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Research Article

Numerical Analysis and Comparison of Magnetic Fields Caused by Constant and Time Varying Currents in Medium Voltage Underground Cables

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Abstract

The magnetic fields formed around the conductors carrying current alternating current in the power system adversely affect human health. Especially in medium voltage systems, where energy is mostly carried by underground cables for electrical safety, due to the high current levels and the installation of cables in areas where people live, studies in this field have gained importance. In literature, many studies have been carried out on the calculation of magnetic fields caused by underground cables using numerical methods and their comparison with limit values. In some of these studies, the boundary conditions for phase currents are defined as constant. However, alternating current, which is the source of the magnetic field, is a time-varying vector quantity. For this reason, it is important for the accuracy of the analysis to take into account the direction of the current, the time-dependent change of the current and the phase difference while calculating the magnetic flux density. In this study, the magnetic flux density values caused by a sample medium voltage underground cable system at the reference plane one meter above the ground surface are determined using Comsol Multiphysics. Analyzes are performed both in the stationary domain where the current is constant and in the time domain when it changes depending on time, and the results are discussed and compared. According to the results, it is determined that the maximum magnetic flux density exceeded the limit value of 0.2 mT, while the phase current values are constant. However, it is seen that the magnetic flux density obtained in time-dependent analyzes remains within the safe limit. In addition, it has been determined that the results obtained in the stationary domain are considerably higher than the results obtained in the time domain. As a result, it has been revealed that the time-dependent variation of the current must be taken into account in order to accurately determine the magnetic flux density in the magnetic field analyzes to be performed for underground cables or overhead lines carrying alternating current.

Keywords: Magnetic Flux Density, Underground Cable, Finite Element Method.

Orta Gerilim Yeraltı Kablolarında Sabit ve Zamanla Değişen Akımların Neden Olduğu Manyetik Alanların Sayısal Analizi ve Karşılaştırılması

Öz

Güç sistemi içerisindeki alternatif akım taşıyan iletkenlerin etrafında oluşan manyetik alanlar, insan sağlığını olumsuz etkilemektedir. Özellikle, enerjinin elektriksel güvenlik amacıyla yeraltı kabloları ile taşındığı orta gerilim sistemlerinde, akım mertebelerinin yüksek olması ve kabloların insanların yaşadığı bölgelerde tesis edilmesi nedeniyle bu alanda yapılan çalışmalara önem kazandırmıştır.

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Literatürde, yer altı kablolarının neden olduğu manyetik alanların sayısal yöntemler kullanılarak hesaplanması ve bunların sınır değerlerle karşılaştırılması üzerine pek çok çalışma gerçekleştirilmiştir. Bu çalışmaların bazılarında faz akımları için sınır koşulları sabit olarak tanımlanmıştır. Ancak, manyetik alanın kaynağı olan alternatif akım zamana bağlı olarak değişen vektörel bir büyüklüktür. Bu nedenle, manyetik akı yoğunluğu hesaplanırken akım yönünün, akımın zamana bağlı değişiminin ve faz farkının dikkate alınması analizlerin doğruluğu bakımından önem arz etmektedir. Bu çalışmada, örnek bir orta gerilim yeraltı kablo sisteminin, toprak yüzeyinden bir metre yukarıdaki referans düzlemde meydana getirdiği manyetik alan yoğunluğu değerleri Comsol Multiphysics kullanılarak belirlenmiştir. Analizler, hem akımın sabit alındığı stasyoner domende hem de zamana bağlı olarak değiştiği zaman domeninde gerçekleştirilmiş olup sonuçlar karşılaştırılarak değerlendirilmiştir. Sonuçlara göre, faz akım değerleri sabitken, maksimum manyetik alan yoğunluğunun 0.2 mT sınır değeri aştığı tespit edilmiştir. Ancak zamana bağlı yapılan analizlerde elde edilen manyetik alan yoğunluğu güvenli sınır içerisinde kaldığı görülmektedir. Ayrıca, stationary domainde elde edilen sonuçlarının zaman domeninde elde edilen sonuçlara göre oldukça yüksek olduğu tespit edilmiştir. Sonuç olarak, alternatif akım taşıyan yeraltı kabloları veya havai hatlar için gerçekleştirilecek manyetik alan analizlerinde, manyetik akı yoğunluğunu doğru belirleyebilmek için akımın zaman bağlı değişiminin mutlak surette dikkate alınması gerektiği ortaya konmuştur.

