

# ESD Induced EM Field Coupling to Braided and Non-braided Shielded Cables

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**Abstract** A Transmission Line coupling model is developed for determining the transient currents and voltages induced within braided and non-braided shielded cables by an impinging transient pulse generated by an Electrostatic Discharge (ESD) event. The Transmission Line theory is applied to establish the differential equations describing the behaviour of the cables in the presence of a uniform plane travelling wave. At first, induced sheath currents are calculated taking into account coupling in shielded cables. Then internal voltages and currents are computed via the surface transfer impedance of cable shields for single layer outer conductors. The penetrating field from an ESD event may induce unwanted transient voltage in the centre conductor of the cable. The calculation of the induced voltage in the centre conductor of the coaxial cable requires the details of the ESD waveform, the induced sheath current and the surface transfer impedance. The modelling of the shielded cable exposed to the free space-radiating field due to IEC 61000-4-2 ESD current waveform is carried out to compute the surface transfer impedance, sheath current, induced voltage and current in the centre conductor.

**Keywords** Electrostatic Discharge (ESD), Electromagnetic (EM), IEC Standard, Shielded Cable, Transmission Line Theory

## 1. Introduction

In order to ensure reliable operation in a world where electrical devices are everywhere, the circuits of sensitive devices must be shielded against outside electromagnetic interference (EMI). Radio frequency interference, either radiated or conducted can seriously disrupt the proper operation of the equipments[1]. The most common way to reduce a device's sensitivity to external EMI is to shield it with a conducting material which is electrically grounded. Equipments may be shielded by manufacturers but external cables that connect these devices should also be shielded to reduce their sensitivity to interference. The primary way to combat EMI in cables is through the use of full shielding. The shield surrounds the inner signal or power carrying conductors. The shield can act in two ways. First, it can reflect the energy. Second, it can pick up the noise and conduct it to ground. In either case, some energy still passes through the shield and may affect the equipment.

The aim of the present paper is to describe a method of calculating the induced transients due to ESD in an aerial shielded cable. A coupling model based on Transmission Line Theory is developed for determining the transient

currents and voltages induced within braided and non-braided shielded cables by an impinging transient pulse generated by an ESD event. At first, induced sheath currents are calculated taking into account coupling in shielded cables. Then internal voltages and currents are computed via surface transfer impedance of cable shields for single layer outer conductors. The calculation of the induced voltage in the centre conductor of the coaxial cable requires details of the ESD waveform. The modeling of the shielded cable exposed to the free space-radiating field due to IEC 61000-4-2 ESD current waveform is carried out to compute the surface transfer impedance, sheath current, induced voltage and current in the centre conductor.

The computer program provides parametric data by which the relative importance of different external conditions and cable shield constructions can be evaluated. It has been shown that the Transmission Line theory[2-6] provides a suitable approximation to the problem and leads to differential equations describing the behavior of cables in presence of an electromagnetic excitation. In many practical cases of interconnecting cable systems the entire problem of field coupling is difficult to interpret due to the immense variety of possible cable configurations. So it is necessary to define a simplified cable model, which corresponds to the most practical case of cable configuration. Such a consideration implies that a worst-case philosophy must be adopted in defining a model, which is most likely to collect the maximum induced energy. In this study we have taken

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coaxial cable RG 58C/U for carrying out analysis on the shielded cable.

## 2. Model of Aerial Cable

The Transmission Line theory is applied to establish various differential equations describing the behaviour of the cable in the presence of a uniform plane travelling wave. A schematic diagram of the model considered for determining the induced transient voltage response within a shielded cable is shown in Figure 1.

The cable of length  $L$  is considered parallel to the ground surface and it is placed at a height  $h$  above the ground. Both the ends of the cable are terminated by arbitrary impedances  $Z_1$  and  $Z_2$ , which represent the input and output impedances of the terminal equipments. The cable sheath terminated to the ground at both ends through impedances  $Z_A$  and  $Z_B$ , which represent the equivalent grounding impedances at the cable entry points. The soil is characterized by its permittivity  $\epsilon_s$  and conductivity  $\mu_s$ . The ESD generated wave

is assumed to be a travelling plane waves with an incident angle  $\theta_i$ , and its electric field component is parallel to the plane of incidence.

For a single braided wire shield, the transfer impedance depends on frequency, so the whole computation is done in Frequency domain. Then the Transmission Line theory is used to calculate the sheath current. This sheath current is multiplied with the transfer impedance  $Z_t$  of the coaxial cable to get the induced voltage and current in the centre conductor.

## 3. ESD Pulse in Free Space

In the present model the ESD pulse is assumed to be a travelling plane wave. Spine interpolation is used for computing the current values from the standard IEC 61000-4-2 ESD waveform[7] as shown in Figure 2 which has a 1 ns rise time and peak amplitude of 37.5A at 8 kV. The standard IEC 61000-4-2 ESD waveform for contact discharge holds good for air discharges at 2kV and 8kV.

