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Inductive Coupling of the Electrical Systems

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Summary: **This papers deals with the computer analysis of the inductive coupling of the electromagnetic compatibility (EMC) problem focused at the area of power electronics and electrical drives and tests performed by the numerical computer simulation, which can also disclose the startling facts concerning the electromagnetic compatibility (EMC) problems.**

Key words:
Electromagnetic compatibility, Power electronics, Electrical systems

1. INTRODUCTION

The importance of the electromagnetic compatibility (EMC) of all electrical products is rapidly increasing during the last decade. The environment is increasingly polluted with electromagnetic energy. The interference output into the surroundings, is doubled every three years, and covers a large frequency range.

The possibility of the disturbances of equipments and errors becomes more serious as the consequence of the growth of the electronic circuit complexity. According to the new technical legislation and also due to economic consequences the EMC concept of all products must be strictly observed. It must start with the specification of the equipment performance and end with the equipment installation procedures.

2. EMC AND ENVIRONMENTAL WASTE

We all know the problems of environmental pollution caused by solid, liquid and gaseous wastes. We are aware of most of these pollutants through our senses. Due to increasing life standard, the contamination of our environment with the electromagnetic energy is constantly increasing too. Since human beings have no organs of perception for such contamination, they cannot perceive it. The "great sufferers", producing such waste, are the electronic systems developed by man and meant to be effective within these electromagnetic surroundings, producing of course, electromagnetic waste in turn. On one side, interferences are deliberately or involuntarily produced. The place of their origin is called interference source. One the other side, devices may be hindered in their function by such interferences. Those objects are called interference objects.

The possible interfaces between sources and objects are shown in Figure 1. The four basic types of coupling ways can realize these interfaces.

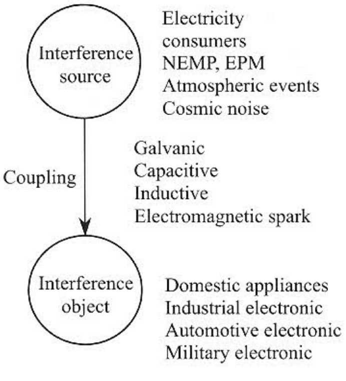

Fig. 1. Interference diagram

3. EMC – THE INTERFERENCE MECHANISM

The interference mechanism can be described in a simplified form as follows. The interference source can be for instance, the power semiconductor converter or motor. Interference is produced in interference source, which gets into electronics in undesirable ways, and due to various effects distorts the signals. The transmission can be direct, for example by galvanic coupling between interference source and interference sink. The interference can be spread through air or via ducts, or coupled inductively or capacitively into signal lines.

The development of power semiconductor parts has caused vehement evolution of the power electronics branch in the last ten years. For the investigation of the converter functionality it was necessary first theoretically analyze and then practically verify the assumed activity of the converter. Now, we can eliminate the laborious theoretical analysis by numerical computer simulation, which can also disclose the startling facts concerning of the electromagnetic compatibility (EMC) problems.

4. INDUCTIVE COUPLING

The inductive coupling is typical for two and more galvanically separated electrical loops at the moment when minimum one of them is flowing by a time variable current, which is creating the corresponding time variable magnetic field. In such case the mutual intercircuit influence is given as the dependence on the slope of the current increases or decreases, the circuit's environment magnetic property and as well as the circuit's geometrical dimensions.

For the predictive investigation of the intercircuit inductive coupling we will focus our interest on the case of the two electrical loops l_1 and l_2 with the currents i_1 a i_2 and we will try to state the influence of the loop l_1 on loop l_2 as it is shown in Figure 2.

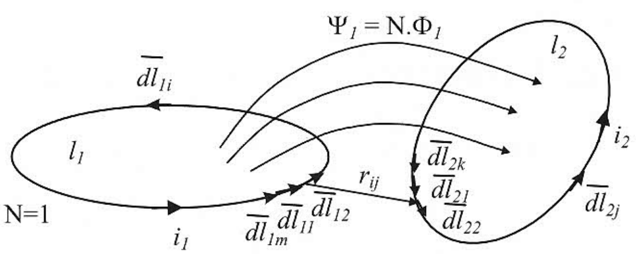

Fig. 2. The investigated loops

According to Maxwell's equation for a quasi-stationary magnetic field:

$$rot\ \ \overline{E} = -\frac{\partial \overline{B}}{\partial t} \tag{1}$$

and following by its integral form:

$$\int_S rot\ \ \overline{E}.d\overline{S} = -\int_S \frac{\partial \overline{B}}{\partial t}.d\overline{S} = -\frac{\partial}{\partial t}\int_S \overline{B}.d\overline{S} \tag{2}$$

and after the application of the Stoke's theorem, we can obtain the equation for the induced voltage:

$$u_{i2} = -\mathbf{N}.\frac{\partial \phi_1}{\partial t} = -\frac{\partial \psi_1}{\partial t} = -M\frac{\partial i_1}{\partial t} \tag{3}$$

