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Electrothermal Models Predict Power MOSFET Performance More Accurately

by Andy Berry, Nexperia, Manchester, U.K.

One of the biggest challenges facing engineers when designing with discrete power MOSFETs is the fact standard simulation models provided by many manufacturers are limited in how well they emulate real-world performance. This reduces the usefulness of SPICE simulations when attempting to understand how a circuit will perform in a practical application.

For example, most standard models can only be used to simulate how a discrete device will behave at a nominal temperature (typically 25°C). In addition, standard simulation models are usually not comprehensive because they neglect to include some important device parameters that could provide some insight into the electromagnetic compatibility (EMC) performance of a circuit. In this regard, discrete circuit designers could be considered the "poor relation" of their integrated circuit design counterparts who are spoiled by all-encompassing models that leave nothing to chance.

In this article we explore the limitations of standard models for power MOSFETs in more detail by simulating a simple half-bridge circuit typically used in a range of motor control applications. We then simulate the same design using a new and much more advanced electrothermal model that belongs to a new set of models being released by Nexperia. These models have been developed to provide circuit designers with much greater and more accurate insight into how Nexperia's power MOSFETs will really perform on a printed circuit board (PCB) in a real-world application.

Limitations Of Standard Models

In order to correctly predict the switching and EMC behavior of a MOSFET, it is critical to have an exact model of its static and dynamic characteristics across the full operating temperature range. This allows accurate circuit simulations to be performed using a SPICE software package.

However, standard models provided by many device manufacturers cannot be fully relied upon because they do not provide all of this information. This means discrete designers are sometimes required to make assumptions about aspects of device behavior and must therefore err on the side of caution by assuming worst-case scenarios will occur.

Adopting this approach can mask more subtle board-level performance issues or even result in designs which are overspecified for their purpose. In most cases, the available models cannot be used to gain any insight into the EMC performance of a device before a board is physically constructed.

Power MOSFET Testing

Double pulse testing is an industry-standard method used to characterize the switching behavior of power semiconductors specifically intended for testing device performance in inductive clamp switching applications. It consists of a half-bridge configuration with an inductive load with a low-side MOSFET switch and a high-side MOSFET configured to act as a freewheeling diode (Fig. 1).

A train of two pulses is applied to the gate of the low-side MOSFET (hence the test name). The first pulse turns on the low-side MOSFET causing current to flow through and charge up the inductor. Next, the gate signal is grounded, and this turns off the MOSFET causing the current in the inductor to begin flowing through the body diode of the high-side freewheeling MOSFET. During this time charge accumulates in the p-n junction of the high-side body diode—this is referred to as reverse recovery charge (Q_{rr}).

Once the second pulse is applied to the gate of the low-side device, it switches on again. This causes current to once again flow in the circuit, but the charge previously stored in the p-n junction of the upper device must also be removed. This Q_{rr} charge creates a short-duration, high-frequency transient signal (referred to as reverse recovery current) which interacts with the parasitics on the PCB and in the MOSFET itself. This phenomenon affects the EMC performance of the circuit because of the voltage and current overshoots which result.

To accurately determine the magnitude of this effect, it is important for device models to capture the reverse recovery behavior of the body diode so that the frequency and damping of the resulting oscillations (ringing) can be measured. This reverse-recovery diode behavior is not normally captured in the simulation models provided by many manufacturers and as a result, the magnitude of the ringing caused at second switch-on can appear to be quite large.

For example, Fig. 1 shows the results of a double-pulse simulation using a standard MOSFET model for Nexperia's BUK7S1R0-40H n-channel 40-V, 1-mΩ MOSFET in an LFPAK88. These simulation results show a 75% voltage overshoot that lasts for almost 0.5 µs. When real devices are subsequently evaluated in the lab, this amount of ringing does not occur in practice.

The discrepancy is caused by the fact that the standard model does not capture the reverse-recovery behavior of the body diode. This is a concern because the amount of ringing is sufficient to hide other effects that may occur due to the presence of other parasitic effects, and these may only be revealed to be problematic once a board has been constructed.

The limitations of these models mean they cannot be used to gauge the EMC performance of the circuit and it can only be quantified after extensive lab testing is performed much later in the product development process. At this stage, any design changes that might be required to help improve EMC performance become much more difficult and costly to implement.

