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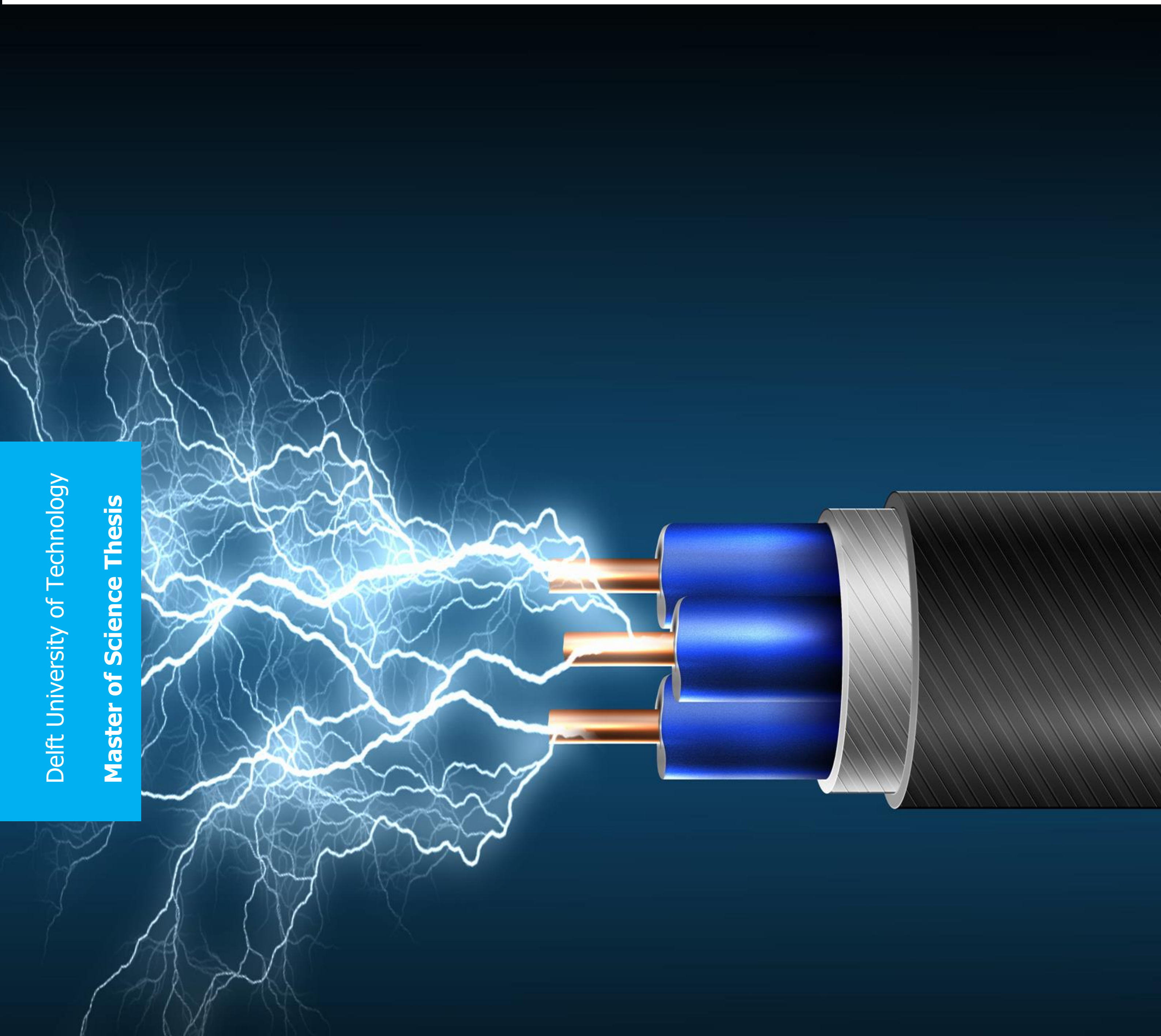

Delft University of Technology

Master of Science Thesis

Magnetic and Induced Electric Field Management for Underground cable Installation - Calculations, analysis and Design Optimization

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TU Delft — Delft University of Technology

Challenge the future

Magnetic and Induced Electric Field Management for Underground cable Installation - Calculations, analysis and Design Optimization

By

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4325346

in partial fulfilment of the requirements for the degree of

Master of Science
in Electrical Power Engineering

at the Delft University of Technology,
to be defended publicly on Friday August 28, 2015 at 2:30 PM.

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TU Delft Delft University of Technology

DCE&S
DC systems, Energy conversion & Storage

Summary

The international growing concern for the human exposure to magnetic fields generated by electric power lines has unavoidably led to imposing legal limits. The world health organization sets limits for exposure to magnetic and induced electric fields. Basically, the world health organization references to the guidelines provided by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). For 50 Hz exposure, this guideline is 1000 μT for occupational workers and 200 μT for the general public. In several countries however, stricter limits are set, down to 0.3 μT. However, it is stressed that the calculation methods and starting points also differ significantly and these values can therefore not be compared one-to-one.

In this study the magnetic and induced electric fields of different cable installation methods like directly burial, underground tunnels were calculated and evaluated against the ICNIRP guidelines. Different operating conditions such as normal operation at 1450 A, emergency operation at 1760 A, 80 kA short circuit currents and operation during maintenance were assessed. Based on the study, it could be concluded that all situations were below the ICNIRP values for 50 Hz exposure, except for the short circuit conditions. However, these are only during a very short duration of maximal 1 second and their allowance needs to be discussed with the relevant authorities. Moreover, voltage might be induced in other metallic structures (due to magnetic induction) which might lead to unsafe situations, like where public or animals come in contact to energized metal object and experience shocks.

The ultimate outcome of this thesis study is to answer the part of questions arising for health concern due to exposure of magnetic fields, as this study limits to underground installation (direct burial and tunnels).

Thesis work focus on safety limits and design optimization of underground installations which includes following goals:

- Universal tool to calculate magnetic and induced electric fields.
- Optimized design parameters for underground cable installations with respect to safe limits of magnetic fields exposure.
- Analysis of underground installations with design parameter for different operating conditions.

Preface

This thesis is written as a partial fulfillment for the requirements of the Master of Science Degree in Electrical Power Engineering at the faculty of Electrical Engineering, Mathematics and Computer Science, at Delft University of Technology. The work presented here is a result of almost a year's work at the DNV-GL. It involves developing of a calculation tool for magnetic and induced electric field and the result obtained is used to suggest design optimization for improving the design parameters to have safety of the general public and working professionals getting exposed to magnetic fields as well as coming in contact with electrically energized metal objects due to magnetic fields.

I have faced many challenges and difficulties along the way and looking back I can only say it helped me become better with understanding the problem and presenting my views. This work would not have been possible without the help I received from many people. First and foremost, I would like to thank my supervisors, Dr. Armando Rodrigo Mor and Dr. ir. Sander Meijer for their guidance, mentorship, patience and support.

The report begins with a discussion on the importance on growing of electricity and social demand for underground installation and magnetic as well as induced electric fields along with ICNIRP guidelines, its introduction Chapter 1. The next Chapter 2 provides the basic theory used for calculations for next chapters. Chapter 3 deal with design optimization for different factors on which the magnitude of magnetic and induced electric field values depends. Chapter 4 gives the details about the configurations used as an example to analyze the magnetic and induced electric fields under different operating conditons. Chapter 5 presents the results and analysis of the magnetic and induced electric fields. Lastly, Chapter 6 gives a conclusion to the report based on the results and safety limits.

Shree Harsha Muralidhar
Delft, August 2015

Acknowledgments

My journey until today would never have been accomplished without the support of my dearest family and friends around me. I take this opportunity to thank my dearest wife, my parents, and my friends.

I am very grateful to my esteemed supervisors Dr. Armando Rodrigo Mor and Dr. ir. Sander Meijer for all their constant support, guidance, help and encouragement during my thesis work and being penitent to answer my questions.

With this chance, I want to express my thankfulness to DNV-GL for giving me the opportunity to be a part its global family. I also want to thank DNV-GL colleagues for their support: Mr. Frank De Wild, Mr. Wim Boone, Mr. Gert-Jan Meijer, and Mr. Roy Zuijderduin.

Lastly, I want to thank other committee members for my thesis defense: Dr. ir. P.H.F. Morshuis and Dr. ir. J.L. RuedaTorres.

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"We Know What We Are, But Not What We May Be"
By William Shakespeare

To my loving wife, dear parents and my supervisors

1

1 Introduction

Underground cable networks have become an important element in the power delivery chain from generation to the doorstep of consumer. Underground cable network and its efficient management in the modern day electric utility are of prime importance. Underground cable networks have hidden benefits of reliability and safety provided with suitable technological developments. The underground cables has several advantages when compared to traditional overhead lines like less space needed, less disruption of environment, less liable to damage through storms or lightning, low maintenance cost, less chances of faults, smaller voltage drop and better general appearance. However, their major disadvantage is that the total costs of underground cable systems are significantly higher than that of the equivalent overhead system. For this reason, underground cables are employed where it is impracticable or impossible to use overhead lines. Impractical locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction. Impossible situations are “over sea” connections, where the submarine cable appears to the only appropriate alternative.

The underground installation for high voltage cables in urban and suburban areas is usually accomplished by direct burial. Direct burial of cables involves excavating trenches into which the cables are installed on a bed of sand by the use of winches or power rollers. Trenches approximately 1.5m wide and 1-2m deep are required for each cable circuit. Sheet piling or timber is used to support the sides of the trenches. Reinstatement of the excavated trench is often carried out using special backfill material placed directly around the cables with concrete protection covers placed above the cables in the excavation. If thermally stable backfill materials such as cement bound sand are used they must be carefully compacted around the cables to ensure no air pockets exist, which decrease the effective thermal resistivity and consequently degrade the cable rating (figure-1.1). Direct burial of cable system has some problems associated with the installation, such as the disruption to traffic, noise, vibration, visual intrusion and dust generation and deposition due to the excavation of trenches along the route. Heavy goods vehicle traffic will also be generated by the work, removing spoil and bringing in plant and materials, including backfill, to trenches.

Direct burial is normally the “low cost” method for the installation of underground cables where restrictions on land use are not an issue.

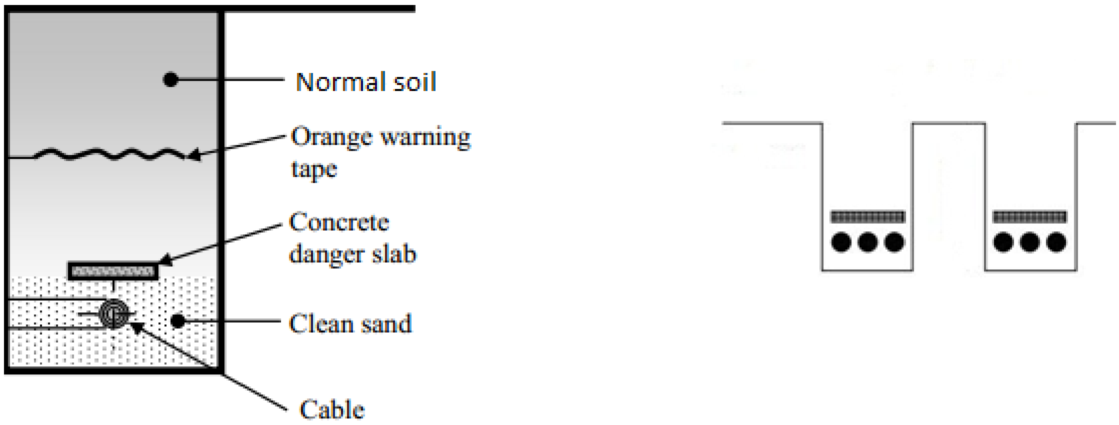


Figure 1.1: Example of Direct burial Installation

With rapid growth and urbanization of metropolitan cities (like Bremen, London, Qatar, Singapore) economy and population, demand for power supply has increased and there is a need to build reliable solution to the ongoing renewal of grid infrastructure to ensure the continued power supply and maintain the quality. The space for installing underground power cable systems directly buried is very limited. Therefore ducts and more radial-tunnels at 10-60 meters deep are increasingly being used (figure 1.2), crossing below all other infrastructures and reducing the impact on daily life in the city. Even though the initial installation cost is higher when compared to direct burial, power transmission through tunnels has its own various advantages like major disruption to the road network throughout the city is avoided, additional cables can be installed in the tunnels to meet future demand.

Figure 1.2: Example of Tunnel systems

Following are few examples of utility tunnel used for power transmission:

- Poundbury village in Duchy of Cornwall, Prince Charles' master planned community in England incorporates common utility ducts.
- Bremen, Germany has integrated in tunnel with footways, cycle ways and streets, with virtually no visible repairs or disturbances.
- The Dartford Cable Tunnel allows high voltage electricity line to cross the River Thames.

- The Utility Tunnels in Qatar built on the Lusail, 15 km north of Doha, is approximately 14~15 km in length.
- In Singapore, the North-South Cable Tunnel will span 18.5 km from Gambas to May Road while the East-West Cable Tunnel will span 16.5 km from Ayer Rajah to Paya Lebar.

1.1 State of Art

In high voltage engineering, we are interested in electric and magnetic fields. Electric fields are caused by the voltage difference between electrodes while magnetic fields are caused by currents flowing in conductors. Overhead lines are a source of two fields, whereas underground cables eliminate the external electric field altogether as it usually is screened out by the metal sheath around the cable but they still produce magnetic fields.

Within the past years there has been very significant growth of extremely low frequency (ELF) magnetic fields at frequencies of 50 and 60 Hz predominantly from electric energy generation, transmission and distribution in urban as well as suburban areas. Human organisms are endogenous electromagnetic fields and currents that play a vital role in the bio-complex mechanisms of physiological control such as neuromuscular activity, glandular secretion, cell membrane function and tissue development, growth and repair. It is well aware that, because of the role of electromagnetic fields and currents in so many basic physiological processes, questions arise concerning possible effects of artificially produced fields on biological systems. The advancement in technology and the ever increasing demand for electric energy, human exposure to 50 and 60 Hz magnetic fields has increased to the point that valid questions are raised concerning safe limits of such exposure. Public concern is growing and in many countries regulatory and advisory agencies have been requested to evaluate possible adverse effects of ELF electromagnetic fields on human health as to consider this as a factor for installation design. Exposure standards have been developed internationally, that provide adequate protection against all known adverse effects of exposure to EMF.

Epidemiology is the science that studies the patterns, causes, and effects of health and disease conditions in defined populations. It is the cornerstone of public health, and informs policy decisions and evidence-based practice by identifying risk factors for disease and targets for preventive healthcare. Epidemiologists help with study design, collection, and statistical analysis of data, and interpretation and dissemination of results (including peer review and occasional systematic review). Epidemiology has helped develop methodology used in clinical research, public health studies, and, to a lesser extent, basic research in the biological sciences. Further, epidemiological studies have consistently found that everyday chronic low intensity (above 0.3– 0.4 µT) power frequency magnetic field exposure is statistically associated with an increased risk of childhood leukemia.

Country	Remark	Exposure limits
Netherlands	Annually averaged magnetic flux density	0.4% of reference value from ICNIRP (0.8 µT)
Bulgaria	Long exposure time	0.25% of reference value
Denmark	Average exposure per year	0.4% of reference value from ICNIRP (0.8 µT)
Italy	Exposure to 4 hours or more per day	3% of the reference value
Poland	Long exposure time	75% of the reference value
Australia	24 hours exposure time	100 µT

Table 1.1: Special limits adopted in various countries

These limits are adopted for the purpose of minimizing progressively to the exposures of magnetic fields generated by 50 Hz power lines and is applied in designing new power lines in the neighborhood of children's playgrounds, residential dwellings, school premises, and in areas where people are staying for 4 hours or more per day, as well as in planning developments in the proximity of existing electric power lines and installations, including the categories mentioned above. The quality objective is the median of values recorded over 24 hours, under normal operational conditions.

