Switch Mode Power Supply Measurements

Application Note

**Using an Agilent InfiniiVision 3000/4000/6000 X-Series Oscilloscope
With the Power Measurements Option**

Introduction

Agilent's 3000, 4000, and 6000 X-Series oscilloscopes with the Power Measurements option provide a quick and easy way to analyze the reliability and efficiency of switching power supplies. This application note provides step-by-step instructions on how to perform a broad range of power analysis measurements on your switch mode power supply (SMPS), as well as detailed instructions on how to perform these same measurements when using Agilent's SMPS Measurements Training Kit as the device under test (DUT). The following power analysis measurements are enabled when an Agilent InfiniiVision 3000, 4000, or 6000 X-Series oscilloscope has been licensed with the Power Measurements option DSOX3PWR/DSOX4PWR/DSOX6PWR:

Input analysis

- Power Quality
- Current Harmonics
- Inrush Current

Switching/modulation analysis

- Switching Loss
- Slew Rate
- Modulation

Output analysis

- Output Ripple
- Turn on/Turn off
- Transient Response
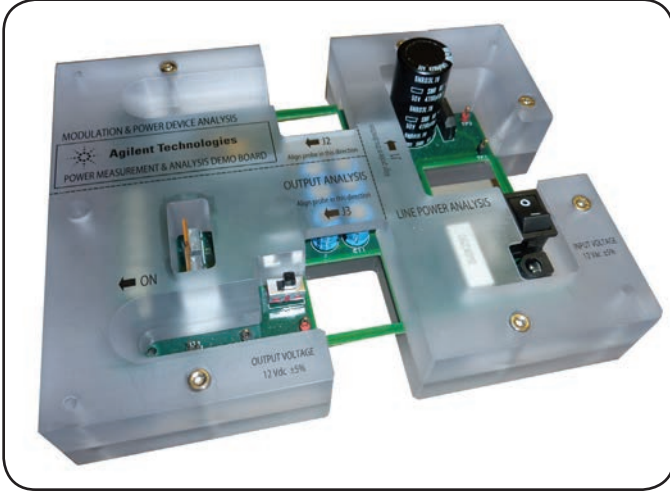- Power Supply Rejection Ratio (PSRR)
- Efficiency

Anticipate ___*Accelerate* ___*Achieve*

Agilent Technologies

Figure 1: Agilent's Switch Mode Power Supply Measurements Training Kit.

Required equipment

- Agilent 3000, 4000, or 6000 X-Series Oscilloscope with the Power Measurements option (DSOX3PWR, DSOX4PWR, or DSOX6PWR)
- U1880A Deskew Fixture with USB cable for power
- N2790A High-voltage Differential Active Probe, or equivalent
- 1147B or N2893A 15A Current Probe, or equivalent
- 10:1 Passive Voltage Probe
- Your Switch Mode Power Supply (SMPS) or Agilent's SMPS Measurements Training Kit (Figure 1)

Probing tips

If using Agilent's N2790A high-voltage differential active probe (Figure 2) for your power measurements, this probe can be manually set for either **50:1** attenuation for up to 140 V (DC plus peak AC) measurements, or **500:1** attenuation for up to 1400 V measurements. If you are using Agilent's SMPS training kit as your DUT, the **50:1** setting is appropriate. But, if you are performing measurements on your own switching power supply that may have higher input and switching voltages, then you may need to use the 500:1 setting.

When you initially connect the N2790A probe to one of the input channels of the Agilent 3000/4000/6000 X-Series oscilloscope, the scope will automatically detect and set its own probe attenuation factor for that channel to **50:1**, but if you have the probe attenuation manually set on the probe to **500:1**, then you will need to manually enter a **500:1** attenuation factor in the scope's probe menu for that particular channel.

The 1147B or N2893A current probe (Figure 3) is a 0.1 V/A probe (10:1 attenuation). When this probe is connected to any input channel of an Agilent 3000/4000/6000 X-Series oscilloscope, the scope will automatically detect that a current probe is connected to provide measurements in units of Amps. It will also automatically detect and compensate for the 10:1 probe attenuation. No user settings are required.

When you connect the current probe to a current loop in your device under test, make sure to fully close *AND* lock the probe clamp. To lock it in place, slide the locking mechanism fully forward until you feel and hear it click in place.

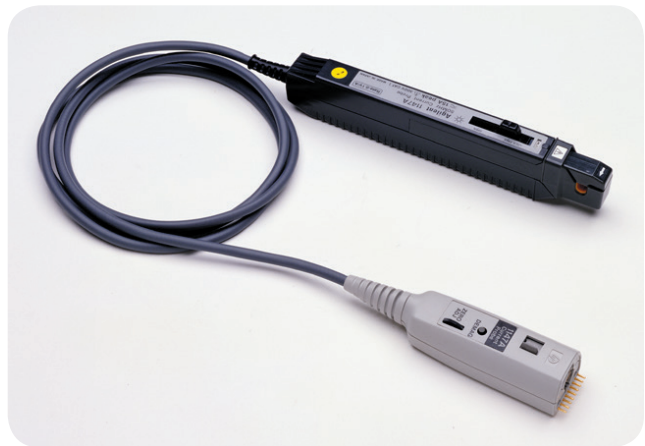*Figure 2: Agilent's N2790A 100-MHz high-voltage differential active probe.*

Figure 3: Agilent's 1147B 50-MHz, 15A AC/DC current probe.

Probing tips

When using the 1147B or N2893A current probe to make current measurements on Agilent's SMPS training kit, it is very easy to connect to various designed-in PC board current loops. But, if you are making measurements on your own switching power supply, rarely are designed-in current loops available. This means you will probably need to create temporary current loops in your prototype power supply's circuitry in order to measure current and power. Figure 4 shows an example of a wire-loop in series with the Source terminal on a FET switching device in order to measure drain-to-source current. To measure input AC current, engineers will often just strip back the insulation on the power cord to access the line current wire. Note that although this may be quick and easy, this is NOT an Agilent-recommended technique.

After extended use, a magnetic field can build up in a current probe. When you are making power supply measurements using a current probe, you should occasionally "degauss" (de-magnify) the probe. To do this, simply disconnect the current probe from the device under test, close and lock the current probe clamp, and then press the **DEMAG** button near the base of the probe where it connects to the scope. Note that you can also calibrate the offset of the probe (and scope) at the same time by rotating the **ZERO ADJ** thumb-wheel until the baseline current waveform aligns with the ground indicator on the scope's display.

Figure 4: Creating a special current loop in your power supply to measure current.

Deskewing the probes

When using dissimilar type probes, such as a voltage probe and current probe, it is important to perform a probe deskew calibration. This automatic procedure using the recommended U1880A deskew fixture (Figure 5) will null-out the difference in propagation delay between your probes to provide more accurate power measurements. This is especially important for the Switching Loss measurement where just a few nanoseconds can sometimes make a big difference in power and energy loss measurements during the turn-on and turn-off phases of transistor switching.

1. Connect the U1880A's USB cable between the deskew fixture and the USB port on the back of the oscilloscope.
2. Press the **[Default Setup]** front panel key.
3. Press the **[Analyze]** front panel key; then press the **Features** softkey and select the **Power Application**.
4. Press the **Analysis** softkey; then select **Power Quality**.
5. Press the **Signals** softkey; then press the **Deskew** softkey. Note that the automatic deskew calibration is also available within the **Current Harmonics** and **Switching Loss** measurement menus.
6. Set the **S1** switch on the deskew fixture to the "Small Loop" setting as shown in the on-screen diagram in Figure 6.
7. Connect the N2790A high-voltage differential active probe between the scope's channel-1 input to **J6** (red lead to red test point) and **J7** (black lead to black test point) on the U1880A deskew fixture as illustrated in the on-screen diagram.
8. Connect the current probe from the scope's channel-2 input to the "Small Loop" in the direction indicated on the deskew fixture (current flow towards the top of the board).
9. Press the **Auto Deskew** softkey on the scope.

When the automatic deskew calibration completes, your scope's display should look similar to Figure 7. The deskew calibration factor will remain in the channel-2 probe settings menu and is non-volatile. But you can manually change the deskew factor, or perform a "factory default setup" within the scope's **[Save/Recall]** menu to reset it back to zero. Performing a standard front panel **[Default Setup]** will NOT reset the deskew calibration factor.
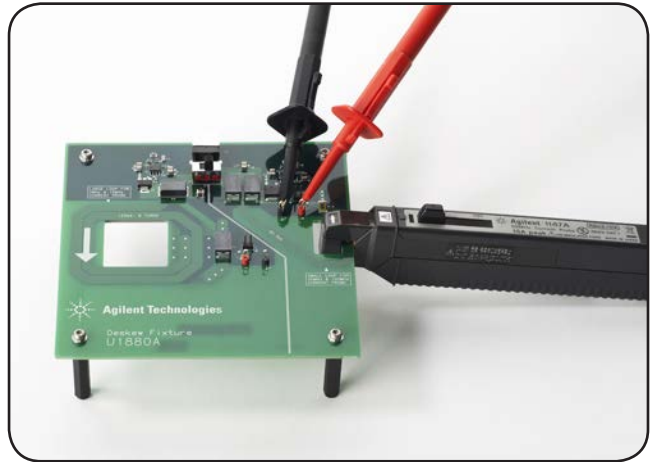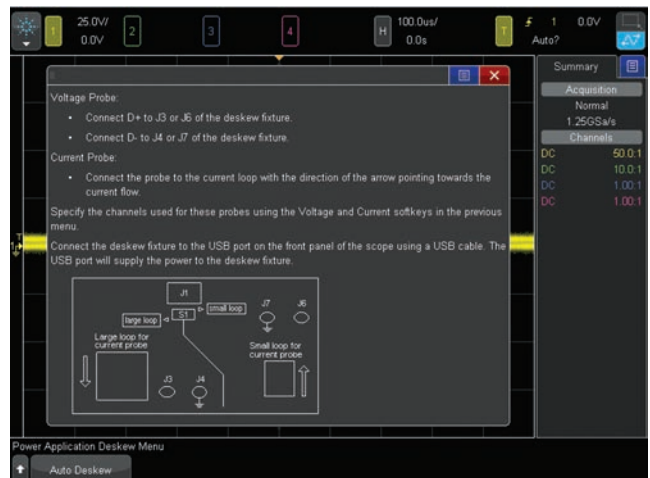

Figure 5: Agilent's U1880A deskew fixture.

