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Electromagnetic interference in a multiconductor transmission system - MTL

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Abstract. In electrical and electronic practice, many connection and transmission elements (cables) are used as a multi-conductor transmission lines (MTL). The electromagnetic fields existing in the environment of these multiconductor transmission lines and can generate different types of coupling phenomena, causing EMC problems by the appearance of the unwanted EMI, disturbing the correct function and altering the information.
Electromagnetic coupling between the circuits/cables of a circuit (also known as crosstalk) can also occur between the signal and power paths of an assembly made on printed circuit boards, PCB (printed board circuit), so it is important that when designing such an electrical / electronic circuit, these aspects should be taken into account.

Keywords: *Multi-conductor transmission line (MTL), crosstalk, near-end and far-end*

1. Three conductor transmission line model

In the following will be analyzed through the mathematical model the interferences that appear at the level of the model of a transmission line with three conductors (generator, receiver and reference). The figure below shows the model of a multi-conductor transmission line consisting of three conductors, one generator, one receiver and a third conductor considered as reference. Also represented are the electrical quantities inside the circuit, both those applied intentionally and those that appear as a result of the electromagnetic interference /coupling between the conductors within the circuit.

The electrical / magnetic induction coupling appear at the level of the three conductors are called crosstalk. For a better understanding of the phenomenon, the degree of coupling / influence at both ends of the circuit is determined (near-end / far-end).

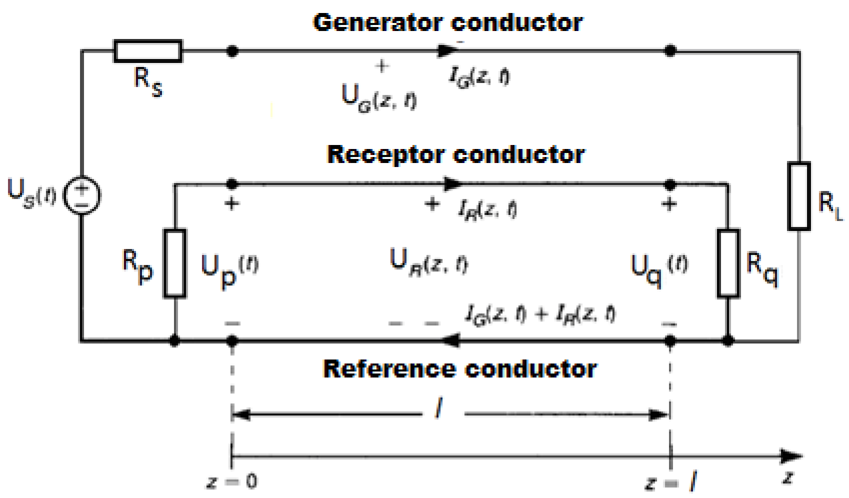

Fig.1 The general three conductor transmission line, illustrating crosstalk

Considering the lines of circuits from the electronic systems as being the majority of the short lines, the phenomenon of propagation can be ignored.

It can be defining *short lines* those lines that can be describe like:

- $l << \frac{\lambda}{10}$, λ - wavelength, l – line length.

For example: $f = 300Mhz \rightarrow \lambda = 1m, \frac{\lambda}{10} = 0{,}1m$.

For these reasons, the discussion will continue for a part of the circuit considered with the concentrated parameters.

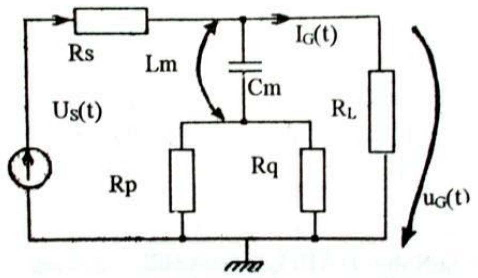

Fig.2 Equivalent scheme of a circuit with concentrated parameters

- L_m și C_m, concentrated parameters are calculated with formulas:

$$\begin{cases} L_m = L'_m \cdot l \\ C_m = C'_m \cdot l \end{cases} \tag{1.1}$$

- L'_m și C'_m, are distributed parameters, and l represent the length of the line.

