Initial Evaluation of a DC/DC Switch Mode Power Supply

Application Note

Products:

- R&S®RTO
- R&S®RTO-K31

This application note will describe the evaluation of the main dynamic behaviors of a DC/DC buck converter. The test procedures and measurements described will determine whether the converter operates in a safe manner, and whether it meets its design goals for start-up time, inrush current, peak inductor current, inductor behavior, and output ripple and ripple spectrum.

Application Note

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ROHDE&SCHWARZ

Table of Contents

1 Introduction

In modern electronic equipment, the use of the Switch Mode Power Supply (SMPS) has become almost universal; it replaces bulky, heavy and inefficient transformers and linear power supplies with a more efficient, smaller, lighter, lower-cost power supply. In addition, SMPSs are able to work effectively over large input voltage ranges.

SMPSs appear in a wide range of applications and topologies; they can be generally-classified according to whether they convert the input voltage to a lower (Buck) or higher (Boost) output voltage, and can be further classified as AC/DC, AC/AC, DC/DC, or DC/AC.

Many of the specifications of SMPSs may be evaluated with digital multimeters (DMMs) and power supplies, but the dynamic behavior and stability of an SMPS are best evaluated using a digital oscilloscope, appropriate probes and auxiliary equipment.

Important parameters and behaviors include: inrush current, inductor peak current, output and input current and voltage ripple, ripple spectrum, switching speed, and switch voltages. The evaluation of these measurements determines the requirements of the test equipment needed.

For those who must design, test, validate or evaluate SMPS circuits, measurement software can enhance their ability to efficiently make, and document, a range of measurements and analyses of the characteristics of inductive SMPS circuitry.

Many applications, especially in portable electronics, use a Buck-type DC/DC SMPS to reduce and regulate a higher battery voltage to the correct operating voltage for LDO's (Low Drop Out regulator), CPU's, Logic, RF, Audio, LED drive, memory and other subsystems. There are often 10 to 20 power domains in a smartphone, laptop or tablet computer.

Buck converters normally provide conversion efficiencies >90%. Depending on the design and selected components, efficiencies of >95% can be achieved.

This Application Note details a process to perform the first-level testing on a prototype Buck-type DC/DC subsystem, confirming its correct basic operation and performance. Measurement equipment and software tools discussed will include R&S®RTO series oscilloscopes, the R&S®RTO-K31 power analysis option, passive and active voltage probes, current probes, the R&S®RT-ZF20 Deskew fixture, and supporting test equipment, such as power supplies, pulse/signal generators, digital multimeters and electronic loads.

As a 'top-level' evaluation, it should be stressed that much of the evaluation depends on the ability of the person making these measurements and observations to interpret waveforms and measurements in the context of the circuitry being evaluated, and the intended application environment.

Oscilloscope screen shots and measurements have been obtained by testing a modified Texas Instruments TPS62090EVM (Evaluation Module) [1]. Some of the modifications, made to make test points easily-accessible, degrade the performance of the TPS62090 [2] DC/DC buck converter, and should not be considered to be representative of the optimal performance of the TPS62090, or of the TPS62090EVM.

2 Overview of DC/DC Buck Converter Operation

Figure 1 introduces the basic operation of a buck converter. In the simplest control mechanisms, the duty cycle of the switching phases is controlled by voltage feedback. In a buck converter, operating in Continuous Current Mode ("CCM"), the case where there is always current flowing in the inductor at the switching points, the duty cycle ($\frac{t_{on}}{t_{off}}$) of the switch connected to V_{in} controls the output voltage, and the output voltage (V_{out}), is (ideally) equal to:

$$V_{out} = V_{in} \times \frac{t_{on}}{t_{off}}$$

SMPS control theory is beyond the scope of this application note. In addition to extensive information provided by SMPS controller IC manufacturers, a few of the many websites that provide a starting point for SMPS design exploration are referred to in [3] [4] [5].

In

Figure 1 the oscilloscope waveforms illustrate the expected behavior of the switch node voltage (referred to GND), inductor current, and output voltage ripple, during normal operation; the two switching phases of the DC/DC operation are indicated by the color of the diagram for each of the phases.

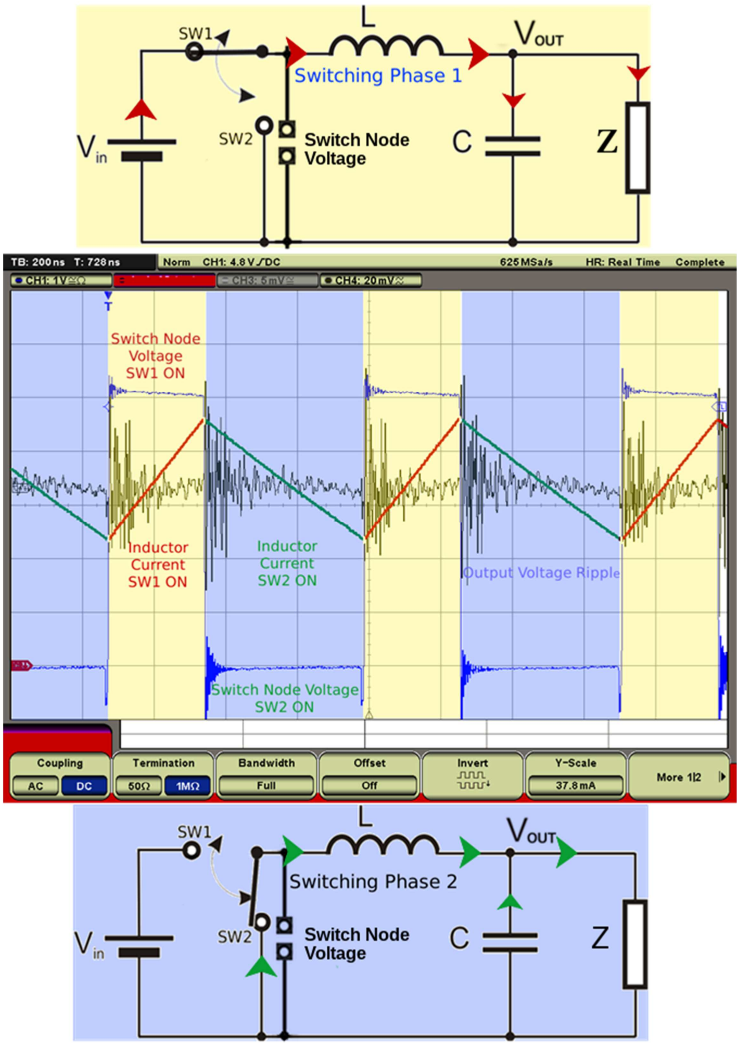


Figure 1: Block diagram and operating principle of a DC/DC Buck converter

In the first switching phase, current flows (red arrows) from the voltage source (V_{IN}) through SW1 into the inductor (L), the output capacitor(C), and the load (Z).

The inductor current increases at a rate determined by the voltage across the inductor. In the case of a well-regulated and well-filtered V_{in} and V_{out}, the voltage across the inductor during this phase remains constant, (ideally) equal to V_{in} - V_{out} , and the slope of the current remains constant; any divergence from a constant slope of the inductor current may indicate excessive ripple on V_{in}, saturation of the inductor, or significant DC resistance ("DCR") or AC resistance ("ACR") in the inductor. As switching devices have non-zero resistance, the voltage across the switch device will be seen to rise with increasing inductor current.

ACR comprises the frequency-dependent (and flux-dependent) losses in the inductor, some of which include: skin effect in windings, proximity effect (magnetic interaction among adjacent windings), eddy current losses and hysteresis effects in the core material. [6] [7]

In the second switching phase, SW2 connects the inductor to Ground, and energy stored in the inductor and output capacitor, during the first phase, produces the current flow (green arrows) into the load. During this phase, as the energy stored in the inductor is discharged, the voltage across the inductor is reversed from that in the first phase, becoming (ideally) V_{out} – GND. Because the switching device has non-zero resistance, there will be a negative voltage seen at the switching device connection to the inductor, which slopes toward 'ground' as the inductor current decreases; in the case of the second switch being a diode, there will also be an additional negative voltage 'offset' that is the forward voltage of the diode type in use. Again, the inductor current slope should remain constant, with any significant divergence from linear slope indicating inductor saturation or excessive DCR or ACR.

3 Measurement setup

3.1 Oscilloscope

A 500 MHz oscilloscope will provide sufficient bandwidth for this application. A four-channel oscilloscope is preferred, as it will enable simultaneous viewing of the most-critical signals. The R&S®RTO1004 [8] , preferably equipped with the R&S®RTO-K31 power analysis option, is suitable.

3.1.1 Probes

Probes recommended for this application are:

- one current probe, RT-ZC20, or similar
- 2 x passive probes, RT-ZP10, or similar, with grounding accessories and probe compensation tool
- active single-ended probe, RT-ZS10, or similar
- active differential probe, RT-ZD10, or similar.

3.2 Power Supply

A power supply is needed that is capable of providing the currents and voltages required for testing the SMPS; this means that the supply must be able to provide the entire range of voltages and currents needed during the test procedures, while maintaining output stability and accuracy. A source/measure power supply can, in many cases, provide a substitute for additional meters, and can also provide data-recording functions.

Where possible, lead lengths should be kept short, and twisted to reduce inductance. Capacitive decoupling may also be used, at or near the DUT, to ensure stability of the power supply under dynamic test conditions. If available, a 4-wire connection (remote sense) may provide additional stability and accuracy.

3.3 Digital Multimeter (DMM)

A DMM may assist in accurately setting or monitoring steady-state voltages and currents during test procedures, and may also be used to confirm the accuracy and stability of voltages and currents measured by the oscilloscope and associated probes. Two DMMs, allow monitoring two parameters/inputs. (NOTE: most of the Rohde & Schwarz active probes include a DVM function, allowing measurement of DC voltage levels at the probe tip.)

A Hameg HMC8012 5¾-digit, or the HM8112-3 6½-digit, DMM, is suitable for this application.

3.4 Pulse or Arbitrary Waveform Generator

When performing sequential/repetitive tests, a pulse or arbitrary-waveform generator can provide waveforms to drive switches, enable lines, control signals, and voltage sources or loads used in tests.

The Hameg HMF2525 arbitrary function generator, from Rohde & Schwarz, offers a frequency range to 25 MHz and a 14-bit, 250 MSa/s arbitrary-waveform generator, as well as a full range of built-in waveforms and pulses.

3.5 Load

A suitable electronic load enables testing of the DC/DC converter with a range of loads and provides the potential for further automation.

Where an electronic load is not used, resistive loads may be used, preferably controlled by fast power FETs; ensure that the drivers for the power FETs can provide sufficient gate drive to achieve the load-switching times needed for the specific application.

It should be noted that the design philosophy of this DC/DC buck converter, and others, is based on the reasonable assumption that they will be driving silicon-based circuitry, which presents little load below 0.7 V to 0.8 V; therefore, when the output voltage is below 0.8 V, the current-limit is set to a lower value, as the device is primarily charging the output capacitor, and not driving a load. This prevents large current input during the initial start-up of the converter, under these conditions. To accommodate this behavior, it may be necessary to incorporate a silicon diode, of an appropriate current rating, in series with load resistors, and to calculate load resistor values with the diode forward voltage taken into account, in order for the device to start-up properly under load.

4 Overview of typical Measurements for a DC/DC Buck Converter

To confirm safe and correct operation of a DC/DC buck converter, the behavior during the following operational conditions will be investigated:

- correct power-up behavior: start-up of switching cycles, ramp-up of V_{out} and soft-start ramp (special control of inductor current when the converter is started, either by power-on or Enable, to reduce the effects on other parts of the system, and to control inductor current within safe limits)
- inductor current behavior with nominal load, start-up and regulation
- load transient behavior
- output-voltage ripple and spectrum.

To accomplish this evaluation goal various measurements on the DC/DC buck converter have to be executed. This chapter provides an overview of the required measurements at the various probing points, separated into voltage and current measurement types.

