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The interaction of Electromagnetic Pulse with buried Armoured Fiber Optic Cables

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Abstract: The use of fiber optic cables is rapidly increasing all over the world with the advantages such as reliable, economic and high data transmission, low weight and wide bandwidth. However, due to its fragile and sensitive structure, the protection and performance of fiber optic cable can be a problem in some harsh environments such as underground and underwater. Thus, armoured fiber optic cables are designed to solve this problem. With the addition of steel wire or galvanized steel and aluminium tape layers, the fiber optic cables become durable and reliable for underground applications. In this study, the effect of a high intensity of an electromagnetic pulse on armoured fiber optic cable is considered. With steel tape/wire layer, the armoured fiber optic cable is considered as a cylindrical shell and analytical calculations carried out via a matrix model.

Keywords: armour, fiber optic cable, electromagnetic pulse, matrix model

I. INTRODUCTION

There is an increasing interest on underground installations such as telecommunication cables, power cables, tunnels, pipelines in last decades. The interaction of high intensity radiated fields to underground installations become an important issue[1]–[6]. Especially, the effects of high-altitude electromagnetic pulses such as lightning, EMP etc. with buried cables is an important area of interest[7]–[10]. Underground cables are commonly used for telecommunication and power lines.

With development of technology, fiber optic cables are commonly used for communication with the advantages such as good repeatability, low cost, low weight, wide bandwidth, low delay, immunity to electromagnetic interferences and high transmission speed[11], [12]. Also, with its non-metallic structure, there is no electromagnetic interference on the cable. However, there is a risk of corrosion and damage on the cables in harsh conditions such as underground[13] and underwater applications[14]. Armoured fiber optic cables are designed and used for protection from any damages. Galvanized steel tapes, steel wires are placed as a layer inside the outer jacket for this type of cables. The metallic armour of the fiber optic cable can induce and transmit current due to external sources. Also, an electromagnetic interference can be occurred due to electromagnetic fields.

In this study, armoured fiber optic cable is considered as a cylindrical shell. The armour of the fiber optic cable is assumed to be the surface of the cylinder. It is aimed to obtain the electric field levels on the axis of the cable due to a high intensity external electromagnetic source such as an electromagnetic pulse (EMP). Analytical analysis is carried out at cylindrical coordinates and the electric field levels on the axis of the cable is calculated via a matrix model presented at previous works[15], [16].

In Section 2, analytical model is presented for TM electromagnetic wave interaction with cylindrical shell model. The results of analytical calculations are presented in section 3 and finally, the results are discussed at Section 4.

II. MATHEMATICAL MODEL

A fiber optic cable and its inner layers are presented in Fig. 1. The description of the layers is also given in Table I.

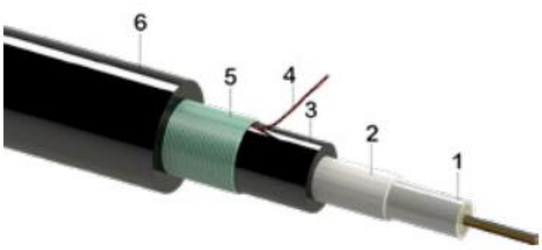

Fig. 1. Fiber Optic Cable and layers[17]

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TABLE I. THE LAYERS OF FIBER OPTIC CABLE

No.	Description	No.	Description
1	Loose tube with optical fibers	4	Ripcord
2	Aramide yarn/Water blocking e-glass yarn	5	Steel Wire, Galvanized or Corrugated Steel Tape
3	PE Inner Jacket	6	PE Outer Jacket

Also, some additional layers can be added to the cable due to the working conditions. For underwater applications, an aluminium layer is added to improve the water blocking and shielding performance. For the fiber optic cable in Figure 1, all layers are non-conductive except steel tape/wire layer. So, the fiber optic cable is modelled as a cylindrical shell in which the steel armour is considered as the shell of the cylinder.

TM polarized electromagnetic plane wave is considered to interact with a cylindrical shell as shown in Fig. 2. The cable is located at the depth of ***d***.

