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Slammers And Software Verify Performance Of Advanced Voltage Regulators

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Digital integrated circuits (ICs) continue to increase rapidly in capability and application. Much of this improvement is due to new processing technology, including smaller feature size, larger transistor count and larger die sizes. With these trends come higher supply current and current step loads, simultaneously with lower voltages and tighter regulation tolerances.

In turn, voltage regulators must meet these increasingly stringent supply requirements. Peak load currents of several hundred amperes are common, and transient load steps can be a high percentage of full load current. Test equipment designed to exercise and verify these regulators has previously existed only in the realm of custom testers for vendor-specific ICs. In this article we look at the utilization of load slammers, a class of off-the-shelf voltage regulator test devices from ProGrAnalog—and sometimes constructed by engineers for in-house use—as a test utility for high-performance transient load testing.

We begin by discussing the differences between load slammer measurements versus simulation results, and how load slammers compare with Bode and impedance analyzers in terms of their respective measurement capabilities. Mainly the focus here will be on how we configure the LoadSlammer's GUI to perform a variety of transient, pulse train and impedance tests. Example test results are presented and analyzed with attention given to the various features of the GUI that aid our analysis.

The ability of the LoadSlammer to perform dc load testing and the delay feature are also briefly discussed. Finally, we note the various benefits in product design and manufacturing that can be obtained by using the LoadSlammer in combination with test suites.

Different Approaches To Verifying Regulator Performance

Measuring regulator performance under actual operating conditions is the best final way to verify performance. Simulation is valuable if models are accurate over all conditions and if all parasitic components, including layout, have been included. In this case, a LoadSlammer from ProGrAnalog is an invaluable addition to correlate test results with simulated predictions, leading to more accurate and useful simulations.

Other tools include Bode and impedance analyzers. These are also useful but fall short of providing a complete picture for transient analysis. Why this limitation?

The short answer is that they are limited to small-signal, linear measurements while under steady-state conditions. Large-signal response of a voltage regulator may be much different. Here are some factors to consider as to why large-signal measurements are needed:

- For high di/dt conditions, output inductors may hit their maximum slew rate as determined by input voltage, output voltage, and output inductance. This occurs commonly in high-performance applications and when it does, control loops exceed their linear operating range. Voltage regulator (VR) output impedance increases, and regulation suffers.
- Control loops coming out of nonlinearity can have delays or introduce nonlinearities of their own, especially those with larger integrating capacitors for good dc regulation. A Bode analysis may not reveal this recovery behavior.
- Output inductance can vary significantly with current. Small-signal analysis at various loads may not adequately describe response at high loads or during large current transitions.
- Ceramic capacitor effective capacitance may vary with applied ac voltage, which is affected by load step size and VR response.

- Multiphase VRs often do phase shedding at light load, potentially changing loop response and output response during phase transition.
- High-performance VRs often have nonlinear control options including, but not limited to the following—multiple phase injection or turn-on (for fast load steps, pulse truncation (for COT regulators), frequency bursts with increased load, light-load hysteretic response and diode braking. These control options typically have a threshold, usually adjustable, for engaging them. Accordingly, regulator response and performance will not be correctly evaluated by simple Bode analysis.

Regarding impedance analyzers, they are useful, especially at higher frequencies and with passive components and decoupling networks. But again, they are limited to small-signal, steady-state analysis. Meanwhile, LoadSlammers are capable of output impedance analysis up to 1 MHz, with the regulator operating, and at varying amplitudes and offset currents.

Device Under Test (DUT) Setup

In this article a series of tests are performed using a single Pro 1000RS slammer, rated to 500-A peak current and including remote sense capability for accurate voltage measurements at the output of the regulator (the device under test or DUT is a multiphase regulator operating from 12-V input). Using the test setup shown in Fig. 1, the DUT will be tested to the following specifications:

- 0.90 Vdc nominal (0.70 V min, 1.10 V max)
- Maximum current 255 A
- Maximum step size 175 A with offset of 80 A.

Fig. 1. LoadSlammer Pro1000RS connected to DUT.

The level of specificity and number of test conditions or variables may vary significantly from one digital IC manufacturer to another.

Adding And Performing Tests

The LoadSlammer test tool integrates an AFE (analog front end) with stimulus and measurement capability. Simply connect the LoadSlammer USB interface to your PC. You will then be able to control the LoadSlammer via the graphical user interface (GUI).

Using the software, tests may be performed individually or combined into an automated sequence of tests. The test options are transient test, impedance, delay, pulse train and dc load with timer.

