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Simulating DC-DC Converter Efficiency More Accurately With State-Space Averaging VRM Models

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In today's ever-more power-conscious electronic world, the efficiency of power delivery networks is paramount. From the smallest battery-powered IoT device to the largest data center server, every milliwatt saved translates directly into extended battery life, reduced operating costs, and enhanced system reliability. At the heart of these power delivery networks often lie dc-dc converters, specifically voltage regulator modules (VRMs), which play a critical role in transforming input voltages to the precise levels required by high-performance integrated circuits like CPUs, GPUs, and FPGAs.

This article will delve into the critical importance of dc-dc converter efficiency, explore when this metric becomes a design imperative, highlight applications where its simulation is indispensable, and ultimately demonstrate how our advanced state-space average VRM models within Keysight ADS provide a powerful solution for accurate and efficient efficiency analysis.

The Imperative Of Efficiency: Why Every Percentage Point Matters

At its core, the efficiency of a power supply or dc-dc converter is a measure of how effectively it converts input electrical power into usable output electrical power. Expressed as a percentage, it's defined by the ratio of output power (Pout) to input power (Pin):

$$\text{Efficiency}(\eta) = \text{Pout}/\text{Pin} \times 100\%$$

The difference between input and output power represents the power lost within the converter, primarily dissipated as heat. These losses arise from various sources, including:

- Switching losses: Occurring during the on-off transitions of switching elements (MOSFETs, IGBTs), these losses are proportional to switching frequency, gate charge, and voltage/current overlap.
- Conduction losses: Due to the on-state resistance ($R_{DS(ON)}$) of switching devices and the equivalent series resistance (ESR) of inductors and capacitors. These are proportional to the square of the current (I^2R).
- Gate drive losses: Power consumed by the circuitry that drives the gates of the switching elements.
- Magnetic losses: Hysteresis and eddy current losses within inductors and transformers.
- Quiescent current/no-load losses: Power consumed by the control circuitry and other internal components even when no load is present.

This example addresses the main power loss mechanisms, but other losses can be added if higher fidelity is required.

A "good" dc-dc converter typically boasts efficiencies exceeding 90%, and for many applications, designers strive for 95% or even higher.

When Is This Metric Useful And Why Is It Important?

The significance of high efficiency extends across several critical domains.

First, there is thermal management and reliability. The most direct consequence of inefficiency is heat generation. Higher losses mean more heat, which must be dissipated by cooling solutions (heatsinks, fans, etc.). Excessive heat directly impacts the lifespan and reliability of electronic components.

According to the Arrhenius relationship, chemical reaction rates (and thus aging and failure rates) approximately double for every 10°C increase in temperature. A more-efficient VRM (or voltage regulator) generates less heat, leading to a cooler-running system and significantly extending its operational life. This also reduces the complexity and cost of thermal management solutions.

Secondly, efficiency impacts energy consumption and operating costs. In systems that run continuously or in large quantities (e.g., data centers, industrial equipment), even a few percentage points of efficiency improvement can translate into substantial energy savings and reduced electricity bills over the product's lifetime.

For instance, a 1-kW power supply with 94% efficiency wastes 60 W, whereas a 96% efficient supply wastes only 40 W. Over a year, this seemingly small difference can amount to hundreds of kilowatt-hours (kWh) of wasted energy, easily exceeding the initial cost of the power supply itself.

Battery life and portability are also affected. For battery-powered devices like smartphones, laptops, IoT sensors, and wearable electronics, efficiency is paramount. Every joule of energy conserved directly extends battery runtime, a key differentiator in the consumer market. Higher efficiency allows for smaller batteries, reducing device size, weight, and material costs.

Other issues closely tied to efficiency are power density and miniaturization. As electronic devices become smaller and more integrated, there's a constant drive to increase power density (power delivered per unit volume). Higher efficiency means less heat generation for a given power output, allowing designers to pack more functionality into a smaller footprint without compromising thermal limits. This is crucial for compact designs in mobile, automotive, and aerospace applications.

Finally, for products that are subject to such regulations, efficiency determines compliance with energy standards. Governments and regulatory bodies worldwide are increasingly imposing stringent energy efficiency standards (e.g., 80 PLUS certification for PC power supplies, various international efficiency marking protocols). Designing for high efficiency from the outset is essential to meet these requirements and gain market access.

Applications Where VRM Efficiency Simulation Is Crucial

The ability to accurately simulate VRM efficiency at the design stage is a game-changer for a wide range of applications.

Given the attention on AI, perhaps the most timely example is in high-performance computing (HPC) and data centers. CPUs, GPUs, and specialized accelerators in servers and data centers consume significant power. Maximizing VRM efficiency is vital to minimizing operating costs, reducing cooling requirements, and improving the overall power usage effectiveness (PUE) of data centers.