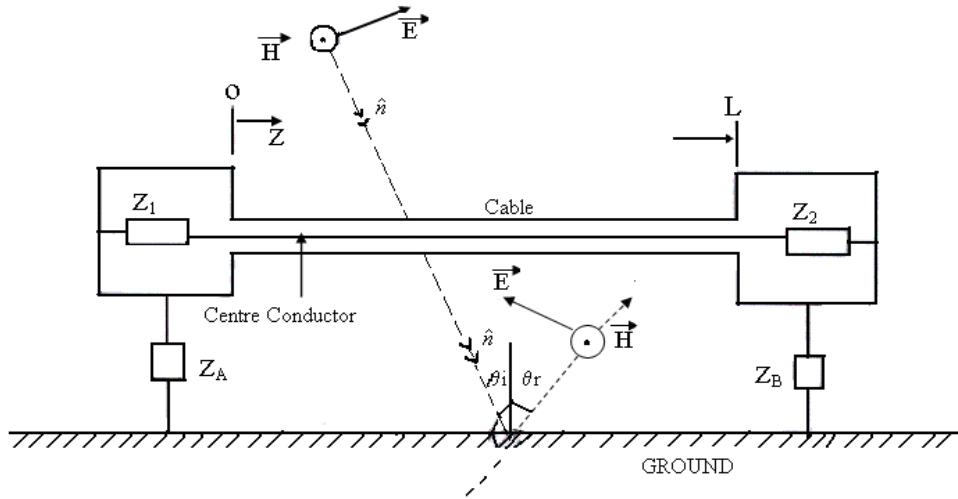


Figure 1. Model of the cable

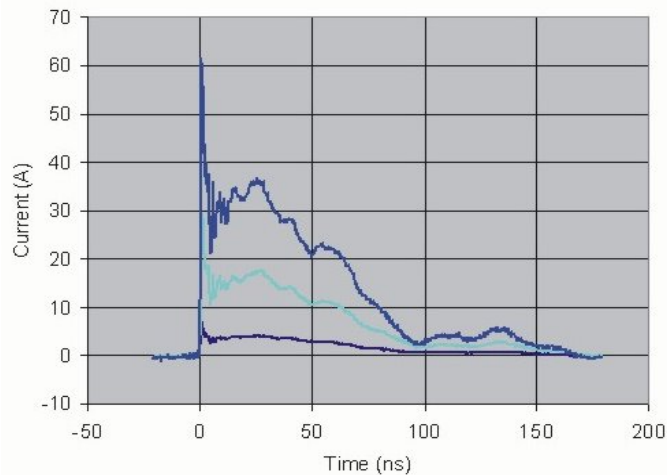
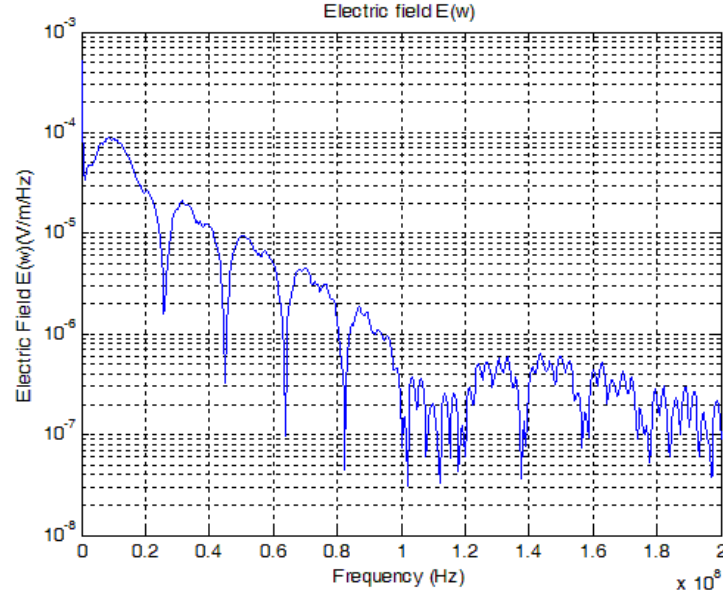


Figure 2. IEC 61000-4-2 standard ESD waveform



**Figure 3.** Frequency Spectrum of E-field  $E(\omega)$

The current elements have been modelled as Hertzian dipoles[8, 9]. The field components at any point  $P(r, \theta, \phi)$  of the dipoles expressed in terms of spherical coordinates  $r$ ,  $\theta$ , and  $\phi$  are

$$E_r(t) = \frac{L \cos \theta}{2\pi} \left( \eta_0 \frac{i(t)}{r^2} + \frac{\int i(t) dt}{\epsilon_0 r^3} \right) \quad (1)$$

$$E_\theta(t) = \frac{L \sin \theta}{4\pi} \left( \frac{\mu_0}{r} \frac{d}{dt} i(t) + \eta_0 \frac{i(t)}{r^2} + \frac{\int i(t) dt}{\epsilon_0 r^3} \right) \quad (2)$$

$$H_\phi(t) = \frac{L \sin \theta}{4\pi} \left( \frac{1}{rc} \frac{d}{dt} i(t) + \frac{i(t)}{r^2} \right) \quad (3)$$

where  $\mu_0$  is the permeability of free space,  $\epsilon_0$  is permittivity of free space,  $c$  is the velocity of light in free space,  $\eta_0$  is the intrinsic impedance of free space,  $L$  is the length of the current element (object under test), and  $r$  is the distance between the centre of current element  $i(t)$  and the point under consideration.

The field intensities at any point on the x-y plane due to transient current flow in the object under test can be obtained from equations (1) to (3) by substituting  $\theta = \pi/2$  with  $L = 1\text{m}$ [10]. The frequency spectrum  $E(\omega)$  given in Figure 3 is obtained by taking the Fourier Transform of the E-field.

#### 4. ESD Coupling in Shielded Cables

At the location of the shielded cable above the ground surface, the total ESD field is the sum of the incident field ( $E_i$ ,  $H_i$ ) and the reflected field ( $E_r$ ,  $H_r$ ). To find out the total electric and magnetic field components at the cable height, the incident and reflected field components are calculated. The ESD wave is incident obliquely on the cable and ground surface at an angle  $\theta_i$  as shown in Figure 1.

The electric and magnetic field components in x, y and z directions are given by

$$E_x = E(\omega) \sin \theta_i \exp(-jk_0 z \sin \theta_i) \left\{ \exp(jk_0 x \cos \theta_i) - \exp(-jk_0 x \cos \theta_i) \right\} \quad (4)$$

$$E_z = E(\omega) \cos \theta_i \exp(-jk_0 z \sin \theta_i) \{ \exp(jk_0 x \cos \theta_i) + \exp(-jk_0 x \cos \theta_i) \} \quad (5)$$

$$H_y = \frac{E(\omega)}{\eta_0} \exp(-jk_0 z \sin \theta_i) \{ \exp(jk_0 x \cos \theta_i) - \exp(-jk_0 x \cos \theta_i) \} \quad (6)$$

The above field equations are used to calculate the sheath current using Transmission Line theory.

## 5. Calculation of Cable Sheath Current

In this analysis the Transmission Line model is followed to calculate the sheath current in the coaxial cable by ESD generated transient interaction. The differential equations for voltage and current along the transmission line in the presence of distributed excitation due to the ESD generated field can be written as

$$\frac{dV_s}{dz} + ZI_s = E_z(z) + j\omega\mu_0 \int_0^h H_y(x, z)dx \quad (7)$$

$$\frac{dI_s}{dz} + YV_s = -Y \int_0^h E_x(x, z)dx \quad (8)$$

where  $Z = R + j\omega L_1$  is the impedance per unit length;  $R$  is the resistance per unit length;  $L_1$  is the inductance per unit length;  $Y = G + j\omega C_1$  is the admittance per unit length;  $C_1$  is the conductance per unit length;  $G$  is the susceptance per unit length.

