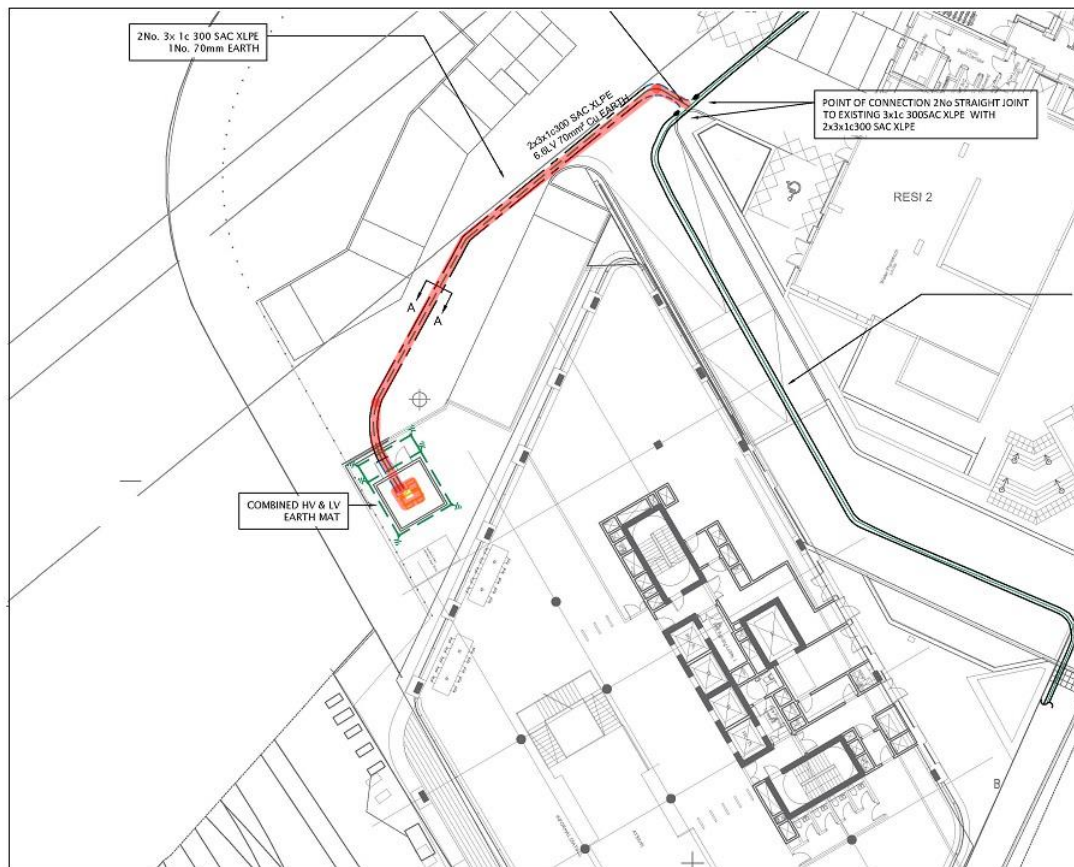


Figure 4.1 Detail from sketch of the new substation adjacent to the TFGM MetroLink tram line, showing the zones in which the 100 μ T limit for AIMD (pacemaker/defibrillator etc) wearers could be exceeded (displayed as a red mesh).

4.1.3 37.6 μT (30 A/m) 50 Hz Magnetic Field Limit for Class 4: Industrial Environment (Rail Environment)

(i) 6.6 kV Conductors

For the 6.6 kV conductors associated with the new substation, a magnetic field of 37.6 μT is predicted to be produced within a radius of 1.11 m of these cables. As previously stated, the closest 6.6 kV conductor is several metres away from the tram lines. Therefore, these 6.6 kV cables present no EMI hazard from an EMF exposure point of view to rail equipment or infrastructure within the tram line.

(ii) 400 V Conductors

Similarly, the LV 400 V conductors will not present a hazard to rail equipment and infrastructure within the tram lines. Figure 4.2 shows these zones for the substation within which the 37.6 μT limit for Class 4 equipment could be exceeded (displayed as a red mesh).