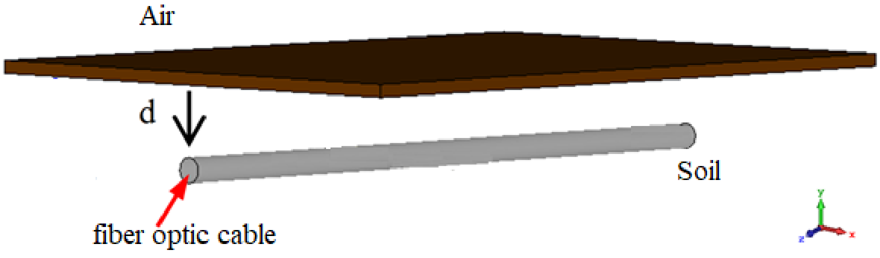

Fig. 2. Interaction Model

The electric and magnetic fields in cylindrical coordinates

$$E^{inc}(r,\phi,z) = E_z^{inc}(r,\phi)\overrightarrow{a_z} = E_0^{inc} e^{-jk_0 r\cos\phi}\overrightarrow{a_z}$$
$$H^{inc}(r,\phi,z) = H_r^{inc}(r,\phi)\overrightarrow{a_r} + H_\phi^{inc}(r,\phi)\overrightarrow{a_\phi} = -\frac{E_0^{inc}}{\eta_0}(\overrightarrow{a_r}\sin\phi + \overrightarrow{a_\phi}\cos\phi)e^{-jk_0 r\cos\phi} \quad (1)$$

The tangential field to the cylindrical surface is given as

$$E_z^{inc}(r,\phi) = E_0^{inc}\sum_{n=-\infty}^{\infty} j^{-n} J_n(k_0 r)e^{jn\phi}$$
$$H_\phi^{inc}(r,\phi) = \frac{1}{jw\varepsilon_0}\frac{\partial E_z^{inc}}{\partial r} = -j\frac{E_0^{inc}}{\eta_0}\sum_{n=-\infty}^{\infty} j^{-n} J_n^{'}(k_0 r)e^{jn\phi} \quad (2)$$

$J_n(\cdot)$ is the nth order Bessel function of the first kind and $J_n'(\cdot)$ is the derivate of $J_n(\cdot)$. η_0 and k_0 are the characteristic impedance and the wavenumber of the free space, respectively.

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$
$$k_0 = w\sqrt{\varepsilon_0\mu_0} \quad (3)$$

where ω is the angular frequency, ε_0 is the permittivity and μ_0 is the permeability of free space. For TM wave incidence, the relation between the tangential fields can be obtained at the boundaries of the layers by the equation given below. **b** is the outer radius of the cylindrical shell and **a** is the inner radius.

$$\begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_b = \sum_{n=-\infty}^{\infty}[Z_n]_{TM}\begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_a \quad (4)$$

$[Z_n]_{TM}$ is the transfer impedance matrix and given

$$[Z_{TM}] = \frac{\pi k_p r}{2}\begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (5)$$

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where the related expansion terms are expressed by Wronskian's results on J_n and Y_n[18]

$$\begin{aligned} A &= J_n(k_p \cdot r_b) \cdot Y_n{}'(k_p \cdot r_a) - J_n{}'(k_p \cdot r_a) \cdot Y_n(k_p \cdot r_b) \\ B &= -i\eta_s (J_n(k_p \cdot r_a) \cdot Y_n(k_p \cdot r_b) - J_n(k_p \cdot r_b) \cdot Y_n(k_p \cdot r_a)) \\ C &= \frac{1}{i\eta_s}(J_n{}'(k_p \cdot r_a) \cdot Y_n{}'(k_p \cdot r_b) - J_n{}'(k_p \cdot r_b) \cdot Y_n{}'(k_p \cdot r_a)) \\ D &= J_n(k_p \cdot r_a) \cdot Y_n{}'(k_p \cdot r_b) - J_n{}'(k_p \cdot r_b) \cdot Y_n(k_p \cdot r_a) \end{aligned} \tag{6}$$

$Y_n(\cdot)$ is nth order Neumann function of the first kind and $Y_n'(\cdot)$ is the derivate of $Y_n(\cdot)$. η_s is the characteristic impedance and k_p is the wavenumber of the cylindrical shell surface.

$$\eta_s = \sqrt{\frac{jw\mu_s}{\sigma_s + jw\varepsilon_s}} \tag{7}$$

$$k_s = \sqrt{-jw\mu_s(\sigma_s + jw\varepsilon_s)} \tag{8}$$

$$k_p = \sqrt{k_s{}^2 - k_z{}^2} \tag{9}$$

where σ_s is the conductivity, ε_s is the relative permittivity and μ_s is the relative permeability of the shell surface.

