Academic Science

International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017

Lightning Induced Electromagnetic Field Coupling to Braided Shielded Cables

Prof. A.M. Nagaraj,
Assosciate Professor, Department of Electrical & Electronics Engineering,
Dayananda Sagar College of Engineering
Dr. Puttamadappa. C,
Registrar, Dayananda Sagar University,
Dr. R. Prakash
Professor, Department of Electrical & Electronics Engineering, Don Bosco Institute of Technology

ABSTRACT: *A Transmission Line coupling model is developed for determining the transient currents and voltages induced within braided shielded cables by an impinging transient pulse generated by Lightning event. The Transmission Line theory is applied to establish the differential equations describing the behavior 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 Lightning 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 Lightning waveform, the induced sheath current and the surface transfer impedance. The modelling of the shielded cable exposed to Lightning current waveform is carried out to compute the surface transfer impedance, sheath current, induced voltage and current in the centre conductor.*

KEYWORDS: Lightning, Electromagnetic (EM), IEC Standard, Shielded Cable, Transmission Line Theory, Shielded Cable

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. 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 Lightning 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 shielded cables by an impinging transient pulse generated by Lightning 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 Lightning waveform. The modeling of the shielded cable exposed to Lightning 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 theoryprovides a suitable approximation to the problem and leads to differential equations describing the

International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017

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 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 Z1 and Z2, which represent the input and output impedances of the terminal equipments. The cable sheath terminated to the ground at both ends through impedances ZA and ZB, which represent the equivalent grounding impedances at the cable entry points. The soil is characterized by its permittivity εs and conductivity µs. The Lightning wave is assumed to be a travelling plane waves with an incident angle θi, 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 Zt of the coaxial cable to get the induced voltage and current in the centre conductor.

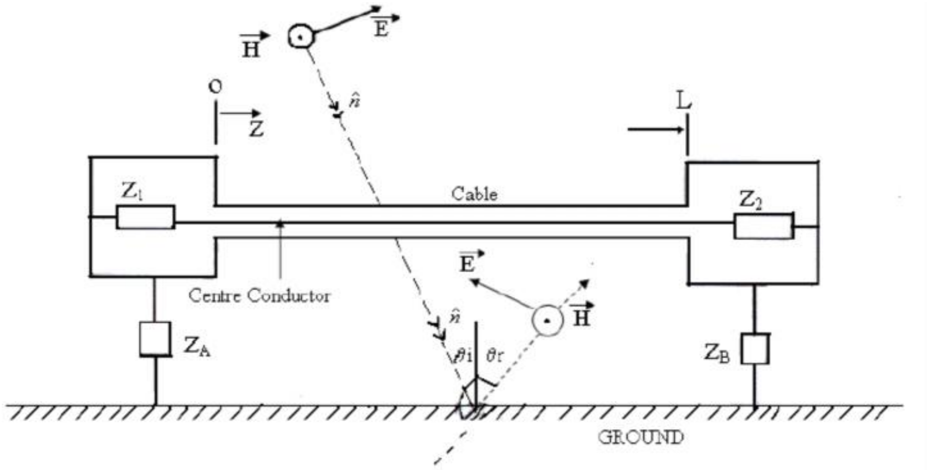


Figure 1

3. SIMULATION OF LIGHTNING WAVEFORM

3a. Current component 1 - First return stroke:

This waveform combines the severe parameters of both the negative and the positive first return strokes. It occurs most frequently to aircraft flying at lower altitudes. For analysis purposes and indirect effect considerations the double exponential waveform shown in Figure 1.1 shall be applied.

This waveform is defined mathematically by the double exponential expression as below:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$$

Damped sinusoidal form: $I = I_0(\sin(\omega)\, e^{-\alpha}\ )$

Constraints for first return stroke are given below:

I_0 = 218,810 A

α = 11,354 s^{-l}

β = 647,265 s^{-l}

t is time in second

The frequency content of first return stroke is given in Figure 2. F or direct effects testing purposes component 1 can be simulated by an oscillatory or unidirectional waveform like those presented in the Figure 2. The current must have an amplitude of 200kA (± 10%) with a rise time of up to 50µs (the time between 10% and 90% of peak amplitude). The action integral has to be 2 X $10^6 A^2s$ (± 20%), and the total time to 1 % of peak value shall not exceed 500µs.