Where M is the coefficient of the mutual inductance. For the magnetic flux Ψ_1 definition the equation:

$$\phi_1 = \oint_{l_2} \overline{A}_2.d\overline{l}_2 \tag{4}$$

is valid where $\overline{A}_2$ is the vector of the magnetic field potential created by the current i_1. We can calculate the value of this vector by the following equation:

$$\overline{A}_2 = \frac{\mu.i_1}{4\pi}\oint_{l_1}\frac{d\overline{l}_1}{r_{12}} \tag{5}$$

After the substitution of the last equation to the equation valid for the magnetic flux ϕ_1 we can receive the next relation:

$$\phi_1 = \oint_{l_2}\left[\frac{\mu.i_1}{4\pi}\oint_{l_1}\frac{d\overline{l}_1}{r_{12}}\right].d\overline{l}_2 = \frac{\mu.i_1}{4\pi}\oint_{l_1}\oint_{l_2}\frac{d\overline{l}_1.d\overline{l}_2}{r_{12}} \tag{6}$$

and then:

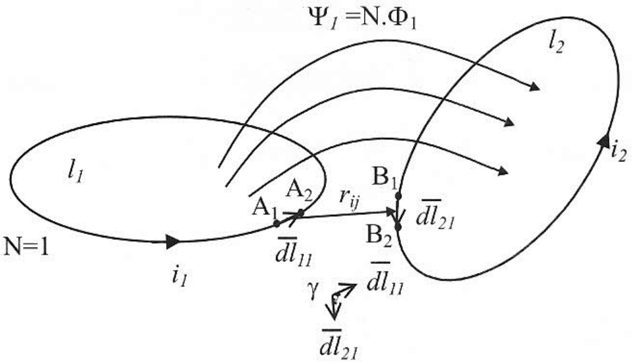

Fig. 3. The geometrical dimensions of the investigated loops

$$u_{i2} = -\frac{\partial\left(\frac{\mu.i_1}{4\pi}\oint_{l_1}\oint_{l_2}\frac{d\overline{l}_1.d\overline{l}_2}{r_{12}}\right)}{\partial t} = -\frac{\left(\frac{\mu}{4\pi}\oint_{l_1}\oint_{l_2}\frac{d\overline{l}_1.d\overline{l}_2}{r_{12}}\right)\partial i_1}{\partial t} = -M\frac{\partial i_1}{\partial t} \tag{7}$$

For the practical use, it is more advantageous to express the induced voltage in the form of a differential:

$$u_i = -\frac{di}{dt}.\sum_{i=1}^{m}\sum_{j=1}^{k}\frac{\mu}{4\pi}\frac{dl_{1i}.dl_{2j}.\cos\gamma_{dlij}}{r_{ij}} \tag{8}$$

If we know the geometrical dimensions of the investigated loops - Figure 3. and we want to state their mutual inductive coupling then we can use the next relation (9) for the induced voltage, which is based on the 3D Cartesian coordinate system.

For the global solution of the inductive coupling part of the Electromagnetic Compatibility (EMC) problem inside the total electrical system, it is necessary to do the global circuit analyze, respecting the mutual intercircuit inductance couplings. It results into the following integral-differential system of equations 9 (see on the bottom of page).

$$u_{cc1} = R_{c1}.i_1 + L_{c1}.\frac{di_1}{dt} + \frac{1}{C_{c1}}\int i_1.dt + \sum_{\substack{j=1\\ j\neq 1}}^{k} u_{ij} \tag{10}$$

For this purpose it is very suitable to explore the existing simulation programs such as for instance the PSPICE program utilized worldwide.

