Circuit Models to Study the Radiated and Conducted Susceptibilities of Multiconductor Shielded Cables Connected to Non-linear Load

Mohamed Saïh¹*, Zahra Bouzidi², Youssef Rhazi³

1- Laboratory of Automatic, Energy Conversion and Microelectronics, Faculty of Sciences and Technology, University of Sultan Moulay Slimane, Beni-Mellal, Morocco.
Email: saïh.mohamed2@gmail.com (Corresponding author)
2- Laboratory of Electrical Systems and Telecommunications, Faculty of Sciences and Technology, CadiAyyad University, Marrakech, Morocco.
Email: zahra.bouzidi@edu.uca.ma
3- Laboratory of Automatic, Energy Conversion and Microelectronics, Faculty of Sciences and Technology, University of Sultan Moulay Slimane, Beni-Mellal, Morocco.
Email: rhazi.lastid@gmail.com

Received: February 2021 Revised: May 2021 Accepted: July 2021

ABSTRACT:
This paper presents an efficient Multiconductor Shielded Cable model, for conducted and radiated coupling, developed for circuit applications. In the case of radiated coupling, the interaction of the external incident field is modeled by equivalent voltage and current generators placed on shield only. The model works in frequency and time domain with linear and non-linear loads, respectively. Different applications are presented, for validation and physical interpretation. Finally, we will discuss the effect of the connection of the voltage limiter on the induced voltages.

KEYWORDS: Multiconductor Shielded Cable Cables, Branin’s Model, Radiated Susceptibility, Conducted Susceptibility, Incident Electromagnetic Field.

1. INTRODUCTION
When the surface of a conductor is subjected to an electric field, displacement of charge in the conductor takes place by cause of the induced current. Consequently, the data transferred through the cable can be degraded. The best way to combat electromagnetic interference (EMI) in cables is through the use of shielding. Cable shielding allows for the most part the elimination of perturbing signals that originated outside. Therefore, the prediction of the susceptibility of Multiconductor shielded cables will be important for a good optimization of system design.

There are several models available to analyze transmission lines, in both the frequency and time domains. The most popular technique consists in modeling the transmission by cascading a large number of Resistors, Inductors, Capacitors and Conductance (RLCG) [1]. It can also be employed in the case of Multiconductor Transmission Lines (MTLs) [2]. However, the method uses a large number of nodes that greatly increases the simulation time.

Recently, to analyze the susceptibility of transmission lines, circuit models have received much attention in the past 10 years, due to the ability to implement it into a general circuit simulator such as SPICE. It can also be used without considering the nature of the loads applied to the extremities [3], [4]. Saïh, Orlandi and Antonini presented some models to Analyze Radiated Susceptibility of lossless Shielded Cables for time and frequency domain [5], [6]. However, the radiated immunity cannot be handled with these models. After then, some circuit models were developed in order to study both the radiated and the conducted immunity of lossless shielded cables [7], [8], and lossy [9] shielded cables. These models can be used directly in the time and frequency domains. However, the authors did not consider the case when the shielded cables terminated with nonlinear loads, like diode, transistors, etc.

In this paper, an equivalent circuit model of Lossy Multiconductor shielded cables connected to non-linear loads is presented for the analysis of both the conducted and the radiated susceptibilities. The model is valid in both time and frequency domains. The effect of the
connection of the voltage limiter is studied with the proposed model. The method is validated by comparing results with other methods.