4.1 Voltage Measurements – What to measure, where to measure, and why.

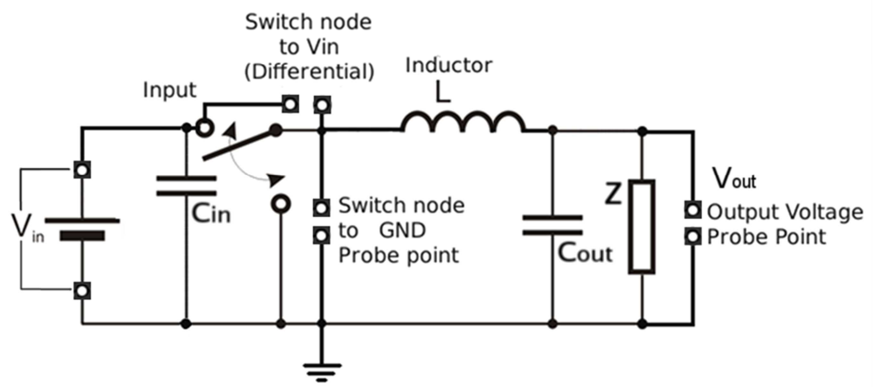


Figure 2 Overview of probing points for voltage measurements on a DC/DC buck converter

(1) Input voltage - V_{in}

- V_{in} provides a trigger source for start-up/power-on tests with “cold-start” where the device is turned-on from an OFF state, with input and output capacitors fully-discharged.
- The key dynamic parameters to be measured at V_{in} are droop and V_{in} ripple during start-up and operation.

(2) Switch node – Referred to GND, or referred to V_{in}

- At the switch node the user can observe the voltage during switching and confirm expected behaviors, such as low ringing, absence of overshoot/undershoot, and that the slope of both switch ON period voltages are not excessive. The voltage referred to Vin during switching phase (with SW1 ON, in
- Figure 1) is preferentially measured with a differential probe, while the voltage referred to Ground during the low-side switching phase (with SW2 ON, SW1 OFF, in) can be measured with a single-ended voltage probe. The key driver for these measurements is to confirm the voltage drop is as expected for each phase.
- The voltage at the switch node may also be used as the trigger source for inductor current observations.

(3) Output voltage - V_{out}

- The output voltage behavior needs to be observed during cold-start in order to confirm that the correct output voltage is achieved and maintained.
- When the SMPS controller is provided with an Enable control pin, the V_{out} behavior also needs to be observed during Enable On/Off cycling, where the device normally makes transitions from a standby state to operating, and *vice versa*.
- V_{out} observations will confirm whether the load transient behavior is within expected limits.
- Observation and measurement of the ripple waveform and ripple spectrum can be made at the V_{out} test point.

4.2 Current Measurements -– What to measure, where to measure, and why

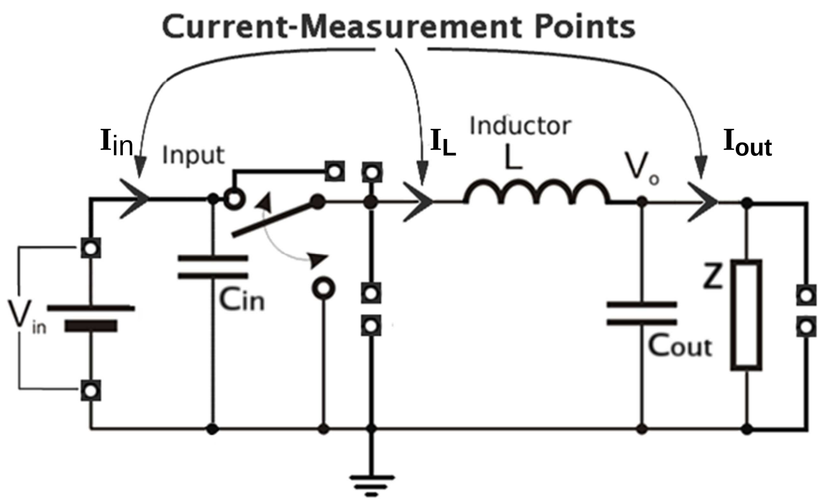


Figure 3 Important current measurement points

(1) Input current - I_{in}

I_{in} is measured between the power supply and input capacitor.

- I_{in} needs to be observed during cold-start in order to confirm its expected dynamic behavior.

- I_{in} needs to be measured with selected loads to confirm that currents are within the expected ranges.
- The dynamic behavior of the input current needs to be checked during various start-up modes (cold-start, warm-start, rapid power cycling) to detect unexpected pulses, glitches or reverse flow.

(2) Inductor current - I_L

The inductor current is measured between the switch node and inductor.

- I_L needs to be measured during all start-up modes, to confirm its expected behavior, and to confirm that there is no saturation of the inductor, the current is well-controlled, and that any reverse-current events are expected and controlled.
- Part of the I_L measurement is to determine the current linearity during peak current levels (inductor should not be saturated).
- The I_L measurement can also be used to check the duty cycle characteristics and compare them to expected values.

(3) Output current - I_{out}

The output current is measured between the output capacitor and the load.

- I_{out} may be measured during start-up sequences (cold-start, warm-start, Enable control) to confirm expected behavior.
- The output current needs to be checked for unexpected pulses or glitches.
- The output current may also be used as a trigger source for load transient testing.

5 Example of a DC/DC Buck Converter Evaluation Process

In demonstrating the following typical measurements of a DC/DC buck converter with the Rohde & Schwarz RTO oscilloscope, the evaluation module TPS62090EVM from Texas Instruments was used. Modifications to the TPS62090EVM, made to make test points easily-accessible, degrade the performance of the TPS62090 DC/DC buck converter, and should not be considered to be representative of the optimal performance of the TPS62090, or of the TPS62090EVM.

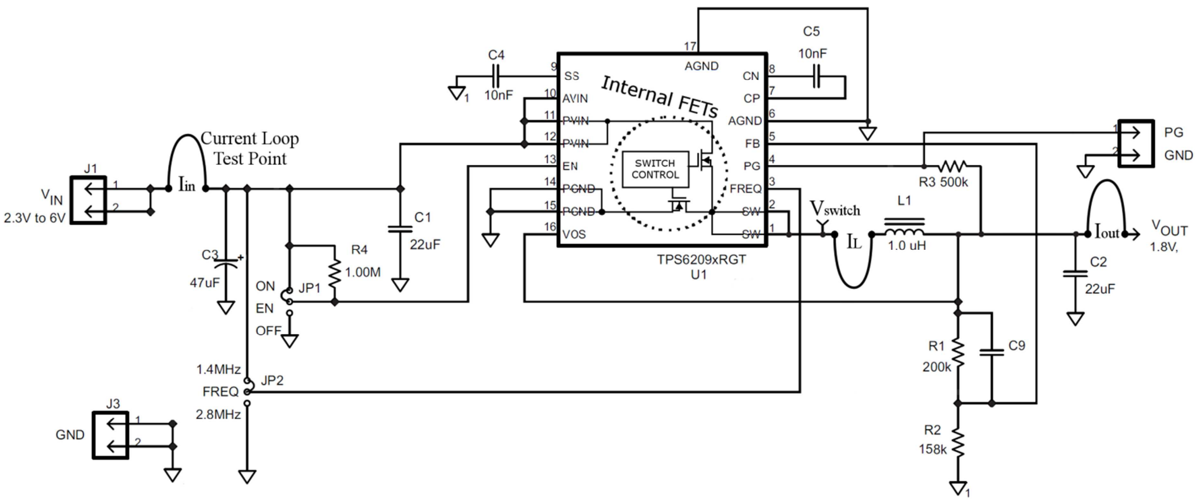


Figure 4: TPS62090 EVM simplified schematic, showing added current and voltage test points

5.1 Power-up Behavior Test Procedures

For the evaluation of its Power-up behavior, the DUT should be set up with probe points to measure V_{in}, I_{in}, I_L, and V_{out}. We will describe how the power analysis function for “Inrush Current” measurements, in combination with manual configuration of additional channels, will provide a powerful tool for documenting and analyzing the DC/DC converter power-up behavior.

Typically, this type of testing is best performed with at least three channels connected to the DUT, as described in the individual test procedures. If a second current probe is available, it can reduce the total number of steps needed for the test procedure.

The first task is to ensure that the DUT behaves in a safe and expected manner when power is applied to the circuit.

Monitoring the input current, the inductor current, the input voltage and the output voltage will provide the primary information needed to confirm correct power-on behavior.

5.1.1 Initial 'Safe' Power-up Testing:

The DUT may be tested first with the following steps. Applying V_{in} in a carefully-controlled way, while monitoring input current, will help to determine whether there are any serious PCB or soldering flaws, and will determine the point at which the DUT comes out of its Under-Voltage-Lockout ("UVLO") state, if implemented.

(1) Set the power supply current limit to a low value, as an example, 10% of nominal current for the DUT under light load. Set the power supply output voltage to its lowest level, and the output state to 'DISABLED', if possible.

(2) Connect a small resistive load, calculated to be 5% to 10% of nominal maximum, to $V_{out.}$

(3) Ensure that ENABLE (if implemented) is in its inactive state; if necessary, disconnect ENABLE from any resistor or connection that makes it active.

(4) Next, insert a DMM, in current-measuring mode, in series with the V_{in} signal. If you are using a source/measure power supply, it provides the needed current and voltage measurements. Optionally, connect a DMM in voltage mode to V_{out}; the DMM can be replaced by the R&S®ProbeMeter, built into several R&S active probes, which provides DC measurements with 0.1% accuracy.

(5) Confirm that the power supply settings are correct, and it is DISABLED (where applicable), before connecting the power supply to the DUT.

(6) Enable the power supply output, and/or slowly increase the power supply output voltage at V_{in} from 0 V to the nominal V_{in} level, monitoring the V_{in} current at all times. If there is a 'STANDBY' current specification, check to see that the V_{in} current is within acceptable limits. At this point, if there is an ENABLE control implemented, reconnect it, and repeat the above process.

During this process observe whether there are any sudden changes in current, and at what V_{in} level they occur.

If there is no excessive current, or unexpected current *vs*. voltage, observed during this process, power-on testing may be safely continued with a more detailed analysis of the dynamic start-up behavior.

5.1.2 Start-up Behavior

V_{out} should now be connected to a nominal load, e.g. 10% of rated current.

During power-on testing, it will not be possible to measure all of the measurement points with a single capture, so it is recommended to capture V_{in}, I_{in}, V_{switch} and V_{out} as a first set of measurements. If two current probes are available, the second current probe should be connected to monitor the inductor current, I_L with a 2nd acquisition.

The power supply, with output voltage set to the nominal applied voltage, in the "Disabled" state, or through a switch in the OFF position, is connected to $V_{in.}$

Current-limiting may also be set on the power supply, where available, to the maximum rated/expected input current of the DUT. Current-limiting provides a level of safety in the initial power-on tests, but may, however, prevent observation of large inrush currents.

There will, normally, be two kinds of power-on inrush current phases: the initial input capacitor charge, followed by the start-up of the DC/DC converter, usually with a 'soft-start' period with current-limited

I_{in}, and a ramp-up of V_{out}. When the initial capacitor charge inrush is very large, the current scale that is needed may make it difficult to see and measure the soft-start current phase. Selecting ‘High-Res’ mode in the Acquisition control of the oscilloscope will allow finer resolution viewing of the waveform in Zoom mode.

The DC/DC converter control circuit is receiving increasing V_{in} during the input capacitor charge time; at some point, when V_{in} reaches the operating point of the circuit, the converter will become active. When the circuit starts to operate, it will (normally) begin a ‘soft-start’ sequence. It is possible that the soft-start current behavior will be ‘buried’ in the capacitor inrush. In order to see the current that is specific to the DC/DC converter, it may be possible to place a current probing point between the input capacitor and the controller V_{in} connection, so that the input capacitor charge current is eliminated from the inrush current.

This behavior will depend heavily on the soft-start strategy of the DC/DC controller, the input and output capacitance, the output load applied during power-on, the resistance and inductance of the input leads, and the slew rate of the power supply.