The guidelines developed by the International Commission on Non Ionizing Radiation Protection (ICNIRP) [1] are widely recognized and have formed the basis for national regulations in several countries. European Union has also established a common framework [2], [3] for giving the general public a high level of protection against the potential harmful effects of exposure to electromagnetic fields, particularly by limiting exposure to sources of non-ionizing radiation. Institute of Electrical and Electronic Engineers (IEEE) [13] has also established a framework for harmful effects of exposure to electromagnetic fields. The exposure limits provided varies a factor of 3 when compared with ICNIRP, this variations is due to the models considered for calculations. ICNIRP considers the exposure limits for human until waist level that is approximately 1 meter from ground where as IEEE considers until head. In this master thesis we consider the limits set by ICNIRP, as it is widely recognized and World Health Organization (WHO) also recommends these limits.

As far as the relegations in urban and suburban cities are concerned, the limits (ICNIRP) currently in force for magnetic fields generated by 50 Hz power cables are set by:

- The exposure limit: 200 µT (rms value). This limit must never be exceeded in case of general public exposure.
- The exposure limit: 1000 µT (rms value). This limit must never be exceeded in case of occupational worker.
- The exposure limit: 100 µT (rms value). This limit must never be exceeded in case of occupational worker with pacemaker implanted.

Exposure to time-varying magnetic fields results in induced electric fields and in body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. Human bodies will conduct electricity and are sensitive to electric currents at frequencies of 50-60 Hz. If the body makes contact with an electrically 'energized' surface while simultaneously making contact with anther surface at a different potential (or 'ground') then an electric current will flow through the body, entering the body at one contact point, traversing the body, and exiting at the other contact point. Certain tissues in the body have traditionally been considered most sensitive to electricity because they normally use bio-electric signals. Cells in the central and peripheral nervous system (neurons) use bio-electrical signals to rapidly process and communicate information. Neurons regulate the contraction of cardiac cells, diaphragm muscle cells (inducing lung inspiration), and peripheral muscle cells (controlling movement). Cardiac and muscle cells, in turn, also use bioelectric signals to trigger their contraction. These cells are collectively referred to as 'electrically excitable cells'. The magnitude of this current will increase as the voltage difference across the 'contact points' increases. Knowing, these magnetic parameters, it is necessary in order to identify suitable methods and techniques that will be able calculate induce electric fields and ways to reduce the unwanted effects and to increase the protection of the working staff. The maximum electric field is induced in the body when the external fields are homogeneous and directed perpendicular to the body axis.

As far as the relegations in urban and suburban cities are concerned, the limits (ICNIRP) currently in force for induced electric fields generated by 50 Hz magnetic fields from power cables are set by:

- The exposure limit: 0.4 V/m (all body tissue). This limit must never be exceeded in case of general public exposure.
- The exposure limit: 0.8 V/m (all body tissue). This limit must never be exceeded in case of occupational worker.

The above considerations have stimulated the search for methods of arranging the conductors of power cables to evaluate and compare the magnetic field values under balanced and unbalanced conditions in such a way that the surrounding magnetic fields will be greatly reduced.

1.2 Goal of This Thesis

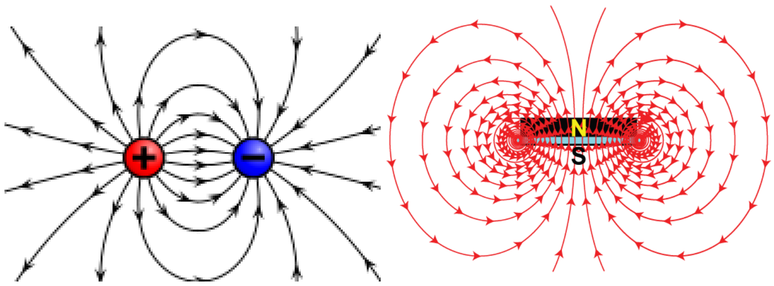
The overall objective is to be able to understand safety limits for the underground cable installation (direct burial and tunnel) with respect to exposure of 50 Hz magnetic fields. To achieve that goal, there are many areas that need to be covered. This project focused on determining the exposure magnetic fields values under different operating conditions and evaluate against ICNIRP guidelines. The primary goals of this study are:

- To develop calculation tool for measurement of exposure values under different operating conditions.
- Optimizations of installations design.
- To answer how safe human being is when walking over or in the neighborhood of underground cable installations.

2

2 Theory of Magnetic and Induced Electric Fields

Electromagnetic fields (EMF) are a combination of invisible electric (E) and magnetic (B) fields of force that surround any electrical device (figure 2.1) as the presence of these fields are not seen through human eyes but can only be felt. Power cables, electrical wiring, and electrical equipment all produce EMF. The focus of this report is on power-frequency EMF—that is, EMF associated with the generation, transmission, and use of electric power at 50 or 60 Hz. Electric fields are produced by voltage, electric and magnetic fields are inextricably linked to each other and electric field increase in strength as the voltage increases. The electric field strength is measured in unit of volts per meter (V/m). Magnetic fields result from the flow of current through wires or electrical devices and increase in strength as the current increases. Magnetic fields are measured in units of amperes per meter (A/m). Often for magnetic flux density, Tesla (T) is used to identify the magnitude of the magnetic field as SI (International System of Units) unit. It is convenient to use as majority of measuring units are represented in SI system. Most electrical equipment has to be turned on, i.e., current must be flowing, for a magnetic field to be produced [4]. Electric fields are often present even when the equipment is switched off, as long as it remains connected to the source of electric power.



[1]

Figure 2.1: Electric and Magnetic field lines

Power cables have metal sheath around the current carrying conductor, hence electric fields (E) are shielded (figure 2.2) considering effects of sheath current as negligible. On the contrary, magnetic fields (B) are not restricted by the metal sheath and therefore more attention is given to the calculations of magnetic fields in this thesis.

[1] physics.stackexchange.com, www.hawaii.edu

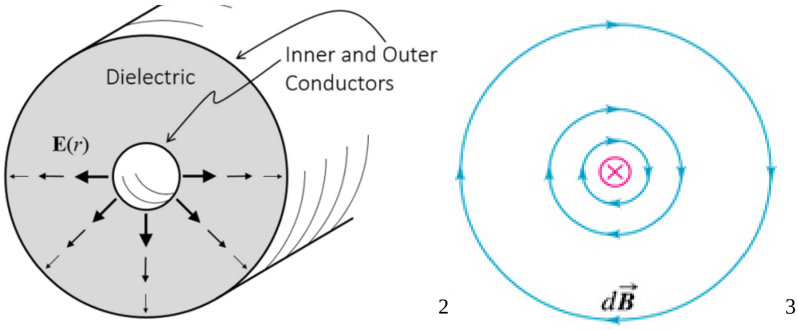


Figure 2.2: Field lines in co-axial cable configuration with metallic sheath

2.1 Biot-Savart Law

Currents which arise due to the motion of charges are the source of magnetic fields. When charges move in a conducting wire and produce a current I, the magnetic field at any point P due to the current can be calculated by adding up the magnetic field contributions, $d\vec{B}$, from small segments of the wire ds [5].

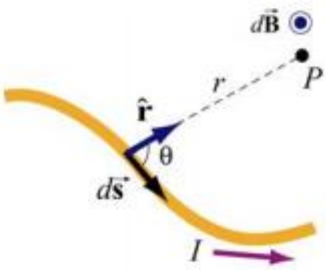


Figure 2.3: Magnetic field dB at point P due to a current-carrying element I ds

These segments can be thought of as a vector quantity having a magnitude of the length of the segment and pointing in the direction of the current flow. The infinitesimal current source can then be written as $Id\vec{s}$.

Let r denote as the distance from the current source to the field point P, and r the corresponding unit vector. The Biot-Savart law gives an expression for the magnetic field contribution, $d\vec{B}$ from the current source $Id\vec{s}$.

$$d\vec{B} = \frac{\mu_o I}{4\pi} \cdot \frac{Id\vec{s} \times \hat{r}}{r^2} \tag{2.1}$$

The magnetic field at the point P requires integrating over the current source and the total magnetic field is given by

$$\vec{B} = \int_{wire} d\vec{B} = \frac{\mu_o I}{4\pi} \int_{wire} \frac{d\vec{s} \times \hat{r}}{r^2} \tag{2.2}$$

[2] www.comsol.com

[3] http://www.physics.sjsu.edu/becker/physics51/mag_field.htm

2.2 Ampere's Circuital Law

Ampere's circuital law states that the line integral of magnetic field B around any closed path in vacuum or air is equal to μ_o times the total current I enclosed by the path [12].

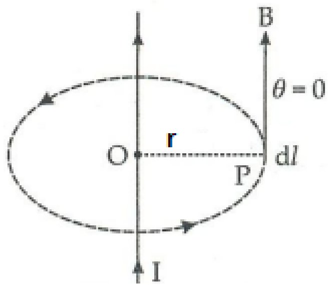


Figure 2.4: Ampere's Law

Consider a long straight cable conductor carrying a current I in the direction as show in figure 2.1. Due to current in the conductor, the magnetic lines of force are concentric circles cantered on the conductor.

$$\oint B \cdot dl = \mu_o I \tag{2.3}$$

Consider magnetic line of force of radius r. On this circular closed path, the magnitude of B is same everywhere. The direction of B at every point is along tangent to the circle i.e. the angle between B and dl at every point is zero, therefore the line integral B over this closed path is given by:

$$\oint B \cdot dl = B \oint dl = 2\pi r B \tag{2.4}$$

Now, from equation 2.1 and 2.2

$$B = \frac{\mu_o I}{2\pi r} \tag{2.5}$$

2.3 Magnetic Field Theory & calculation

The physical parameters are shown in figure 2.2 and the same theory is used for calculations for different configurations. The scenario for the power cable is that it is buried and the distance from the point of interest to the cable is r [6].

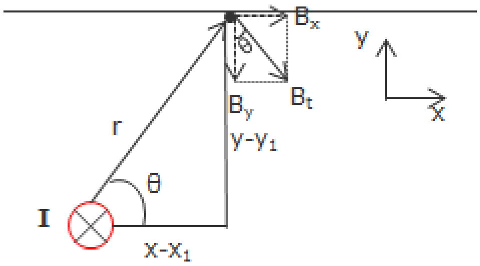


Figure 2.5: Magnetic field of Cable positioned at arbitrary point

The approach for calculating the magnetic field around cables is given for one phase in figure 2.4 (for one phase only). I is the current through power cable. Magnetic field along x and y direction are obtained with knowledge of "Ampere's Law" and through vector algebra of magnetic field in the x- and y-directions, the actual magnetic field for the cable for a particular current rating can be calculated (root mean square (RMS) value of magnetic field).

From equation 2.3:

$$B_t = \frac{\mu_0 I}{2\pi r} \qquad r = \sqrt{(x - x_1)^2 + (y - y_1)^2} \tag{2.6}$$

The total magnetic flux density B_t at a certain position can be extracted from the magnetic flux density in x- and y-direction (B_x respectively B_y).

$$\cos\theta = \frac{(y - y_1)}{r}, \sin\theta = \frac{(x - x_1)}{r} \tag{2.7}$$

$$B_x = B_t \cdot \cos\theta = \frac{\mu_0 I}{2\pi}\left(\frac{(y - y_1)}{r^2}\right) \qquad B_y = B_t \cdot \sin\theta = \frac{\mu_0 I}{2\pi}\left(\frac{(x - x_1)}{r^2}\right) \tag{2.8}$$

The total magnetic field at the point of interest is given by:

$$B_t = \sqrt{B_x^2 + B_y^2} \tag{2.9}$$

2.4 Induced Electric Fields Theory & Calculation

A magnetic field can induce electric fields on nearby de-energized and isolated metallic objects. The induced electric field by magnetic induction is usually less than that induced electric field by the electrostatic induction. Underground cables have metallic sheath around them which limits the electric field, therefore we consider induced electric field from magnetic field.

Following are the instances where we can experience high induced electric field [7]:

- When the energized conductor is under fault conditions.
- When industrial equipment is carrying high currents.

Magnetic fields can induce electric field values as high as 3 V/m up to 5 V/m under short circuit conditions. The current inside an energized conductor produces a magnetic flux Φ that surrounds the conductor, as shown in the figure 5.1. These flux contours are circular and concentric with conductor.

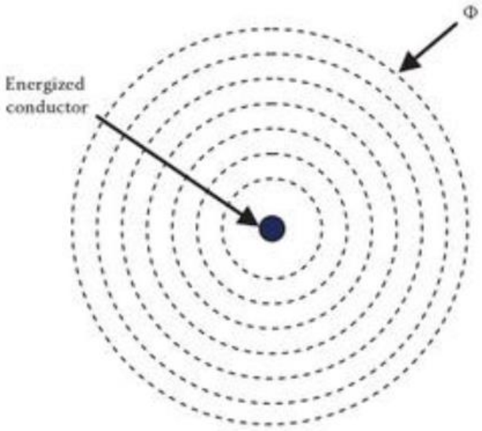


Figure 2.6: Flux from energized conductor

There are two important terms for flux that has to be understood: flux Φ and flux linkage λ (Wb/m). A flux is generated by a current inside the conductor. The flux linkage is the amount of the flux that surrounds an object located within the flux contours.

Assume an energized conductor is in space and a de-energized conductor or an isolated metal is placed near to energized conductor as shown in figure 5.2. Some of the total flux will surround the de-energized conductor or metal object (dashed lines in the figure 5.2).

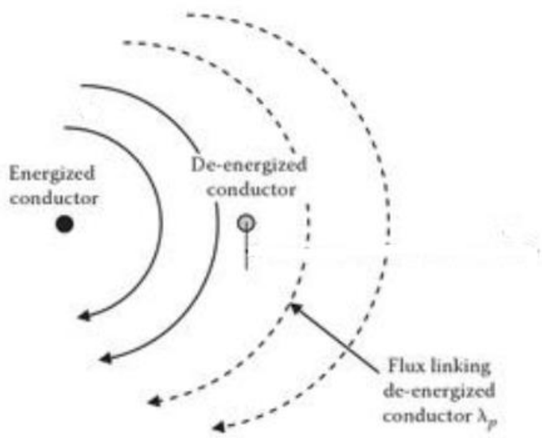


Figure 2.7: Flux and Flux linkage in space

The flux that links the de-energized conductor or metal object λ_p is all the flux contours that pass through the de-energized conductor from its location.

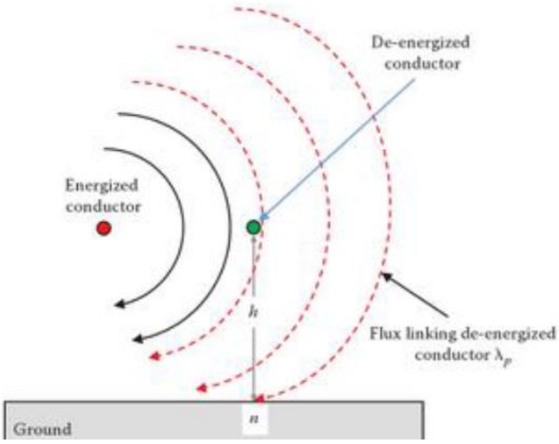


Figure 2.8: Flux and Flux linkage for induced electric field

As shown in figure 5.3, *n* is the ground below the de-energized conductor. For the calculations, the flux linking the de-energized conductor and the induced electric field above the ground level is all the flux that passes in between the de-energized conductor and the point *n*.

The amount of flux linking the de-energized conductor is dependent on two factors:

- Distance of de-energized conductor with respect energized conductor. The flux density is reduced when distance is increased.
- The current in the energized conductor, higher the current higher will be the flux.