2. DESCRIPTION OF SHIELDED COAXIAL CABLE

2.1. Model of Shielded Coaxial Cable

The telegrapher's equations for a Multiconductor shielded cable in the presence of external electromagnetic radiation, as shown in Fig. 1, can be described by[5], [9]:

\[
\begin{align*}
\frac{\partial V}{\partial z} + j\omega L_i I + R I &= V_{\text{field}} \\
\frac{\partial I}{\partial z} + j\omega C_i V + G_{sh} V_{sh} &= I_{\text{field}}
\end{align*}
\]  

(1)

Outer system (Shield)

Inner system (wire)

Where \( C_{sh}, L_{sh}, G_{sh} \) and \( R_{sh} \) are the per-unit-length -pul- capacitance, inductance, conductance and resistance of the outer system (shield), respectively. \( C, L, G \) and \( R \) are the per-unit-length -pul- capacitance, inductance, conductance and resistance matrices of the inner system (wires), respectively. \( V_{sh}(z,t) \) and \( I_{sh}(z,t) \) are the voltage and current of the outer system, while \( V_{w}(z,t) \) and \( I_{w}(z,t) \) are the voltage and current vectors of the inner system.

\( Z_t \) represents the transfer impedance [7]. \( V_{\text{field}} \) and \( I_{\text{field}} \) are the equivalent distribution voltage and current sources.

![Fig. 1. Multiconductor shielded cable excited by an external plane.](image)

2.2. Conducted Immunity

In the case of the conducted mode, \( I_{\text{field}} \) and \( V_{\text{field}} \) of equation (1) are zero. The difficulty in the solution of (2) is related to the fact that, because the equations in Eqn (2) are coupled sets of partial differential equations. To decouple them, a similar transformation is needed [9], using a change of variables. New modal quantities are defined as

\[
\begin{align*}
V &= T_v V_m \\
I &= T_i I_m
\end{align*}
\]  

(3)

Where \( T_v \) and \( T_i \) are \( N \times N \) matrices, they have been chosen to simultaneously diagonalize \( C \) and \( L \). The system of equations (2) for the internal conductors becomes:

\[
\begin{align*}
\frac{\partial V_m}{\partial z} + j\omega L_m I_m + R_m I_m &= T_v^{-1} Z I_s \\
\frac{\partial I_m}{\partial z} + j\omega C_m V_m + G_m V_m &= 0
\end{align*}
\]  

(4)

Where

\[
\begin{align*}
L_m &= T_v^{-1} L T_v \\
C_m &= T_v^{-1} C T_v \\
R_m &= T_v^{-1} R T_v \\
G_m &= T_v^{-1} G T_v
\end{align*}
\]  

(5)

After calculating the \( L_m \) and \( C_m \) matrices, we determine the characteristic impedances and delay associated with each conductor.
\[ Z_{\text{in}} = \sqrt{R_{\text{in}} + jL_{\text{in}} \omega} \approx R_{\text{in}} + \frac{1}{jC_{\text{in}} \omega} \quad (6) \]

\[ T = \frac{\ell}{\sqrt{L_{\text{in}} C_{\text{in}}}} \quad i = j; i = 1 \ldots N \quad (7) \]

Where

\[
\begin{aligned}
R_{\text{in}} &= \sqrt{L_{\text{in}} / C_{\text{in}}} \\
C_{\text{in}} &= \frac{2L_{\text{in}}}{R_{\text{in}} R_{\text{in}}} 
\end{aligned}
\]

\[ \ell \text{ and } Z_{\text{in}} \text{ represent the length of the cable (m) and the characteristic impedance (} \Omega) \text{. } T_i \text{ is the delay of the line (s). After calculating the different parameters of the Multiconductor lines, we move on to the representation of the shielding/internal conductors assembly by an equivalent circuit model. To solve equations (1) and (2) we use the 'discretized line' model. For this purpose, the cable is discretized into cells, the length of each cell is } \lambda / 10, \text{ as shown in Fig. 1. The solution of equations (1) and (2) for each cell is}
\]

\[ V_j(z_0) - Z_{cs} I_j(z_0) = e^{-\gamma_j \Delta z} \begin{bmatrix} V_j(z_0 + \Delta z) \\ Z_{cs} I_j(z_0 + \Delta z) \end{bmatrix} \quad (9) \]

\[ V_j(z_0 + \Delta z) + Z_{cs} I_j(z_0 + \Delta z) = e^{-\gamma_j \Delta z} \begin{bmatrix} V_j(z_0) \\ Z_{cs} I_j(z_0) \end{bmatrix} \]

