Modeling of IGBT-based power electronics systems for hybrid and electric vehicles

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According to independent consulting and research organization IDTechEX, any vehicle manufacturer without a compelling line up of electric vehicles by 2025 is signing its “death warrant.” It’s not surprising, then, that today the hybrid and electric vehicle (H/EV) market is undergoing unprecedented growth and innovation.

My employer, Magna Electronics, focuses on supporting this nascent H/EV market by engineering, integrating, and producing innovative solutions for traction drive and control applications. This includes the design of inverters, DC-DC converters, motors, battery management systems, and other critical components (Figure 1).
Power semiconductor devices and modules are the key components of each power converter. Insulated-gate bipolar transistor (IGBT) modules are commonly used for mid- to high-power applications such as H/EV inverters, because of their high voltage and current capability. IGBTs are key components in inverter design because the characteristics of the device determine the inverter behavior and the periphery circuit.

**Improving Designs by Simulation**

Generally, it is very time consuming and expensive to change a design or verify circuit functionality in the laboratory. Circuit simulation provides a more efficient way for electrical engineers to do the design work.
We use Saber Model Architect to model the static and dynamic behavior of the IGBT modules based on the corresponding datasheets. The curves can be imported into Saber using a scan tool, and the anchor points are adjusted to match the curves. The key requirement is to characterize the dynamic behavior of the IGBT, which includes junction capacitances, tail current, and the reverse recovery behavior of the freewheeling diode, to match the turn on/off delay and the rise and fall time. The key parameters can be tuned to enable use of the model for different circuit designs, which greatly helps the product development process.

Modeling IGBTs to exactly match the test results is difficult. One of the major issues is that the device characteristics are very nonlinear. Saber helps by providing support to optimize difficult models. It is also difficult to identify the parasitics in the circuit, since the switching behavior depends on the device itself and on the parasitics of the circuit. Specifically, the stray inductance in the power circuit can cause voltage overshoot at turn off, and the parasitics in the gate drive circuit affect the switching speed. By tuning the circuit over several iterative loops it is possible to get a good match.

Two different IGBT-based applications are highlighted below to illustrate the benefits of accurate IGBT analysis.

**Overshoot Voltage Protection**

Reliability is one of the most important issues for any industrial product. There are various protections in the IGBT gate-drive board that protect the IGBT from over-voltage, current, or temperature. This application is related to the voltage protection of the IGBT module. When there’s a short circuit in the load, the current can instantaneously increase to several thousand amperes. Over-current protection in the circuit detects the large current and turns off the IGBT immediately. However, the rapid rate of current change acts on parasitic inductance in the circuit, leading to an overshoot voltage in the transistor (**Figure 2**). This voltage will destroy the device if it isn’t clamped.

![Figure 2](image)

**Figure 2:** Switching applications like motor drives or converters can lead to overshoot voltages (shown in red) when the IGBT switches off (shown in blue)

The protection circuit senses the Vce and turns on the reaction circuit. One of the key factors for the protection to work properly is the IGBT module turn-off delay and fall time, which is why it’s so
important to have an accurate IGBT model. The other key factor is selecting components for use in the protection circuit to ensure the reaction time meets the requirement. In this case, the aim is to keep Vce below 550V. The red curve in Figure 3 is the voltage overshoot during turn-off, without protection. The blue and green curves show the difference in behavior by changing the time delay in the control loop and the gate driver. Using Saber or Spice models of the driver circuit ensures the accuracy of the overall simulation model.

![Figure 3: Using simulation to understand the effects of changing device parameters within the protection circuitry](image)

Accurate Saber models help to verify the function of the designed circuit, select proper components, and tune the parameters. By using simulation in advance of implementing hardware, significant time has been saved and engineering costs reduced.

**Conducted Electromagnetic Interference (EMI) Prediction**

Conducted emissions exist in every power circuit. They occur as a result of fast-changing switch currents or voltages, which are common in pulsating circuits. The frequency of interest for EMI usually ranges from 100kHz to 100MHz.

The pulsating current or voltage in a power electronics circuit looks like the square wave in Figure 4a. The FFT (Fast Fourier Transform) analysis of the square wave is shown in Figure 4b. The attenuation of the spectrum depends on two factors of the square wave: the first crossover frequency depends on pulse width, and the second corner frequency depends on the rise and fall time of the square wave. Hence we need to model the rise and fall time of the IGBT model because it affects the result.
Figure 4a: The signal is modeled as a trapezoidal waveform. The waveform duration ($t_0$) defines the first corner frequency, the rise or fall time ($T_r$ or $T_f$) defines the second corner frequency.

Fundamental frequency $= 1/T$

Figure 4b: Corresponding frequency spectrum
Figure 5 shows the results of analyzing device models with different switching speed. The waveform in blue shows an ideal switch with a switching time of 50ns, while the red waveform shows the actual IGBT model. It’s apparent that there is significant difference in the high-frequency ranges.

Figure 5: Comparing the frequency response of an ideal switch (blue) with an accurate IGBT model (red).

Summary

Accurate modeling of IGBT devices with Saber helps us in the development of inverter products, including gate driver board design and EMI filter design. It typically takes 6-12 months to build the hardware, but simulation enables optimization of the designs before any prototypes are created. Simulation helps to:

- Identify potential problems
- Understand system behavior
- Validate solutions and functions
- Accelerate the design cycle
- Reduce costs
- Improve efficiency

While just two applications have been outlined here, Saber is used to simulate many circuits and subsystems to investigate EMI for a variety of control boards.

Also see:

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- 1200-V IGBT technology platform claims benchmark efficiency, ruggedness for industrial apps
- Snubber capacitor allows direct IGBT mounting
- IGBT/MOSFET Gate Drive Optocoupler
- International Rectifier AUIRS2332J MOSFET- and IGBT-gate-driver IC: Device targets use in EV, HEV applications
- MCUs Simplify Hybrid and Electric Vehicle Motor Control Designs