Transient Test

For most switching regulators, after line and load regulation characterization, the next performance test is often a simple step-load test. A marginally stable regulator (one with poor phase margin) will typically show ringing and overshoot during step changes, as will an inadequate output filter and decoupling solution. Fig. 2 shows the configuration of the LoadSlammer to perform a step-load test.

Fig. 2. LoadSlammer settings for a step-load test on the DUT.

In Fig. 2, offset is the minimum current used for the test. Amplitude is the size of the load step and is added to the offset. Time-on is the programmed pulse width. Each test does a single pulse and capture unless repeated. Minimum off-time is used between multiple captures to reduce dissipation in the slammer MOSFETs. Edge time is the rise time of the current step. Finally, the number of captures enables up to 1000 captures to be taken per test.

In Fig. 3 the measurement results are presented with the voltage graph at the top with V_{Droop} and $V_{LiftOff}$ lines shown for reference and the programmed delay time and current pulse. V_{Droop} and $V_{LiftOff}$ may vary depending on VR output ripple and where in the PWM cycle the step occurs. Multiple captures will aid in finding min and max values.

After choosing a setup, with the DUT powered, click on the Run button to initiate the test. When complete, select the Results tab to see a screen like that shown in Fig. 3.

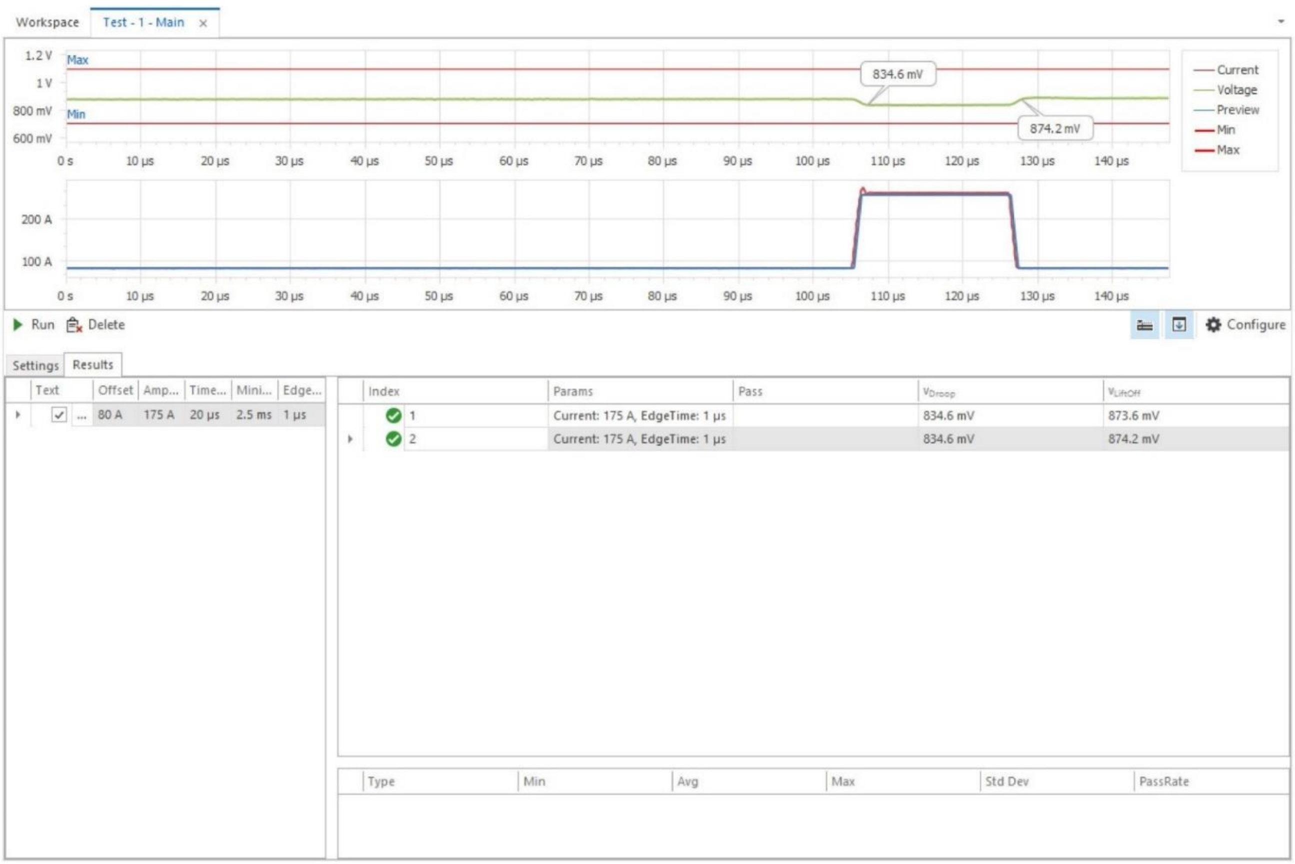


Fig. 3. Test results for the step-load test on the DUT.

