ESTIMATION OF POWER CABLES MAGNETIC FIELDS IN MINE TUNNELS

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Abstract - The magnetic fields generated by power cables in concrete mine tunnels are investigated using Finite Element Method simulations. Also the influence on humans is considered. The armored and unarmored cable, admitted by Romanian standards for mining operations and the bounding applicable techniques for the armor conductors are the sources of magnetic fields. Some recommendations about the cables management in mine tunnels are outlined at the end of investigations.

Keywords: Electromagnetic compatibility, power cables, magnetic field, finite element method, human exposure, mine tunnels.

1. INTRODUCTION

Nowadays, the electromagnetic fields (EMFs) are considered important environmental factors, [1]. ICNIRP 1998, [2], guidelines specify, for occupational exposures at power frequencies, the basic restriction: current density at 10 mA/m^2. For the general public, is applied an extra factor of 5, giving a basic restriction of 2 mA/m^2. They also give investigation reference levels for EMFs: 500 µT and 10 kV/m for workers and 100 µT and 5 kV/m for the public. The fields required to produce the basic restriction are higher.

In underground mining exploitations the tunnels are one of the most important parts, they provide access for workers and for the needed infrastructure to feed all the activities with energy. Due to them reduced transversal surfaces and the rejection effect of the conductive media that surrounds the tunnels, the interferences between EMFs and humans are more acute than for underground cables. The dimensions and the architecture of main tunnels are standardized, [3] and the distributions of the electric power is exclusively done based on power cables with also standardized voltages: for primary distributions and for punctual consumers is 3.6/6 KV and the 0.4 KV and lower voltages are used for secondary distributions and for power demand.

Other important standardized aspect is referring to the available power cable types for mining activities, [4]. For 3.6/6 KV, only cables with concentric earth conductor of copper wires and copper tape helically wounded are admitted, i.e. NYCY type, according with VDE 0276. In terms of installation conditions (temperature, mechanical risk, indoor atmosphere,) will be used armored or unarmored cables. For armor are recommended the galvanized flat steel wires armor (FSWA) or galvanized round steel wires armor (RSWA), required to be earthed at both ended. Unfortunately, based on author experience (12 years in mining sector) the armor earthed connections are some times skipped (or done improperly) in contrast with concentric earth conductor.

2. MAIN MINE TUNNEL

The tunnel is constructed normal to [3] from concrete, 0.01 S/m, and is detailed in Fig.1. The soil from outside of the tunnel has a 0.05 S/m conductivity. Both resistivities, of soil and concrete, are taken lower then the usual average values to maximize the effect of the tunnel and the surrounding material in magnetic field distributions.

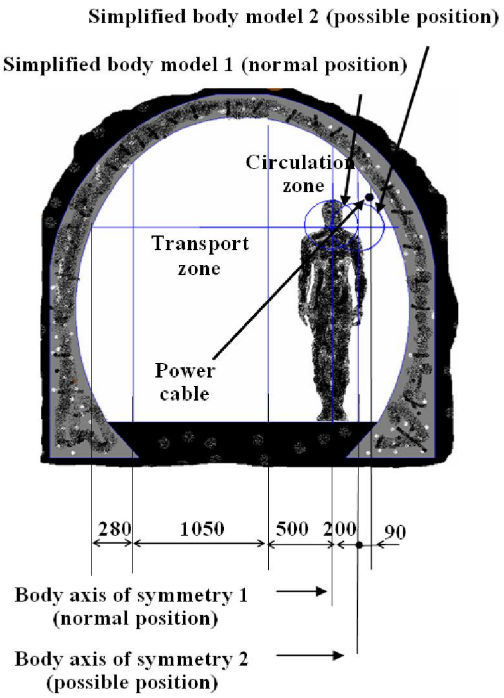


Fig. 1. Main mine tunnel section

The circulation zone is minimum 800 mm wide measured at 1.69 m above base (here due to elliptic section is 970 mm) and it had to be arranged considering the infrastructure needed for mining exploitation such as electric power, compressed air, water. So the workers are exposed to a close vicinity to power cables. Two positions are taken into account: the normal and possible one.

The simplified model of human body consist of a homogeneous 0.2 m radius sphere with a conductivity of 0.2 S/m [1] placed with it centre at 1.6 m above ground corresponding to normal and possible positions of worker in tunnel. This approximation has the advantage of simplicity with an acceptable accuracy in induced current density evaluation in human tissues [5].

