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Powering RF Systems: Why So Many Power Supply Designs Have Problems and What IC Suppliers Should Do About It

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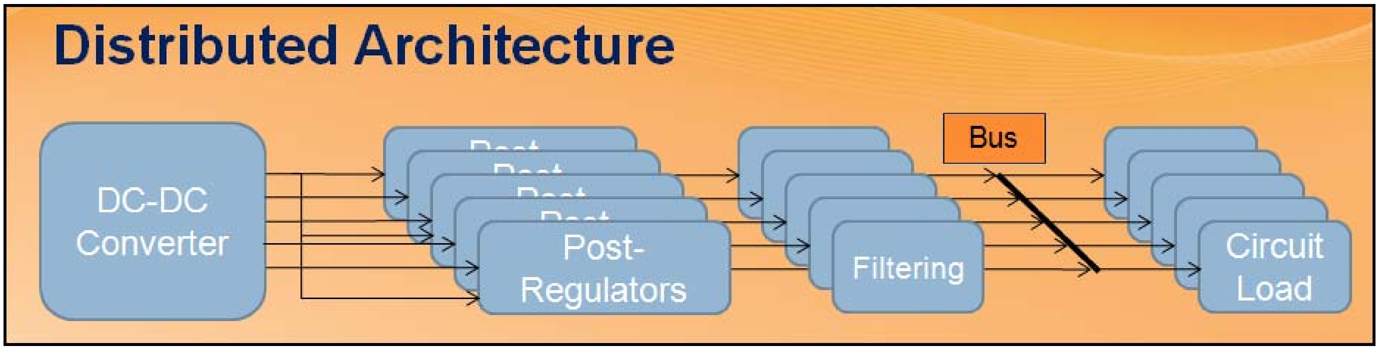
As design consultants specializing in circuit and systems reliability analysis, we evaluate many power supply designs used to power microwave and RF applications. Unfortunately, many of these power designs simply don't work as well as they need to; from the simplest linear regulators, to the switching converters, all the way up to the complete distributed power systems. These designs often fail to meet key specifications such as stability, regulation, ripple, and headroom.

There are a variety of technical reasons why these power supply designs perform poorly, and we can examine these issues individually. However, in many cases, the problems can be traced back to a lack of adequate information from the power component vendors. Their datasheets simply don't tell RF system designers what they need to know to develop power conversion circuitry.

Nevertheless, this problem presents a great opportunity. If they're willing, power IC developers and FAEs can do a lot to help.

Overlapping Disciplines

The same power supply (converter and regulators) is used to feed various types of loads, which are often digital or RF in nature (Fig. 1.) Devices in these circuits have become so fast that the transient edges of the load currents are much more of a problem than they used to be. The di/dt of the loads can be extremely fast. The regulators are also much faster, so that the old 2-MHz network analyzer is no longer adequate. Today's regulators often have bandwidths in the 5- to 10-MHz region. As a result of these issues, the power electronics engineer suddenly finds himself struggling with RF issues.



Characteristics	**Problems**
• Converter feeds multiple regulators • Regulators feed filters • Filters feed circuit loads	• Multi-winding feedback o Difficult to analyze, large ripple, cross-regulation issues • Regulators o Stability, headroom, require extensive filtering o Not designed to properly handle low or wide load ranges • Filters o Large tolerances • Loading o Fast changes, high current create dynamic problems in regulation and stability o High-current FPGAs, low-noise LNAs, etc.

Fig.1. A distributed power system architecture relies heavily on linear regulators plus filtering to clear up poor dc-dc converter performance. Heavy filtering causes regulators all sorts of problems including poor phase margin, which leads to the breakdown of system performance.

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Inexperience With Power System Design

Who is designing the distributed power systems used in RF products? Analog power supply engineers? Generally not. It is the RF or system engineers putting these architectures together, many times with an off-the-shelf or generically designed dc-dc converter. These RF engineers are adept at what they do, though they are not familiar with the intricate details of a distributed power system and its pitfalls. The typical scenario is that a visit from an applications engineer or field sales engineer results in some literature, application notes and free sample parts.