$E_z(z)$  = tangential component of electric field at the surface of the ground (i.e. at  $x = 0$ ) and in the absence of the cable

$E_x(x, z)$  = x-component of the electric field in absence of the cable

$H_y(x, z)$  = y-component of the magnetic field in the absence of the cable

Substituting  $E_z(z)$ ,  $E_x(x, z)$  and  $H_y(x, z)$ , (7) and (8) can be simplified as

$$\frac{dI_s}{dz} + YV_s = I_e \quad \text{and} \quad \frac{dV_s}{dz} + ZI_s = V_e \quad (9)$$

$$V_e = 2E(\omega) \exp(-jk_0 z \sin \theta_i) \left[ \cos \theta_i + \frac{1}{\cos \theta_i} \left\{ \cos(k_0 h \cos \theta_i) - 1 \right\} \right] \quad (10)$$

is the distributed voltage source and

$$I_e = j2Y \frac{E(\omega)}{k_0} \tan \theta_i \exp(-jk_0 z \sin \theta_i) \left\{ \cos(k_0 h \cos \theta_i) - 1 \right\} \quad (11)$$

is the distributed current source.

Knowing the voltage and current at a particular point in the cable the Green's function solution[11] is used for different source and load conditions. Then the total sheath current at any point along the cable is obtained by the use of superposition integrals. The sheath current in terms of Greens function  $I_G$  is given by

$$I_s = \int_0^L I_e(z') \cdot I_G^I(z, z') dz' + \int_0^L V_e(z') \cdot I_G^V(z, z') dz' \quad (12)$$

Let us consider a transmission line of length  $L$ , which has terminating impedance  $Z_1$  at  $z = 0$  and  $Z_2$  at  $z = L$  as shown in Figure 4. The line is excited by a constant current generator of unit amplitude at the point  $z = z'$ .

The solutions for Greens functions for point current source are (here  $z = z'$ )

$$I_{2G}^I = \frac{[1 + \rho_1 \exp(-2\gamma z')]}{2\{1 - \rho_1 \rho_2 \exp(-2\gamma L)\}} \left[ \exp\{-\gamma(z - z')\} - \rho_2 \exp\{\gamma(z + z' - 2L)\} \right]$$

and

$$I_{1G}^I = \frac{[1 + \rho_2 \exp\{2\gamma(z' - L)\}]}{2\{1 - \rho_1 \rho_2 \exp(-2\gamma L)\}} \left[ -\exp\{\gamma(z - z')\} + \rho_1 \exp\{-\gamma(z + z')\} \right]$$

The Solutions for Greens functions for point voltage source are

$$I_{2G}^V = \frac{1}{Z_0} \frac{[1 - \rho_1 \exp\{-2\gamma z'\}]}{2\{1 - \rho_1 \rho_2 \exp(-2\gamma L)\}} \left[ \exp\{-\gamma(z - z')\} - \rho_2 \exp\{\gamma(z + z' - 2L)\} \right]$$

and

$$I_{1G}^v = \frac{1}{Z_0} \frac{[\rho_2 \exp\{2\gamma(z' - L)\} - 1]}{2\{1 - \rho_1 \rho_2 \exp(-2\gamma L)\}} \left[ -\exp\{\gamma(z - z')\} + \rho_1 \exp\{-\gamma(z + z')\} \right]$$

$$\text{Where } \gamma = \sqrt{YZ}; \quad Z_0 = \sqrt{Z/Y}; \quad \rho_1 = \frac{Z_1 - Z_0}{Z_1 + Z_0}; \quad \rho_2 = \frac{Z_2 - Z_0}{Z_2 + Z_0}$$

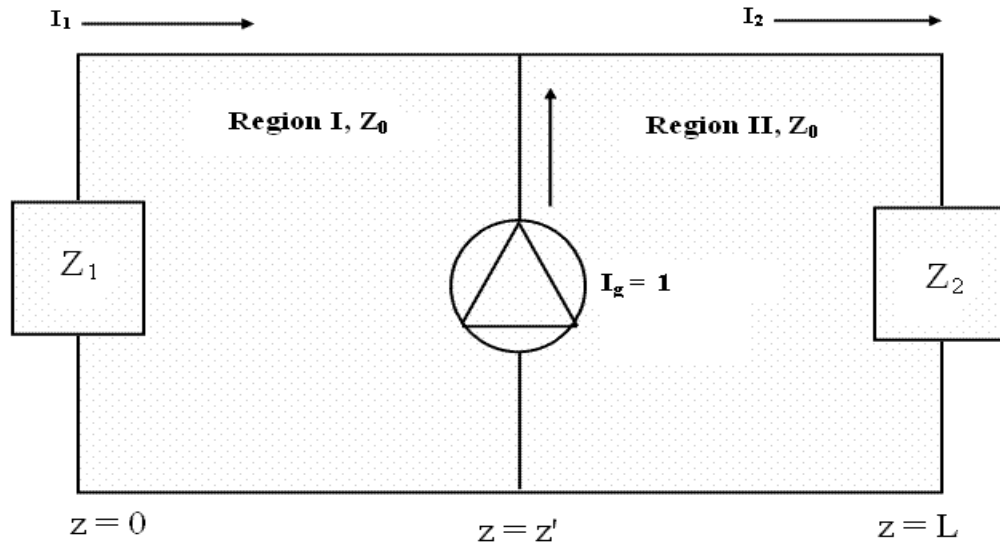


Figure 4. Point current source on an arbitrarily terminated line

## 6. Calculation of Surface Transfer Impedance

The characteristic of braided shield can be defined in terms of the inner conductor radius  $a$ , the number of carriers  $C$  (belts of wires) in the braid, the picks  $p$  (number of carriers crossing per unit length), the ends  $N$  (number of wires or strands in each carrier), the mean radius  $b$  of the shield, the wall thickness  $T$  of the shield and the wire or strand diameter  $d$ .

Resistance per unit length  $R_0$  of the shield and the mutual inductance per unit length  $M_{12}$  for a braided shield in terms of shield parameters for different weave angles  $\alpha$  is then calculated [12]. The surface transfer impedance for the braided shielded cable is calculated using

$$Z_t = R_0 \frac{\gamma d}{\sinh \gamma d} + j\omega M_{12} \quad (13)$$

where

$$M_{12} \approx \begin{cases} \frac{\pi\mu_0}{6C} (1-K)^{3/2} \frac{e^2}{E(e) - (1-e^2)K(e)} & \text{for } \alpha < 45^\circ \\ \frac{\pi\mu_0}{6C} (1-K)^{3/2} \frac{e^2}{\sqrt{(1-e^2)} \{K(e) - E(e)\}} & \text{for } \alpha > 45^\circ \end{cases} \quad (14)$$

$$e = \begin{cases} \sqrt{(1 - \tan^2 \alpha)} & \text{for } \alpha < 45^\circ \\ \sqrt{(1 - \cot^2 \alpha)} & \text{for } \alpha > 45^\circ \end{cases}$$

$$R_0 = \frac{4}{\pi d^2 N C \sigma \cos \alpha} \quad (15)$$

Where  $K$  is the optical coverage;  $K(e)$  and  $E(e)$  are complete elliptic integrals of the first and second kind and  $\sigma$  is the conductivity of the shield.