The flux density *B* is defined as the amount of flux falling on a given area divided by the area itself:

$$B = \frac{d\phi}{dA} \tag{2.10}$$

Where
Φ is the total flux produced by the energized conductor in Wb
$d\Phi$ is the flux falling in a small area dA
dA is the area receiving $d\Phi$
B is the flux density in Wb/m^2 or T

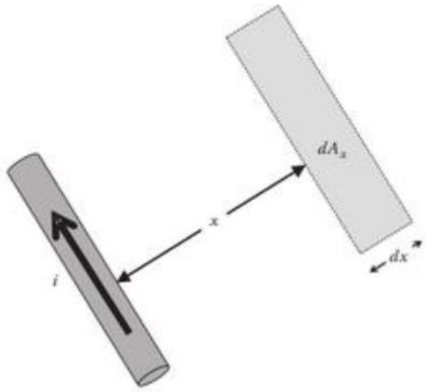


Figure 2.9: Conductor carrying current and adjacent area

Consider figure 5.4 where a conductor carries a current *i*. The nearby small area *d*A is at a distance *x* from the conductor. The flux density *B* is this area is:

$$B = \frac{d\phi_x}{dA_x} = \frac{d\phi_x}{dl \times dx} \tag{2.11}$$

Where
$d\Phi_x$ is the flux falling in a small area *d*A
dx is the width of the area
dl is the length of the area

Hence, the flux density at a distance *x* is:

$$\begin{aligned} d\lambda &= \frac{d\phi}{dl} \\ B &= \frac{d\lambda}{dx} \end{aligned} \tag{2.12}$$

From the theory of Ampere's Law (section 3.1):

$$\begin{aligned} B &= \frac{\mu_0 i}{2\pi x} \\ \frac{d\lambda}{dx} &= 2 \times 10^{-7} \frac{i}{x} \end{aligned} \tag{2.13}$$

Equation 5.4 is general and can be used to compute the flux linking an object near cables. In figure 5.5, for example, the flux linking the de-energized conductor λ_p by integrating Equation 5.4 with respect to distance *x*. In this case, the limits of *x* are from *d* to *D*. Hence:

$$\lambda_p = 2\times10^{-7}\int_d^D \frac{i}{x}dx$$
$$\lambda_p = 2\times10^{-7}\times i\times\ln\left(\frac{D}{d}\right) \qquad (2.14)$$

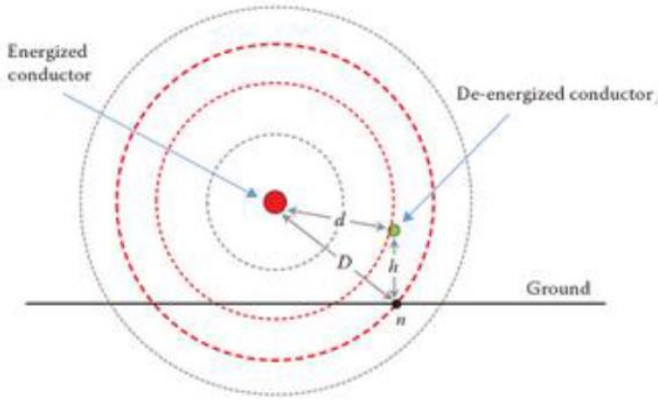


Figure 2.10: De-energized conductor in the vicinity of energized conductor

Where
x is the distance of de-energized conductor and angle dependency not important
d is the distance between the energized conductor and the de-energized conductor
D is the distance between the energized conductor and the ground below the de-energized conductor (n)

The induced electric field e_p on the de-energized conductor per unit length is proportional to the rate of change of flux linkage λ_p with respect to time.

$$e_p = \frac{d\lambda}{dt} = 2\times10^{-7}\times\ln\left(\frac{D}{d}\right)\times\frac{di}{dt}$$
$$i = I_{\max}\sin(\omega t) \qquad (2.15)$$
$$\frac{di}{dt} = \omega I_{\max}\cos(\omega t) = \omega I$$

Where
I is the rms value of the current.
Now, we can rewrite Equation 5.6 in rms quantities as:

$$E_p = 2\times10^{-7}\times\omega I\times\ln\left(\frac{D}{d}\right) \qquad (2.16)$$

E_p is the induced electric field in rms on the de-energized conductor per unit length. The total induced voltage V_p on the de-energized conductor is:

$$V_p = E_p\times l \qquad (2.17)$$

Where, l is the height or length of the de-energized conductor.

2.5 Summary

In this chapter we discussed electromagnetic field. Electric and magnetic fields are inextricably linked to each other, and, as mentioned earlier, a changing magnetic field automatically creates a changing electric field (induced electric field). The electric charge is stationary in some frame, then it only generates an electric field; an electric charge moving at some constant velocity generates both electric and magnetic fields. Changing (time varying) $\mathbf{B}$ fields generate an induced $\mathbf{E}$ field respectively. The magnetic field by itself is of prime importance. Our contemporary civilization cannot even be imagined without the presence of electric power. Time varying magnetic fields are interesting in their own right, and we will briefly study a few examples of these in coming chapters based on exposure and its safe limits.

3

3 Management & Optimization

In this chapter, we will go through special cases for directly buried and tunnel configurations and consider possible way to optimize the design for initial calculation in chapter 4. Finally, we conclude this chapter by presenting the design limits, magnetic field management and other comparison values.

3.1 Factors detrimental for Magnetic fields

There are many factors which affects the values of the magnetic fields produced by the underground transmission cables. These factors may be grouped into the following categories [8]:

- Current magnitude, phase balance and system grounding
- Cable installation parameters such as:
    - Depth of burial
    - Flat and trefoil cable arrangement
    - Spacing between cable phases and cable circuits.
- External factors such as the presence of nearby source of current which may flow on cable sheath or ground continuity conductor.

3.2 Magnetic field management

In this section the factors which affect the magnetic field produced by the transmission cable system, as mentioned in section 3.1, are being considered:

Below are guidelines for magnetic field management:

- Advantage of mutual magnetic field reduction in double and multiple cable circuits.
    - If the transmission cable system has two or more circuits, then we can arrange cable phases such a way that more field reduction is attained.
- Type of installation configuration chosen can results in relatively low magnetic fields.

  - We will compare the results for cable phase in flat and trefoil configurations and also we will increase the magnitude of current to achieve till what value the value of magnetic field is within safe limits.
  - Horizontal and vertical cable circuit configurations are compared and spacing limits are identified keeping the magnetic field limits specified by ICNIRP.

- Burial depth in case of direct burial configuration will be increased to achieve minimum magnetic field.

  - This method is ideal for reduction of maximum magnetic field directly above the cable circuit.

- In case of tunnel configuration, having double or more circuits the working professional have to be in safe limits at 1 meter from the nearest cable surface.

  - We will see the percentage change in values, if we add cable circuit having same current magnitude and see if they still remain in the safe limits and check the safe distance.
  - We will check the percentage change in value of magnetic field, if the magnitude of current increased.
  - By changing the location of cable circuit, check if the magnitude of magnetic fields is in safe limits and recommend for reduction of tunnel diameter.

3.3 Optimization of the design

In this section, above mentioned approach for magnetic field management will be further elaborated and safe limits with respect to distance will be presented.

3.3.1 Mutual Field reduction and Spacing between cable phases

Given:

For directly buried cable installation with horizontal configuration of 400 kV and current of magnitude 1450 A, with double circuit and cable phase arranged (Red Yellow Green) RYG RYG with spacing varying from 200 mm till 2000 mm, spacing between circuits of 1250 mm and cable circuit depth 2267 mm.

Required:

It is required that the maximum magnetic field at one meter above the ground at the centre of the cable circuit be limited to no more than 200 µT at full load for general public.

Approach:

The approach is to have mutual field reduction between double circuit direct burial cable systems by having combination of phasing like both circuit RYG, RYG GYR, RYG YGR, RGY YGR, GYR RGY and both circuit GRY. The spacing between the cable phases is varied and from the results the limit till the spacing can be increased will determined.

Results and discussion:

Below is the table 3.1 with calculation summary for above scenario and there simulation are presented in figure 3.1.

Scenario	**Cable spacing/ Phase arrangement**	**Magnetic field in µT**	**Remarks**
Spacing	200 mm	8	Reduction in rating
	400 mm	19	Good but additional cooling[4] system arrangements are not easily performable
	600 mm	30	Ideal cable phase spacing and effective for cooling system
	800 mm	43	Underground digging results in additional cost
	1000 mm	54	Underground digging results in additional cost
	1200 mm	65	Underground digging results in additional cost
	1400 mm	77	Underground digging results in additional cost
	1700 mm	87	Underground digging results in additional cost
	2000 mm	97	Underground digging results in additional cost
Cable Phase arrangement	Both RYG	37	7 µT more compared to reverse phasing
	RYG GYR	30	Minimum magnitude in compare to other phase arrangements
	RYG YGR	36	6 µT more compared to reverse phasing
	RGY YGR	31	1 µT more compared to reverse phasing
	GYR RGY	30	Minimum magnitude in compare to other phase arrangements
	Both GRY	37	7 µT more compared to reverse phasing

Table 3.1: Mutual cancelation and cable spacing

[4] Forced cooling by means of separate pipe installed close to cable with following water

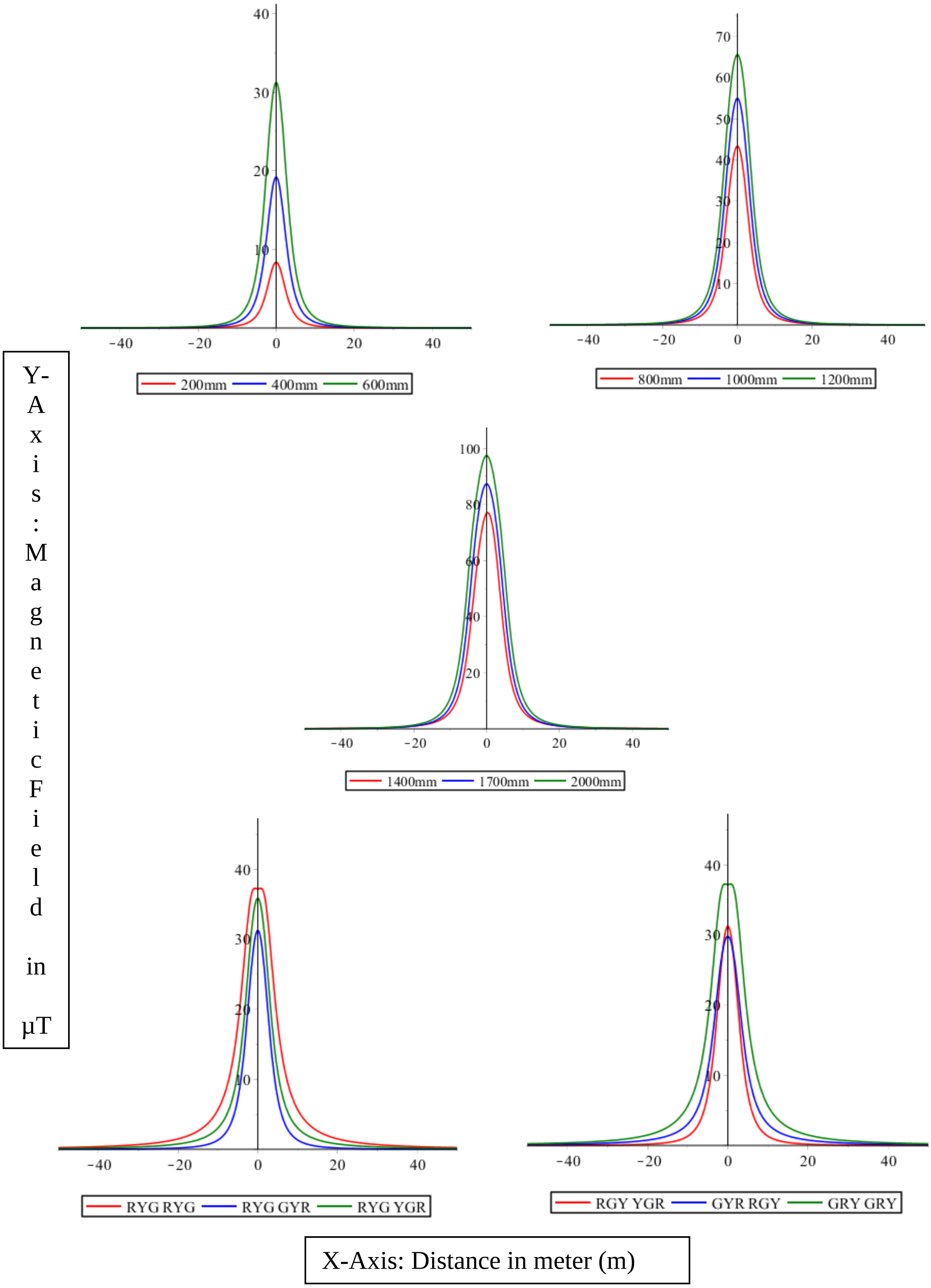


Figure 3.1: Mutual cancelation and cable phase spacing optimization

From the simulation results in figure 3.1, it is well understood that when cable phase distance increase the magnitude of the magnetic field also increases. Here in this case we increased the space distance by factor of 200 mm up till 2000 mm and we observed that for every 200 mm increase the magnitude of corresponding magnetic field increased by 10 µT. Next, is the condition where we altered the phase arrangements and understood that reverse phasing (RYG GYR) results in minimum magnitude of magnetic field in comparison with other phase arrangements. It is also observed that for a distance of 200 mm the magnitude of magnetic fields for general public exposure is within safe limits but placing the cable phases close may result in mutual heating which will results in reduced ampacity. So it is recommendable to have the transmission lines at distance of 1 m below ground level and cable space distance of 600 mm which allows the application of cooling pipes placed between the phases to improve heat loss management.

3.3.2 Flat and trefoil cable arrangement

Given:

A directly buried cable installation with horizontal configuration of 400 kV and current of magnitude 1450 A, with double circuit and cable phase arranged in reverse phasing RYG GYR with spacing for flat configuration 650 mm, for normal trefoil and 240 mm for open trefoil arrangement, circuit spacing of 1250 mm and cable circuit depth 2267 mm.

Required:

It is required that the maximum magnetic field at one meter above the ground at the centre of the cable circuit to be limited to no more than 200 µT at full load for general public.

Approach:

The approach is to calculate the magnitude for different configuration and check which has the highest value. Based on the comparison the design will be proposed. Secondly the cable circuit configurations with respect to horizontal and vertical plan will be altered to estimate the percentage change in the magnetic field magnitude.

Results and discussion:

Below is the table 3.2 with calculation summary for above scenario and there simulation are presented in figure 3.2.

Scenario	**Phase arrangement**	**Magnetic field in µT**	**Remarks**
Flat	RYG GYR	31	23 µT more compared to trefoil
Trefoil	RYG GYR	8	Minimum magnitude but high heat losses due to close cable spacing
Open trefoil	RYG GYR	11	Less compared to flat and

			provides flexibility of cooling system for heat dissipations
Horizontal	RYG GYR	31	Ideal configurations
Vertical	RYG GYR	61	Magnitude of magnetic field increased by twice, which not acceptable

Table 3.2: Cable circuit arrangements

From the simulation results in figure 3.2, it is well understood that when cable phase arrangement for flat formation the magnetic field is higher in comparison with cable in trefoil and open trefoil. Here in this case magnetic field increased with 20 µT in flat arrangement. The magnitude of the magnetic field increases when cable circuit arrangement is changed from horizontal to vertical. It is also observed that the magnitude of magnetic fields for general public exposure is within safe limits but for cable arrangements in trefoil and vertical the heat loss will dominate and may results in cable failure and ampacity reduction. In case of open trefoil, the spacing between the phases is increased as to accommodate cooling system in practice for better heat loss management. In our case we have considered cable spacing in open trefoil as 240 mm and it is ideal to use trefoil arrangement with pipe jacking to hold the cable in position, this will increase the cost for installation. From the above calculations flat cable arrangement and horizontal cable circuit is cost wise and magnetic field exposure limit, both are in permissible limits and no special pipe jacking to hold cable phases in position is required.