To simplify the following calculations, it will be considered to be dealing with a weak coupling between the two circuits, i.e. the *generator circuit* (disruptor) will influence the *receiver circuit* (disrupted) through the induction phenomenon, but the *receiver circuit* (disrupted) will not influence in turn the generator circuit (disruptor).

$$\begin{cases} i_G(t) = \dfrac{1}{R_S + R_L} \cdot u_S(t); \\ u_G(t) = \dfrac{R_L}{R_S + R_L} \cdot u_S(t); \end{cases} \tag{1.2}$$

By analyzing the receiver/disrupted circuit separately, it can also be represented in an equivalent scheme as shown in the figure below.

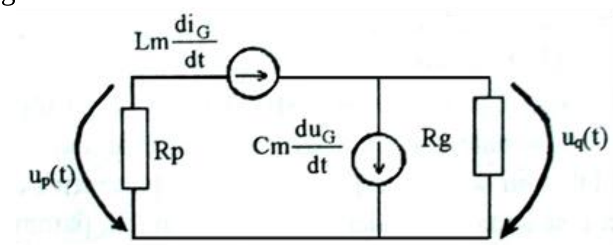

Fig.3 Equivalent scheme of the disrupted circuit

In the frequency domain the above equations, (1.2), become:

$$\begin{cases} \underline{I}_G = \dfrac{1}{R_S + R_L} \cdot \underline{U}_S; \\ \underline{U}_G = \dfrac{R_L}{R_S + R_L} \cdot \underline{U}_S \end{cases} \tag{1.3}$$

In the frequency domain the equivalent of the receiver/disrupted circuit is shown in the figure below:

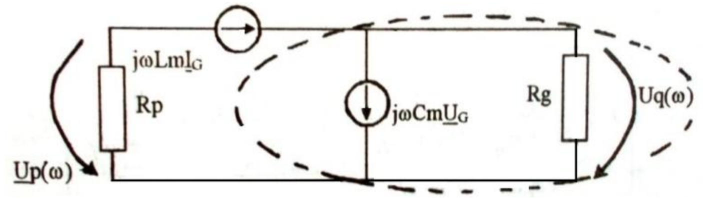

Fig.4 Equivalent scheme circuit disrupted in frequency domain

The main objective of the study is to determine the values of tensions $U_p(\omega)$ and $U_q(\omega)$.

The equivalent circuit in figure 4 may also be represented by the diagram in figure 5, where the equivalent source $j\omega C_m U_G$ was replaced with the series scheme R_q and $\underline{U}'$.

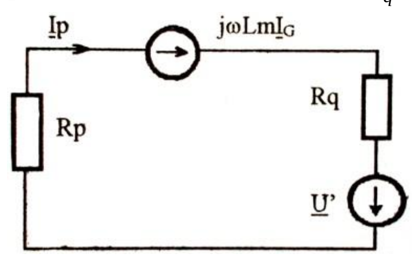

Fig.5 Circuit diagram disrupted equivalent in frequency domain

The calculations resulting from figure 5 are:

$$\underline{U}' = j\omega C_m U_G \cdot R_q \tag{1.4}$$

$$R_p \cdot \underline{I}_p + j\omega L_m \underline{I}_G + R_q \underline{I}_q + j\omega C_m \underline{U}_G R_q = 0 \tag{1.5}$$

$$\underline{I}_p = -j\omega L_m \frac{1}{R_p + R_q} \cdot \underline{I}_G - j\omega C_m \frac{R_q}{R_p + R_q} \cdot \underline{U}_G \tag{1.6}$$

Taking into account relations (1.3), the following relationships will be obtained for I_p and U_p:

$$\begin{cases} \underline{I}_p = -j\omega L_m \dfrac{1}{R_p + R_q} \cdot \dfrac{1}{R_S + R_L} \cdot \underline{U}_S - j\omega C_m \dfrac{R_q}{R_p + R_q} \cdot \dfrac{R_L}{R_S + R_L} \cdot \underline{U}_S \\ \underline{U}_p = -R_p \cdot \underline{I}_p \end{cases} \tag{1.7}$$

$$\underline{U}_p = -j\omega \left[L_m \frac{R_p}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L} \right] \cdot \underline{U}_S \tag{1.8}$$