5.1.2.1 Manual Measurement of Inrush Current and Soft-Start Behavior

Following is a description of the manual test procedure for the Inrush Current and start-up/soft-start, with the oscilloscope and probes connected to monitor V_{in}, I_{in} and V_{out}. The Inrush current measurement focuses on the Input current I_{in} at the initial input capacitor charge, while the soft-start behavior measurement analyses the soft-start profile of the I_{in} and the output voltage V_{out}.

Inrush current measurement

(1) Set the horizontal scale to a period that you think will capture the whole power-on sequence; the power-on behavior of interest may last for < 100 µs for the capacitor inrush in a small DC/DC, or > 100 ms for AC line-powered devices. For the DUT we are testing, 200 µs (20 µs/division) captures the initial V_{in} capacitor charge period (blue), and shows the beginning of V_{out} ramping up (red), as shown in

(2) Figure 5, below.

(3) Set the record length to 10k samples (or more) to ensure enough horizontal resolution, so that details of the power-on waveforms may be zoomed for finer examination, if desired.

(4) Set the trigger source to the V_{in} channel.

(5) Set the trigger level to about 20% of the V_{in} voltage setting.

(6) Set the trigger position to about 2 divisions from the left side of the screen.

(7) Set the V_{in} channel vertical scale so that the specified nominal input voltage will be at about 80% of full screen height.

(8) Set the I_{in} channel vertical scale to a range that will allow the inrush current to be ‘on-screen’ (this may be on the order of 10x-20x the steady-state current of the DUT at normal full load).

(9) Set the V_{out} channel vertical scale so that the specified nominal output voltage will be at about 80% of full screen height.

(10) After configuring the oscilloscope, as detailed above, enable/switch ON the power supply output and capture the power-on behavior.

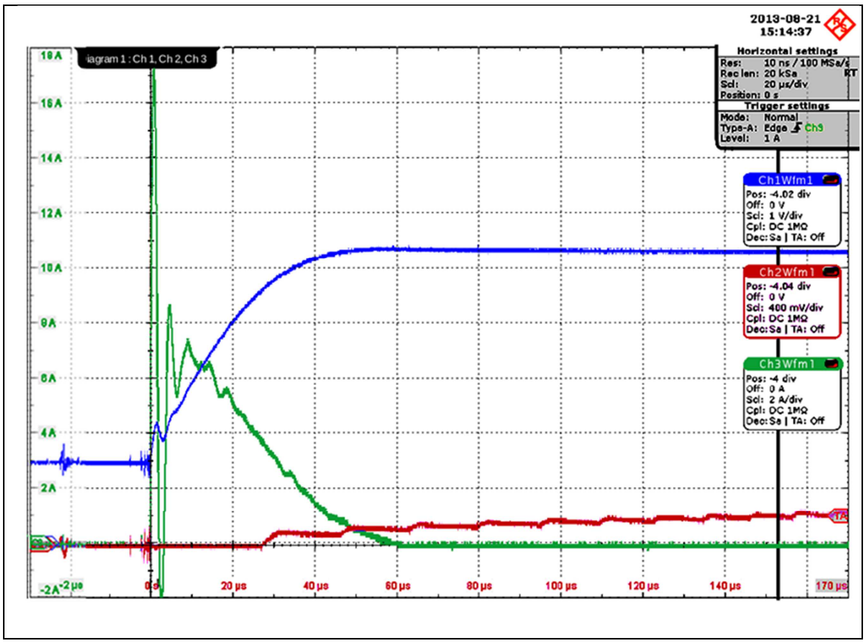


Figure 5: Waveform display of manual Inrush Current and start-up/soft-start measurements
(Ch 1 blue - Vin / Ch 2 red - Vout / Ch 3 green - Iin)

(11) Zooming in by a factor of 10, Figure 6, shows the detail of the capacitor charge peak (Ch 3, green trace) of nearly 18 A! Note that the peak is almost off-screen, indicating the care needed to estimate the peak inrush current.

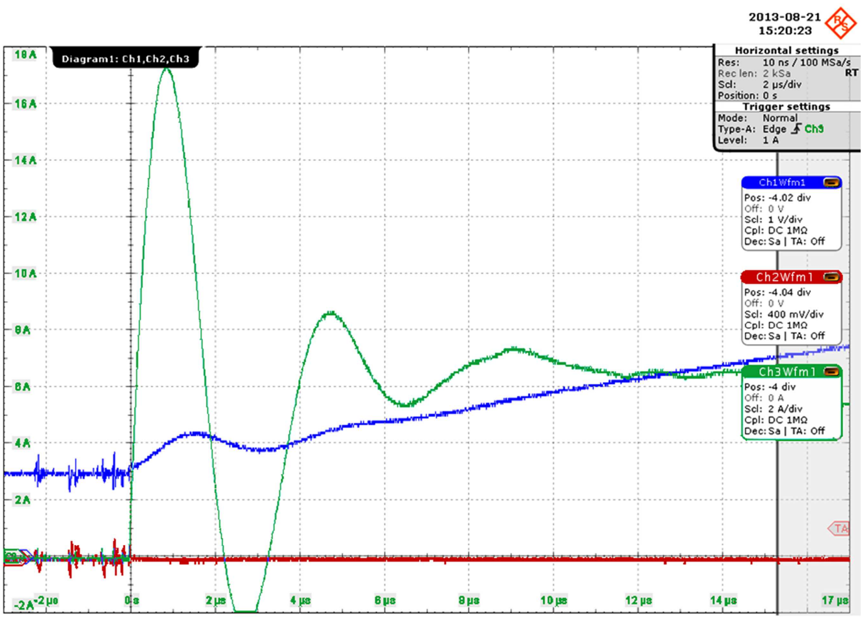


Figure 6: Zoom-in of Waveform display of manual Inrush Current and start-up/soft-start measurements
(Ch 1 blue - Vin / Ch 2 red - Vout / Ch 3 green - Iin)

Soft-start Sequence

The soft-start sequence is implemented to reduce the effects on the overall system caused by large currents that would flow if the DC/DC converter operated with the control loop in its normal mode. If the device operated in its ‘normal’ control mode, and the device started up with V_{out} at zero Volts, it would sense a very large error signal on V_{out} compared to the desired V_{out}, and try to correct this voltage error. In voltage-mode controlled DC/DC converters, the soft-start is often implemented with a capacitive ‘ramp’ of the reference voltage.

In modern DC/DC converters, with current-mode control, soft-start is often implemented by simply changing the current-limit during start-up; the DC/DC converter may also function in a variable-frequency mode during soft-start.

Observation and measurement of the soft-start behavior can be performed manually, or as part of the power analysis option’s Inrush Current evaluation; if the Inrush Current measurement is performed in the normal way, the capacitor inrush current can ‘swamp’ the soft-start behavior. In order to avoid this interaction, the user can select a low value for maximum current, approximately as expected for the soft-start peak current, which will set the appropriate vertical scale value.

The measurement start/stop times can be set to start after the initial capacitor inrush current; if the capacitor inrush current is very large, there is a possibility of input amplifier overload, but this effect should be over by the time the DC/DC converter begins operating in the soft-start phase.

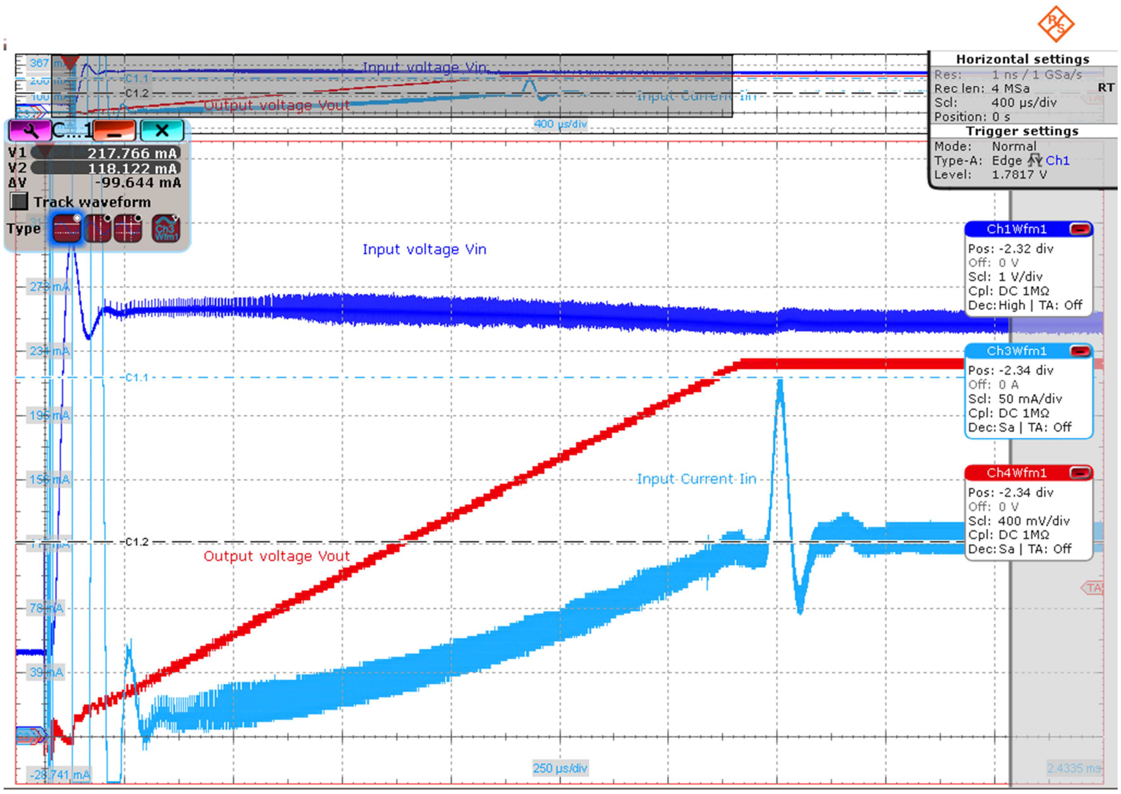


Figure 7: TPS62090 Soft-start at 10% load Vin = 5 V
(Ch 1 blue - Vin / Ch 2 red - Vout / Ch 3 light blue - Iin)

In Figure 7, the TPS62090 has an increase in input current, which appears to occur just when it is making the transition from soft-start to full regulation; this ‘bump’ is quite small, and short, at approximately 220 mA and <150 µs. The inrush current is also visible, as several almost-vertical trace sections at the left of the screen. Other DC/DC converter designs will produce different soft-start profiles.

Figure 8 shows the first few switching cycles of the TPS62090, showing the current-limit behavior at start-up; the current-limit here is much lower than the current-limit during operation, and switching frequency is lower than normal, as part of the soft-start strategy for this device. Other devices may exhibit quite different behavior.

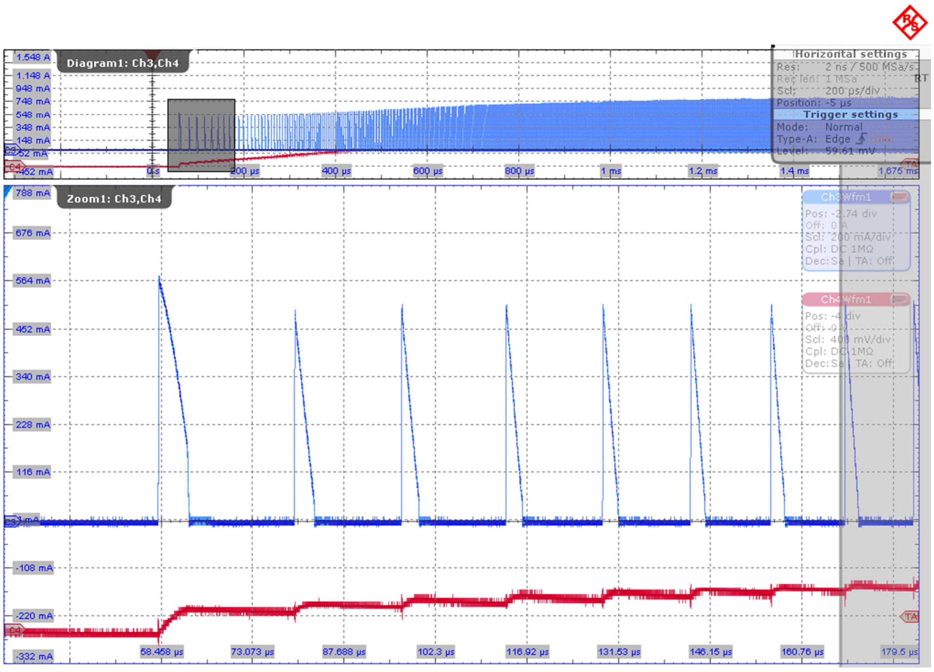


Figure 8: TPS62090 Soft-start at 10% load Vin = 5 V; Zoom of first few cycles (Ch 4 red - Vout / Ch 3 blue - Iin)

Below (Figure 9), the start-up behavior of the TPS62090 is shown, with a resistive load equivalent to 50% of maximum rated current at the nominal 1.8 V output level.

