Simulation and Optimization of Diode and Insulated Gate Bipolar Transistor Interaction in a Chopper Cell Using MATLAB and Simulink

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***Abstract*—Recently, a simulation method for power electronic devices has emerged, which has high accuracy and short run times based on a Fourier model of the device physics. This paper describes the use of the Fourier models for diodes and insulated gate bipolar transistors (IGBTs) and implementation in MATLAB and Simulink in a formal optimization strategy. In particular, this paper investigates coupled circuit, diode, and IGBT behavior. Conclusions are drawn concerning device loading and circuit design, particularly the role of stray inductance.**

***Index Terms*—Circuit modeling, diode, insulated gate bipolar transistor (IGBT), MATLAB, optimization, physics-based semiconductor device models, power semiconductor modeling, simulation, Simulink.**

I. Introduction

THE SWITCHING process in conventional insulated gate bipolar transistor (IGBT) inverters is associated with significant losses in semiconductor switching devices. These losses impose a limit on the switching frequency and contribute to the total losses, defining the converter cooling and temperature rise.

When the current is commutated between the IGBT and the freewheel diode, current and voltage overshoots and delays usually appear. These increase the losses and may create further issues in the design. As a result, it is important to carefully consider the stray inductances found in the circuit and the gate drive conditions that are applied to the IGBT. Detailed simulation, based on finite-element simulators such as Medici[1] and ATLAS,[2] is very slow. However, circuit simulator device models that are able to account for the details of the device behavior in a consistent manner have emerged [1]–[5]. These allow the operation of the devices to be examined in detail while retaining a very high speed of simulation. A formal numerical optimization method that employs these circuit simulator device models provides a way of thoroughly exploring the issues that are present in device switching.

In practice, the coupling of the diode and IGBT is such that a change in the characteristics of one device affects the performance of the other, and an effective design of the circuit requires matching of the devices and circuit. Historically, it has been rare to optimize IGBTs and diodes concurrently within a single optimization procedure. Here, the devices and circuit are optimized as a single entity.

The MATLAB/Simulink environment[3] is ideally suited to complex studies of system behavior. Simulink is able to solve coupled linear or nonlinear ordinary differential equations and is therefore ideally suited for simulating device behavior using the Fourier-based solution method [1], [2]. The analytical and Fourier models that comprise the diode and IGBT are neatly assembled into Simulink blocks, and the coupled diode and IGBT behavior may be investigated, where both devices have detailed models. This paper briefly describes the circuit simulator models, which are implemented in MATLAB and Simulink, the use of a formal numerical optimization strategy, the Tabu search, and the outcome of a series of optimizations. Both the device and the circuit design are considered for optimization. The results are discussed, and conclusions are drawn with regard to common practice and future approaches.

II. Simulation of the Chopper Cell

A. Circuit Considerations

Most power electronic circuits can be reduced to the standard chopper cell for device simulation purposes, where the voltage across an inductive load is switched at a high frequency to produce a particular load current. The cell comprises a switching device [e.g., metal–oxide–semiconductor field-effect transistor (MOSFET), thyristor, or IGBT] and a freewheeling diode to

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[1]Medici is part of the Taurus TCAD software [Online]. Available: http://www.synopsys.com/.

[2]ATLAS is part of Silvaco's TCAD software [Online]. Available: http://www.silvaco.com/.

[3][Online]. Available: http://www.mathworks.com.

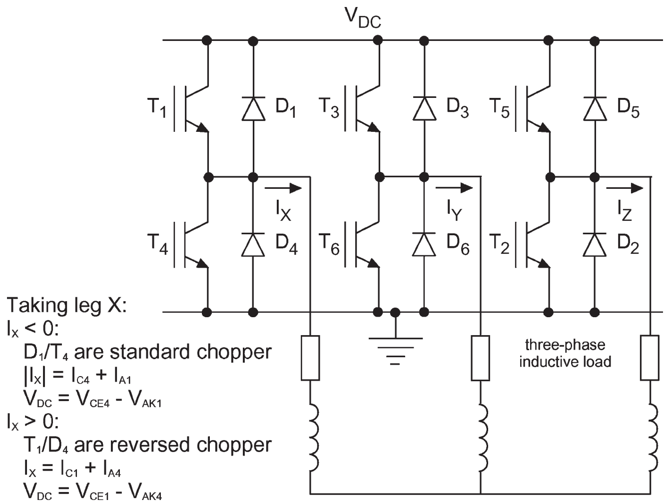

Fig. 1. Reduction of full bridge taking phase X as an example.

