

EMC AND PARASITIC CAPACITANCES OF CONVERTERS

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Abstract. The paper is dealing with some electromagnetic compatibility (EMC) problems of converters and inverters, which are utilized for feeding of electric machines and its analyzing by PSpice program. The main attention is focused on implications of parasitic capacitance and capacitive coupling existence.

Key words: EMC, converter, PSpice simulation, parasitic capacitances, capacitive coupling.

1. Introduction

Now we can eliminate laborious theoretical analysis and economical exacting realization by numerical computer simulation, which can also disclose the startling facts concerning of the electromagnetic compatibility (EMC) problems.

2. Converters parasitic capacitance calculation

Capacitive coupling is typical for galvanically separated circuit nodes, between which exists mutual influence by individual intensity vectors \vec{E}_i of electrostatic field, Figure. 1. In such case the influence value is given by rising or decreasing slope of potential in described nodes, electrode area dimensions, space dielectric property and wire geometrical ordering in described nodes.

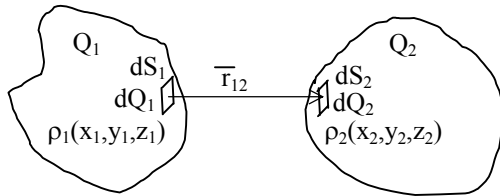


Fig. 1. Capacitive coupling

For predictive investigation of capacitive coupling implications we will come out from well-known Maxwell's equations valid for electrostatic field:

$$\text{rot } \vec{E} = 0 \quad (1)$$

$$\text{div } \vec{D} = \rho \quad (2)$$

where the vector of electric induction \vec{D} is given as

$$\vec{D} = \epsilon \cdot \vec{E} \quad (3)$$

Based on physics knowledge we can state the force acting between two elementary charges Q1 and Q2.

$$\vec{F} = \frac{1}{4\pi\epsilon_0} \iint_{S_1, S_2} \frac{\vec{r}_{12}}{r_{12}^3} \cdot \rho_1 \cdot dS_1 \cdot \rho_2 \cdot dS_2 \quad (3)$$

where $\rho_1 = dQ_1/dS_1$ and $\rho_2 = dQ_2/dS_2$. One element \vec{E}_{1i} of electrostatic intensity vector \vec{E}_1 can be expressed as:

$$\vec{E}_{1i} = \frac{\vec{F}_{1i}}{Q_{2i}} = \frac{\frac{1}{4\pi\epsilon_0} \int_{S_1} \frac{\vec{r}_{12}}{r_{12}^3} \cdot \rho_1 \cdot dS_1}{Q_{2i}} = \frac{1}{4\pi\epsilon_0} \int_{S_1} \frac{\vec{r}_{12}}{r_{12}^3} \cdot \rho_1 \cdot dS \quad (4)$$

Total electrostatic intensity vector \vec{E} at investigated place will be given as sum of vectors \vec{E}_1 and \vec{E}_2 induced by both charged volumes. Existing voltage between these volumes is possible to express by next equation.

$$U_{12} = \varphi_1 - \varphi_2 = \int_1^2 (\vec{E}_1 + \vec{E}_2) \cdot d\vec{r}_{12} = \int_1^2 \left(\frac{1}{4\pi\epsilon_0} \int_{S_1} \frac{\vec{r}_{12}}{r_{12}^3} \cdot \rho_1 \cdot dS_1 + \frac{1}{4\pi\epsilon_0} \int_{S_2} \frac{\vec{r}_{21}}{r_{21}^3} \cdot \rho_2 \cdot dS_2 \right) \cdot d\vec{r}_{12} \quad (5)$$

If we will suppose that $Q_1 = Q$ and $Q_2 = -Q$, so we can write the equation for created capacitance.

$$C_{12} = \frac{Q}{U_{12}} \quad (6)$$

In many cases the engineers must state mutual parasitic capacitance of two wires, which have

optional routing as it is shown in Figure 2. The analytical expression of resulting capacitance is very difficult in such case and in due to they are utilizing analytic-numerical method consist in differential form utilizing. For all that the following basic assumption must be done.

