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INDUCTIVE ELECTROMAGNETIC COUPLING MECHANISM AND INFLUENTIAL FACTORS

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Abstract: *General approaches of electromagnetic disturbances coupling paths talk too little about the condition they occur and about the dimensions of their effects. With the objective to highlight inductive electromagnetic coupling mechanism, using a simple conductive rectangular loop placed in the vicinity of a straight conductor crossed by a periodical current with sinusoidal and trapezoidal waveform, and by solving the equivalent circuits in sinusoidal regime and the corresponding differential equations for trapezoidal waveform of electric current pulses, the electrical quantities and the influence of extrinsic factors were obtained. This paper is a concrete, precise, simple and clear approach that establish theoretical base of some useful large scale applications like high frequency shielding.*

Key words: *electromagnetic disturbances, inductive coupling, inductance, high frequency shielding, screens.*

1. Introduction

With the widespread introduction of electronics, the electromagnetic compatibility became an important issue. Moreover, the use of increasingly higher frequency in industrial applications causes that the coupling paths between sources of disturbance and equipment/victim to be more complex.

Electromagnetic compatibility issue has been addressed in the past 50 years research, in treatises like [1], [6], articles [2], [5], and many solutions for electromagnetic inductive or capacitive coupling have been also patented [3]. The electromagnetic coupling is described and analyzed, and general relationships for electrical quantities (currents and voltages) that characterize the induced disturbances have been obtained.

However, a detailed analysis of the physical phenomena of the electromagnetic coupling under variable frequency conditions is less studied. Understanding and knowledge of the in electromagnetic coupling phenomena are required in order to substantiate mitigation methods and techniques of electromagnetic disturbances coupling pathways.

This paper deals with the analysis of the phenomena occurring at coupled simple electric circuits in order to establish the values of the induced currents, highlighting the factors that contribute to electro-magnetic disturbances amplification or mitigation.

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2. The Inductive Coupling Analysis

The analysis of frequency dependence of inductive coupling provides valuable knowledge on how an electrical installation can be carried out to the best possible high frequency electromagnetic disturbances protection.

Inductive electromagnetic coupling is realised when a variable and relatively high intensity current induces in a victim circuit considerable voltages, which determine by different ways of closing the disturbance currents.

For a detailed inductive electromagnetic coupling analysis, the case of a long straight conductor, crossed by a periodic, variable frequency electric current $i(t)$, which is located at a distance s from a conductive rectangular loop, with dimensions l and w (Figure 1). Also, an inserted serial $R_2 = 50\ \Omega$ resistance in the loop circuit is taken in account. The skin effect is neglected.

The dependence of the loop induced current intensity on the coupled electric circuits parameters and on the inductor current waveform and frequency is analyzed.

The analytical calculus of the electrical quantities describing inductive coupling has the following steps.

2.1. Mutual Inductance Calculus

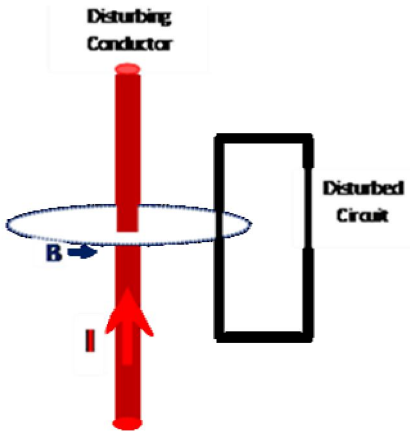
For the case of AC current i_I flowing in the straight conductor, with the magnetic circuit law [4] applied along the curve Γ:

$$\oint_{\Gamma} \mathbf{H} \cdot \mathbf{dl} = 2\pi \cdot r \cdot H = i_I , \tag{1}$$

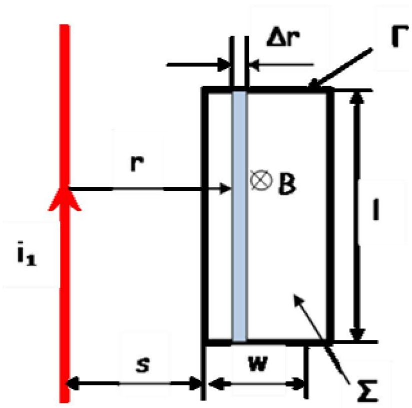
the expression of magnetic induction in a point of the surface enclosed by the victim circuit is obtained:

$$B = \frac{\mu_0 \cdot i_I}{2\pi r}, \tag{2}$$

where μ_0 is the vacuum permeability and r is the distance from inducting conductor to victim circuit.