The action integral, $\int i^2\ d$, is a critical factor in the extent of damage. It relates to the energy deposited or absorbed in a system. However, the actual energy deposited cannot be defined without knowledge of the resistance of the system. For example, the instantaneous power dissipated in a resistor is I^2R, and is expressed in Watts. For the total energy expended, the power must be integrated over time to get the total Watt-seconds (or Joules). Action integral can be applied to any resistance value to identify the total energy deposited.

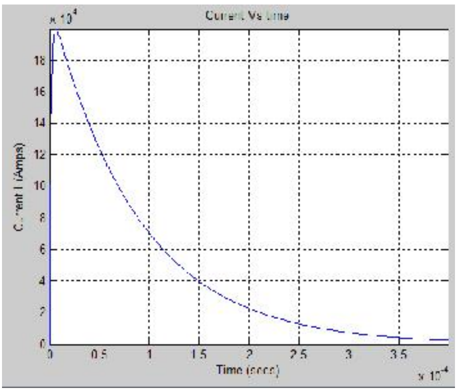


Figure 2

3b. Current component 2: Transition zone first return stroke

The amplitude and Waveform of the first return strokes, which might hit an aircraft, depend on the flight altitude. In general, lower amplitudes and action integrals can be expected at higher altitudes. For analysis purposes a double exponential shall be applied. This Waveform is applicable in the transition Zone 1 C and represents the estimated shape of the first return stroke (Component 1) at higher altitudes. This Waveform is defined mathematically by the following double exponential function:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$$

where:

I_0= 164,903 A

α = 16,065 s^{-l}

β = 858,888 s^{-l}

t is time (s)

For direct effects testing, component all can be simulated by an oscillatory or unidirectional waveform as shown in Figures 3. The current must have an amplitude of 150kA (± 10%) with a rise time of up to 37.5µs (the time between 10% and 90% peak amplitude). The action integral has to be 0.8 x 10^6 A^2s (± 20%), and the total time for the current to decay to 1 % of peak value shall not exceed 500µS.

International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017

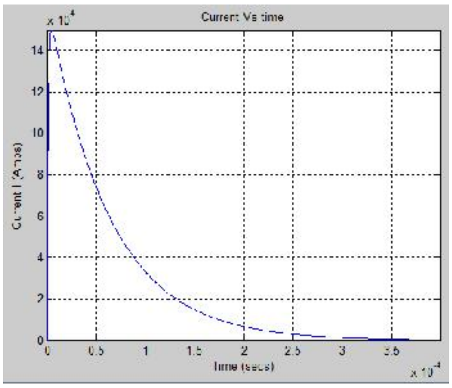


Figure 3

3c. Current component 2- intermediate current

This component represents mainly the intermediate currents following some of the negative initial return strokes and/or restrikes. For analysis purposes a double exponential current waveform could be used. This waveform is described mathematically by the following expression:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$$

where:

I_0= 11,300 A

α = 700 S^{-1}

β = 2,000 S^{-1}

t is time (s)

The average amplitude must be 2kA (± 20%) flowing for a duration of 5 milliseconds (± 10%) with a charge transfer of 10 coulombs (± 10%).

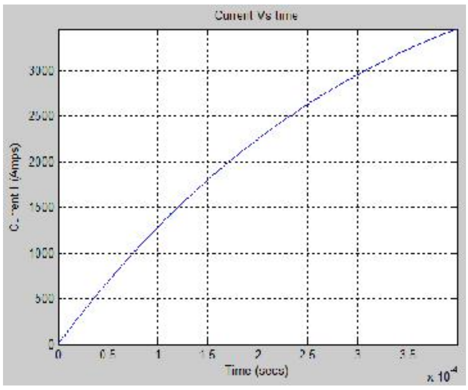


Figure 4

3d. Current component 3: Subsequent stroke current

Current Component 3 has two applications.

For direct effects assessments current Component 3 represents a subsequent stroke. The amplitude shall be 100kA (± 10%), the rise time shall not exceed 25μs (time between 10% and 90% of the amplitude). The action integral is 0.25 x $10^6 A^2 s$ (± 20%).

For indirect effects investigations and analysis purposes, the double exponential current waveform presented in Figure 5 should be used.

The waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t})$$

where:
1_0 = 109,405 A
α = 22,708 S^{-l}
β = 1,294,530 S^{-l}
t is time (s).