In the next part, we will try to state the influence of the one quadrant impulse converter, to the sensing circuit as it is shown in Figure 4. The circuit dimensions are $a = 0{,}2$ m, $b = 0{,}3$ m, $c = 0{,}1$ m, $d = 0{,}05$ m, $e = 0{,}005$ m. The copper wires,

$$u_i = -\frac{di}{dt}.\sum_{i=1}^{m}\sum_{j=1}^{k}\frac{\mu}{4\pi}\frac{(A_{x2i}-A_{x1i}).(B_{x2j}-B_{x1j})+(A_{y2i}-A_{y1i}).(B_{y2j}-B_{y1j})+(A_{z2i}-A_{z1i}).(B_{z2j}-B_{z1j})}{\sqrt{\left(\left(B_{x1j}+\frac{|B_{x2j}-B_{x1j}|}{2}\right)-\left(A_{x1i}+\frac{|A_{x2i}-A_{x1i}|}{2}\right)\right)^2+\left(\left(B_{y1j}+\frac{|B_{y2j}-B_{y1j}|}{2}\right)-\left(A_{y1i}+\frac{|A_{y2i}-A_{y1i}|}{2}\right)\right)^2+\left(\left(B_{z1j}+\frac{|B_{z2j}-B_{z1j}|}{2}\right)-\left(A_{z1i}+\frac{|A_{z2i}-A_{z1i}|}{2}\right)\right)^2}}$$

Equation 9

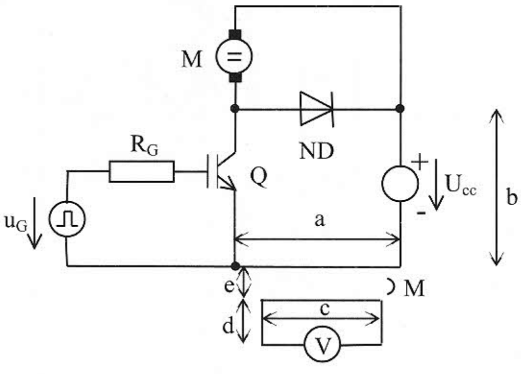

Fig. 4. The investigated circuits

have the radius $R = 0{,}0006$ m and the relative permitivity of the circuits environment is $\mu_r = 0{,}991$.

The inductance of the first loop is given as:

$$L_1 = L_{e1} + L_{i1} = \frac{\mu_0 b}{\pi} ln\frac{a-R}{R} + \frac{\mu_0 a}{\pi} ln\frac{b-R}{R} + \frac{\mu.2.(a+b)}{8\pi} = 1{,}294\mu H \tag{12}$$

and the second as:

$$L_2 = L_{e2} + L_{i2} = \frac{\mu_0 c}{\pi} ln\frac{d-R}{R} + \frac{\mu_0 d}{\pi} ln\frac{c-R}{R} + \frac{\mu.2.(c+d)}{8\pi} = 0{,}294\mu H \tag{13}$$

The mutual inductance M calculated, from the above mentioned equation, is $M = 477{,}4$ nH. The magnetic coupling coefficient k is given as:

$$k = \frac{M}{\sqrt{L_1 + L_2}} = 0{,}774 \tag{14}$$

Now we can use the PSPICE simulation program for solving the inductive coupling problem between the both circuits. The parameters of the circuit simulation are $R_Z = 11{,}66\ \Omega$, $L_Z = 400\ \mu H$, $R = 10\ \Omega$, $R_G = 100\ \Omega$ and $U_{CC} = 70V$. The schematic connection is shown in Figure 5. The