a)



b)

Fig. 1. *Inductive coupling in a conductive rectangular loop: a) general view; b) geometrical dimensions*

Considering the loop surface element $dA_b = l dr$, the total inducting magnetic flux is:

$$\Phi_b = \iint_{\Sigma} \mathbf{B} \cdot \mathbf{dA} = \frac{\mu_0 \cdot i_I \cdot l}{2\pi} \int_{s}^{s+w} \frac{dr}{r} .$$

It results:

$$\Phi_b = \frac{\mu_0 \cdot i_I \cdot l}{2\pi} \cdot \ln\left(\frac{s+w}{s}\right). \tag{3}$$

The mutual inductance, inductive coupling responsible will be:

$$M_{12} = \frac{\Phi_b}{i_1} = \frac{\mu_0 \cdot l}{2\pi} \cdot \ln\left(\frac{s+w}{s}\right). \tag{4}$$

The relation points the directly proportional dependence of loop's mutual inductance on length l which circuits are coupled and on and the natural logarithm of the ratio of width w and s distance to victim circuit.

2.2. Self Inductance Calculus

Starting from the definition relation for the loop's self inductance:

$$L_2 = \frac{\Phi_2}{i_2}, \tag{5}$$

where i_2 is the induced current in the rectangular loop, the self inductance could be obtained. For rectangular loops, a fairly good approximation is given with relation:

$$L_2 = \frac{\mu_0}{2\pi} \cdot \left[\ln\left(\frac{2P}{p}\right) - \ln\frac{P^2}{A} + 0.25\right], \tag{6}$$

where P is loop's perimeter, p is loop's conductor radius, and A is the loop's surface.

Mutual and self inductance value is just a matter of geometry and is independent on the disturbance current's magnitude, but only on the geometry of the loop and on the distance from the disturbing circuit.

The case study is performed for the loop dimensions: l = 0.3 m, w = 0.1 m, and the distance between disturbing circuit and rectangular loop: s = 2 mm.

Loop conductor's radius is p = 0.001 m, perimeter P = 2(0.3 + 0.1) = 0.8 m, loop's surface A = 0.3 x 0.1= 0.03 m^2.

With the relations (4) and (6) it results: the loop's mutual inductance value: M_{12} = 0.2 μH, and the loop's self inductance value: L_2 = 0.9 μH.

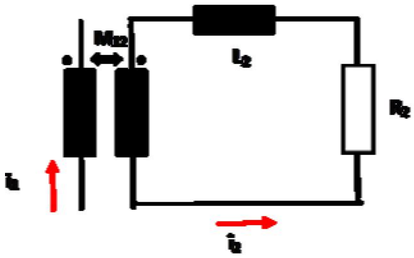


Fig. 2. *Disturbing and victim circuit equivalent scheme*

3. Inductive Coupling Induced Current Analysis

3.1. The Case of Sinusoidal, Variable Frequency Inducting Current Waveform

For the case analysed in Par. 2.1, the equivalent circuit is shown in Figure 2. The relationship between disturbing (source) current phasor $\mathbf{I_1}$ and disturbed (victim) current phasor $\mathbf{I_2}$ is:

$$\mathbf{I_2} = \frac{j\omega \cdot M_{12}}{R_2 + j\omega \cdot L} \cdot \mathbf{I_1}. \tag{7}$$

It results the I_2/I_1 ratio of source/victim currents effective values:

$$\frac{I_2}{I_1} = \frac{\omega \cdot M_{12}}{R_2 \cdot \sqrt{1 + \left(\frac{\omega L}{R_2}\right)^2}}. \tag{8}$$

Figure 3 shows I_2/I_1 dependence on disturbing current's frequency.

Note that the I_2/I_1 ratio increases with the increasing of the inductor current frequency.

Regarding the frequency, two limit cases can be distinguished:

- At low frequencies ($\omega L << R$), when relation (8) becomes:

$$\frac{I_2}{I_1} = \frac{\omega \cdot M_{12}}{R_2}. \tag{9}$$

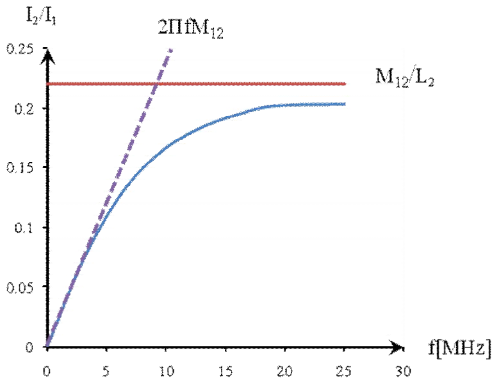


Fig. 3. *Induced current to inducting current ratio as a function of frequency*

The I_2/I_1 ratio increases linearly with the frequency. For the case considered, at $f = 1$ MHz, $I_2\ I_1 = 0.015$.