In (1.8) : - $L_m \dfrac{R_p}{R_p + R_q} \cdot \dfrac{1}{R_S + R_L}$ is specific term of the ***inductive coupling***; (1.9)

- $C_m \dfrac{R_q \cdot R_p}{R_p + R_q} \cdot \dfrac{R_L}{R_S + R_L}$ is the specific term of the ***capacitive coupling.*** (1.10)

Note:

$$M_p = \left[L_m \frac{R_p}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L} \right] \tag{1.11}$$

(1.8) became:

$$\underline{U}_p = j\omega \cdot M_p \cdot \underline{U}_S \tag{1.12}$$

Applying the same algorithm obtains the formula for the *Iq* current:

$$\underline{I}_q = -j\omega L_m \frac{1}{R_p + R_q} \cdot \frac{1}{R_S + R_L} \cdot \underline{U}_S + j\omega C_m \frac{R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L} \cdot \underline{U}_S \tag{1.13}$$

$$U_q = R_q \cdot \underline{I}_q \tag{1.14}$$

Finally the formula for U_q:

$$\underline{U}_q = -j\omega \left[L_m \frac{R_q}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L} \right] \cdot \underline{U}_S \tag{1.15}$$

$$M_q = \left[L_m \frac{R_q}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L} \right] \tag{1.16}$$

(1.15) became:

$$\underline{U}_q = j\omega \cdot M_q \cdot \underline{U}_S \tag{1.17}$$

With the help of relationships for $\underline{U}_p$ and $\underline{U}_q$ it can be appreciated the level of coupling by electromagnetic induction/high frequency in the field, considering that the coupling effect can be seen as a transfer function between *input terms* and *output terms*:

$$K_{NE} = \frac{\underline{U}_p}{\underline{U}_S} = j\omega\left[L_m \frac{R_p}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L}\right] \tag{1.18}$$

$$K_{FE} = \frac{\underline{U}_q}{\underline{U}_S} = j\omega\left[L_m \frac{R_q}{R_p + R_q} \cdot \frac{1}{R_S + R_L} + C_m \frac{R_q \cdot R_p}{R_p + R_q} \cdot \frac{R_L}{R_S + R_L}\right] \tag{1.19}$$

In time domain, the following specific relationships are:

$$u_p(t) = M_p \frac{du_s}{dt} \tag{1.20}$$

$$u_q(t) = M_q \frac{du_s}{dt} \tag{1.21}$$

2. Experimental determination of electromagnetic induction coupling

In order to study and observe practically the electromagnetic induction coupling at the level of a multiconductor transmission line system, we have practically made the assembly presented in the figure below. The system consists of two circuits (one disturbing and one disturbed), respectively three conductors (one considered generator, one considered victim and the third considered as reference).

In the experiment, a function generator was used, with which the generator circuit was fed with a sinusoidal signal, whose frequency was modified in the range: 1 KHz -10 MHz, and with an amplitude that varied according to the frequency of the signal as shown in *Table 1* below.

Also used was a digital oscilloscope HANTEG DSO 5062B, to visualize the waveforms for the signal applied to the disturbing circuit as well as for the signal induced to the disturbed circuit. It is worth mentioning that the HANTEG digital oscilloscope was also used as a spectrum analyzer, as shown in the images below.

In the assembly were used copper conductors with a diameter of *4mm*, the length of *20 cm*, and the distance between the conductors was *1.5 cm*.