The surface transfer impedance for the non-braided shielded cable is calculated using

$$Z_t = R_{01} \frac{\gamma T}{\sinh \gamma T} \quad (16)$$

where  $\gamma = \left( \frac{1+j}{\delta} \right)$  and  $\delta = (\pi F \mu \sigma)^{-1/2}$  is the skin depth of the wire and the dc resistance per unit length  $R_{01}$  of the shielded cable is

$$R_{01} = \frac{1}{2\pi b \sigma T} \quad (17)$$

## 7. Calculation of Induced Voltage and Current in the Centre Conductor

Due to the current flowing in the sheath of the shielded cable, a voltage will be induced in the centre conductor. Surface transfer impedance gives a measurement for this shield leakage and is given by

$$Z_t = \frac{1}{I_s} \frac{dV}{dz} \quad (18)$$

where  $I_s$  is the total current flowing in the shield;  $dV/dz$  is the change in open circuit voltage generated by this current  $I_s$  along the transmission line formed by the shield and the conductor enclosed by the shield.

Thus to calculate the induced voltage in the centre conductor of a shielded cable, first the surface transfer impedance of the cable is calculated. This surface transfer impedance  $Z_t$  is then multiplied by the sheath current  $I_s$  to get the distributed voltage excitation in the centre conductor. The induced voltage at the load terminal is calculated by applying the Green's function to solve the Transmission Line equations.

The magnetic field diffusion into the inner conductor of the shield (transfer impedance penetration) may be regarded as a series voltage source distribution. Thus the differential equations for the voltage and current along the line are given by

$$\frac{dV_a}{dz} + ZI_a = Z_t I_b(z) \quad (19)$$

$$\frac{dI_a}{dz} + YV_a = 0 \quad (20)$$

The voltage  $V_a(z)$  and the current  $I_a(z)$  on the inner conductor of the shielded cable are determined by the superposition integrals as

$$V_a(z) = \int_0^L V_G(z, z') Z_t I_b(z') dz' \quad (21)$$

$$I_a(z) = \int_0^L I_G(z, z') Z_t I_b(z') dz' \quad (22)$$

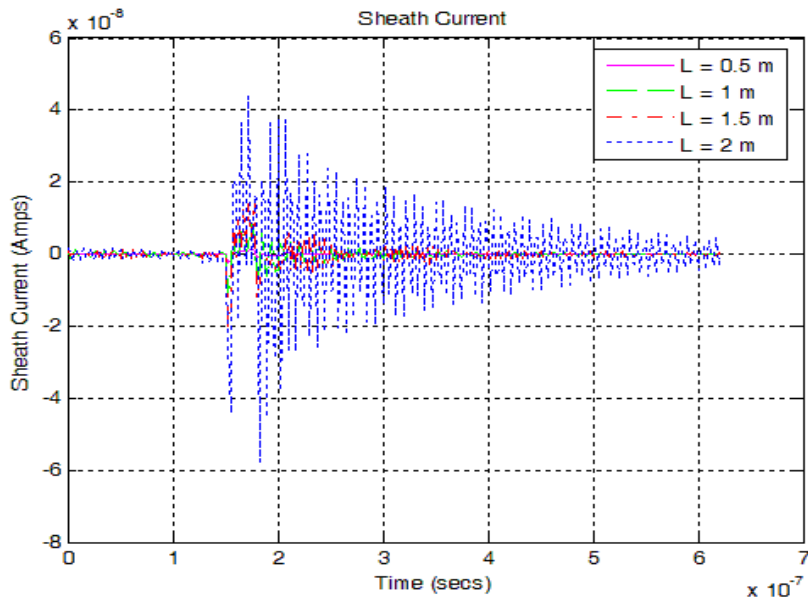
where  $V_G$  and  $I_G$  are Greens functions. The total current is given by  $I = I_a + I_b$  where  $I_a$  is the part of the total sheath current which returns inside the shield and  $I_b$  is the part of the total sheath current that returns outside the shield, since  $I_a \ll I_b$ , the current  $I_b$  can be considered as total current  $I$ .

## 8. Results and Discussion

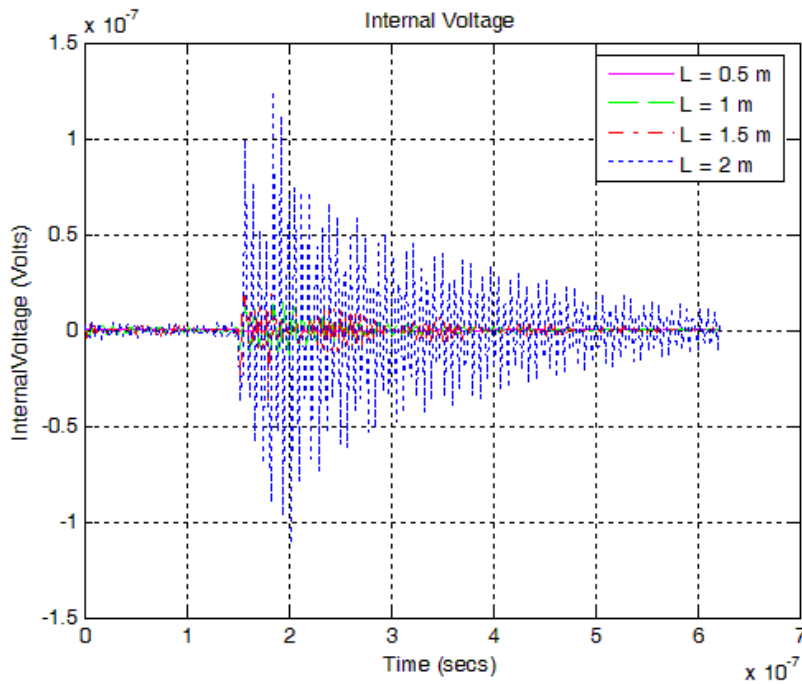
A computer program has been developed to calculate the induced voltage and current in the inner conductor of the shielded cable due to ESD. In all the calculations it has been considered that the shielded cable is terminated at both ends by its characteristic impedance ( $Z_0$ ), which implies  $Z_1 = Z_2 = Z_0$ . The ground impedances  $Z_A$  and  $Z_B$  are considered as  $1.0 \times 10^7$  ohms and 2 ohms respectively. The entire analysis has been carried for both braided and non-braided shielded cable.