This capability is also essential in automotive electronics. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) rely heavily on efficient dc-dc converters for power management across various voltage domains (for example, 400-V or 800-V bus to 12-V battery, traction inverters). High efficiency is critical for extending range, reducing battery size, and managing thermal loads in confined spaces. Bidirectional dc-dc converters, in particular, demand high efficiency in both buck and boost modes.

Other applications benefiting from VRM efficiency simulation are those in consumer electronics, industrial and telecom infrastructure, medical devices and aerospace and defense systems. Consumer products such as smartphones, tablets, laptops, gaming consoles, and smart home devices all benefit immensely from efficient power conversion to extend battery life and reduce heat in compact designs.

Medical applications have some similar concerns. Wearable and implantable medical devices often have extremely tight power budgets. Highly efficient dc-dc converters are essential for maximizing battery life and minimizing heat generation in sensitive applications.

For industrial and telecom, reliability becomes a key factor. Power supplies for base stations, industrial control systems, and power tools require robust and efficient VRMs to ensure reliable operation, minimize downtime, and reduce energy consumption in always-on environments. Likewise, reliability factors into aerospace and defense**.** But in aerospace applications, weight and thermal management are critical. Efficient power converters contribute to lighter systems and simpler cooling, enhancing mission duration and reliability.

The Power Of State-Space Average VRM Models For Efficiency Simulation

Traditional transient simulations of switching power supplies can be computationally intensive and time-consuming, especially when trying to analyze efficiency across a wide range of operating conditions. This is where the Sandler State-space average (SSA) VRM models[1] in Keysight ADS revolutionize the design process.

State-space averaging is a powerful modeling technique that provides a simplified, yet highly accurate, representation of a switching power converter. Instead of simulating the fast, cycle-by-cycle switching behavior, SSA models average the behavior over a switching period, allowing for significantly faster simulations without sacrificing fidelity for small-signal ac and large-signal transient analysis relevant to efficiency.

Key advantages of using our Sandler State-space average VRM models in Keysight ADS for efficiency simulation include:

- *Accelerated simulation speed.* By abstracting away, the high-frequency switching details, SSA models dramatically reduce simulation time, enabling designers to perform extensive parametric sweeps and corner analyses for efficiency optimization in minutes rather than hours or days.
- *Accurate loss mechanisms*. Advanced SSA models, such as the Sandler State-Space Average model, can accurately capture various loss mechanisms (switching losses, conduction losses, gate drive losses, etc.) as a function of operating conditions (input voltage, output current, duty cycle, switching frequency). This allows for a precise calculation of efficiency across the entire load range.
- *Comprehensive power integrity analysis.* Keysight ADS, with its robust simulation capabilities, allows for the seamless integration of SSA VRM models with other power delivery network (PDN) components (PCB traces, decoupling capacitors, IC package models, die models). This provides an end-to-end power integrity simulation environment, enabling designers to understand how VRM efficiency interacts with the broader PDN and impacts overall system performance, including ripple and transient response.
- *Early design optimization*. Simulating efficiency early in the design cycle allows engineers to evaluate different VRM topologies, component choices (MOSFETs, inductors, capacitors), and control strategies, enabling rapid iteration and optimization for peak efficiency before committing to hardware prototypes. This proactive approach significantly reduces design cycles and development costs.
- *Sensitivity analysis and tolerancing*. With fast simulation, designers can easily perform sensitivity analyses to understand how variations in component parameters (e.g., $R_{DS(ON)}$ tolerance, inductor DCR tolerance) affect overall efficiency, enabling robust design for manufacturing.

In the upcoming sections of this article, we will walk through practical examples in Keysight ADS, demonstrating how to set up and run simulations using our state-space average VRM models to extract critical efficiency data. Get ready to unlock new levels of power design optimization!

How To Set Up An Efficiency Simulation

After adding the Sandler State Space Average Converter model from the Signal Edge Solutions (SES) model library to your schematic, you will need to set up your VRM, regulator, or buck converter circuit for simulation. The video in reference 2 shows how to get started with our SI/PI library in ADS.[3] For this example, we will use the Texas Instruments TPS62816-Q1 converter.[4]

The TPS62816-Q1 is a high-efficiency, easy-to-use synchronous stepdown dc-dc converter employing peak-current-mode control. It is designed for automotive applications such as infotainment and advanced driver assistance systems. Low-resistive switches allow up to 6-A continuous output current.

The circuit in Fig. 1 demonstrates how to simulate efficiency with a 5-V input and a 1.8-V output. Notice on the TPS62816-Q1 model, we have two outputs depicted, a large-signal output and a small-signal output. For this simulation, we only need to use the small-signal output. We will use an I_DC source to sweep our output load current, which is depicted by SRC6. After setting up your circuit, add a current probe at the input and output of the regulator, as shown below. You can see we have named these "I_Probe_vin" and I_Probe_vout" respectively.