\[
\begin{aligned}
\begin{bmatrix} V_{\text{in}}(z_0) \\ -Z_{\text{om}} I_{\text{in}}(z_0) \end{bmatrix} &= e^{-\gamma \Delta z} \begin{bmatrix} V_{\text{in}}(z_0 + \Delta z) \\ -Z_{\text{om}} I_{\text{in}}(z_0 + \Delta z) \end{bmatrix} \\
\begin{bmatrix} V_{\text{om}}(z_0 + \Delta z) \\ +Z_{\text{om}} I_{\text{om}}(z_0 + \Delta z) \end{bmatrix} &= e^{\gamma \Delta z} \begin{bmatrix} V_{\text{om}}(z_0) \\ +Z_{\text{om}} I_{\text{om}}(z_0) \end{bmatrix} \\
\end{aligned}
\quad (10) \]

In equation (9), \( Z_{cs} \) is the characteristic impedance of the outer system.

\[ Z_{\text{in}} = \sqrt{R_{\text{in}} + j\omega L_{\text{in}}} \approx R_{\text{in}} + \frac{1}{j\omega C_{\text{in}}} \quad (11) \]

Where

\[
\begin{aligned}
R_{\text{s}} &= \sqrt{L_{\text{s}} / C_{\text{s}}} \\
C_{\text{s}} &= \frac{2L_{\text{s}}}{R_{\text{s}} R_{\text{s}}} 
\end{aligned}
\]

\[ \gamma_s \text{ and } \gamma_m \text{ are the propagation constants of the outer and the inner system, respectively, and defined as}
\]

\[ \gamma_s = \frac{R_s}{2R_s} + j\omega \sqrt{L_s C_s} \quad (13a) \]

\[ \gamma_m = \frac{R_m}{2R_m} + j\omega \sqrt{L_m C_m} \quad (13b) \]

2.3. Radiated Immunity

It is the same representation as the conducted mode with the addition of the 'forced' voltage and current generators \( V_{\text{f宇宙}} \) and \( I_{\text{f宇宙}} \), which represent the coupling between the shield and the incident field [10] (see Fig.2), which are given by the following equation. They are given by

\[ V_{\text{f宇宙}}(\Delta z) = \int_{z_0}^{z_0 + \Delta z} \varphi_{p11}(\Delta z + z_0 - \tau) V_{\text{f宇宙}}(\tau) d\tau \quad (14a) \]

\[ I_{\text{f宇宙}}(\Delta z) = \int_{z_0}^{z_0 + \Delta z} \varphi_{p21}(\Delta z + z_0 - \tau) I_{\text{f宇宙}}(\tau) d\tau \quad (14b) \]

Where \( \varphi_{p11}(\Delta z), \varphi_{p21}(\Delta z), \varphi_{p22}(\Delta z) \) and \( \varphi_{p12}(\Delta z) \) are the elements of the chain parameter matrix, denoted as

\[ \varphi_{p11}(\Delta z) = \varphi_{p22}(\Delta z) = \cosh(\gamma \Delta z) \]

\[ = e^{\gamma \Delta z} + e^{-\gamma \Delta z} \]

\[ \varphi_{p21}(\Delta z) = -\sinh(\gamma \Delta z)Z_{\text{om}} \quad (15a) \]

\[ = -Z_{\text{om}} e^{\gamma \Delta z} - e^{-\gamma \Delta z} \]

\[ \varphi_{p22}(\Delta z) = -\sinh(\gamma \Delta z)Z_{\text{om}}^{-1} \quad (15b) \]

\[ = -Z_{\text{om}} e^{\gamma \Delta z} - e^{-\gamma \Delta z} \]

\[ \varphi_{p12}(\Delta z) = -\sinh(\gamma \Delta z)Z_{\text{om}}^{-1} \quad (15c) \]

\[ = -Z_{\text{om}} e^{\gamma \Delta z} - e^{-\gamma \Delta z} \]
3. SIMULATION RESULTS AND VALIDATION