The general belief is that a linear regulator, or LDO when it's a low-dropout type, is simply a drop-in part that receives an input and generates an output. There is a lack of understanding regarding the relationships between the power devices and the system. For example, how decoupling capacitors and filter capacitors affect the stability or transient performance of the voltage regulator. In space applications, large capacitors are needed to support single-event and other radiation effects. However, these capacitors drastically impact the stability of the regulator.

Power system design typically begins with what voltages are needed and uses switching regulators with multiple outputs. Rarely is a trade-off study performed to assist with the selection of a converter topology. This is certainly not the optimum approach. Often, a flyback topology with a multi-output transformer winding is selected for the converter. This can result in very large ripple and unpredictable cross-regulation and stability issues due to the intricate nature of the transformer [1-3]. Analyses of these types of power supplies are difficult and often intractable. Simplified analyses hide possible issues at certain operating points that don't readily reveal themselves until they are encountered during the mission. Analyses of these types of power supplies are difficult and often intractable. Simplified analyses hide possible issues at certain operating points that don't readily reveal themselves until they are encountered during the mission. So then the first mistake is patched with linear regulators and enough filtering to address single-event effects (SEE), electromagnetic interference (EMI) and other noise and ripple concerns.

Interestingly, one of the reasons why the multiple-output-winding flyback is used—as opposed to several single or dual converters that would provide better ripple performance—is because of its low parts count. Unfortunately, this benefit is wiped out by the large amount (in both quantity and board area) of filtering required by the post regulators.

Inadequate Datasheets

Look at just about any regulator datasheet. It doesn't say anything! Where is the information regarding stability, power supply rejection ratio (PSRR) vs. differential voltage, reverse transfer effects, impacts of adding filters, etc. Most of the data contained in a typical voltage regulator or LDO datasheet is focused on the regulation accuracy and the dropout voltage. A survey of xx117 or xx317 datasheets is eye opening.

Where is the information on how to set the adjustment-pin capacitor value or the load-capacitor ESR range for which the regulator is stable?

For example, ON Semiconductor's LM317 datasheet shows some information and provides this advice:

"Although the LM317 is stable with no output capacitance, like any feedback circuit, certain values of external capacitance can cause excessive ringing. An output capacitance (CO) in the form of a 1.0 µF tantalum or 25 µF aluminum electrolytic capacitor on the output swamps this effect and insures stability."

A few things to note. The typical phase margin of the LM317 application circuit with no output capacitor and a small (2 mA) load step is pretty poor and looks nothing like the picture in the datasheet (Fig. 2.)

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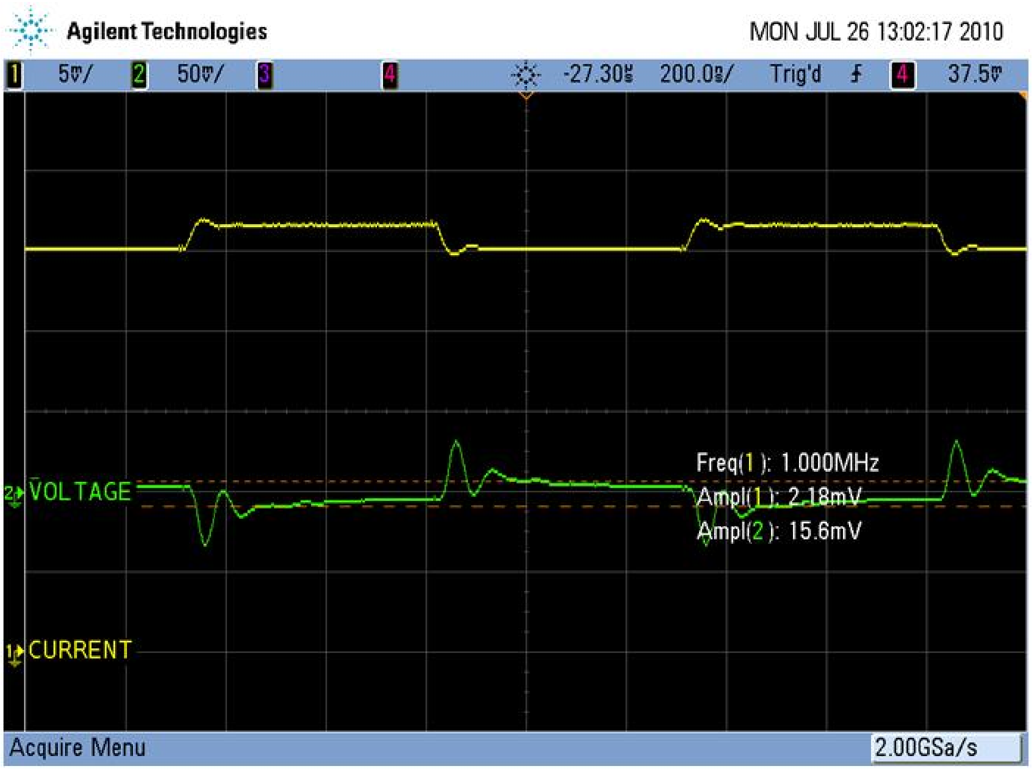