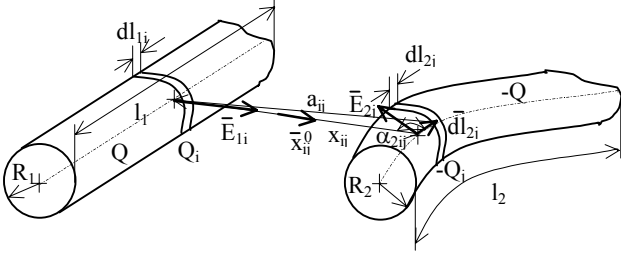


Fig. 2. Capacitive coupling

$$l_1 = \sum_{i=1}^{m \rightarrow \infty} dl_{1i}, \quad l_2 = \sum_{j=1}^{k \rightarrow \infty} dl_{2j} \quad (7)$$

The potential at the second wire place we can express by next equation.

$$\begin{aligned} \varphi_2 &= \sum_{i=1}^m \frac{Q_i}{2\pi\epsilon dl_i} \cdot \ln \frac{x_{ij} - R_2}{R_1} \cdot \sin(\alpha_{2ij}) = \\ &= \sum_{i=1}^m \frac{Q_i}{2\pi\epsilon dl_i} \cdot \ln \frac{x_{ij} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ij}^2 + \left(\frac{dl_{2j}}{2}\right)^2 - a_{ij}^2}{x_{ij} \cdot dl_{2j}} \right)^2} \end{aligned} \quad (8)$$

Similar we can state the potential for first wire position.

$$\begin{aligned} \varphi_1 &= \sum_{j=1}^n \frac{-Q_j}{2\pi\epsilon dl_j} \cdot \ln \frac{x_{ji} - R_2}{R_1} \cdot \sin(\alpha_{1ji}) = \\ &= \sum_{j=1}^n \frac{-Q_j}{2\pi\epsilon dl_j} \cdot \ln \frac{x_{ji} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ji}^2 + \left(\frac{dl_{1i}}{2}\right)^2 - a_{ji}^2}{x_{ji} \cdot dl_{1i}} \right)^2} \end{aligned} \quad (9)$$

Voltage between both wires will be given as:

$$\begin{aligned} U &= \frac{Q}{2\pi\epsilon} \left(\sum_{i=1}^m \frac{\ln \frac{x_{ij} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ij}^2 + \left(\frac{dl_{2j}}{2}\right)^2 - a_{ij}^2}{x_{ij} \cdot dl_{2j}} \right)^2}}{dl_i} + \right. \\ &\quad \left. + \sum_{j=1}^n \frac{\ln \frac{x_{ji} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ji}^2 + \left(\frac{dl_{1i}}{2}\right)^2 - a_{ji}^2}{x_{ji} \cdot dl_{1i}} \right)^2}}{dl_{2j}} \right) \end{aligned} \quad (10)$$

Searched value of parasitic capacitance is possible to state by Coulomb's law.

$$C_{12} = \frac{2\pi\epsilon}{\left(\sum_{i=1}^m \frac{\ln \frac{x_{ij} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ij}^2 + \left(\frac{dl_{2j}}{2}\right)^2 - a_{ij}^2}{x_{ij} \cdot dl_{2j}} \right)^2}}{dl_i} + \sum_{j=1}^n \frac{\ln \frac{x_{ji} - R_2}{R_1} \cdot \sqrt{1 - \left(\frac{x_{ji}^2 + \left(\frac{dl_{1i}}{2}\right)^2 - a_{ji}^2}{x_{ji} \cdot dl_{1i}} \right)^2}}{dl_{2j}} \right)} \quad (11)$$

Expressing of individual equation members for 3-D Cartesian system shown in Figure 3 is possible to do by the following equations.