Anahtar Kelimeler: Manyetik Akı Yoğunluğu, Yeraltı Kabloları, Sonlu Elemanlar Yöntemi.

1. Introduction

The rapidly increasing energy demand in today's world has brought many issues such as the search for new resources, the integration of these resources into the system and energy efficiency. In particular, the increase in the number of wind and solar power plants connected to the power system has caused the system to become more complex in terms of control and operation (Ateş et al., 2021; Erduman et al., 2018; Gökçek & Ateş, 2019). With the expansion of this complex network every day, the control and operation becomes also more difficult. In order to find solutions to these problems, many studies are carried out in the literature, and issues such as fault, protection, load flow, predictive maintenance, and energy quality are the leading ones. (Arabul et al., 2015, 2014; Carvalho et al., 2019; Kryltcov et al., 2021; Shen et al., 2019; Zeineldin et al., 2015). This kind of studies is encountered at every section of power system, from energy production to consumption. However, the number of studies on distribution network is higher since the distributed generation is mostly connected to the power system through medium voltage (MV) (Kryltcov et al., 2021; Reyes & Andrés, 2007).

MV underground cables are among the main components of the distribution network. Although underground cables are used for critical areas in the past, they are widely preferred today due to the expansion of metropolises. Because the use of overhead lines in energy distribution poses a life safety risk in crowded areas. In addition, failure of overhead lines due to environmental conditions such as pollution, wind, storm, etc. directly affects energy continuity. In this regards, using underground cables for energy distribution is quite advantageous in terms of system reliability and human safety (Al-Khalidi & Kalam, 2006; Kocatepe et al., 2012). However, due to the alternating current passing through MV cables, magnetic field is formed around them. If the magnetic field occurring under nominal operating conditions, is above a certain limit value, it poses a risk to human health (ICNIRP, 2010). For this reason, analysis of magnetic fields caused by underground cables and examining their possible effects are among the subjects that need to be studied.

In today's literature, there are many studies on magnetic fields caused by underground cables (MacHado, 2010, 2012). In these studies, magnetic flux density is usually calculated analytically (Rozov et al., 2018). However, since the duct geometry, duct type, cable types, soil and filling material used in the application differ regionally, calculations specific to each cable system are required. For this reason, use of numerical analysis methods for magnetic field analysis has become quite common (Mohamed et al., 2021). Especially with the increase in the processing capacity of computers, most analyzes can be performed more quickly with numerical method-based software. The finite element method is one of the most preferred numerical methods in the literature for magnetic field analysis. Using this method, magnetic field analyzes for many different cable systems, cable geometries and loading conditions have been carried out in the literature. In addition, this method is widely preferred for cable layout optimization (MacHado, 2010; Ulku & Alabas-Uslu, 2020; Yang et al., 2021). It is quite important to determine boundary conditions in magnetic field analyzes using finite element method. Especially when defining the current values of the cables, the phase difference should be taken into account. Because the instantaneous amplitudes and directions of the phase currents are different from each other and change periodically over time (Kumru et al., 2015). The fact that the current amplitudes and directions of the phases are different directly affects the value of the magnetic flux density they cause at any point. In other words, magnetic flux density is a vector dependent on the amplitude and direction of the current. For this reason, it is important to consider the phase difference when calculating the magnetic flux density caused by underground cables and to perform the analyzes in the time domain.