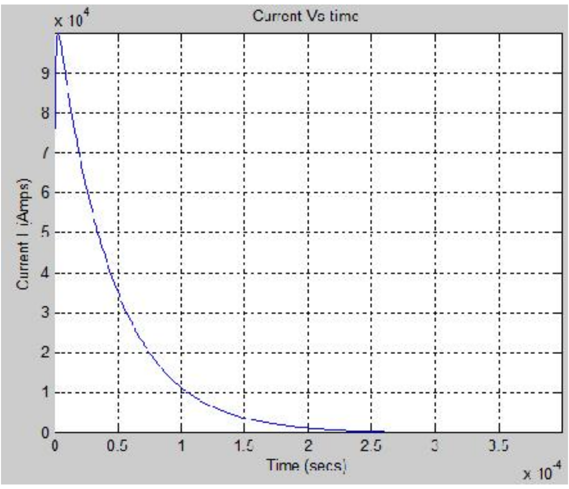


Figure 5

$$E0 = \frac{l}{4\pi}\frac{\mu 0}{r} I_(\left(\beta e^{-\beta\ 1} - \alpha e^{-\alpha\ 1}\right) + \frac{e\ \ 0}{r\ \ 2} I_(\left(e^{-\alpha\ 1} - e^{-\beta\ 1}\right)$$

$$E1 = \frac{l}{4\pi}\frac{\mu 0}{r1} I_(\left(\alpha e^{-\alpha\ 2} - \beta e^{-\beta\ 2}\right) + \frac{e\ \ 0}{r1^2} I_(\left(e^{-\alpha\ 2} - e^{-\beta\ 2}\right)$$

$$E = E0 + E1$$

4. CALCULATION OF CABLE SHEATH CURRENT

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

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

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

where Z = R + jωL1 is the impedance per unit length; R is the resistance per unit length; L1 is the inductance per unit length; Y = G + jωC1 is the admittance per unit length; C1 is the conductance per unit length; G is the susceptance per unit length. Ez(z) = tangential component of electric field at the surface of the ground (i.e. at x = 0) and in the absence of the cable Ex(x, z) = x-component of the electric field in absence of the cable Hy(x,z) = y-component of the magnetic field in the absence of the cable

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

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

is the distributed voltage source

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

is the distributed current source and

Knowing the voltage and current at a particular point in the cable the Green's function solutionis 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 IG is given by

$$I_S = \int_0^L I_e(z').I_G^I(z,z')dz' + \int_0^L V_e(z').I_G^V(z,z')dz'$$

Let us consider a transmission line of length L, which has terminating impedance Z1 at z=0 and Z2 at z=L. 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

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

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

Academic Science

International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017

5. 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

$$Z_t = \frac{1}{I_s}\frac{dV}{dz}$$

where Is is the total current flowing in the shield; *dV/dz* is the change in open circuit voltage generated by this current Is 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 Zt is then multiplied by the sheath current Is 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

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

$$\frac{dI_a}{dz} + YV_a = 0$$

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

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

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

where *VG* and *IG* are Greens functions. The total current is given by I=Ia+Ib where Ia is the part of the total sheath current which returns inside the shield and Ib is the part of the total sheath current that returns outside the shield, since Ia<<Ib, the current can be considered as total current *I*.

6. 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 Lightning strikes. In all the calculations it has been considered that the shielded cable is terminated at both ends by its characteristic impedance (Zo), which implies Z1 = Z2 = Zo. The ground impedances ZA and ZB are considered as 1.0×10^7 ohms and 2 ohms respectively. The entire analysis has been carried for braided shielded cable.

Figure 6to figure 10 with corresponding tables shows the sheath current, induced voltage and induced current in braided shielded cables. The values are calculated for different lengths , different cable height (h)from ground level and different angle of incidence θi. 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.