Figure 6: Deskew Connections diagram.

Figure 7: Deskew display after completing automatic deskew between voltage and current probes.

Power quality analysis

Power Quality analysis measures the quality of the input AC line signal that supplies power to your switching power supply while operating. This measurement provides the following input signal quality parameters:

- **Real Power** (P = $V_{Instantaneous}$ x $I_{Instantaneous}$ Averaged over N cycles)
- **Apparent Power** (S = V_{RMS} x I_{RMS} over N cycles)
- **Reactive Power** (Q = Apparent x SIN(φ))
- **Power Factor** (PF = Real/Apparent)
- **Voltage Crest Factor** (CF V = V_{Peak} / V_{RMS})
- **Current Crest Factor** (CF I = I_{Peak} / I_{RMS})
- **Phase Angle** (φ = ACOS(PF))

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Default Setup]** front panel key.
3. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
4. Press the **Analysis** softkey; then select the **Power Quality** measurement.
5. Press the **Signals** softkey.
6. Ensure that **Voltage** is set to **1** (channel-1), and **Current** is set to **2** (channel-2).
7. Connect the N2790A high-voltage differential active probe from the scope's channel-1 input to Line (red lead) and Neutral (back lead) as illustrated in the connections diagram shown in Figure 8. If using Agilent's SMPS training kit, connect the probe to **TP2** (red lead) and **TP1** (black lead).
8. Connect the current probe from the scope's channel-2 input to a wire-loop of the input line signal. If using Agilent's SMPS training kit, connect the current probe to the **J1** loop in the direction indicated.
9. Press the **AutoSetup** softkey; then press **Apply**.

When **AutoSetup** is pressed, the scope optimally scales the voltage (yellow trace) and current (green trace) waveforms, turns on the waveform math power waveform (purple trace), and then sets the timebase to display two cycles (default setting) across the screen. Note that if you observe the current waveform (green trace) out of phase relative to the voltage waveform (yellow trace), which will result in negative power waveform pulses (purple trace), then your current probe is probably connected backwards.

When **Apply** is pressed, the 4000 or 6000 X-Series scope will automatically measure all of the power quality parameters as shown in Figure 9. The 3000 X-Series scope will measure just Power Factor, Real Power, Apparent Power, and Reactive Power. To measure the Crest Factor of the voltage and current waveforms, make sure **Type** is set to **Crest**; then
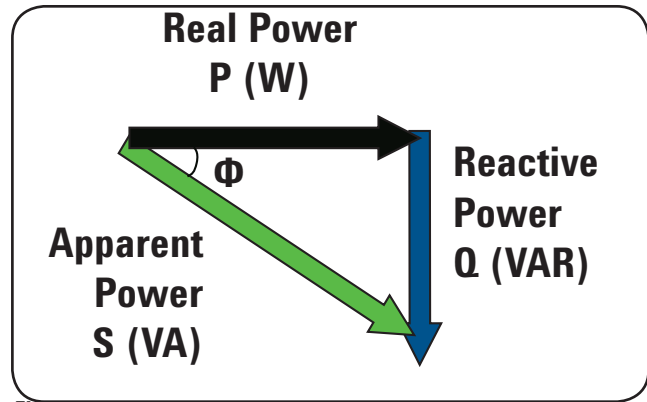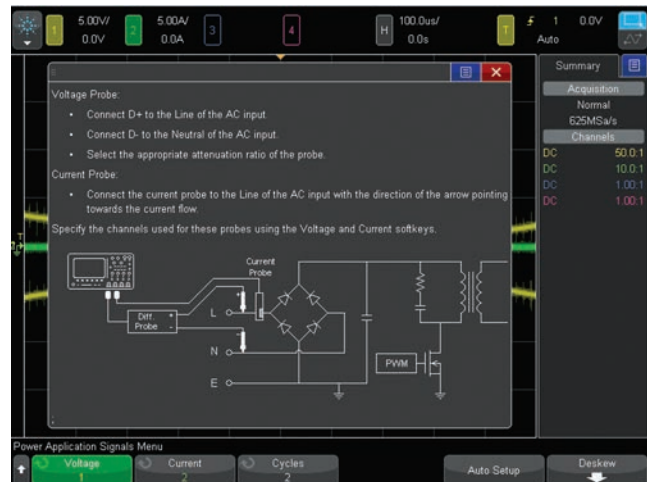

Figure 7: Apparent, Real, and Reactive power

Figure 8: Connections diagram for the Power Quality measurement.

Figure 9: Input Power Quality measurements.

press **Apply**. To measure the phase between the voltage and current waveforms, press the **Type** softkey, select **Phase Angle**, and then press the **Apply** softkey again.

Current harmonics analysis

Current harmonics analysis measures the amplitude of frequency components that can be injected back into the AC lines. End-products must often meet specific standards of compliance in order not to disturb other equipment connected to the AC supply grid. This measurement will perform an FFT measurement on the current waveform, compare the results of the amplitudes of odd and even harmonics against a user-selected IEC standard, and also provides color-coded pass/fail indicators for each tested frequency up to the 40th harmonic.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Current Harmonics** measurement.
4. Press the **Signals** softkey.
5. Connect the N2790A voltage probe from the scope's channel-1 input to Line (red lead) and Neutral (back lead) as illustrated in the connections diagram shown In Figure 10. If using Agilent's SMPS training kit, connect the probe to **TP2** (red lead) and **TP1** (black lead).
6. Connect the current probe between the scope's channel-2 input to a wire-loop of the input line signal. If using Agilent's SMPS training kit, connect the current probe to the **J1** loop in the direction indicated.
7. Ensure that **Voltage** is set to **1** (channel-1), and **Current** set to **2** (channel-2).
8. Press **AutoSetup**. If you use the default settings, the scope will display 20 cycles of the input line voltage (yellow trace) and current (green trace) waveforms on the scope's display.
9. Press the **Settings** softkey; then press the **Line Freq** softkey and set the frequency to either **50 Hz**, **60 Hz**, or **400 Hz** depending upon the line frequency in your part of the world or application. Note that you can also select the appropriate **IEC** standard to test against in this menu as well.
10. Press the **[Back]** softkey to return to the previous menu; then press the **Apply** softkey to begin the Current Harmonics measurement.

When **Apply** is pressed, the scope performs an FFT waveform math operation (purple trace) on the current waveform with the results shown in a tabular format in the upper half of the scope's display as shown in Figure 11. The scope measures up to the 40th harmonic and compares against the selected IEC standard. To view the higher harmonics, press the **Scroll Harmonics** softkey and then rotate the knob.

11. To view the results in a bar chart format, press the **Settings** softkey, then press the **Display** softkey and change from the **Table** setting to the **Bar Chart** setting as shown in Figure 12.
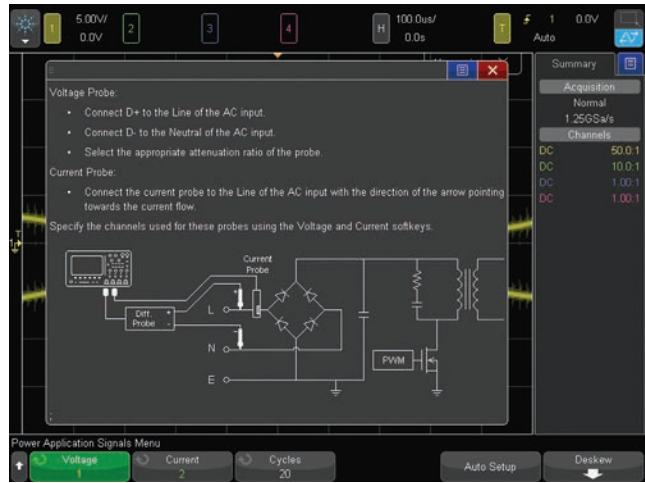

Figure 10: Connections diagram for the Current Harmonics measurement.

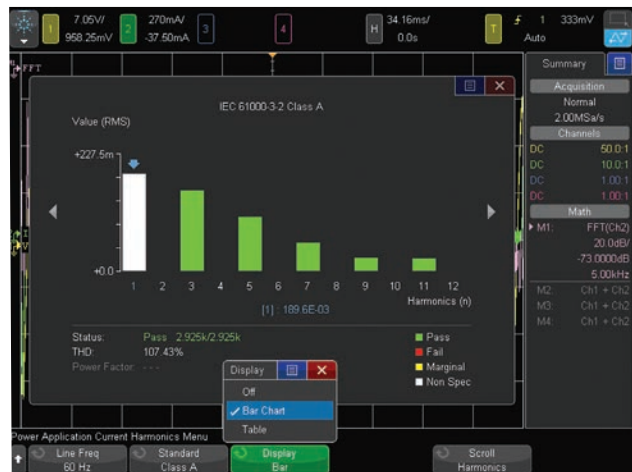*Figure 11: Current Harmonics measurement in a tabular format.*

Figure 12: Current Harmonics measurement in a Bar Chart format.

7

Inrush current analysis

Inrush Current Analysis measures the peak input current (positive or negative) when power is initially turned on. Since this measurement is based on the acquisition of a single-shot event, there is not an **AutoSetup** selection for this measurement (**AutoSetup** requires a repetitive input signal). For this reason, you must enter the "expected" peak current surge, as well as the steady-state peak-to-peak line voltage so that the scope can establish initial vertical scaling. The scope then provides step-by-step instructions on how to perform this single-shot measurement.