Figure 2. Measured small-signal step-load response (2 mA step) of an LM317T-based regulator with 3.3-V output, 6.3-V input, and no capacitors.

Adding a 1-µF ceramic capacitor to the output only makes the performance worse.

Figure 3. Measured small-signal step-load response (4 mA step) of an LM317T-based regulator circuit with 3.3-V output, 6.3-V input, and a 1-µF capacitor.

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So why is this so different than the datasheet information?

1. The datasheet often shows large-signal response as opposed to the small signal, so the datasheet is not a valid representation of stability.
2. The datasheet uses very slow rising and falling edges for the step load, masking the high-frequency instabilities.

Today, there are many different types of capacitors, so a 1-µF tantalum can have an ESR that is very low or very high. Additionally, ESR and ESL are generally uncontrolled parameters, so that only a maximum is specified. The ESR of the capacitor is responsible for the stability of the regulator.

Some other interesting affects are observed in the measurement of PSRR (Fig. 4.)

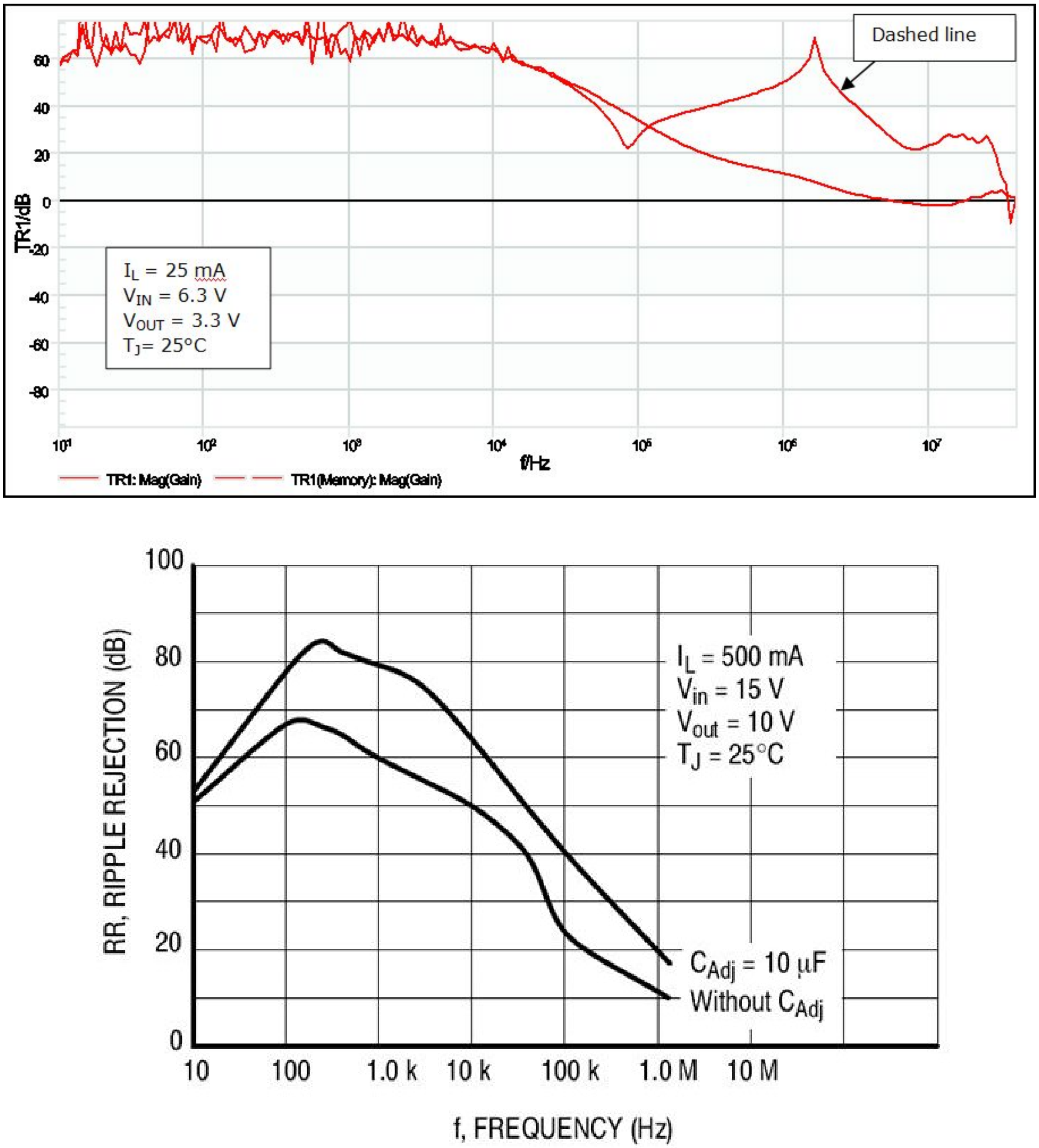

Figure 4. The measured PSRR of the example voltage regulator is shown in the top graph. The measurement goes up to 40 MHz. The dashed line is with a 1-µF ceramic output capacitor and the solid line is without any capacitor. Contrast the measured PSRR with the datasheet specification shown in the bottom graph.

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What is in the datasheet is misleading as it is a 120-Hz measurement. But more importantly, it is the load current that optimizes PSRR. Furthermore, the datasheet PSRR is only measured to approximately 1 MHz, missing a great deal of information. The same is true of the output impedance, which is also only measured to 1 MHz.

In addition, the data is provided at a single operating current and limited frequency. The output impedance varies depending on load current, and of course the important data is above 1 MHz, since the bandwidth of the circuit is in this region. (This corresponds to the load step in Fig. 3.)

As mentioned previously, phase margin is largely determined by how the voltage regulator is loaded. This missing data sheet information becomes even more important when we need to figure out how the full regulator performance will be impacted by poor phase margin.