3.1. Conducted Susceptibility Analysis

A two-wire, shielded, flat cable over a ground plane is considered, as shown in Fig. 3. The length is $L=300\text{m}$. The current source in parallel to near side pigtail of the shield is $I = 1\text{A}$. The transfer resistance is $R=0$, the transfer inductance, different for each internal wire, is $L_{T1}=1.3\text{nH/m}$ and $L_{T2}=1.2\text{nH/m}$. The relative permittivity of the internal dielectric $\varepsilon_r$ is 1.77. The height above the ground plane is $h=1\text{cm}$. The wire radius $r_{w1}=r_{w2}=0.25\text{mm}$ and the distance from central axis of symmetry is $d_1=d_2=0.25\text{mm}$. The values of the terminal loads between the shield and the ground are given in Table I.

![Diagram of multiconductor shielded cable](image)

**Fig. 2.** Multiconductor shielded cable in the form of cells for “conducted and radiated coupling.”

| Table 1. Description of the terminal constraint network of Fig. 3. |
|---------------------------------------------------------------|
| Impedance | Value |
| $R_{wL1}=R_{wL2}=R_{w1}=R_{w2}$ | 176$\Omega$ |
| $R_{wL3}$ | 61$\Omega$ |
| $R_1$ | 124.7$\Omega$ |
| $R_2$ | 1G$\Omega$ |
Fig. 3. Configuration adopted of the simulation for conducted susceptibility analysis.

Figs 4. shows Differential-mode voltages obtained by the proposed model together with the outcomes determined by the theatrical results presented in [8], which are in a good agreement. In Fig.4, the coupling into end side load is clearly stronger than in near side load, because the injection is asymmetrically located on near side of external shield.
The configuration is physically similar to the coupling into single wire over ground plane with an illumination $E_{x} - K_{z}$, travelling along the wire in $+z$ direction [9] because the internal line is well matched by both side terminations, the total coupling is under a flat envelop and the anti-resonance frequencies are located as by the following formula

$$f_n = n \left( \frac{3 \times 10^4}{\lambda/2 \sqrt{E_x}} \right), \quad n = 1, 3, 5, \ldots$$

The coupled value is increasing with frequency at $+20$ dB/dec due to preponderant effect of transfer inductance (the transfer resistance is zero).

### 3.2. Radiated Susceptibility Analysis

The setup proposed for the radiated susceptibility analysis is presented in Fig. 5. The length of cable and the height above the ground plane are $L=1$m and $h=1$cm, respectively. The illuminating field is $E_{x} - K_{z}$, a wave with vertical polarisation, normalised amplitude $E=1$V/m and travelling along $z$–axis. The transfer impedance values are similar to the previous example, $R_t = 0.01\Omega/m$; $L_{t1}=1.3\text{nH/m}$ and $L_{t2}=1.2\text{nH/m}$, respectively, for conductor n. 1 and conductor n.2. Other parameters are the same as those in the conducted analysis. The validity range is $F_{max}=1\text{GHz}$.

![Configuration adopted of the simulation for radiated susceptibility analysis.](image-url)
Fig. 6 shows the differential voltages on both the differential resistance at input and output of internal line obtained by the proposed model and by the theoretical results presented in [8]. Like in similar conducted case with current generator as input source, the different voltages at input and output are related to asymmetry of shield transfer impedance attributed to two conductors, to simulate the effect of supposed longitudinal fence on external shield. In addition, it is crystal clear that the line resonates at \( \frac{\lambda}{4n} \) with \( n = 1,3,5... \) due to resonance of external shield.

![Graph](image-url)

**Fig. 6.** Differential mode voltage at input and output of internal line when the incident wave propagates along the z-axis - shield grounded one side.

### 3.3. Conducted susceptibility analysis with non-linear loads

There are many forms of electromagnetic interference, EMI that can affect circuits and prevent them from working in the way that was intended. To protect an electrical signal transport device, non-linear protection devices (voltage limiters here) are always connected to the devices in parallel. As mentioned above, the proposed model can also be used when the loads are non-linear.

