Continuous Field Analysis of Distributed Parasitic Effects Caused by Interconnects in High Power Semiconductor Modules

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Abstract

A practical methodology for the analysis of distributed parasitic effects is presented and demonstrated for bus bars connecting fast switching semiconductor devices in high power modules. Our study shows that only a full three-dimensional transient simulation of the entire module under realistic switching conditions can give the necessary insight in the time-dependent electromagnetic behavior. In order to illustrate the method, a problem encountered in an industrial application is solved.

1. Motivation

In the field of power electronics, rapid progress has been made in the development of applications which are based on the pulse width modulation method. Using modern high power semiconductor devices, such as the IGBT, switching times of about 100 ns or shorter and switched currents in the range of one kiloampere have been demonstrated. As a consequence of the steep current ramping, distributed electromagnetic parasitic effects become an increasingly serious problem which governs the design of the bus bars interconnecting the individual devices in a high power module. According to the basic laws of electrodynamics, these effects are basically inevitable but have to be reduced to a minimum. Eddy currents, for instance, are induced inside the bus bars which contribute to the quasi-static current flow in such a way that the resulting transient current distribution is forced to a thin region underneath the conductor surfaces (skin effect). The local crowding of the current density leads to considerable electro-thermal heating on certain locations within the bus bars. Furthermore, the distributed parasitic self- and cross-inductances of the interconnects produce overvoltage peaks which endanger the safe operation of the attached devices and other circuit elements. Moreover, parasitic inductances cause a significant delay in the time the current can be switched on.

2. Physical Model Equations

Eddy current problems are commonly solved by using a scalar potential φ representing the quasi-static contribution to the electric field in the conducting region(s), and a vector potential $\vec{A}$ for the magnetic field inside and between the conducting region(s). Using Coulomb's gauge, $div\vec{A} = 0$, the time-derivative of $\vec{A}$ constitutes the transient contribution to the electric field. Starting with Maxwell's equations, assuming the validity of Ohm's law in the interior of the conducting interconnects and linear material relations, neglecting the formation of electromagnetic waves and noting that the dielectric relaxation time is short compared to the switching times considered, we arrive at the following governing equations for φ and $\vec{A}$ in the interior of the interconnects:

$$rot\frac{1}{\mu}rot\vec{A} + \sigma\dot{\vec{A}} = -\sigma grad\varphi \tag{1}$$

Here, σ is the (piecewise uniform) electric conductivity inside the bus bars, while μ denotes the (piecewise uniform) magnetic permeability of the conducting material(s) and the regions in between. The electric potential is determined by $div(\sigma\nabla\varphi) = 0$ in each of the bus bars. Having calculated the potenials φ and $\vec{A}$, the total current density is obtained by

$$\vec{j} = -\sigma grad\varphi - \sigma\dot{\vec{A}} \tag{2}$$

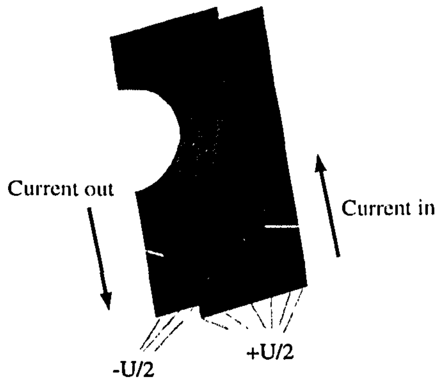
where $-\sigma grad\varphi$ represents the quasi-stationary eddy-free part of the current flow, whereas the second contribution $-\sigma\dot{\vec{A}}$ is divergence-free and represents the rapidly varying eddy currents. In further postprocessing steps, we can extract other quantities of interest, in particular the heat dissipation rate $H_{therm} = \frac{\vec{j}^2}{\sigma}$ or the stored electromagnetic energy $W_{em} = \int(\frac{1}{2\mu}\vec{B}^2 + \frac{\epsilon}{2}\vec{E}^2)d^3r$, the inductive portion of which can be conveniently expressed in terms of a generalized inductance operator $L_{\alpha\beta}(\tau)$ according to $\frac{\partial W_{ind}(t)}{\partial t} = \sum_{\alpha,\beta}\int I_\alpha(t)L_{\alpha\beta}(t-\tau)\dot{I}_\beta(\tau)d\tau$. Here $I_\alpha(t)$ are the terminal currents entering or leaving the interconnects through the attached devices. Based on these quantities and with a view to shape optimization, we are able to define target functionals ("figures of merit") to assess the quality of a given bus bar set-up with respect to uniformity of current flow, switching time delay, overvoltage and overheating limitations and related quantities of interest.

3. Numerical Procedure

Various computational approaches to the eddy current problem based on magnetic vector potential formulations have been reported . One of the well-known difficulties lies in satisfying Coulomb's gauge. Our numerical simulations make use of the so-called $\vec{A}, V\text{-}\vec{A}$ formalism, developed by Bíró [1]. $\vec{A}, V\text{-}\vec{A}$ stands for solving the scalar and vector potentials $(\varphi, \vec{A})$ inside the conducting region(s) and $\vec{A}$ in the nonconducting region(s). In this approach, the uniqueness of the potentials $(\varphi, \vec{A})$ is ensured by a penalty term $-\nabla\frac{1}{\mu}\nabla\cdot\vec{A}$ at the left-hand side of (1) and by choosing a special setup of interface conditions along the boundaries of the conducting parts of the simulation domain.