In Fig. 3, the green line in the voltage display shows output voltage, including the minimum value during load step and the max value during load release. The red current waveform is superimposed on the programmed waveform. A list of test configurations appears in the left box with test settings, time and date stamp for that run and a check box to choose which tests to display in the section to the right.

Individual captures are listed to the right and may be sorted according to the columns at the top. A right click on any capture will open an option to export to a CSV file.

Waveforms zoom windows may be opened by left double clicking on the desired capture. Zooming is accomplished by placing the cursor in the numerical area of the graph legends and scrolling the mouse up and down (Figs. 4 and 5).

Fig. 4. Transient waveform measurement, partially zoomed in.

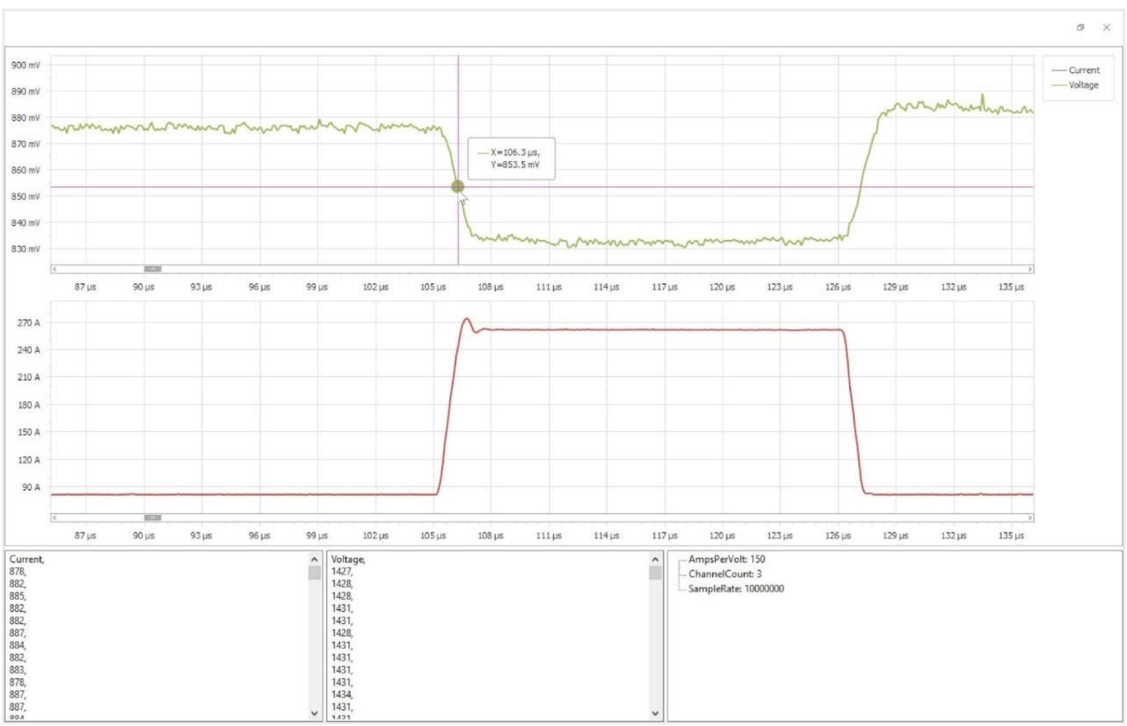


Fig. 5. Zooming-in on waveforms from the step-load measurements in Fig. 4.

A measurement cursor automatically displays when the mouse cursor moves into the graph area. In addition to these options, both amplitude and edge time may be swept. Checking the Sweep box on either opens menus for the sweep range and the number of points in the sweep.

From the waveform in Fig. 5, the shape of both droop and liftoff may observed and measured.

The 1000RS slammer has a practical limitation regarding positive slew rate which depends on input voltage and connector/PCB inductance. For the 0.90-V regulator example, edge rate falls off after about 200 A/µs. This is not an issue for the example above with a 175-A step and 1-µs edge time (175 A/µs). However, if a faster slew rate is desired, two or three slammers may be operated in parallel for reduced overall inductance. Negative slew rate is not affected by connector impedance.