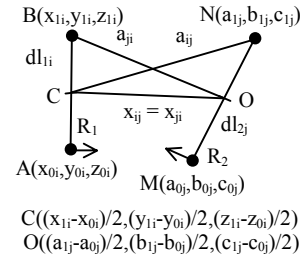


Fig. 3. 3-D Cartesian system

$$dl_{1i} = \sqrt{(x_{1i} - x_{0i})^2 + (y_{1i} - y_{0i})^2 + (z_{1i} - z_{0i})^2} \quad (12)$$

$$dl_{2j} = \sqrt{(a_{1j} - a_{0j})^2 + (b_{1j} - b_{0j})^2 + (c_{1j} - c_{0j})^2} \quad (13)$$

$$a_{ij} = \sqrt{(a_{1j} - (x_{1i} - x_{0i})/2)^2 + (b_{1j} - (y_{1i} - y_{0i})/2)^2 + (c_{1j} - (z_{1i} - z_{0i})/2)^2} \quad (14)$$

$$a_{ji} = \sqrt{(x_{1i} - (a_{1j} - a_{0j})/2)^2 + (y_{1i} - (b_{1j} - b_{0j})/2)^2 + (z_{1i} - (c_{1j} - c_{0j})/2)^2} \quad (15)$$

$$x_{ij} = x_{ji} = \sqrt{\left((a_{1j} - a_{0j})/2 - (x_{1i} - x_{0i})/2 \right)^2 + \left((b_{1j} - b_{0j})/2 - (y_{1i} - y_{0i})/2 \right)^2 + \left((c_{1j} - c_{0j})/2 - (z_{1i} - z_{0i})/2 \right)^2} \quad (16)$$

Only such wire length elements dl1i and dl2j must be taken for total parasitic capacity calculation, which are fulfilling the next conditions.

$$x_{ji}^2 + \left(\frac{dl_{1i}}{2}\right)^2 = (x_{li} - (a_{1j} - a_{0j})/2)^2 + (y_{li} - (b_{1j} - b_{0j})/2)^2 + (z_{li} - (c_{1j} - c_{0j})/2)^2 \quad (17)$$

$$x_{ij}^2 + \left(\frac{dl_{2j}}{2}\right)^2 = (a_{1j} - (x_{li} - x_{0i})/2)^2 + (b_{1j} - (y_{li} - y_{0i})/2)^2 + (c_{1j} - (z_{li} - z_{0i})/2)^2 \quad (18)$$

Correctness verification of obtained results can be done by simulation and measuring. For this purpose is possible to utilize the connection of DC impulse converter shown in Figure 4.

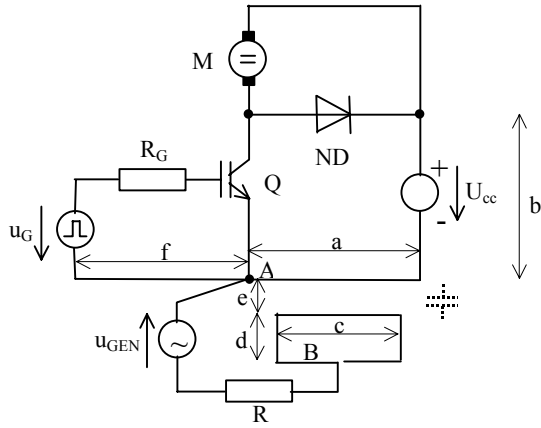


Fig. 4. . Investigated circuit

We will try to state the value of parasitic capacitance between the node A of impulse converter and node B of sense loop. Space dielectric material is created by air. Geometrical dimensions of investigated circuits are $a = f = 0,2$ m, $b = 0,3$ m, $c = 0,1$ m, $d = 0,05$ m, $e = 0,00135$ m. Wires are made from cooper with the radius $R = 0,0006$ m. Based on above mentioned parameters it is possible to calculate the individual partial parasitic capacitances.