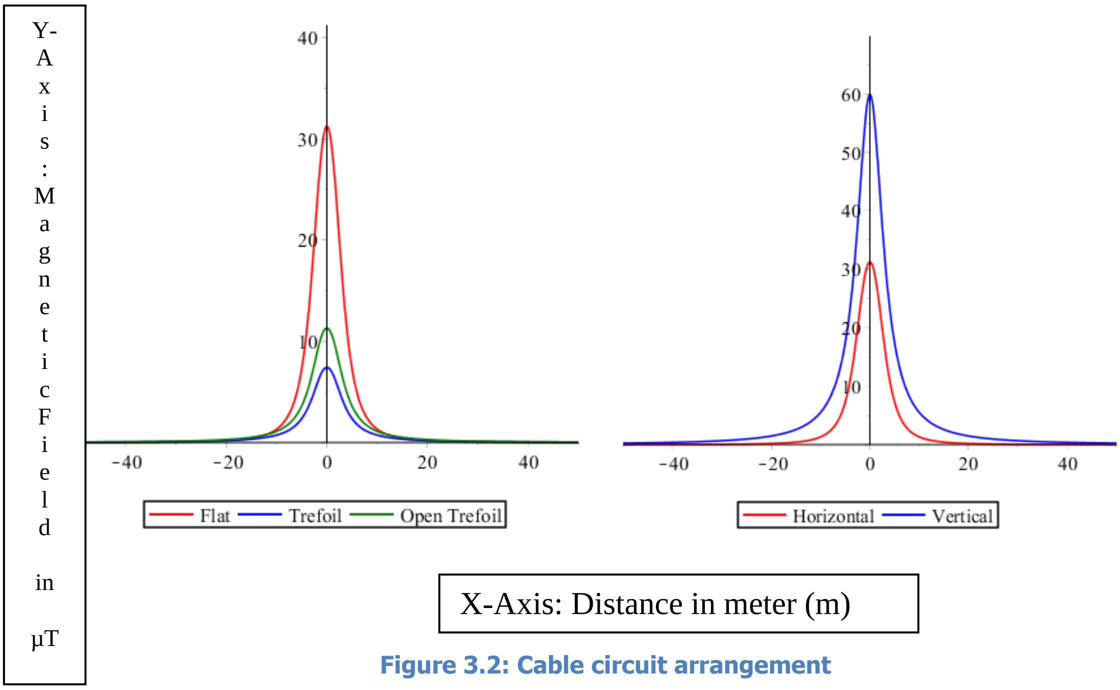


Figure 3.2: Cable circuit arrangement

3.3.3 Burial depth

Given:

A directly buried cable installation with horizontal configuration of 400 kV and current of magnitude 1450 A, with double circuit and cable phase arranged in reverse phasing RYG GYR with spacing for flat configuration 650 mm, normal trefoil and 240 mm for open trefoil arrangement, circuit spacing of 1250 mm and cable circuit depth varied from 500 mm till 2000 mm.

Required:

It is required that the maximum magnetic field at one meter above the ground at the centre of the cable circuit be limited to no more than 200 µT at full load for general public.

Approach:

The approach is to calculate the magnitude for different configuration and check which has higher value. Based on the comparison propose the design for optimum depth requirement to avoid unnecessary ground digging.

Results and discussion:

Below is the table 3.3 with calculation summary for above scenario and there simulation are presented in figure 3.3.

Scenario	Distance from ground	Magnetic field in µT	Remarks
Burial depth	500 mm	150	Risk for third party damage
	700 mm	123	Magnitude is high in compare to 1100 millimetre
	900 mm	101	High value in compare to 1100 millimetre
	1100 mm	83	Protected but digging results in additional cost
	1300 mm	70	Protected but digging results in additional cost
	1500 mm	58	Protected but digging results in additional cost
	1700 mm	48	Protected but digging results in additional cost
	1900 mm	41	Protected but digging results in additional cost
	2000 mm	38	Protected but digging results in additional cost

Table 3.3: Burial depth variation

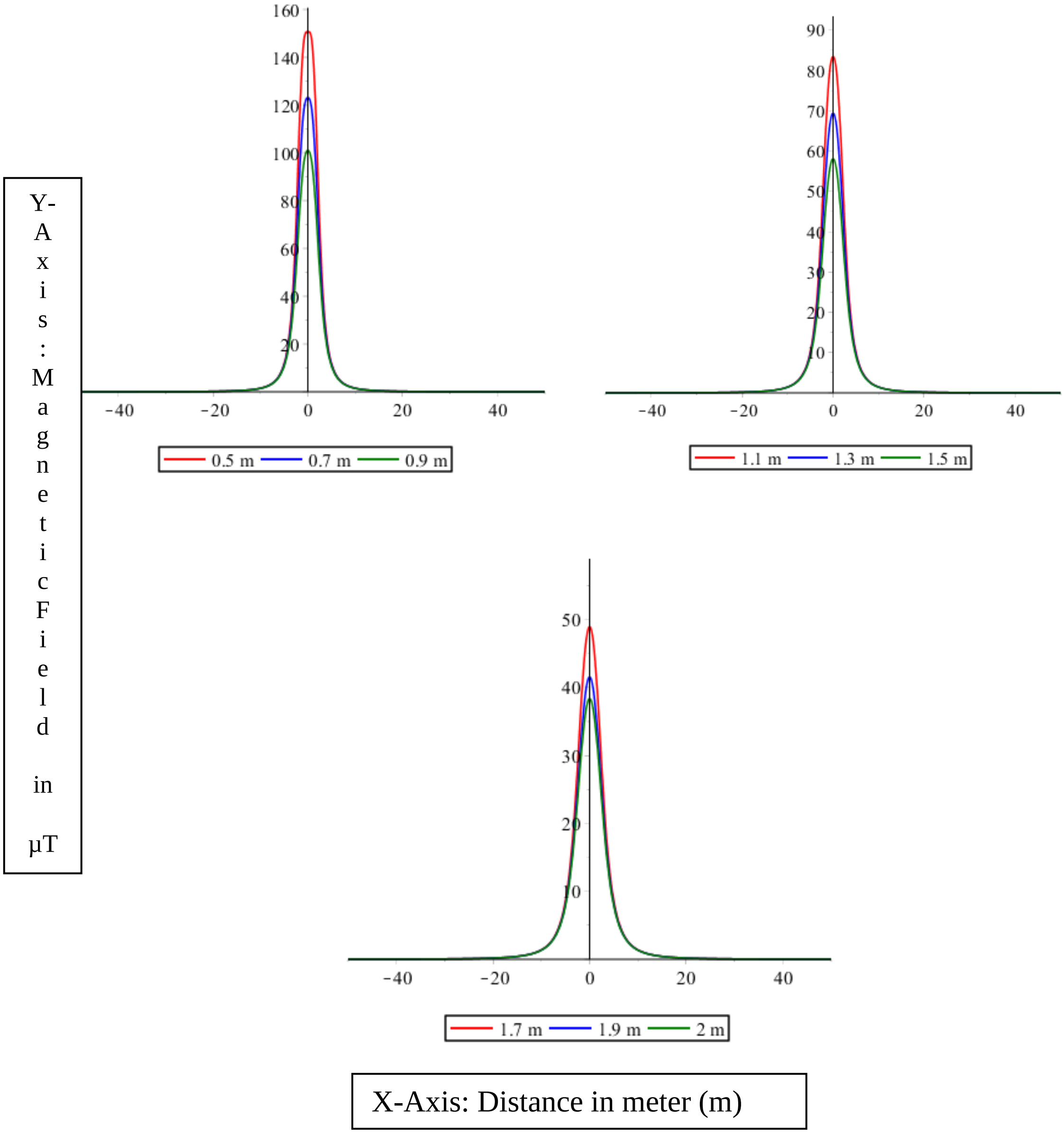


Figure 3.3: Burial depth variation

From the simulation results in figure 3.3, it is well understood that with cable circuit burial distance increase the magnitude of the magnetic field decreases. Here in this case we increased the burial distance from 200/500 mm up till 2000 mm and we observe that for every 200 mm increase the magnitude of corresponding magnetic field decreased by 20 µT up to 1000 mm and for higher depths with 10 µT. It is also observed that for a distance 500 mm the magnitude of magnetic fields for general public exposure is within safe limits but placing the cable circuit depth close to ground level may result in risk of third party damage. It is recommendable to use burial depth of more than 1 meter (for case study burial depth is considered as 2267 mm).

3.3.4 Tunnel symmetry and addition of cable circuit

Given:

A directly buried cable installation with horizontal configuration of 400 kV and current of magnitude 1450 A, with double, quadruple and twelve circuits and cable phase arranged in reverse phasing RYG GYR with spacing for open trefoil configuration 240 mm, normal flat configuration 450 mm and tunnel depth 60m.

Required:

It is required that the maximum magnetic field at one meter above the ground at the centre of the cable circuit be limited to no more than 1000 µT at full load for general public.

Approach:

The approach is to calculate the magnitude for different configuration and check which has the highest value. Based on the comparison propose the optimum design requirement to avoid unnecessary increase in magnetic field magnitude. Lastly, compare magnetic field magnitude increase between twelve, twenty and twenty four cable circuit arrangement and compare magnitude increase when current magnitude of 1450 A, 2000 A and 3000A and define the safe limits for exposure to time varying magnetic fields.

Results and discussion:

Below is the table 4.4 with calculation summary for above scenario and there simulation are presented in figure 4.4.

Scenario	**Current/shift & number of cable circuit**	**Magnetic field in µT**	**Remarks**
Twelve circuit with different current	1450 A	93	Normal configuration considered
	2000 A	113	The field values are in safe limits the nominal current could be increased
	3000 A	150	Field values are in safe limits but high current values relate to more heat loss and to high temperature
Shifting cable circuits	Normal twelve circuit arrangement	93	Normal configuration considered
	0.5 m towards centre of tunnel	99	Cable circuit could be shifted and the tunnel diameter is reduced by 1 meter
	1 m towards centre of	105	Cable circuit could be shifted,

	tunnel		but it will be very close to occupational worker which is not acceptable
Addition of cable circuit	Twelve circuit	93	Normal configuration considered
	Twenty circuit	140	Could be a possibility provided the tunnel has cooling system to have better heat dissipation and related temperature control
	Twenty four circuit	160	Could be a possibility but more heat loss due to more circuits and may demand for increase of tunnel diameter which results in cost additions

Table 3.4: Tunnel dimensioning and addition of cable circuit

From the simulation results in figure 4.4, it is well understood that with increase in current rating for each cable phase the magnitude of magnetic field increased, but 1 meter form closest cable surface still the exposure values for working professional are in safe values. Higher current values up to 3000 A can be applied, but the heat losses will be high so optimal current values of in between 1450 to 2000 A can be considered for cable installation. In another scenario the tunnel diameter considered was 6 meter, we can see shifting the cable circuits by half meter or 1 meter both side, the change in the magnitude of magnetic field is is less than 20 to 30 µT. Considering this we can minimize the tunnel diameter to avoid extra cost. Lastly, we have added additional eight and twelve circuit to existing twelve circuits to understand the behaviour. It was observed that 1 meter from closet cable surface the magnitude of magnetic field exposure was in safe value. We see that from simulations, the magnitude increase was between 40 to 50 µT.

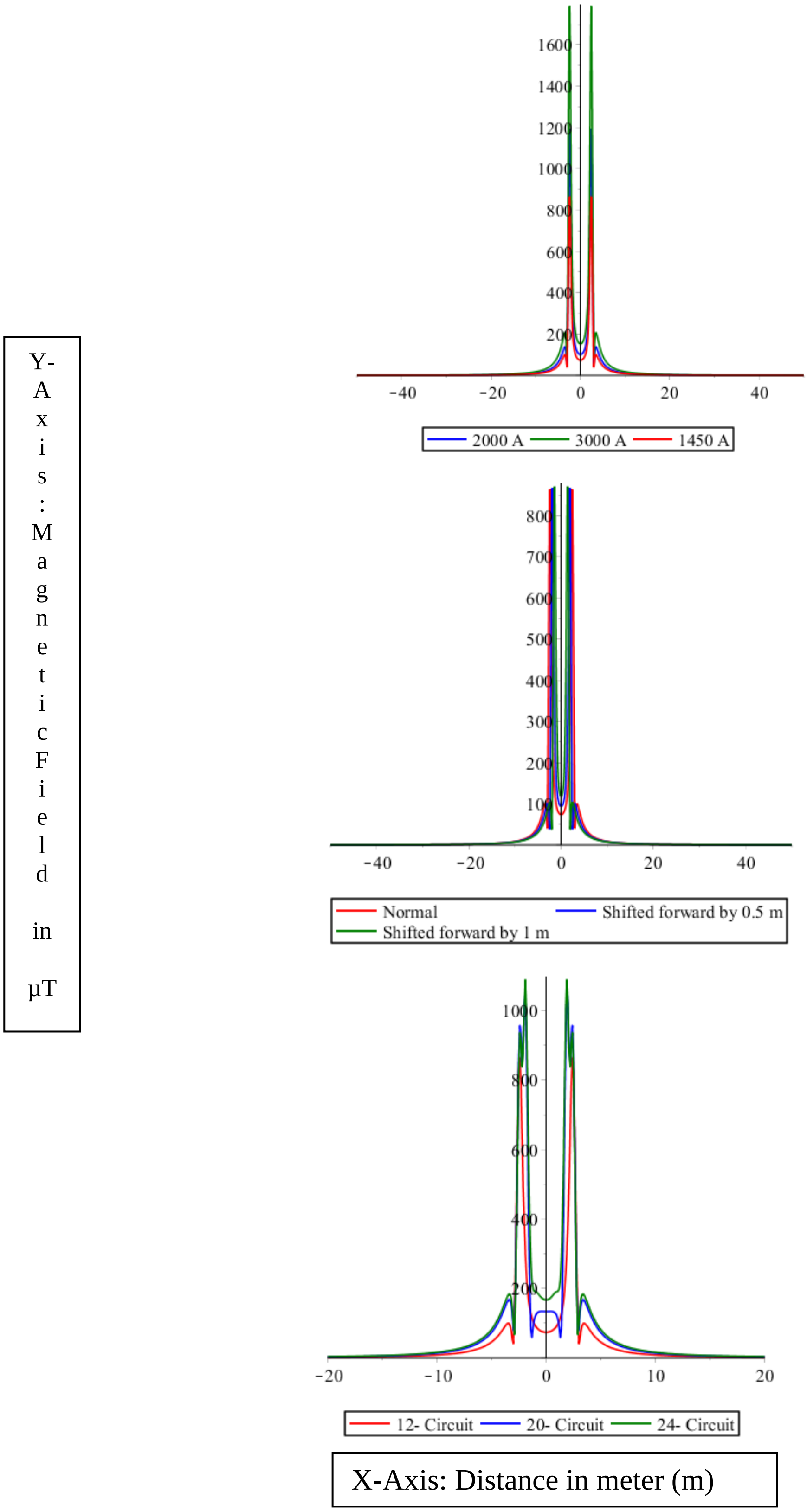


Figure 3.4: Addition of circuit, shifting circuits and increasing the nominal current

3.4 Summary

In this chapter we discussed about optimization of the installation design. The ideal values are listed in table 3.5 and these values are used in coming chapters for the analysis of magnetic field exposure limits.

Parameter		Values
Direct Burial	Cable formation	Flat
	Number of cable circuit	Single and double
	Cable spacing	600 to 650 mm
	Burial depth	1500 to 2200 mm
	Configurations	Reverse phasing (RYG GYR)
	Current	1450 A
Tunnel	Number of circuit	Open trefoil
	Cable formation	Single, double, and Multiple
	Cable spacing	240 mm
	Tunnel depth	60 m
	Configurations	Reverse phasing (RYG GYR)
	Current	1450 A

Table 3.5: Design Parameters

4

4 Configurations and Scenarios

What are the reasons cables installed and being used, as this solution usually is far more expensive than overhead lines? Cables use less space, are invisible, need less maintenance and require a shorter period of time to receive necessary permits and public approval.

The most basic and economical method to install cables is by traditional open cut trenching. The situation of direct buried [10] for installing underground power cables requires that long sections of trench remain open until cable lying is performed. But this method can cause considerable inconvenience to the public when the whole trench is excavated for the cable to be installed and protection of the cable against third party damage is limited.

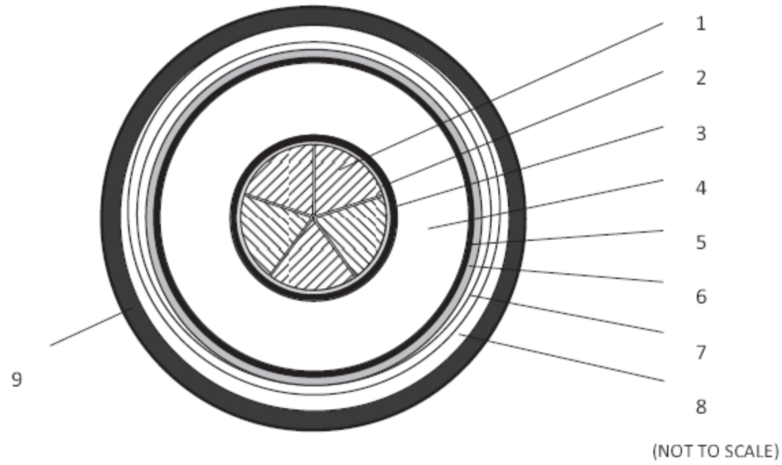
In Asian countries, it is standard practice to use tunnels for EHV cable systems. Actually this increasingly is used in other parts of the world as well: big cities like London, Berlin [11], Barcelona and Madrid. The major advantages are: no disruption to traffic in case of installation and maintenance, however the total costs are significantly high. To reduce cost more often different infrastructures are combined resulting in so called multipurpose tunnels, where the total costs are shared by several parties.

