DC/DC-converter Spice model speeds simulation

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A dc/dc-converter macro model provides fast and accurate simulation of any fixed-frequency converter. By replacing the oscillator with a stable element, the model provides simulation speeds more than 100 times higher than an equivalent oscillator in transient-mode simulation.

DC/DC converters are notoriously difficult to simulate as component models in Spice because of the inherent instability of oscillator circuits in computer simulation. All too often, Spice settles into a static mode in which the circuit no longer oscillates, or it takes so long to converge between time iterations that the simulation is useless.

For a designer of dc/dc converters, these problems are difficult enough. But for a user who requires the simulated function of an off-the-shelf device as a part of a larger circuit, these problems are intolerable. Attempting to obtain a load-circuit dc-bias point further exacerbates the dc/dc converter's oscillator-circuit problems because oscillators don't produce an output during a dc simulation.

Fortunately, you can avoid the oscillator-related problems simply by not using an oscillator in the model. Instead, you can model a dc/dc converter's dc-transfer characteristic by using a voltage-controlled voltage source. Despite the limitations that are inherent in all macro models, the resultant model closely represents the behavior of a fixed input dc/dc converter (**Figure 1**). **Listing 1** is the corresponding netlist.

The model provides a fast and accurate simulation in both ac- and dc-analysis modes. The results for the model and the actual measured results for a 1W board-mounted dc/dc converter show an exceptionally close correlation between the dc-transfer curves of load regulation, line regulation, and efficiency, as well as accurate noise spectra at the correct dc-bias offset during a transient simulation.

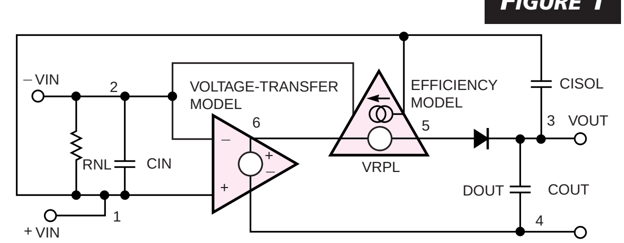
Manufacturers of dc/dc converters can use the model to provide their customers with accurate modeling data without disclosing the entire circuit design of their products. Likewise, customers using dc/dc converters can produce their own models when such models are unavailable from the supplier. The user of the dc/dc converter can then model the characteristic of their target circuits, including the behavior of the dc/dc converter, without the previously high simulation overhead or the nonconvergence problems of an oscillator circuit.

To develop the model, you first need to identify the key aspects of the dc/dc converter that describe its transfer characteristic. An unregulated, 1W, single-output, board-level dc/dc converter, the NME0505S (Newport Components Ltd, www.newport-comps.com), is an example of a relatively straightforward device. Operating from a 5V-dc input and producing an isolated 5V-dc output, this device features a fixed switching frequency of 100 kHz, a load regulation better than 15%, and a line regulation better than 1.1%. Other characteristics you might include in the model are the efficiency load curve (for the converter in this example, efficiency is a maximum with 1W load applied) and the ripple noise at the input and output terminals. All the required data is available from the dc/dc-converter data sheet.

Construct the macro model

When developing a macro model, your aim is to use stable components and elements to model the function of the tar-

FIGURE 1



The dc/dc-converter model uses a voltage-controlled voltage source to emulate the converter's voltage transfer and a current-controlled current source to emulate the ripple and efficiency characteristics.