1. If using Agilent's Power Measurements training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Inrush Current** measurement.
4. Press the **Signals** softkey; then connect the N2790A voltage probe between the scope's channel-1 input to Line (red lead) and Neutral (back lead) as illustrated in the connections diagram shown in Figure 13. If using Agilent's SMPS training kit, connect to **TP2** (red lead) and **TP1** (black lead) on the demo board.
5. Connect the current probe between the scope's channel-2 input to a wire-loop of the input Line signal. If using Agilent's training kit, connect the current probe to the **J1** loop in the direction indicated.
6. Ensure that **Voltage** is set to **1** (channel-1), and **Current** is set to **2** (channel-2).
7. Set **Max Vin** and the approximate **Expected** surge current for your device under test. If using Agilent's SMPS training kit, then the default settings should be appropriate for this measurement.

Note that the default **Expected** surge current and **Max Vin** settings have been optimized (default setup) for Agilent's SMPS training kit. Although the steady-state peak current of the demo board is approximately 1 A (with the S2 load switch set ON), the peak inrush current is much higher and can sometimes exceed ± 30 A. Determining the "expected" peak current of your device under test will be an iterative/trial & error process. The value that you enter for **Expected** should be higher than the actual peak current that will be captured and measured.

8. After accepting or changing the settings in the **Signals** menu, press the **[Back]** front panel key (left side of scope) to return to the previous menu.
9. Press the **Apply** softkey; then follow the step-by-step on-screen instructions, which are repeated below.
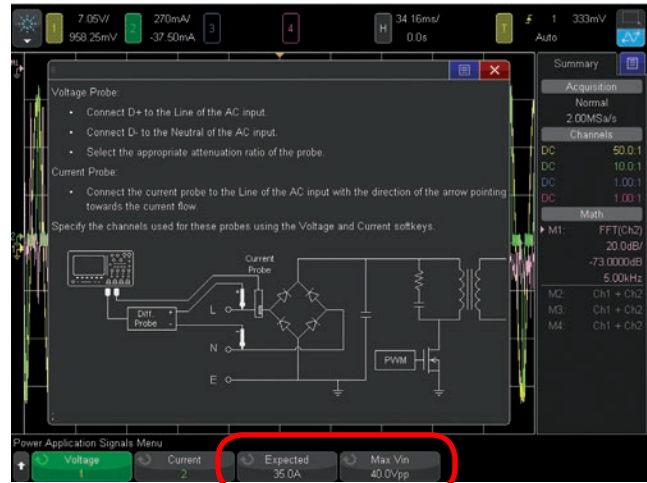10. Turn **OFF** power; then press **Next**.

Figure 13: Setting "expected" inrush current and peak-to-peak line voltage for a single-shot inrush current measurement.
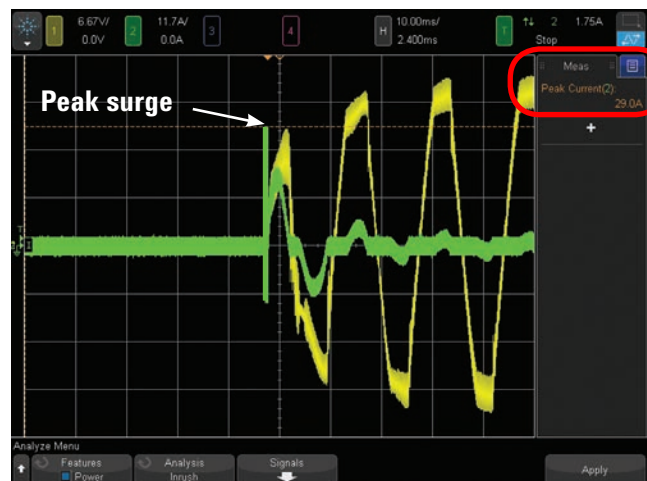

Figure 14: Inrush current measurement.

11. Turn **ON** power; then press **Next**.
12. Repeat several times in order to obtain the worst-case peak inrush current as shown in Figure 14.

If the Peak Current measurement indicates either ">" or "<", this is an indication that the current waveform is "clipped" and that you should then increase the **Expected** current setting in the **Signals** menu for a more accurate measurement. The absolute peak inrush current will typically occur if the power switch is turned on at the same instance in time that the input line voltage is either at its absolute positive or negative peak value. This means that you should repeat this measurement several times in order to measure the worst-case inrush current.

Switching loss analysis

Switching loss analysis measures power and energy losses of your switching device (typically an FET). In a Switch Mode Power Supply (SMPS), most power and energy losses occur during the switching phases of the transistor when it turns on and turns off. During these phases the switching transistor goes in and out of saturation and momentarily operates in its linear region. Power and energy losses also occur during the conduction phase of the switching transistor. This is when voltage is at the transistor's saturated minimum and current flows. Losses during the non-conduction phase are typically insignificant, and should theoretically be zero. The Switching Loss measurement automatically measures losses over one switching cycle. But you can then optimize the scope's horizontal and vertical settings to perform more accurate power and energy loss measurements during particular switching phases.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Switching Loss** measurement.
4. Press the **Signals** softkey.
5. Connect the N2790A high-voltage differential probe between the scope's channel-1 input to the drain/collector (red lead) and source/emitter (black lead) of your switching transistor as illustrated in the on-screen connections diagram of Figure 15. If using Agilent's SMPS training kit, connect to **TP3** (red lead) and **TP4** (black lead).
6. Connect the current probe between the scope's channel-2 input to a wire-loop from the source/emitter trace. If using Agilent's SMPS training kit, connect the current probe to the **J2** current loop in the direction indicated. Note that before connecting the current probe to the current loop, this might be a good time to de-gauss the current probe.
7. Ensure that **Voltage** is assigned to **1** (channel-1), and **Current** to **2** (channel-2) within the **Signals** menu.
8. Press the **AutoSetup** softkey; then press **Apply**.

When **AutoSetup** is pressed, the scope will establish optimum vertical scaling on the voltage (yellow trace) and current (green trace) waveforms, sets the main timebase (upper display) to show two switching cycles, and sets the zoom timebase (lower display) to show one switching cycle.
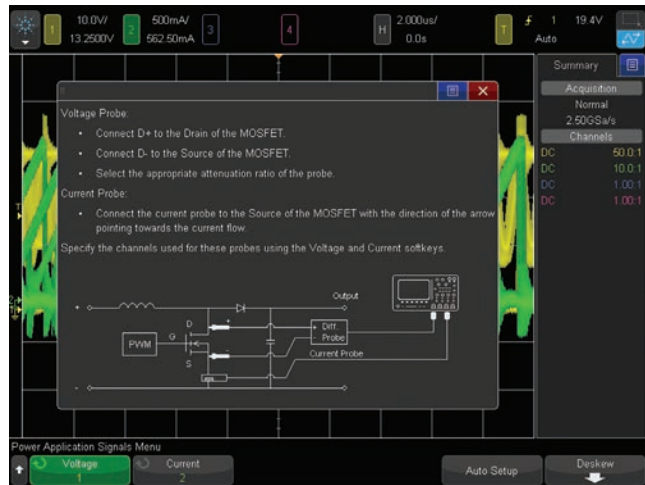

Figure 15: Connecting the voltage and current probes to the transistor switching device.
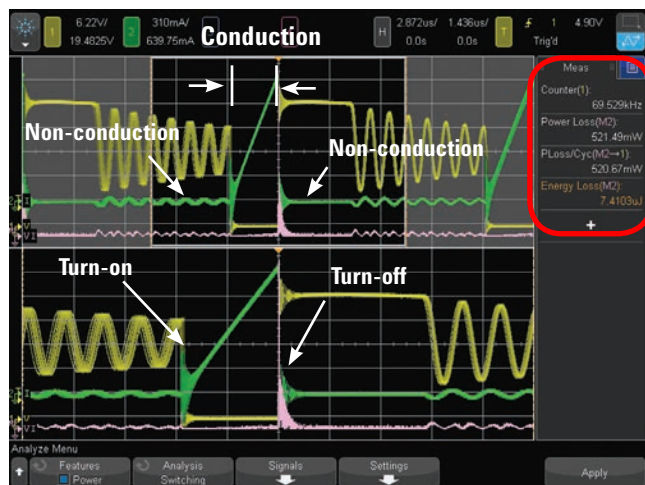

Figure 16: Power and Energy loss measurement over one switching cycle.

When **Apply** is pressed, the scope turns on a math function to show the power waveform (purple trace), and also measures the following parameters as shown in Figure 16:

- Switching Frequency (Counter measurement)
- Power Loss (average power across zoom window)
- Power Loss/cycle (same as power loss at initial setting)
- Energy Loss (integration of Power Loss)

9

Switching loss analysis

Oscilloscopes don't typically have sufficient dynamic range and resolution to perform accurate power and energy loss measurements during the conduction and non-conduction phases based on the voltage and current waveforms (Power = Voltage x Current). When amplitudes of the voltage and current waveform are near zero, a few tenths of a division of oscilloscope and/or probe offset error (even if they are within specification) can contribute to significant measurement error. Power and energy loss measurements can be performed more accurately if power is computed during the conduction phase using a entered and specified value of Rds(on) or Vce(sat). The scope will then compute and plot the power waveform based on the measured current waveform during just the conduction phase using the entered constant to compute power (Pwr = I^{2}Rds(on) or IxVce(sat)). Let's now setup the scope to perform a power and energy loss measurement over one switching cycle based on Rds(on).

9. Press the **Settings** softkey.
10. Press the **Conduction Waveform** softkey; then change from the **Voltage Waveform** setting to the **Rds(on)** setting.
11. Press the **Rds(on)** softkey; then enter an appropriate value of Rds(on) for your DUT. If using Agilent's SMPS training kit, enter **200 mΩ**.

Your scope's display should now look similar to Figure 17, and the power and energy loss measurements shown on the right-hand side of the display should be more accurate — assuming that the entered value of Rds(on) is correct for the device under test. Compare the results of this power and energy loss measurement over one switching cycle based on an entered value of Rds(on) to the measurement shown in Figure 16, which was based purely on the digitized values of the voltage and current waveforms.

When you select to make power and energy loss measurements based on **Rds(on)** or **Vce(sat)**, the scope uses the **V Ref** and **I Ref** settings (also set in the **Settings** menu) to determine to the appropriate method for computing the power waveform for each switching phase.

