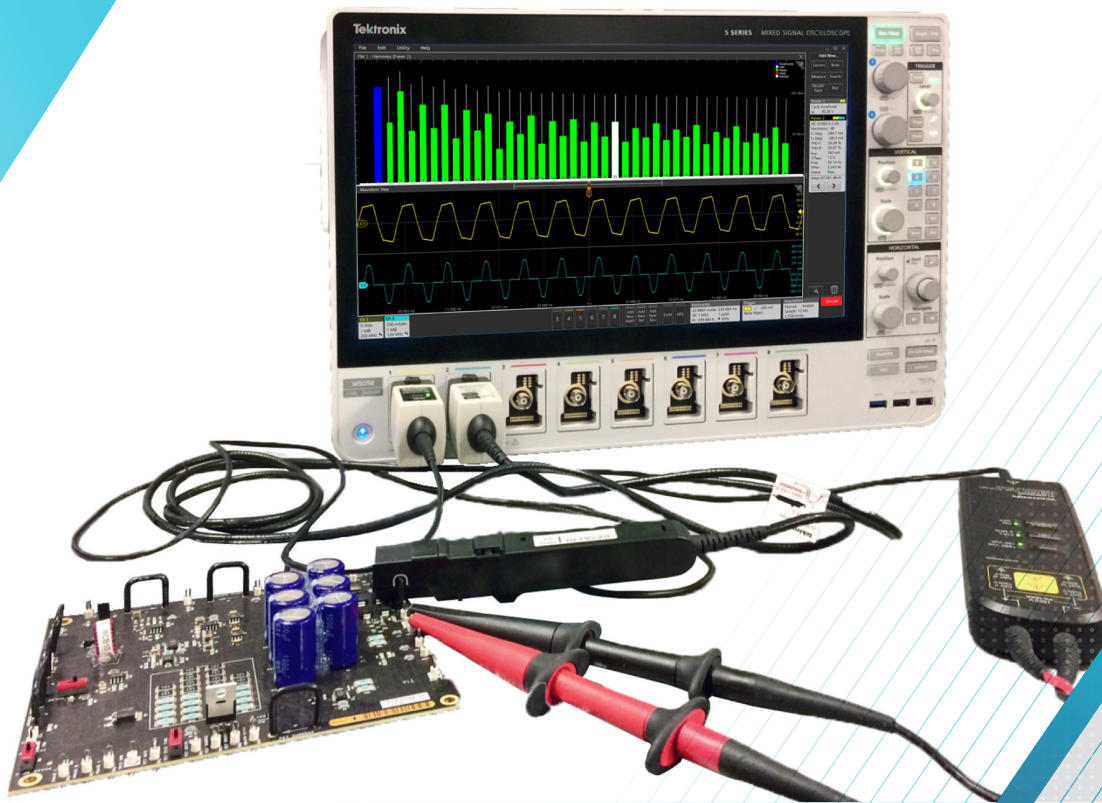


# Power Supply Measurement and Analysis with 5-PWR Application Software

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## APPLICATION NOTE



## Introduction

Today's power supply designers are faced with increasing pressure to achieve power conversion efficiencies of 90% and even higher. This trend is driven by demand for longer battery life in portable electronics, the Internet of things and demand for "greener" products that consume less power. Many designs are replacing silicon FETs and IGBTs with GaN or SiC switching devices. As always, the pressure of time to market continues to push faster (but still accurate) testing.

The MSO 5 Series with its FlexChannel® inputs and innovative graphical user interface enables designers to test multiple test points at one go, thereby speeding up testing. The Advanced Power Measurement and Analysis option (5-PWR) automates the setup process for key power measurements and provides tools to evaluate test results based on norms and standards in power supply design.

This application note gives an overview of how to make important power supply measurements using a Tektronix 5 Series MSO oscilloscopes with 5-PWR power analysis software.