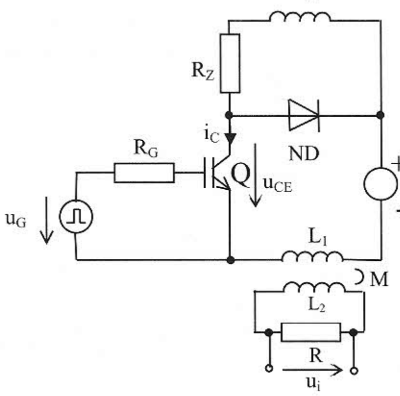

Figure 5. The simulation circuit

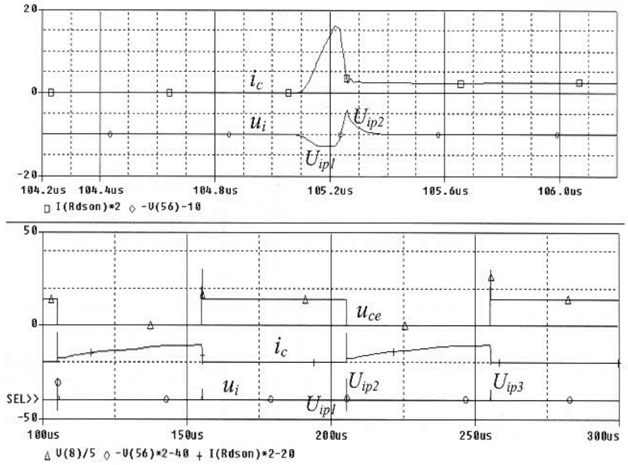

Fig. 6. The simulation results

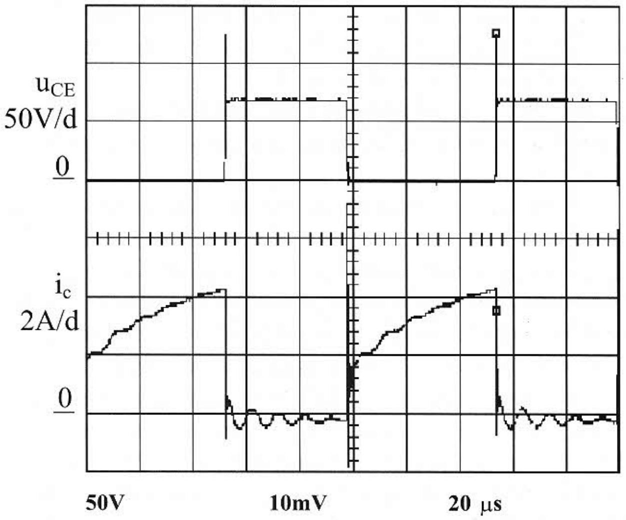

Fig. 7. The measured voltage u_{CE} and current i_C

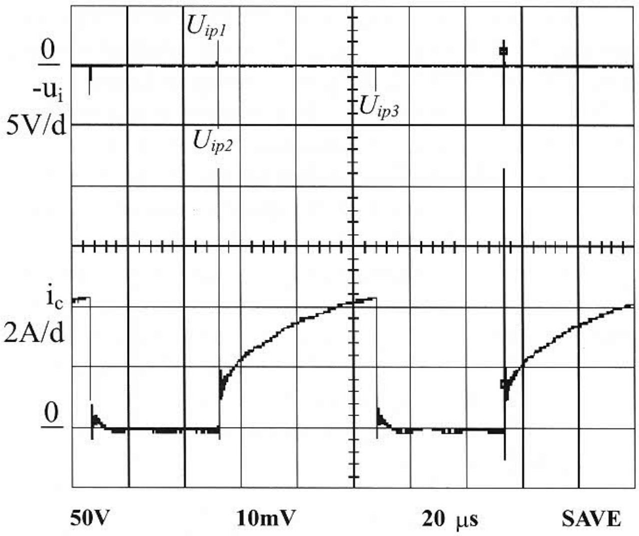

Fig. 8. The measured voltage $-u_i$ and current

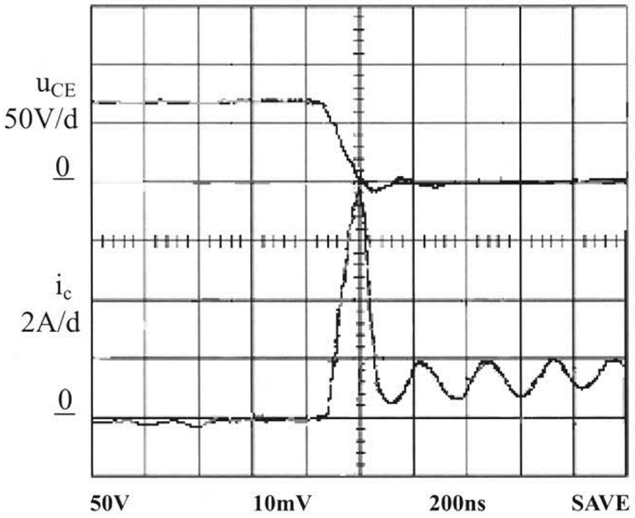

Fig. 9. The switching on detail of the voltage u_{CE} and current i_C

IGBT transistor Q was switching with the frequency 10 kHz and switch on/off ratio equals to 0,5. The results obtained by the simulation are shown in Figure 6.

The results obtained by the measurement are shown in Figure 7 and Figure 8, the switching details in Figure 9 and Figure 10.

Comparing the simulated and measured results we can see, that the peaks of the transistor current i_c have the same values of 8,4 A in the both cases. The equal values of 4,4 A have both the simulated and measured transistor current at the moment, when transistor is switched of. A small difference exists only between the simulated and measured curves of the transistor voltage u_{CE}. The overvoltage generated at the moment, when the transistor is switched, reaches the value of 150 V, in the case of the simulated result. However the corresponding overvoltage has only the value of 130 V, in the case of the measured result. The peaks of simulated and measured induced voltages have the same values of U_{i1} = -2,2V, U_{i2} = 5,02V, U_{i1} = 2,1V. It means, that such method of analysis should be accepted, for the inductive coupling investigation of the EMC problem.

