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Equivalent cable harness method generalized for predicting the electromagnetic emission of twisted-wire pairs

Introduction. *In this paper, the equivalent cable harness method is generalized for predicting the electromagnetic emissions problems of twisted-wire pairs.* ***The novelty*** *of the proposed work consists in modeling of a multiconductor cable, in a simplified cable harness composed of a reduced number of equivalent conductors, each one is representing the behavior of one group of conductors of the initial cable.* ***Purpose.*** *This work is focused on the development and implementation of simplified simulations to study electromagnetic couplings on multiconductor cable.* ***Methods****. This method requires a four step procedure which is summarized as follows. Two different cases, of one end grounded and two ends grounded configurations can be analyzed.* ***Results.*** *The results had shown that the model complexity and computation time are significantly reduced, without, however, reducing the accuracy of the calculations.* References 20, tables 1, figures 8.

Key words: **electromagnetic emission, asymmetric digital subscriber line, crosstalk, equivalent cable harness method, multiconductor transmission line network, power loss, twisted-wire pairs.**

Вступ*. У цій статті метод еквівалентного кабельного джгута узагальнюється для прогнозування задач електромагнітного випромінювання кручених пар дротів.* ***Новизна*** *запропонованої роботи полягає в моделюванні багатожильного кабелю в спрощеному джгуті проводів, що складається зі зменшеної кількості еквівалентних провідників, кожен з яких репрезентує поведінку однієї групи провідників вихідного кабелю.* ***Мета****. Робота зосереджена на розробці та реалізації спрощеного моделювання для дослідження електромагнітних зв'язків у багатожильних кабелях.* ***Методи****. Цей метод вимагає чотириступінчастої процедури, яка коротко описана у статті. Можна проаналізувати два різні випадки: конфігурації із заземленням одного кінця та заземлення двох кінців.* ***Результати****. Результати показали, що складність моделі та тривалість обчислень значно знижуються, проте без зниження точності обчислень.* Бібл. 20, табл. 1, рис. 8.

Ключові слова: **електромагнітне випромінювання, асиметрична цифрова абонентська лінія, перехресні перешкоди, метод еквівалентного кабельного джгута, мережа багатопровідних ліній передачі, втрати потужності, кручені пари дротів.**

Introduction. For transmission signal in complex telecommunication network one of principle resources of noise that affect the signal quality is due to the crosstalk coupling. The crosstalk among twisted-wire pairs (TWPs) is commonly classified into near end crosstalk (NEXT) and far end crosstalk (FEXT) [1–4]. Furthermore, we distinguished two types of coupling crosstalk, the inductive coupling and the capacitive coupling, the dominant coupling at an arbitrary configuration is due to the termination impedance effects [5, 6].

The survey of literature shows that reducing the number of wires is not a new task. An efficient simplification technique called the «equivalent cable bundle method» (ECBM) has been proposed for modelling electromagnetic (EM) common-mode currents on complex cable bundles for telecommunications networks applications with arbitrary loads [7]. This method, allows, using the theory of Multiconductor Transmission Line Network (MTLN), to take into account the phenomena of propagation and couplings on and between all the wires of the network.

In recent years, the increase in the frequency of disturbances electromagnetic that can potentially attack the wiring network encourages the research to extend digital immunity to high frequencies. This will unfortunately comes up against the limitation in MTLN frequency.

In high frequencies, the use of three-dimensional methods, solving the Maxwell equations in space then proves to be obligatory. However, they require a fine discretization of each conductor of the beam in segments whose length is usually less than one tenth of the wavelength. The computation times then become prohibitive as soon as the number of conductors of the beam in important.

It must therefore find simplifying hypotheses allowing the complexity to be reduced wiring harness without, however, reducing the accuracy of the calculations [8, 9]. The goal final is to generalize the feasibility of such an approach for twisted-wire pairs.

Purpose of the work is focused on the development and implementation of simplified simulations to study electromagnetic couplings on multiconductor cable.

