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Magnetic Field Exposures due to Underground Power Cables: A Simulation Study

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Abstract **-** In urban areas, underground power cable utilizations have been increasing dramatically due to increasing energy demand. However, the magnetic fields around the underground power cables may cause harmful effects on human health. In this study, the induced magnetic field strengths and current densities caused by underground cables on a human body model are presented. The analytical and simulation studies are implemented using a two-dimensional cylindrical model. Magnetic flux and induced current density levels are obtained for the realistic body model. Results are evaluated according to the magnetic field exposure limits and standards for the body tissue. The solution proposals and techniques for the magnetic field mitigation are presented on behalf of the human health.

Keywords**:** Magnetic Field Exposure, Underground Power Cables, Biot-Savart Law, Finite Element Method

1. Introduction

Extremely low frequency (ELF) based magnetic fields due to high voltage elements (transformer centers, transmission lines, substations, etc.) cause drastic influences, especially for the human health [1, 2, 3]. This hazard has dramatically increased for thirty decades. The studies over this topic have been carried out with analytical studies [4, 5] and experimental observations [6]. There is not any linear correlation between the magnitude of magnetic field and their effects for the human tissue according to the presented studies. Therefore, well-known associations and organizations published their own coercive exposure limits (Table 1).

The strongest scientific evidences for the health effects published by health associations and organizations which have been observed from the human population reveals with two forms of cancer: childhood leukemia and chronic lymphocytic leukemia in occupationally exposed adults [7]. Power-frequency magnetic field exposure draws the attention of many researchers worldwide, who investigate their health effects on the human body. For a quantitative assessment of the effect of magnetic fields around the power cables on the human tissue, it is necessary to describe the magnetic field distributions produced by the power cable lines.

Table 1: Maximum exposure limits of ELF based magnetic flux densities (µT) [8, 9].

Target	ICNIRP	IEEE
Occupational	1000	2710
Public	200	904

Many developed-countries have forced these rules for the sake of their citizens [10]. Russia has realized 100 µT for the occupational and 10 µT for the public exposure limits. In the other hand, Poland government applies these limits as 160 µT for occupational and 48 µT for the public, respectively. Switzerland laws have restricted limit values as less than 1 µT. Although there are some limit values have been defined, they are not sufficient for the human health. The level of 0.3-0.4µT has been declared as a critical value for a leukemia disease by other well-known environmental health organizations [11]. Moreover, induced current level for the human body is also another important parameter for the healthcare. The occupational reference level for induced current density (J_{rms}) is specified as 10 mA/m^2 in the frequency range of 4 Hz to 1 kHz, and the general public reference level is specified as 2 mA/m^2 in the same frequency range by the International Commission on Nonionizing Radiation Protection (ICNIRP) [12].

In the following part of the paper, the electromagnetic problem is described and the realistic primitive model is simulated. The theory underlined the problem is explained in detail. Analytical calculations according to the underlined theory is figured out at the next chapter. In the proceeding section, numerical study is carried out using the computer-based software tool (COMSOL^{TM}).

2. Problem Definition

Magnetic field occurrence around any conductor can be calculated by Biot Savart Rule. Time dependent currents lead to electromagnetic fields around the conductors due to the Biot Savart Rule. Electromagnetic interference, biomedical systems and communication problems, etc. can be figured out using this phenomena. Magnetic fields around the conductor can be obtained using the following formula:

$$\vec{H} = \oint \frac{I \cdot dl \times \vec{a}_R}{4\pi R^2} \tag{1}$$

where, $I \cdot dl$ is a differential current component, $\vec{a}_R$ is a directional vector and R is a distance between any observation point for magnetic field and current path. According to the Faraday's law, external magnetic field changes produce an internal electric field inside the body. Total induced electric field inside the body can be expressed as,

$$E = \left(E_x^2 + E_y^2 + E_z^2\right)^{1/2} \tag{2}$$

and the induced current density $\vec{J}$ inside the body due to the internal field can be obtained as,

$$\vec{J} = \sigma \vec{E} \tag{3}$$

where σ is the electric conductivity of the body tissue (S/m).