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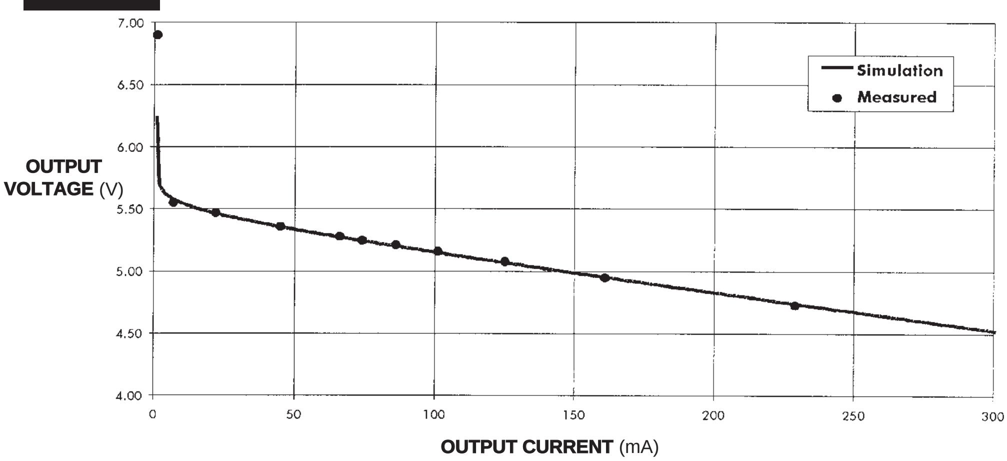
get circuit. For this reason, the Spice model in **Figure 1** uses a voltage-controlled voltage source to describe the dc-transfer characteristic. This approach avoids oscillator and transformer requirements and maintains isolation from input to output. You can easily model the no-load power consumption by using a resistor (RNL) across the input terminals to model the dissipation due to the oscillator operation.

Input and output terminals should appear electrically as they do in the actual component, which means that the model needs a low-impedance input provided by the no-load resistor and a dc blocking output. In the real dc/dc converter, the output dc block uses a diode-rectifier arrangement. Because this arrangement is stable, the model can also use it.

Other input and output features include ripple capacitors. If you use the model with additional external filtering, these capacitors ensure that the simulation includes the effects of any potential poles and zeros.

One of the most unique features of this model is the dual nature of the VRPL source, which is a 0V-dc, ac noise source. This source serves as a current-feedback element and as a ripple generator (hence, the source's name). Emulating the real converter's efficiency curve requires feeding back dc output current to a current sink at the input. Without this feedback, the converter would be more than 100% efficient. This effect results directly from the voltage-controlled voltage source, which provides the voltage-transfer characteristic. The VRPL source provides the necessary feedback. The model effectively connects the voltage-controlled voltage source to the current-controlled current source back-to-back to emulate the action of a transformer-to-voltage conversion in one direction and a current conversion in the reverse direction.

FIGURE 2

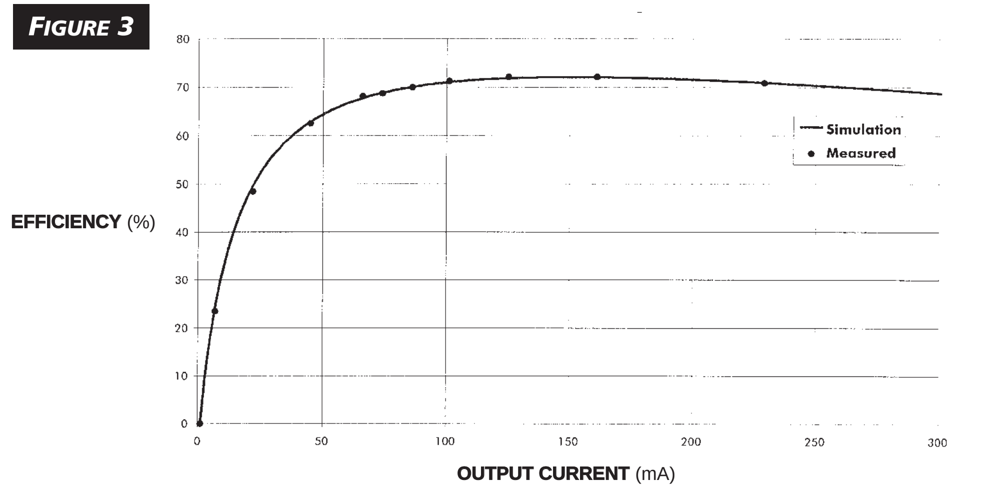


The measured load-regulation curve of the NME0505S almost exactly matches the load-regulation curve of the simulation.