Presentation of the equivalent cable harness method proposed of complex twisted-wire pairs. Description of the main assumption adopted in this modified procedure for a coupling problem in twisted-wire pairs cable will be detailed in this section.

The proposed geometry consists of a cable composed of twisted-wire pairs, both ends or only one end of the each pair circuit can be grounded.

Note that the twisted-wire pairs used here are connected to the ground plane. We would expect common mode current to be dominant. Therefore, the main assumption of the original ECBM is unchanged [10], we make approach that the impedance loads in such case of twisted-wire pairs can be considered such as a common mode loads and the differential loads in one end of the pairs can be neglected.

The determination of geometrical characteristics of the reduced cable is omitted here because the aim of the method is to predict crosstalk in the pairs that we are interested in his currents and voltages [11, 12].

The modified equivalent cable harness method for modeling crosstalk in frequency domain among twisted-wire pairs requires a four-step procedure [9], which is summarized as follows.

Step I. The goal of this step is to classify the pairs of the initial cable in different groups according to their termination loads at both ends of each pair. The culprit and victim pairs are classified into two groups separately and they hold its initial characteristics (including its positions, radius, and medium). The common-mode characteristic impedance Z_{mc} is determined by modal transformation in the MTLN formalism in order to obtain the characteristics of all the modes propagating along the cable. Furthermore, the very important condition of the eigenvector associated with the common mode in the matrix $[T_x]$ is verified, this part is more detailed in the original ECBM [8, 10].

Then all the remaining pairs in the complete cable bundle are sorted into groups by comparing the value of the termination loads (near Z_{0i} and far Z_{Li}) to Z_{mc}. The conductors are installed as pairs; each two conductors for one pair are in the same group because the modal analysis is made of twisted-wire pairs configuration. We define the four groups (may be less than four) which can be determined in each configuration in Table 1.

Table 1

Classification of the pairs according to their termination loads

Termination load	Group 1	Group 2	Group 3	Group 4
Near end (0)	$Z_{0i} < Z_{mc}$	$Z_{0i} < Z_{mc}$	$Z_{0i} > Z_{mc}$	$Z_{0i} > Z_{mc}$
Far end (L)	$Z_{Li} < Z_{mc}$	$Z_{Li} > R_{mc}$	$Z_{Li} < Z_{mc}$	$Z_{Li} > Z_{mc}$

Step II. The determination of the per unit length (p.u.l) parameter matrices of an equivalent cable is based on the determination of p.u. parameter matrices of the pairs from which it is consisted.

We consider a short circuit between conductors of one group of «k» conductors (Fig. 1). This assumption allows: firstly to define the group current I_{ec} for the equivalent cable and secondly the group voltage V_{ec} for the equivalent cable.

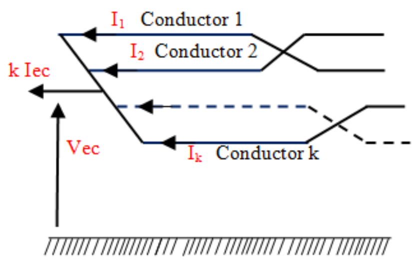

Fig. 1. Mode common current and voltage of k conductors in the same group

To determine the inductance reduced matrix, we need two additional assumptions detailed in [9]:

1) the currents flowing along all the «k» conductors of a cable bundle are decomposed in common mode currents and a differential mode currents. The differential mode current can be neglected [5, 13, 14].

The current and the voltage of «k» conductors in the same group can be written by:

$$I_{ec} = I_1 + I_2 + \ldots + I_k\,; \tag{1}$$

$$V_{ec} = V_1 + V_2 + \ldots + V_k\,. \tag{2}$$

Thus, from the telegrapher's equation on the MTLN formalism for lossless line we can obtain the inductance matrix links the currents and the voltages on each conductor on an infinitesimal segment of length:

$$\frac{\partial}{\partial z}\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_k \end{bmatrix} = -j\omega \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1k} \\ L_{21} & L_{22} & \cdots & L_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ L_{k1} & L_{k2} & \cdots & L_{kk} \end{bmatrix}\begin{bmatrix} I_{c1} \\ I_{c2} \\ \vdots \\ I_{ck} \end{bmatrix}. \tag{3}$$

2) The common mode currents along all the conductors of a same group are identical:

$$I_{ec} = I_1 = I_2 = \ldots = I_k\,, \tag{4}$$

where I_k is the mode common current in the k conductor.