In this study, magnetic field analyzes of three cables (1x400/35 mm^2 Cu, 20/35 kV) buried at a depth of 80 cm in a horizontal arrangement are carried out using Comsol Multiphysics at nominal operating current. Phase current values are both defined as constant and time dependent, and the magnetic flux density in the reference plane one meter above the ground surface is determined. According to the results, when the phase currents are defined as constant, the maximum magnetic flux density calculated is approximately 0.25 mT, while this value is obtained as approximately 0.009 mT in time-dependent analyzes. As a result, a significant difference is observed between the results of two cases, and it is recommended to consider the phase difference in the studies and compare them with the limit values accordingly.

In the second part of the study, magnetic field equations and finite element theory are given. In the third section, problem details are defined and the analysis results are introduced in the fourth section. In the last section, results and suggestions are given together with the future studies.

2. Methodology

In this section, Biot-Savart law, finite element method (FEM) theory and limit values for human health are introduced.

As it is known, Biot-Savart equation is used to analytically calculate the magnetic flux density around a current-carrying conductor.

$$d\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{I \cdot d\vec{s}x\vec{r}}{R^2} \tag{1}$$

Here, B is the magnetic flux density, I is the current flowing through the conductor, $\mu_0=4\pi\cdot10^{-7}$ H/m is the magnetic permeability of the space, ds is the infinitesimal length of the current-carrying conductor, R is the distance between the point where the current passes and the magnetic flux density is calculated, and r is the unit vector. Eq. 1 is the generalized expression of the Biot-Savart law and is used for all conductors of different geometries. However, the expression given in Eq. 2 is used to calculate the magnetic flux density around infinitely long conductors such as underground cables.

$$\vec{B} = \frac{\mu_0 \cdot I}{2 \cdot \pi \cdot R}\vec{r} \tag{2}$$

As can be seen from Eq. 2, the current value passing through the conductor is constant. However, in a three-phase system, the current value changes periodically over time and there is 120° phase difference between the phases as given in Eq. 3, Eq. 4 and Eq. 5.

$$i_{L1}(t) = I_m \cdot \sin(\omega t + 0°) \tag{3}$$

$$i_{L2}(t) = I_m \cdot \sin(\omega t + 120°) \tag{4}$$

$$i_{L3}(t) = I_m \cdot \sin(\omega t + 240°) \tag{5}$$

Eq. 3, Eq. 4 and Eq. 5 are defined in Comsol Multiphysics software for each phase in the study, and magnetic flux density distribution around the cables is determined for t=0 ms and t=5 ms and presented in Figure 1.

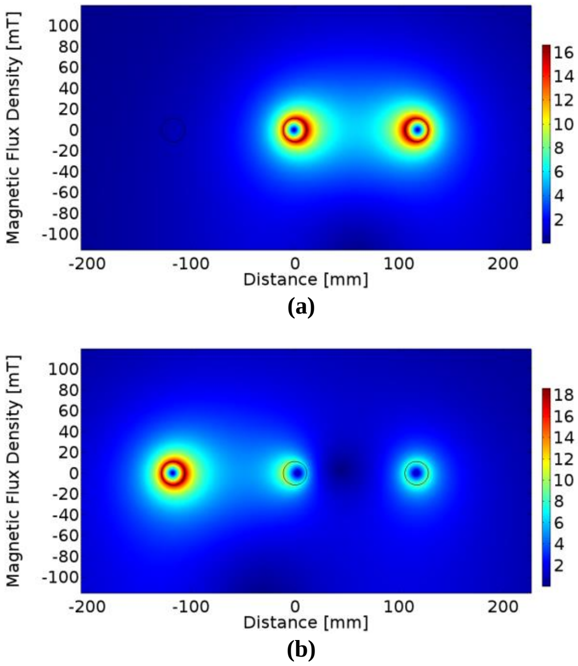

Figure 1. Instant magnetic flux density distribution around cables (a) t=0 ms (b) t=5 ms

Magnetic Fields interface under AC/DC module of Comsol Multiphysics software is used for magnetic field analysis. The problem geometry is defined as 2D in the Cartesian coordinates and analyzes are carried out in time domain. The Magnetics Fields interface uses Eq. 6 and Eq. 7. to calculate time-varying magnetic fields.

$$\sigma\frac{\partial A}{\partial t} + \nabla \times H = J_e \tag{6}$$

$$B = \nabla \times A \tag{7}$$

Here, σ is the electrical conductivity, A is the magnetic vector potential, H is the magnetic flux density, Je is the external current density, and B is the magnetic flux density. In order to evaluate the magnetic flux density calculated in the study in terms of human health, limit values determined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) are used and are given in Table 1.

