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Modeling the Dielectric Mediums Impact on Coaxial Transmission Line Performance

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Abstract: In this research, mathematical modeling for the coaxial cable has been used to analyze transmission line performance under three different dielectric mediums which are propagation medium in the coaxial cable and to illustrate their role in the amount of Characteristic Impedance (Char Imp) of the transmission line. Polyimide, polyethylene and Teflon dielectric materials have been examined to extract the values of the electrical model elements, hence, the total reluctance and attenuation of the line. Also, this analysis is related to dielectric mediums with respect to dielectric heat losses and its influences on coaxial cable inner and outer conductors. Therefore, the mathematical model assembled by MATLAB is used to examine coaxial cables performance according to the above effects of (dielectrics) insulators performance. Extracted results have demonstrated the losses and attenuation in the propagation of electromagnetic waves.

Key words: Coaxial transmission line, mathematical model, electrical model, dielectric mediums, polyimide, polyethylene, Teflon

INTRODUCTION

The coaxial cables combined with inner conducting wire surrounded by cylindrical insulating dielectric material which is surrounded by a cylindrical conducting shield acting as the neutral wire. Also, coaxial cables are protected by an insulating sheath or jacket. Thus, the term coaxial is to express that inner wire and outer tubular shield share same geometric axis as shown in Fig. 1.

Historically in 1880, Oliver Heaviside an English Mathematician studied the skin effect phenomena in the transmission lines of telegraph communications. He has revealed that sheathing the transmission line conductor with insulation materials increases the traveling signal clarity and improves the physical durability of the transmission line. A year after, he invented the coaxial cable in the United Kingdom and Siemens made the first practical coaxial cable in 1884 (Kumar *et al*., 2013; Takada *et al*., 2017; Anonymous, 1991).

Manufacturing a cable in this way is to keep all traveling electromagnetic wave in the area inside it. The coaxial cable is flexible and can be twisted or bent due to its mechanical properties. Furthermore, if the cable is strapped by conductive supporting materials, unwanted currents will be induced. Although, in few gigahertz frequency radiation applications, the propagation in

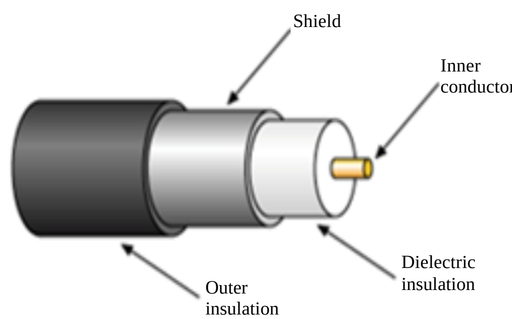

Fig. 1: The cross-section of coaxial cable

transverse electric magnetic mode, i.e., electric and magnetic fields are perpendicular to the focal point of propagation. Yet, the wavelength is remarkably shorter than the circumference of coaxial cable transmission lines. Therefore, transverse electric and transverse magnetic waveguide modes will propagate in the dielectric medium. Coaxial cable inner solid copper conductor conducts the electrical signal is usually made of a copper plated steel or may be stranded copper wire. The conductor is surrounded by a dielectric and all reserved by a conducting shield. The propagation of electromagnetic waves through the coaxial cable before they suffer either sucking or reflection in the dielectric materials. So, physically the Speed (S) of electromagnetic waves,

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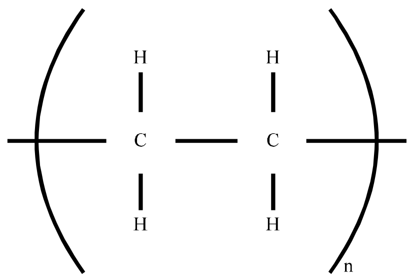

Fig. 2: The basic chemical PE polymer chain

propagating through coaxial cable, is affected by the physical and the composition of the dielectric materials and given by:

$$S = \frac{C}{\sqrt{K}}$$

$$K = (\mu r \times \varepsilon r)$$

Where:

C = The light velocity in vacuum = 0.3 G (m/sec)

μr and εr = Dielectric medium magnetic relative permeability and relative permittivity, respectively