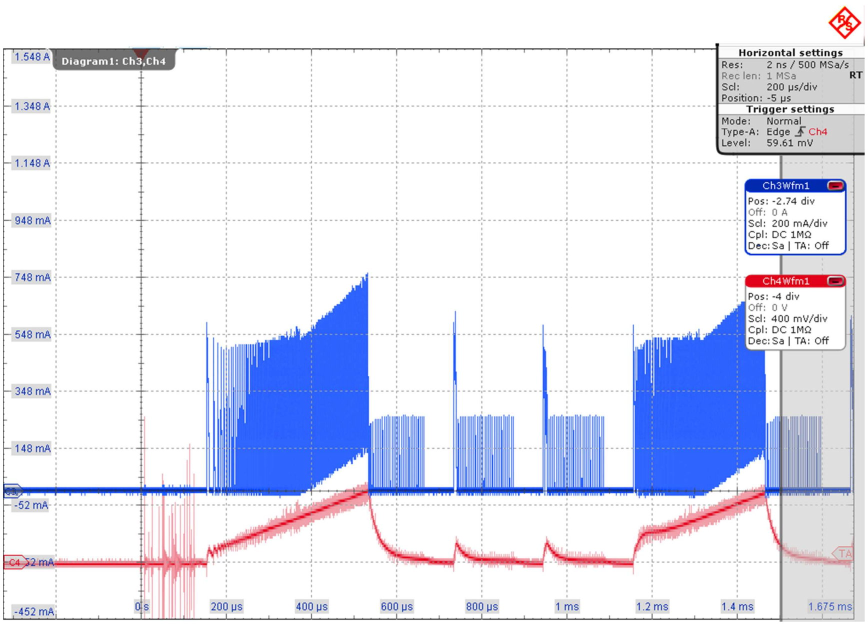


Figure 9: TPS62090 does not start with heavy loads below 0.8 V (Ch 4 red - Vout / Ch 3 blue - Iin)

Here, it can be seen that the DC/DC converter begins to start, but stops switching when the inductor current rises to about 750 mA, and V_{out} is still below 0.8 V. The design philosophy of this DC/DC converter, and many others, is based on the reasonable assumption that they will be driving silicon-based circuitry, which presents little load below 0.7 V to 0.8 V, therefore, when $V_{out\ is}$ below 0.8 V, the current-limit is set to a lower value, as the device is primarily charging the output capacitor, and not driving a load. This prevents high input current during the initial start-up of the converter, under these conditions.

5.1.2.2 Evaluating Power-on/Start-up behavior using R&S®RTO-K31

The R&S®RTO-K31 Power Analysis option supports setup, execution, viewing test results, and documentation. In the following, the power-on behavior will be evaluated, using the "Inrush Current" measurement function of the K31 option. 'One-shot' documentation of the primary parameters-of-interest in the DC/DC converter start-up is achieved with the following additional channel selections and adjustments.

- Attach passive voltage probes to points selected for V_{in} and V_{out}.
- Attach a differential probe, such as the RT-ZD10 between V_{in} and V_{switch} (V_{in} to (-) V_{switch} to (+)); if a RT-ZD10 is not available, attach an RT-ZS10 or a passive probe to V_{switch}, paying particular attention to grounding and lead length at this point, as the edge rates are very high.
- Set the baseline position of all channels to approximately one division from the bottom of the screen, allowing visibility of any negative-going undershoot phenomena.
- Set the vertical scale of the channel connected to V_{in} to a range that will show V_{in} at 50% to 80% of full-screen height.
- Set the vertical scale of the channel connected to V_{out} to a range that will show V_{out} at about 80% of full-screen height.

Set the vertical scale of the channel connected to V_{switch} to a range that will show V_{switch} at about 50% of full-screen height. If the RTO-ZD10 probe is used, the V_{switch} signal will appear 'inverted' relative to its polarity relative to Ground. The range of V_{switch} is approximately equal to V_{in}; overshoot and ringing phenomena can add significantly to the voltage range needed for V_{switch}, depending on circuit layout and probing technique.

(1) Select the power analysis tool on the RTO by using the softkeys in the menu at the bottom of the screen; touch "Analysis" menu -> "Power", as shown in Figure 10.

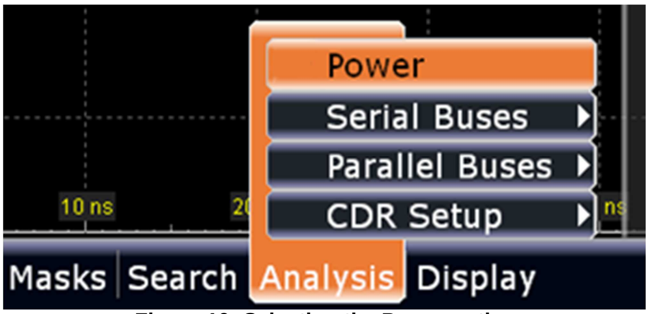


Figure 10: Selecting the Power option

(2) Now select the ‘Inrush Current’ measurement, shown in Figure 11.

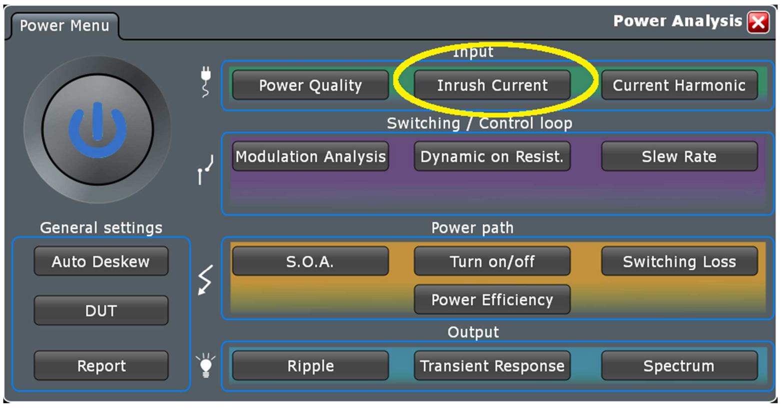


Figure 11: Main Menu for RTO-K31 Power Analysis

(3) In the ‘Channels’ tab, select the channel that to which the I_{in} current probe is connected (Figure 12). (Note that the graphic displayed refers to an AC-input SMPS; place the current probe at the location shown as Iin in Figure 13.)

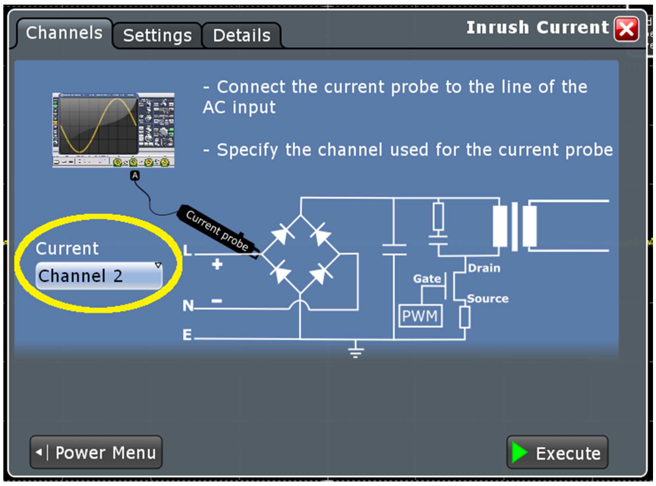


Figure 12: Channels Tab for Inrush Current setup

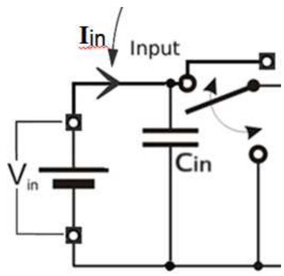


Figure 13: Current probe point for DC/DC converter Inrush Current measurement

(4) Touch the 'Settings' tab, and enter the maximum current expected and set the trigger level in the field labeled "Trigger (T) current value" (Figure 14).

Note: As the measurement is designed to handle AC inputs, the current-measurement channel zero-level will be set to the middle of the screen, and the scale will be set so that the entered maximum current will be ½ of the screen height. For DC measurements, it may be advisable to manually set the zero-level to one division from the bottom of the screen, and input a maximum current that is ½ of that expected, in order to get a 'full-screen' measurement.

(5) Enter the 'Start time' and 'Stop time' in the 'Gate configuration' area; you can set multiple 'Start time' and 'Stop time' periods in which to measure the current, if needed.

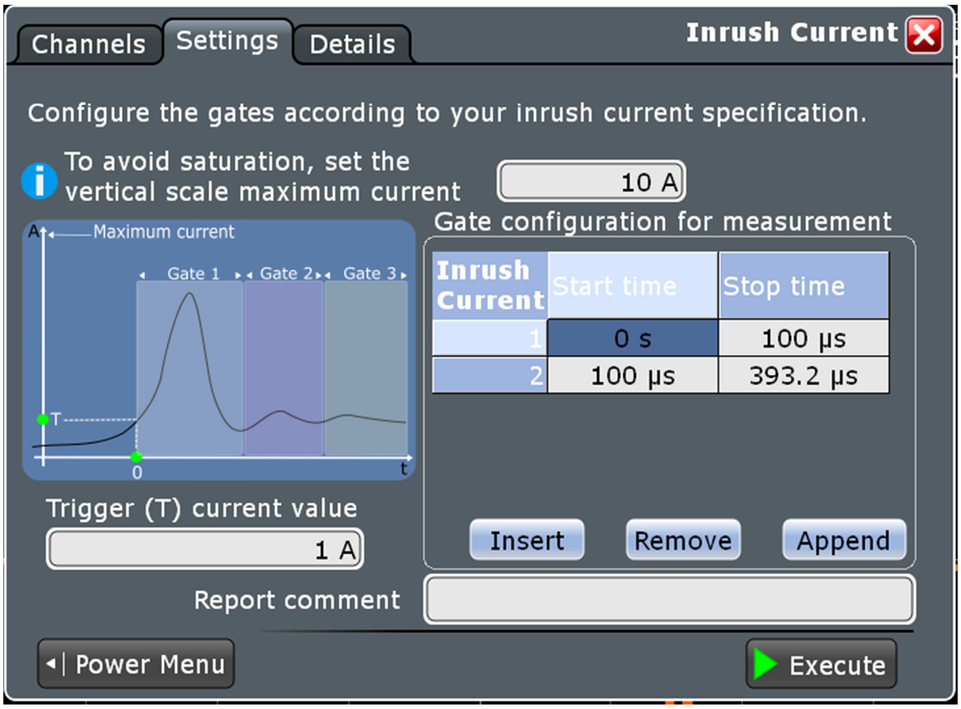


Figure 14: Setting options for the Inrush Current measurement

(6) Touch the 'Execute' button (lower right in any of the Inrush Current tabs,) then press the oscilloscope hard key 'RUN Nx /SINGLE'

Note: The K31 Inrush Current measurement will turn off all channels, except the current measurement channel, when Execute is pressed. You can, before triggering the waveform capture, turn on additional channels that you wish to see in the captured screen shot, and then press 'RUN Nx /SINGLE' and apply power to the DUT

(7) Apply power to the DUT, then turn Power OFF

(8) Figure 15 shows the acquired waveforms and measurement results of the Inrush Current measurement procedure with RTO-K31.