Since the frequency of the power frequency magnetic fields is extremely low, the displacement current component can be neglected ($\sigma >> \omega\varepsilon$) according to the Quasi-Static Approximations [13, 14], where ε is the permittivity of the body. In this scenario (Fig. 1), a magnetic field source is the three-phased underground cable. The cable comprises of the copper conductors and the cross section area of each phase is 185 mm^2. The outer diameter of the cable is 44.5 mm and the maximum loading capacity of the underground cable is 503 A.

According to epidemiological studies, ELF based magnetic fields may pose serious hazard for the human tissue [2, 3]. Aforementioned field generally exists in the vicinity of power frequency magnetic field (PFMF) source at the urban residential. Due to the occupational and public exposure of this ELF based magnetic fields and also insufficient protection, some symptoms such as the leukaemia, brain cancer and miscarriage may occur. In this study, the human is modelled with a two-layered cylindrical model. The inner layer simulates the muscle tissue and the outer layer mimics the skin tissue (see Fig. 1). The electrical properties of muscle and skin tissue are denoted in Table 2.

Table 2: Electrical properties of the body tissue at 50 Hz [15, 16, 17]

Tissue	**Conductivity (S/m)**	**Permittivity**
Skin	0.43	1136
Muscle	0.35	177.19×10^5

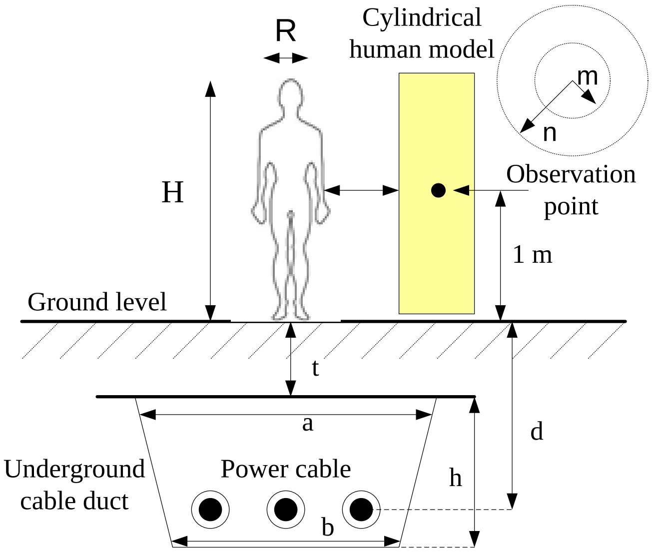

Fig. 1: 2D Problem Space.

The relative permittivity of soil and underground cable duct are 3.5 and 150 and electrical conductivities of these materials are 0.01 and 10^{-4} S/m, respectively [18].

3. Analytical Calculation

Analytical study is implemented using the Biot-Savart law (Fig. 3). Biot Savart rule is used to calculate the magnetic field by using time dependent current I. Fig.2 demonstrates the geometry of the three-phased underground cable configuration for magnetic field calculation.

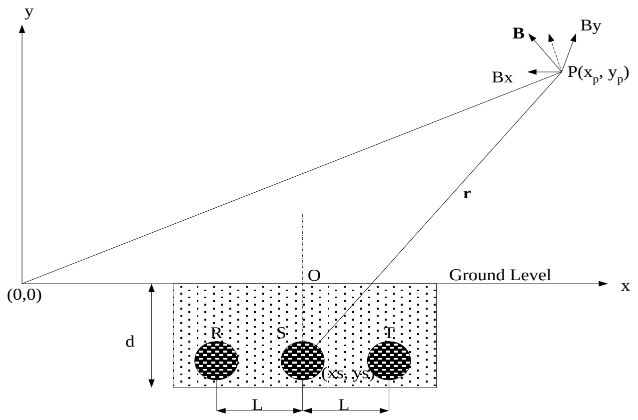

Fig. 2: The cable duct and three phased underground cable configuration.