It was considered one power cable placed at 1850 mm above the tunnel ground. The outside diameter of cable is 66 mm.

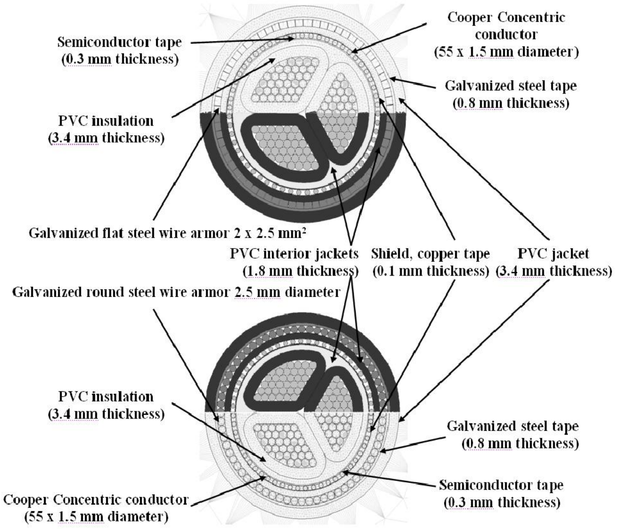


Fig. 2. ANYCYRGBY and ANYCYFGBY cables

The cable is a 3.6/6 KV, PVC SWA 3 x 185 mm^2 + 95 mm^2, phase conductors from aluminum (37 x 2.5 mm diameter per phase), 34.45 MS/m conductivity and 58 MS/m conductivity cooper wires concentric earth conductor. It were analyzed both types of armored cables: ANYCYRGBY and ANYCFGBY. For unarmored cable, the material of the steel wires was simply replaced with insulator, the other dimensions and materials remaining unchanged. In Fig. 2, are shown the constructions of cables.

Only the armor is magnetic material, having a relative magnetic permeability equal to 500 and a conductivity of 7 MS/m.

The semiconductor tape is considered with a resistivity of 1000 Ωm [6].

3. FINITE ELEMENT METHOD SOLUTIONS

The Finite Element Method analyses were done using David Meeker Finite Element Method Magnetics FEMM® for 2D configurations.

In FEMM® the mathematical model of time harmonic magnetic problems is defined as follows [7]: the electric field intensity, *E*, and the current density, *J*, obey the constitutive relationship.

$$J = \sigma \cdot E, \tag{1}$$

Substituting the vector potential, A, form of magnetic flux density, *B*, into Faraday's Law:

$$\nabla \times E + \frac{\partial B}{\partial t} = 0, \tag{2}$$

yields:

$$\nabla \times E = -\nabla \times \frac{\partial A}{\partial t}, \tag{3}$$

In the case of 2-D problems, (3) can be integrated to give:

$$E = -\frac{\partial A}{\partial t} - gradV, \tag{4}$$

and the constitutive relationship, (1) goes to:

$$J = -\sigma \cdot \frac{\partial A}{\partial t} - \sigma \cdot gradV, \tag{5}$$

Substituting into Maxwell-Ampere law, written in terms of vector potential *A:*

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = J, \tag{6}$$

yields the partial differential equation:

$$\begin{aligned} \nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) &= -\sigma \cdot \frac{\partial A}{\partial t} + \\ &+ J_{SRC} - \sigma \cdot gradV \end{aligned}, \tag{7}$$

where J_{src} represents the applied currents sources. FEMM® considers (7) for the case in which the field is oscillating at one fixed frequency. For this case, a phasor transformation yields a steady-state equation that is solved for the amplitude and phase of *A*. This transformation is:

$$\begin{aligned} A &= \mathrm{Re}\left[a(\cos\omega t + j \cdot \sin\omega t)\right] = \\ &= \mathrm{Re}\left(a \cdot e^{j \cdot \omega t}\right) \end{aligned}, \tag{8}$$

Substituting into (7) and dividing out the complex exponential term yields the equation that FEMM® solves for harmonic magnetic problems:

$$\begin{aligned} \nabla \times \left(\frac{1}{\mu(B)} \nabla \times a \right) &= -j \cdot \omega \cdot \sigma \cdot a + \\ &+ \underline{J}_{SRC} - \sigma \cdot gradV \end{aligned}, \tag{9}$$

with $\underline{J}_{SRC}$ representing the phasor transform of the applied current sources and *a* being the complex amplitude of the phasor transformation, of *A*.