$$C_{ace} = \frac{1}{\frac{1}{2\pi\epsilon_0 a} \ln \frac{e-R}{R} + \frac{1}{2\pi\epsilon_0 c} \ln \frac{e-R}{R}} = 16,63 \text{ pF} \quad (19)$$

$$C_{aced} = \frac{1}{\frac{1}{2\pi\epsilon_0 a} \ln \frac{(d+e)-R}{R} + \frac{1}{2\pi\epsilon_0 (c-0,001)} \ln \frac{(d+e)-R}{R}} = 0,8306 \text{ pF} \quad (20)$$

$$C_{fcd} = \frac{1}{\frac{1}{2\pi\epsilon_0 a} \ln \frac{\sqrt{e^2+a^2}-R}{R} + \frac{1}{2\pi\epsilon_0 c} \ln \frac{\sqrt{e^2+a^2}-R}{R}} = 0,6391 \text{ pF} \quad (21)$$

$$C_{fced} = \frac{1}{\frac{1}{2\pi\epsilon_0 a} \ln \frac{\sqrt{(d+e)^2+a^2}-R}{R} + \frac{1}{2\pi\epsilon_0 (c-0,001)} \ln \frac{\sqrt{(d+e)^2+a^2}-R}{R}} = 0,6314 \text{ pF} \quad (22)$$

$$C_{bdac} = \frac{1}{\frac{1}{2\pi\epsilon_0 \frac{b}{2}} \ln \frac{\sqrt{\left(\frac{b+e+d}{4} + \frac{a+c}{2}\right)^2 - R}}{R} + \frac{1}{2\pi\epsilon_0 d} \ln \frac{\sqrt{\left(\frac{b+e+d}{4} + \frac{a+c}{2}\right)^2 - R}}{R}} = 0,3989 \text{ pF} \quad (23)$$

$$C_{bdac} = \frac{1}{\frac{1}{2\pi\epsilon_0 \frac{b}{2}} \ln \frac{\sqrt{\left(\frac{b+e+d}{4} + \frac{a+c}{2}\right)^2 - R}}{R} + \frac{1}{2\pi\epsilon_0 d} \ln \frac{\sqrt{\left(\frac{b+e+d}{4} + \frac{a+c}{2}\right)^2 - R}}{R}} = 0,3658 \text{ pF} \quad (24)$$

$$C = C_{ace} + C_{aced} + C_{fcd} + C_{fced} + 2C_{bdac} + 2C_{bdac} = 20,26 \text{ pF} \quad (25)$$

Based on calculated capacitance the simulation analyze in PSPICE program is possible to do now by circuit connection shown in Figure 5.

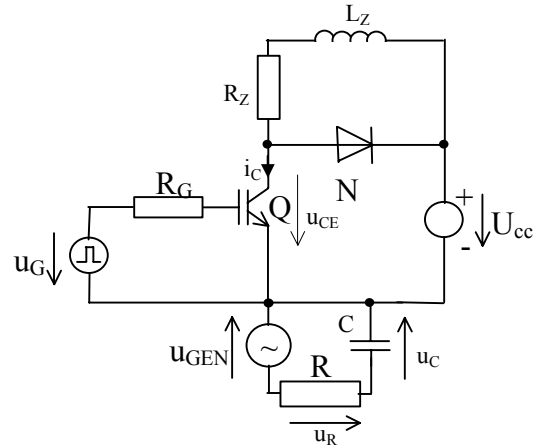


Fig. 5. Simulation circuit

Parameters of individual elements are $U_{CC} = 70V$, $R_Z = 11,66 \Omega$, $L_Z = 400 \mu H$, $R = 1 M\Omega$, $u_{GEN} = 2 \sin(\omega t)$ V. Simulation results for frequency $f = 10kHz$ are pictured in Figure 6.