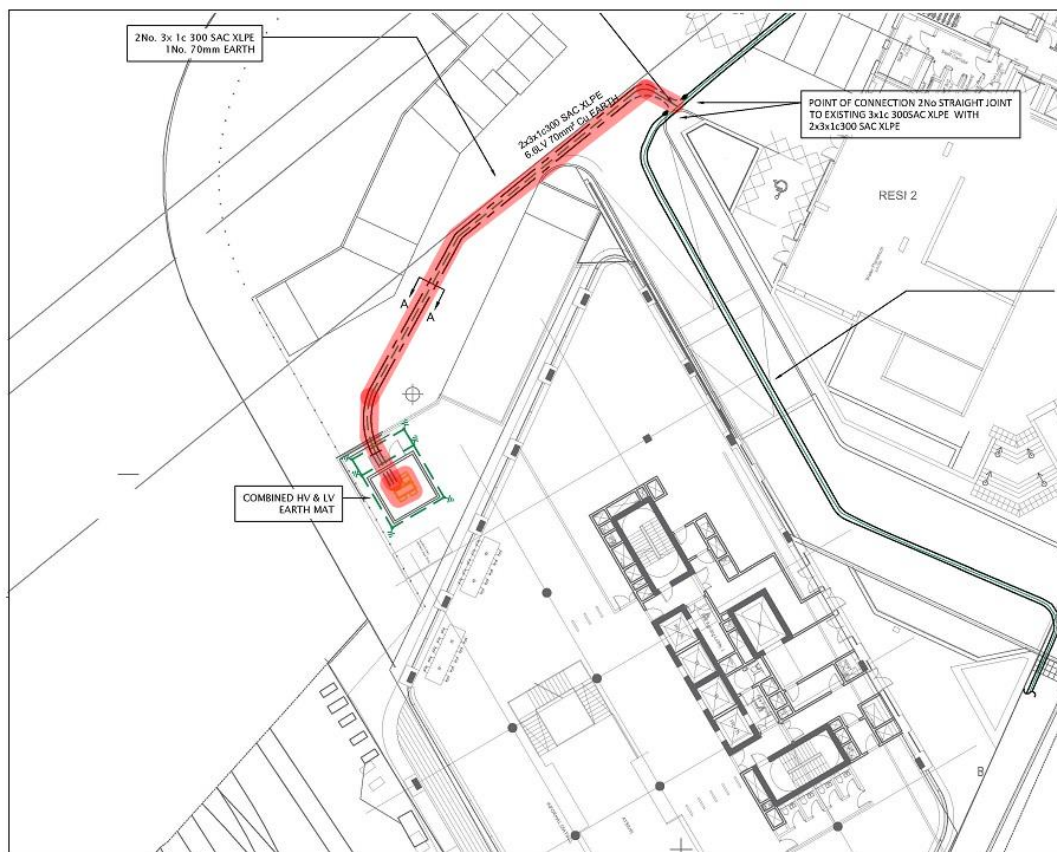


Figure 4.2 Detail from sketch of the new substation adjacent to the TFGM MetroLink tram line, showing the zones within which the 37.6 μT magnetic field level could be exceeded (displayed as a red mesh).

4.2 Action Plan

The risk of electromagnetic interference from electromagnetic fields produced by the proposed new substation development with equipment and infrastructure associated with the adjacent TFGM MetroLink tram line is extremely low. Similarly, the risk of electromagnetic interference from fields produced with rail workers active implanted medical devices is also extremely low. Therefore, no mitigation actions are required.

5 Conclusions

EMFcomp Limited have carried out an EMC/EMI assessment for a new substation, associated with the Phase 2 Office Development, to be constructed on the New Victoria site in Manchester. The assessment was due to concerns related to potential interference to rail equipment and infrastructure within the adjacent TFGM MetroLink tram line. There are no unshielded electrical conductors associated with the development that could penetrate through to the tram line, therefore there are no significant sources of low frequency electric fields present. There are no significant antennas related to the substation design, hence there are no significant sources of radiofrequency fields in existence. Because of this, the focus of the study was related to low frequency magnetic field emissions for the substation.

Calculations to predict magnetic fields produced by high current electrical equipment and associated conductors within and around the substation have been carried out.

The relevant EMI guidance and standards is contained in BS EN 50121-4:2016 Railway applications. Electromagnetic compatibility. Emission and immunity of the signalling and telecommunications apparatus, IEC 6100-4-8:2009 Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test, the EMC Regulations 2016, BS EN 61000-6-4 (high freq - 9 kHz to 400 GHz) - Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments, the Council Recommendations 1999/519/EC and the Control of Electromagnetic Fields at Work Regulations 2016. These guidelines, regulations and standards are intended to avoid established hazards related to electromagnetic interference.

The calculations demonstrate that the predicted field values produced by the Phase 2 Office Development substation transformer and associated conductors will not be higher than limits presented in BS EN 50121-4:2016, IEC 6100-4-8:2009, the EMC Regulations 2016, BS EN 61000-6-4, the Council Recommendations 1999/519/EC, and the EMF Regulations 2016, beyond the New Victoria development site boundary. In short, the limits stated in these documents for EMC/EMI would not be exceeded at any relevant distance outside of the facility when the substation is operating under an estimated full electrical load. Therefore, electromagnetic emissions from the proposed substation design do not present a hazard to rail equipment, rail workers or rail infrastructure located within the nearby TFGM MetroLink tram line, and no mitigation actions are predicted to be required.

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Date Produced: 20 February 2023

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6 References

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<https://shop.bsigroup.com/ProductDetail?pid=000000000030394653>

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