The magnetic field intensity **B** can be expressed by:

$$\vec{B} = \frac{-\mu_0 \mu_r I}{2\pi r} \hat{a}_\phi \, (\mathrm{T}) \tag{4}$$

where, B is the magnetic field flux density (T), H is the magnetic field intensity (A/m), μ_0 is the permeability of the free space, and $\hat{a}_\phi$ is the unit vector along the direction of ϕ.

$$B_x = \frac{-\mu_0 I}{2\pi r^2}(y_p + d) \tag{5}$$

$$B_y = \frac{-\mu_0 I}{2\pi r^2}(x_p - O) \tag{6}$$

$$r^2 = \left(x_p - O\right)^2 + \left(y_p + d\right)^2 \tag{7}$$

Total magnetic field at anywhere can be given by the following equation:

$$B = \sqrt{\left(\sum_{n=1}^{3} Bxn\right)^2 + \left(\sum_{n=1}^{3} Byn\right)^2} \tag{8}$$

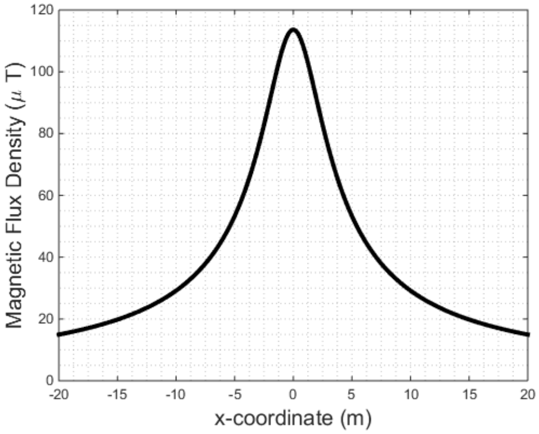

Fig. 3: Magnetic flux densities with respect to horizontal axes. Observation point is selected at x=0. Magnetic flux density values are obtained in ± 20 m proximity of the observation point.

The 2-D problem geometry for the analytical studies is depicted by Fig. 1. To simulate the realistic case, the distance between observation point and the current source is adjusted as 265 cm (d=165 cm, the distance between the ground and the observation point is 100 cm) and the distance among each phase of the cable is selected as 0.1 m. Current source is considered as balanced three phase power transmission line and the operating frequency of the power system is 50 Hz.

4. Numerical Simulation

In this part of the study, magnetic flux density created by the underground cable and magnetic field and induced current density penetrated into the human tissue are obtained. Underground power cable and the human body are two-dimensionally modelled (Fig. 1). 3Φ underground power cable system is simulated as the realistic case. Balanced 3Φ flat configuration is considered for the underground cable and the operating frequency of the power system is assumed as 50 Hz. Distances in between phases of a to b and b to c are designed as 10 cm and a to c phase is 20 cm according to the electrical authority regulations for the respected cable configuration [19]. The dimensions of the underground cable duct are a=60 cm, b=40 cm, h=80 cm (see Fig. 1). They are also adjusted according to the electrical authority restrictions. Human body is modeled by two layered cylindrical model. Tissue is mimicked as realistic skin and muscle tissue. Average thickness of the skin and muscle tissue are considered as m=2.5 mm and n=25 cm, respectively. The height of the human model is assumed as 2 m and the observation point for the calculations is selected as the middle point of the human body. Simulation study is implemented with COMSOL™ software by using the finite element method (FEM) [4]. In the finite element method, the number of mesh is so critical to obtain the most accurate results. Therefore, mesh number is increased by reducing the dimension of the mesh in the problem geometry.

Fig. 4 & 5 show the magnetic flux density levels. At the observation point, almost 113 μT magnetic flux density is obtained in analytical study and 110 μT is obtained in the simulation study. The results are strongly correlate to each other. Magnetic field levels are much higher than the maximum safety exposure limit values. Precautions should be taken in order to reduce the magnetic field levels below the safety exposure limits.