The common-mode characteristic impedance of the harness can be obtained:

$$V_{ck} = \frac{V_{ec}}{kI_{ec}} = \frac{Z_i}{k}, \tag{5}$$

where Z_i is the common-mode characteristic impedance of each conductor in the group (Fig. 2).

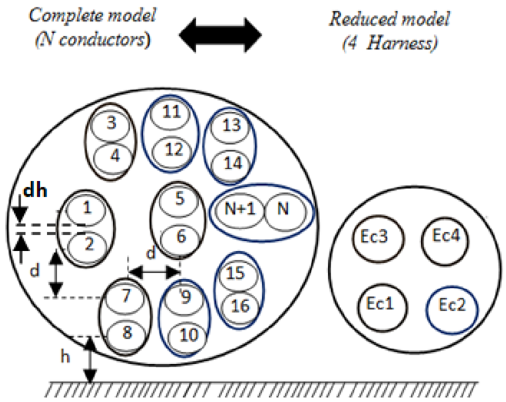

Fig.2. Cross section view of complete and reduced cable

These assumptions may allow finding the final system matrix; we index the conductors of each group as follows:

- N_1 conductors of the first group indexed 1 to x;
- N_2 conductors of the second group indexed x+1 to y;
- N_3 conductors of the third group indexed y+1 to z;
- N_4 conductors of the fourth group indexed z+1 to N.

The final system that allows finding L_{red} can be obtained:

$$\frac{\partial V_1}{\partial x} = -j\omega\begin{bmatrix} \dfrac{\sum_{i=1}^{x} L_{1i}}{N_1} I_{ec1} + \dfrac{\sum_{i=x+1}^{y} L_{1i}}{N_2} I_{ec2} \\ \dfrac{\sum_{i=y+1}^{z} L_{1i}}{N_3} I_{ec3} + \dfrac{\sum_{i=z+1}^{N} L_{1i}}{N_4} I_{ec4} \end{bmatrix}; \tag{6}$$

$$\frac{\partial V_N}{\partial x} = -j\omega\begin{bmatrix} \dfrac{\sum_{i=1}^{x} L_{Ni}}{N_1} I_{ec1} + \dfrac{\sum_{i=x+1}^{y} L_{Ni}}{N_2} I_{ec2} \\ \dfrac{\sum_{i=y+1}^{z} L_{Ni}}{N_3} I_{ec3} + \dfrac{\sum_{i=z+1}^{N} L_{Ni}}{N_4} I_{ec4} \end{bmatrix}. \tag{7}$$

The voltages of each conductor belonging to the same group being equal (2), the insertion of this property in previous equations leads to the following system connecting the voltages and currents of the four groups of conductors [7]:

$$\frac{\partial V_{ec1}}{\partial x}=-j\omega\left[\frac{\sum_{i=1}^{x}\sum_{j=1}^{x}L_{ij}}{N_1^2}I_{ec1}+\frac{\sum_{i=1}^{x}\sum_{j=x+1}^{y}L_{ij}}{N_1N_2}I_{ec2}+\right.$$
$$\left.+\frac{\sum_{i=1}^{x}\sum_{j=y+1}^{z}L_{ij}}{N_1N_3}I_{ec3}+\frac{\sum_{i=1}^{x}\sum_{j=z+1}^{N}L_{ij}}{N_1N_4}I_{ec4}\right]; \tag{8}$$