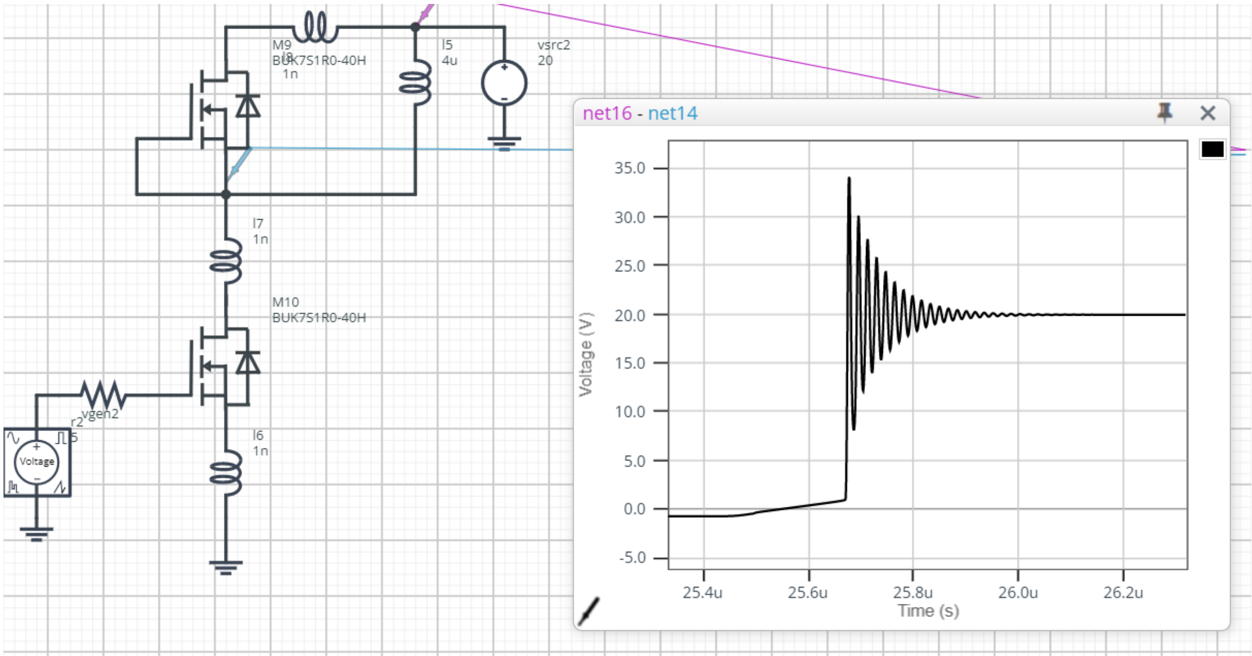

Fig. 1. Simulated double-pulse testing using standard power MOSFET models. In this example, simulation using the standard model of the BUK7S1R0-40H shown on the left produces unrealistic, excessive voltage overshoot and ringing.

Advanced Electrothermal Models

Nexperia recognized the limitations of standard MOSFET models and set about developing a new set of advanced electrothermal models for use with SPICE and VHDL-AMS that more accurately captured the behavior of their power MOSFET devices. These now also include an accurate model of reverse recovery for the body diode.

For example, Fig. 2 shows the results of the same device simulation (the BUK7S1R0-40H) performed previously, but this time carried out using the advanced model. In this case, much less ringing is evident, and oscillations settle out in a much shorter time interval (less than 0.2 μs) than was the case using standard models.