When the voltage waveform (yellow trace) is above the **V Ref** setting (default = 5%), the scope computes the power waveform as the product of the voltage and current waveforms (V x I). This typically only occurs during the transistor turn-on and turn-off phases. Note that you may
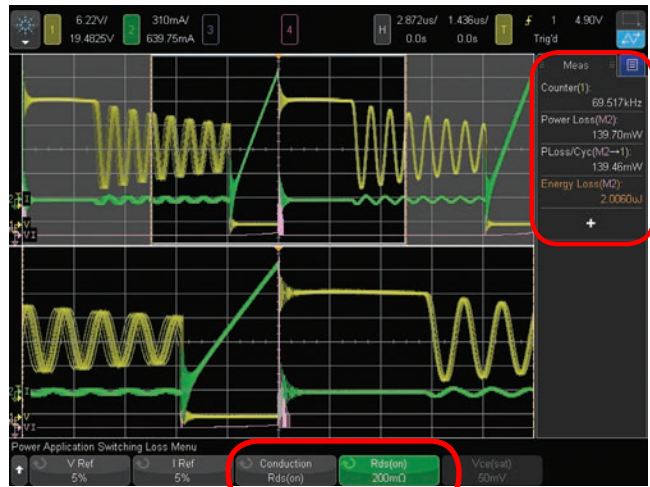

Figure 17: Measuring power and energy loss over one switching cycle based on an entered value of Rds(on).

observe a large power spike near center-screen (turn-off), and possibly a shorter power spike (turn-on) coincident with the voltage waveform when it drops to near zero volts. It is during these relatively short phases of the waveform that the scope computes the power based on the product of the instantaneous voltage and current waveforms.

When the voltage waveform is below the **V Ref** setting, the scope will compute the power waveform as either I^{2}Rds(on) or I x Vce(sat). This provides for a more accurate measure of losses during the conduction phase. We will zoom-in on this segment of the waveform next.

If the current waveform is below the **I Ref** setting (default = 5%), then the scope will compute the power waveform as V x 0 Amps, which will always be zero Watts. The scope uses this calculation method during the non-conduction phase of the switching waveforms when current drops to zero (theoretically).

Switching loss analysis

Fully characterizing and optimizing the efficiency of switching power supplies often requires that engineers isolate and measure power and energy losses during each switching phase individually. The accuracy of switching loss measurements over one switching cycle can also be improved if performed on each switching phase and then summed to determine to the total losses over one cycle. Doing this requires that you window-in on each phase while manually optimizing vertical and horizontal settings of the scope. Let's now perform a more accurate power and energy loss measurement when the transistor turns off; sometimes referred as the T_{OFF} phase. Using the scope's current setup, this occurs at approximately center-screen where you can see a spike in the power waveform (purple trace) of Figure 17.

12. Decrease the zoom timebase setting (larger horizontal knob) to zoom-in on the power waveform spike near center-screen.
13. Adjust the horizontal delay/position setting (smaller horizontal knob) to center the power spike within the lower zoom display as shown in Figure 18.

"Tuning" the zoom timebase and delay settings to window-in on just the turn-off power spike is an iterative process.

The **Power Loss** measurement is the average power over the short/zoomed-in time-span, and this measurement is somewhat meaningless. **Energy loss**, which is meaningful, is the integration of the power loss over the zoomed-in display. **Power Loss/cycle** is the portion of power lost relative to one complete switching cycle.

Note that some switching power supplies will also exhibit losses during the transistor turn-on phase (when voltage goes low and current begins to flow). If this is the case, then you will observe two power spikes in the main/upper timebase display. When using Agilent's SMPS training kit as the DUT, power and energy losses during the turn-on phase are relatively insignificant as evidenced by the lower amplitude power spike in the main timebase display shown in Figure 18. But if you observe a significant second power waveform spike, then you should also window-in on the second spike that may occur during the turn-on phase to measure losses during this phase as well.

Let's now measure the power and energy loss during the conduction phase (when the voltage/yellow waveform is at/near its minimum). The power and energy loss during the conduction phase will be based on the entered value of Rds(on).

Figure 18: Windowing-in on the power spike at center-screen to measure the power and energy loss during just the transistor's turn-off phase.
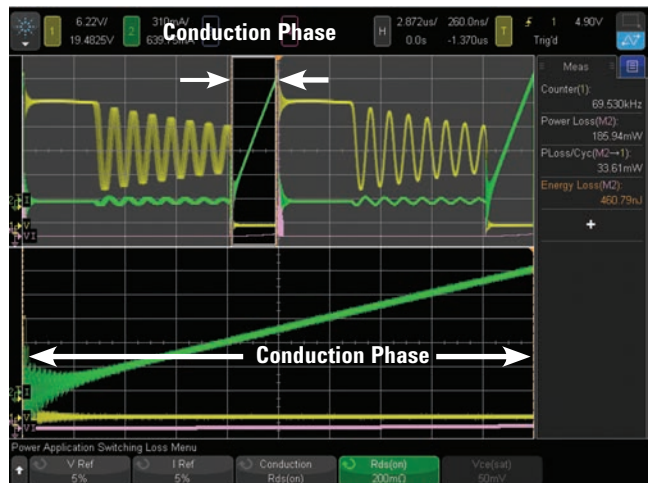

Figure 19: Adjusting the zoom timebase to window-in on the just the conduction phase.

14. If using Agilent's SMPS training kit, increase the zoom timebase setting to approximately 300 ns/div. Note that if you press the timebase knob (larger horizontal knob), you can toggle between coarse and fine adjust.
15. Adjust the horizontal delay/position setting (smaller horizontal knob) to window-in on the region of the waveform where the voltage waveform (yellow trace) is low.
16. Re-adjust the zoom timebase setting using "fine adjust" (push horizontal timebase knob to toggle between fine and coarse) until all power waveform spikes (purple trace) are off-screen to the left and right in the zoom/lower display.

Switching loss analysis

Note that you may also need to re-adjust the horizontal delay/position setting as well. This is an iterative process of adjusting sec/div and delay for the optimum zoom window settings. All power and energy loss measurements will be "gated" and performed within the zoom display only. Once you have properly set the zoom timebase (sec/div and horizontal delay/position) to window-in on just the conduction phase, you should see what appears to be a near flat-line power waveform (purple trace) near the bottom of the zoom/lower display as shown in Figure 19. To perform an accurate power and energy loss measurement on this waveform now requires that we vertically zoom-in on the power waveform (purple trace). But don't attempt to vertically zoom-in on the voltage waveform (yellow trace) to gain more resolution and accuracy. Vertically zooming in on the voltage waveform will drive the scope's vertical amplifier into saturation which can result in waveform distortion due to overdrive recovery.

17. Press the waveform math vertical position knob to approximately center the power waveform (purple trace). The waveform math position knob is the lower knob close to the **[Math]** key near the right-hand side of the scope's front panel.
18. Turn the waveform math vertical scaling knob (upper knob near the **[Math]** key) clock-wise to vertically expand the power waveform (purple trace).
19. Re-adjust the waveform math vertical position knob to again center the power waveform (purple trace) on-screen without clipping the power waveform on either the top or bottom as shown in Figure 20. Note that adjusting the waveform math vertical position and scaling knobs is an iterative process until you obtain optimum scaling without clipping within just the zoom/lower display.

Even though portions of the power waveform in the upper/main timebase display are clipped off-screen to the top, nothing is being overdriven. This is because the power waveform is a waveform math calculation based on the current waveform (green trace), which should not be clipped or overdriven, and the entered value of Rds(on). In addition, the power loss/cycle and energy loss measurements are based on just the calculated data within the zoom/lower display. In this particular measurement documented in this procedure, Agilent's SMPS training kit measured a power loss/cycle of approximately 35 mW and energy loss of approximately 500 nJ during the conduction phase. Referring back to Figure 18 when we measured losses during the turn-off phase, we measured a power loss/cycle of approximately
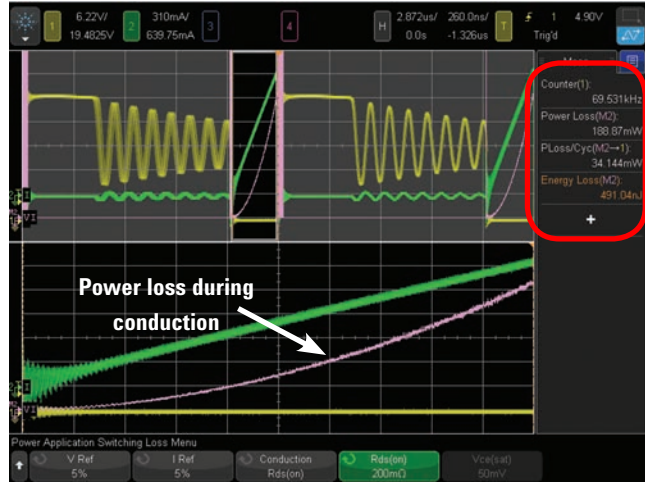

Figure 20: Windowing-in on the power waveform during the conduction phase.

65 mW and energy loss of approximately 930 nJ. Total losses for one switching cycle is the sum of the power loss/cycle and energy loss during the turn-off, turn-on (measured, but not shown) and the conduction phases which is summarized in the table below:

Phase	Pwr loss/cycle	Energy loss
Turn-on	2.6 mW	38 nJ
Turn-off	69 mW	997 nJ
Conduction	34 mW	491 nJ
Non-conduction	0 mW	0 nJ
Total Losses	**106 mW**	**1.53 µJ**

Now compare these summed and more accurately measured values of power loss/cycle and energy loss to the measured results when the scope was setup to measure total losses over one complete switching cycle (Figure 17).