To simulate efficiency, we will use the DC simulator in ADS and add a parameter sweep. If you'd like a more granular sweep option, you can also add a sweep plan, as shown in Fig. 1.

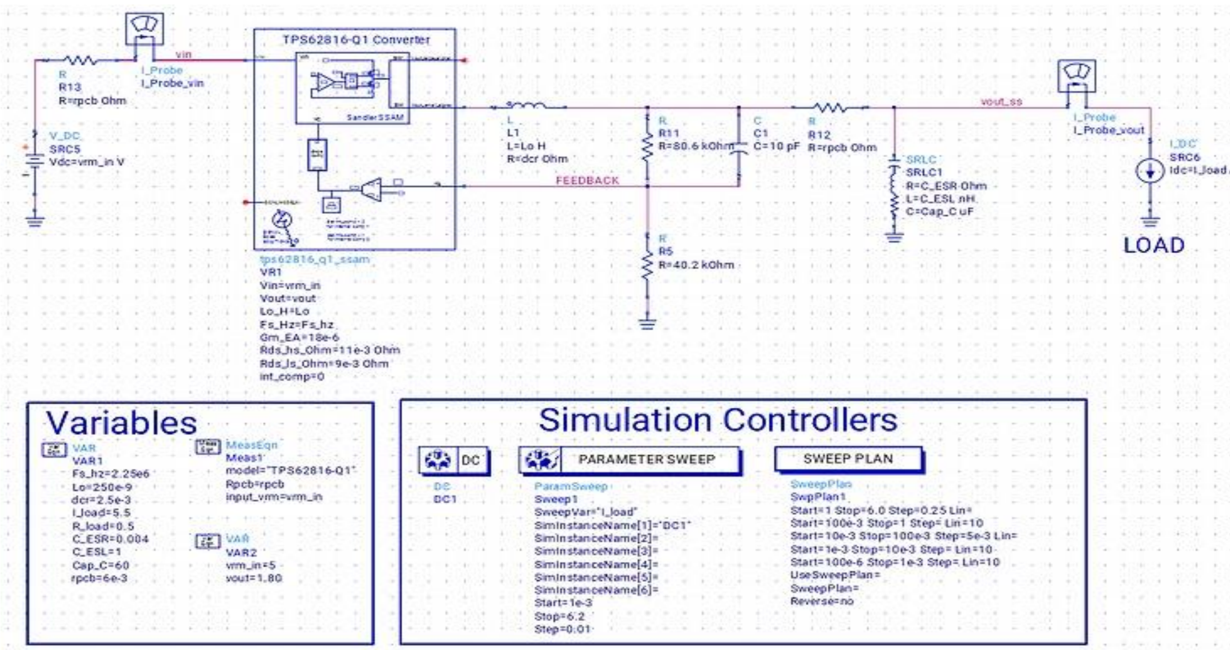

Fig. 1. Example Keysight ADS efficiency simulation with the TPS62816-Q1 converter.

Setting Up Your Sweep

An example of how to set up our dc simulation, with a parameter sweep and a sweep plan in Keysight ADS, is shown in Figs. 2 and 3. A sweep plan is not necessarily required unless a more granular sweep is desired. Generally, an efficiency simulation can be achieved with only a parameter sweep.

In this example, we are sweeping the "I_load" variable, which is the dc current on our current source shown in Fig. 1 by SRC6.

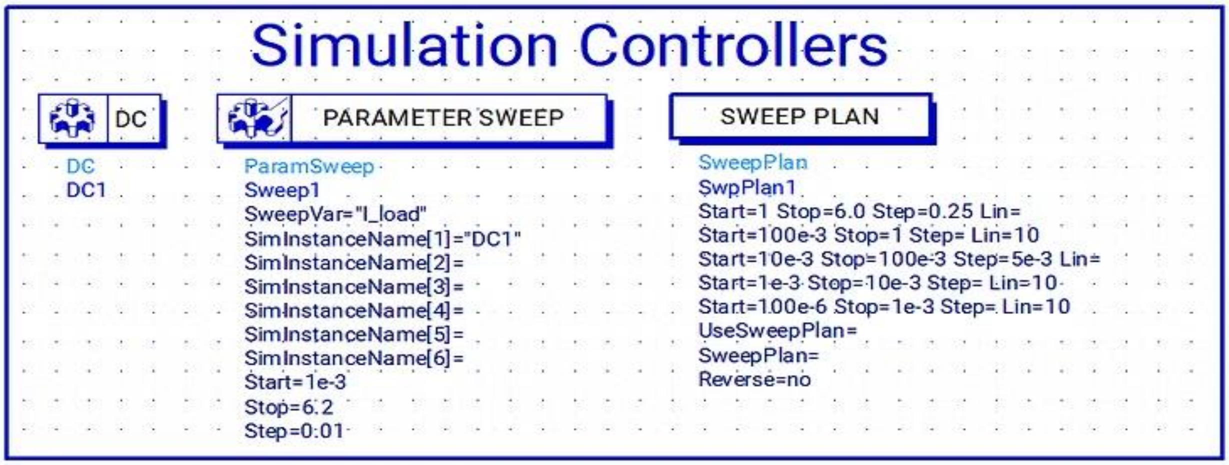

Fig. 2. Keysight ADS dc simulation setup with parameter sweep and sweep plan.