$$\frac{\partial V_{ec2}}{\partial x}=-j\omega\left[\frac{\sum_{i=x+1}^{y}\sum_{j=1}^{x}L_{ij}}{N_1N_2}I_{ec1}+\frac{\sum_{i=x+1}^{y}\sum_{j=x+1}^{y}L_{ij}}{N_2^2}I_{ec2}+\right.$$
$$\left.+\frac{\sum_{i=x+1}^{y}\sum_{j=y+1}^{z}L_{ij}}{N_2N_3}I_{ec3}+\frac{\sum_{i=x+1}^{y}\sum_{j=z+1}^{N}L_{ij}}{N_2N_4}I_{ec4}\right]; \tag{9}$$

$$\frac{\partial V_{ec3}}{\partial x}=-j\omega\left[\frac{\sum_{i=y+1}^{z}\sum_{j=1}^{x}L_{ij}}{N_1N_3}I_{ec1}+\frac{\sum_{i=y+1}^{z}\sum_{j=x+1}^{y}L_{ij}}{N_2N_3}I_{ec2}+\right.$$
$$\left.+\frac{\sum_{i=y+1}^{z}\sum_{j=y+1}^{z}L_{ij}}{N_3^2}I_{ec3}+\frac{\sum_{i=y+1}^{z}\sum_{j=z+1}^{N}L_{ij}}{N_3N_4}I_{ec4}\right]; \tag{10}$$

$$\frac{\partial V_{ec4}}{\partial x}=-j\omega\left[\frac{\sum_{i=z+1}^{N}\sum_{j=1}^{x}L_{ij}}{N_1N_4}I_{ec1}+\frac{\sum_{i=z+1}^{N}\sum_{j=x+1}^{y}L_{ij}}{N_2N_4}I_{ec2}+\right.$$
$$\left.+\frac{\sum_{i=z+1}^{N}\sum_{j=y+1}^{z}L_{ij}}{N_3N_4}I_{ec3}+\frac{\sum_{i=z+1}^{N}\sum_{j=z+1}^{N}L_{ij}}{N_4^2}I_{ec4}\right]; \tag{11}$$

$$\frac{\partial}{\partial z}\begin{bmatrix}V_{ec1}\\V_{ec2}\\V_{ec3}\\V_{ec4}\end{bmatrix}=-j\omega[L_{red}]\begin{bmatrix}I_{ce1}\\I_{ce2}\\I_{ce3}\\I_{ce4}\end{bmatrix}; \tag{12}$$

$$[L_{red}]=\begin{bmatrix}L_{11r} & L_{12r} & L_{13r} & L_{14r}\\L_{21r} & L_{22r} & L_{23r} & L_{24r}\\L_{31r} & L_{32r} & L_{33r} & L_{34r}\\L_{41r} & L_{42r} & L_{43r} & L_{44r}\end{bmatrix}; \tag{13}$$

$$L_{11r}=\frac{\sum_{i=1}^{x}\sum_{j=1}^{x}L_{ij}}{N_1^2}. \tag{14}$$

The expression of p.u. capacitance matrix for the reduced model $[C_{red}]$ can be obtained with the same reasoning in no homogenous and polar medium.

For a weakly polar medium, one can ignore the dispersion of the dielectric constant and, accordingly, the phase velocity [11]:

$$[C_{red}]=\frac{1}{\upsilon^2}[L_{red}]^{-1}, \tag{15}$$

where $\upsilon=c/\sqrt{\varepsilon_r}$.

So, using the assumptions and approximations set out above, the matrix inductance and capacitance with ($N\times N$) dimension can be reduced into matrix (4×4) which coefficients exerted on and between the conductors.

Step III. The aim of this step is to determine the termination loads to be connected at both ends of the equivalent conductor. Here, all load impedances are considered as pure resistance and are not frequency dependent. There are two kinds of the termination loads, differential-mode loads and common-mode loads:

• *Common-mode loads*. Each load connected to the ground plane at his terminal end (Fig. 3).