The ANYCYFGBY, ANYCYRGBY, ANYCY cables, positioned in tunnel as in Fig. 1, considered the armors earthed, respectively unearthed were feed with 300 A, 50 Hz current trough phases, which is closed to maximum load for 300 mm^2 aluminum cable. The load is considered symmetrically, and then the currents of each phase have the expressions:

$$\begin{aligned} i_R[A] &= 300\cdot\sqrt{2} \\ i_S[A] &= 300\cdot\sqrt{2}\cdot\left(-\frac{1}{2}-j\cdot\frac{\sqrt{3}}{2}\right), \\ i_S[A] &= 300\cdot\sqrt{2}\cdot\left(-\frac{1}{2}+j\cdot\frac{\sqrt{3}}{2}\right) \end{aligned} \qquad (10)$$

The resulted configurations with and without the human body simplified model were analyzed on FEMM®.

To close the studied domains without loosing the soil influences it were imposed asymptotic boundary conditions [7] on a 10 m radius circle around the tunnel:

$$\frac{1}{\mu_r\mu_0}\frac{\partial A}{\partial n}+c_0A+c_1=0, \qquad (11)$$

with:

$$c_0=\frac{1}{\mu_0 r}, \qquad (12)$$

and:

$$c_1=0, \qquad (13)$$

where r_o is the outer radius of the region in meters.

4. RESULTS

The time-varying magnetic field effect on humans is caused by generates circulating tissue currents, which are basic restrictions in ICNIRP guidelines. Because these currents are very hard to be measured, the values of the magnetic flux density are considered as reference levels.

The limit values of the magnetic fields in the regulations are not risk limits, but they include very big safety factors, so that the ambiguities from the limited knowledge of the fields' effect are covered and the requirement for prevention of health hazards is fulfilled [8].

In Fig. 3 a detailed distribution of magnetic flux density for ANYCYRGBY cable is shown. The mutual influence between phases is visible. Also the effect of the galvanized steel tape, which bound together the armor steel wires, on field map outline the important shielding effect of magnetic materials. This tape has just a mechanical role. At industrial frequency, the soil and concrete conductivities play small roles in magnetic field spectrum; a small effect on repulsing the field by the induced currents can be seen.

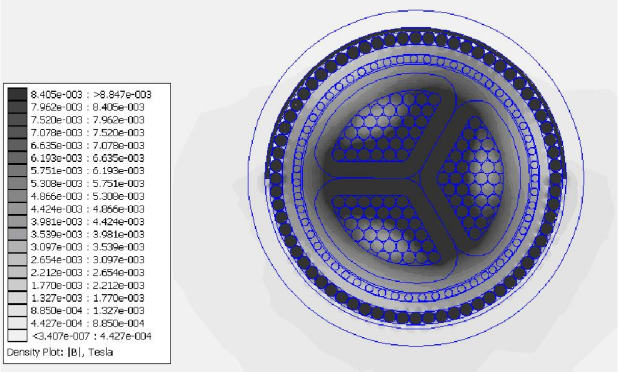
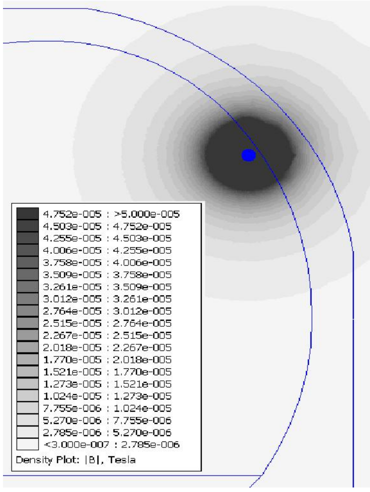
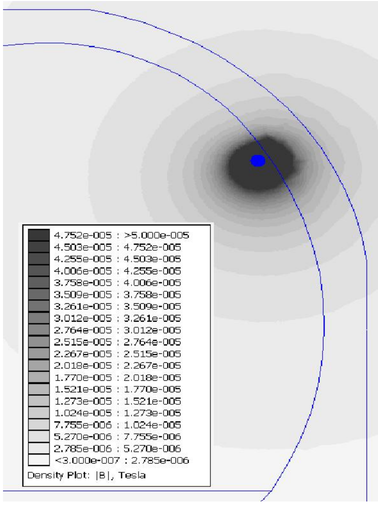


Fig.3. Distribution of magnetic flux density for ANYCYRGBY cable

The resulted magnetic field distributions for unarmored and armored cables (with steel wires and steel tape earthed and unearthed) respectively, in circulation area of the mine tunnel, are shown in Fig. 4.



no armor



RSWA unearthed

Fig. 4. Distributions of magnetic fields in mine tunnel for AYNCY and SWA cables

These representations permit to take some conclusions on the field strengths. Unearthed armors have better shielding effects for both types of wire. We outline that unearthed armor is against the standards for mining operations and is known that this fact generate an increased potential on armor and increased dielectric strength for insulations, but more important it increase the electric hazards for workers.