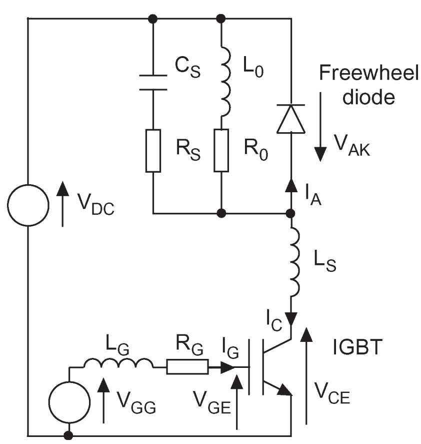

Fig. 2. Single chopper cell (R_0, L_0: load; R_S, C_S: snubber; L_S: stray inductance; L_G: gate inductance; and R_G: gate resistance).

provide a path for the current when the switch is off. A snubber may be included to limit any transients when switching.

Fig. 1 shows a three-phase full bridge, with detailed conditions for phase X. Depending on the direction of load current I_X, which may be assumed to be near constant due to the inductive nature of the load, the IGBT and diode pairs can be reduced to a simple chopper. Fig. 2 shows the chopper in more detail, including the lumped stray inductance, snubber, and IGBT gate drive. The small junction capacitances of the parallel off devices may be neglected.

The stray inductance is crucial to the circuit performance. It determines the rate at which the current commutates between the diode and the IGBT when the latter switches on or off. Most importantly, the removal of charge from the diode when it switches off is significantly affected by this inductance, which, in turn, influences the power dissipation of both devices during this switching event. It can also determine whether the devices approach their maximum ratings during the switching process.

B. Device Models

Carrier storage within the lightly doped base region of a power semiconductor device is critical to the transient response

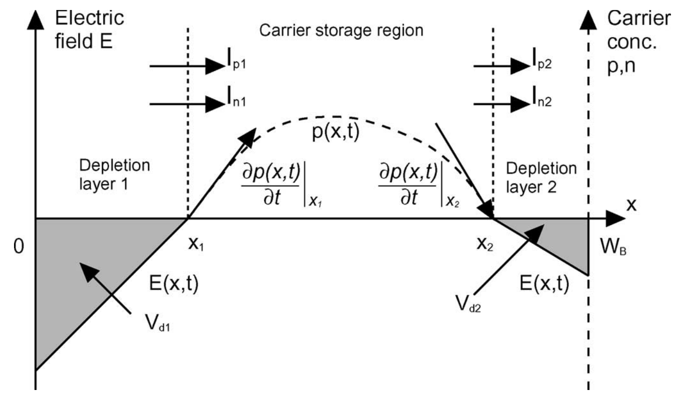

Fig. 3. General arrangement of carrier storage region and depletion layers (the IGBT has only one depletion layer).

of the device and its behavior within a particular circuit. IGBTs and diodes exhibit carrier storage, which enables them to have low on-state voltages at high currents and a high breakdown voltage capability when off.

For diodes, the carrier distribution across the wide drift region is approximately 1-D. For IGBTs, it is 1-D across 90% of the drift region and so may be reasonably assumed as such for the whole region, provided that some modifications are made [2]. For both devices, space-charge neutrality is maintained when the device is on, where the majority carrier profile closely matches the minority (injected) carrier profile. Under these conditions, assuming high-level injection, carrier dynamics are described by the following classic ambipolar diffusion equation:

$$D\frac{\partial^2 p(x,t)}{\partial x^2} = \frac{p(x,t)}{\tau} + \frac{\partial p(x,t)}{\partial t} \tag{1}$$

where D is the ambipolar diffusion coefficient, τ is the carrier high-level lifetime, and p is the carrier density (equal for holes and electrons) at a point in time t and space x.

A simple solution of this was proposed in [1], where the carrier distribution with space at any point in time is transformed into a cosine Fourier series. This effectively reduces a partial differential equation into a set of coupled first-order ordinary differential equations. The carrier distribution is therefore given by

$$p(x,t) = p_0(t) + \sum_{k'=1}^{\infty} p_{k'}(t) \cos\left[\frac{k'\pi(x-x_1)}{x_2 - x_1}\right]. \tag{2}$$

This requires the boundaries of the undepleted carrier storage region, which are given by x_1 and x_2, and the carrier gradients at these points (see Fig. 3). The latter are derived from the corresponding hole and electron currents at the boundaries.

x_1 and x_2 are calculated from the voltages across the depletion layers (V_{d1} and V_{d2}) on each side of the carrier storage region. These are derived from the carrier densities at the boundaries between the depletion layers and the carrier storage region using a high-gain feedback loop. The effect of the feedback is to produce a depletion layer voltage when the boundary carrier density falls to zero. The high gain ensures that the boundaries x_1 and x_2 move to maintain a negligible