The radiated immunity analysis with non-linear loads is carried out considering the similar twinax cable previously illustrated. In this configuration, a voltage limiter constituted by two anti-parallel diodes, is connected to the right termination, as shown in Fig. 7.
Fig. 7. Configuration adopted of the simulation for radiated susceptibility analysis.

Fig. 8. The voltage responses at the cable end in the transient analysis in presence and in absence of the diode.

Fig. 8 shows the differential mode voltages at the cable ends obtained by the proposed model in the time domain analysis for two cases, no voltage limiters, and a voltage limiter added in parallel to $R_{w3}$. From the results of Fig. 8, it is noticed that the voltage limiter is able to limit the output voltage.

4. CONCLUSION

In this paper, a Multiconductor shielded cables model was proposed, the implemented model has the advantages of uniformity of processing for both conducted and radiated coupling in the time and frequency domain. In addition, the model takes into consideration both, linear and nonlinear loads. The accuracy of the proposed model was verified by comparing the results with those from other methods. It is easy to extend this model to nonuniform Multiconductor shield cables, this point will be detailed in further study.

REFERENCES

[1] Z. Bouzidi, A. El Idrissi, H. Rouijaa, and M. Saih, “Transmission Lines Modeling Approach Based on the Approximation of Pade,” presented at PhotonIcs & Electromagnetics Research Symposium - Spring (PIERS-Spring), pp. 4009–4017, Rome, Italy, Jun. 2019.

[2] Y. Mejdoub, H. Rouijaa, and A. Ghammaz, “Variation effect of plane-wave incidence on multiconductor transmission lines,” Int. J. Microw. Wirel. Technol., vol. 8, no. 6, pp. 891–898, March. 2015.

[3] S. Caniggia and F. Maradei, “Equivalent circuit models for the analysis of coaxial cables immunity,” IEEE Symposium on Electromagnetic Compatibility. vol. 2, pp. 881–886, Aug. 2003.

[4] S. Caniggia and F. Maradei, “SPICE-Like Models for the Analysis of the Conducted and Radiated Immunity of Shielded Cables,” IEEE Trans. Electromagn. Compat., vol. 46, no. 4, pp. 606–616, Nov. 2004.
[5] M. Saih, H. Rouijaa, and A. Ghammaz, “Circuit Models for Conducted Susceptibility Analyses of Multiconductor Shielded Cables,” International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, vol. 9, no. 4, pp. 435–439, 2015.

[6] G. Antonini, A. Orlandi, “Spice equivalent circuit of a twoparallelwires shielded cable for evaluation of the RF induced voltages at the terminations,” IEEE Trans. Electromagn. Compat., vol. 46, 189–198, 2004.

[7] H. Xie, J. Wang, R. Fan, and Y. Liu, “Spice models for radiated and conducted susceptibility analyses of multiconductor shielded cables,” Prog. Electromagn. Res., vol. 103, pp. 241–257, 2010.

[8] H. Xie, J. Wang, R. Fan, and Y. Liu, “SPICE Models to Analyze Radiated and Conducted Susceptibilities of Shielded Coaxial Cables,” IEEE Trans. Electromagn. Compat., vol. 52, no. 1, pp. 215–222, Feb. 2010.

[9] M. Saih, H. Rouijaa, and A. Ghammaz, “Circuit models of multiconductor shielded cables: incident plane wave effect: Incident Plane Wave Effect,” Int. J. Numer. Model. Electron. Netw. Devices Fields, vol. 29, no. 2, pp. 243–254, Mar. 2016.

[10] M. Stumpf and G. Antonini, “Electromagnetic Field Coupling to a Transmission Line—A Reciprocity-Based Approach,” IEEE Trans. Electromagn. Compat., vol. 62, no. 2, pp. 461–469, Apr. 2020.

[11] AA. Smith, Coupling of External Electromagnetic Fields to Transmission Lines, 2nd ed., John Wiley & Sons, California, USA, 1989.