VRPL saves elements

VRPL's second role, as a ripple generator, reduces the number of necessary elements in the model. VRPL's ac source produces ripple at the output so that an explicit input ripple generator is unnecessary. The ripple voltage is offset to produce a zero-dc level that doesn't affect the dc-level output from the voltage-controlled voltage source. Also, the effective feedback of the VRPL-generated ripple current produces an input ripple that is synchronous with the output-voltage ripple. You can observe this synchronous-ripple effect in the real device because the same oscillator produces both the input and output ripple. Thus, the VRPL source effectively provides current feedback, output-ripple generation, and input-ripple generation.

FIGURE 3



The simulated efficiency curve is close to the measured result.

Finally, the model in-

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cludes an element for the isolation capacitance (CISOL), which allows you to include common-mode effects if necessary.

LISTING 1—DC/DC-CONVERTER SPICE NETLIST

```
.SUBCKT NME0505 1 2 3 4
DOUT 5 3 NCLD105
.MODEL NCLD105 D (IS=1E-7 N=2.3 RS=2.8
+ EG=1.11 XTI=3 BV=50 IBV=25.9E-3 TT=2E-9)
COUT 3 4 0.5UF
E1 6 4 1 2 1.25
F1 1 2 VRPL -1.25
RNL 2 1 250
CIN 2 1 0.5UF
VRPL 5 6 DC 0 PULSE -0.68 0.02 0 0.25US 0.25US 4.5US 5US
CISOL 1 3 24PF
.ENDS NME0505
```

Choose values for the elements

Once you decide on the elements, you're only halfway to completing the model. The next step is to determine values for all of the elements and modeling terms. You can choose the input and output capacitors from the known input and output capacitor values (for this example, COUT=CIN=1 μF). The manufacturer does not always explicitly state these values, but you can determine them from application notes that discuss appropriate filter values. In reality, isolation capacitance is a measure of the capacitive coupling across the transformer and is a much lower value than that of most discrete capacitors. For this case, CISOL=24 pF.

You can calculate the no-load resistor value (RNL) using the no-load power consumption (P_{inNL}) or input current (I_{inNL}) at the nominal input voltage (V_{NOM}), as follows:

$$RNL = \frac{V_{NOM}^2}{P_{inNL}} = \frac{V_{NOM}}{I_{inNL}}.$$

For the NME0505S, P_{inNL}=100 mW, and V_{NOM}=5; hence, RNL=250Ω.

You can determine the voltage- and current-transfer characteristics from the transfer ratio of the internal transformer; use the direct ratio for the voltage-transfer characteristic, and use its reciprocal for the current. If the transformer ratio is unknown, you can obtain an approximation from the transfer ratio of the dc/dc converter. For a 5V-to-5V converter, the ratio is 1-to-1.