4.1 Cable Profile

The conventional HV (High Voltage) or EHV (Extra-High Voltage) power cable consists of following main part:

- Conductor (copper or aluminium)
- Insulations (cross-linked polyethylene)
- Radial water barrier (copper or aluminium sheath)
- Longitudinal water barrier (swelling tape)
- Outer covering (High density polyethylene)

The selected XLPE cable for thesis study is 400 kV 2500 mm^2 Copper Conductor, XLPE Insulated, corrugated Aluminium Sheathed and PE Outer sheathed Power cable, shown in figure 3.3.



1. COPPER CONDUCTOR (INDIVIDUAL WIRE INSULATED)
2. CONDUCTOR BINDER TAPE(S)
3. CONDUCTOR SCREEN
4. XLPE INSULATION
5. INSULATION SCREEN
6. BEDDING TAPE(S)
7. CORRUGATED ALUMINUM SHEATH
8. BITUMEN COMPOUND
9. PE OUTERSHEATH WITH EXTRUDED SEMI-CONDUCTING PE

Figure 4.1: 400 kV XLPE Cable Model

System Operating Conditions considered for thesis study:

- Nominal Voltage — 400 kV
- Nominal Current — 1450 A
- System Frequency — 50 Hz
- Number of Phases — 3
- Maximum Continuous Conductor Temperature — 90 ºC (under normal conditions)
- Maximum Short circuit current — 40-80 kA (from cable data)

4.2 Input data

The following assumptions are made for carrying out calculations on magnetic fields.

- The relative permeability μ_r of cable material, earth and free air is 1 (equation 4.1).

  For example, the permeability μ of air is 1.256 microH/m [9].

$$\mu_r = \frac{\mu}{\mu_o} = \frac{1.26 \times 10^{-6}}{4\pi \times 10^{-7}} \cong 1 \qquad (4.1)$$

- For all the calculation 3-phase rms current with phase shift is considered.
- The total magnetic field at any point is determined by linear superposition of the magnetic fields produced by the currents flowing in each individual conductor (explained in section 2.3).
- In direct burial the cable circuit the sheath has cross bonding arrangement, which results minimum residual voltage and the calculated sheath circulating current (7 A rms) is very less with respect to nominal current (1450 A rms). In case of open trefoil the sheath current is less and hence considering the worst case the sheath current is neglected.
- For tunnel, safe limits are calculated keeping occupational worker under consideration only (no public is expected to walk around in the cable tunnel) and the depth of tunnel is 60 meter for which the magnetic fields will be negligible above ground.
- For both configuration calculations are carried out for single and double circuit.

4.3 Configurations

4.3.1 Directly Buried Cable Trench

For directly buried trench construction, the cable system consists of single or double 400 kV cable circuits for the thesis study. The direct buried cables are laid direct in the soil.

The magnetic fields are calculated for directly buried single and double cable circuit under the following conditions (figure 4.2):

- Single cable circuit with three cables in horizontal flat formation with the following space between phases: 400, 500 and 600 mm (B2 in figure 4.5).
- Double cable circuit with three cables in horizontal flat formation with the following space between phases: 400, 650 and 900 mm (B1 in figure 4.6).
- Spacing between the cable circuits is 1250 mm (C in figure 4.6).
- The average cable depth is 2267 mm.

4.3.2 Deep Bore Tunnels

For tunnel installation, figures 4.3 show the configurations for single, double and multiple (12) circuit based on below details (yellow dashed lines are the reference axis):

- Depth of laying 60 meter
- Cable laying Open trefoil
- Spacing of cables 240 mm
- Width of laying 6 meter

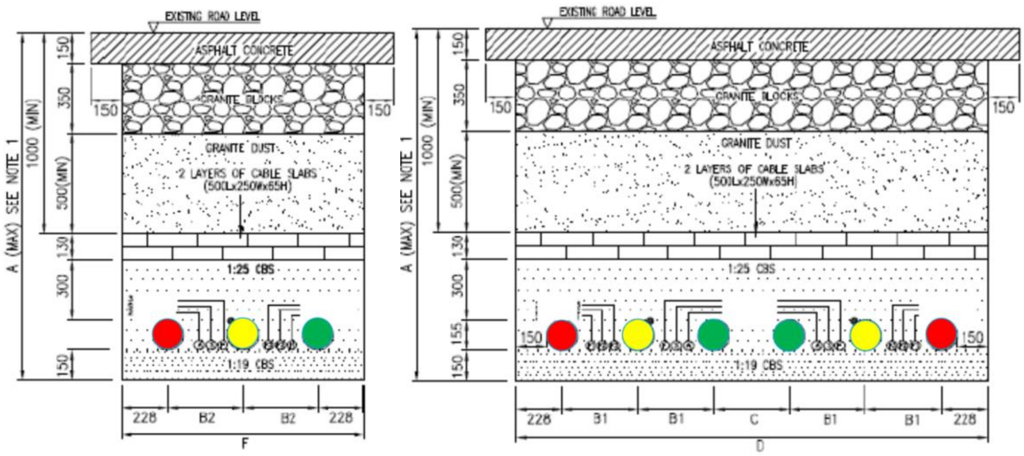


Figure 4.2: Direct Burial- Single & Double Circuit with reverse phasing

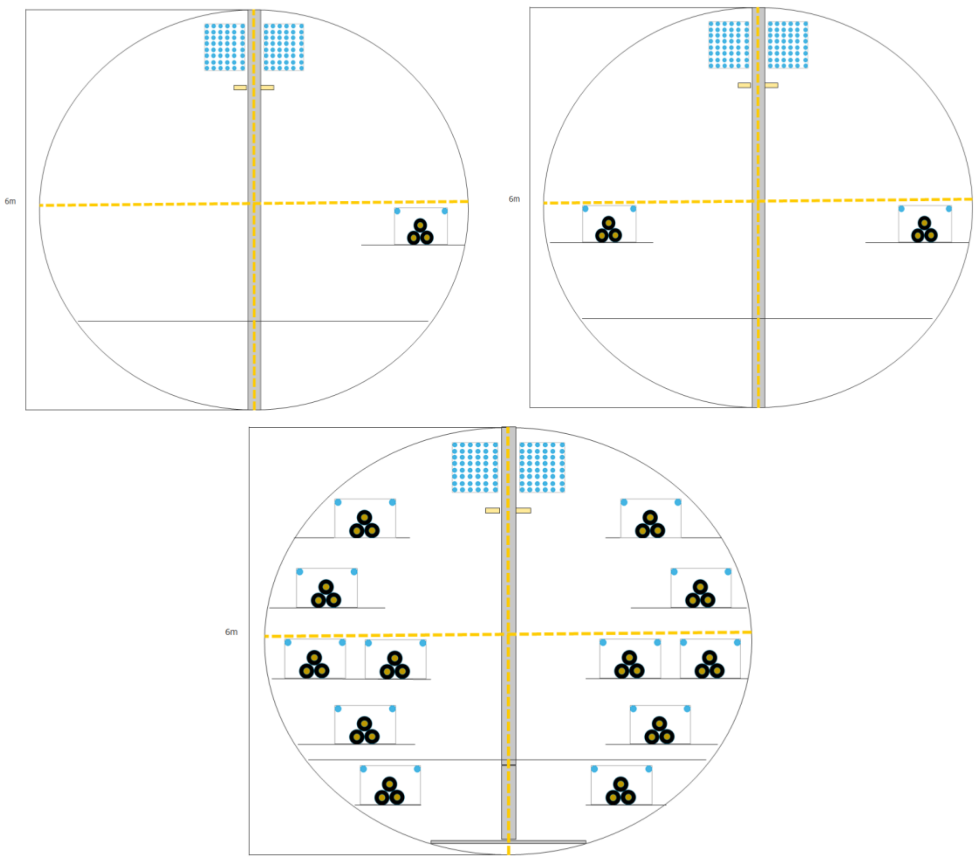


Figure 4.3: Tunnel- Single, Double & multiple circuits open trefoil

4.4 Calculation Tool

The theoretical approach discussed in section 2.3 is implemented in Maple18 environment. For a ***underground cable installation- directly buried and tunnel*** a script is obtained for which – given the coordinates of the first, (x_1,y_1), second, (x_2,y_2), and third, (x_3,y_3) etc., cables in a 2- dimensional Cartesian reference system orthogonal to line axis. The axis is considered at $x = 0$ and ground level is located at $y = 0$ – calculates the value of the magnetic field generated by the underground cable installation for a three-phase power cable line along a horizontal line parallel to the to the ground and placed at a certain vertical distance *d* from the cables in directly buried system and for tunnel, it is distance form nearest cable surface. This script uses equation (2.6) - (2.9) for the calculation of magnetic fields, and equation (2.19) for induced electric field respectively, and different operating conditons has been applied to perform case studies taking into account of different cable types and different geometric configurations.

4.5 Scenarios

In this section we will discuss the basic day to day and some rare special operating conditons.

4.5.1 Normal steady supply at rated current

For normal buried situation we consider the situation where a human being is walking on streets (figure 1.4 left), where the underground installation present and are exposed to magnetic field. For the situation in a tunnel we consider the working professional passing by the neighbourhood of the cable and getting exposed to magnetic fields (figure 4.4. right).

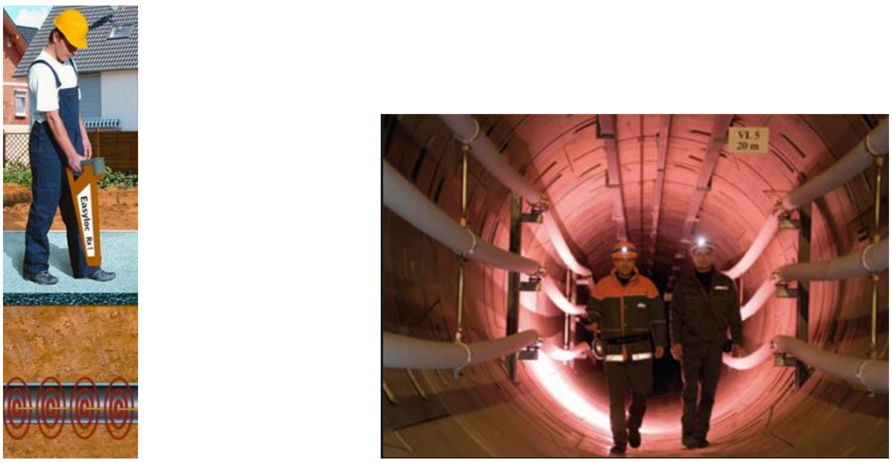


Figure 4.4: Normal operating condtions-examples

The electric fields which are induced by time varying magnetic fields or electrically energizes the any conducting object example metal poles, human body etc., this applies to all scenarios described below.

4.5.2 Maintenance of cable circuit

Maintenance of power cable system is very important and keeps us updated life and functioning of the power system. It showed that power cable circuits need to be checks regularly and have therefore to be switched off. In case of double circuits, this means that the other circuit will be live with nominal current of 1450 A and will produce magnetic fields. Under this condition the worker will be exposed to magnetic fields of live circuit (figure 4.5) and the magnitude which will be analysed in chapter 5. During maintenance, general public are restricted to the working zone, so the prime importance is for worker and the focus is on safety limits applied for workers.

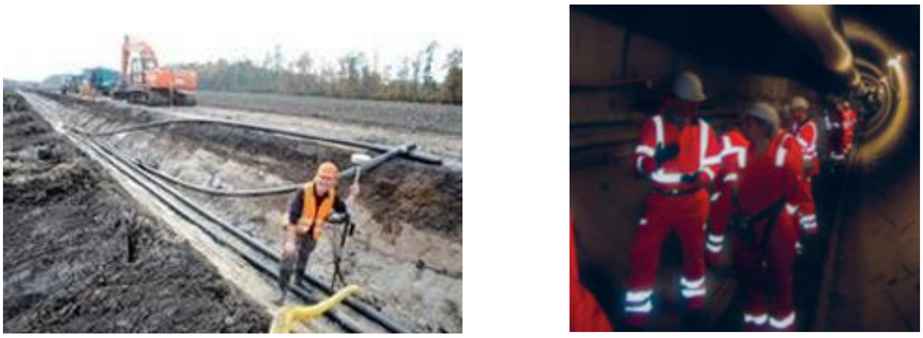


Figure 4.5: Maintenance Direct burial and tunnel

4.5.3 Increase for power demand

In case of contingencies, the cable loading can be increased, and in our case we increase the nominal current with emergency loading of 120%. This could be a case of increased magnetic field value in comparison with normal operating conditons. This increase of nominal current could be for short period of time, it can be in between 1 to 6 hours or may be more (figure 4.6).

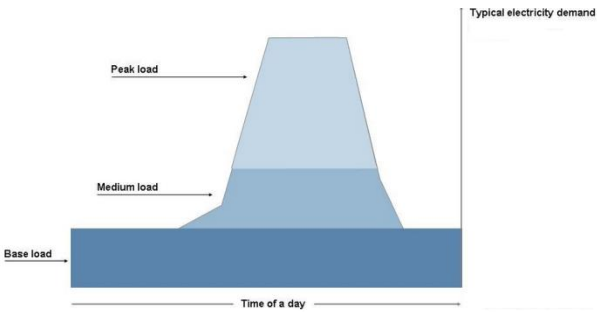


Figure 4.6: Peak demand with respect to time

4.5.4 Short circuit

Short circuit occurs rarely, but it is important to evaluate them as their impact may be significant. With a huge current of 80kA the magnetic fields generated will be very high and will cause short duration electrical, mechanical and thermal effects. Short circuit disturbs the environment around the fault point by causing a sudden drop in voltage. All the equipment and connections (power cable in our case) subjected to strong mechanical stress which can cause breaks, and thermal stress which can melt conductors and destroy insulation (figure 4.7). In this thesis we are talking on human safety, so when short circuit fault conditions occurs humans in the vicinity of underground installation experiences high magnitude of magnetic field and if these values are safe and will be presented in chapter 5. All the plots will generated having one circuit experiencing the short circuit (1-phase and 3- phase).

Figure 4.7: Cable damage- short circuit condition

4.5.5 Cable phase dis-positioned

In some situation, where the cable phase arrangements are altered and this could result in magnitude increase in the magnetic field exposure. There could be one more possibility like the combinations of cable phase of different circuit can be made into one or cable phase are into symmetric arrangements (figure 4.8).

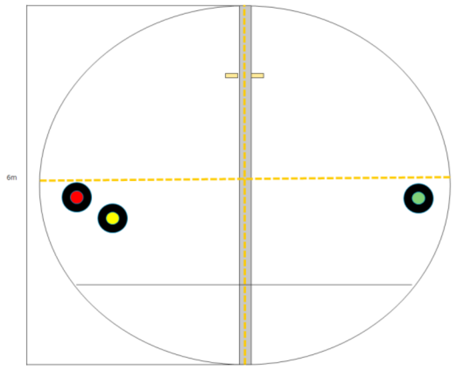


Figure 4.8: Cable phases- dis-positioned

4.6 *Summary*

In this chapter we discussed about optimization of the installation design. The operating conditons are listed in table 4.1 and these conditons are used in chapter 5 for the analysis of magnetic field exposure limits.

Operational Condition		Directly Buried	Tunnel	RMS Current (A)
1. Normal		Single circuit	Single circuit	1450
		Double circuit	Double circuit	
			Twelve Circuit	
2. Maintenance		Double circuit with one circuit under maintenance.	Double circuit with one circuit under maintenance	1450
			Twelve circuit with one side completely under maintenance	
			Twelve circuit with one circuit under maintenance on one side only above and below circuit switched off rest are in live	
3. Emergency		Single circuit	Single circuit	1740 (120% of 1450)
		Double circuit	Double circuit	
4. Short Circuit	3 phase	Double circuit with one circuit experiencing short circuit	Double circuit with one circuit experiencing short circuit	80000 (All three phase)
	1 phase	Double circuit with one circuit experiencing short circuit	Double circuit with one circuit 1 phase experiencing short circuit	80000 (other phase 0)
5. Cable Phase dis-positioned		Double circuit with phase change	Cable phase dis-positioned inside tunnel	1450

Table 4.1: Summary on operating scenarios

5

5 Results & Discussion

In this chapter, we will go through the results for operating conditons, including maintenance, emergency and short circuit current conditions as mentioned in chapter 4 for directly buried and tunnel configurations. Using the parameters from table 3.5, magnetic field plots are generated with two regions. The Red region indicates the area of high magnetic fields exceeding the reference limits set by ICNIRP for general public (200 µT), occupational worker (1000 µT and 100 µT with medical care). The green region corresponds to the safe region where the magnetic fields are below the reference limits.