Slew rate analysis

Slew rate analysis measures the rate of change of the voltage and/or current waveform when the switching transistor of your power supply switches on and off.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Slew Rate** measurement.
4. Press the **Signals** softkey; then connect the N2790A voltage probe between channel-1 of the scope to the drain/collector (red lead) and source/emitter (black lead) of your switching transistor as illustrated in the on-screen connections diagram of Figure 21. If using Agilent's SMPS training kit, connect to **TP3** (red lead) and **TP4** (black lead).
5. Connect the current probe to a wire-loop of the source/emitter trace. If using Agilent's SMPS training kit, connect the current probe to the **J2** current loop in the direction indicated.
6. Ensure that **Voltage** is set to **1** (channel-1), and **Current** is set to **2** (channel-2).
7. Press the **AutoSetup** softkey; then press **Apply**.

Your scope's display should now look similar to Figure 22. **AutoSetup** will optimally scale the voltage and current waveforms, sets the main timebase (upper display) to show one switching cycle across screen, and sets the zoom timebase (lower display) windowed-in on the turn-off phase of the switching voltage and current waveforms.

When **Apply** is pressed, the scope turns on the differentiate (dv/dt) math function (purple trace) based on the voltage waveform in order to dynamically plot the slew rate of the voltage waveform. **Apply** also turns on the **Max** and **Min** measurements in order to automatically measure the maximum and minimum slew rates of this waveform.

To measure the maximum and minimum slew rates of the current waveform, press the **Source** softkey and change the source setting from **Voltage** to **Current**.

To measure the slew rates of the voltage and current waveform during the transistor turn-on phase, adjust the horizontal delay/position knob until the zoom timebase is windowed-in on the turn-on phase (when voltage drops to near zero) as shown in Figure 23. Note that for a more stable display of the turn-on phase, you may want to leave the delay setting at zero, but then change the trigger edge from rising to falling. This will establish a more stable trigger during the turn-on phase with the zoom display centered on-screen.
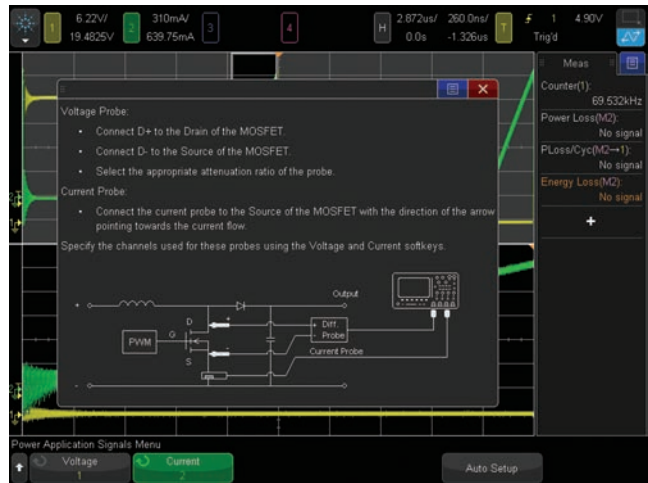

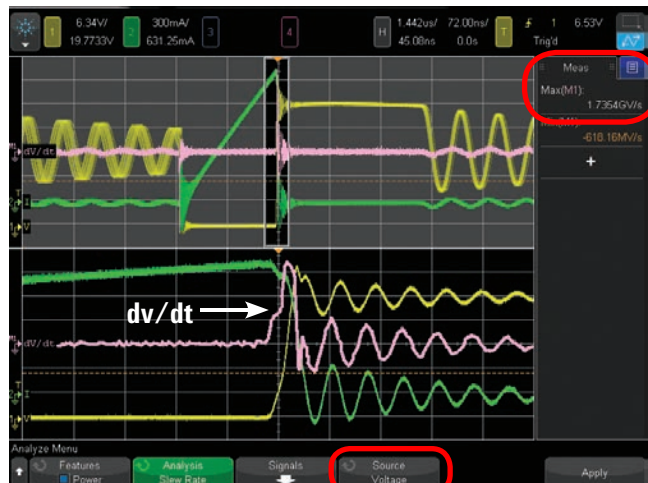*Figure 21: Slew Rate measurement connections diagram.*

Figure 22: Slew rate measurement of the voltage waveform during the transistor's turn-off phase.

Figure 23: Slew rate measurement of the current waveform during the transistor turn-on phase.

Modulation analysis

Modulation analysis is typically used to characterize the pulse-width modulation (PWM) feedback from the DC output to the switching transistor's gate terminal for dynamic voltage regulation. Unfortunately, this measurement cannot be demonstrated using Agilent's SMPS training kit since the FET's Gate terminal is not accessible for probing.

1. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
2. Press the **Analysis** softkey; then select the **Modulation** measurement.
3. Press the **Signals** softkey.
4. Connect the N2790A voltage probe between channel-1 of the scope to the gate/base (red lead) and source/emitter (black lead) of your switching transistor as illustrated in the on-screen connections diagram of Figure 24. Note that although the connection diagrams also shows a current probe connected to the drain, this probe connection is not necessary for this measurement.
5. Ensure that **Voltage** is set to **1** (channel-1).
6. Press the **AutoSetup** softkey; then press **Apply**.

When **AutoSetup** is pressed the scope optimally scales the voltage waveform (gate-to-source signal) and sets the timebase based on the user-defined **Duration** setting.

When **Apply** is pressed, the scope turns on the **Measurement Trend** waveform math function (purple trace) based on sequential **Duty Cycle** measurements of the Gate-to-Source signal (yellow trace) across the scope's display as shown in Figure 25. This is basically a plot of duty cycle on the vertical axis and time on the horizontal axis.

In this example, we have rescaled the timebase to 200 µs/div (2 ms duration) in order to optimally observe duty cycle modulation of the gate signal. The duty cycle of this switching device's gate signal appears to be modulating at a 1 kHz rate with a maximum measured duty cycle of approximately 15% and minimum measured duty cycle of approximately 13%.

The **Modulation** measurement can also be very useful for characterizing turn-on characteristics of your switching power supply. Figure 26 shows an example of a single-shot measurement of the frequency of the switching transistor's Gate signal when power is initially applied. In this case we have changed the measurement **Type** from **Duty Cycle** to **Frequency**, and then manually set up the scope to perform a single-shot acquisition. In this example we can observe the amplitude of the gate-to-source signal (yellow trace) ramp up to its steady-state condition in approximately 1.8 ms. And the **Measurement Trend** waveform (purple trace), which is based on sequential frequency measurements of the Gate signal across the display, shows that the transistor quickly ramps up to a steady-state switching frequency of 69 kHz in 600 µs.
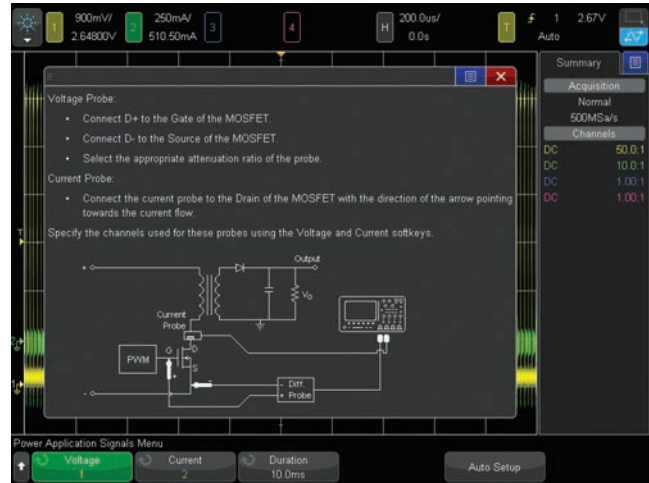

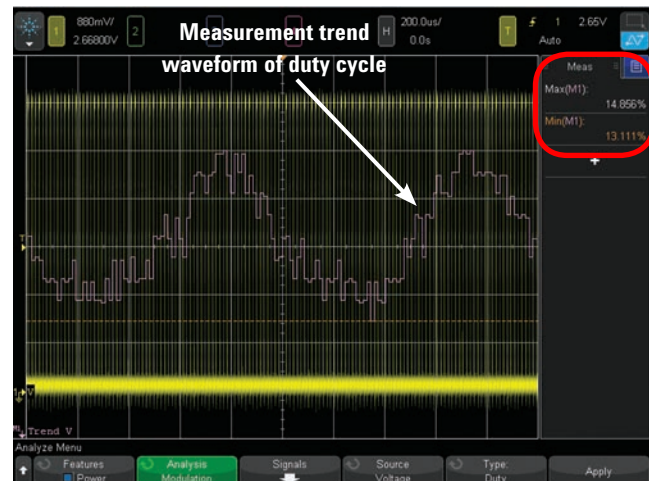*Figure 24: Modulation measurement connections diagram.*

Figure 25: Modulation measurement of Duty Cycle on the switching transistor's Gate input.
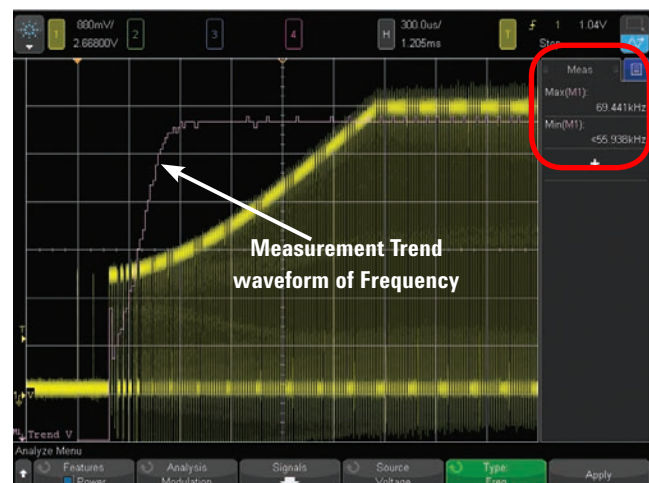

Figure 26: Modulation measurement of Frequency on the switching transistor's Gate input during power-up.