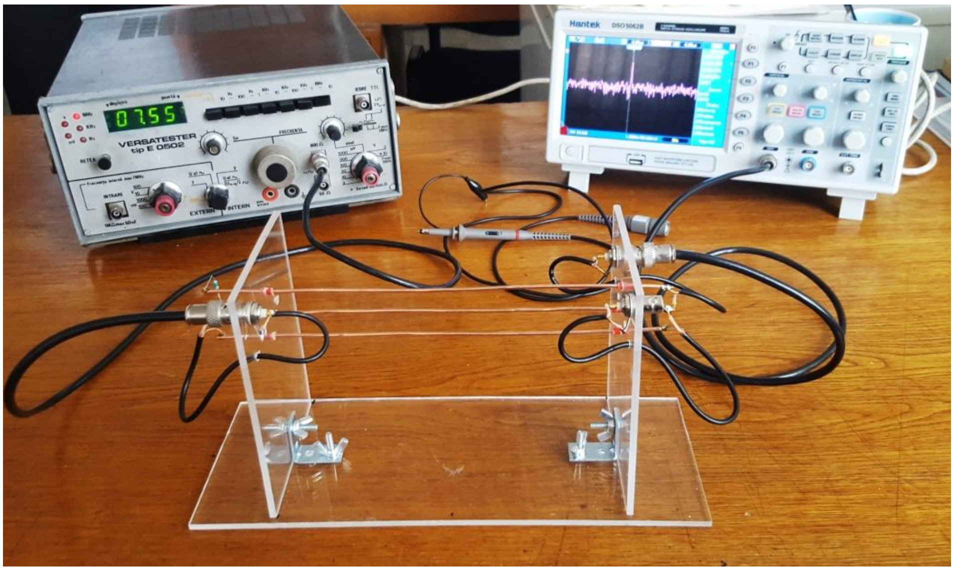

Fig.6 Experimental setup for determination of electromagnetic induction

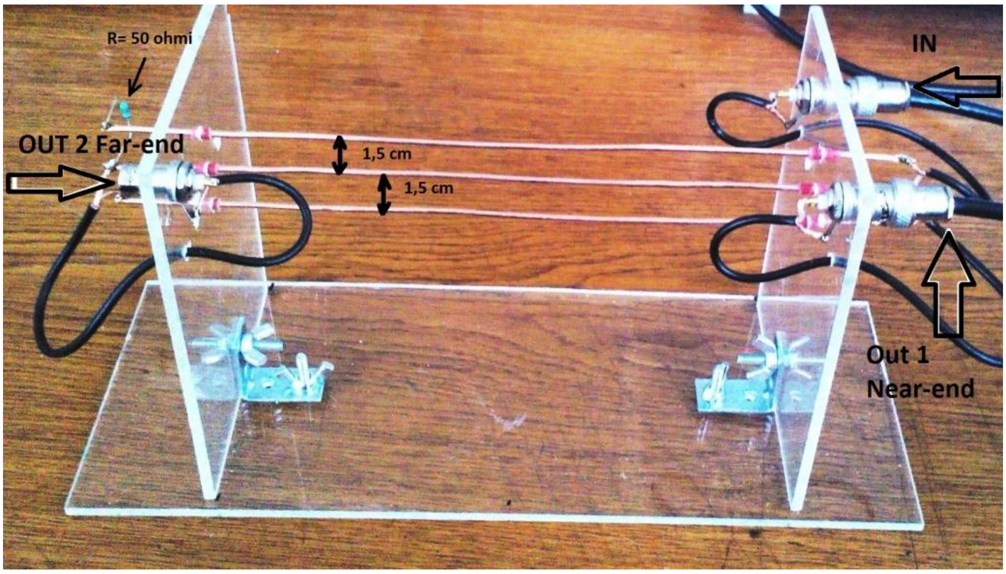

Fig.7 Experimental setup for the determination of electromagnetic induction coupling – constructive details