III.RESULTS

EMP is described by an double-exponential equation given by[19], [20]

$$E(t) = E_0 \times (e^{-\alpha t} - e^{-\beta t}), \qquad t > 0 \tag{10}$$

where the parameters E_0=5x10^4 V/m, α=4x10^7 s^{-1}, β=6x10^8 s^{-1}. The waveforms of EMP are shown in Fig. 3 for both time and frequency domains.

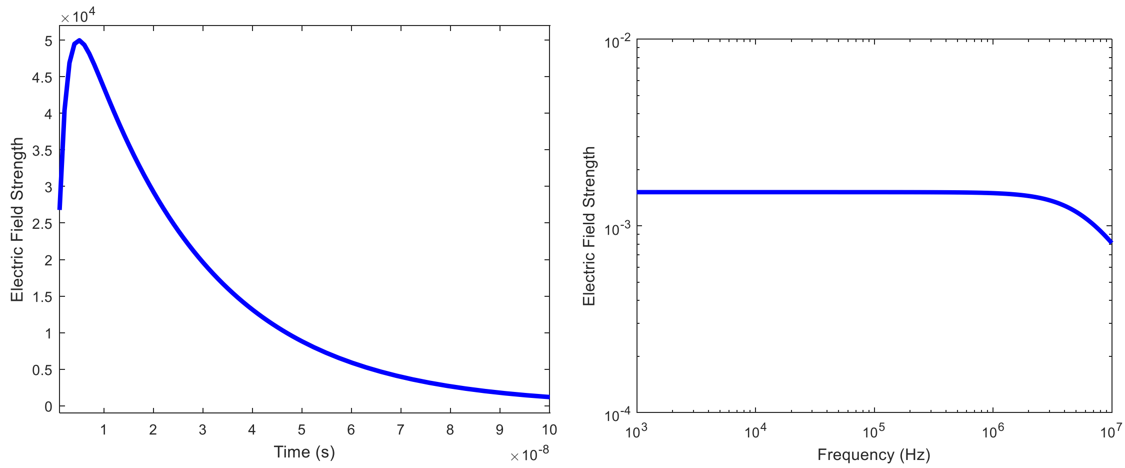

Fig. 3. EMP waveform at time and frequency domains

EMP interact with the armoured fiber optic cable which is modelled as a cylindrical shell. Diameter of the cable is 15 mm and thickness of the steel tape is 0.15 mm. Cable is located at 1 m depth in soil.

The tangential electric field component of EMP at cable location is calculated given in Figure 4.

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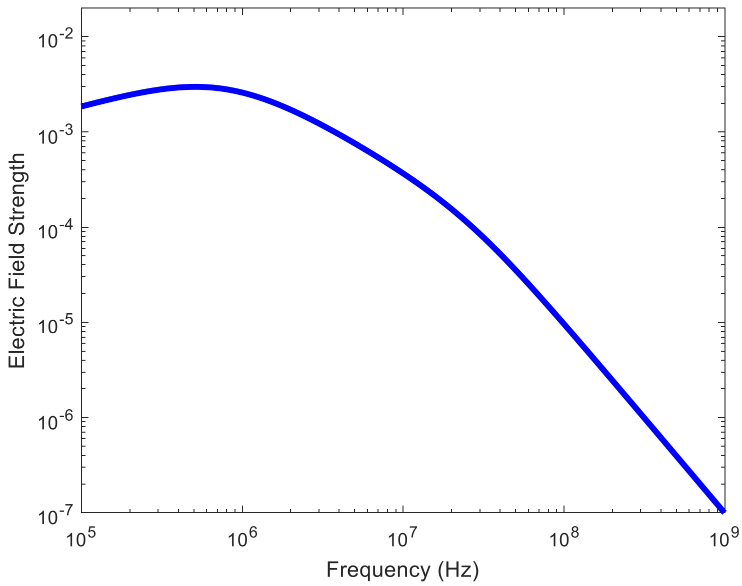

Fig. 4. The tangential electric field component at cable location

The electric field component calculated in Fig. 4 is used in equations given in section II and electric field on the axis of the cable is given in Fig. 5.