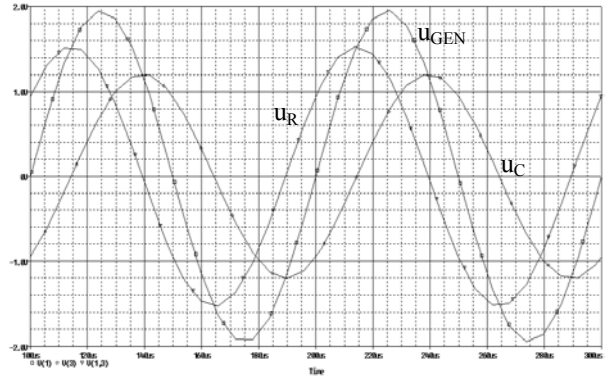


Fig. 6. Simulation results for $f = 10$ kHz

The same output values obtained by simulation, but for frequency $f = 50 \text{ kHz}$ are shown in Figure 7.

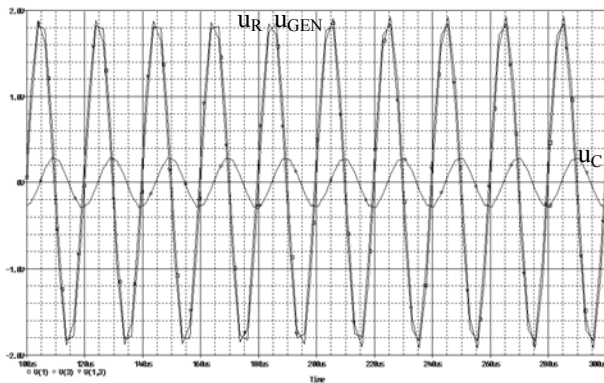


Fig.7. Simulation results for $f = 50 \text{ kHz}$

Measured values of u_{CE} , u_{GEN} and u_C are shown in next figures Figure 8 till to Figure 11.