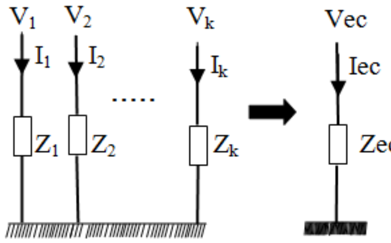

Fig. 3. Equivalent termination common-mode loads

The impedance equivalent Z_{ec} for «k» conductors in the same group (Z_1, Z_2 …Z_k), is:

$$\frac{1}{Z_{ec}}=\frac{1}{Z_1}+\frac{1}{Z_2}+\ldots+\frac{1}{Z_k}. \tag{16}$$

• *Differential-mode loads*. We consider the type differential loads connected between conductors from different groups (Fig. 4). The impedance equivalent Z_{d12}, for two conductors (1 and 2) in group 1 and two conductors (N1+1 and N1+2) in group 2, is:

$$\frac{1}{Z_{d12}}=\frac{1}{Z_{1-N1+1}}+\frac{1}{Z_{2-N1+2}}. \tag{17}$$

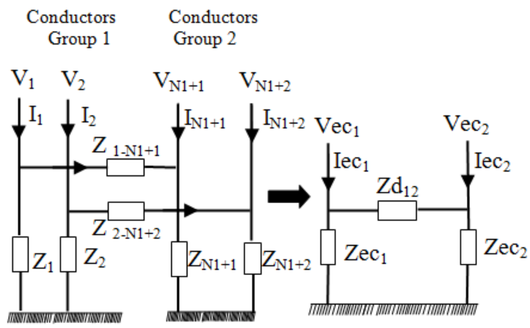

Fig. 4. Equivalent termination differential-mode loads

The type of differential loads connected between conductors in the same group is neglected.

Step IV. The aim of this step is to determine the section geometry (radius, coating radius, permittivity relative of coating, height, distance between harnesses), of each reduced harness using the linear parameter matrices determined at the Step II. This part is more detailed in the original ECBM [8, 10].

For modeling the twist of pairs on complete model the matrix P [1] was used, in the reduced model this matrix is evaluated to take into account only the twisted wires of the pairs which we not apply the method [1].

For the equivalent cable for each group the current and voltage are multiplied by 1 in the matrix P.

In order to determine currents and voltages in both ends of each pair, the excited pair is assumed to be a disturber and the crosstalk in an arbitrary victim pair in term of power loss (PL) is shown.

Note that the values of the power loss crosstalk (PL_{NEXT}, PL_{FEXT}) in decibels can be calculated as follows [15–18]:

$$PL_{NEXT/dB} = -10\log_{10}(|H_{NEXT}(f)|^2)\,; \qquad (18)$$

$$PL_{FEXT/dB} = -10\log_{10}(|H_{FEXT}(f)|^2)\,, \qquad (19)$$

where H_{NEXT} and H_{FEXT} are the transfer function.

The PL expression can be written as follows:

$$PL_{NEXT,i/dB} = 10\log_{10}\left|(V_i(x_1)/V_1(x_1))^2\right|; \qquad (20)$$

$$PL_{FEXT,i/dB} = 10\log_{10}\left|(V_i(x_L)/V_1(x_1))^2\right|, \qquad (21)$$

where V_i is the voltage in the victim wire which we want calculates his crosstalk; x_1, x_L are the first and the last extremities of the line [19].

Application of the equivalent cable harness method. The mathematical model established will be used for obtaining the power loss near and far (PL_{NEXT} and PL_{FEXT}) in a bundle of twisted wire pairs. Twisted wire-pair is connected by two ends of each pair to the ground plane. Figure 5 illustrates the geometry used, they shows the first case of initial model of twenty-eight pairs denoted from 1 to 56, and the reduced cable of two pairs and two equivalent harness denoted ec_1, ec_2.