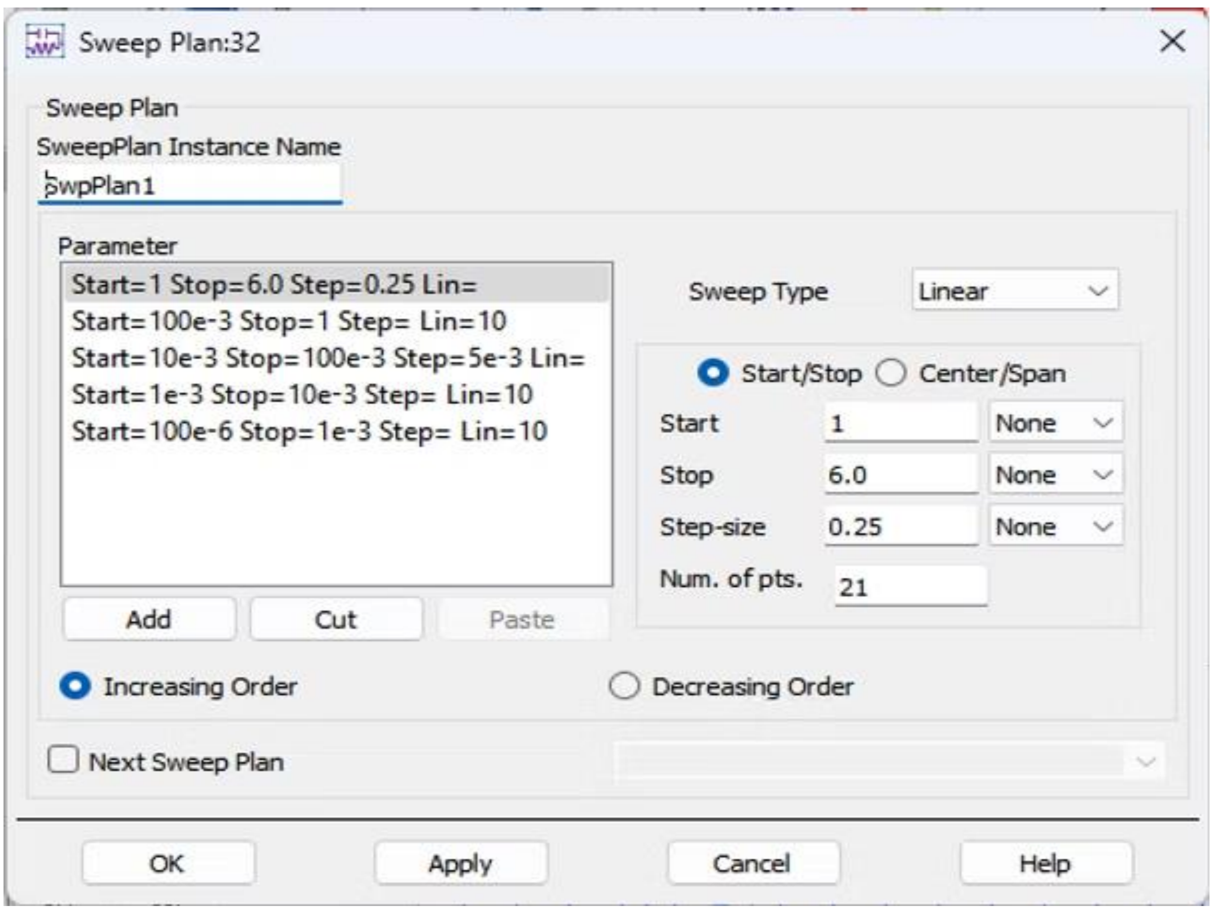

Fig. 3. Keysight ADS sweep plan setup example.

Setting Up The Data Display

After running your simulation, we need to add some equations to our ADS data display before plotting the efficiency curves.

For our current probes, the vin and vout_ss nodes (shown in Fig. 1), we need to note that these are arrays that contain multiple responses for each swept current value. So our arrays are two columns each—one for the array index and the other for the respective array value at the array index.