Figure 5 shows the sheath current for both the braided and non-braided shielded cables. The values are calculated for

different lengths  $L = 0.5\text{ m}$ ,  $1\text{ m}$ ,  $1.5\text{ m}$  and  $2\text{ m}$  with the other parameters  $h = 0.1\text{ m}$  and  $\theta_i = 300$  kept constant. The peak amplitude of the cable sheath current correspondingly decreases with decrease in the length of the cable. This change in occurrence of the peak is due to smaller value of inductance in case of shorter cables as compared to long cables. The sheath current decreases from a maximum value of  $4.5 \times 10^{-8}\text{ A}$  for a cable length of  $2\text{ m}$ , to  $0.2 \times 10^{-8}\text{ A}$  for a cable length of  $0.5\text{ m}$ .



**Figure 5.** Cable Sheath Current of a braided and non-braided coaxial cable for different values of length of the cable



**Figure 6.** Induced Voltage in a braided coaxial cable for different length

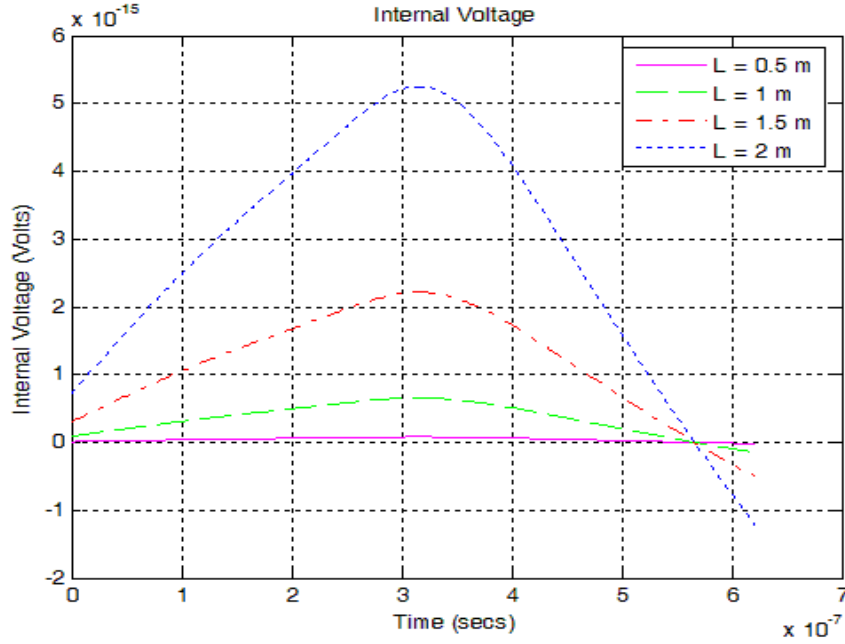


Figure 7. Induced Voltage in a non-braided coaxial cable for different length

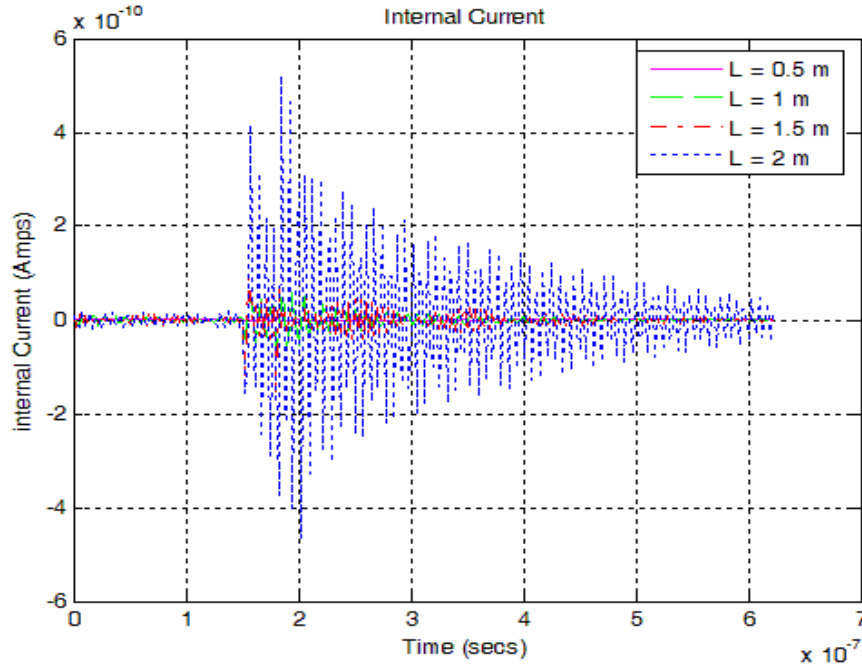


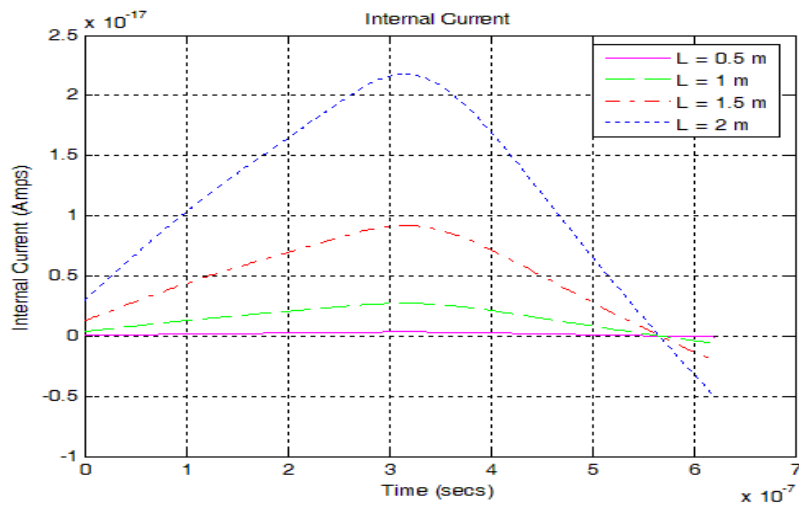
Figure 8. Induced Current in a braided coaxial cable for different length

The induced voltage depends upon the sheath current and surface transfer impedance of the cable. The induced voltage for the braided cable is given in Figure 6 and for non braided cable in Figure 7. The peak value of the induced voltage for a braided cable increases from a maximum value of  $0.125 \times 10^{-7}$  V for a cable length of 0.5 m to  $1.25 \times 10^{-7}$  V for a cable length of 2m. The induced voltage for a non braided cable being  $5.3 \times 10^{-15}$  V for a cable length of 2m is very small for a non-braided cable compared to a braided cable. The induced current in the centre conductor shown in Figure 8 and Figure 9 for a non braided cable being  $2.2 \times 10^{-17}$  A is also very small compared to  $5.25 \times 10^{-10}$  A for a braided cable of length 2m.