5.1 Normal operations

Directly Buried

Figure 5.1 and 5.2 shows the magnetic field contour and normal plot for respectively single and double circuit directly buried configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in the right parts of figure 5.1 and 5.2 with different cable spacing, for a current of 1450 A through each conductor. The reference axis is indicated in figure with yellow dashed lines and the “d1” refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for general public. As it is clearly seen in figure the values are is safe limits that is green region and comply with ICNIRP for general public.

The width of the corridor in which the magnetic fields exceeds 0.4µT is from 16-20 m.

Tunnels

Figure 5.3 shows the magnetic field contour and normal plot for single, double and multiple circuit tunnel configurations with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right parts of figure 5.3 for one, two and twelve circuits for a current of 1450 A through each conductor. The reference axis is indicated in figure with yellow dashed lines and the “d” refers to 1m form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in figure the values are is safe limits that is green region and comply with ICNIRP for occupational workers.

The width of the corridor in which the magnetic fields exceeds 0.4µT is 13 m.

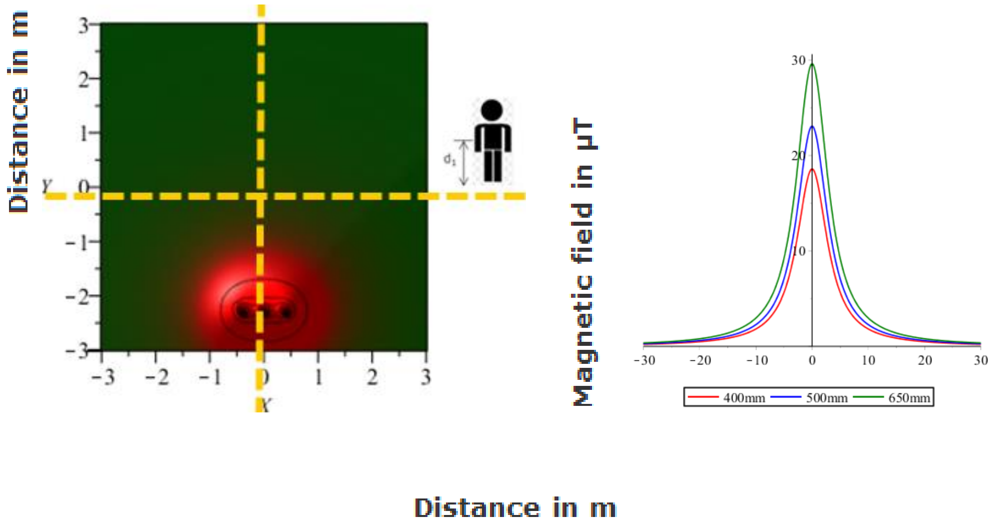


Figure 5.1: Directly Buried-single circuit plot (until waist)

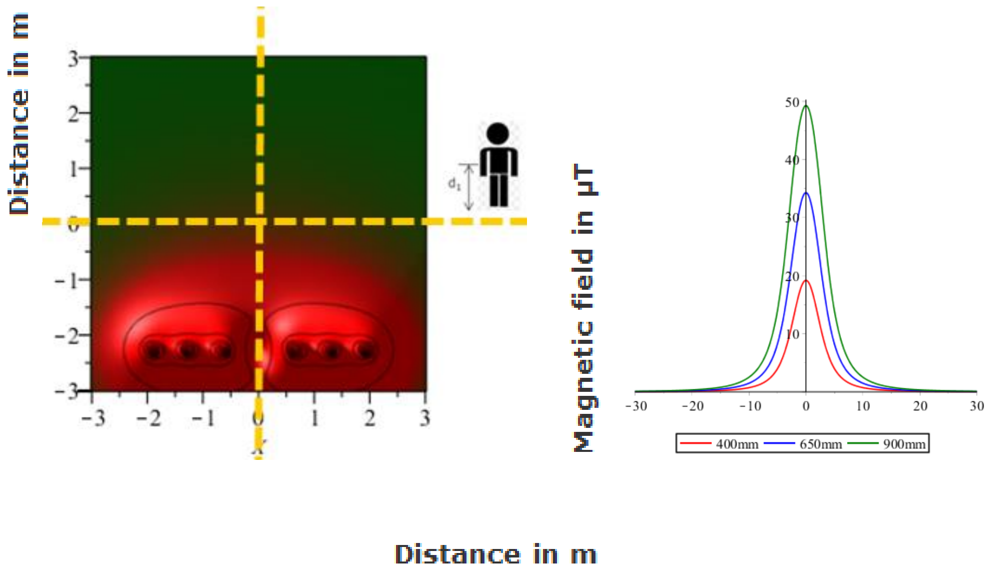


Figure 5.2: Directly Buried-Double circuit- plot (until waist)

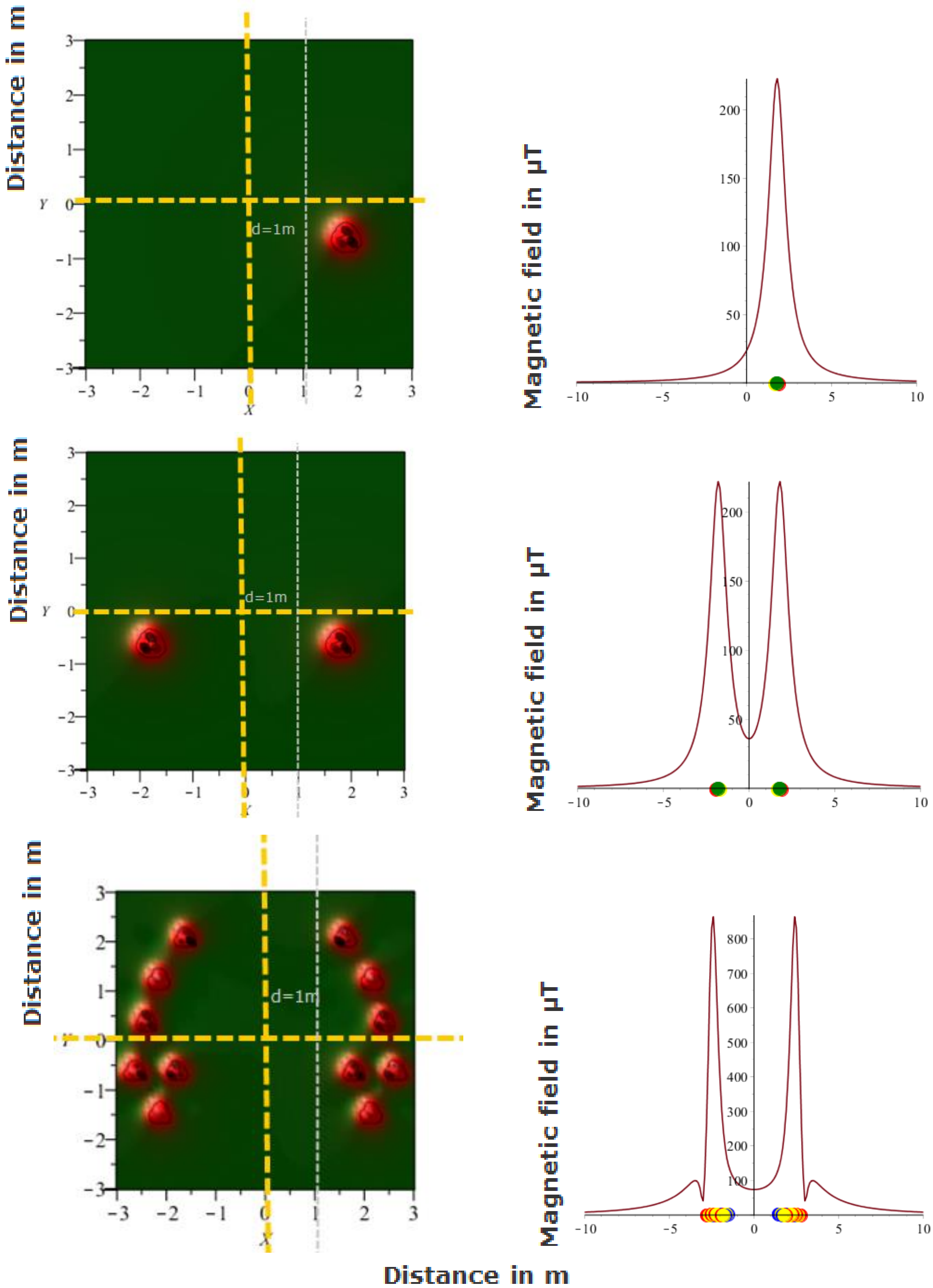


Figure 5.3: Tunnel-one, two, and twelve circuit-plots

Summary Normal Operating Conditions

Table 5.1 summarizes the findings for different configurations under normal operating conditions (1450 A) and provides conclusion on whether it is in the reference limits. It can be understood that at 1 meter from the cable the magnetic fields are within the reference limits provided by ICNIRP. We also mention the electric field limiting values, respectively 0.4 and 0.8 V/m, induced by time varying magnetic field.

At the outer cable sheath, the magnetic field values exceed the reference limits significantly. Thus it is of utmost important that the occupational workers keep sufficient distance from the vicinity of cables.

Configuration		**Calculated value (microTesla)**	**Within reference limit (200 µT-public and 1000 µT-worker)**	**Calculated value (V/m)**	**Within reference limit (0.4 V/m-public and 0.8 V/m-worker)**
DBC (single circuit)	At cable sheath	8900	No	0.2 (Light pole above the installations)	Yes
	1 meter above (until waist level)	18	Yes		
Tunnel (single circuit)	At cable sheath	28526	No	0.15 (Metal object inside tunnel)	Yes
	1 meter from reference	85	Yes		
DBC (double circuit)	At cable sheath	7200	No	0.279 (Light pole above the installations)	Yes
	1 meter above (until waist level)	34	Yes		
Tunnel (double circuit)	At cable sheath	28530	No	0.24 (Metal object inside tunnel)	Yes
	1 meter from reference	86	Yes		
Tunnel (twelve circuit)	At cable sheath	56230	No	0.5 (Metal object inside tunnel)	Yes
	1 meter from reference	93	Yes		

Table 5.1: Evaluations for Normal Operation

5.2 Magnetic Fields under maintenance

Power circuits need regular maintenance. During maintenance one of the double circuits will be switched off for maintenance while the other circuit will be in normal operation. Based on the mentioned reference limits for occupational worker (it is expected that public will not be in the vicinity of the cable circuit under maintenance), magnetic field plots were generated. The magnetic field value at the locations of the switched off circuit due to live circuit is considered for the comparison with exposure standard which is 1000 µT for occupational workers. The plot has two regions red indicates region with higher magnetic field and green is the safe region where the worker can safely carry out maintenance.

Directly buried

Figure 5.4 shows the magnetic field contour and maintenance plot for directly buried cable configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in the right parts of figure 5.4 with different cable spacing, for a current of 1450A through each conductor of one circuit and other switched off with phase arrangement of RYG GYR. The reference axis is indicated in figure with yellow dashed lines and the “d1” refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for general public. As it is clearly seen in figure the values are is safe limits that is green region and comply with ICNIRP for occupational workers.

The width of the corridor in which the magnetic field exceeds 0.4μT is 26 m.

Tunnel

Figure 5.5 shows the magnetic field contour and maintenance plot for two and twelve circuits in tunnel cable configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right parts of figure 5.5 for a current of 1450A through each conductor of one circuit and other switched off with phase arrangement of RGY YGR (open trefoil). The reference axis is indicated in figure with yellow dashed lines and the “d” refers to 1m form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in figure the values are is safe limits that is green region to carry out maintenance without getting severely exposed to magnetic fields and comply with ICNIRP for occupational workers.

The width of the corridor in which the magnetic field exceeds 0.4μT is 13 m.

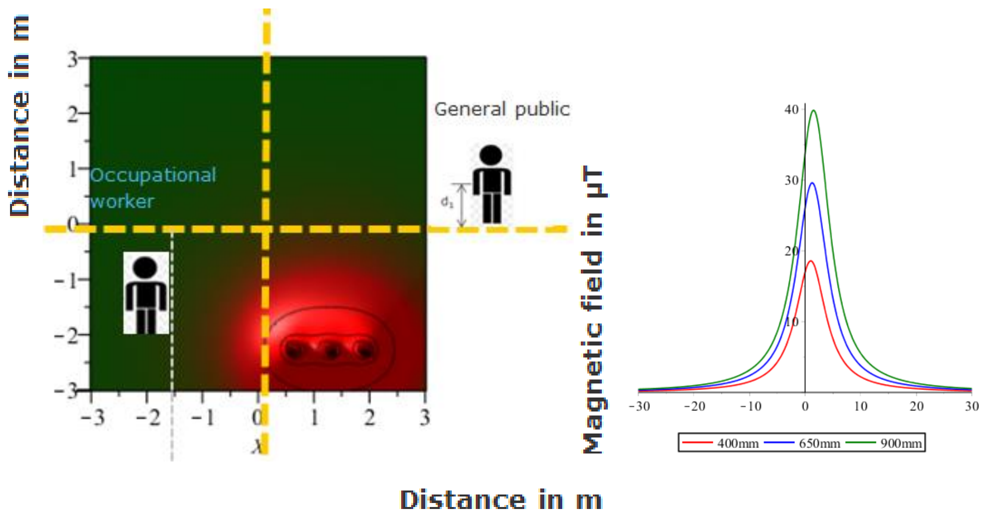


Figure 5.4: Directly buried-maintenance- plot (until waist)

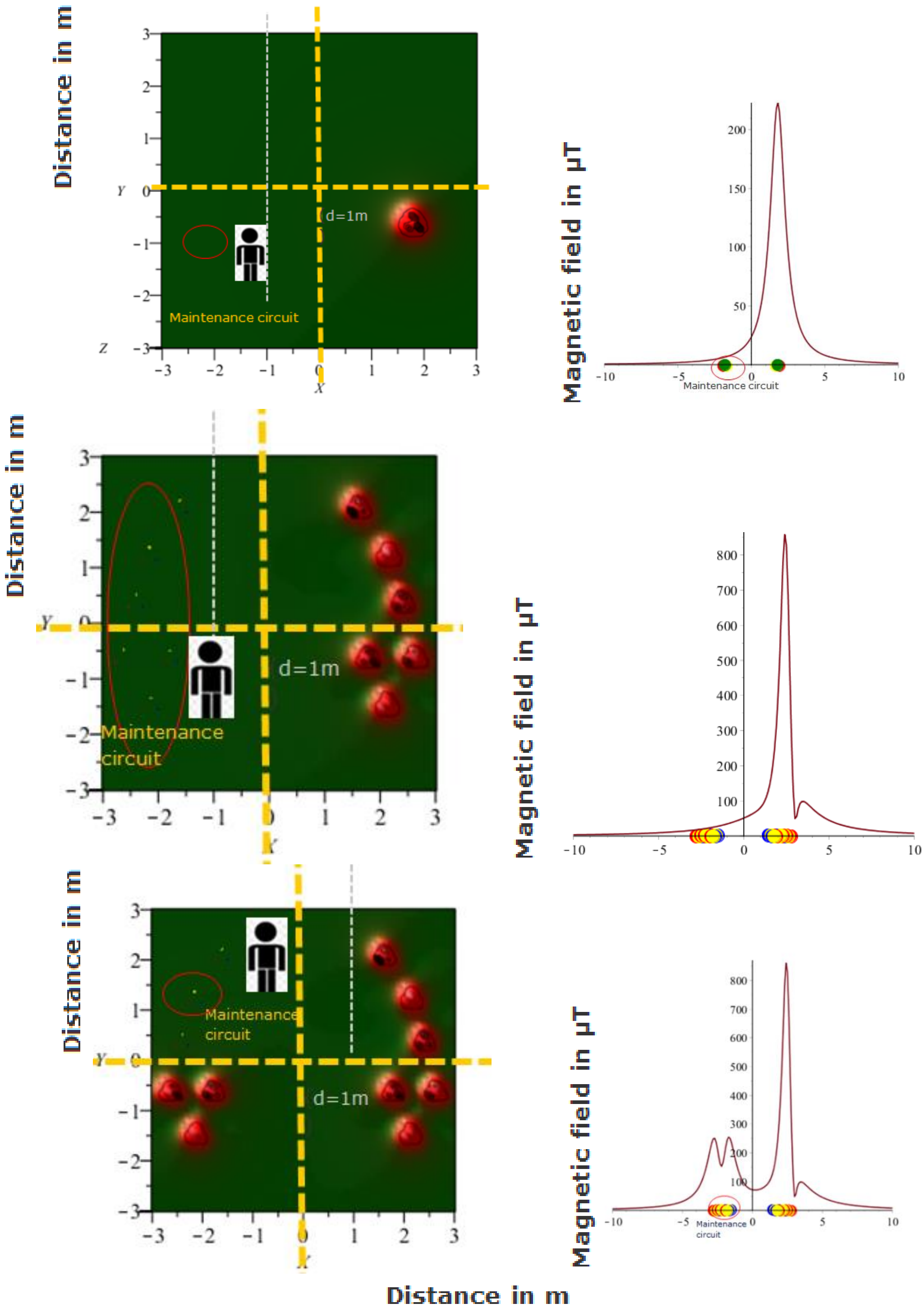


Figure 5.5: Tunnel-Twelve circuit-maintenance- plot

Summary Maintenance Operating Conditions

Table 5.2 summarizes the findings for different configurations under maintenance operating conditions (1450 A) and provides conclusion on whether it is in the reference limits. It can be understood that the magnetic fields are within the reference limits provided by ICNIRP. We also mention the electric field limiting values, respectively 0.4 and 0.8 V/m, induced by time varying magnetic field.

