Physics Based Modeling of Power Converters from Finite Element Electromagnetic Field Computations

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Abstract-In this paper, we propose a novel high frequency integral model for power converters including the semiconductor devices such as power Diodes and MOSFETS. The obtained models include the electro-thermal and electromagnetic behavior of the semiconductors. These models are obtained using Finite Elements (FEM). The proposed model was verified by comparing the numerical results of the implemented components to experimental results implemented in a converter circuit. The model was also used to study the high frequency behavior of the whole converter.

I. INTRODUCTION

High Frequency (HF) models of the converter containing power semiconductor devices such as Diodes and MOSFETS are based on circuit models that are only related to the parasitic inner parameters of the power devices and the connections between these devices. These parameters are measured when the converter is switched off [1]. Nevertheless, the main objective of our research is to obtain the high frequency physics-based model for the power converter which acts exactly as the physical device with high accuracy and with little or no compromise. For modeling the whole converter, the first step is to model all the constitutive elements in the structure of the converter. For instance, an uncontrolled rectifier or a three-phase inverter is comprised of six diodes and six power MOSFETS or IGBTs, respectively. It also includes all required traces and wires which connect all these components together.

In the literature, there exist low and high frequency models for passive elements of the power converter including transformers, inductors, resistors and capacitors. However, there is little or no effort on the active elements of the power converter i.e. MOSFETS or IGBT switches, diodes and/or any other combination of active components in the converter circuit. The switching patterns in these devices are mostly the main source of EMI/EMC issues in power converters.

For this reason, this paper is primarily centralized on the high frequency physics-based modeling of active devices. The developed individual models for these active elements are used in combination to construct the whole converter physics based model.

II. PHYSICS BASED MODELING OF THE SEMICONDUCTOR DEVICES

This section focuses on modeling the semiconductor devices specifically PiN diodes and MOSFETS with thermal and magnetic dependent features. In each case, the semiconductor structure and geometry was modeled using FEM to evaluate their electrical, thermal and magnetic characteristics.

Part A-Modeling the PiN diode

In this part, the physics-based model for a PiN diode is described. To obtain the physics based model, the geometry of the actual PiN diode is constructed in the FE software. The convection, diffusion, and electromagnetic equations are defined for the device structure. This model initially describes the physical behavior of the diode

The basic equation for the semiconductor devices operation describes the behavior of the carriers in the semiconductors under the influence of external fields can be set as given in [1]. These basic equations can be classified in three groups; Maxwell equation, current density equations and continuity equations.

In the first step, the *I-V* characteristic of the Diode is calculated through the numerical analysis by FEM and is compared to the diode's analytical equation which expresses the relation between the voltage and current as:

$$J = J_s\left[\exp\left(\frac{eV_a}{KT}\right) - 1\right] \tag{1}$$

where $J_s = \left[\frac{eD_p p_{n0}}{L_p} + \frac{eD_n n_{p0}}{L_n}\right]$

Dividing equation (1) by the conducting surface of the diode “A”, equation (1) is rewritten as:

$$I_D = I_s\left[\exp\left(\frac{eV_a}{KT}\right) - 1\right] \tag{2}$$

Part B- Modeling the Power MOSFET

For modeling the MOSFETs, A similar procedure was followed for the Diode's physical model. Figure 1 shows the power MOSFET structure used in the FE model. A 2-D electromagnetic FE analysis is performed to obtain resistances and inductances of the different layers in the semiconductor structure. This analysis is a steady state time harmonic form of the diffusion equation. The electromagnetic field inside this device is governed by the following set of nonlinear partial differential equations:

$$\vec{\nabla} \times \left((\nu)\vec{\nabla} \times \vec{A}\right) = \vec{J} \tag{3}$$

$$\nabla.\sigma\left(\frac{\partial \vec{A}}{\partial t} + \nabla V\right) = 0 \tag{4}$$

where $\vec{A}$ is the magnetic vector potential, $\vec{J}$ is the total current density, ν is the magnetic reluctivity, V is the electric scalar potential, and σ is the electric conductivity. Solving these sets of equations, the parasitic resistance and inductance of the device is calculated as a function of frequency.

The electrostatic problem is solved for the calculation of Capacitances. The electrostatic analysis determines the electric scalar potential distribution caused by the applied voltage in different layers then capacitances are calculated based on the energy principle. By applying voltage on the gate and Drain, considering the source as a ground, the capacitance matrix is calculated from the stored static energy. The following Maxwell equation was solved during the electrostatic analysis.

$$\nabla.(\varepsilon\nabla V) = -\rho \qquad (5)$$

where ρ is surface charge density, ε is permittivity, V is electric scalar potential.