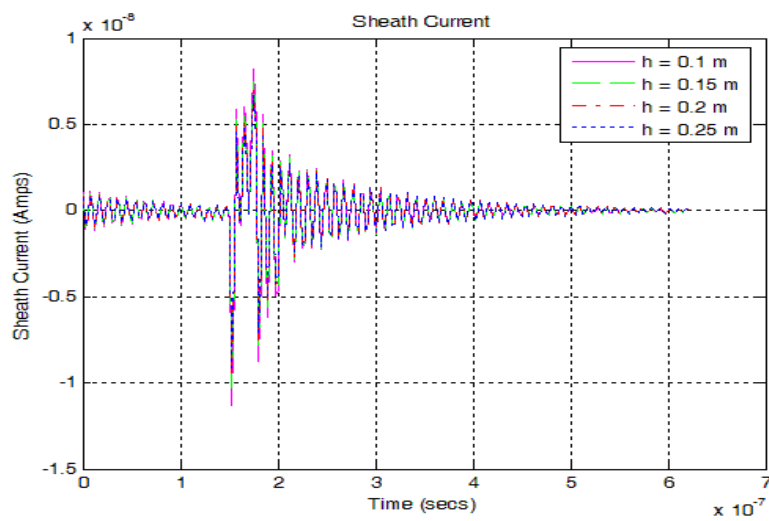
Figure 10 shows the sheath current for both the braided and non-braided shielded cables for different heights. The induced voltage for the braided cable is given in Figure 11 and for non braided cable in Figure 12. The peak value of the induced voltage for a braided cable decreases with an increase in height of the cable, from a maximum value of  $1.4 \times 10^{-8}$  V for a cable height of 0.1 m to  $1.1 \times 10^{-8}$  V for a cable height of 0.25m. The induced voltage for a non braided cable being  $6.6 \times 10^{-16}$  V for a cable height of 0.1m is very small for a non- braided cable compared to a braided cable. The induced current in the centre



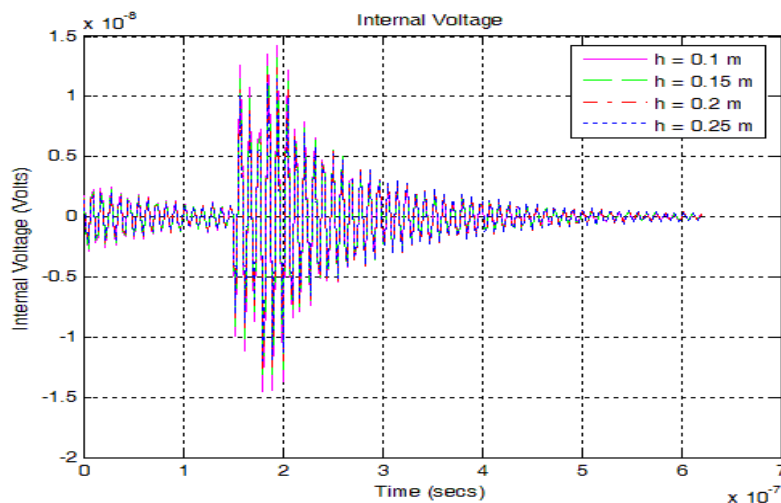
conductor shown in Figure 13 and Figure 14 for a non braided cable being  $2.75 \times 10^{-18}$  A is also very small compared to  $6.0 \times 10^{-11}$  A for a braided cable of height 0.1m.



**Figure 9.** Induced Current in a non-braided coaxial cable for different length



**Figure 10.** Cable Sheath Current of a braided and non-braided coaxial cable for different values of height of the cable