It is concluded that the propagation velocity of an electromagnetic wave traveling through a dielectric medium is always less than their propagation velocity through a vacuum, since, (K>1) for dielectric materials. Practically the most common dielectric materials are Solid Polyethylene (PE) which supports low-temperature applications, Foamed Polyethylene (FPE) which provides less capacitance and attenuation than solid PE. However, the Air spaced coaxial cables support a lower dielectric constant than polyethylene but they allowed only in short diameter cable size (Konecna, 2016; Anonymous, 2009; Kliros, 2011). In this study, the air has been examined as a dielectric to depict its performance, despite it offers a good option as a dielectric, it cannot always be used due to mechanical and practical limitations. Beside containing and maintaining propagation, the dielectric material maintains the critical spacing between the outer shield and inner center conductor. A certain percentage of signal energy is inevitably dissipated in the dielectric medium itself, since, it is an imperfect insulator. Thus, low-loss cables can be achieved by utilizing dielectric materials with better insulating characteristics. According to these requirements, polyethylene is a most common dielectric material option has good electrical properties, besides it is cheap and flexible. Also, PE has less dielectric losses than Polyvinyl Chloride (PVC). However, under voltage stress, PE is sensitive to humidity. The chemical formula for PE is (C_2H_4) nH_2 as shown in Fig. 2. The material breaks down at high temperatures (Godio, 2007).

The ideal dielectric materials cannot exhibit electrical conductivity if an electric field would be applied. Practically, dielectric mediums have some electric conductivity increases with the temperature increase and applied field, i.e. when the applied field increases in critical magnitude, the dielectric suddenly starts conducting, thus, large current flows, accompanied by a visible spark breaking out in most cases. That causes an immediate partial destruction happens depending on the size of supplied energy sent by a source in such low conductivity path. This threshold of electric field is defined by many factors such that the specimen geometry, electrodes material and shape, the ambient medium shielding the dielectric medium and time variation of the electric field signal. Also, there can be temperature instability due to the generated heat by conductors or dielectric losses which end with a thermal breakdown. Practically this breakdown may be caused by other reasons such as operating several of neighboring cables simultaneously. However, careful experiments can possibly measure the critical field which is depending on the intrinsic insulating characteristics of the material. This field is expressed as the intrinsic electric strength of the tested dielectric material (Ullman, 2011; Kahimba *et al*., 2007; Zhang *et al*., 2010).

MATERIALS AND METHODS

Coaxial cables equivalent circuit: The coaxial cable transmission lines contain many parameters dictating his performance; Sending Voltage (Vs), Receiving voltage (Vr), Capacitance (C), inductance (L), Resistance (R) and conductance (G). The equivalent circuit of a coaxial cable is shown in Fig. 3.

The dielectric medium and conductors in coaxial cable have a remarkable electrical impact on the test setup. Coaxial cables are lossy elements with inductance and lumped capacitance. However, practically the electric effects of a coaxial are more complex compared with single shunt capacitance value.

In this study, the examination of the coaxial cable electrical performance has been carried out. The ohmic resistance, distributed capacitance and inductance affect the signal clarity. Thus, different dielectrics change these values and hence the coaxial cable performance. The coaxial cable modeling circuit contains:

Series resistance (Ω/ m) represents the copper losses in the inner conductor and neutral shield at low signal frequency (Kahimba *et al*., 2007; Zhang *et al*., 2010; Skierucha and Wilczek, 2010). However, at high frequencies, the skin effect phenomena can increase the cable effective resistance by decreasing the sectional area and confines the current conduction to a thin skin layer of the inner conductor. Series resistance is given by Eq. 1:

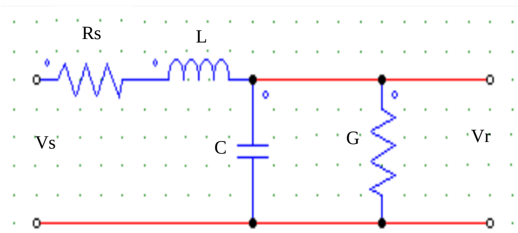

Fig. 3: Transmission line coaxial cable model

$$R = (1/2\pi)\times((1/d)+(1/D))\times\sqrt{(\pi f\mu/\sigma)} \quad (1)$$

Where:

d = Inner conductor diameter
D = Outer shield diameter
μ = Dielectric magnetic permeability
σ = Inner wire conductivity

Shunt capacitance (Farad per meter) is the coaxial cable capability carrying a charge:

$$C = 2\pi\sigma/\text{In}(D/d) \quad (2)$$

Also, as mentioned before when the stress increases due to high frequencies traveling signal, the dielectric medium becomes significantly lossy because the insulating material absorbs some of alternating electric field energy and consequently causing high heat.