Pulse Train

Pulse train testing is an automated sweep of transient tests for a fixed offset and step amplitude, but over a range of frequencies and duty cycles. This can be used to determine if there are weak areas in the voltage regulator response. In addition to offset, amplitude, and captures, the following parameters are adjustable:

- Frequency may be chosen as a fixed value or swept over a range (check box). The sweep may be linear or logarithmic, and number of points may be specified.
- Duty cycle may be similarly specified—either fixed or swept. In this manner, either frequency or duty cycle, or both may be swept.
- On-time specifies the test/dwell time at each set of parameters.

While the test is running, the Results tab will show progress. If many points are desired for granularity, total captures often number in the hundreds or thousands. A review of that many captures would be unnecessarily cumbersome.

Fortunately, there are two useful options to aid analysis. One, as mentioned earlier, is the option of exporting to a CSV file where data may be manipulated and displayed. A powerful second option is a 3D graph, which is accessed by clicking on the symbol with three arrows (Fig. 6).

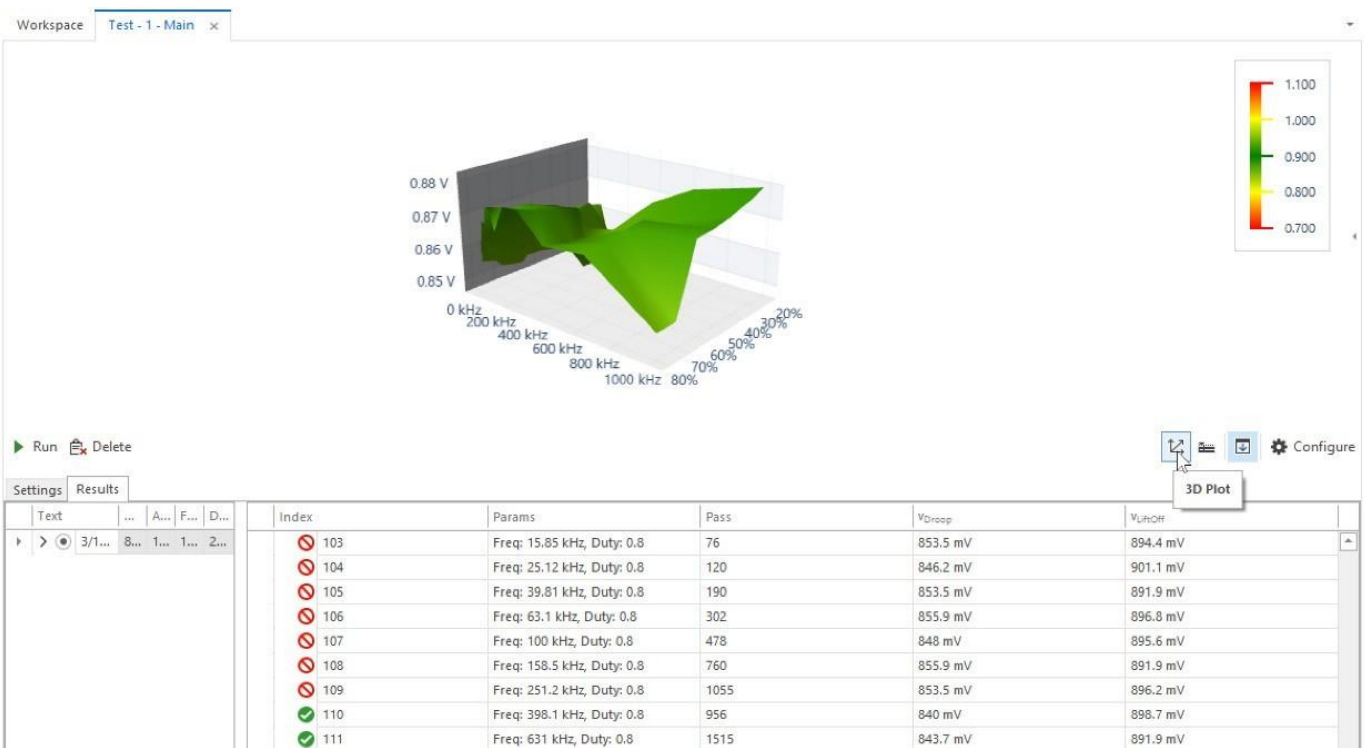


Fig. 6. The results of pulse train testing may be displayed in the form of a 3D graph.