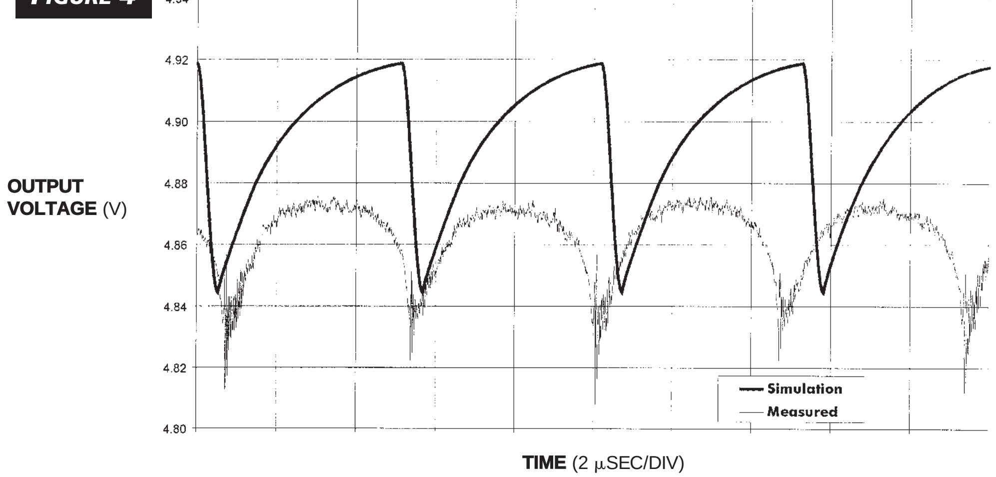
The chosen ac ripple voltage gives a zero dc-bias effect so that the model doesn't offset the output-voltage bias levels during ac simulations. Thus, the model produces a small positive and negative excursion. The ripple frequency equals twice the nominal switching frequency because the NME0505S uses full-wave rectification. The oscillator's switching waveform is a square wave. To produce this signal, the model uses a pulse waveform with fast rise and fall times.

Determining values for the diode is the most difficult decision. In Spice, a diode is a model in itself, and the diode model for DOUT includes an estimation of all of the dc-resistance effects due to tracking, wire, and the active components (**Listing 1**). This model is similar to the actual diode manufacturer's model but includes a better estimation of the resistive contribution. The model in **Listing 1** also adjusts the values of the parameters that govern resistance (RS) and saturation current (IS) to produce a load curve that matches that of the data sheet. If you don't have a model of the actual diode, you can create an adequate model by using an ideal diode and manually adjusting the RS and IS parameters.

Measurements of the output voltage and efficiency from an NME0505S device were graphically compared to the simulated load and efficiency curves (**Figures 2** and **3**). The results illustrate that the model is an extremely close representation of the real circuit's dc operating characteristic. Additional tests of the line regulation at a fixed output load exhibit similar levels of agreement.

Ripple was measured on a digital sampling oscilloscope and compared with the simulated response (**Figure 4**). The measured result has much more noise than the simulation, and the switching frequency is not an exact match. Despite these small differences, the general shape of the ripple is not drastically different, although the measured result is slightly more rounded than the simulation. The magnitudes of the measured and simulated ripples are

FIGURE 4



Output-ripple curves reveal some differences between the simulation and actual measurements, but the ac simulation is still a reasonably close representation of the measured result.

approximately 60 and 75 mV, respectively. The simulated dc offset differs from the measured results by only 40 mV. Hence, the ac simulation is a reasonably close representation of the measured result.

Take note of the model's limitations

A macro model is always a compromise; it usually sacrifices accuracy under all operating conditions for convenience and ease of use. This converter model is no exception, and, although the ripple, dc-load, line-regulation curves match well with the device's actual performance, this situation is true only over the device's normal operating conditions.

Outside the maximum recommended load condition, the real oscillator circuit produces a relatively rapid fall in output voltage as the ripple capacitor fails to hold up the output. The model continues to hold a linear regulation curve. At zero load, the actual output voltage rises to a high value as the ripple voltage charges up the capacitor until the output capacitor leakage and ripple charge are in equilibrium. Simulations using this model indicate a much lower zero-load output voltage.

The output ripple voltage is constant in the model, regardless of load conditions, but the real converter's ripple is much lower at light loads. The oscillation frequency also changes with input voltage. The model doesn't include these features, and simulation results using the model always indicate a constant ripple magnitude and frequency. EDN

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Author's biography

Martin O'Hara is a technical manager in the Development Division at Newport Components Ltd (Milton Keynes, UK). He received his BSc in applied physics from the University of Durham (Durham, UK) and his MSc in instrumentation from Manchester Polytechnic (Manchester, UK). During his seven years at Newport Components, he has designed products including safety-approved dc/dc converters and wound products. He also produces application circuits and is a member of IEE.

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