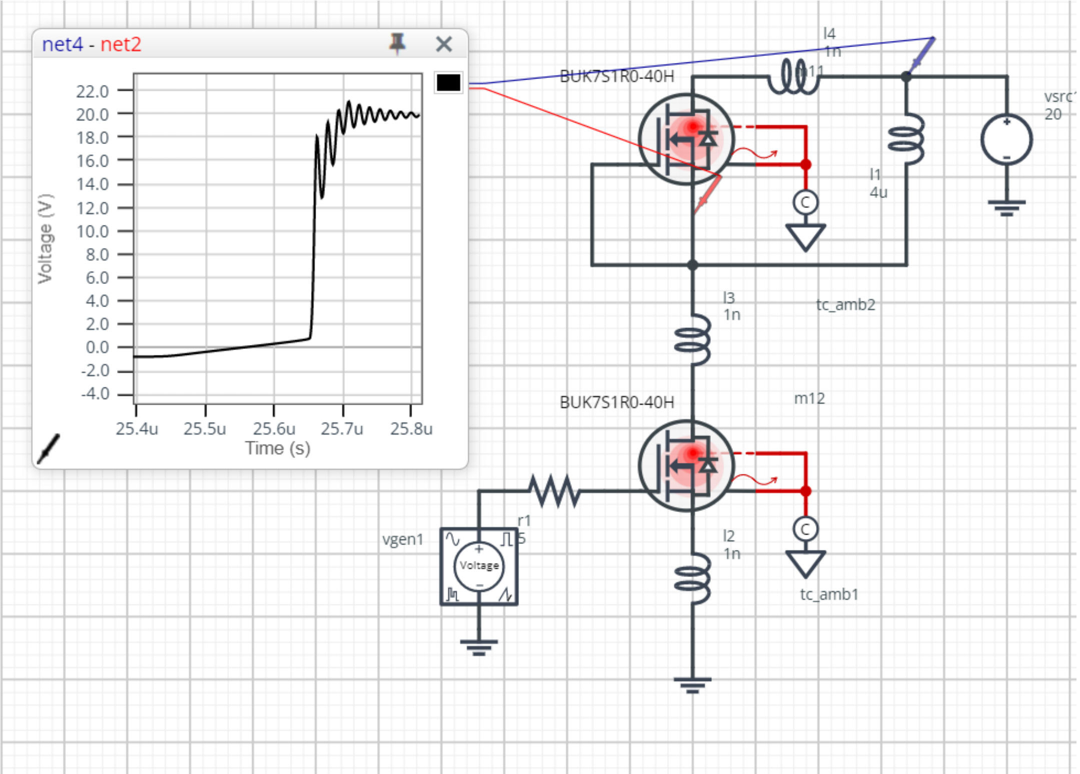

Fig. 2. Simulated double-pulse testing using advanced electrothermal power MOSFET models. In this simulation using Nexperia's advanced model of the BUK7S1R0-40H (shown on the right) with its accurate modeling of reverse recovery for the body diode, the amplitude and duration of the ringing are much reduced.

Taking this one step further, we can see the comparison between simulation and real measurements in an industry-standard double pulse test circuit. The test PCB and schematic are shown in Figs. 3 and 4, respectively.

Fig. 3. Double-pulse test board for the BUK7S1R0-40H.

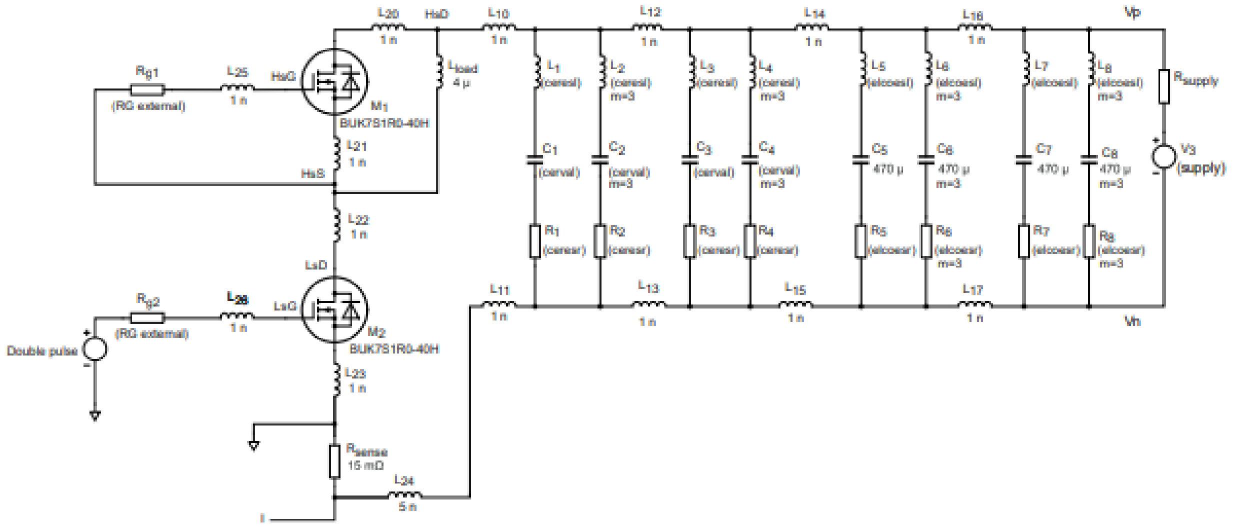

Fig. 4. Double-pulse test circuit, including parasitic impedances used in the simulation.