The 3D graph displays voltage (on the vertical axis) compared with duty cycle and frequency (horizontal axes). Using the mouse, the graph may be rotated in any direction and zoomed in or out. This quickly shows where problem areas are located.

To the right of the graph is a small arrow at the edge of the window, which accesses two tabs. The View tab allows quick zooming as well as horizontal and vertical offset.

The Data tab allows choosing what data to display, either V_{Droop} or $V_{LiftOff}$. An additional option is provided for displaying data for each pulse train—average, min, or max.

Referring to our evaluation board, Figs. 7 and 8 contain 3D plots of V_{Droop} and $V_{LiftOff}$.

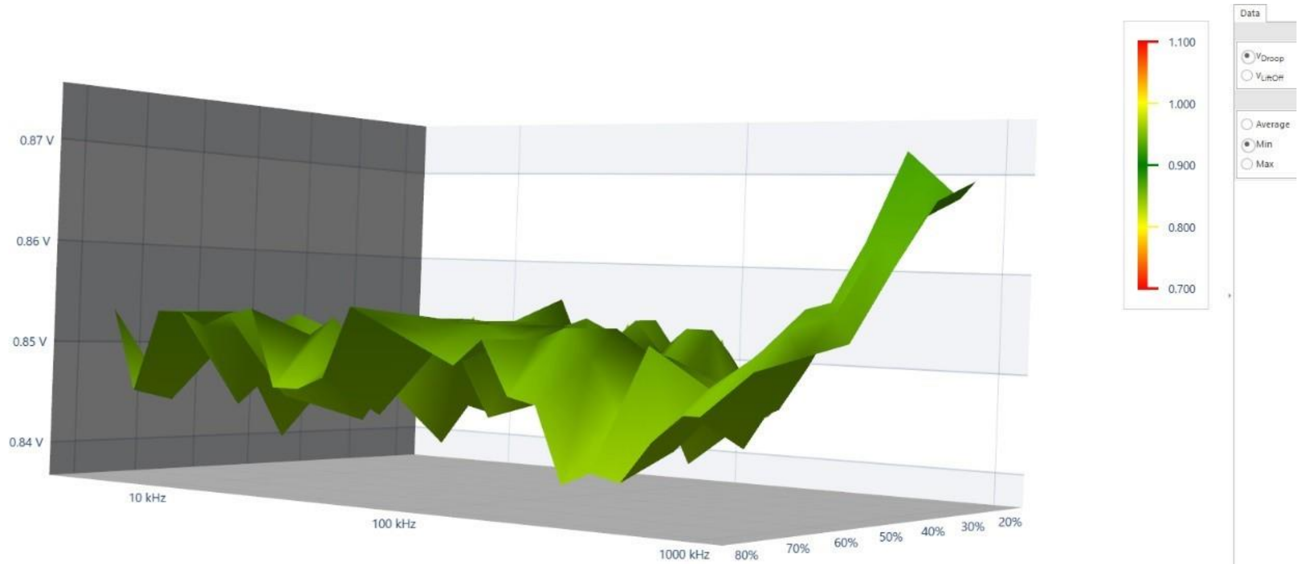


Fig. 7. 3D plots of V_{Droop} minimum with an 80-A offset and a 175-A amplitude.