Table 1. Reference levels for general public exposure to timevarying magnetic fields (unperturbed rms values) (ICNIRP, 2010).

Frequency Range f [Hz]	**Magnetic Field Strength H [A/m]**	**Magnetic Flux Density B [T]**
1 - 8	3,2·104 / f2	4·10-2 / f2
8 - 25	4·103 / f	5·10-3 / f
25 - 50	1,6·102	2·10-4
50 - 400	1,6·102	2·10-4

3. Problem Definition

In this section, geometry, boundary conditions, mesh statistics and material properties of the problem designed with Comsol Multiphysics are introduced. As it is known, there are 7 basic steps to be followed in order to solve a problem using the FEM:

1. Definition of problem geometry
2. Definition and assignment of the materials,
3. Specifying the boundary conditions or initial conditions of the problem,
4. Separating the solution region into finite elements or sub-domains (meshing),
5. Writing the basic equations for each element,
6. Combining all the elements in the solution region and obtaining the set of equations to be solved,
7. The solution of the set of equations

In this context, the problem geometry is first designed as in Figure 2.

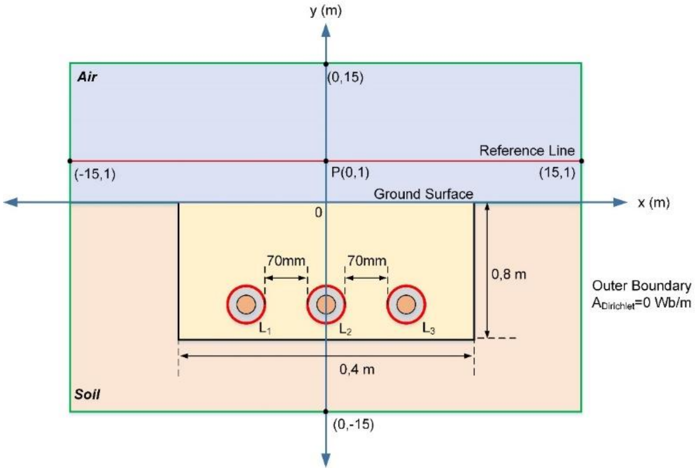

Figure 2. Problem geometry

A typical cable system commonly used in distribution networks is presented in Figure 2. Cables are located in a channel 80 cm deep and 40 cm wide in horizontal arrangement, with 70 mm space between them. 20.3/35 kV, 1x400/35 mm2 Cu, XLPE insulated cables are used for each phase, and the outer diameter of the cables is 50.5 mm (Kablo, n.d.). For the outer boundary, 30 m x 30 m square is used as in Figure 2. In the literature, it is recommended to limit the open boundary type problems to an area with a radius of at least 5 times the maximum width of the studied region to keep the results consistent. In this context, considering the channel width (80 cm) in the study, the problem is limited by using an area larger than 800 cm and the magnetic vector potential, A=0 Wb/m Dirichlet boundary condition is assigned. As given in Figure 2, all magnetic flux density values are calculated for the reference plane one meter above the ground surface.

The materials used in the study are copper, soil and air and their properties are given in Table 2.

Table 2. Material Properties(Widodo et al., 2018)

Material	Relative Permeability	Relative Permittivity	Electrical Conductivity [S/m]
Copper	1	1·107	5.998·107
Soil	1.0006	5	0.01
Air	1	1	0

Other layers of the cable such as semiconductor and XLPE do not significantly affect the analysis results and are not taken into account in the study to reduce the number of finite elements and analysis time. In addition, relatively thin layers make it difficult to divide these parts into the finite elements.