Following the FE computations, the I-V characteristics of the power MOSFET is calculated from low to high frequencies. The method used in this study is based on the lumped-parameter model presented in [2]. This method is used to obtain the s-domain model of semiconductor devices which can be used to find the frequency response of the device. The high frequency physics-based model of the power MOSFET at an operating frequency of 2-kHz is represented in figure 2(a) and also superimposed on the physical model of figure 1. An analytical model that is typically used for this device is also shown in figure 2(b). As can be noticed, the latter does not consider the HF parameters as in figure 2(a).

Figure 3 shows the model of a cascaded back to back rectifier and an inverter supplying a three-phase RL load. In this model, all the diodes and MOSFETs as well as other parameters are substituted with their corresponding physics-based models, shown in figure 2. In figure 3, the effects of capacitance between the source of the MOSFET and heat sink is also modeled.

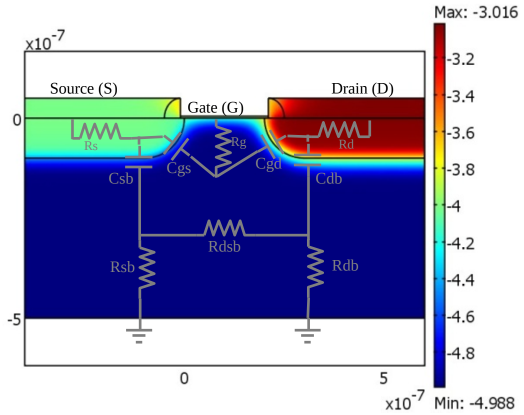
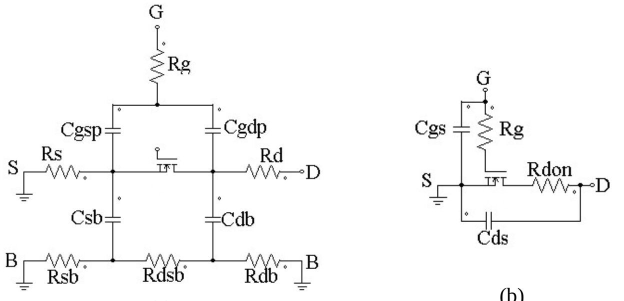


Fig. 1 Electric potential inside the MOSFET geometry (V)



(a) (b)

Fig. 2 Schematic of the sub-circuit model at f=2 kHz, for: (a) Physics based power MOSEFT model, (b) Power MOSFET dynamical model

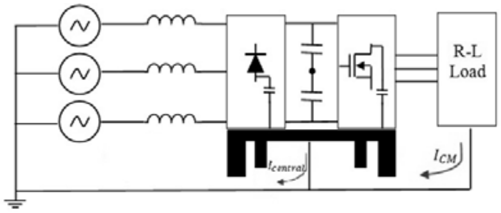
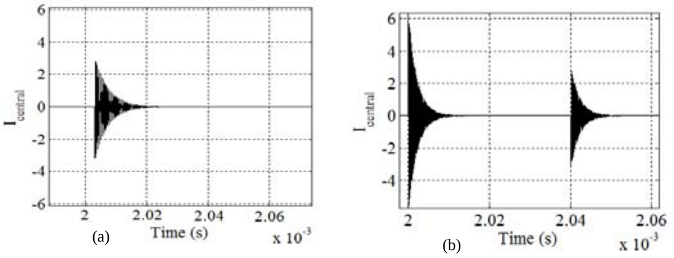


Fig. 3 High Frequency model of a power converter.



(a) (b)

Fig. 4 Simulated Common Mode current of the converter

(a) Analytical model, (b) Physics based model.

The presence of Common Mode (CM) current in the power converter of figure 3, is demonstrated in figure 4, where the current flowing in the connection to the DC link central point, *Icentral*, is illustrated in two different cases. One of the cases is when the analytical model was used for each of the components while the other case is when the components of the converter are all represented by the corresponding physics based model. As can be seen, accurate results were obtained using the latter. Also it should be noted that the accuracy of the high frequency model is potentially influenced by many factors including the circuit board layout, nearby conductors, grounding surfaces proximity to magnetic materials, etc. By adding the high-frequency model of these elements, a more precise model is obtained. In this study, the effects of the connection traces are also added to the physics based model as will be shown in the full paper.

III. Conclusion

In this paper, a physics based model for power converters with all of its components including semiconductor devices is presented. The physics based FE model can represent a more precise model for the system. This would make the study of the dynamic behavior of these systems possible. The analysis of common mode disturbance propagation in the power converter system was performed using the developed physics based high-frequency model of the whole system. The internal CM propagation paths and EMI emissions towards the input stage were identified. The HF circuit model also can be used to design the input CM/ EMI filters and to verify its performance.

IV. REFERENCES

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