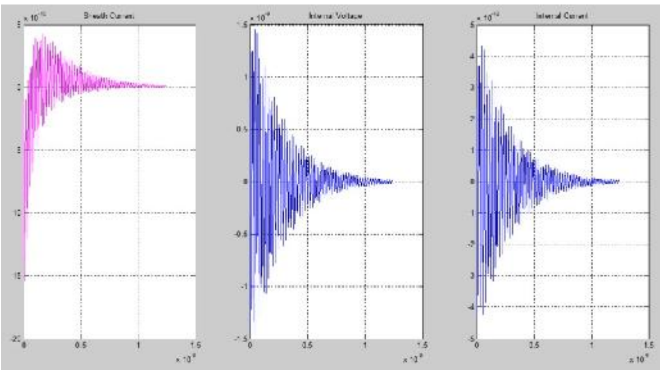


figure 6

Table No. 1

length of the cable in Meter	1
Cable height above the ground in Meter	0.5
Angle of incidence in Degrees	15

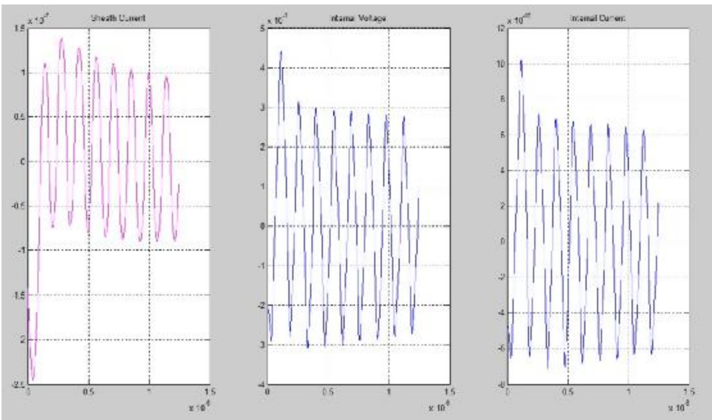


figure 7

Table No. 2

length of the cable in Meter	15
Cable height above the ground in Meter	2
Angle of incidence in Degrees	15

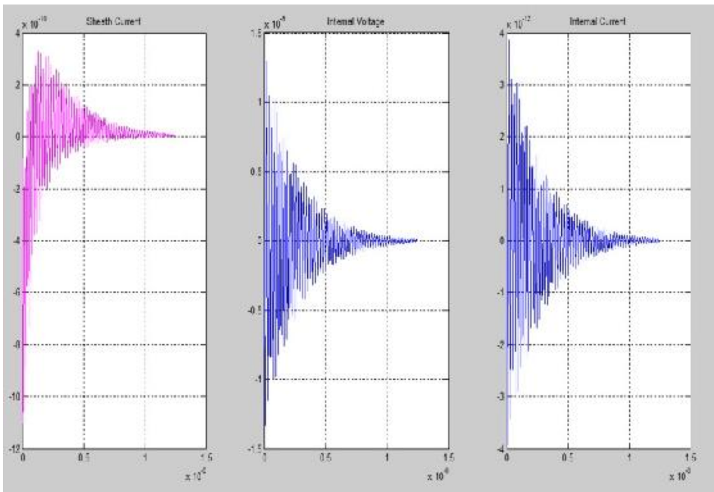
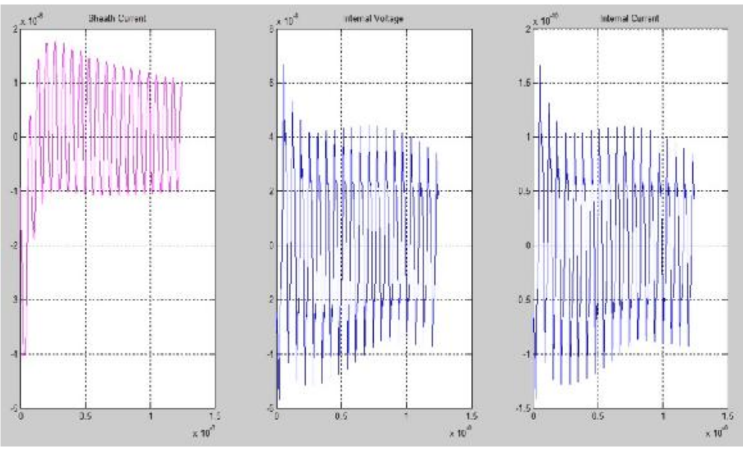


figure 8

Table No. 3

length of the cable in Meter	1
Cable height above the ground in Meter	0.5
Angle of incidence in Degrees	45