Series inductance (Henries per meter) represents the circulating magnetic field along the inductor. Thus, self-inductance is represented by a series inductor given by:

$$L = (\mu/2\pi)\times\text{In}(D/d) \quad (3)$$

Shunt conductance is a very small value when efficient dielectric mediums with low dielectric constant are used. The dielectric medium has high resistive losses at high frequencies:

$$G = 2\pi\sigma/\text{In}(D/d) \quad (4)$$

Char Imp Z is the total reluctance to the electrical energy flow in the transmission line. It is defined and calculated by the coaxial cable electrical parameters; capacitance, resistance, conductance and inductance combined in the following Eq. 5:

$$Z = \sqrt{\frac{(R+jL)}{(G+jC)}} \quad (5)$$

Generally, among all forms of coaxial cable losses, radiation losses are the least effective losses. Therefore, reducing coaxial cable losses such as impedance matching, skin effect and dielectric losses is more important in the coaxial cable industry.

Dielectric losses: Dielectric medium losses are due to the electric absorption of energy, since, it suffers fast polarization in a different direction. Also, it rises with the conductance. Besides, dielectric losses are increasing with the increasing sending voltage on the cable conductor. The dielectric losses increase with the frequency (stress) because shunt conductance increases linearly with signal frequency. This loss represents another major loss accompany most coaxial cables shown as dissipated heat power in the dielectric and increase with frequency causing signal attenuation.

The electrical dissipated power losses also can be raised due to heating up the inner conductor and braid shield by the surrounding hot dielectric medium. Also, there is a capacitive energy loss depends on the dielectric insulator kind used between the two inner and outer shield conductors, causing heating up the dielectric material with electric field variation (Nguyen *et al*., 1997). The Capacitance C in the cable can be calculated as follows:

$$W_d = \omega C V_o^2 \tan(\delta) \quad (6)$$

$$C = [(\varepsilon r/18)\times\text{In}(D/d)]\times 10^{-9}\ (\text{F.m}^{-1}) \quad (7)$$

Where:

d = Inner conductor diameter (mm)
V_o = The rated voltage of the cable
W_d = Dielectric loss per length unit (W.m^{-1})
tan (δ) = Insulation loss factor
ω = The propagation angular frequency

RESULTS AND DISCUSSION

Coaxial cable line modeling: The coaxial transmission line with many different dielectrics is tested by MATLAB to illustrate the influence of different dielectric on the transmission quality of the coaxial cable. Using theoretical Eq. 1-10, the MATLAB code can measure the electric parameters affecting the performance of the transmission lines which mostly defined by the effect of the dielectric mediums (polyimide, polyethylene and Teflon) whose relative permeability constants are illustrated in Table 1 and finally display the electric parameters in Table 2-5. Every dielectric has different properties which mean different attenuation constant. The assumed physical specifications of the cable are:

Table 1: Relative permittivity of tested dielectrics

Dielectric medium	εr
Polyimide	3.4
Polyethylene	2.25
Teflon	2.1

Table 2: Results of air dielectric medium

Coaxial parameters	Air (εr = 1)
Conductance (S/m)	5.3078×10^{-16}
Capacitance (F/m)	4.6931×10^{-11}
Inductance (H/m)	2.3675×10^{-7}
Resistance (ohm/m)	9.3354
Gamma	0.0657+125.664i
Alpha α (Np/m)	0.065718
Beta β (rad /m)	25.6637
Char imp Z (Ω)	71.026-0.03714i

Table 3: Result of polyimide dielectric medium

Coaxial parameters	Polyimide (εr = 3.4)
Conductance (S/m)	5.3078×10^{-16}
Capacitance (F/m)	1.5957×10^{-10}
Inductance (H/m)	2.3675×10^{-7}
Resistance (Ω/m)	9.3354
Gamma	0.1212+231.71i
Alpha α (Np/m)	0.12118
Beta β (rad /m)	231.7125
Char imp Z (Ω)	38.52-0.0201i

Table 4: Result of polyethylene dielectric medium

Coaxial Parameters	Polyethylene (εr = 2.25)
Conductance (S/m)	5.3078×10^{-16}
Capacitance (F/m)	1.0559×10^{-10}
Inductance (H/m)	2.3675×10^{-7}
Resistance (Ω/m)	9.3354
Gamma	0.0986+188.495i
Alpha α (Np/m)	0.098577
Beta β (rad /m)	188.4956
Char imp Z (Ω)	47.351-0.02476i