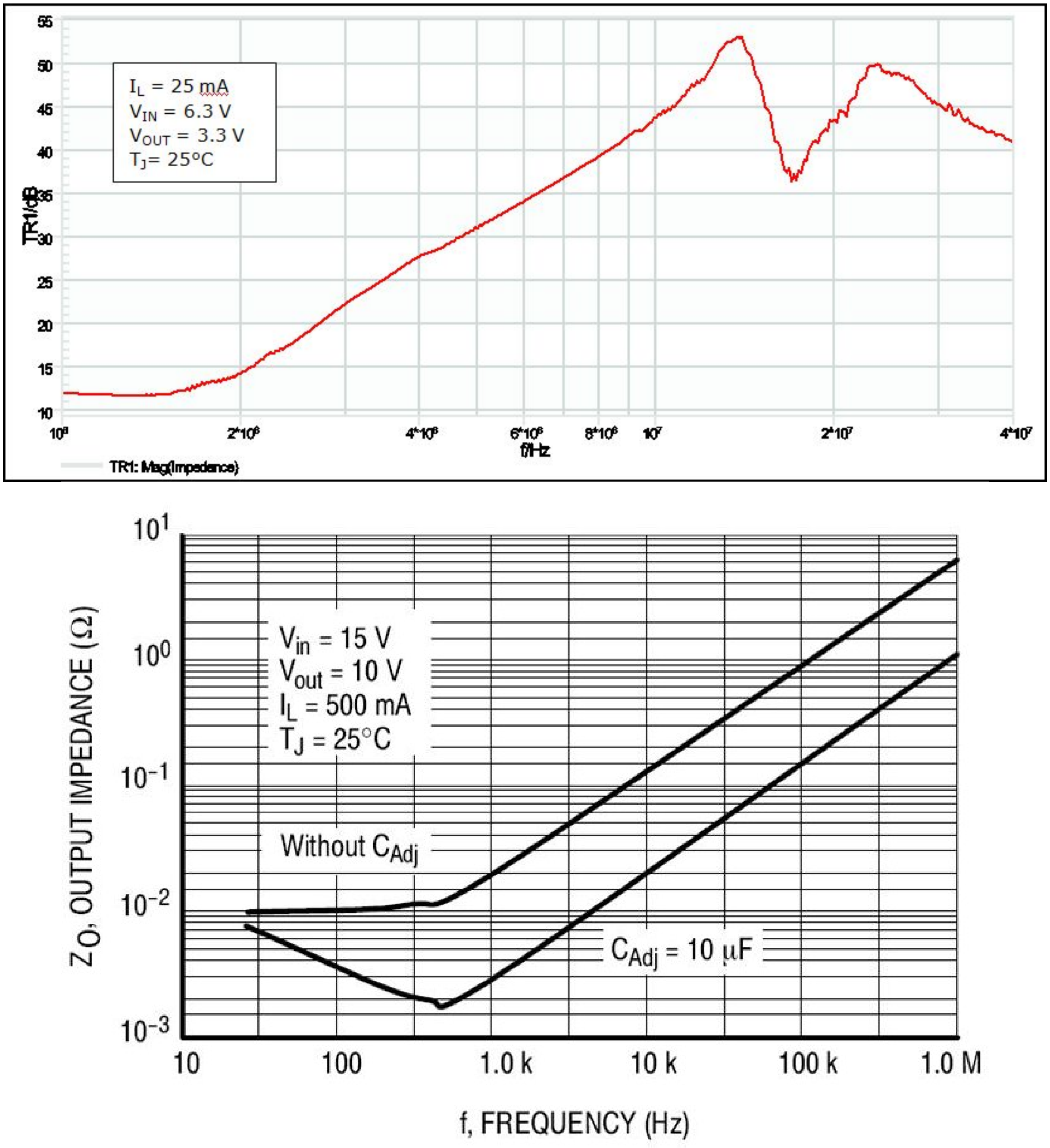

Fig. 5. The measured output impedance of the example voltage regulator is shown in the top graph. The measurement goes up to 40 MHz. Contrast the measured output impedance with the datasheet specification shown in the bottom graph.

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Inadequate Tools

IC manufacturers generally do not provide models that work in common RF simulators. In some cases, SPICE models with questionable accuracy are provided. The problem is RF engineers don't use SPICE. They have RF simulators, such as ADS or Microwave office, which are much more capable then SPICE for RF analysis and include many capabilities that SPICE does not include like large-signal ac simulation. The RF or system designer needs to see what the results are in their systems' output. That means in the RF circuit simulation. Therefore, regulators must be included with the RF circuitry in order to perform the system simulation. SPICE cannot run the RF simulations, so to run the higher-level analysis the RF engineer needs the appropriate power IC models translated to their tools.

Inadequate Test Equipment To See The True Performance

Another issue has been the lack of test-equipment interface adapters and signal injectors capable of making the necessary, high-fidelity measurements.

While network analyzers, impedance testers and other test equipment with great enough resolution are commonly available, the interface adapters used to connect the device under test can distort the system performance to the point where the measured data is erroneous [4-6].

Several manufacturers have been providing better Bode injection transformers [7]. But there are some very poor ones also. Not all injection transformers are capable of the small-signal wide-bandwidth measurements required for a good Bode plot. Some engineers believe that audio and video transformers can be used and that the transformer is not a part of the measurement. Both beliefs are untrue.

The bandwidth required for a proper Bode plot or impedance measurement is generally several octaves above the control-loop bandwidth, at a minimum. The typical linear regulator has a bandwidth of several megahertz. This requires very high-fidelity equipment to reveal the regulator's true performance.