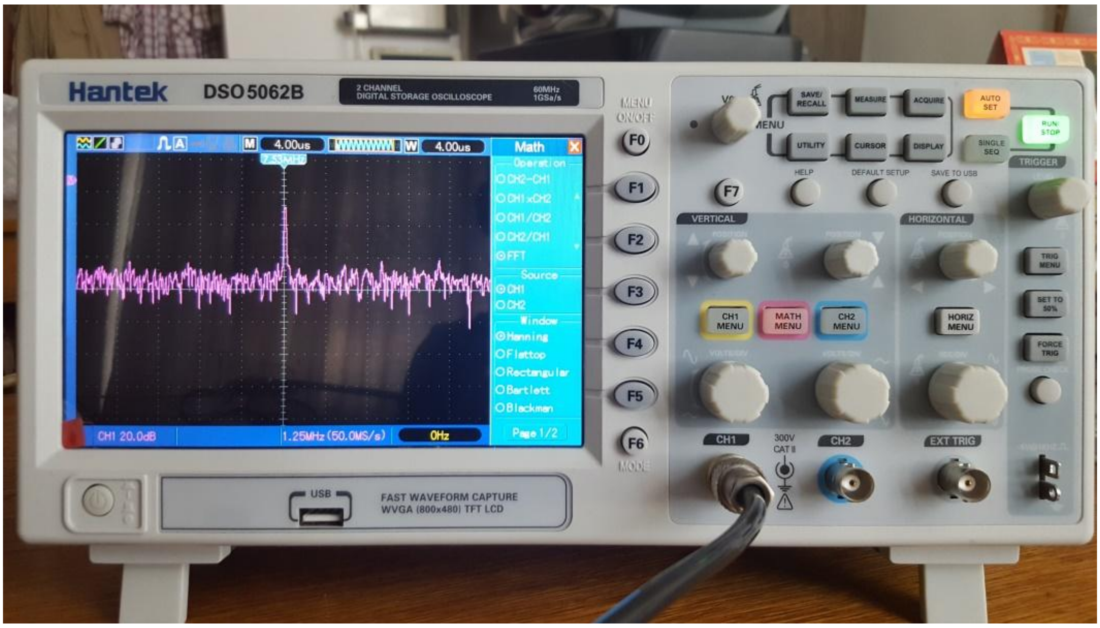

Fig.8 Using the HANTEK oscilloscope as a spectrum analyzer

Table 1. *Values of the amplitudes Us, Up, Uq [V], depending on the frequency of the signal applied to the circuit input*

Nr. Meas.	**Us (Input)**		**Up (Nearend)**		**Coupling coefficient**	**Uq (Farend)**		**Coupling coefficient**
	Frecv. F[Mhz]	Amplit. Vp-p [V]	Frecv. F[Khz]	Amplit. Vp-p [V]	$K_{NE} = \frac{Up}{Us}$	Frecv. F[Khz]	Amplit. Vp-p [V]	$K_{FE} = \frac{Uq}{Us}$
1	0,001	25.80	1	4.68	0.18	1	4.24	0.16
2	0,010	25.60	10	4.96	0.19	10	5.36	0.21
3	0,050	25.00	50	5.28	0.21	50	5.40	0.22
4	0,100	25.00	100	5.36	0.21	100	5.44	0.22
5	0,300	25.00	300	5.40	0.22	300	5.30	0.21
6	0,500	25.00	500	5.52	0.22	500	5.68	0.23
7	1,000	24.20	1 000	5.12	0.21	1 000	5.20	0.21
8	1,500	23.60	1500	5.00	0.21	1500	5.36	0.23
9	1,800	23.20	1800	5.36	0.23	1800	5.40	0.23
10	2,000	23.00	2000	5.10	0.22	2000	5.28	0.23
11	2,200	22.40	2200	4.90	0.22	2200	5.16	0.23
12	2,500	21.80	2500	4.88	0.22	2500	5.00	0.23
13	2,750	21.20	2750	4.84	0.23	2750	4.90	0.23
14	3,000	20.60	3000	4.80	0.23	3000	4.88	0.24
15	3,500	18.60	3500	4.24	0.23	3500	4.40	0.24
16	4,000	15.40	4000	4.00	0.26	4000	3.88	0.25
17	4,500	12.40	4500	3.30	0.27	4500	3.40	0.27
18	5,000	10.70	5000	2.50	0.23	5000	2.20	0.21
19	5,500	9.04	5500	1.84	0.20	5500	2.00	0.22
20	6,000	8.24	6000	1.76	0.21	6000	1.76	0.21
21	6,500	7.36	6500	1.44	0.20	6500	1.60	0.22
22	7,000	6.16	7000	1.36	0.22	7000	1.44	0.23
23	7,500	5.60	7500	1.12	0.20	7500	1.20	0.21
24	8,000	4.96	8000	1.08	0.22	8000	1.12	0.23
25	8,500	4.24	8500	1.04	0.25	8500	1.06	0.25
26	9,000	3.68	9000	1.02	0.28	9000	1.04	0.28
27	9,500	3.36	9500	0.90	0.27	9500	0.90	0.27