<table>
<tr><th colspan="2">Configuration</th><th>Calculated value (microTesla)</th><th>Within reference limit (200 µT-public and 1000 µT-worker)</th><th>Calculated value (V/m)</th><th>Within reference limit (0.4 V/m-public and 0.8 V/m-worker)</th></tr>
<tr><td rowspan="2">DBC (double circuit)</td><td>At cable sheath</td><td>30</td><td>Yes</td><td rowspan="2">0.16 (Light pole above the installations)</td><td rowspan="2">Yes</td></tr>
<tr><td>1 meter above</td><td>20</td><td>Yes</td></tr>
<tr><td rowspan="2">Tunnel (double circuit)</td><td>At cable sheath (Maintenance circuit)</td><td>6</td><td>Yes</td><td rowspan="2">0.12 (Metal object inside tunnel)</td><td rowspan="2">Yes</td></tr>
<tr><td>1 meter from reference (from live circuit)</td><td>223</td><td>Yes</td></tr>
<tr><td rowspan="2">Tunnel (twelve circuit)</td><td>At cable sheath (Maintenance circuit)</td><td>72</td><td>Yes</td><td rowspan="2">0.19 (Metal object inside tunnel)</td><td rowspan="2">Yes</td></tr>
<tr><td>1 meter from reference (from live circuit)</td><td>300</td><td>Yes</td></tr>
<tr><td rowspan="2">Tunnel (twelve circuit)</td><td>At cable sheath (Maintenance circuit with top three off)</td><td>200</td><td>Yes</td><td rowspan="2">0.27 (Metal object inside tunnel)</td><td rowspan="2">Yes</td></tr>
<tr><td>1 meter from reference (from live circuit)</td><td>400</td><td>Yes</td></tr>
</table>

Table 5.2: Evaluations for Maintenance

5.3 Magnetic Fields under Emergency load

During emergency conditions like loss of a companion circuit in double circuit or temporary extra load, power cables required to carry higher current than permitted steady state current. Emergency conditions usually last only few hours, SPPA considers 2 hours window for this current. As discussed in beginning the magnitude of magnetic field is dependent on the magnitude of current, therefore the magnetic field plot and values will change in comparison to normal operations. In this section, we will see the magnetic field values for different configurations under emergency load.

Directly Buried

Figure 5.6 and 5.7 shows the magnetic field contour and emergency load plot for respectively single circuit directly buried configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in the right parts of figure 1.6 and 1.7 for a current of 1740A through each conductor. The reference axis is indicated in figure with yellow dashed lines and the “d1” refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for general public. As it is clearly seen in figure the values are is safe limits that is green region and comply with ICNIRP for general public.

The width of the corridor in which the magnetic fields exceeds 0.4 µT is 26 m.

Tunnel

Figure 5.8 shows the magnetic field contour and emergency plot for single and double circuit tunnel configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right parts of figure 5.8 for one and two circuits for current of 1740A through each conductor. Twelve circuits with one or two circuit having emergency load will have the magnitude increase by 20 µT with respect to magnetic field values under nominal current. The reference axis is indicated in figure with yellow dashed lines and the “d” refers to 1m form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in figure the values are is safe limits that is green region and comply with ICNIRP for occupational workers.

The width of the corridor in which the magnetic fields exceeds 0.4 µT is 13m.

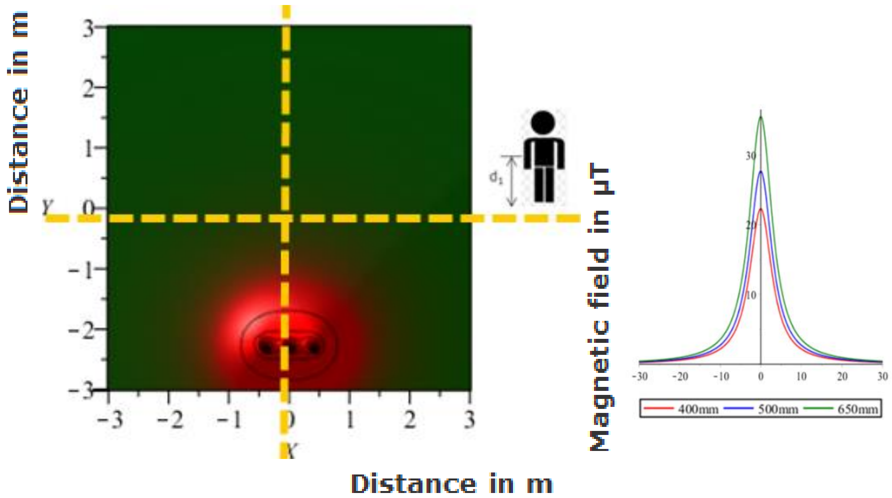


Figure 5.6: Directly Buried-single circuit plot-emergency (until waist)

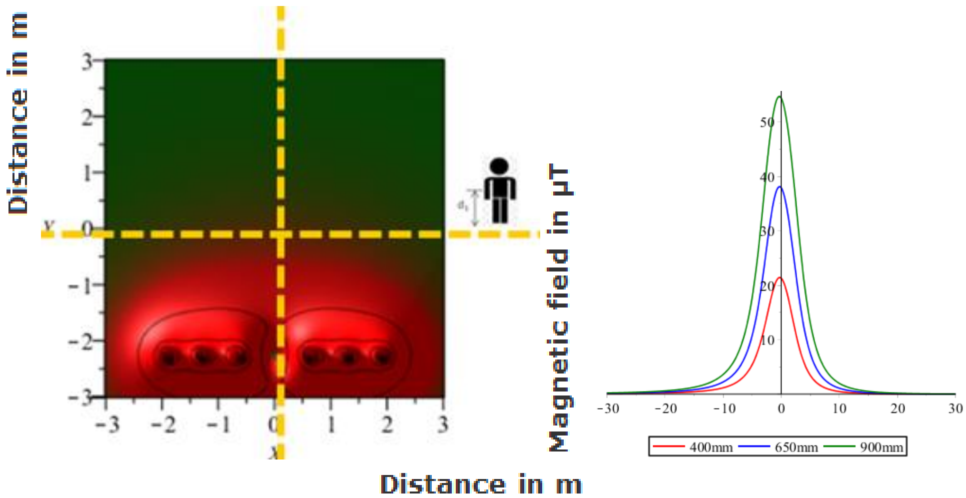


Figure 5.7: Directly Buried-double circuit plot-emergency (until waist)

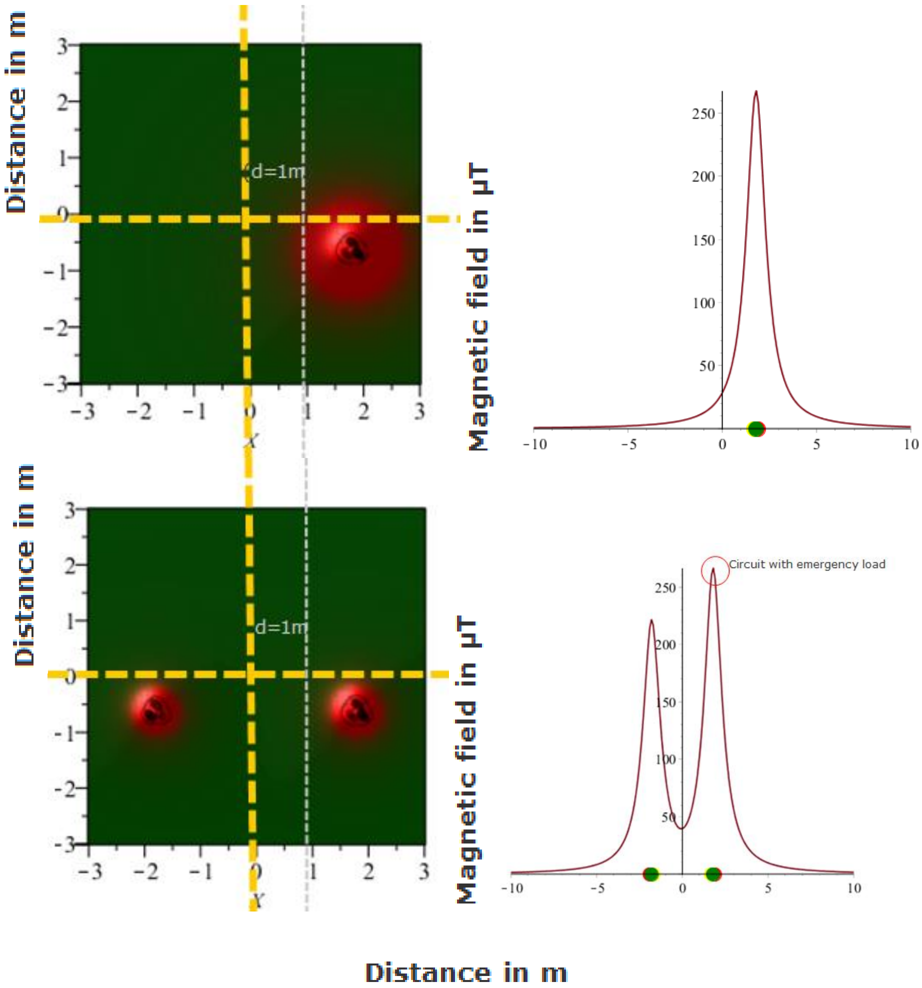


Figure 5.8: Tunnel-single circuit emergency- plot

Summary Emergency Operating Conditions

Table 5.3 summarizes the findings for different configurations under emergency operating conditions (1740 A) and provides conclusion on whether it is in the reference limits. It can be understood that at 1 meter from the cable the magnetic fields are within the reference limits provided by ICNIRP. We also mention the electric field limiting values, respectively 0.4 and 0.8 V/m, induced by time varying magnetic field.

At the outer cable sheath, the magnetic field values exceed the reference limits significantly. Thus it is of utmost important that the occupational workers keep sufficient distance from the vicinity of cables.

Configuration		Calculated value (microTesla)	Within reference limit (200 µT-public and 1000 µT-worker)	Calculated value (V/m)	Within reference limit (0.4 V/m-public and 0.8 V/m-worker)
DBC (single circuit)	At cable sheath	9000	No	0.20 (Light pole above the installations)	Yes
	1 meter above (until waist level)	25	Yes		
Tunnel (single circuit)	At cable sheath	34232	No	0.21 (Metal object inside tunnel)	Yes
	1 meter from reference	102	Yes		
DBC (double circuit)	At cable sheath	8500	No	0.30 (Light pole above the installations)	Yes
	1 meter above (until waist level)	35	Yes		
Tunnel (double circuit)	At cable sheath	34234	No	0.27 (Metal object inside tunnel)	Yes
	1 meter from reference	102	Yes		

Table 5.3: Evaluations for Emergency Operation

5.4 *Magnetic Fields for short circuit current*

Short circuit currents occur rarely, but having them evaluated is important. Short circuit currents cause several effects in the utility system; Voltage drops can have impact on costumers and even a part of the grid can be switched off. Moreover in the cable system mechanical forces will occur and which may cause breaks, thermal stress occurs and which may melt conductors and even destroy insulation. In case short circuit current has a value of 80 kA rms temporally high magnetic and induced electric fields will be generated. All the plots will be generated having one circuit experiencing the short circuit current. It is assumed that the maximum value of the 1-phase short circuit current is equal to the value of the 3-phase short circuit current.

5.4.1 1-Phase short circuit condition

Following sections provides the magnetic field plots for the cable circuit experiencing single phase short circuit fault conditions.

Directly Buried

Figure 5.9 shows the magnetic field contour and single phase short circuit fault current plot for double circuit directly buried configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis in right part of figure 5.9 with different cable spacing for a current of 80 kA through one phase of a circuit and phase arrangement of whole configuration is RYG GYR. The reference axis is indicated in figure 5.9 with yellow dashed lines and the "d1" refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in the figure the values are very high and beyond safe limit. That can be seen in below plot as major area is under red zone and occupational worker is exposed with very high fields.

Tunnel

Figure 5.10 shows the magnetic field contour and single phase short circuit fault current plot for double circuit tunnel configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis in right part of figure 5.10 for a current of 80 kA through one phase of a circuit and phase arrangement of whole configuration is RYG GYR. The reference axis is indicated in the figure 5.10 with yellow dashed lines and the "d" refers to 1 meter form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in the figure the values are very high and beyond safe limit. That can be seen in below plot as major area is under red zone and occupational worker is exposed with very high fields.

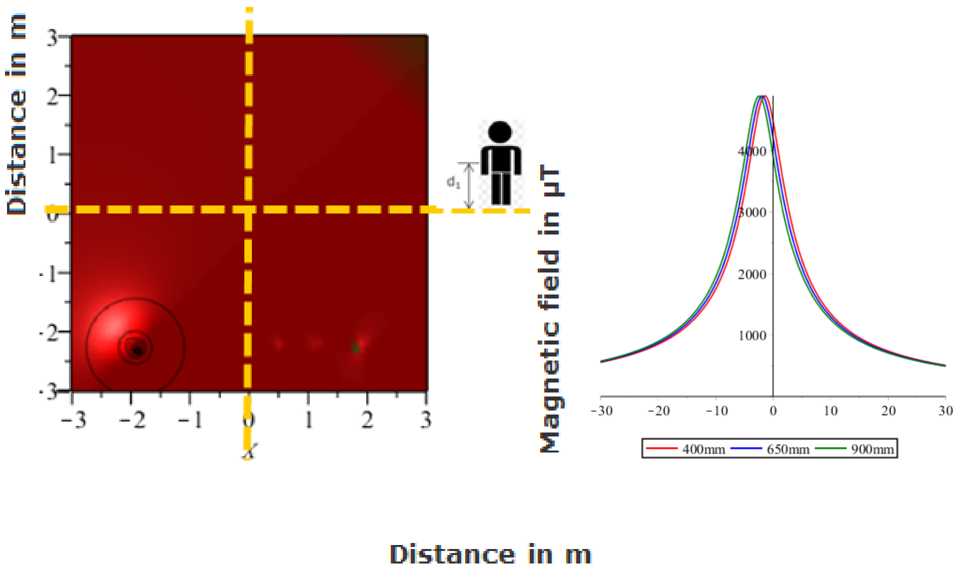


Figure 5.9: Directly Buried-double circuit contour plot-1-phase short circuit

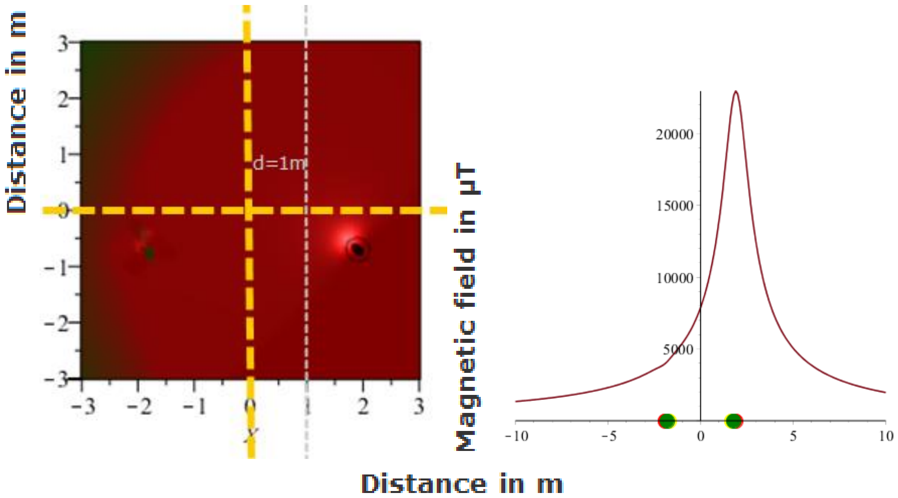


Figure 5.10: Tunnel-Double circuit plot-1-phase short circuit

5.4.2 3-Phase Short circuit condition

Following sections provides the magnetic field plots for the cable circuit experiencing three phase short circuit fault conditions.