The leftmost (light blue) trace shows the initial inrush current of the capacitor charging, the blue trace of the V_{in} ramp shows clearly. The red trace, near the bottom of the screen, shows the 'stepped' characteristic of V_{out} as the DC/DC converter's switching cycles begin to transfer energy to the output capacitor.

If the inrush current exceeds the screen range, you can change the vertical scale on that channel, then press the oscilloscope hard key 'RUN Nx /SINGLE', and re-apply power. This can be repeated, *without pressing the Execute button*, as needed, to get the correct scale/range, and to get the desired screen appearance.

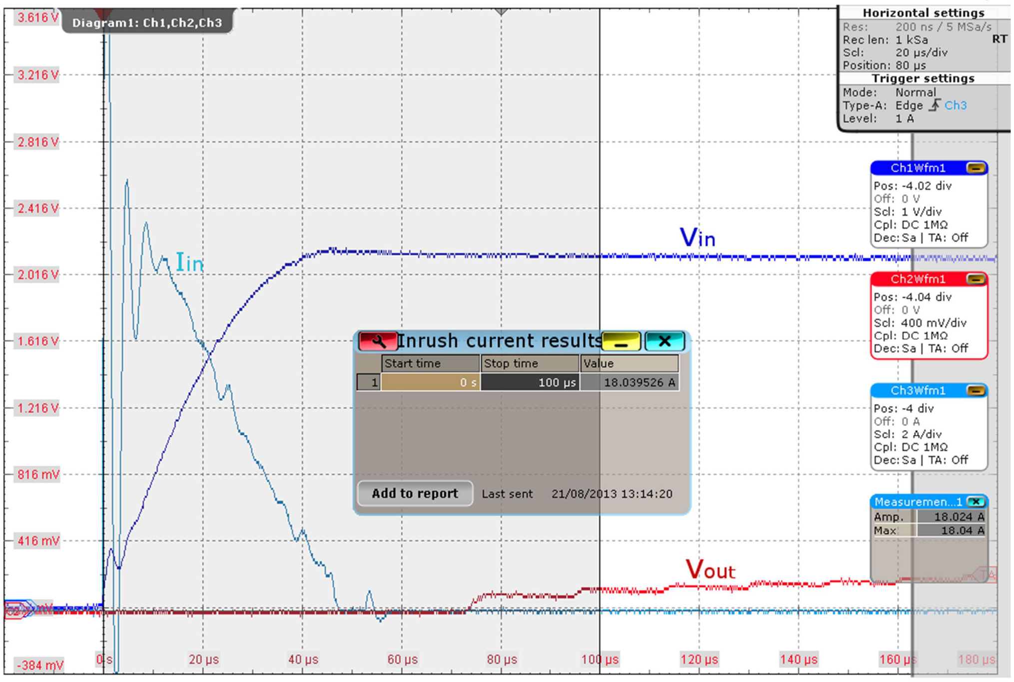


Figure 15: Start-up waveforms and result table of the Inrush Current measurement function; V_{switch} is not shown, as its activity, at this horizontal scale, appears to be a solid 'wall' from ground to V_{in}.

Ch 1 blue - V_{in} / Ch 2 red- V_{out} / Ch 3 light blue - I_{in}

(9) As a final step, the user may save the results to a report by touching the 'Add to report' button in the measurement result window.

5.2 Nominal Load Start-Up and Regulation

The set-up is similar to the power-on test, but instead of a 10 % load, a nominal load is applied to the output. Measure and evaluate the waveforms as described above, in Chapter 5.1, checking for inductor saturation (5.2.1), V_{out} overshoot on start-up (Figure 16), output ripple and output ripple spectrum, and converter stability (V_{switch} - switching frequency, duty cycle) with the nominal static load.

In order to place probes at the necessary measurement points, with four channels available, this set of tests needs to be performed with several different probing and oscilloscope set-ups.

R&S®RTO-K31-based measurements used include:

- Inrush Current for inductor saturation evaluation
- Output Ripple
- Output Spectrum

5.2.1 Inductor Current Behavior

Inductor current behavior is most critical during peak current flow through the inductor, therefore this evaluation should be done under worst-case conditions for inductor current levels.

Peak current flow may occur at start-up (see Figure 16), during positive load steps, or when the DC/DC converter is operated with an external PWM signal to the Enable (most typically found in LED drivers). In the case shown in Figure 16, the horizontal resolution is sufficient to allow the zoom function to correctly display the inductor waveform detail.

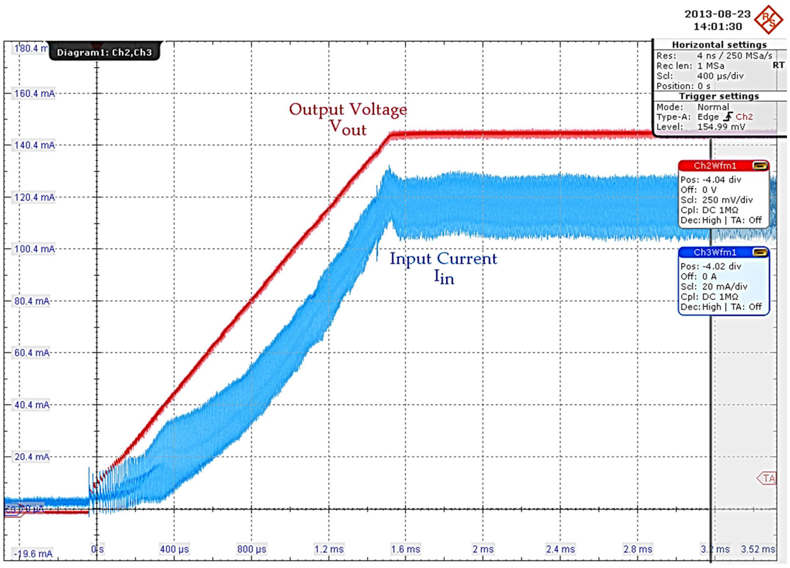


Figure 16: Start-up of DC/DC converter, showing inductor current peak at the end of the soft-start period
(Ch 2 red - Vout / Ch 3 light blue - Iin)

Figure 17 shows a different DC/DC controller IC and associated inductor behaviors; at the point of peak inductor current on start-up, the curvature on both slopes of the inductor current waveform indicates that the inductor is operating in a partially-saturated condition, and may have significant DCR or ACR.

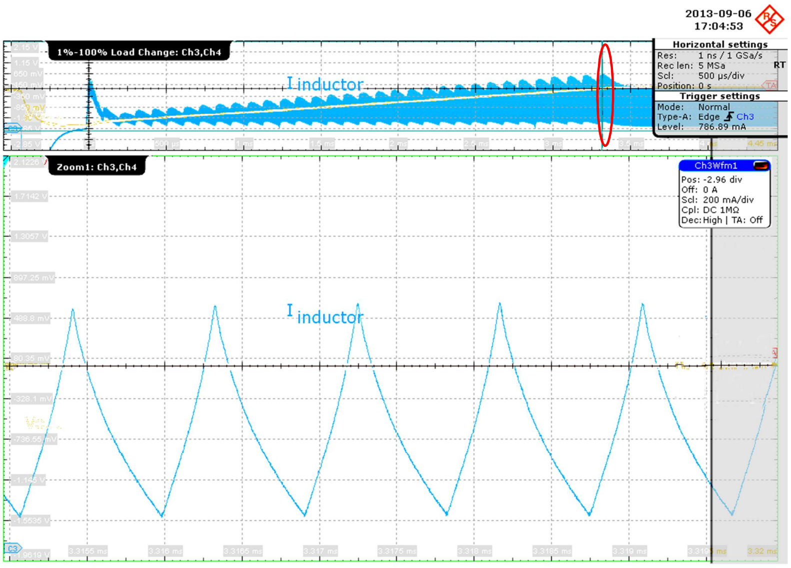


Figure 17: A different controller IC and components, showing distorted inductor-current waveforms, at peak inductor current (red oval indicates the zoomed area.)
(Ch 3 light blue - Iin)

In comparison to the DUT in Figure 17 the inductor current waveform of the TPS62090 in Figure 18 is linear on both slopes, with no curvature of either current slope. This indicates that the inductor is not operating near saturation current, and that it has low DCR and ACR at this frequency and current.

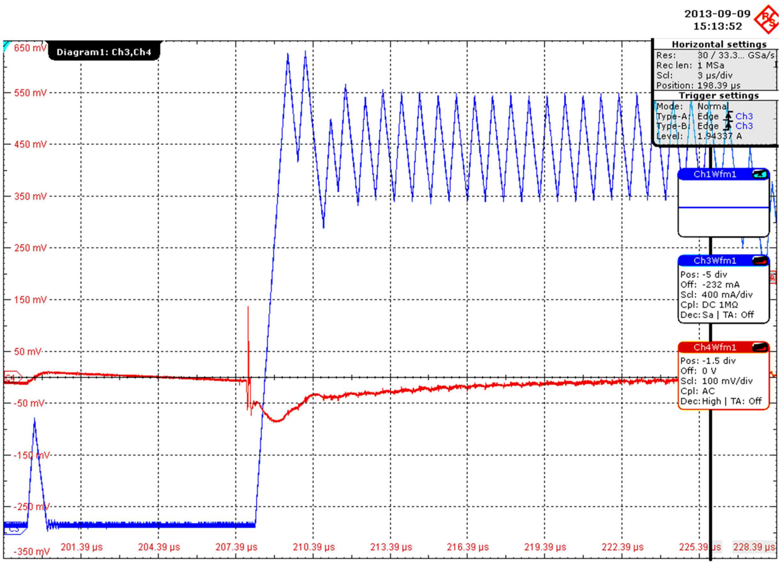


Figure 18: A 1% - 100% load step of TPS62090 showing no apparent distortion of inductor-current waveform at peak current of transition (Ch 4 red - Vout / Ch 3 light blue - Iin)

5.2.2 Output Voltage Ripple

In order to measure the output voltage ripple, of a "good" DC/DC converter, the oscilloscope needs to offer sufficient resolution, and a good "noise floor". Output voltage ripple measurement is included in the power analysis option, or may be performed manually. Figure 19 shows a result screen of the output ripple measurement with the R&S®RTO-K31.

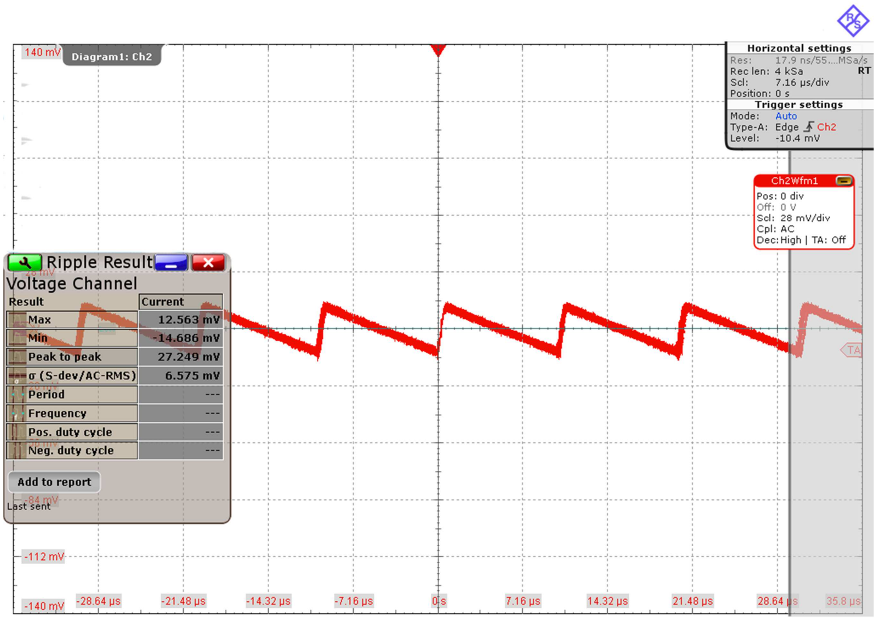


Figure 19: R&S®RTO-K31 Output ripple measurement screen

5.2.3 Output Voltage Ripple Spectrum

Measurement of the V_{out} ripple spectrum demands that the oscilloscope has sufficient resolution, a good "noise floor", and FFT capability that allows for measurement of frequencies below the switching frequency (sub-harmonic oscillation and ripple/transients from the input), and frequencies up to 40 harmonics of the switching frequency (EMC characterization is not covered in this Application Note).