• At high frequency ($\omega L >> R$), when relation (8) becomes:

$$\frac{I_2}{I_1} = \frac{\omega \cdot M_{12}}{L_2}. \tag{10}$$

The I_2/I_1 curve tends asymptotically to M/L. For the considered case, it results $I_2/I_1 = 0.13$.

The above relation underlies inductive coupling disturbances mitigation methods:

• Mutual inductance M_{12} mitigation by:

- reduction of length l, that disturbing circuit and victim circuit are coupled;
- reduction of rectangular loop's width w, such as the ratio $(s+w)/s$ to be as small as possible; for $w \to s$, this ratio tends to the minimum value ln 2.

• Maximisation of victim circuit's self inductance L_2.

3.2. The Case of Trapezoidal, Variable Frequency Inducting Current Waveform, Having Different Increasing/Decreasing Slopes

The case of two disturbing currents i_{1a} and i_{1b} of trapezoidal waveform, with different slopes is considered. The i_{1a} has the slope twice as fast than current i_{1b}.

For this case (Figure 4), the disturbing current variation laws are:

a) For disturbing current i_{1a}:

$$\begin{aligned} i_{1a} &= 2t, && \text{for } t \in [0, 1],\\ i_{1a} &= 2, && \text{for } t \in (1, 4],\\ i_{1a} &= 4 - 2t, && \text{for } t \in (4, 5]. \end{aligned} \tag{11}$$

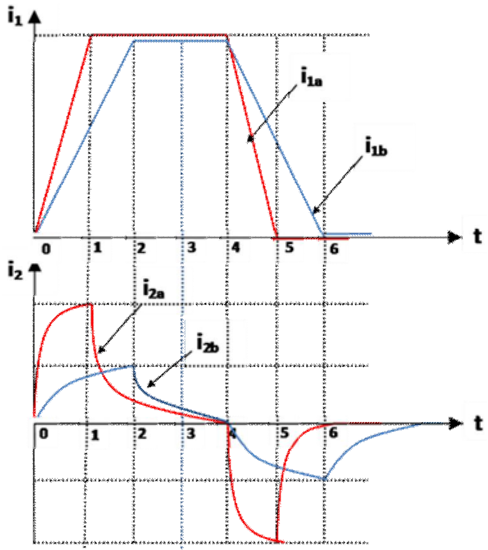


Fig. 4. *The influence of the rate of change of disturbing current on the induced current*

b) For disturbing current i_{1b}:

$$\begin{aligned} i_{1b} &= t, && \text{for } t \in [0, 2],\\ i_{1b} &= 2, && \text{for } t \in (2, 4],\\ i_{1b} &= 6 - t, && \text{for } t \in (4, 6]. \end{aligned} \tag{12}$$

The disturbing currents induce the currents in the victim circuit whose the shape variation is obtained by solving the following equation:

$$\frac{\mathrm{d}(\Phi_{i1} - \Phi_{i2})}{\mathrm{d}t} = M_{12}\frac{\mathrm{d}i_1}{\mathrm{d}t} - L_2\frac{\mathrm{d}i_2}{\mathrm{d}t} = R_2 \cdot i_2. \tag{13}$$

a) Establishing the induced current expression in case of steep slope trapezoidal disturbing current.

Victim circuit equation is:

$$M_{12}\frac{\mathrm{d}i_1}{\mathrm{d}t}-L_2\frac{\mathrm{d}i_2}{\mathrm{d}t}=R_2\cdot i_2\,. \tag{14}$$

Considering the variation law of disturbing current i_{1a}, relation (10) in the period [0,1], the equation becomes:

$$\frac{L_2}{R_2}\cdot\frac{\mathrm{d}i_{2a}}{\mathrm{d}t}=2\cdot\frac{M_{12}}{R_2}-i_{2a}\,. \tag{15}$$

The solution is:

$$i_{2a}(t)=I_{2a}-\mathrm{e}^{-\frac{R_2\cdot t}{L_2}+\ln\left(2\cdot\frac{M_{12}}{R_2}\right)}, \tag{16}$$

where $I_{2a} = 2M_{12}/R_2$ is the maximum value of induced current, when $t \rightarrow 1$.