For unarmored cable the shielding effect of cooper tape is weak for magnetic field so the magnetic flux density is bigger in cable vicinity but also faster decreasing that the filed corresponding to armored cables.

For deeper investigations, the graphical variations of magnetic flux density on body axes of symmetry for normal and possible positions of worker in mine tunnel sections, Fig. 5 and Fig. 6, respectively are very useful instruments.

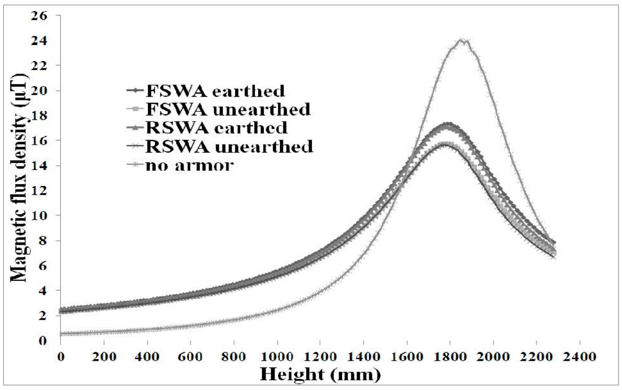


Fig. 5. Magnetic flux density on body axis for normal position

For normal position it is obviously that the steel wire armor is a very efficient shield for magnetic field. The maximum values correspond to the shorter distance between the axis and the cable. The maximum values of the magnetic flux density are: 17.35 µT, for FSWA earthed, 15.75 µT for FSWA unearthed, 17.1 for RSWA earthed, 15.66 µT for RSWA unearthed and 24 µT for no armor on cable construction.

Another useful hint visible on the graph is the height of approximately 1600 mm from where the field is weaker for unarmored cable, so if the ANYCY (NYCY) cable are used on mines it is recommendable to be placed at a minimum 250 mm from highest body part (for 300 A rms current). This space will bring the magnetic field in worker area comparable to the field produced by armored cables.

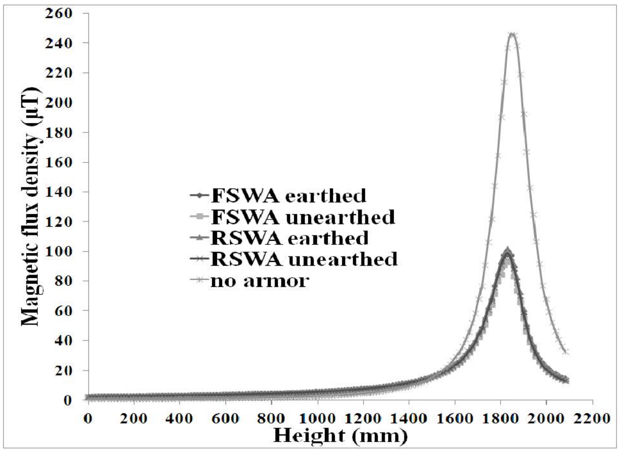


Fig. 6. Magnetic flux density on body axis for possible position

Because in the possible position the worker axis of symmetry is very close to the cable, the shielding effect of armor is more evident. So the values for maximum strength of the magnetic fields reach a 245.7 µT, for unarmored cable, 97.63 µT, for FSWA earthed, 93.38 µT for FSWA unearthed, 101.89 for RSWA earthed, 99.14 µT for RSWA unearthed.

It is important to mention that neither cables construction create an outer magnetic field exceeding the ICNIRP guidelines for worker. Of course for bigger currents an unarmored cable could reach 500 µT. In this paper were not considered bigger currents and corresponding bigger phase conductor sections because 300 A rms at 6 KV mean a total apparent power of 3.118 MVA, which is an usual value for a mining exploitations.

To link the field with the effects on humans, a simplified model is introduced in tunnel, Fig.1. The induced currents are computed via FEMM® in the body.

As results were graph the modulus of total induced current density on peripheral circumference of the sphere. The highest value corresponds to the closest point of circumference to the cable.

Two graphs were plotted, for normal and possible positions, Fig. 7 and Fig. 8, respectively.