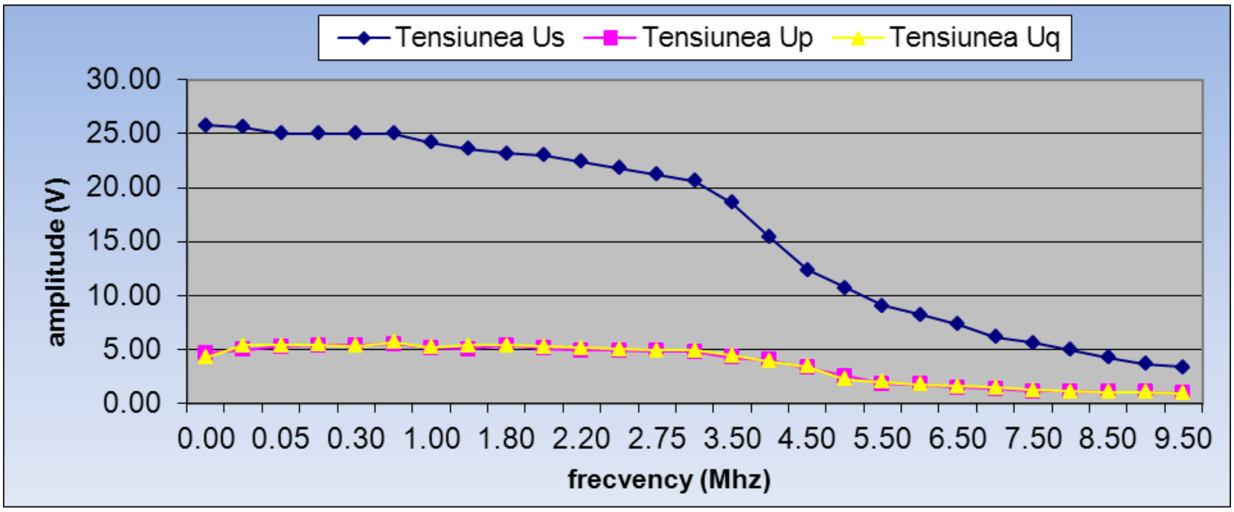

Fig. 9 Us, Up, Uq depending on the frequency of the signal applied to the circuit input

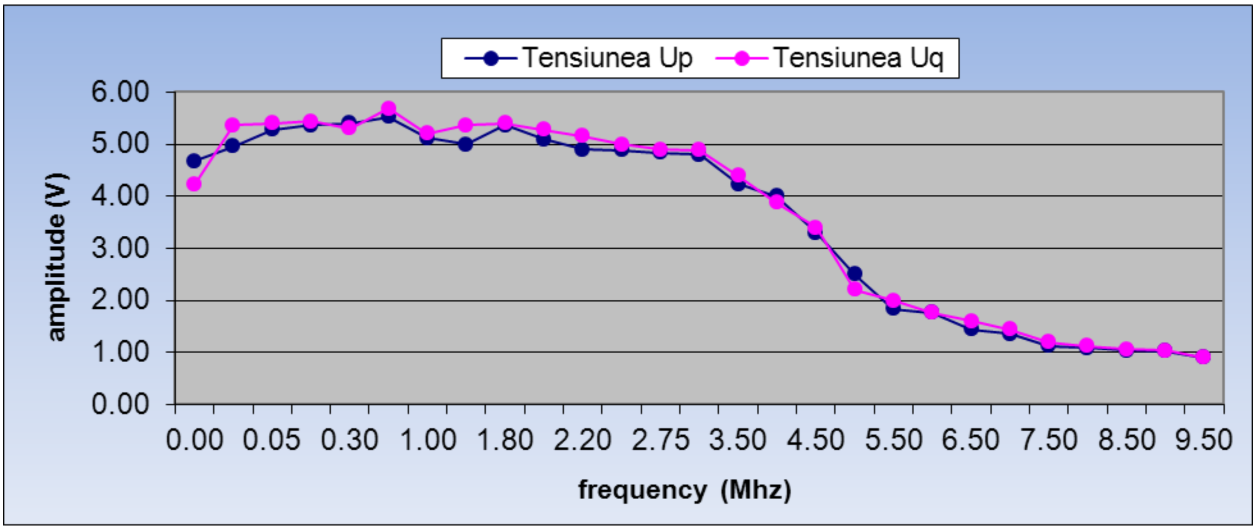

Fig. 10 Up, Uq depending on the frequency of the signal applied to the circuit input