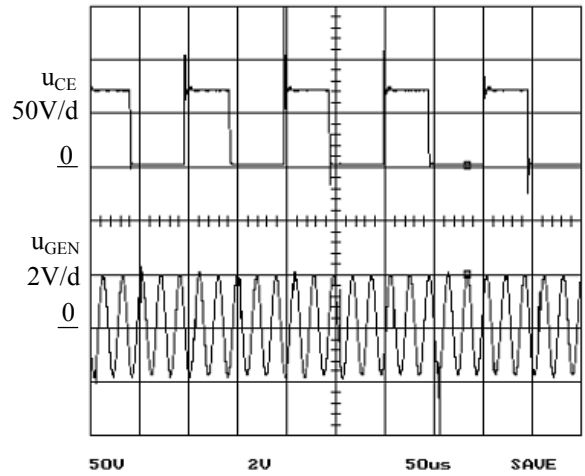


Fig.10. Measured results for $f = 50 \text{ kHz}$

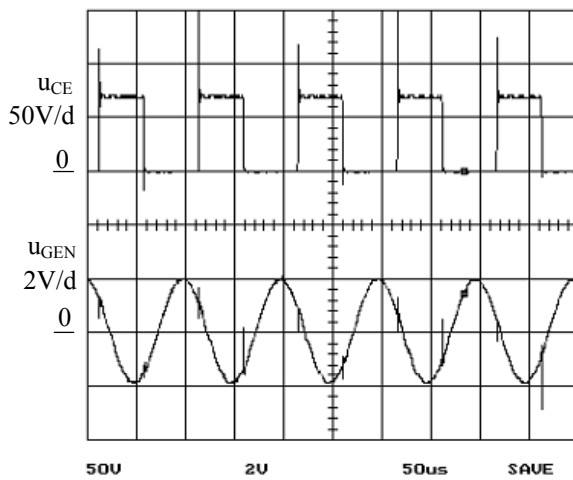


Fig. 8. . Measured results for $f = 10 \text{ kHz}$

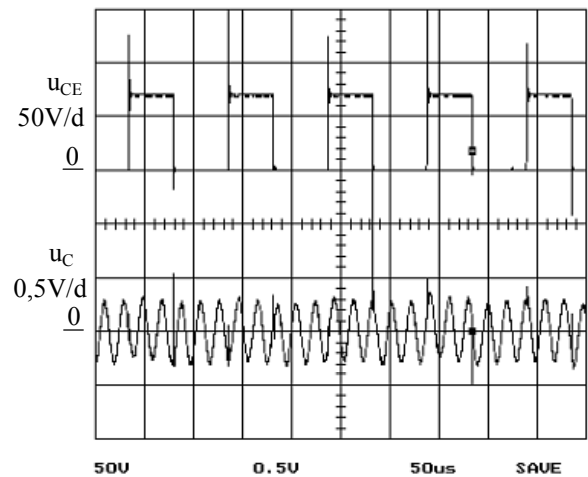


Fig.11. Measured results for $f = 50 \text{ kHz}$

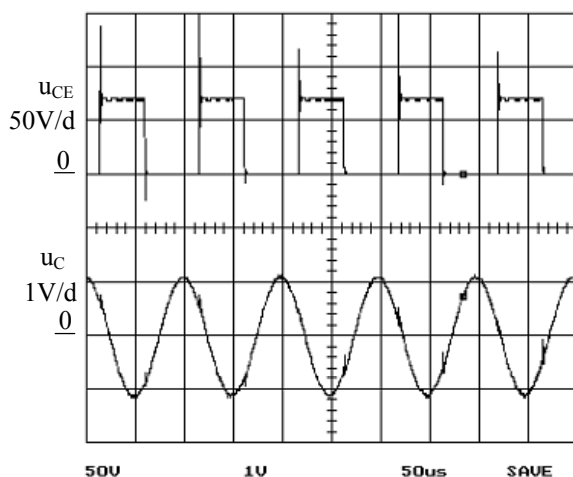


Fig. 9. Measured results for $f = 10 \text{ kHz}$

By comparing of simulated and measured results one can see that obtained results are identical and it means that derived analytical formula for parasitic capacitance calculation is valid.

In due to additional verification requirement the same problem is possible to analyze also by numerical, finite element simulation method of electrostatic field. Obtained result is shown in Figure 12.

From data window is possible to state that the value of electrical flux between both nodes is $5,4357 \cdot 10^{-12} \text{ C}$. Based on the program property we must multiple this value by value of wires perimeter $l = 2 \cdot \pi \cdot R = 2 \cdot \pi \cdot 0,6 = 3,76 \text{ mm}$. Total electrical flux is then $20,4382 \text{ C}$. In due to fact that the voltage between nodes have value 1V, so the resulting parasitic capacitance is $C = 20,4382 \text{ pF}$.

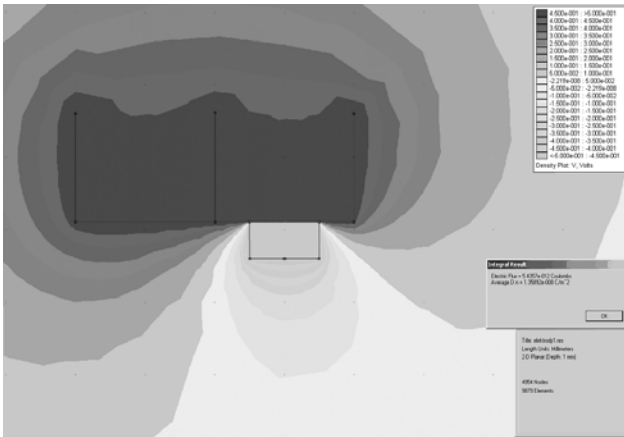


Fig. 12. Finite element method simulation

By comparing of all results we can state that difference is only 0,879% and it means that the correctness of derived formula for parasitic capacitance calculation is satisfy.

3. Conclusion

Performed analyzes indicates that not only large current switching frequency has the main influence on the converter's EMC but equally important is also the switch off state with small parasitic resonant load current.

Obtained formula for parasitic capacitance calculation enabling predictive EMC investigation. Although such converter capacitances seem to be negligible so performed analyze show to us that it can have important influence. Mainly in the case when the switching frequency is high or one of the both nodes belong to the circuit with great impedance. It is obviously in the case of capacitive coupling existence between CMOS integrated circuits and power converter circuit when EMC quality can be very fundamental for right equipment operation.

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