Output ripple analysis

Output ripple analysis measures the peak-to-peak extremes of the output DC signal of your power supply. It also measures AC-RMS of the output DC signal. The AC-RMS measurement is the same as Standard Deviation (σ), which is a commonly-used measurement to characterize random noise. Output Ripple is typically dominated by switching noise, but can also include other random noise and signal coupling from various sources in your system. This measurement basically measures the quality of the power supply's voltage regulation and filtering to reject switching noise, as well as other noise/interference sources.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Output Ripple** measurement.
4. Press the **Signals** softkey
5. Connect a standard 10:1 passive voltage probe between the scope's channel-3 input to the DC output signal and ground as illustrated in the on-screen connections diagram shown in Figure 27. If using Agilent's SMPS training kit, connect the 10:1 passive probe from channel-3 to **TP5** (probe tip grabber) and **TP6** (ground).
6. Press the **Voltage** softkey; then change setting to **3** (measured source will be channel-3).
7. Press the **AutoSetup** softkey; then press **Apply**.

Your scope's display should now look similar to Figure 28. When **AutoSetup** is pressed the scope AC couples the input signal on the selected channel to eliminate the DC component, and then optimally scales the selected input channel's vertical setting to display just the output ripple of the DC output signal.

When **Apply** is pressed, the scope measures the output ripple of the DC output signal in terms of peak-to-peak voltage, as well as AC-RMS (σ).

Note that for a well-regulated power supply that generates a very low level of output ripple, a 1:1 passive probe such as Agilent's N2870A or 100070D, may be required for this measurement.
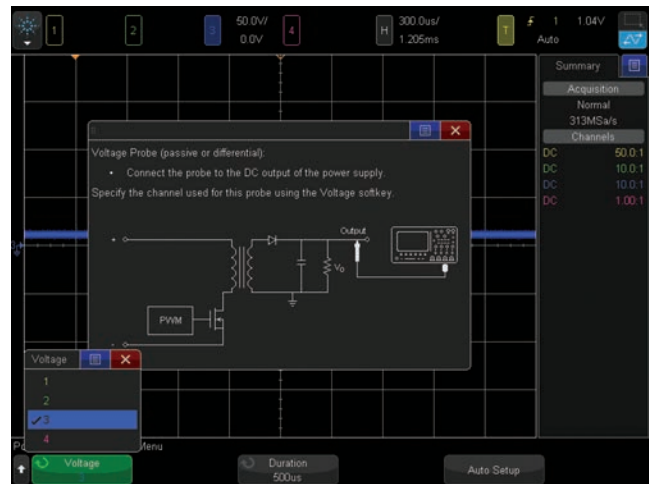

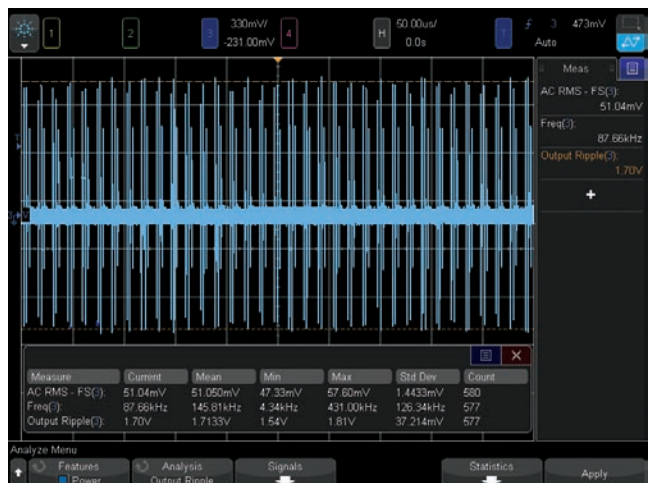*Figure 27: Output Ripple measurement connections diagram.*

Figure 28: Output Ripple measurement on the DC output signal.

Turn on/turn off analysis

Turn-on analysis measures the time from when power is initially switched on until the dc output reaches 90% of its expected steady-state level. Turn-off analysis measures the time from when power is switched off until the DC output decays to 10% of the steady-state on level.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Turn On/ Turn Off** measurement.
4. Press the **Signals** softkey.
5. Connect the N2790A differential active probe between the scope's channel-1 input to Line (red lead) and Neutral (black lead) as illustrated in the on-screen connections diagram shown in Figure 29. If using Agilent's power training kit, connect to **TP2** (red lead) and **TP1** (black lead).
6. Connect a standard 10:1 passive voltage probe between the scope's channel-3 input to the DC output of your DUT. If using Agilent's SMPS training kit, connect to **TP5** (probe tip grabber) and **TP6** (ground).
7. Press the **Input V** softkey; then set to **1** (channel-1).
8. Press the **Output V** softkey; then set to **3** (channel-3).

Note that the default settings for **Duration, Max Vin**, and **Steady Vout** have been optimized for Agilent's SMPS training kit. If testing a different power supply, then enter the appropriate values for **Max Vin** (peak-to-peak) and **Steady Vout**. Also, you may want to begin your test with the default **Duration** setting of **500 ms**, which will determine the scope's timebase setting for this measurement.

9. Press the **[Back]** front panel key to return to the previous menu.
10. Press the **Apply** softkey to begin the test; then follow on-screen instructions, which are repeated below.
11. Turn **OFF** power; then press **Next**.
12. Turn **ON** power; then press **Next**.

If the turn-on time of your device under test is less than 400 ms, then your scope's display should look similar to Figure 30. If the initial **Duration** setting is too low, then the measurement cannot be performed. If this is the case, then set the **Duration** time to a higher value as indicated by the on-screen message; then try again. Alternatively, to improve the timing resolution of this measurement you may want to set the Duration time to a lower value. After determining the best Duration time for this measurement, repeat the test several times to determine best- and worst-case turn-on time. Figure 31 shows this same test with the Duration time set to **50 ms**.
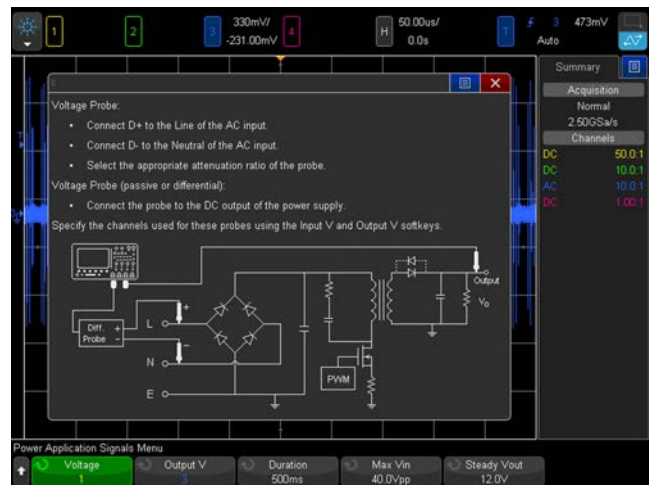

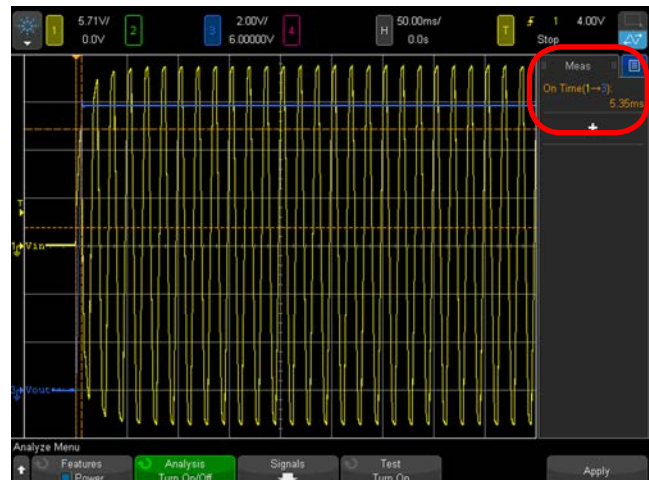*Figure 29: Turn-on/Turn-off connections diagram in the Signals menu.*

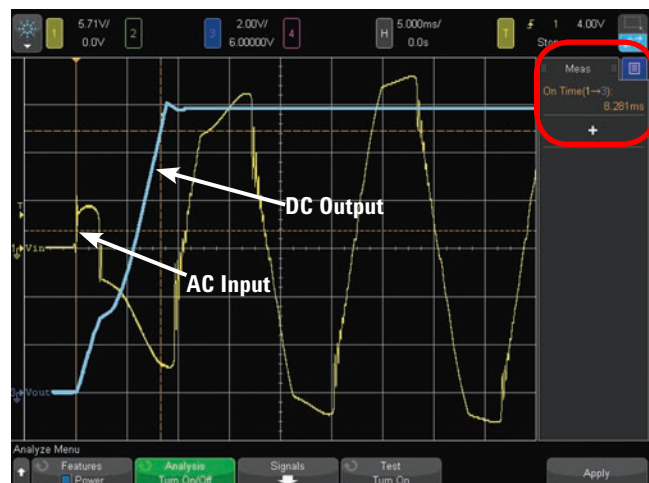*Figure 30: Turn-on test using a default Duration time setting of 500 ms.*

Figure 31: Turn-on time test using a Duration time setting of 50 ms to improve measurement resolution and accuracy.

Turn on/turn off analysis

Let's now perform a turn-off time measurement.

13. Continuing from the previous **Turn On** time measurement, press the **Test** softkey; then change from **Turn On** to **Turn Off.**

14. Press the **Signals** softkey; then note the default settings of **Duration**, **Max Vin**, and **Steady V**$_{out}$. These setting have been optimized for Agilent's SMPS training kit used in this demo procedure. If testing a different power supply, **Max V**$_{in}$ and **Steady V**$_{out}$ should already be set to the correct values based on the previous **Turn On** test. But the default **Duration** time setting of 1.00 second may not be a valid setting for your power supply.

15. Press the **[Back]** front panel key to return to the previous menu; then press the **Apply** softkey and follow the step-by-step on-screen instructions, which are repeated below.

16. Turn **ON** power; then press **Next.**

17. Turn **OFF** power; then press **Next**.

Your scope's display should now look similar to Figure 32. Repeat this measurement several times to determine the best- and worst-case turn-off times. Note that you may need to adjust the **Duration** time setting for this test.