The equations shown below in Fig. 4 detail how to calculate our VIN, Iin, Vout, Iout, input power, output power, and lastly our efficiency.

```
Eqn Vin_ss_dc=mag(DC.vin[::,0])
Eqn Iin_ss_dc=mag(DC.I_Probe_vin.i[::,0])
Eqn Vout_ss_dc=mag(DC.vout_ss[::,0])
Eqn Iout_ss_dc=mag(DC.I_Probe_vout.i[::,0])
Eqn PWR_in_ss_dc=Vin_ss_dc * Iin_ss_dc
Eqn PWR_out_ss_dc=Vout_ss_dc * Iout_ss_dc
Eqn EFF_ss_dc=PWR_out_ss_dc / PWR_in_ss_dc * 100
```

Fig. 4. ADS data display equations for efficiency and other parameters.

As the next step to plot our efficiency, we need to add a plot to our data display and add the following trace expression, as depicted in Fig. 5.

Trace Expression: plot_vs(EFF_ss_dc, Iout_ss_dc)

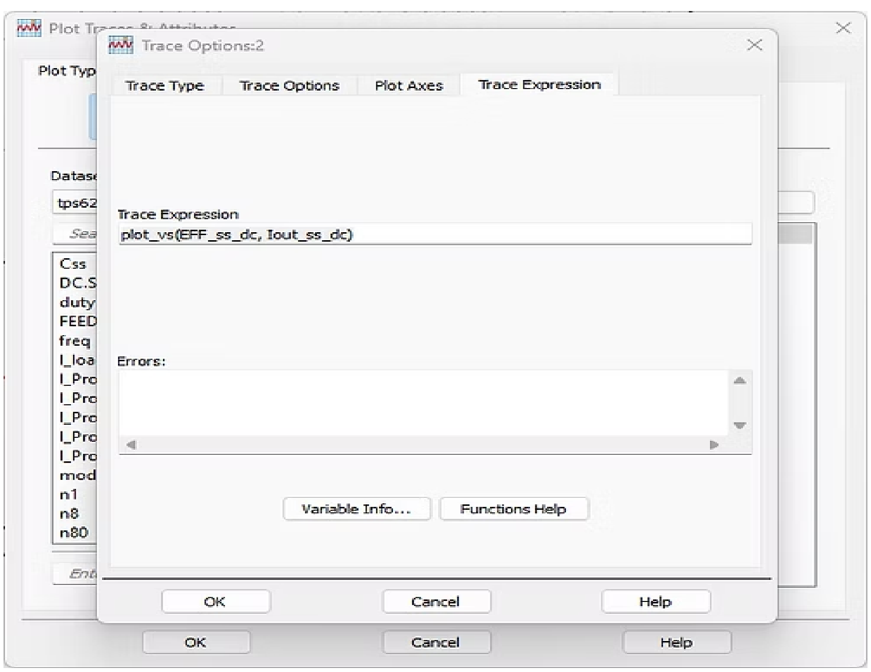

Fig. 5. Data display trace expression example for efficiency versus output current.

Our efficiency results are shown below in Fig. 6, in comparison to the TI datasheet,[4] specifically Fig. 10-5 on page 18 of the datasheet, which details a result for a 1.8-V output. After a quick observation, we can see our result for 5-Vin does not match up well at all with the datasheet. Why is that?

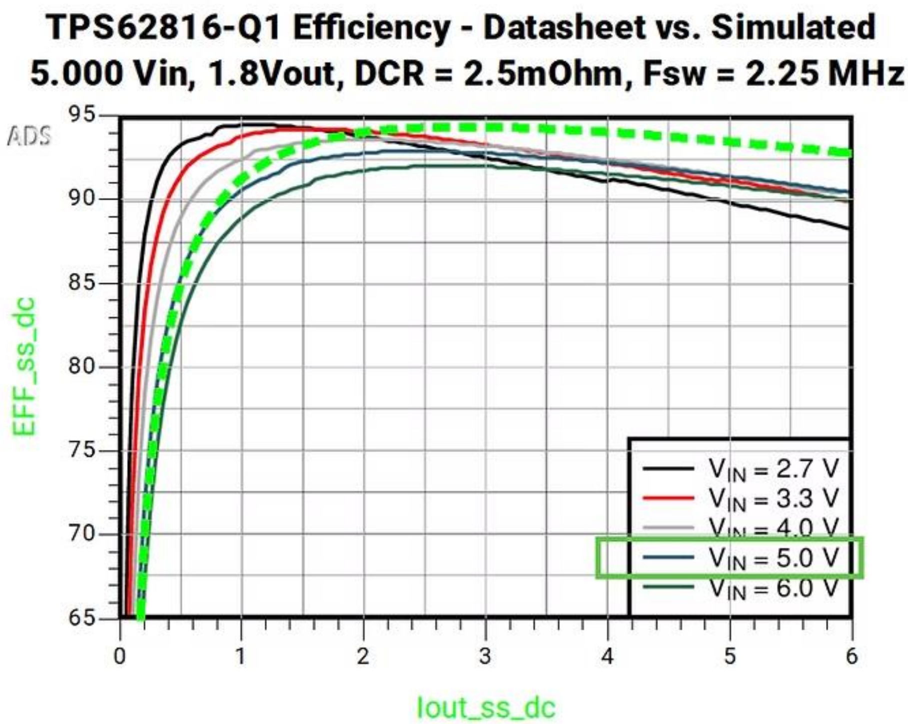

Fig. 6. TPS62816-Q1 datasheet (solid lines) vs. simulated (dashed green line) efficiency without inductor core losses.