In the period (1,4], the Eq. (15) becomes:

$$L_2\cdot\frac{\mathrm{d}i_{2a}}{\mathrm{d}t}=R_2\cdot i_{2a}=0\,, \tag{17}$$

with solution:

$$i_{2a}(t)=I_{2a}\cdot\mathrm{e}^{\frac{R_2\cdot t}{L_2}}\,. \tag{18}$$

In the period (4,5], the solution for Equation (15) is:

$$i_{2a}(t)=-I_{2a}+\mathrm{e}^{-\frac{R_2\cdot t}{L_2}+\ln\left(2\cdot\frac{M_{12}}{R_2}\right)\frac{4R_2}{L_2}}\,. \tag{19}$$

b) For i_{1b}, a current with a smoother slope, the maximum value becomes:

$$I_{2b}=\frac{M_{12}}{R_2}\,. \tag{20}$$

The current $\mathbf{I_{2b}}$ is two times smaller than $\mathbf{I_{2a}}$.

In Figure 4, the comparison between the wave shape of i_{2a}, the current induced by the steep slope trapezoidal disturbing current i_{1a}, and the waveform of $i_{2b,}$ the current induced by the slow slope trapezoidal disturbing current i_{1b} is shown.

Note that the signal with steeper front ($\Delta i_{1a}/\Delta t > (\Delta i_{1b}/\Delta t)$ generates higher amplitude disturbances ($I_{2a} > 2\, I_{2b}$).

High induced current values occur in digital signals due to their very short rise time (with very steep slope).

4. Application - Cable Shielding Effect at High Frequencies

By induction effect, the induced current i_2 (Figure 1), (Figure 2) will generate in the victim circuit a magnetic field opposite to disturbing magnetic field. This property can be used to shield the sensitive electrical or electronic systems nearby the inductor circuits. Practical examples of this application are cables screens, the cables routes or any unused core of cables used as screens.

The case of a cable screen as a conductive rectangular loop with different (depending on the quality of the type of material) resistance R_2 values, in the vicinity of a conductor crossed by a sinusoidal current is considered.

The net magnetic flux flowing in the loop area is:

$$\Phi_b=\Phi_{i1}-\Phi_{i2}=M_{12}\cdot i_1-L_2\cdot i_2\,. \tag{21}$$

In complex, with consideration of relation (7), it is obtained:

$$\mathbf{\Phi_b}=\frac{M_{12}\cdot R_2}{R_2+j\omega\cdot L_2}\cdot\mathbf{I_1}\,, \tag{22}$$

or, in effective values:

$$\mathbf{\Phi_b}=\frac{M_{12}\cdot R_2}{\sqrt{(R_2)^2+(\omega\cdot L_2)^2}}\cdot\mathbf{I_1}\,. \tag{23}$$

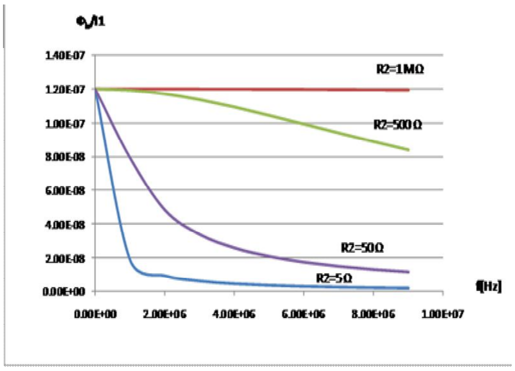


Fig. 5. *Dependence of ratio between the magnetic flux Φ_b through the victim circuit and induction current I_1, on the frequency, for different shield resistance R_2 values*

Note that the shielding effectiveness increases dramatically with loop resistance decreasing (Figure 5), the net magnetic flux is minimized for low values of resistance R_2, so, all connections of shielded facilities, trunks, cable ducts, cabinets, must have low resistance at high frequencies.

The skin effect should be considered. Optimal geometry of the conductors is flat strips, solid or traces, where the area is large and the thickness small. Circular conductors are not indicated.

The screen works effectively if the induced current finds appropriate closure pathways and found no breaks in the loop circuit. The screens should be connected to ground at both ends to allow free circulation of current.

5. Conclusions

Some fundamental and simple calculus gives a clear image of what the inductive coupling means.

The magnitude of the inductive coupling phenomena in the real world, was emphasized and the theoretical base of some useful applications like high frequency shielding have been established.

For cables working at high frequency, the capacitive electromagnetic coupling phenomenon will be considered, and the importance of the cable's dielectric quality will be revelled.

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