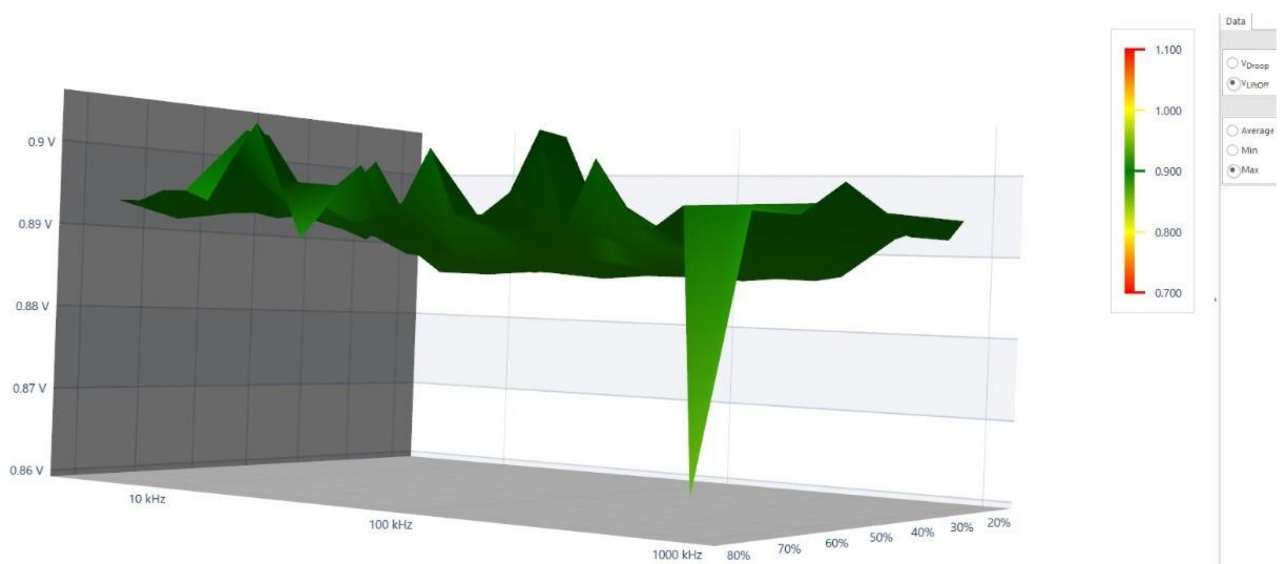


Fig 8. 3D plots of $V_{LiftOff}$ maximum with an 80-A offset and a 175-A amplitude.

Observing both of the above plots, we see that the greatest anomalies occur at high frequencies. A good follow-on would be to narrow the frequency range, such as limiting it to 100 kHz and up. Simultaneously, taking more test points in both frequency and duty cycle might reveal more detail. Proximity to the nominal 500-kHz switching frequency may be a factor but output filter resonance or other cause may be indicated.

A subset of pulse train testing—using a single frequency and duty cycle—can be of benefit in some cases. Since transient testing is a single pulse only, a series of pulses may reveal more regarding regulator operation. Here in Fig. 9 are measurements of the evaluation board again, this time with a string of 20-µs pulses at a 5-kHz rate (D = 10%).

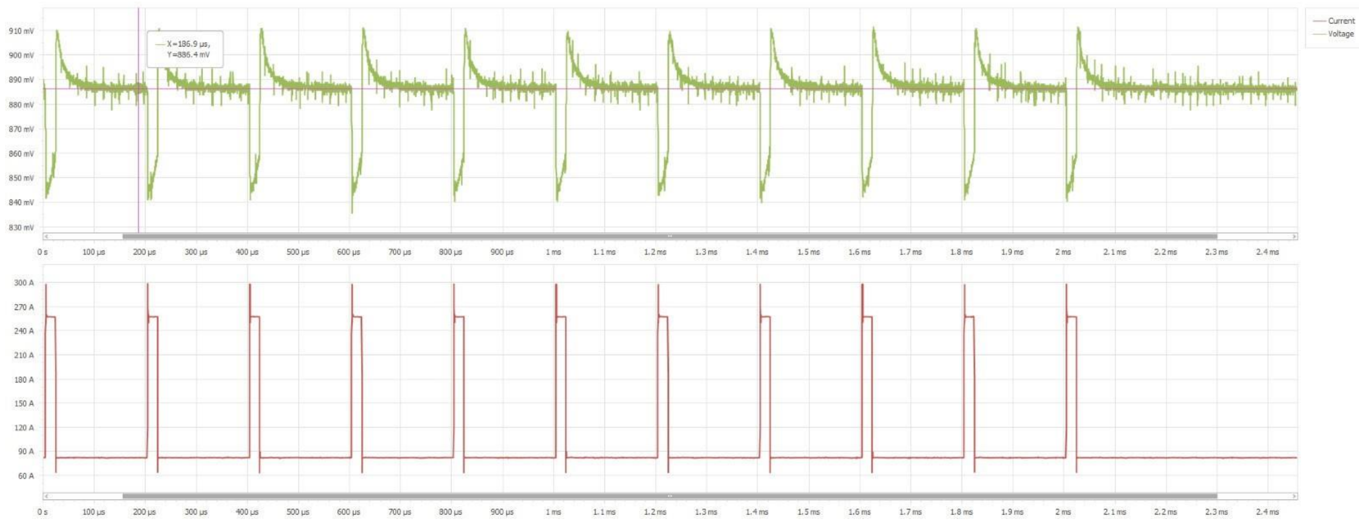


Fig. 9. Results of pulse train testing with a pulse train featuring a single pulse frequency and duty cycle.

Note that compared to the result obtained with the single-pulse waveform, there is considerable tilt in the trough of the voltage, along with extended liftoff overshoot. This may not be a performance issue but could be a useful observation.