Table 5: Result of Teflon dielectric medium

Coaxial Parameters	Teflon (εr = 2.1)
Conductance (S/m)	5.3078×10^{-16}
Capacitance (F/m)	9.8555×10^{-11}
Inductance (H/m)	2.3675×10^{-7}
Resistance (Ω/m)	9.3354
Gamma	0.09523+182.1i
Alpha α (Np/m)	0.09523
Beta β (rad /m)	182.1
Char imp Z (Ω)	49.0127-0.02563i

- 6 MHz propagation wave
- The inner conductor diameter (d = 0.45)
- Inside diameter of shield (D = 1.47)
- Conductor conductivity = 5.8×10^{7}

The propagation constant (γ) can be calculated equation:

$$\gamma=\sqrt{\frac{(R+jwL)}{(G+jwC)}} \tag{8}$$

Using the Eq. 1-8 the assumed physical constant values, the MATLAB cod has been assembled.

MATLAB code:

- m = pi*4e-7
- eo=1e-9 /(36pi)
- a = 0.45; % the inner cond.radius
- b = 1.47; % the outer shield radius
- er = 2.1; % relative permittivity
- sd = 1e-16; % dielectric conductivity
- sc = 5.8e7; % conductor conductivity
- ur = 1; % conductor permeability
- f = 6e9 % input frequency

Percent calulations:

- Rs = sqrt(pi*f*ur*m/sec)
- L = m*log(b/a)/(2*pi)
- C = 2pi*er*eo/log(b/a)
- R = (1000*(a^{-1}+b^{-1}))*R_s)/(2pi)
- G = 2pi*sd/log(b/a)
- O = 2*pi*f; % Omega
- RL = R+i*O*L
- GC = G + i*O*C
- G = sqrt(RL*GC); % Gamma
- Zo = sqrt(RL/GC); % Char Imp
- A = real(G); % Alpha
- B = imag(G); % Beta

Char Imp: This value is directly determined by homogeneous dielectric relative permittivity. Typically, it can be computed using electrical modeling of the coaxial cable. In this study, MATLAB Simulation illustrates the pattern of char Imp with respect to the signal frequency band traveling in the line (Shaeffer and Siegel, 1982). The MATLAB code to demonstrate the value of the char imp with the respect of frequency as follows:

MATLAB code:

- v = 3e8
- Er = 3.4
- u = v/sqrt (Er)
- a = 4.30

Percent calulations:

- f = (u/(2*.0254*a))
- flo = 1.7e9/sqrt (Er)
- fhi = 2.6e9/sqrt (Er)
- N = 1e2
- df = (fhi-flo)/N
- fo = flo: df: fhi
- K= sqrt (1-((f./fo).^2)
- Z =(120*pi/sqrt(er))./K
- fr = f./1e9
- plot (fr,Z)
- ylabel ('impedance (Ω)')
- xlabel ('frequency(GHz)')

As illustrated in Fig. 4, char Imp has indirect correlation with the frequency. It decreases with the increasing of frequency. Thus, the impedance for frequency bandwidth 0.9-1.8 GHz is high but frequency increases more than 2 GHz such as in the satellite frequency band, the impedance is ranging from 50-100 Ω. As depicted in Fig. 4, polyamide offers the lowest char imp. However, PE is wider used as the dielectric medium in coaxial cable industry due to the bending flexibility and other physical properties that polyimide cannot offer, besides it is cheaper as well.

Generally, this impedance defines and limit the amount of transferred power and attenuation along the transmission line. Also, it determines the percentage of the traveling, standing and reflected waves. Thus, the char Imp directly affects the propagation and equality of the signal transmission. The most important consideration of transmission and propagation that char Imp value should be equal at both the transmitting and receiving terminals of the transmission line to reduce the propagation losses.

Attenuation: Term attenuation defines the losses in the coaxial cable measured in decibels per meter (dB/m) to represent the losses on a logarithmic scale. The typical coaxial cable used for satellite application contains an inner copper conductor with 1 mm radius and an outer shield copper conductor with radius b. Practically, outer shield thickness must be typically narrower than the skin depth to minimize the influence of attenuation. The ratio of the outer shield to the inner diameter (b/a) is typically 1.5-10.