4. Numerical Results and Discussion

As an illustrative example, we refer to the numerical analysis of a bus bar encountered in an industrial application. It consists of two parallel copper plates with a circular



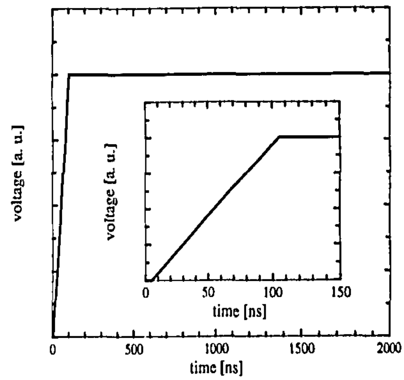
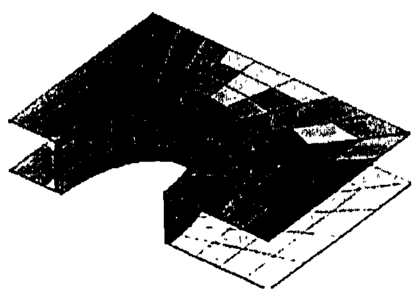


Figure 1: Typical bus bar structure encountered in high power applications. The vertical dimensions of the double-plate structure are stretched by a factor of 25

Figure 2: Voltage ramp used as bias condition for the transient simulation of current turn-on



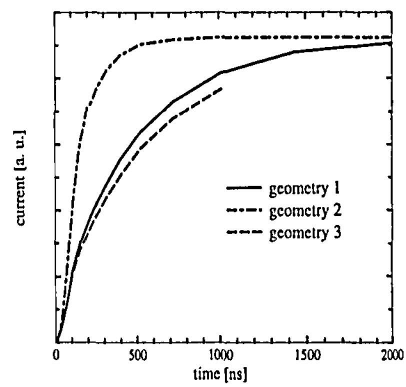


Figure 3: Transient FEM simulation of the current distribution inside the bus bars at a time step half way during turn-on (light grey: high, dark grey: low current density).

Figure 4: Simulated current flow through the contact electrodes driven by the voltage drop across the bus bar for different geometries

cut, having a length and width of about $20cm$ and separated by an insulating layer of about $2mm$. The two layers themselves have a thickness of $100\mu m$. They are connected by a perpendicularly attached curved sheet-metal (Fig.1). At the front side of the double plate structure two additional highly resistive plates of the same thickness were added, one at the upper plate and one at the lower plate. The open ends of these two additional plates represent the contact electrodes where a voltage source is connected to the bus bars. The resistivity of these plates was adjusted in such a way that, under quasi-stationary conditions, the applied voltage produces the measured terminal current through the electrodes of the bus bar. Then transient current flow through the bus bars was simulated by ramping up the voltage at the contact electrodes until the end of the turn-on time and maintaining the maximum value afterwards (Fig.2).

Our simulations allowed us to extract all information relevant to the optimization of the bus bar geometry (transient current distribution, electrothermal heat dissipation, terminal current transients and inductance matrix). As expected, eddy currents lead to a dramatic redistribution of the current densities in the bus bars. Because of the antiparallel current flow through the plates, the current density is enlarged along the inner side of the sandwich, whereas it is nearly unchanged along the outer side. Furthermore, we find pronounced current crowding at the source-bound side of the curved perpendicular plate, leading to an additional inhomogeneity of the current density and a significantly higher heating rate (Fig.3).

Looking at the quasi-stationary current flow $\vec{j} = -\sigma grad\varphi$ through the contact electrodes, which is driven by the voltage drop across the bus bar, allows us to analyze the turn-on transients of the terminal currents passing the contact electrodes. Since their behavior is mainly determined by the inductances of the interconnects, we would expect a behavior similar to that of a simple RL-network. This idea is clearly confirmed by Fig.4. Varying the geometrical shape of the bus bar leads to different inductances and, thereby, influences the turn-on time of the module. This is therefore the dominant factor which limits the switching frequency and determines switching losses. By decomposing the voltage drop into an ohmic and an inductive contribution, it is possible to extract time-dependent inductance values $L(t) = \frac{U(t)}{\frac{\partial I}{\partial t}}$ at any time step of the simulation.

5. Future Perspectives

Parameter studies based on the presented methodology give us the opportunity to optimize bus bars with respect to distributed parasitic effects. The next step would be an automated shape optimization tool. This requires a fast and stable solution-algorithm for the $\vec{A}, V\text{-}\vec{A}$-field problem, which is at the moment not yet available but under development. As a final result, we note that the capability of solving eddy current problems for complex geometric domains and topographies opens new ways to the interconnect problem in other fields as, for instance, highly integrated circuits (ULSI).

References

[1] O. Bíró and K. Preis, "On the Use of the Magnetic Vector Potential in the Finite Element Analysis of Three-Dimensional Eddy Currents," *IEEE Trans. Magn.*, vol. 25, 3145-3159, 1989.