If using Agilent's SMPS training kit for this measurement, try setting the **S2** switch to the **OFF** position (low-load, minimum current) and then repeat the **Turn Off** time measurement. You will probably need to increase the Duration time to 2.0 seconds with the **S2** load switch in the **OFF** position. With a decreased output load, the output will decay more slowly when power is turned off.
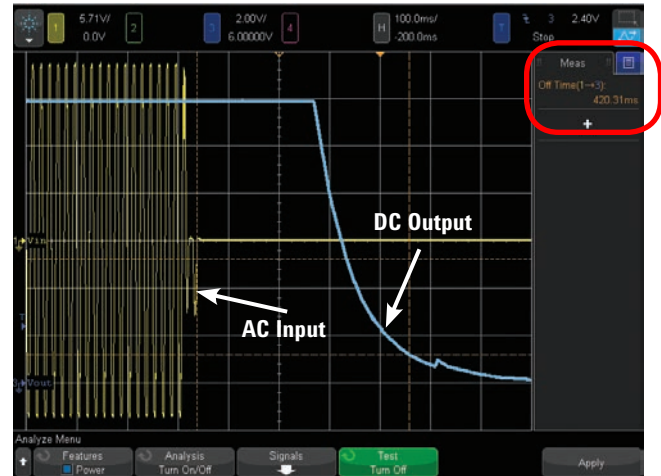

Figure 32: Turn-off time test.

Transient response analysis

Transient response analysis measures the time for the output DC voltage to settle within a user-set percentage of the expected output level after a sudden change in output load (increase or decrease in output current). Before setting up this measurement, you must first determine what the approximate output current levels are for various load conditions.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **OFF** position (low-load, minimum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Transient Response** measurement.
4. Press the **Signals** softkey.
5. Connect the current probe between the scope's channel-2 input to the output current signal on your device under test as illustrated in the on-screen connections diagram shown in Figure 33. If using Agilent's SMPS training kit, connect to the **J3** current loop in the direction indicated on the demo board. Note that the current-direction arrow on the current probe should be facing down towards your bench.
6. Connect a standard 10:1 passive voltage probe between the scope's channel-3 input to the output DC voltage signal. If using Agilent's power demo board, connect to **TP5** (probe tip grabber) and **TP6** (ground).
7. Press the **Voltage** softkey; then select **3** (channel-3).
8. Press the **Current** softkey; then select **2** (channel-2).
9. Set the **Steady V**$_{out}$ for your DUT. If using Agilent's SMPS training kit, the default level of 12.0 V is appropriate.
10. Press the **[Back]** front panel to return to the previous menu.
11. Press the **Settings** softkey; then set **Initial I** to the approximate low-load output current level (assuming that the **S2** load switch is in the **OFF** position (low-load/low current). Also set the **New I** to the approximate high-load output current level. If using Agilent's SMPS training kit, you can use the default settings of **60 mA** and **215 mA** respectively.
12. Press the **[Back]** front panel key to return to the previous menu.
13. Press the **Apply** softkey; then follow the on-screen step-by-step instructions, which are repeated below.
14. Increase the output load (higher current). If using Agilent's SMPS training kit, move the **S2** load switch to the **ON** position (away from the J3 current loop).
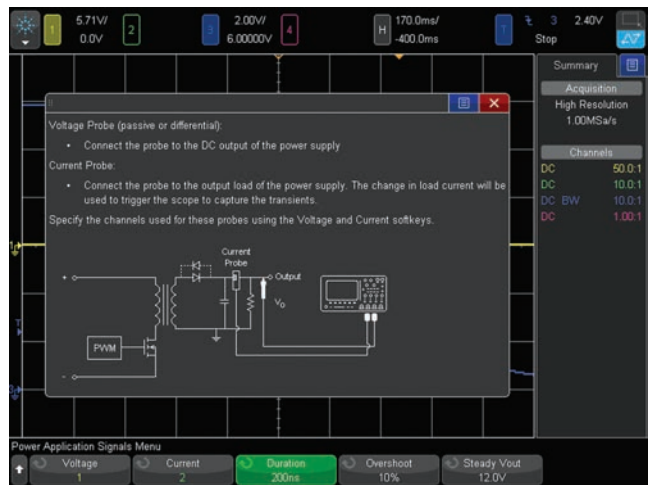15. Press **Next.**

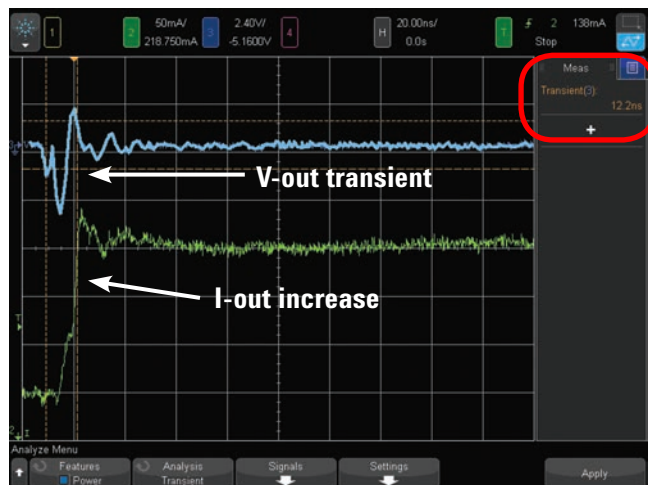*Figure 33: Transient Response connections diagram in the Signals menu.*

Figure 34: Transient Response settling time measurement when output load increases (output current suddenly increases).

Your scope's display should now look similar to Figure 34. When output current measured by the channel-2 current probe (green trace) suddenly increases, output voltage (blue trace) momentarily drops and then settles back to within 10% of the expected output voltage level in approximately 12 ns.

Transient response analysis

Let's now perform this Transient Response settling time measurement for when the output load decreases (lower output current).

16. If using Agilent's SMPS training kit, make sure that the **S2** load switch is now in the **ON** position (away from the **J3** current loop). This will put the training kit into an initial high-load (high output current) condition.
17. Press the **Settings** softkey; if using Agilent's SMPS training kit, then set **Initial I** to approximately **200 mA**, and **New I** to approximately **60 mA**. If making transient response measurements on your own power supply, then set to appropriate values.
18. Press the **[Back]** front panel key to return to the previous menu.
19. Press the **Apply** softkey; then follow the on-screen step-by-step instructions, which are repeated below.
20. Decrease the output load (lower current). If using Agilent's SMPS training kit, move the **S2** load switch to the **OFF** position (towards the **J3** current loop).
21. Press **Next**.

Your scope's display should now look similar to Figure 35. When output current (green trace) suddenly drops, output voltage (blue trace) momentarily increases and then settles to within 10% of the expected output voltage level in approximately 21 ns.

Note the Transient Response settling time measurement for both increasing and decreasing load conditions should be repeated several times in order to characterize best- and worst-case settling times.
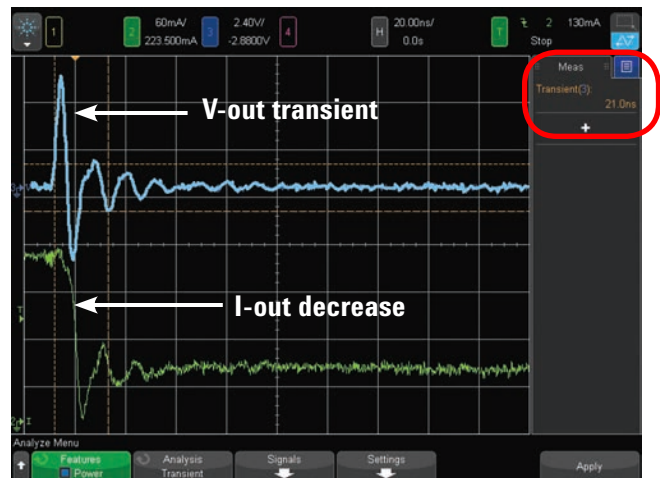

Figure 35: Transient Response settling time measurement when output load decreases (output current suddenly decreases).

PSRR analysis

Power Supply Rejection Ratio (PSRR) analysis, sometimes referred to as Power Supply Ripple Rejection, measures a voltage regulator's ability to reject coupling at various swept frequencies. This analysis is often performed on low drop-out (LDO) regulators using a network analyzer. Although a scope's dynamic range for this measurement is limited to approximately 50 dB, this measurement can be performed automatically with Agilent's InfiniiVision X-Series oscilloscope using the scope's built-in waveform generator.

To perform this measurement you must connect the output of the scope's WaveGen (Gen Out 1 only on the 4000 or 6000 X-Series) to the LDO's DC input via a summing network. If you directly connect the WaveGen output to the input of the LDO without a summing network, the input DC source of the device-under-test will appear as a low impedance load to the scope's WaveGen, and the WaveGen's source impedance of 50-Ω can also excessively load the DUT's input DC source. If an off-the-shelf network analysis summing network is not available, a simple summing network that you can construct might consist of an inductor in series with the input DC source and a capacitor in series with the WaveGen's output. But you must take into account the reactance of these components in relationship to the required band of frequencies that must be tested.

PSRR is logarithmically plotted versus frequency as 20Log(Vi/Vo), which is the inverse of a standard Bode plot. Although a standard 10:1 passive voltage probe is typically used to measure V-in, because of the limited dynamic of an oscilloscope, a 1:1 passive voltage probe such as Agilent's N2870A or 10070D is recommended for measuring V-out.
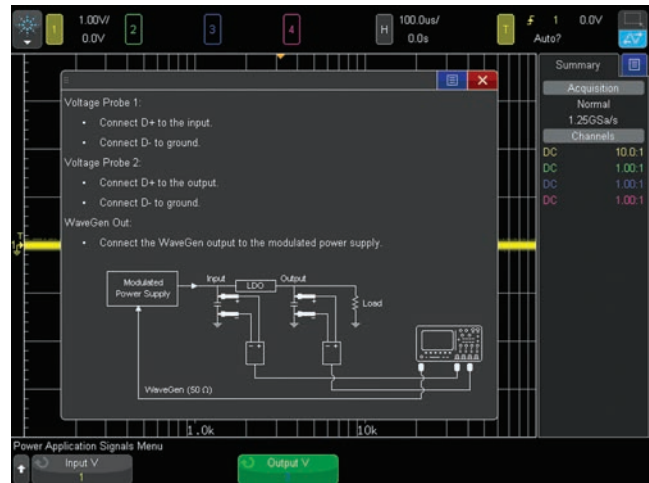

Figure 36: PSRR connections diagram in the Signals menu.