The problem is modeled using Comsol Multiphysics, AC/DC Module, Magnetic Fields interface and analyzes are performed using a time dependent solver. Duration of the simulations and the step time is 20 ms and 0.1 ms, respectively. Nominal current carrying capacity of MV cables used in the study is 701 A in the ground. Accordingly, current boundary conditions of the phases are defined as $I_m=\sqrt{2}\cdot701$ Eq. 3, Eq. 4 and Eq. 5 for each phase. In the analyzes where the phase currents are constant, effective value of the phase currents is defined as 701 A.

In the next step, the problem geometry is divided into triangular finite elements, and the meshed geometry and mesh statistics are given in Figure 3 and Table 3, respectively.

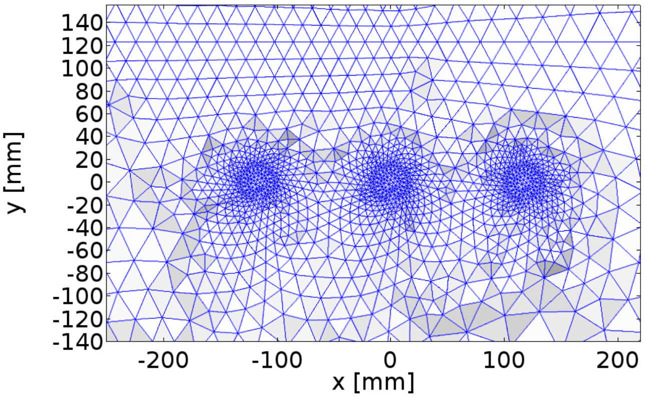

Figure 3. Mesh geometry

Table 3. Mesh statistics of the study

Mesh Parameters	Value
Number of triangular elements	83248
Number of edge elements	1717
Number of vertex elements	22
Minimum element quality	0.6553
Average element quality	0.9824
Element area ratio	3.108·10-6
Mesh area	9.24·108 mm2
Maximum growth rate	2.56
Average growth rate	1.09

4. Results and Discussion

In this section, the results of stationary and time dependent magnetic field analyzes performed with Comsol Muliphysics software are given and discussed. Firstly, time-dependent analyzes are carried out, and the time-dependent variation of magnetic flux density at point P(0,1) is presented in Figure 4.

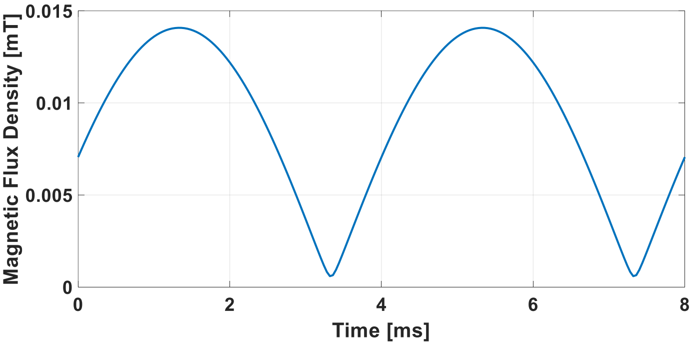

Figure 4. Variation of magnetic field density with time at point P (0,1)

In Figure 4, the time-dependent variation of the magnetic flux density at the P point is given. Within a period, maximum and minimum values of magnetic flux density are determined as 0.014 mT and $0.6\cdot10^{-3}$ mT, respectively. The reason why the magnetic flux density changes in this way over time is that magnetic flux density vectors, which change instantaneously depending on the current direction and amplitude, have weakening and strengthening effects on each other. In order to compare magnetic flux density with the limit values specified by ICNIRP, average value of the waveform need to be calculated. Average value of the waveform given in Figure 4 is calculated as 0.009 mT, and it is less than 0.2 mT limit value specified for 50 Hz magnetic fields in Table 1.

In the case where the phase currents are defined as constant, the variation of the magnetic flux density obtained on the reference plane is given in Figure 5.