Directly Buried

Figure 5.11 shows the magnetic field contour and three phase short circuit fault current plot for double circuit directly buried configuration with respect to horizontal and vertical. The magnitude of magnetic field is along vertical axis in the right part of figure 5.11 with different cable spacing for a current of 80 kA through all phases of one circuit and phase arrangement of whole configuration is RYG GYR. The reference axis is indicated in the figure 5.11 with yellow dashed lines and the “d1” refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in the figure the values are very high and beyond safe limit. That can be seen in below plot as major area is under red zone and occupational worker is exposed with very high fields.

Tunnel

Figure 5.12 shows the magnetic field contour and three phase short circuit fault current plot for double circuit tunnel configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right part of figure 5.12 for a current of 80 kA through all phases of one circuit and phase arrangement of whole configuration is RYG GYR. The reference axis is indicated in the figure 5.12 with yellow dashed lines and the “d” refers to 1 meter form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in figure the values are very high and beyond safe limit. That can be seen in below plot as major area is under red zone and occupational worker is exposed with very high fields.

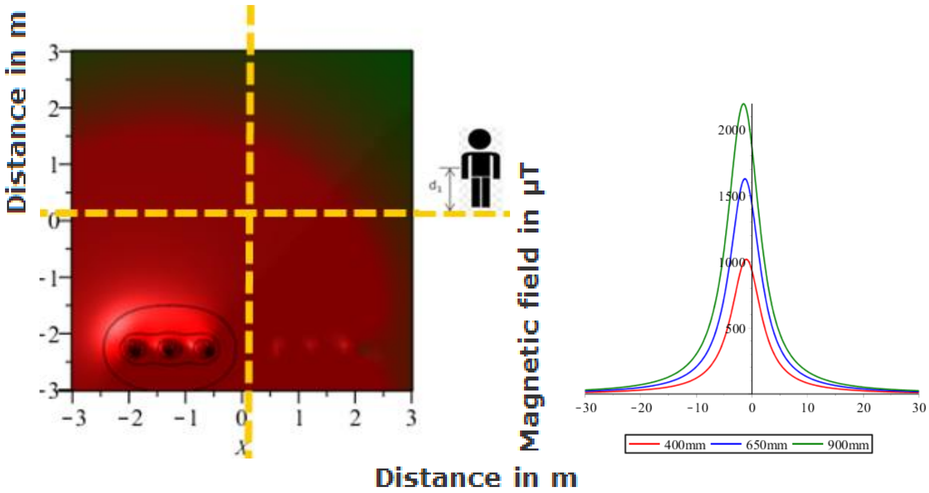


Figure 5.11: Directly Buried-double circuit plot-3-phase short circuit

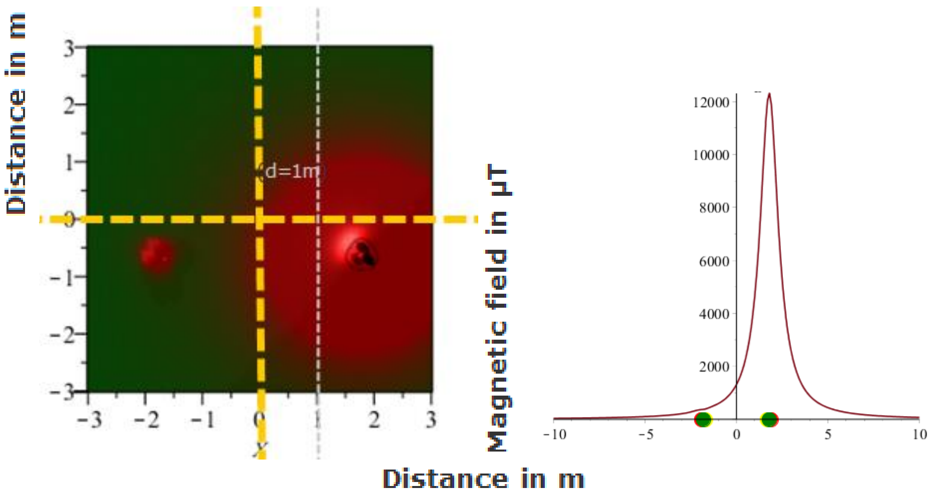


Figure 5.12: Tunnel-Double circuit plot-3-phase short circuit

Summary Short Circuit Operating Conditions

The occurrence of short circuit currents is rare and typically the duration is limited to about 600 ms to 1 s (depends on the settings of protection system). Table 5.4 summarizes the findings for different configurations under short circuit operating conditions (80 kA) and provides conclusion on whether it is in the reference limits.

As expected, the magnetic fields are beyond the reference limits provided by ICNIRP. We also mention the electric field limiting values, respectively 0.4 and 0.8 V/m, induced by time varying magnetic field.

<table>
<tr><th colspan="2" rowspan="2">Configuration</th><th colspan="2">Calculated value (microTesla)</th><th rowspan="2">Within reference limit (200 µT-public and 1000 µT-worker)</th><th colspan="2">Calculated value (V/m)</th><th rowspan="2">Within reference limit (0.4 V/m-public and 0.8 V/m-worker)</th></tr>
<tr><th>1-Phase</th><th>3-Phase</th><th>1-Phase</th><th>3-Phase</th></tr>
<tr><td rowspan="2">DBC (double circuit)</td><td>At cable sheath</td><td>$6x10^5$</td><td>$6x10^5$</td><td>No</td><td rowspan="2">1.80 (Light pole above installation)</td><td rowspan="2">6.30 (Light pole above installation)</td><td rowspan="2">No</td></tr>
<tr><td>1 meter above (until waist level)</td><td>4900</td><td>1600</td><td>No</td></tr>
<tr><td rowspan="2">Tunnel (double circuit)</td><td>At cable sheath</td><td>$1.5 x10^6$</td><td>$1.5 x10^6$</td><td>No</td><td rowspan="2">2.27 (Metal object inside tunnel)</td><td rowspan="2">6.80 (Metal object inside tunnel)</td><td rowspan="2">No</td></tr>
<tr><td>1 meter from reference</td><td>23000</td><td>12300</td><td>No</td></tr>
</table>

Table 5.4: Evaluations for Short circuit

5.5 *Magnetic Fields under special conditons*

The values of magnetic field vary, by changing the phase arrangements and in some rare conditions like dislocated cable phase. In this section, we will see effects of changing cable phase arrangements in flat configurations, that is in directly buried and with tunnel configuration we will see the effects of cable positions dislocated.

Directly buried

Figure 5.13 shows the magnetic field contour and normal plot for double circuit directly buried configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right part of figure 5.13 for a current of 1450A through each conductor with phase arrangement of RYG RYG. The reference axis is indicated in figure with yellow dashed lines and the “d1” refers to the standard human height that is until waist for the measurement of magnetic fields exposure limits for general public. As it is clearly seen in the figure the values are is safe limit that is green region and comply with ICNIRP for general public.

The width of the corridor in which the magnetic field exceeds 0.4µT is 23 m.

Tunnel

Figure 5.14 shows the magnetic field contour and normal plot for single circuit tunnel configuration with respect to horizontal and vertical plain. The magnitude of magnetic field is along vertical axis given in right part of figure 5.14 for a current of 1450A through each conductor and cable phase is dislocated with each other (normal configurations has open trefoil). The reference axis is indicated in figure with yellow dashed lines and the "d" refers to 1 meter form reference point for the measurement of magnetic fields exposure limits for occupational workers. As it is clearly seen in the figure the values are is safe limits that is green region and comply with ICNIRP for occupational workers.

The width of the corridor in which the magnetic field exceeds 0.4μT is 16 m.

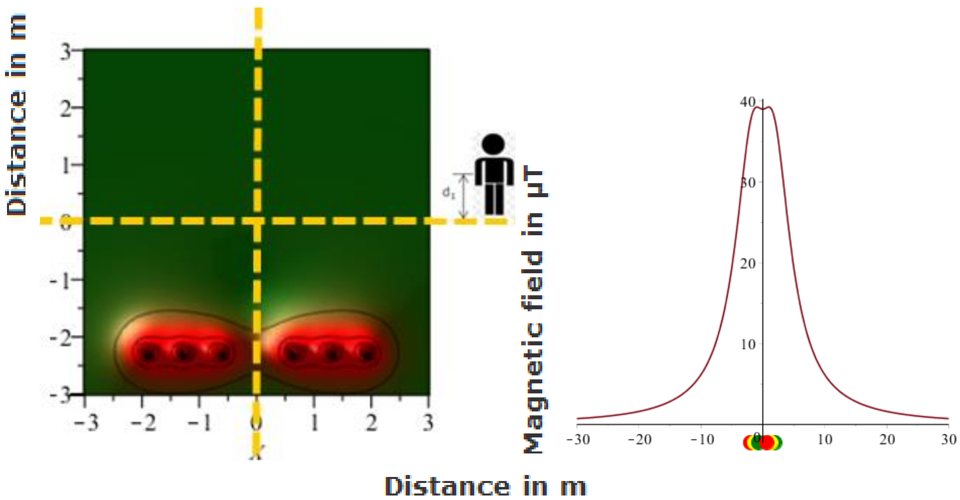


Figure 5.13: Directly Buried-double circuit plot (until waist)

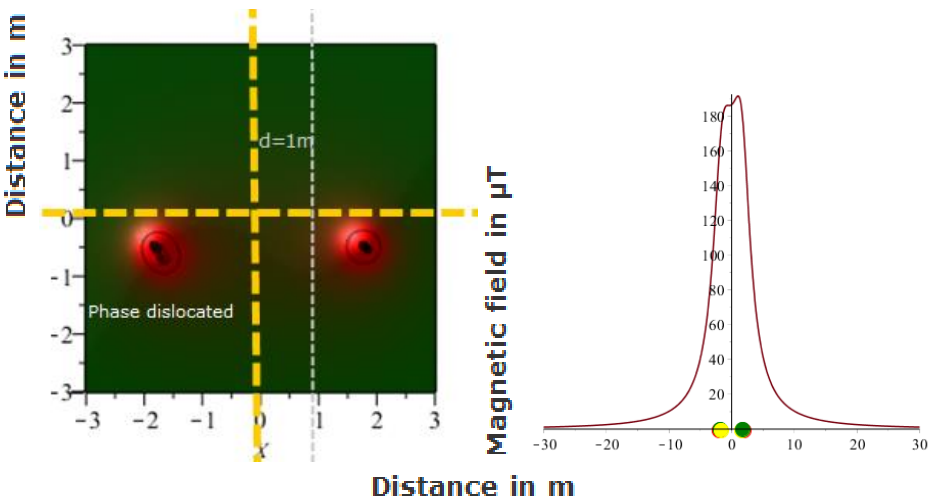


Figure 5.14: Tunnel-double circuit plot-phase dislocated

Summary Special Operating Conditions

Table 5.5 summarizes the findings for different configurations under special operating conditions (1450 A) and provides conclusion on whether it is in the reference limits. It can be understood that at 1 meter from the cable the magnetic fields are within the reference limits provided by ICNIRP.

Configuration		**Calculated value (microTesla)**	**Within reference limit (200 µT-public and 1000 µT-worker)**	**Calculated value (V/m)**	**Within reference limit (0.4 V/m-public and 0.8 V/m-worker)**
DBC (double circuit)	At cable sheath	10500	No	0.28 (Light pole above the installations)	Yes
	1 meter above	40	Yes		
Tunnel (double circuit)	At cable sheath (Normal circuit)	20500	No	0.20 (Metal object inside tunnel)	Yes
	1 meter from reference (from live circuit)	191	No		

Table 5.5: Evaluations for phase change and cable dislocation

6

6 Conclusions

The calculation of the human exposure to magnetic and induced electric field generated by underground power transmission configurations was the subject of this Master of Science Thesis. The importance of evaluation of the magnetic field arises from the public concern about its exposure and impact near sensitive receptors and also for the determination of the safety distances corresponding to a maximum limit value of the rms magnetic induction, as defined by the ICNIRP.

More precisely, the main object of the scientific research made was directed to the calculation of the magnetic and induced electric field generated by directly buried and utility tunnel configurations. Attention was paid to the effect of the conductors arranged in flat, trefoil and open trefoil, on the value of magnetic fields.

Calculation of the magnetic field generated by complex configurations of underground power cable systems has been successfully achieved by:

- Firstly, calculation tool was developed based on the theory of "Amperes Law".
- Secondly, design optimization for directly buried and utility tunnel configuration done based on the magnetic field limits and factors on which it depends.

The following conclusions were drawn from the results of this thesis:

1. Power cables carrying symmetrical three phase current, when the cable spacing is varied the magnitude of the magnetic field increases as described in section 3.3 and the magnitude increase is with 11 µT for the given nominal current rating. From this we can say that the cables should not be placed too far from each other. From an economic point of view it is also recommendable to make the spacing between the cables not to large.

2. From Biot-Savart law, it is observed that the magnitude of the magnetic field is directly proportional to current of the cable system. With increase in the current rating the magnitude increases.

3. Cable circuits in direct burial configuration, when the burial depth of cable circuit is increased the magnitude of magnetic field above center line decreases as described in

section 3.3 and for every 200 mm increase the magnitude of corresponding magnetic field decreased with 20 µT up to 1000 mm and for higher depths with 10 µT for the given nominal current rating.

4. Power cable circuits can be placed one above other or side to each other, placing of the circuit's side to each other has a better magnetic field management as described in section 3.3.

5. When comparing power cable arranged in flat, trefoil and open trefoil, we observed flat arrangement has the highest magnitude compared to others. It is also observed that the trefoil and open trefoil has narrow peak and is concentrated at the center of the configuration where as in flat it is wide and cover large distance to fall back to minimum value.

6. Tunnel with diameter of 6 meters and with twelve circuits the magnitude of nominal current cannot be increased beyond 1450 A as the safe values set for working professional with pacemaker at a distance of 1 meter from closest cable surface is exceeded.

7. The tunnel diameter considered for this thesis was 6 meter and with nominal current 1450 A the diameter can be reduced by a meter and the field values are still in safe limits.

8. Inside tunnel for double circuit configuration as an example the magnitude of the magnetic field is minimum at the center of the tunnel this was due to symmetric placement of the circuits, but in case of phase dis-positioned case we see a high magnitude at the center. From this we can conclude that symmetric arrangements of the cable circuits also plays vital role in magnetic field management.

9. We can conclude that the working professional is safe in terms of magnetic as well as induced electric field values when maintenance is being performed on one circuit next to other circuits still in operation.

10. The values of induced field values are also in safe limits for operating conditons like nominal current, maintenance and emergency but for short circuit currents magnetic and induced electric field values are beyond the safe region this magnitude results in shocks, tissue burns.

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