To depict the pattern of the attenuation and its with respect to the char imp for different permittivity constant

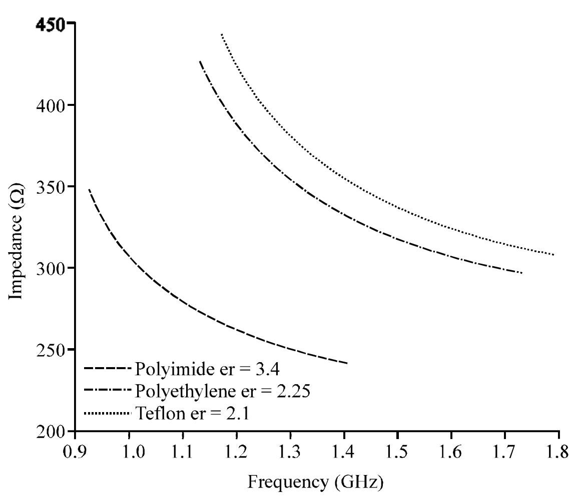

Fig. 4: Char Imp. with frequency

(Teflon, polyimide and polyethylene) dielectrics, considering the frequency fixed at 1 GHz, the MATLAB code below demonstrates the attenuation (dB/m) behavior with respect to the coaxial cable line char Imp.

MATLAB code:

- m = pi*4e-7
- e = 8.854e-12
- a = 1; % inner cond.radius
- Er = 3.4
- sd = 2e-4
- sc = 5.8e7
- f=1e9

Percent calulations:

- b = 1.5:.1:10
- G = 2pi*sd./log(b.*a^{-1})
- C = 2*pi*Er*e./log(b.* a^{-1})
- L = m*log(b./a)/(2pi)
- Ro = sqrt(pi*f*m/sc)
- R=(1e3*((.a^{-1})+(b^{-1}))*Ro)/(2pi)
- RL = R+i*2pi*f*L
- GC = G+i*2pi*f *C
- G= sqrt(RL.*GC)
- Z = abs(sqrt(RL./GC))
- A = real (G)
- Loss = exp(2*A*1)
- Loss_db = 10*log10(loss)
- Plot(Z,loss_db, 'r')
- xlabel('Characteristic Impedance (Ω)')
- ylabel('attenuation (db/m)')

Assuming the lossless line to calculate char imp. In Fig. 5 is illustrating the attenuation and its pattern due to the variation of the char Imp. that is changing due to the

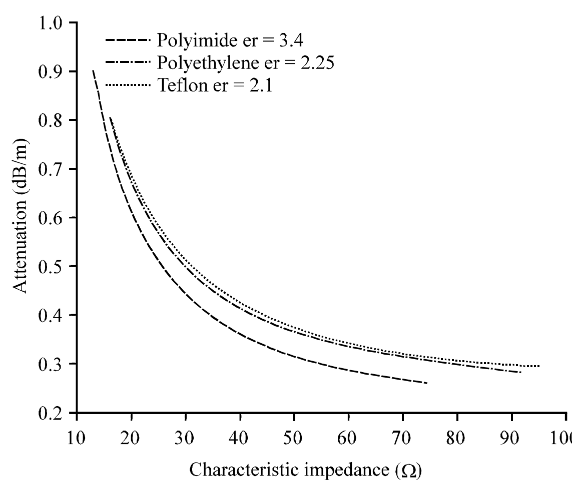

Fig. 5: Attenuation and char Imp.

frequency change of an electromagnetic wave moving through the mediums polyethylene, Teflon and polyamide. Also, Fig. 5 illustrates that polyamide offers the least attenuation in comparison with other examined dielectrics, hence, better performance at high-frequency bandwidths (Shlepnev *et al.*, 2010; Hashmi *et al.*, 2011).

CONCLUSION

In this study, an assessment is represented to evaluate the char imp and attenuation and their effects on the coaxial cable's performance using three different dielectrics mediums (polyamide, Teflon and polyethylene). The analysis has established the dielectric material effect on the parameters of the electrical model of the transmission line. The research is represented by MATLAB Software to depict the pattern of losses in the coaxial cable and to what extent the traveling signal gets affected by the dielectric mediums at a given frequency. According to the outcome of this research, polyimide has proven to be more efficient as a dielectric medium than polyethylene and Teflon, since, the signal suffers less attention and impedance. However, more factors lead PE to be the common used dielectric such as it is cheaper to be made and physically flexible enough to be bent. Furthermore, PE has low relative permittivity thus it can be used in higher frequency transmission.

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