Moving on to Fig. 5, a comparison of measured versus simulated results using the advanced model illustrates the ringing on the switch node during low-side turn-on. It is clear to see there is very good alignment between measurement and simulation data.

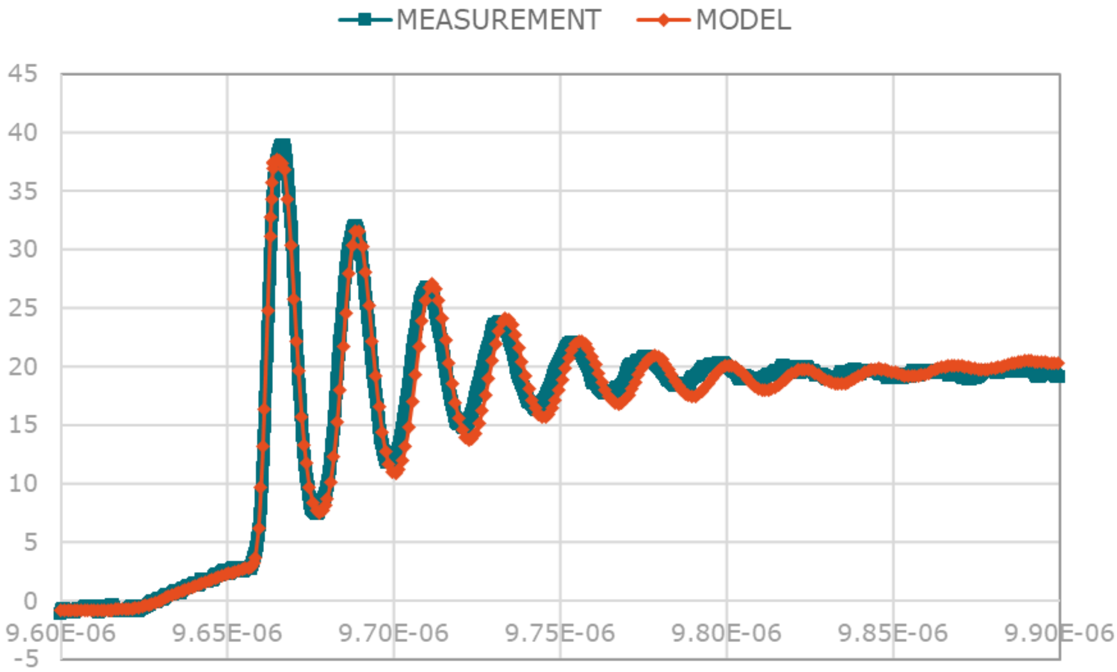

Fig. 5. Switch-node voltage ringing of Nexperia's BUK7S1R0-40H MOSFET in the double pulse test—simulation vs. measurement.

These advanced models reflect much more accurately the actual performance measured in the lab with the discrepancy between simulated and measured lab results being as low as 0.9% for some parameters. This increased accuracy allows designers to be much more confident in gauging what the real-life EMC performance of their circuit will be.

Apart from more accurately capturing device behavior, these models can also be used to examine device performance across the full operating temperature range. Fig. 6 shows the simulated on-resistance ($R_{DS(ON)}$) for the same MOSFET at temperatures ranging from -55°C to 175°C. But note that simulations can be performed at any desired temperature. This provides designers with the ability to more fully understand how the MOSFET's application will perform at operating temperature ranges expected for different applications.