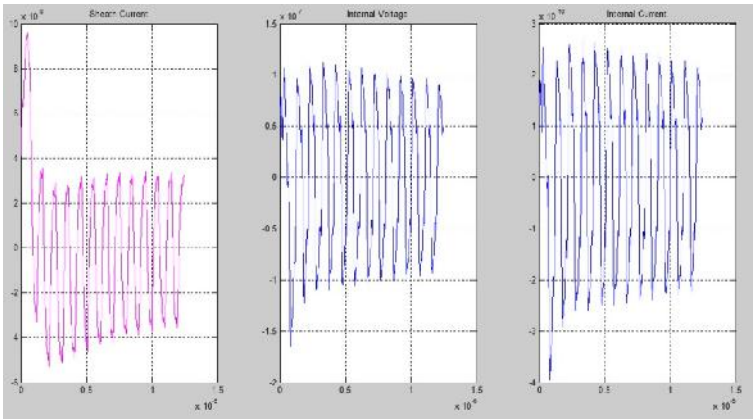
International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017



length of the cable in Meter	10
Cable height above the ground in Meter	1.5
Angle of incidence in Degrees	60

Table No. 4

figure 9



length of the cable in Meter	15
Cable height above the ground in Meter	2
Angle of incidence in Degrees	135

Table No. 5

figure 10

The induced voltage depends upon the sheath current and surface transfer impedance of the cable.

The peak value of the induced voltage for a braided cable decreases with an increase in height of the cable.

The sheath current is calculated for different angles of incidence. The peak amplitude of the cable sheath current correspondingly decreases with an increase in the angle of incidence.

The induced current decreases with an increase in the angle of incidence as the induced current is the function of $\cos\theta i$.

7. 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 shielded cable exposed to the free space-radiating field due to Lightning current waveform. The induced values due to Lightning 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 Lightning 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.

8. REFERENCES

[1] Rajashree Narendra, M.L.Sudheer, V. Jithesh, D.C. Pande, "Mathematical Analysis of ESD Generated EM Radiated Fields on Electronic Subsystem", 2101 Asia –Pacific International Symposium on Electromagnetic Compatibility, Beijing, China, pp. 449-452, April 12-16, 2010.

[2] Ricketts, JE Bridges, J Miletta, "EMP Radiation and Protective Techniques" A Wiley-Interscience Publication, 1976.

[3] E. F. Vance, "Coupling to Shielded Cables", Wiley Interscience Publication, John Wiley and Sons, Inc., New York, 1978.

[4] K. S. H. Lee, and Carl E. Baum, "Application of modal analysis to braided shield cables", IEEE Transactions on EMC, vol. EMC-17, pp. 159-169, Aug. 1975.

[5] M. Aguet, M. Ianovici and Chung-chi Lin, "Transient electromagnetic field coupling to long shielded cables", IEEE Transactions on EMC, vol. EMC-22, Issue 4, pp. 276-282, Nov. 1980.

[6] E. F. Vance, "Shielding effectiveness of braided wire shields", IEEE Transactions on EMC, vol. EMC-17, pp. 71-77, May. 1975.

[7] Robert Ashton, ON Semiconductor "Reliability of IEC 61000-4-2 testing on components', EE Times Design article, 8/10/2008.

[8] S.V.K. Shastry and V.K. Hariharan, "Computer Aided Analysis of ESD Effects In Dual Gate MOSFET VHF Amplifier", IEEE International Symposium on EMC, pp. 424-430, Aug 1990.

[9] P.F. Wilson, M.T. Ma and A.R. Ondrejka, "Fields Radiated By Electrostatic Discharges", IEEE International Symposium on EMC, pp 179-183, Aug 1988.

[10] Rajashree Narendra, M.L.Sudheer, V. Jithesh, D.C. Pande, "Coupling of Transient Electromagnetic Fields Radiated by ESD to Unshielded Cables", INCEMIC, Proceedings of International Conference on EMI/EMC, Bangalore, pp. 493-498, Nov 25-26, 2010.

[11] W. L. Weeks, Electromagnetic Theory for Engineering Applications. New York: Van Nostrand, 1949.

[12] K. F. Casey and E. F. Vance, "EMP coupling through cable shields", IEEE Transactions on EMC, vol. EMC-20, pp. 100-106, Feb. 1978.

[13] Hariharan V.K, S. V. K Shastry and V R Katti, " Coupling of transient electromagnetic field to unshielded cable," INCEMIC, 140-146, India, 1991