To improve the obtained results, the numerical solution of the magnetic field by finite element method program was also used. The result of such analysis is shown in Figure 11.

From the "Integral result" data window, it is possible to state, that the value of the magnetic flux inside the sensing circuit is 3,317.10^{-9} Wb. Based on the basic program's property, allowing semi-real 3D space simulation with the 3rd dimension equal only to the basic unit of the depth (where the basic unit of the depth is 1mm) we have to multiply the obtained value of the magnetic flux by the value of the sensing circuit's depth c = 100 mm. The total magnetic flux is then 331,7.10^{-9} Wb. This flux was excited by the peak circuit current 8,4 A, the rising time of which was 120 ns. On the basis of the above mentioned equations, the first peak of the induced voltage we can calculate as:

$$U_{ip1} = \frac{\Delta \ddot{O}_1}{\Delta t_1} = \frac{0 - 331,7.10^{-9}}{140.10^{-9}} = \frac{-331,7.10^{-9}}{140.10^{-9}} = -2,369 \ V \tag{15}$$

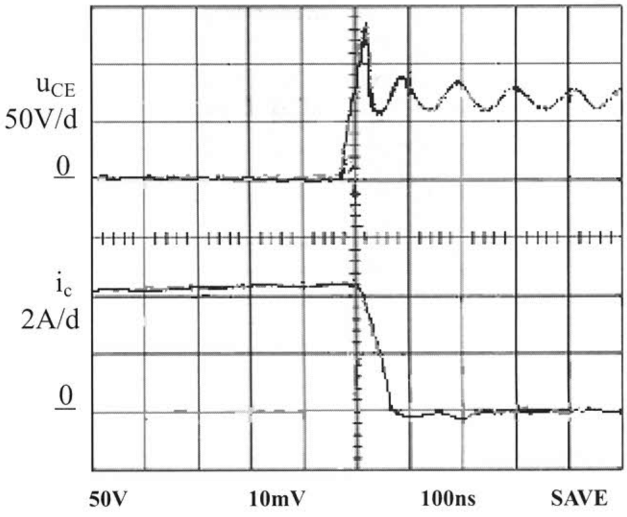

Fig. 10. The switching off detail of the voltage u_{CE} and current i_C

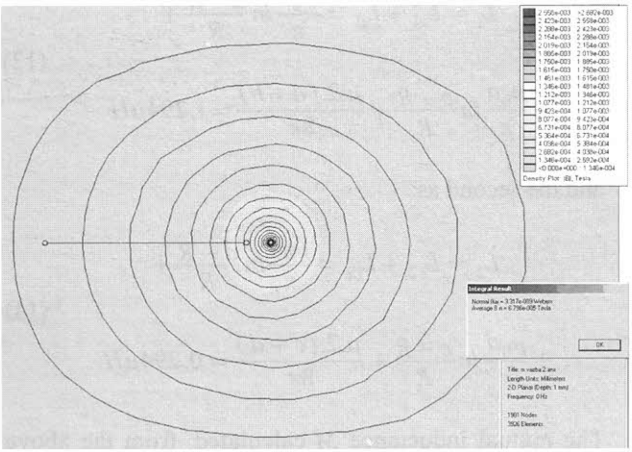

Fig. 11. The finite element simulation method of the magnetic field

Similarly, it is possible to calculate the rest of the peaks of the induced voltage u_i:

$$U_{ip2} = \frac{\Delta \ddot{O}_2}{\Delta t_2} = \frac{331,7.10^{-9} - 55,3.10^{-9}}{55.10^{-9}} = \frac{276,4.10^{-9}}{55.10^{-9}} = 5,025 \ V \tag{16}$$

$$U_{ip3} = \frac{\Delta \ddot{O}_3}{\Delta t_3} = \frac{173,7.10^{-9} - 0}{80.10^{-9}} = \frac{173,7.10^{-9}}{80.10^{-9}} = 2,171 \ V \tag{17}$$

The results obtained by the finite element numerical simulation method are again confirming the correctness of the above mentioned methods.

5. CONCLUSION

The performed analyses indicate, that the fast power field effect transistor switching can produce the induced voltage with the place value of some volts up to some tenths' of volts in the nearby circuits. It is also evident, that the magnitude of the induced voltage depends on the magnetic flux's slope. It means, that the fast switching of the small currents, can generate large peaks of the induced voltage, too.

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