The answer is straightforward, in that we need to remember that inductor power loss is broken down into two parts, the dc loss and the ac loss. If you reference some Coilcraft articles[5] and MuRata's Power Inductor Course - Chapter 3,[6] you will find more details on this topic.

In short, the hysteresis effect is one of the main sources of loss in ferromagnetic materials, or inductors, which must be accounted for to achieve accurate simulation results. This is where the Steinmetz equation[7] is used. However, there are online tools that provide this estimated loss, which we will discuss shortly.

As per Murata's Power Inductor Course, dc loss is proportional to Rdc (direct current resistance) because it is the conductor power loss from a direct current passing through a coil of wire. Meanwhile, ac loss is proportional to Rac (alternating current resistance) and is defined as the power loss in the conductor from an alternating current passing through a coil of wire. Ac loss includes power loss in the core, which is also referred to as iron loss. At high frequencies, power loss in the conductor also tends to increase due to the skin effect.

So, now, how do we determine our dc and ac power loss?

Well, our dc power loss is a function of the inductor's DCR value and the current through the inductor.

To determine the ac power loss, we will use the Coilcraft Power Inductor Analyzer.[8] From this tool, we can calculate our ac and dc power loss in our inductor. An example of this result is shown in Fig. 7 for the XGL4020-251 (250 nH) inductor, which is used in this example.

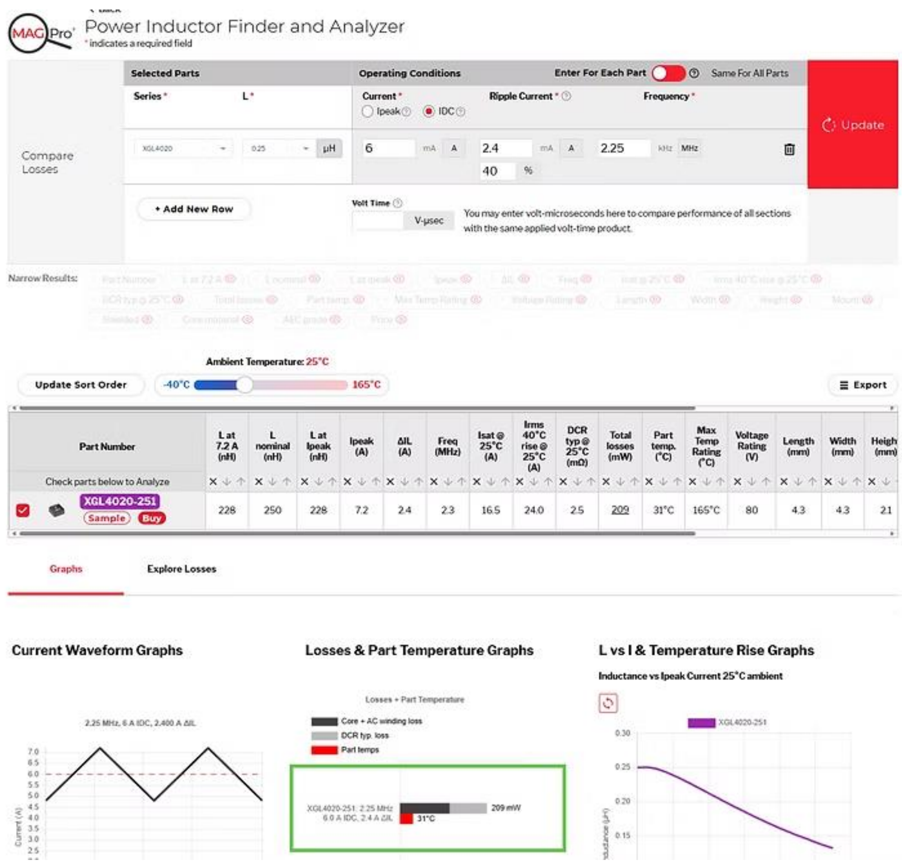

Fig. 7. Coilcraft Power Inductor Analyzer - XGL4020-251 (250 nH) inductor result at 6 A.

From this Coilcraft analyzer, we can plot our ac and dc loss at our switching frequency (2.25 MHz) for multiple dc currents as shown in the table below.

Table. Coilcraft Power Inductor Analyzer ac loss results for XGL4020-251 (250 nH) inductor.