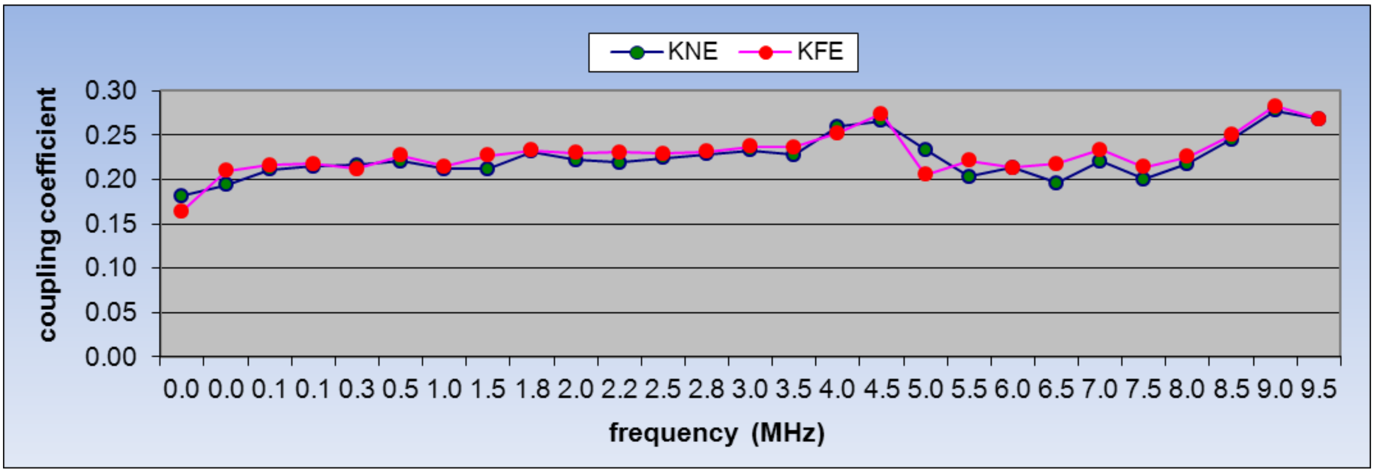

Fig. 11 Coupling coefficient variation

3. Experimental result

As evidenced by the above images, in the experiment the circuit considered generator, which has as its load resistance 50 Ω, with a sinusoidal signal whose frequency has been modified in the range 1KHz - 10 MHz, and the amplitude of the signal varied according to frequency, as shown in *table 1*. Sinusoidal signal was generated by a signal generator. The frequency range chosen was consistent with the theoretical considerations relating to the relationship between the length of the conductors and the wavelength ($l << \frac{\lambda}{10}$, where λ - it is the wavelength, and l is the length of the line). In the case of the experiment were used copper conductors with a diameter of 4mm and length of 20 cm.

During the experiment, by means of BNC-type connectors, specially mounted in this regard, the waveforms of the induced tensions were viewed and their amplitudes measured at near and far ends of the circuit considered disturbed.

Figure 9 and figure 10 shows the measured results of near-end crosstalk voltage between the receptor wire and reference wire respectively when placed in an EM environment and the results of far-end crosstalk voltage between the receptor wire and reference wire respectively.

It can be seen from the figure that magnitude of near-end and far-end increases with frequency at low frequency region, 1-1000 KHz and decrease constantly as the frequency increase in the region 1-10 MHz.

Also the coupling coefficients, K_{NE} *and* K_{FE}, has a similar variation for all the frequency measure range, some undulation appears and this will limit the speed of signal transmission over the MTL structure of the circuit.

4. Conclusions

This paper presents the initial investigation of a simple crosstalk model by predicting the near-end and far-end crosstalk voltage in an EMI/EMC environment. The results from EMI/EMC stand point of view are very important for system design where implementation of multiconductor is necessary in any electronic system.

The time domain experimental results presented in figures 9 and 10 shows an agreement with the theoretical findings.

The measurement of the near-end and far-end crosstalk is an important part of the certification process needed before a device or system can be marked.

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