5.2.3.1 Output voltage ripple spectrum measurement with R&S®RTO-K31

Measuring the V_{out} spectrum requires the same probe and basic oscilloscope setup as the V_{out} ripple measurement. The horizontal setting will be different, and, on the RTO, will be controlled by the FFT setup.

When using the R&S®RTO-K31 option, the output ripple spectrum measurement is accomplished very easily.

(1) In the Output section, touch the "Spectrum" button.

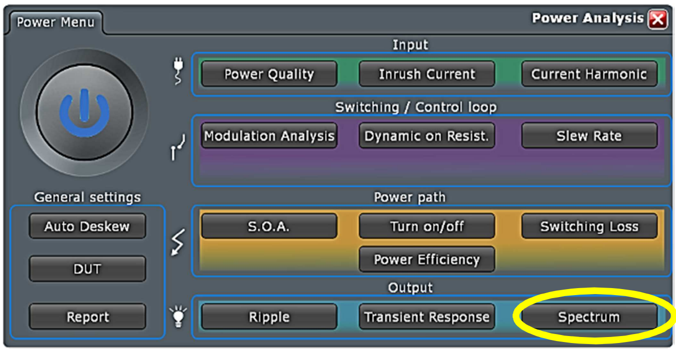


Figure 20: Power Analysis main screen

(2) In the "Channels" tab, select the channel that the output voltage is connected to:

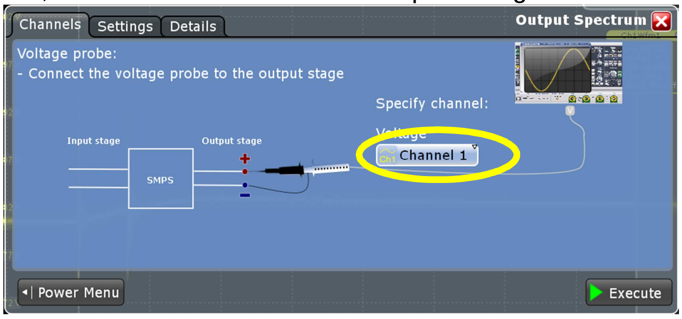


Figure 21: Output spectrum "Channels" tab

In the "Settings" tab (Figure 22), select the switching frequency of the DC/DC converter, if known. If you have manually-adjusted settings that you wish to use for the analysis, select "Keep present settings", otherwise, select "Austoscale the signals" to allow the R&S®RTO-K31 option to choose the settings for the analysis capture and FFT.

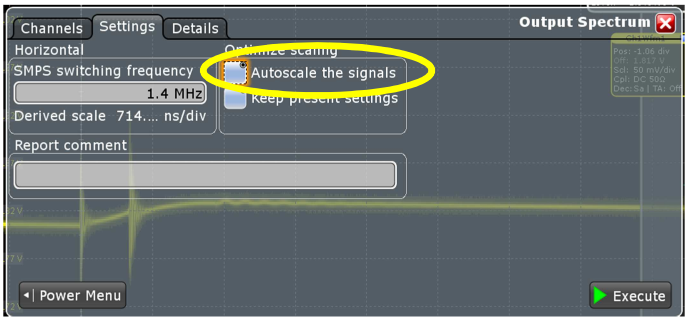


Figure 22: Output spectrum "Settings" tab

Figure 23 shows the output voltage ripple spectrum measurement display from the RTO. The measurement result returns 8 harmonic level measurements, as well as the spectrum display.

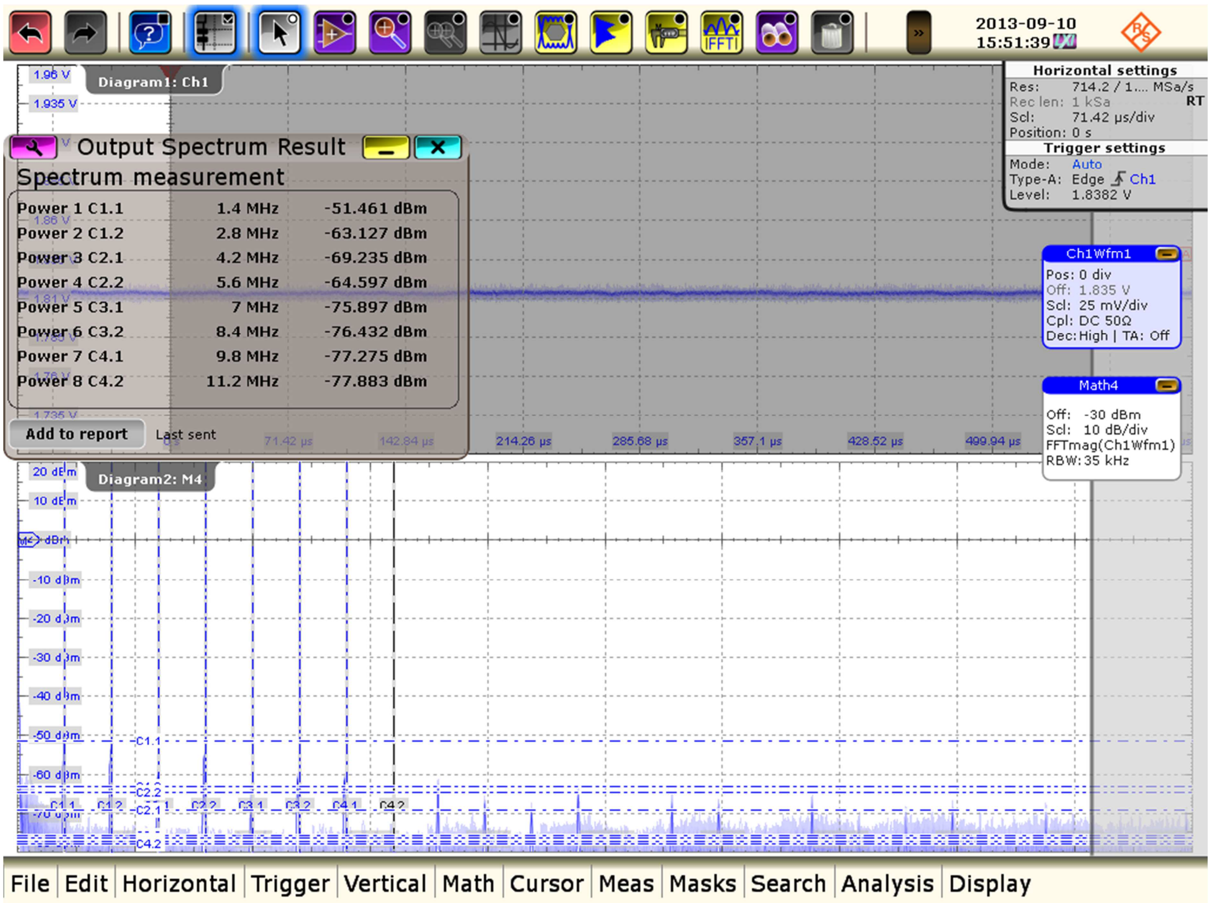


Figure 23: R&S®RTO-K31 Output ripple spectrum auto-scaled measurement display

During testing, the user can make scale adjustments to the FFT display to optimize the report clarity, as shown in Figure 24.

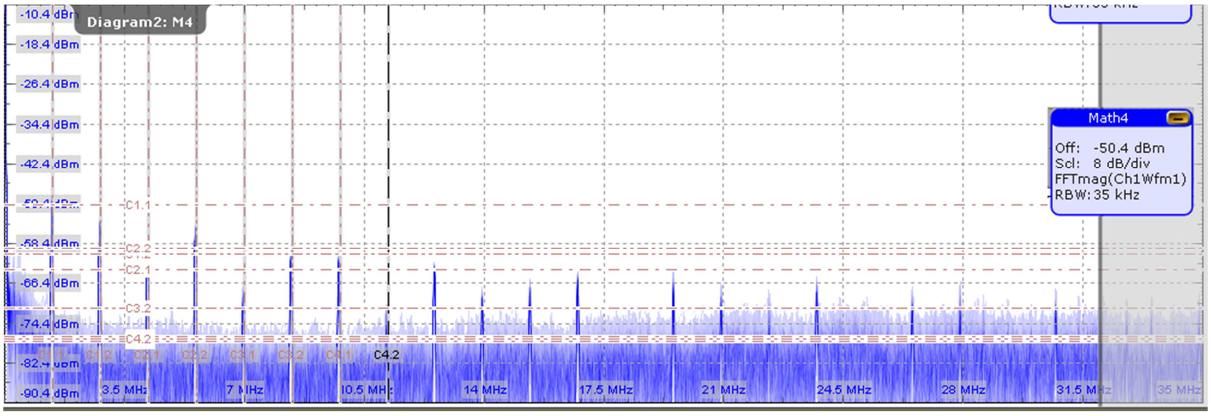


Figure 24: Output spectrum display with manual adjustment of gain and offset

5.2.3.2 Output voltage spectrum manual measurement

To manually set up the RTO for the measurement of the V_{out} spectrum of the test DUT, with 1.4 MHz switching frequency, here is an example setup (see Figure 25): The R&S®RTO-ZS10 probe was used, and the ProbeMeter function measured the DC voltage of the output. This voltage reading was used to set the offset voltage of the R&S®RTO-ZS10.

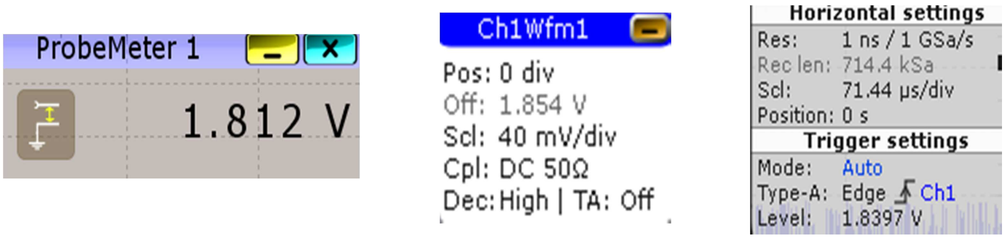


Figure 25: Oscilloscope settings to observe output ripple

After observing the waveform, a sensitivity of 40 mV/division (see Figure 25) was chosen, so that the input signal did not exceed the screen boundaries and saturate the ADC, which could lead to erroneous measurement results; the channel's "Acquisition" setting was set to "High-Res" and the record length is set to a large value to allow for fine resolution in the FFT.

The Math 4 channel is then set up, as in Figure 26, with the "Arithmetic" function set to 'Average', with a count of 20, to remove noise from the spectrum display. The settings in the FFT Setup, Figure 27, show the FFT span set from 0 Hz to 35 MHz, in this example.