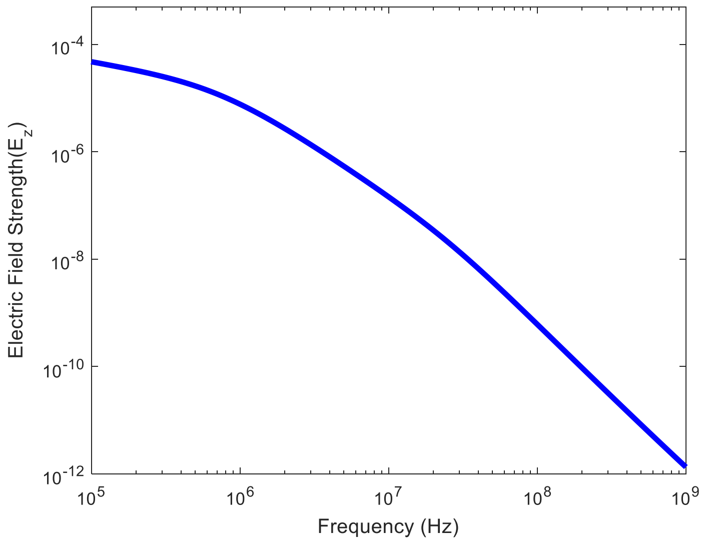

Fig. 5. The electric field component at the axis of the armoured fiber optic cable

A comparison is made between Fig. 4 and Fig. 5. As a result of the comparison, it was clear that the electric field decreased about 100 times at low frequencies and closely 10^5 times at high frequencies.

Shielding performance of the cable also show the attenuation level of the electric field. By using the results given in Figure 4 and 5, shielding performance of the armoured fiber optic cable can be evaluated via equation given below.

$$SE_E = -20\log\left|\frac{E_{in}}{E_{out}}\right| \tag{11}$$

E_{in} is the electric field strength on the axis of the cable and E_{out} is the electric field strength at the location of the cable. The shielding performance of the cable is presented in Fig. 6.

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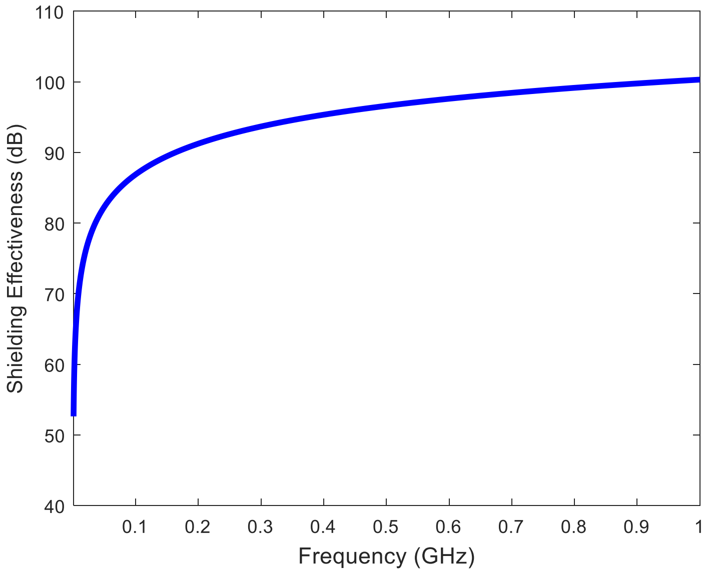

Fig. 6. Shielding performance of the armoured fiber optic cable

The shielding performance of the cable is increasing frequency and between 50 and 100 dB at the frequency range. This shielding level is closely 100 dB at 1 GHz.

Figure Captions

Figures must be numbered using Arabic numerals. Figure captions must be in 10 pt Regular font. Captions of a single line must be centred whereas multi-line captions must be justified. Captions with figure numbers must be placed after their associated figures, as shown in Fig. 1.

IV. CONCLUSION

The interaction of an EMP with buried and armoured fiber optic cable is investigated in this paper. The fiber optic cables become durable with the addition of steel layer against harsh environment. Armoured fiber optic cable is modelled as a cylindrical shell and steel layer is considered as the metallic shell of the cylinder. The electric field at the axis of the cable is evaluated via a 2x2 matrix model used at previous works. The electric field level decreased about 100 times at lower frequencies. With increasing frequency, decrease at electric field increasing and electric field is weakened about 10^5 times at 1 GHz. Also, shielding performance of the armoured fiber optic cable is considered and 50 to 100 dB shielding is achieved for the frequency range.

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