Switching Frequency	2.25E+06			
Ambient Temp	25C			
Pcore AC Loss (W)	DC Loss (W)	Total Inductor Loss	DC Current	Rac
2.0E-3	3.0E-3	5.0E-3	1	2.0E-3
10.0E-3	10.0E-3	20.0E-3	2	2.5E-3
25.0E-3	23.0E-3	48.0E-3	3	2.8E-3
47.0E-3	40.0E-3	87.0E-3	4	2.9E-3
79.0E-3	63.0E-3	142.0E-3	5	3.2E-3
119.0E-3	90.0E-3	209.0E-3	6	3.3E-3
			Average Rac	**2.8E-3**

Using this average Rac value of 2.8 mΩ and the DCR value of 2.5 mΩ, we can plot the inductor dc and ac power losses, which are depicted in Fig. 8. We observe that the ac loss is 101 mW at 6 A, close to the value found (119 mW) in the table above, using the Coilcraft Analyzer tools shown in Fig. 7. This is a significant term that needs to be included in our efficiency calculation, and this demonstrates why we previously did not have a good correlation with the dc-dc converter manufacturer's datasheet.

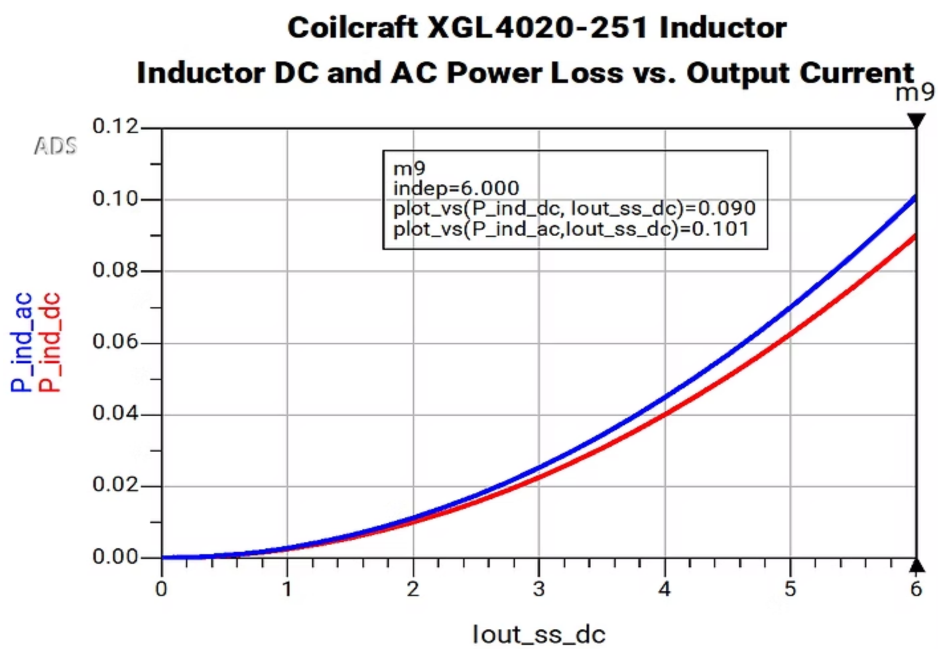

Fig. 8. Coilcraft XBL4020-251 inductor dc and ac power loss versus output current.

Now, let's account for these inductor ac losses in our efficiency equations, which are shown below.

Having accounted for both the inductor ac loss and additionally, the PCB loss in our equations, as displayed in the ADS data display equations below in Fig. 9, we can now calculate a more accurate efficiency result, as shown in Fig. 10.

In this example, our PCB loss is based on a PCB resistance of 6 mΩ. This number was found by fitting our simulated model to the datasheet result after accounting for the inductor ac losses. Additionally, the PCB effects could be included using a generated S-parameter model from a full 3D solver, like Keysight PIPro, to accurately include the PCB loss in our simulation.

Inductor AC Power Losses

Eqn ind_Rac=2.8e-3
Eqn P_ind_ac=mag(pow(Iout_ss_dc,2)*ind_Rac)

PCB Power Losses

Eqn P_pcb_in_loss=mag(pow(Iin_ss_dc,2)*Rpcb)
Eqn P_pcb_out_loss=mag(pow(Iout_ss_dc,2)*Rpcb)

Calculating Power Out and Total Power Loss

Eqn PWR_out_ss_dc=Vout_ss_dc * Iout_ss_dc

Eqn total_pwr_out=PWR_out_ss_dc-(P_ind_ac)-(P_pcb_out_loss)

Calculating Efficiency

Eqn EFF_ss_dc_core_loss=(total_pwr_out) / (PWR_in_ss_dc+P_pcb_in_loss) * 100

Fig. 9. ADS data display equations for losses and efficiency.

When comparing this updated simulated result to the datasheet, we can see that our simulated result correlates very closely with the datasheet at multiple input voltages for a 1.8-V output. Using this method provides an accurate and fast solution to simulate power supply efficiency for your designs.