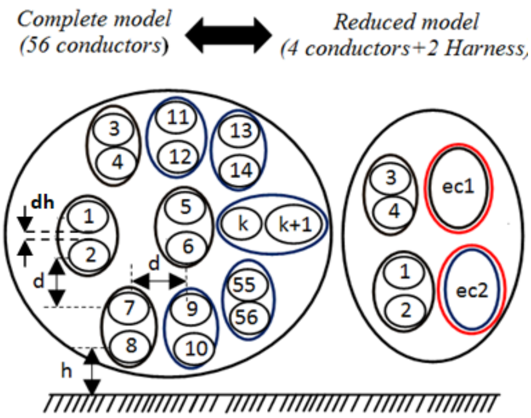

Fig. 5. Complete model cable and reduced model cable twisted-wire pairs cross sectional view

All wires are further assumed to have the same radius a = 0.523 mm and polyvinyl chloride coating radius of b = 0.549 mm. The length of the wire is L = 1 km. The twisted pair consists of N = 10000 loops. The height of the first wire (numerated 8 and 10) above ground conductor is h = 20 mm, the height is very close to the reference plane, the intention in doing so is to avoid the noise produced by the loop between the receptor circuit and the reference plane.

The other conductors are located just above and next to the first wire with vertical distance of 0.127 mm for the same pair conductors and 3.17 mm for other conductors, the horizontal distance between the wires is d = 3.17 mm.

In Fig. 6 the pair one is given as an example, which is connected to the voltage source V_0 at its near end through a load Z_{01} and adapted at its far end through a load Z_{L1}.

The crosstalk will be studied in the frequency range from 1 kHz to 30 MHz with reference to Fig. 6 and in order to make same loads such as in XDSL systems, the loads in the pairs which we are interested are set to $Z_{01} = Z_{L1} = Z_{02} = Z_{L2} = 120\ \Omega$ under the condition, that for a twisted pair the active resistance R of the conductors is much less than the inductive resistance ωL, and the active conductivity G of the insulation is much less than the capacitive resistance ωC, respectively: $R \ll \omega L$, $G \ll \omega C$ [20].

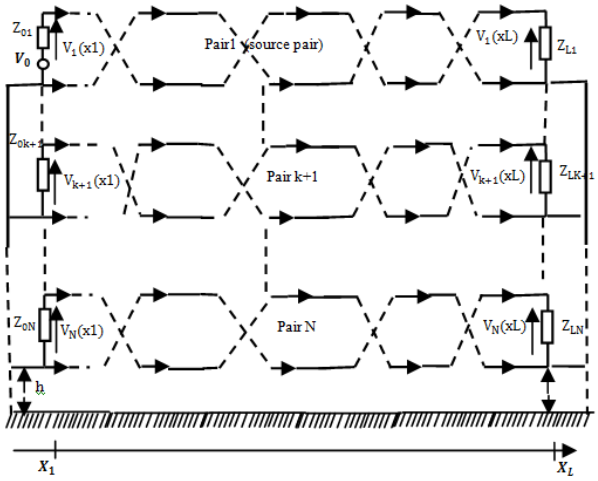

Fig. 6. Model of two ends grounded geometry of twisted-wire pairs longitudinal view

The classification of groups is made according to the comparison with the common-mode loads determined by the modal analysis.

The pairs of the complete cable bundle sorted into four groups as follows (Fig. 5):

- group 1: pairs 1 (conductors 1-2);
- group 2: pairs 2 (conductors 3-4);
- group 3: harness 1 (conductors 5-30);
- group 4: harness 2 (conductors 31-56);

The p.u. parameter matrices $[L_{red}]$ and $[C_{red}]$ of the reduced harnesses cables are calculated in nH/m and pF/m for a 1 km long line respectively:

$$[L_{red}] = \begin{bmatrix} 1.02 & 0.88 & 0.25 & 0.25 & 0.25 & 0.19 \\ & 1.02 & 0.25 & 0.24 & 0.24 & 0.19 \\ & 1.02 & 0.88 & 0.13 & 0.17 & \\ & & 1.02 & 0.13 & 0.17 & \\ & & 0.36 & 0.16 & & \\ & & 0.34 & & & \end{bmatrix};$$

$$[C_{red}] = \begin{bmatrix} 43.74 & -36.56 & -0.53 & -0.47 & -4.13 & -1.21 \\ & 43.74 & -0.47 & -0.52 & -4.64 & -0.71 \\ & & 43.70 & -36.59 & -0.64 & -1.04 \\ & & & 43.72 & -0.65 & -0.64 \\ & & 46.10 & -15.20 & & \\ & & & 46.17 & & \end{bmatrix}.$$

Next before and after applying our equivalent cable harness method the results are compared. The culprit pair is the pair one numerated (1, 2) in Fig. 5, we are interested in the voltage and current of the second pair numerated (3, 4) in Fig. 5.