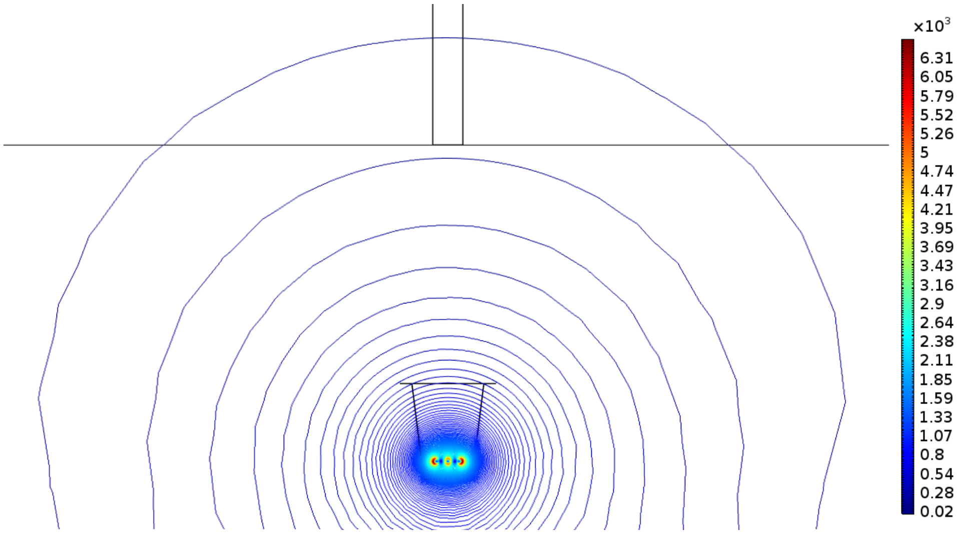

Fig. 4: The contour graphics of the magnetic flux radiation pattern.

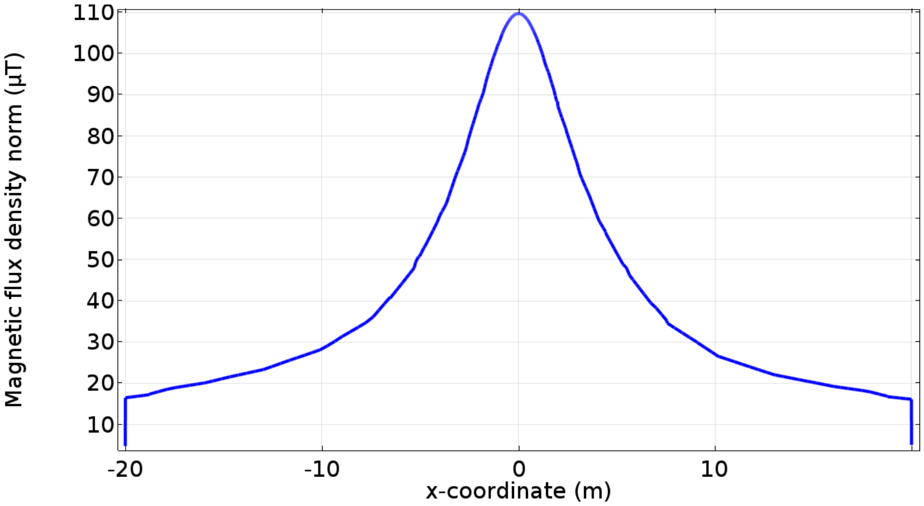

Fig. 5: Magnetic flux density created by the underground power cable.

Fig. 6-7 present the magnetic flux and induced current densities according to the different cable locations. The top point of the cable duct (t) is altered in between 10 to 200 cm with respect to the ground; and respected magnetic flux and induced densities are obtained at the observation point. Magnetic field level decreases almost exponentially by the increasing cable depth (see Fig. 6). Nevertheless, the magnetic field exposure is calculated as almost 80 μT, even the cable duct is located at 2 m depth. This exposure value is very higher than the critical value (0.3-0.4 μT) for a leukemia disease and miscarriage, etc. Fig. 7 shows the induced current density values in the skin and muscle tissue separately. At the observation point, 195 mA/m^2 induced current density is obtained in the muscle tissue and 235 mA/m^2 occurs in the skin tissue. Induced current density values in the tissue reduces linearly by the increasing depth. Due to the thickness and electrical conductivity differences, more changes occur in the skin tissue compared to the muscle tissue. Unfortunately, induced current levels are much higher than the critical exposure limits (occupational reference level is 10 mA/m^2, and the general public reference level is 2 mA/m^2) even if the cable duct is located at deeper regions (200 cm).