**Figure 11.** Induced Voltage in a braided coaxial cable for different height

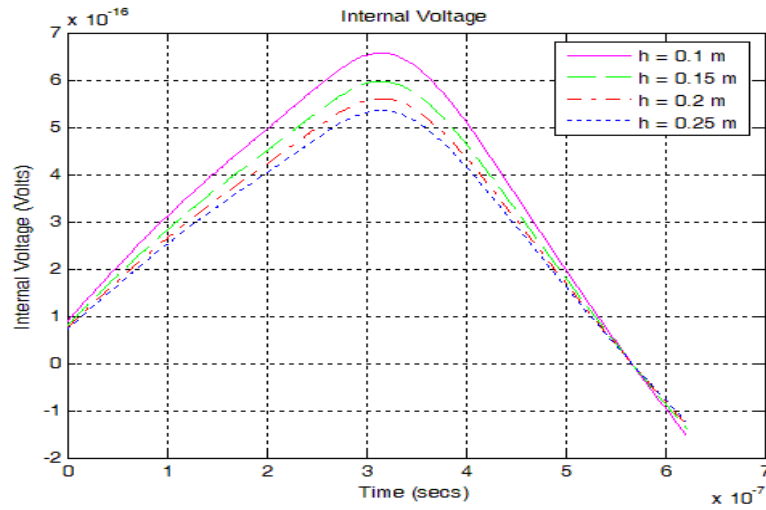


Figure 12. Induced Voltage in a non-braided coaxial cable for different height

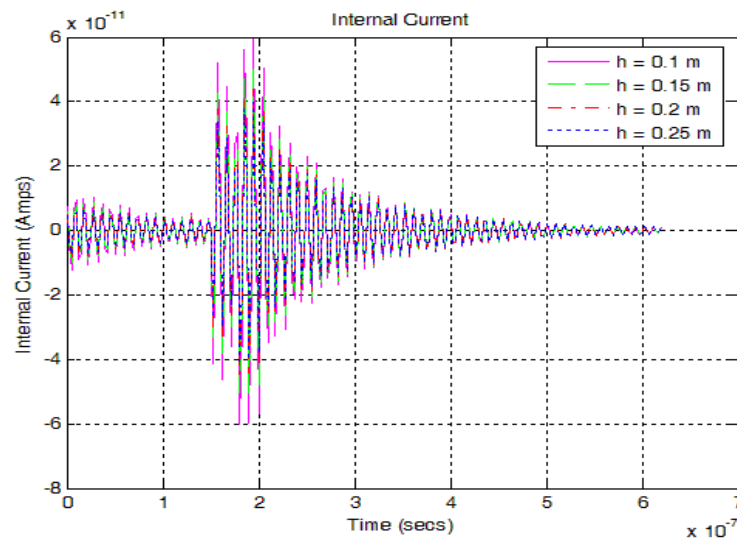


Figure 13. Induced Current in a braided coaxial cable for different height

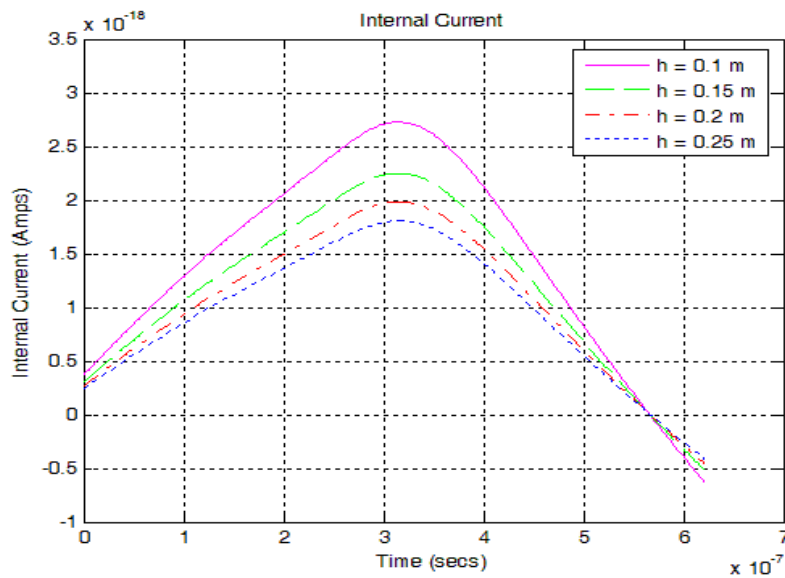
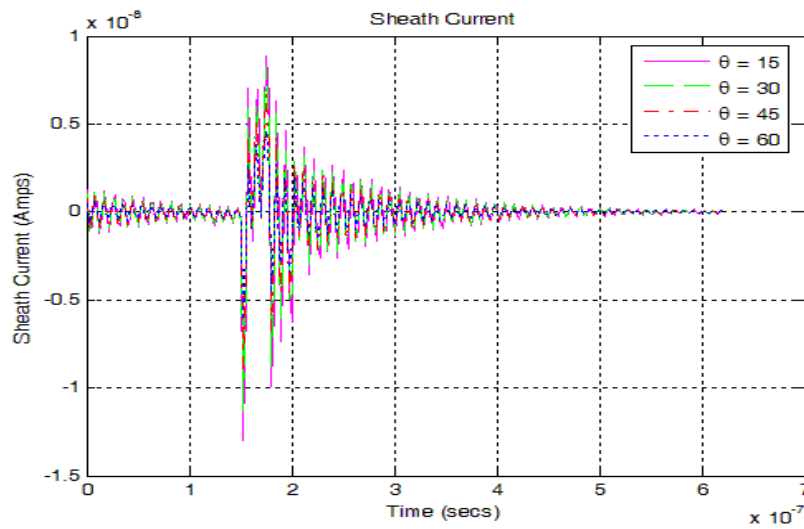
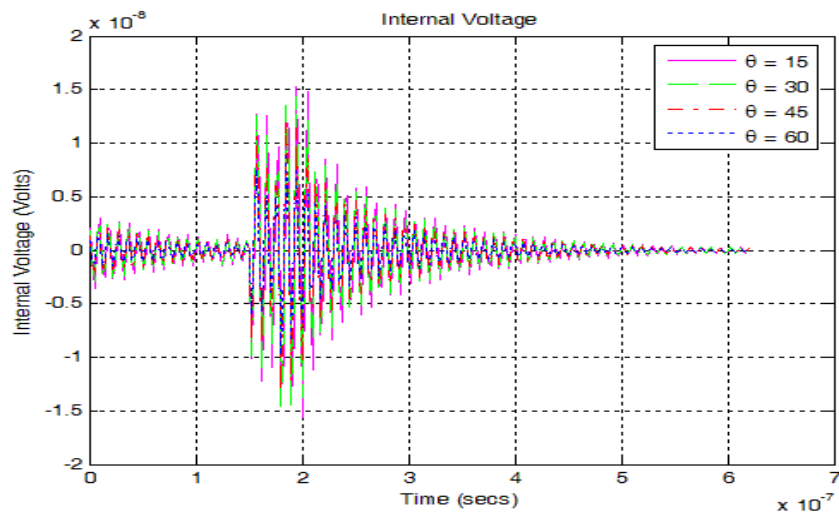


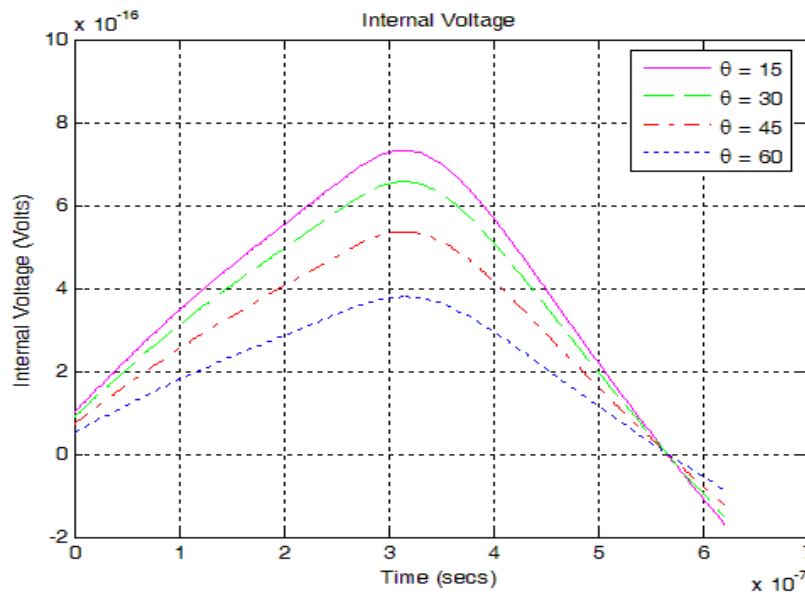
Figure 14. Induced Current in a non-braided coaxial cable for different height



**Figure 15.** Cable Sheath Current of a braided and non-braided coaxial cable for different values of angle of incidence