It is recommended that a good lab setup have several types of injection transformers each optimized for a different bandwidth. PFC applications require an injection transformer with good low-frequency performance (in the 1-Hz range), while offline power supplies and LDOs require much higher bandwidths. Some state-of-the-art voltage regulators with bandwidths in the megahertz region can require a solid-state injector to properly resolve the higher-frequency information.

It should be noted that injection transformers use a very high permeability, specially annealed core material. The typical injection transformer, high quality or not, cannot operate with more than 5 to 10 mA of dc current. Higher currents will provide incorrect results, but also can permanently bias the core rendering the transformer useless and possibly damaging the driving amplifier as a result of the transformer saturation.

Additionally, consideration should be given to how measurements can be made non-invasively under final production conditions, as test boards, prototypes and engineering models with a different layout won't present the same loading and transmission line impedance as the final hardware. Non-invasive stability measurements are possible with the right equipment.

Better Architecture, Datasheets, Models and Equipment

To successfully complete a design for a distributed power system, you need the right tools. These include the right architecture and converter topology, more comprehensive datasheets, high-fidelity simulation models and support for the system-level simulators, which are not SPICE. You also need test equipment capable of making measurements to the correct fidelity.

Solving the problems outlined above, requires a multifaceted approach. First, the RF system designers need to know a little about power conversion so they can make smart decisions.

We need to teach the RF system designers that the power system is not just some black box you can simply insert at the end of the design process. Power requires planning.

All too frequently, we see power systems that are plagued with stability, transient response, and ripple rejection problems due to poor phase and gain margin. Most high-reliability systems require a minimum end-of-life worst-case phase margin of 30 to 45 degrees. Many regulators available today do not meet that initially at room temperature, using the application circuit in the datasheet. Compare a voltage regulator datasheet with a

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video op amp datasheet, for example, and you will see the complete lack of effort put into the voltage-regulator specifications.

It is unfortunate that many companies have cut back or eliminated travel and education budgets due to the poor economy. This is not saving money, it is costing money, since the designers make errors that are expensive and time consuming to correct. The responsibility falls on the semiconductor industry, as well as, the engineers and their employers. The information needs to be made available to the users so that they know how to use power ICs, successfully taking into account all the performance aspects that matter. Without that information, engineers are flying blindly down the design path only to discover all too late in the game that the components they have selected won't meet specification.

We need to provide designers the tools they need, via datasheets and quality simulation models. The datasheets must convey both the bad and good points about a particular part. In general, datasheets are marketing tools and not engineering tools, so they tend to focus on the positives. For their part, RF engineers need to be ready to make high-fidelity measurements to support their design and analysis efforts.

In the end, the component manufacturer does not win by hiding the component flaws. Eventually they get uncovered, resulting in system problems, unhappy customers, and the loss of future business from these customers.

The Top Ten Things RF Engineers Should Know About Voltage Regulators

1. Low dropout is not always a good thing.
2. Most regulators can easily become unstable when a filter is connected.
3. Bigger is not always better— a large pass element has a large capacitance!
4. If the manufacturer did not tell you about the stability performance, it is likely not stable.
5. Not all regulator topologies perform alike.
6. You should be aware of how the datasheet values are measured.
7. You can simulate your regulator in SPICE, ADS, Microwave Office or Designer with good models of the regulator and output capacitors. To do this you will have to model the parts yourself, hire a specialist in modeling, or convince the IC vendor to make a high-fidelity model for you in your chosen simulator's syntax.
8. It takes a very high-quality signal injector to measure a typical regulator control loop—measurement bandwidth likely needs to be higher than expected.
9. Know your capacitors. ESR is not a constant, but a function of many variables. Capacitance can be VERY voltage sensitive, especially in the case of the increasingly popular X5R capacitors.
10. Not all regulators allow stability measurements. You can still get an indication from step-load performance if you know how and where to inject the signal using a high-fidelity current-signal injector.

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Steve Sandler is the founder and chief engineer of AEi Systems, where he leads development of high-fidelity simulation models for all types of simulators as well as the design and analysis of both power and RF systems. Sandler has over 30 years of experience in engineering and is a recognized author, educator and entrepreneur in the areas of power, RF and instrumentation.

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