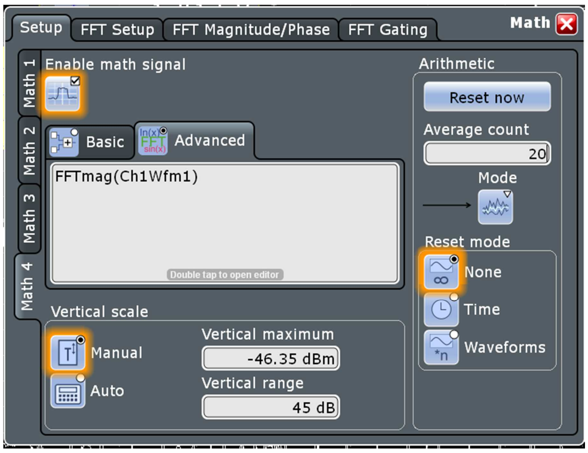


Figure 26 Math channel basic setup for output ripple spectrum

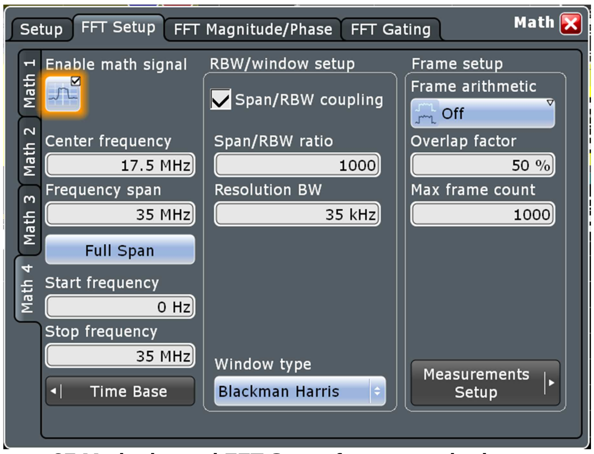


Figure 27 Math channel FFT Setup for output ripple spectrum

The resulting FFT display is shown below (Figure 28):

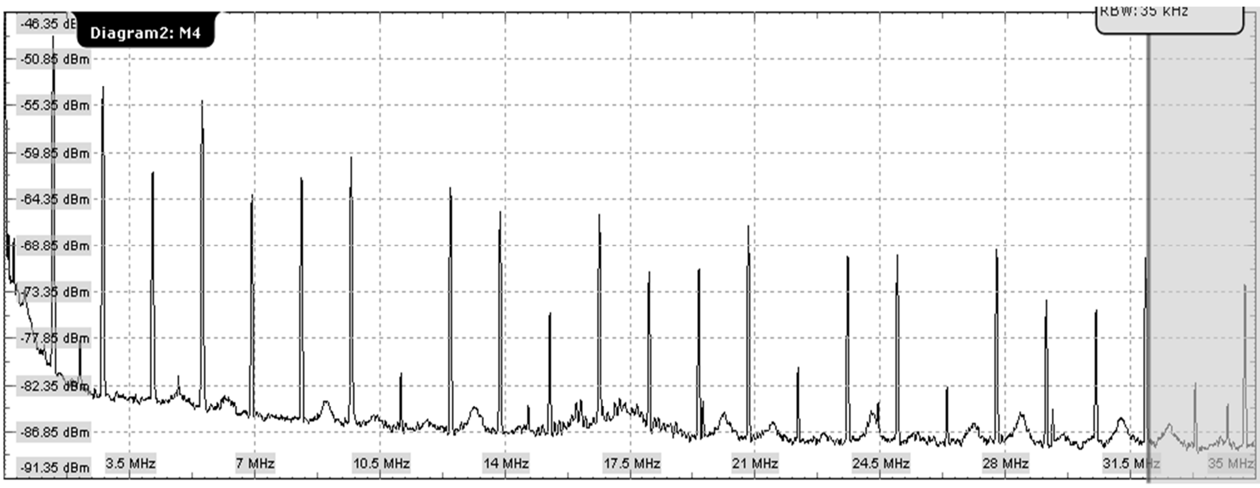


Figure 28 Output ripple spectrum display with waveform averaging over 20 measurements

Cursors may then be used to measure the observed peaks in the spectrum.

5.3 Load Transient Behavior

Load transient behaviors should be tested for both large load range changes, e.g. 1% - 100%, and for more moderate load changes, such as 10% - 90% and 50% - 60%.

In DC/DC buck converters, depending on control strategy, there may be very significant differences in transient response due to changes in V_{in}-V_{out}. Since the V_{in}-V_{out} differential determines the maximum slope of the inductor current change, a lower V_{in}-V_{out} differential reduces the ability of the converter to supply large currents as the load is increased, thus increasing load transient response time for increasing loads.

The following screen shots illustrate V_{out} (red, Channel 4, note the AC coupling) and inductor current (blue, Channel 3) behavior during load transients.

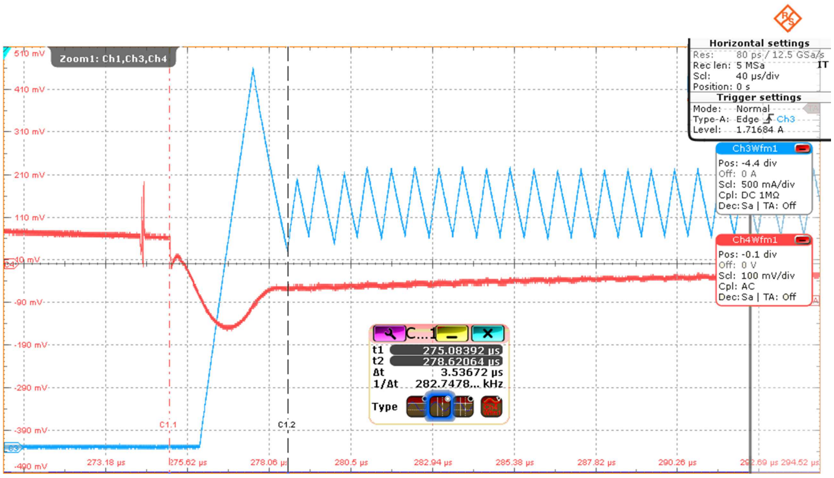


Figure 29: 1% to 100% load change TPS62090 with V_{in} = 5 V; < 4 µs to begin full regulation.

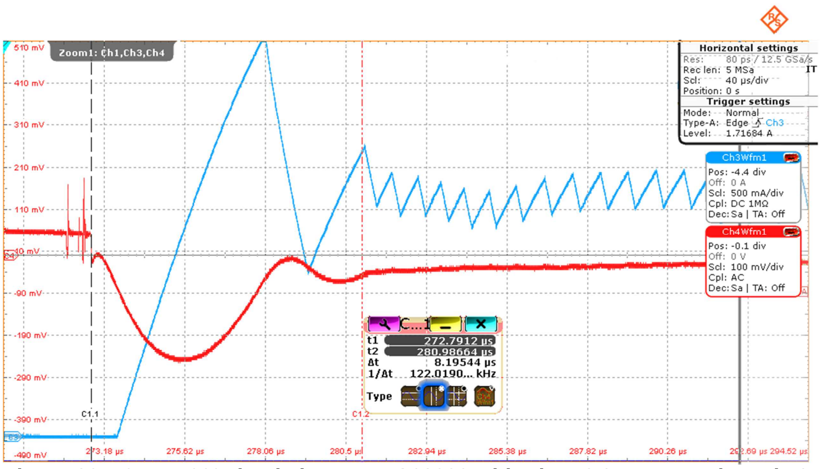


Figure 30: 1% to 100% load change TPS62090 with Vin = 3.3 V; approximately 9 µs to begin full regulation. Note the higher current peak and duty-cycle difference versus the 5 V test result of Figure 29.

Note: If there are problems with switch bounce, or manual connections used to add/subtract loads, this may make isolation of a ‘good’ load change difficult. As shown in Figure 31, the deep memory and high sample rate of the RTO have allowed us to capture several switch-bounce events, and zoom-in on one event that provides a complete view of the load-change behavior.

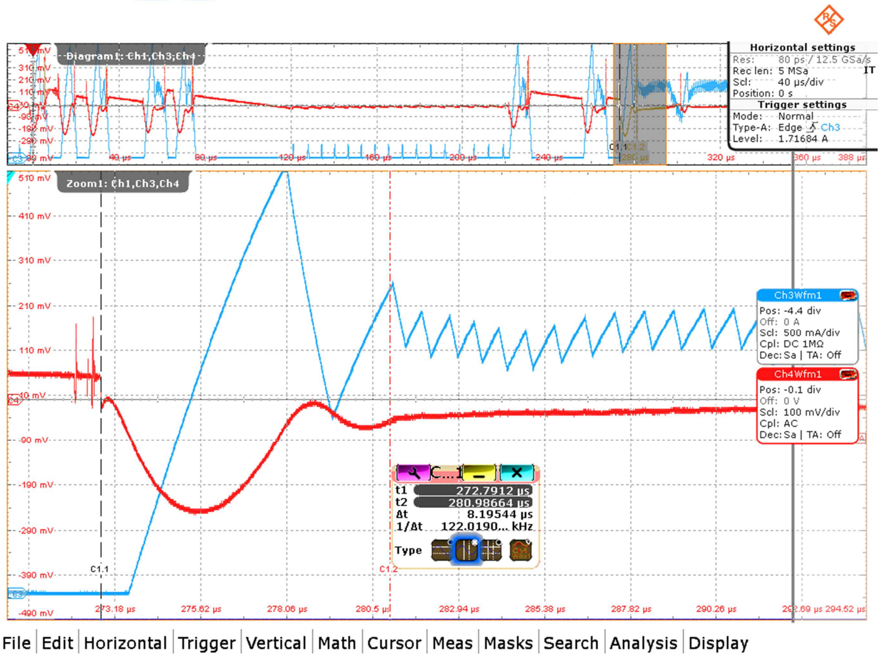


Figure 31: Full-screen capture showing Zoom of 5 Mega-sample record to show region-of-interest.

Because DC/DC buck converters do not generally sink current, their ability to respond to load reduction is controlled largely by switching frequency and output capacitance; higher switching frequency and associated lower output capacitance, usually result in improved response time for a decreasing load. Figure 32, below, shows the much slower response to a load drop, compared to the DC/DC buck converter’s response to a load increase.

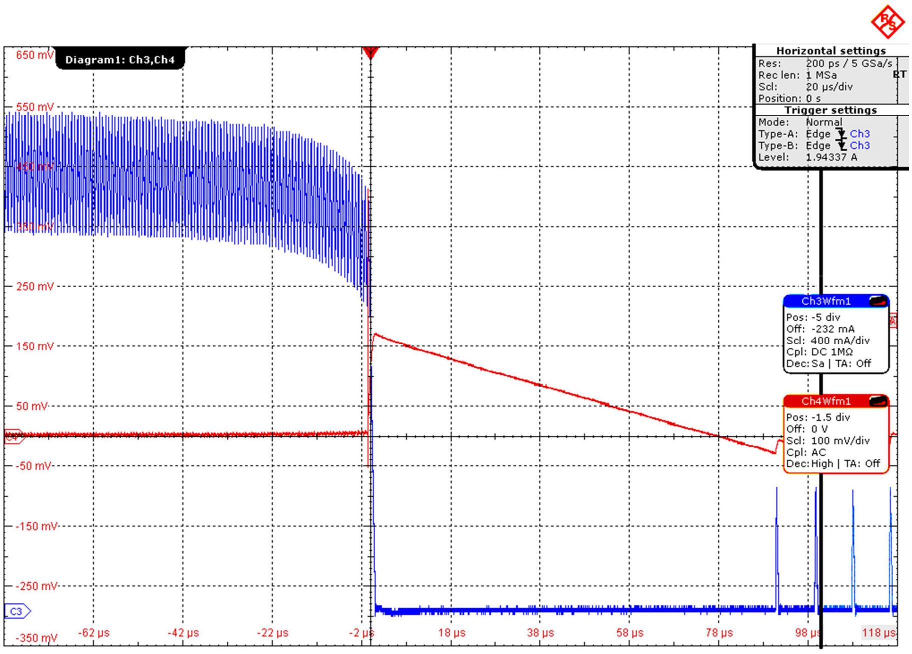


Figure 32 100% to 1% load change TPS62090 – approximately 90 µs to reach regulation point.

6 Documentation of Evaluation Results

Complete documentation will make the job of evaluation and validation review much easier for other team members, or external teams.

The inclusion of details about test equipment used, including oscilloscope probe types, power supply type and settings, all oscilloscope settings, and any comments regarding temperature or other relevant information will enable valid evaluation and comparison of test results.

Oscilloscope screen shots prove the proverb “A picture is worth a thousand words,” providing a wealth of information to an experienced reviewer, enabling faster and easier report reviews, reducing errors and speeding ‘turn-around’.

As described in the following section, the R&S®RTO-K31 Power Analysis option provides excellent tools for document generation, as an integral part of the test and evaluation process; this option provides a wide range of tools suitable for analyzing and documenting AC-input SMPS systems, in addition to the DC/DC converter types discussed in this application note.