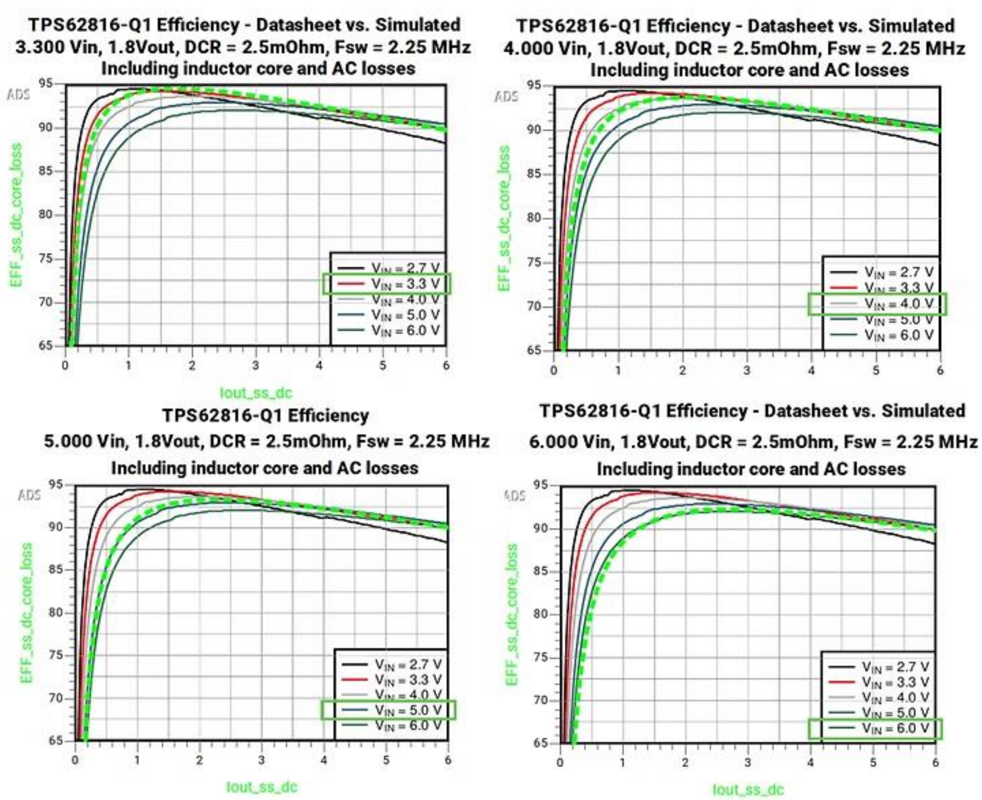

Fig. 10. TPS62816-Q1 datasheet (solid lines) vs. simulated efficiency (dashed green line) with Coilcraft XGL4020-251 inductor core losses.

Wrap Up

In this article, we discussed why efficiency is important and showed a detailed, accurate example of how to simulate efficiency with inductor dc and ac losses using our Sandler State-Space Average VRM models. Furthermore, with this modeling method, if desired, designers can model the efficiency of an entire power system, which could include multiple cascaded regulators.

References

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For Further Information

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About The Author

Benjamin Dannan is the founder and chief technologist at Signal Edge Solutions. He is an experienced signal and power integrity (SI/PI) design consultant developing advanced packaging solutions for high-performance ASICs, chiplets, and complex FPGA designs. Benjamin is also a Keysight ADS Certified Expert with expert-level proficiency in high-speed simulation solutions and multiple 3D EM solutions. In addition, he has expert-level proficiency with multiple test and measurement solutions, including oscilloscopes, vector network analyzers (VNAs), time domain reflectometers (TDRs), function generators, and EMC lab testing equipment.

A senior member of IEEE, Benjamin's engineering experience includes designing, developing, and launching production products, including ASICs, radars, fully autonomous robotic platforms, pan-tilt-zoom (PTZ) camera video systems, and ground combat vehicles.

Benjamin was awarded the DesignCon 2025 Engineer of the Year, has co-authored multiple peer-reviewed journal publications, and has twice received the prestigious DesignCon Best Paper award. He holds a certification in cybersecurity, a BSEE from Purdue University, and a master of engineering in electrical engineering from The Pennsylvania State University.

Benjamin also has extensive military experience. He graduated from the USAF Undergraduate Combat Systems Officer training school with an aeronautical rating. In addition, he is a trained Electronic Warfare Officer in the USAF with deployments on the EC-130J Commando Solo in Afghanistan and Iraq, totaling 47 combat missions, and is a trained USAF Cyber Operations Officer.

For further reading on modeling and simulation of power converters, see the How2Power Design Guide, locate the "Design Area" category and select "modeling and simulation". Also, see the "Power Supply Function" category and select "DC-DC Converters".