The near end of conductor one (first pair (culprit pair)) is excited with a constant voltage source of 1 V.

The first pair is activated and we calculate the PL in the second pair (conductor 3). Next, we apply the method and we calculate again the PL on the second pair when the first pair is activated.

Figures 7, 8 show the power loss in the second pair (conductor 3) for *NEXT* and *FEXT* successively for the initial model and the complete model.

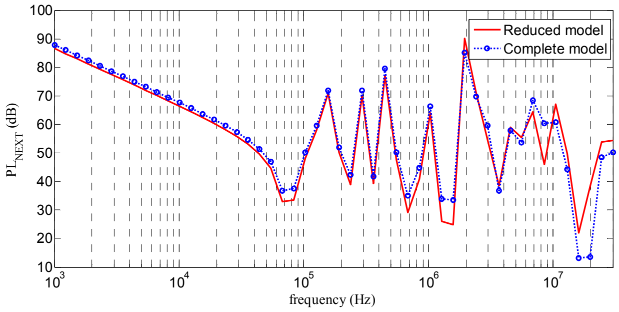

Fig. 7. PL_{NEXT} voltage in the frequency domain on pair two

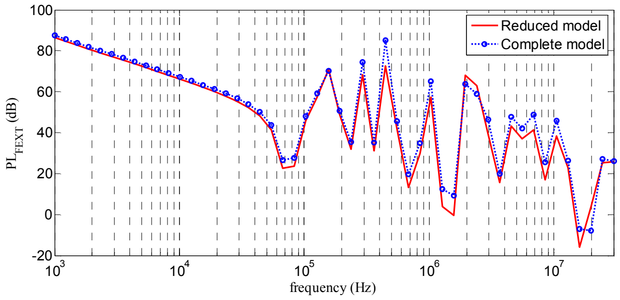

Fig. 8. PL_{FEXT} voltage in the frequency domain on pair two

For this configuration the difference between the two models is a few decibels. In the high frequency some differences are observed which are possibly due to the apparition of the transverse electric and magnetic mode. Results for this case confirm that equivalent cable harness method can be successfully applied in prediction crosstalk in a two ends grounded configuration of twisted-wire pairs cable in frequency domain.

To evaluate currents and voltages at both ends of each pair, the MTLN technique is used [5, 6] because for telecommunications networks the length of the wire is L = 1 km and greater than. For automotive applications where the lengths are too shirt (some meters) we can used three-dimensional methods, solving the Maxwell equations in space, how require a fine discretization of each conductor of the beam in segments.

Conclusion.

In this work the equivalent cable harness method was applied at different groups of pairs and voltages for a model of twisted-wire pairs in a cable bundle of telecommunication networks.

The foremost attributes of the modified method are:

- the study of crosstalk is established in the frequency domain from 1 kHz to 30 MHz where the line is electrically long and the transverse electric and magnetic mode is considered;
- the conductor, twisted wire to wire in both configurations studied which affect the terminal loads and give rise to a new approach of the equivalent loads;
- the victim and culprit pairs considered as different groups and were involved in the reduced per unit length parameter matrices.

The crosstalk *NEXT* and *FEXT* are simulated at an arbitrary culprit pair in term of power loss this task allows reduction of complexity and computation time for a complete cable bundle modeling and maintains a fairly good precision, the total computation time is reduced by a factor of 2.8 after equivalence of the complete model by using the method of Multiconductor Transmission Line Network theory for cable of 28 pairs (56 conductors), which have been performed on a 2.5 GHz processor and a 4 GB RAM memory computer. Numerical simulations presented in this paper validate the efficiency and the advantages of the proposed method.

Conflict of interest. The authors declare that they have no conflicts of interest.

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