6.1 Report Generation with the R&S®RTO-K31 Power Analysis option

R&S®RTO-K31 offers many options for specifying the format and content of reports to be generated. Documentation can be output in either RTF or PDF format, allowing easy exchange of reports, with RTF allowing additional 'personalization' of report contents and formats. Multiple instances of each test type can be included in a single report, and individual test results can be selected from all of the saved tests in a test session.

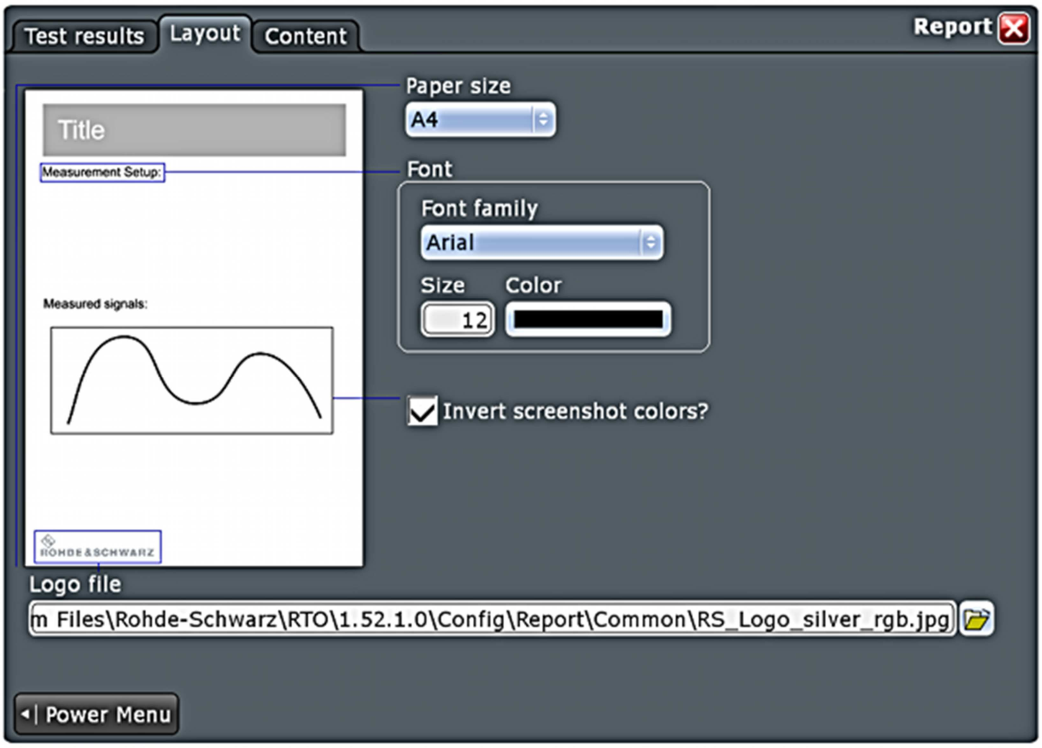


Figure 33: Report "Layout"screen.

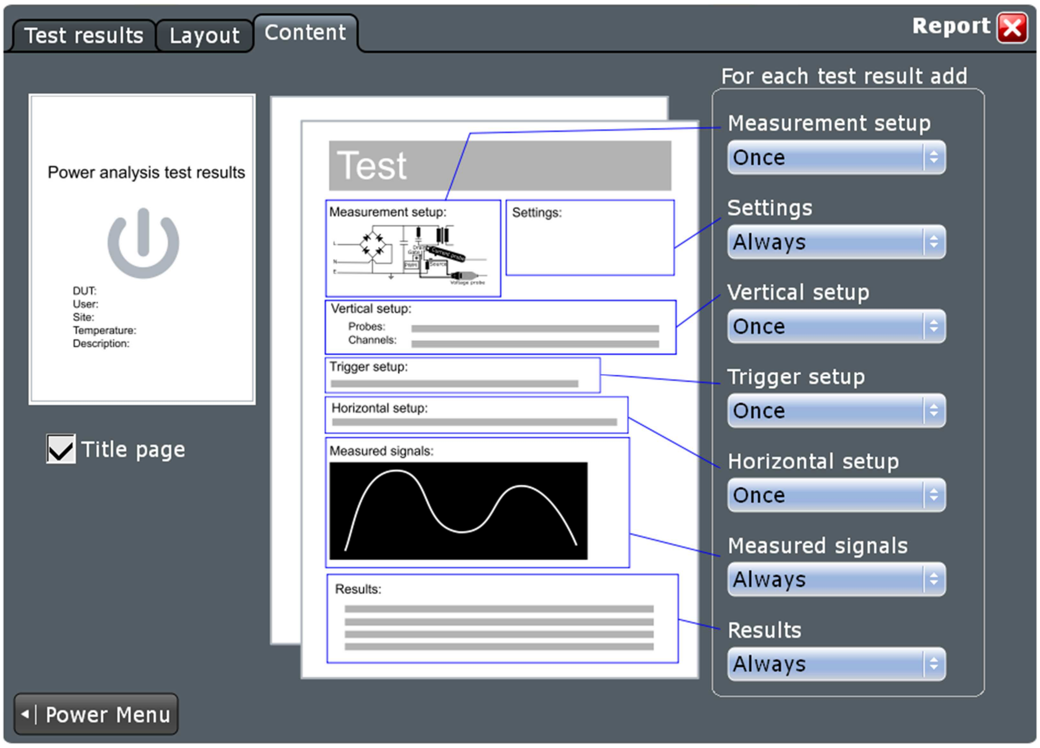


Figure 34: Report generator content selection screen

Figure 35 shows one edited page of an RTF report generated by the R&S® RTO-K31.

Output spectrum

Date: 03/09/2013
Time: 19:32:54
Equipment: RTO1024
Serial number: 200300

Settings:
SMPS frequency: 1400kHz

Vertical setup:

Probes:	Source	Name	Unit	Gain/Att.		
	Voltage Channel 1	None	Volt	1 V/V		
Channels:	Source	Scale	Offset	Coupling	Deskew	Bandwidth
	Voltage Channel 1	20mV/div	1.81V	50Ohm DC	0s	200 MHz

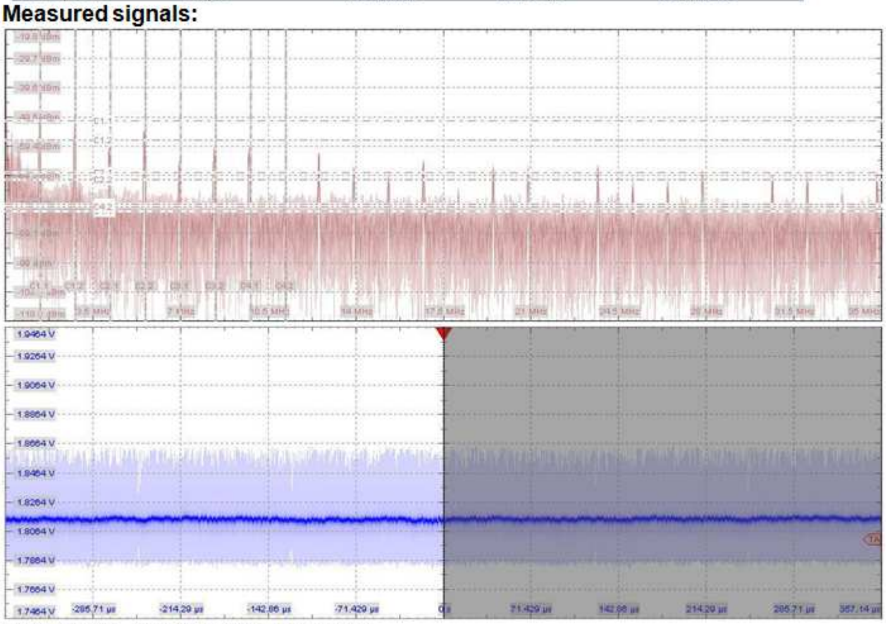
Trigger setup:

Type	Source	Level	Slope
Edge	Channel 1	1.8V	Positive

Horizontal setup:

Time scale	Acq. time	Sample rate	Resolution	ADC sample rate
71.42µs/div	800ps	10000MHz	714.28µs	1250MSa/s

Measured signals:



Comment: 62090 buck-mode dc/dc

Results:

Cursor	Frequency	Level
C1.1	1400kHz	-50.99dBm
C1.2	2800kHz	-57.65dBm
C2.1	4200kHz	-67.75dBm
C2.2	5600kHz	-70.9dBm
C3.1	7000kHz	-77.18dBm
C3.2	8400kHz	-76.89dBm
C4.1	9800kHz	-78.210dBm
C4.2	11.2000MHz	-81.06dBm

ROHDE&SCHWARZ

Figure 35 Sample report page.

7 Conclusions

DC/DC converters are a continually-evolving class of circuits and devices, requiring more dynamic analysis than their predecessor linear regulators; switch-mode operation presents challenges in evaluation of their behavior, over wide ranges of voltage, current and bandwidth.

We have shown in this application note that the R&S®RTO oscilloscopes, with the use of the correct probes, and probing techniques, in association with the R&S®RTO-K31 power analysis option, can provide all of the required capability for analysis and evaluation of the major dynamic behaviors of a DC/DC buck converter and its inductor.

The procedures, tests and measurements outlined in this application note allow validation of the DC/DC buck converter to the point that the user may confidently proceed to further in-circuit test and circuit characterization.

The attributes of the R&S® RTO oscilloscopes, and associated probing solutions, as illustrated in this application note, are equally well-suited to a broad range of SMPS topologies and designs. In addition to uses in analyzing DC/DC converters, the combination of the R&S®RTO oscilloscopes and the R&S®RTO-K31 option provides a powerful tool for testing, analyzing and documenting AC-input SMPS system performance.

8 Literature

[1] Texas Instruments Incorporated, "TPS62090EVM-063 Evaluation Module," 15 05 2012. [Online]. Available: http://www.ti.com/tool/TPS62090EVM-063. [Accessed 25 09 2013].

[2] Texas Instruments Incorporated, "TPS62090," 22 03 2012. [Online]. Available: http://www.ti.com/product/tps62090. [Accessed 25 09 2013].

[3] L. Rozenblat, "LAZAR's POWER ELECTRONICS GUIDE," Lazar Rozenblat, [Online]. Available: http://www.smps.us/. [Accessed 25 09 2013].

[4] J. Foutz, "Switching-Mode Power Supply Design," [Online]. Available: http://www.smpstech.com/. [Accessed 25 09 2013].

[5] P. D.-I. H. Schmidt-Walter, "Design of Switch Mode Power Supplies - Calculations," [Online]. Available: http://schmidt-walter.eit.h-da.de/smps_e/smps_e.html. [Accessed 25 09 2013].

[6] T. Fowler, "Selecting Inductors for Low-Power Buck Regulators," 1 November 2007. [Online]. Available: http://powerelectronics.com/site-files/powerelectronics.com/files/archive/powerelectronics.com/mag/711PET24.pdf. [Accessed 25 09 2013].

[7] T. Fowler, "Selecting Inductors for Low-Power Buck Regulators," *Power Electronics Technology,* pp. 30-33, 1 November 2007.

9 Ordering Information

Designation	Type	Order No.
Power Analysis option for R&S®RTO-series Oscilloscopes	R&S®RTO-K31	1317.5739.02
Oscilloscope, 600 MHz Bandwidth, 4 channels	R&S®RTO1004	1316.1000.04
Active probe, Single-ended, 1 GHz bandwidth	R&S®RT-ZS10	1410.4080.02
Active probe, Differential input, 0.6 pF, 1 MΩ, Extended voltage range, 1 GHz bandwidth	R&S®RT-ZD10	1410.4715.02
Current probe, 100 MHz bandwidth, 30 A maximum DC	R&S®RT-ZC20	1409.7766.02
Power deskew fixture	R&S®RT-ZF20	1800.0004.02

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- Energy-efficient products
- Continuous improvement in environmental sustainability
- ISO 14001-certified environmental management system

Certified Quality System
ISO 9001

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