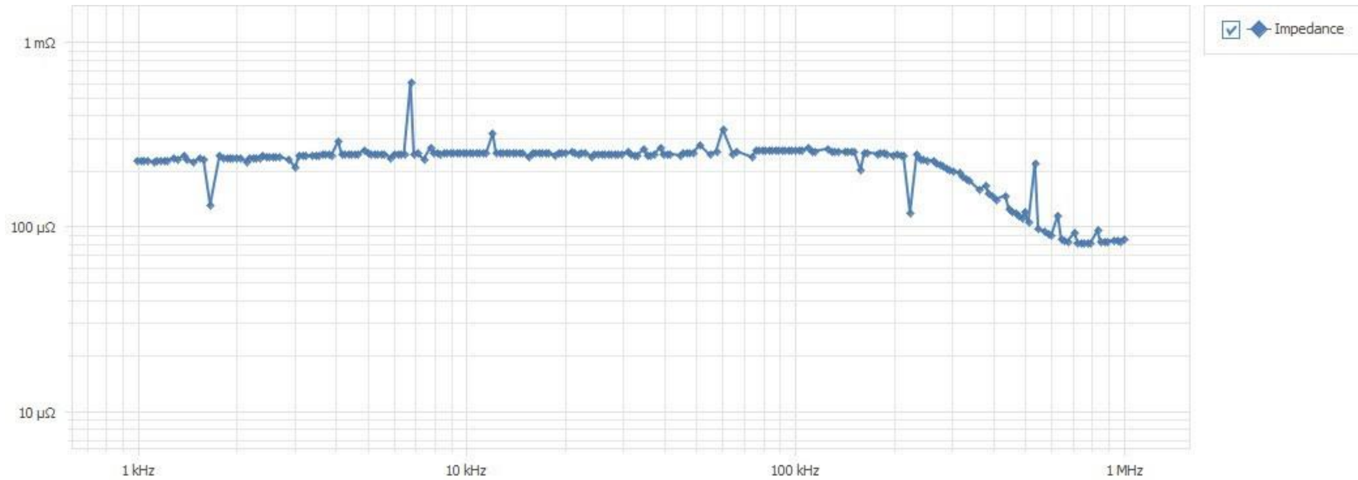
Impedance Test

The impedance test measures output impedance of the DUT. Again, it does not measure loop gain and phase, but does measure output impedance magnitude and phase of the converter and decoupling solution up to 1 MHz. Stability issues and output resonance issues can be identified, and revisions compared and verified. Because of the high-current-step capability, large-signal impedance can be differentiated from small-signal impedance.

Adding an impedance test brings up the LoadSlammer software's Settings window. In this test, offset is defined as an average current that the amplitude operates around, either positive or negative. That is, with an offset setting of 10 A, a 20-A amplitude will step from 0 A to 20 A, or 10 A ±10 A. Because of that, offset is always a minimum of half the amplitude and can increase from there.

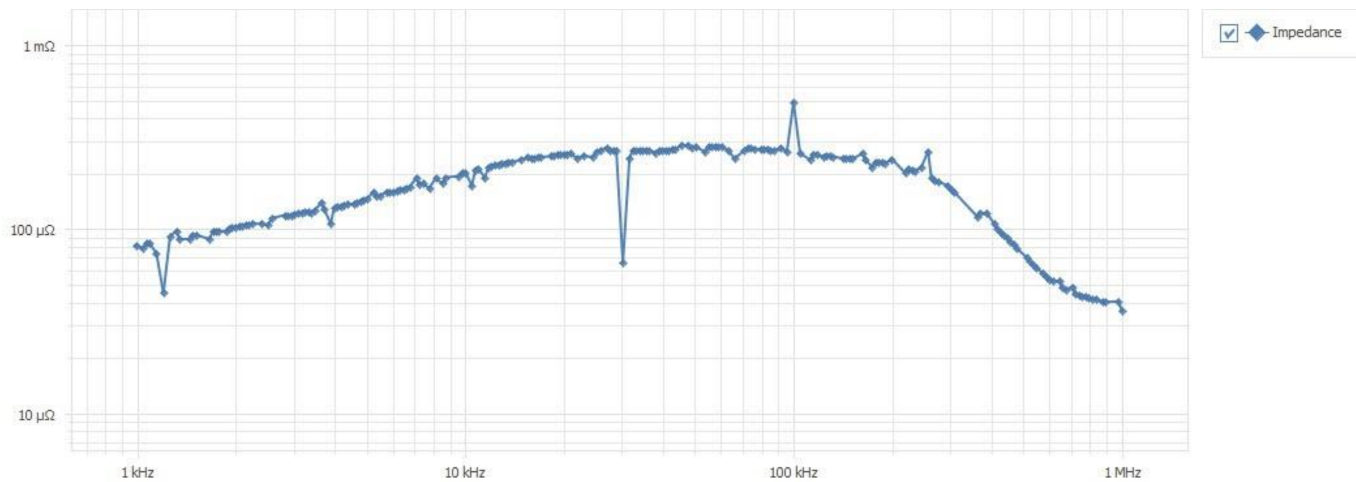
Frequency is adjustable from 1 kHz to 1 MHz and the number of points may be chosen for preferred granularity. Results are displayed in text and graph form and can be exported as previously discussed. Previous runs may be viewed using the text box, allowing comparisons with previous circuit revisions.