**Figure 16.** Induced Voltage in a braided coaxial cable for different  $\theta_i$

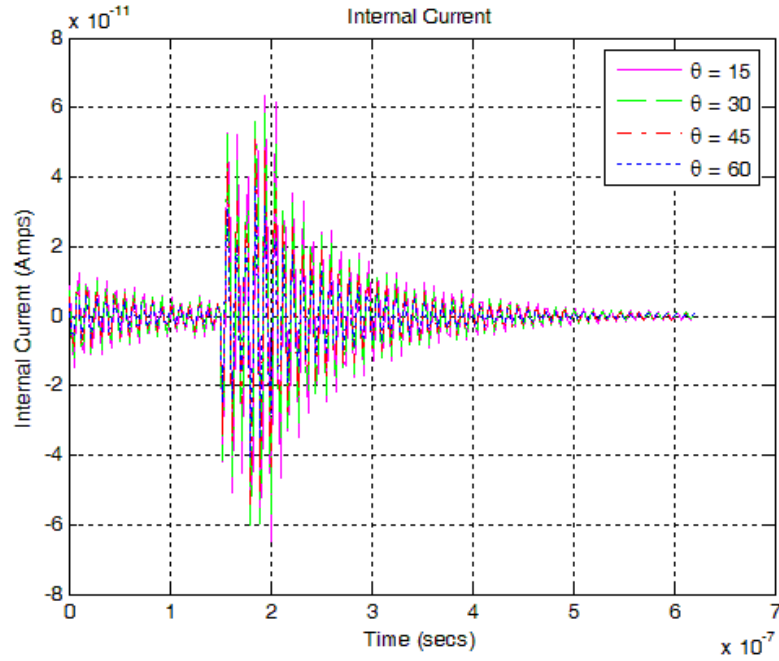


**Figure 17.** Induced Voltage in a non-braided coaxial cable for different  $\theta_i$

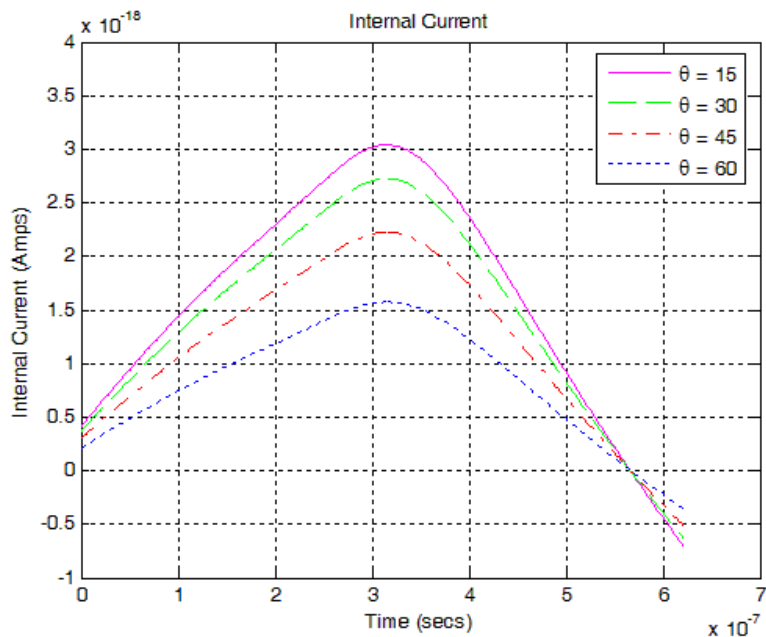
Lastly the sheath current shown in Figure 15 is calculated for different angles of incidence of the ESD generated wave  $\theta_i = 15^\circ, 30^\circ, 45^\circ$ , and  $60^\circ$  keeping other parameters such as  $L = 1\text{m}$  and  $H = 0.1\text{m}$  constant. The peak amplitude of the cable sheath current correspondingly decreases with an increase in the angle of incidence. The sheath current decreases from a maximum value of  $0.85 \times 10^{-8}\text{ A}$  for  $\theta_i = 15^\circ$  to  $0.45 \times 10^{-8}\text{ A}$  for  $\theta_i = 60^\circ$ .

The induced voltage for the braided cable is given in Figure 16 and for non braided cable in Figure 17. The peak value of the induced voltage for a braided cable decreases

with an increase in angle of incidence, from a maximum value of  $1.5 \times 10^{-8}\text{ V}$  for  $\theta_i = 15^\circ$  to  $0.9 \times 10^{-8}\text{ V}$  for  $\theta_i = 60^\circ$ . The induced voltage for a non-braided cable being  $7.5 \times 10^{-16}\text{ V}$  for  $\theta_i = 15^\circ$  is very small compared to a braided cable. The induced current in the centre conductor shown in Figure 18 and Figure 19 for a non braided cable being  $3 \times 10^{-18}\text{ A}$  is also very small compared to  $6.5 \times 10^{-11}\text{ A}$  for a braided cable with  $\theta_i = 15^\circ$ . The induced current decreases with an increase in the angle of incidence as the induced current is the function of  $\cos\theta_i$ .



**Figure 18.** Induced Current in a braided coaxial cable for different  $\theta_i$



**Figure 19.** Induced Current in a non-braided coaxial cable for different  $\theta_i$

## 9. Conclusions

In conclusion, the purpose of the shield is to conduct to ground any EMI it has picked up. The cable shielding and its termination must provide a low-impedance path to ground. Any disruptions in the path can raise the impedance and lower the shielding effectiveness. Shielding effectiveness is determined primarily by the conductive quality of the shielding material and the level of coverage the shield provides. Two materials commonly used as shields are braided copper and non-braided aluminum foil. Copper is a better conductor but the level of coverage is lacking due to the gaps inherent in the braided copper construction. The aluminum foil configuration provides more complete coverage but is not a good conductor. This is seen in the results of the induced voltage and current in the center conductor being larger for a braided cable when compared to a non-braided cable.

The entire analysis is carried out for the braided and non-braided shielded cable exposed to the free space-radiating field due to IEC 61000-4-2 ESD current waveform. The induced values due to ESD generated fields are very small in magnitude in the case of shielded cables. This analysis will be useful to develop appropriate mitigation techniques on the basis of the field coupling result obtained at the input of the sensitive systems that are connected to the shielded cable.

The same analysis can be used to calculate the induced voltage and current in the centre conductor of the shielded cable when it is exposed to any other generated field. Green's function method used to solve the transmission line equations is very efficient to solve such problems. The program written can be used for shielded cables with different cable parameters. In the analysis presented here, the effect of variation of the parameters such the cable length, height of the cable above the ground plane, and the angle of incidence of the ESD pulse has been discussed.

The peak amplitude of the cable sheath current correspondingly decreases with decrease in the length of the cable. This change in occurrence of the peak is due to smaller value of inductance in case of shorter cables as compared to long cables. The peak amplitude of the cable sheath current correspondingly decreases with increase in the height of the cable. The peak amplitude of the cable sheath current also correspondingly decreases with an increase in angle of incidence. The induced voltage for a non braided cable being  $5.3 \times 10^{-15}$  V for a cable length of 2m is very small compared to a braided cable. The induced voltage for a non braided cable being  $6.6 \times 10^{-16}$  V for a cable height of 0.1m is very small compared to a braided cable. The induced voltage for a non-braided cable being  $7.5 \times 10^{-16}$  V for  $\theta_i = 15^\circ$  is very small compared to a braided cable. Since the induced current is a

function of  $\cos\theta_i$ , the induced current decreases with an increase in  $\theta_i$ . In conclusion the induced voltage due to ESD is very small for a non braided cable compared to a braided cable.

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