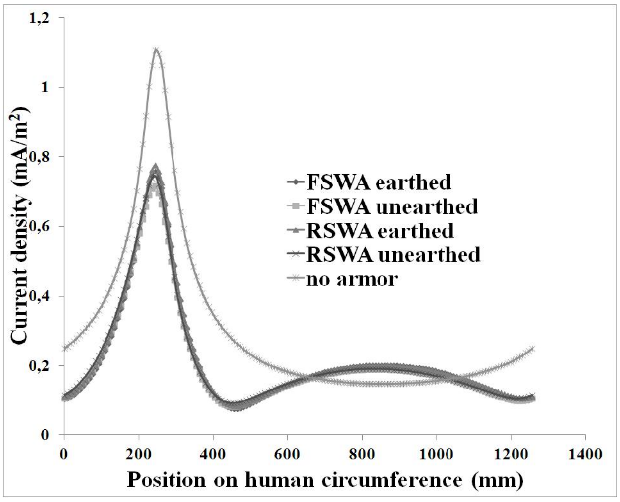


Fig. 7. Induced current density in human body for normal position

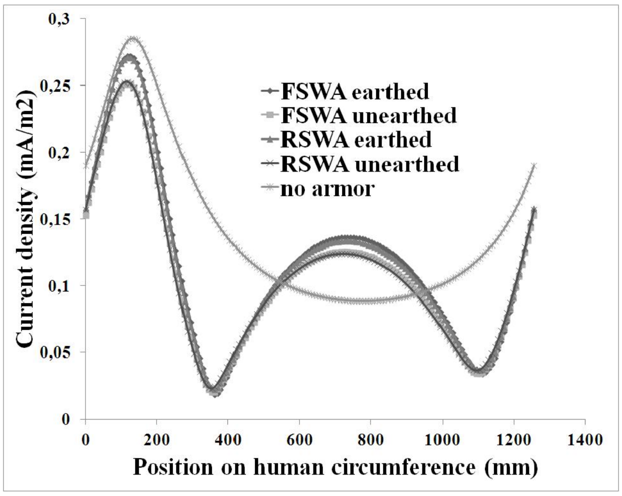


Fig. 8. Induced current density in human body for possible position

From the beginning as it was expected, due to field strength values, the basic restriction, 10 mA/m^2, for occupational exposures at power frequencies, was not exceed.

Induced peripheral current density in human body has the maximum value for unarmored cable, i.e. 1.1 mA/m^2 for possible position of worker in mine tunnel which has a corresponding 0.77 mA/m^2 for armored cables.

Again the influences of earth connections of armors are visible, the shield increased effect of unearthed armor producing a lower induced current density in human model.

It has to be mentioned that in FEMM® all values computed in time harmonic regime are maximum values and not the rms values. Interpreting the EMFs effect on biodiversity by using these values offer a safety comparison, but in case of exceeding the imposed values, the rms can simply be computed via √2 factor

5. CONCLUSIONS

This paper has studied magnetic field distribution resulting from 3 typical power cable types agreed in underground mining exploitations at 6 KV voltage and three phases symmetrically 300 A rms, 50 Hz. The 2D time harmonic FEM analyses were perform to reach the magnetic field around cables and the induced currents in a simplified human model.

All the computations were verified by implementing in FEMM® environment the problems with the results reported in [1], [9]. Also the specific values obtaining here were compared using interpolation, with results of underground power lines EMFs evaluations [10], [11] and [12].

It was clearly outlined that the steel wire cable armor has an important role in magnetic field shielding. The magnetic field strengths is reduced from 245.7 μT, for unarmored cable at 97.63 μT, for FSWA earthed, respectively to 101.89 for RSWA earthed for close vicinity to the cables and from 24 μT for no armor to 17.35 μT for FSWA earthed, or 17.1 for RSWA earthed for increased distance.

Also a 250 mm distance between body and cable ensure a leveling of magnetic field for armored and unarmored cables.

In terms of peripheral induced current density the reduction gained by armoring is from 1.1 mA/m^2 to 0.77 mA/m^2.

Even the values are not exceeding the imposed values for worker exposure, a costless, simple and efficient measure to reduce the power cables EMFs, especially in narrow spaces, as it is the mining tunnels, is to place them in the upper area of tunnels and ensure a minimum distance of 250 mm (at 300 A rms or lower) from human body. The larger the distance, the smaller the electromagnetic interferences that have to be supported by workers.

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