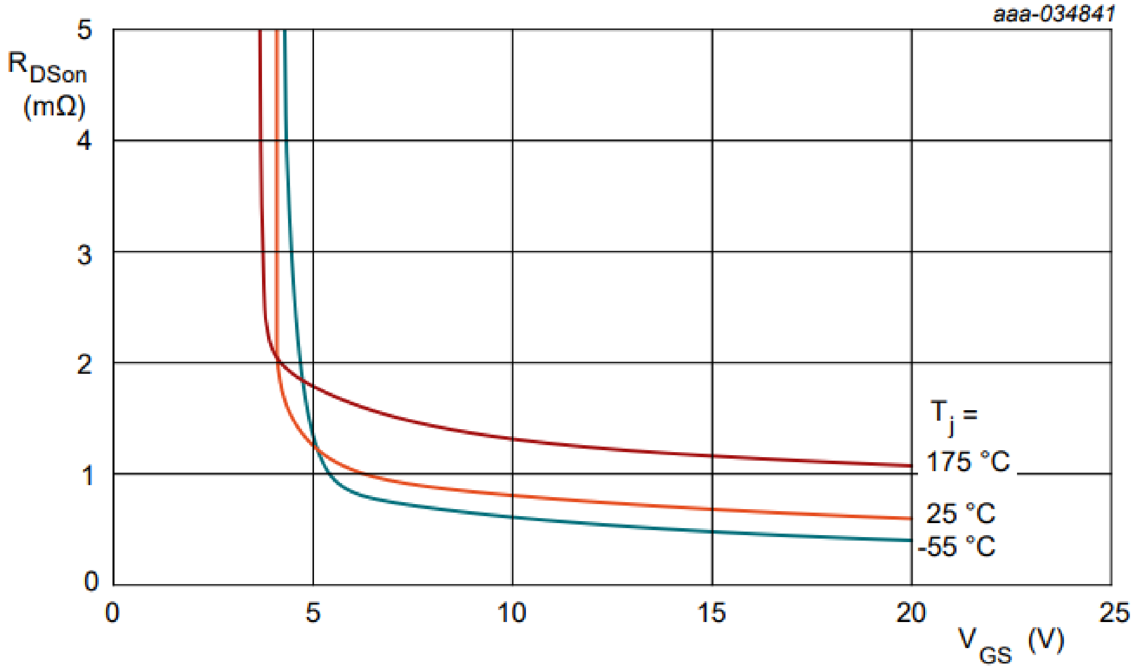

Fig. 6. $R_{DS(ON)}$ of Nexperia's BUK7S1R0-40H power MOSFET across the full temperature range of operation.

Behind The Models

Traditional SPICE models rely on physics-based equations. Trying to build models that match the sophistication of modern power devices via this methodology becomes a cumbersome and time-consuming task. The result is often a bloated model that is difficult to align with the measurement data and runs slow in the simulator. Furthermore, this complexity significantly increases the chance of causing non-convergence in simulator operation (i.e. the simulation will simply not run).

Conversely, the new models just outlined are based around behavioral equations. This allows different operating regions to be modeled independently of one another. As an example, take the linear and saturation regions of MOSFET operation. In traditional models, these would use the same parameter set—meaning that achieving a good fit in one region would have a detrimental effect on its fit in the other region. With behavioral models, this is no longer the case. As a result, the fit and therefore the accuracy attained will be much greater.

Conclusion

Standard power MOSFET simulation models provided by many manufacturers fail to include some vital device parameters which are required to provide insight into circuit performance characteristics like EMC. What's more, these can usually only be used to simulate how a device will perform at a nominal temperature. These limitations often result in designs being unnecessarily overspecified or problems going undetected until late in the product development process, when they become difficult and expensive to address.

A new set of advanced electrothermal models developed by Nexperia accurately models the reverse recovery of the body diode in their power MOSFETs and also allow**s** designers to simulate device behavior across the full operating temperature range. These features represent a significant advance over standard models, allowing designers to be more confident in the results of their SPICE simulations and to gain insight into the EMC performance of their circuit at a much earlier stage in the development process.

The new electrothermal models are currently available for select MOSFET devices from Nexperia. Additional models will be released for the rest of the company's MOSFET portfolio over time. Available models may be downloaded for free from the company's website (see the reference).

Reference

Precision Electrothermal MOSFET models

About The Author

Andy Berry is the principal product modeling engineer at Nexperia where his main focus is on modeling power semiconductor devices, especially for aiding the design and simulation of dc-dc converters and BLDC motor systems. Andy has been working in power electronics and semiconductors for 13 years, has a master's degree in electronic engineering and is working towards a PhD in power semiconductors.

For more on designing with power MOSFETs, see the How2Power Design Guide, locate the Component category and select "power transistors". For more on modeling and simulation, locate the Design Area category and select "Modeling and Simulation".