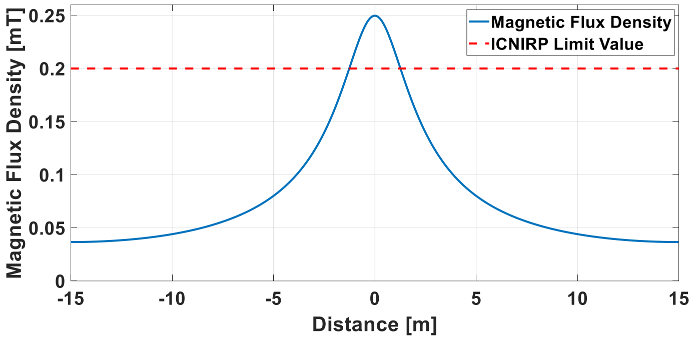

Figure 5. Magnetic field density distribution at one meter above ground (stationary analysis)

In Figure 5, it is seen that magnetic flux density reaches its maximum at point P(0,1) on the reference plane with approximately 0.25 mT. Contrary to the time-dependent analysis results, the maximum magnetic flux density obtained is above the 0.2 mT limit value. However, maximum magnetic flux density obtained in stationary analyzes is approximately 27 times the value in time-dependent analyses. For this reason, it is important to conduct magnetic field analyzes in time domain.

Thereafter step, analyzes made in the time domain are extended and the average values of the magnetic field intensities at each point along the reference plane are calculated. The distribution of mean values of magnetic flux density along the reference plane is presented in Figure 6.

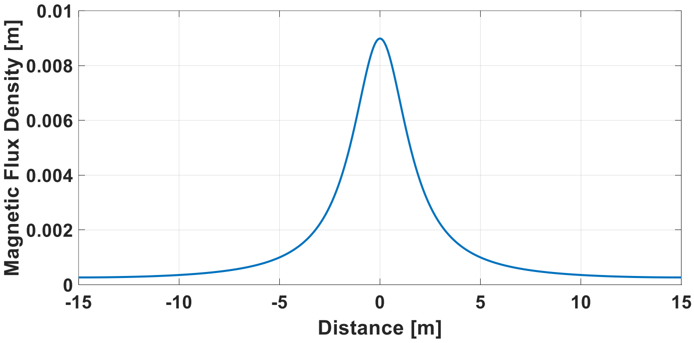

Figure 6. Magnetic field density distribution at one meter above ground (time domain analysis)

5. Conclusion

In this study, magnetic field analyzes around underground cables used in MV distribution network are carried out. Analyzes are performed with Comsol Multiphysics software and the maximum magnetic field intensities obtained in stationary and time domain are compared and evaluated. Nominal current carrying capacity of the cables used in the study is 701 A, and the current boundary conditions of all phases are defined constant in stationary analyses. In the time dependent analysis, boundary conditions of the phase currents are defined as alternating current, 50 Hz mains frequency and 120° phase difference. According to the results, the maximum magnetic flux density values obtained in stationary analyzes where the current value is defined as constant are 27 times higher than the real values (Table 4).

Table 4. Comparison of maximum magnetic flux intensities for stationary and time domain analysis

Analysis	**Maximum Magnetic Flux Density (mT)**	**Limit Value (mT)**
Time Domain	0.009	0.2
Stationary	0.25	

However, in the time dependent analyzes, it is determined that maximum magnetic flux density is significantly lower than the stationary analysis results. While the maximum magnetic flux density obtained as a result of time dependent analysis is below the 0.2 mT limit value determined by ICNIRP, the value obtained at constant current is above the limit value. In this regard, it is important to define the current boundary conditions based on time in the analysis of magnetic fields caused by conductors carrying alternating current such as underground cables or overhead lines.

As future studies, similar analysis can be performed for different cable types, cable layouts and loading currents and critical limit values can be determined. Also, if the power system contains current harmonics, the magnetic flux density distribution will also change due to the change of the current waveform. In this context, the scope of the analyzes can be extended for further studies.

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