Note that this measurement cannot be demonstrated using Agilent's SMPS training kit.

1. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
2. Press the **Analysis** softkey; then select the **Power Supply Rejection Ratio (PRSSR)** measurement.
3. Press the **Signals** softkey.
4. Connect the WaveGen's output (Gen Out 1 only if using an Agilent 4000 X-Series scope) to the DC input source of the DUT via a summing network as illustrated in the on-screen connections diagram shown in Figure 36.
5. Connect a standard 10:1 passive voltage probe from the scope' channel-1 input to the DC input of the DUT.
6. Connect a 1:1 passive voltage probe from the scope's channel-3 input to the DC output of the DUT.
7. Ensure that **Input V** is set to **1** (channel-1), and **Output V** is set to **3** (channel-3).
8. Press the **[Back]** front panel key to return to the previous menu.
9. Press the **Settings** softkey.
10. Set the desired **Minimum** and **Maximum** frequencies to test.
11. Set the **Max Ratio** for plotting of the measured results.
12. Set the output **Amplitude** of the sine wave that will be summed into the DUT's input. A typical setting is 500 mVpp to 1.0 Vpp.
13. Press the **[Back]** front panel key to return to the previous menu.
14. Press the **Apply** softkey to begin the measurement.

PSRR analysis

Figure 37 shows the results a PSRR measurement after the swept test has completed. In this example we tested from 100 Hz to 20 MHz using a 1.0 Vpp input sine wave. The yellow and blue sine waves are the input and output waveforms at the last tested frequency (20 MHz). The purple trace is the PSRR plotted in dB. After the measurement has completed, you can use the scope's tracking markers to measure the amount of rejection at various frequencies. In this test, we measure approximately 50 dB of rejection at the lower frequencies, and approximately 8.4 dB of rejection at the maximum frequency of the test (20 MHz).
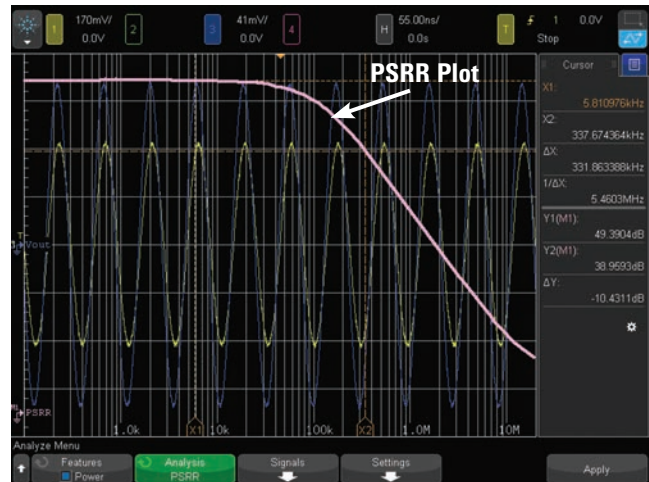
Figure 37: Power Supply Rejection Ratio (PSSR) measurement using the scope's built-in waveform generator as an automatic swept source.

Efficiency analysis

Efficiency analysis measures the input real power and output power in order to compute the efficiency of your power supply (Efficiency = Pwr(out)/Pwr(in) x 100). Performing this measurement requires three active probes that require power (high-voltage differential active probe plus two active current probes). If two current probes are not available, then this measurement can be performed in a 2-step process: measure Input Power, measure Output Power, then compute efficiency. But let's first show how to perform this measurement using two current probes in just one step.

1. If using Agilent's SMPS training kit, set the **S2** load switch to the **ON** position (high-load, maximum current).
2. Press the **[Analyze]** front panel key; then select the **Power Application** under the **Features** softkey.
3. Press the **Analysis** softkey; then select the **Efficiency** measurement.
4. Press the **Signals** softkey; then scroll to the bottom of the connections diagram.
5. Connect the N2790A high-voltage differential active probe between the scope's channel-1 input to Line (red lead) and Neutral (black lead) as illustrated in the on-screen connections diagram shown in Figure 38. If using Agilent's SMPS training kit, connect to **TP2** (red lead) and **TP1** (black lead).
6. Connect a current probe between the scope's channel-2 input to the input Line current loop. If using Agilent's SMPS training kit, connect to the **J1** current loop in the direction indicated.
7. Connect a standard 10:1 passive voltage probe between the scope's channel-3 input to the DC output signal. If using Agilent's power demo board, connect to **TP5** (probe tip grabber) and **TP6** (ground).
8. If using an Agilent 4000 and 6000 X-Series oscilloscope, connect another current probe between the scope's channel-4 input to the output DC current loop. If using Agilent's SMPS training kit, connect to the **J3** current loop in the direction indicated. If using an Agilent 3000 X-Series oscilloscope, you must use a second current probe that receives power from an external source since this scope can only power two active probes.
9. Press the **Input V** softkey; then set to **1** (channel-1).
10. Press the **Input I** softkey; then set to **2** (channel-2).
11. Press the **Output V** softkey; then set to **3** (channel-3).
12. Press the **Output I** softkey; then set to **4** (channel-4).
13. Press the **AutoSetup** softkey; then press **Apply.**

Your scope's display should now look similar to Figure 39. Agilent's SMPS training kit power supply measured an approximate efficiency of just 76% in this example.
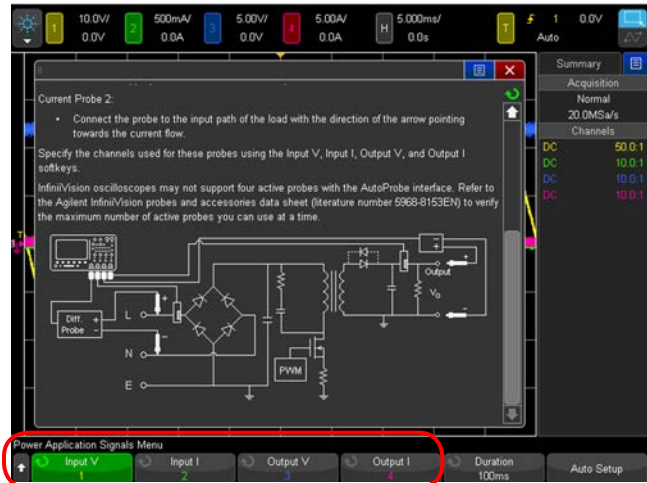

Figure 38: Efficiency measurement connections diagram in the Signals menu.

Figure 39: Power Efficiency measurement results. .

Efficiency analysis

If two current probes are not available for this measurement, then follow the above procedure to measure the Input Power with your current probe connected between channel-2 and the input current loop. Connect nothing to the scope's channel-4 input. After performing the above procedure, take note of the **Input Power** results, but ignore the **Output Power** and **Efficiency** measurements.

Next, move the current probe that is connected to the scope's channel-2 input to channel-4. Then connect it to the output DC current loop (**J3** if using Agilent's SMPS training kit). Manually reposition and rescale channel-3 (V out) and channel-4 until both DC traces can be observed on-screen. Now take note of the **Output Power** results. Efficiency = Pwr-out/Pwr-in x 100%.

Related literature

Publication title	Publication type	Publication number
InfiniiVision 6000 X-Series Oscilloscopes	Data sheet	5991-4087EN
InfiniiVision 4000 X-Series Oscilloscopes	Data sheet	5991-1103EN
InfiniiVision 3000 X-Series Oscilloscopes	Data sheet	5990-6619EN
DSOX3PWR/DSPX4PWR/DSOX6PWR Power Measurements Option	Data sheet	5990-8869EN
InfiniiVision Oscilloscope Probes & Accessories	Data sheet	5968-8153EN
N2790A 100-MHz, N2791A 25-MHz, N2891A 70-MHz Differential Active Probes	Data sheet	5990-3780EN
N2870A Series Passive Probes and Accessories	Data sheet	5990-3930EN

To download these documents, insert the publication number in the URL:
http://cp.literature.agilent.com/litweb/pdf/xxxx-xxxxEN.pdf

Product web site
For the most up-to-date and complete application and product information, please visit our product Web site at:
www.agilent.com/find/InfiniiVision

Agilent Technologies Oscilloscopes

Multiple form factors from 20 MHz to > 90 GHz | Industry leading specs | Powerful applications

myAgilent

www.agilent.com/find/myagilent
A personalized view into the information most relevant to you.

www.axiestandard.org

AdvancedTCA® Extensions for Instrumentation and Test (AXIe) is an open standard that extends the AdvancedTCA for general purpose and semiconductor test. Agilent is a founding member of the AXIe consortium.

www.lxistandard.org

LAN eXtensions for Instruments puts the power of Ethernet and the Web inside your test systems. Agilent is a founding member of the LXI consortium.

www.pxisa.org

PCI eXtensions for Instrumentation (PXI) modular instrumentation delivers a rugged, PC-based high-performance measurement and automation system.

Three-Year Warranty

www.agilent.com/find/ThreeYearWarranty
Beyond product specification, changing the ownership experience. Agilent is the only test and measurement company that offers three-year warranty on all instruments, worldwide.

Agilent Assurance Plans

www.agilent.com/find/AssurancePlans
Five years of protection and no budgetary surprises to ensure your instruments are operating to specifications and you can continually rely on accurate measurements.

www.agilent.com/quality

Agilent Electronic Measurement Group
DEKRA Certified ISO 9001:2008
Quality Management System

Agilent Channel Partners

www.agilent.com/find/channelpartners
Get the best of both worlds: Agilent's measurement expertise and product breadth, combined with channel partner convenience.

Agilent Technologies