Referring to the evaluation board, the advantage of large-signal testing can again be seen by varying amplitude and offset. Figs. 10 and 11 depict two different conditions:



TimeStamp: 3/1/2022 10:08:25 AM SerialNumber: LSP_RS-424B2EAA
Amplitude: 40 A, Offset: 20 A

Fig. 10. Impedance measurement with a 20-A offset and a 40-A amplitude.



TimeStamp: 3/1/2022 3:04:55 PM SerialNumber: LSP_RS-424B2EAA
Amplitude: 175 A, Offset: 167.5 A

Fig. 11. Impedance measurement with a 167.5-A offset and a 175-A amplitude.

The first plot at lower amplitude (Fig. 10) shows a programmed output impedance of approximately 250 µΩ, which is maintained until about 200 kHz. However, the second plot (Fig. 11) shows impedance dropping below 20 kHz, down to 80 µΩ at 1 kHz. High-frequency impedance above 300 kHz also drops off increasingly.

When looking for the source of differences, some possible things to consider are

- Loop compensation settings
- Nonlinear control functions (pulse truncation, phase additions/subtractions, diode braking, etc.)
- Adaptable loop control
- Large signal effects (inductor slew rate limits, saturation, and ceramic cap ac bias levels).

DC Load

DC load testing is simply that—a constant-current load on the DUT. Its limitation is time duration due to high power dissipation at high dc currents. This makes it useful for dc regulation under line and load conditions, but not for thermal analysis.

For long-term dc loading, plug-in PTO boards are available from ProGrAnalog with high-current connections for external dc loads. There are two adjustable settings—amplitude and on-time.

Delay

Delay is the last item on the test menu but is not actually a test. Rather, it is an optional delay time between tests. This could be used for setup time (if desired) of subsequent tests in the series, for observation, or for reducing average power dissipation in the load.

Reaping The Benefits

Besides simply being able to test voltage regulator performance per a specification, there are additional ways to benefit from using LoadSlammers with a suite of tests. They enable reduced development and debugging time from automated testing. They also permit faster optimization, enabling smaller output filtering, saving cost and board space.

Meanwhile, testing is made easier with the ability to generate documentation over a wide range of electrical and environmental conditions for a more-robust design. Similarly, LoadSlammers with test suites support manufacturing testing to verify and document performance of individual boards and fixtures for future reference, increasing production yield. Designers can also verify board performance over time as components degrade, and use the test suites to debug field returns.

Finally, it's possible to reduce the heat and power consumption by using the LoadSlammer to improve transient response of the regulator. A tighter responding regulator can potentially be used to implement dynamic voltage scaling or other voltage-reduction methodologies.

Overall, fast transient load testers provide unique, large-signal testing capabilities for qualifying high-performance board-level power converters. This capability can yield multiple reliability, cost, and time benefits for boards and systems.

References

1. LoadSlammer website.
2. "Optimizing Regulator Output Capacitance (Part 1): Selecting Load Slammers" by David Baretich, Hpw2Power Today, August 2018 issue.
3. "Optimizing Regulator Output Capacitance (Part 2): Using Load Slammers" by David Baretich, How2Power Today, September 2018 issue.
4. "Optimizing Regulator Output Capacitance (Part 3): Analyzing Load Slammer Results" by David Baretich, How2Power Today, October 2018 issue.

About The Author

David Baretich is an electrical engineer and consultant to ProGrAnalog. He has 42 years' experience in power conversion, working at companies such as Texas Instruments, MicroPlanet, onsemi, Tektronix and Biamp Systems. An IEEE member, David holds 10 U.S. patents. He received a BSEE from Iowa State University.

For more information on the subject of transient response and transient load testing, see How2Power's Design Guide, locate the Design Area category and select Transient Response.