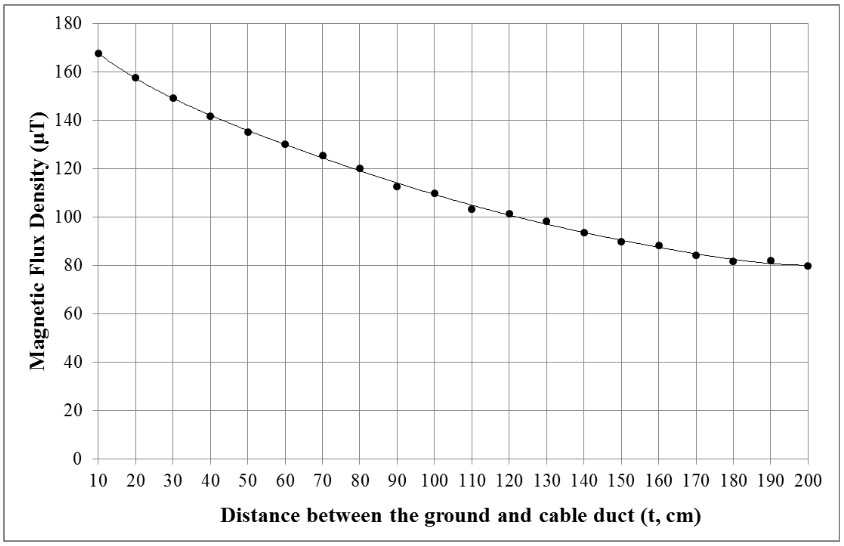

Fig. 6: Maximum magnetic flux density level in the skin and muscle tissue for the various distances of the cable duct.

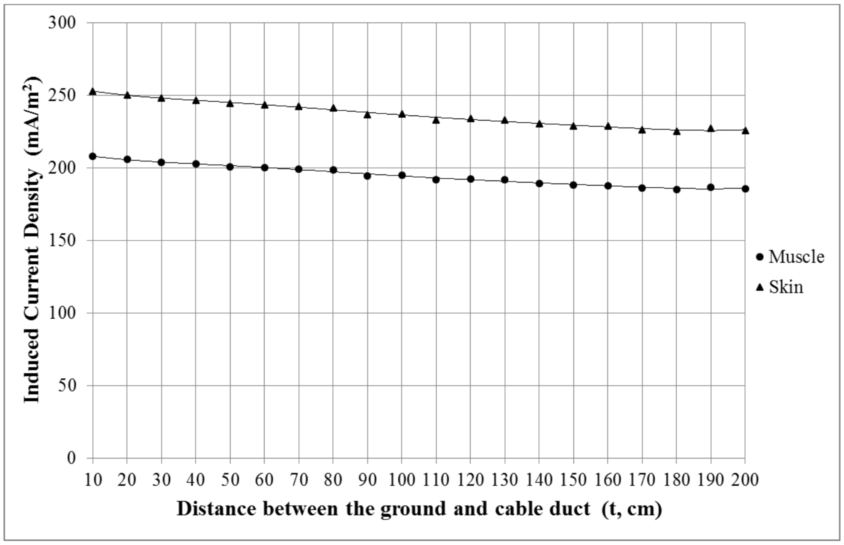

Fig. 7: Induced current density levels in the skin and muscle tissue for the various distances of the cable duct.

5. Conclusion

The long-term ELF based magnetic field exposures may cause detrimental effects on the human health. The aim of this study is presenting the magnetic field exposures due to the underground power cables. In this paper, an underground power cable duct is two-dimensionally modelled and magnetic field and induced current density exposures on the human body is presented by the analytical and simulation studies. Analytical calculation is figured out using Matlab^{TM} software and numerical simulation is implemented by COMSOL^{TM} software. Finite element method is used in the numerical study.

Typical underground power cable causes almost 110 μT magnetic flux density in the human body which is very higher than the maximum exposure limit values determined by the well-known environmental health organizations. Furthermore, the induced current density exposure level for the typical underground cable configuration is obtained 195 mA/m^2 in the muscle and 235 mA/m^2 in the skin tissue, which are also very higher than the maximum exposure limits. The difference of the exposure levels of the skin and muscle tissue causes by the electrical conductivity differences. The electrical conductivity of the skin is almost 20 % more than the muscle tissue.

Finally, this kind of studies may shed light on making predictions about the ELF based magnetic field and induced current exposure levels in the vicinity of the power frequency systems and some precautions may (shielding, etc.) be taken in order to prevent serious diseases such as the leukaemia, brain cancer and miscarriage, etc.…

Acknowledgements

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