## Preparing for Power Supply Measurements

In order to make accurate measurements, the power measurement system must be setup correctly to precisely capture waveforms for analysis and troubleshooting. Important topics to consider are:

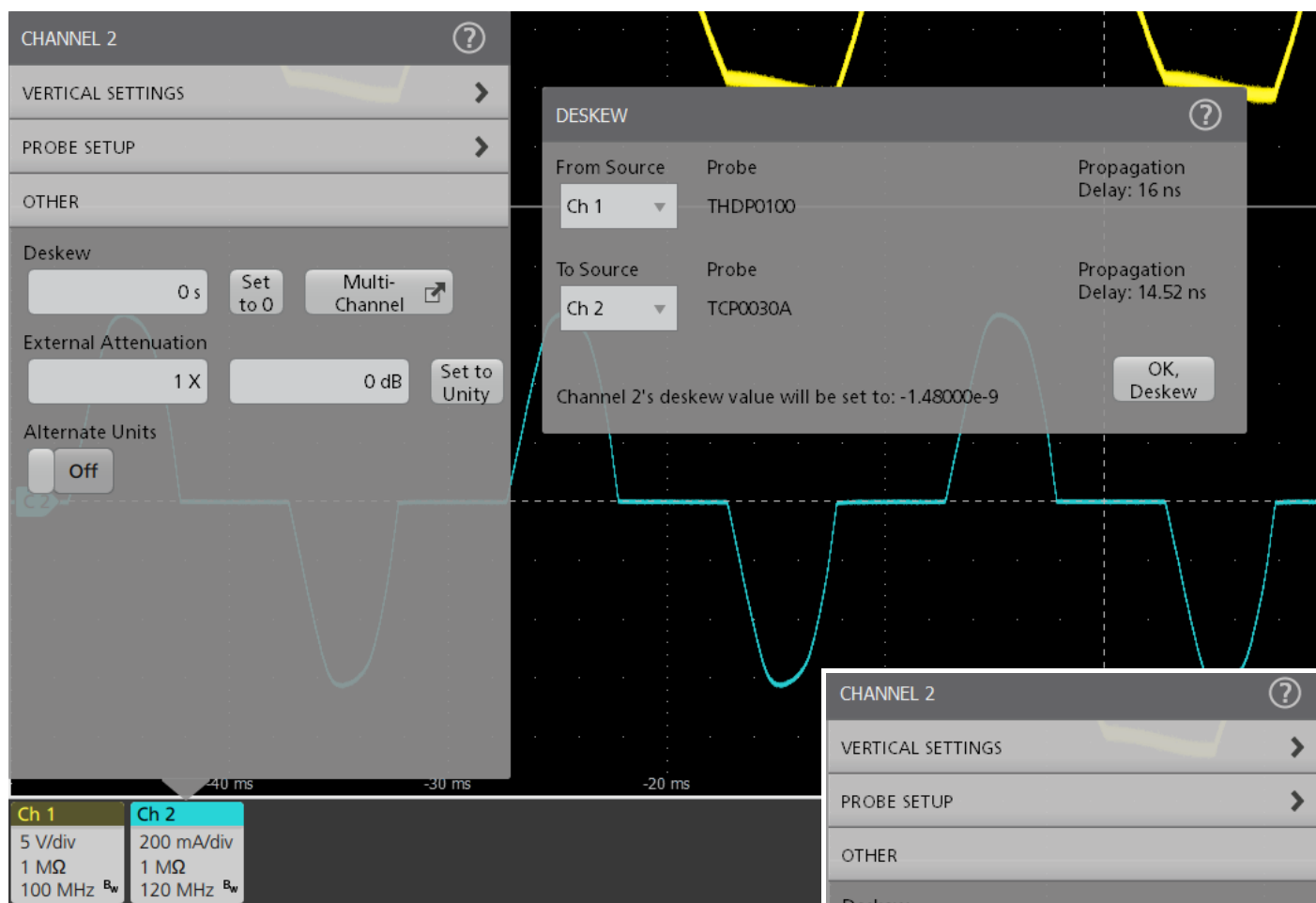
- Eliminating skew between voltage and current probes
- Eliminating probe offset
- Degaussing your current probe

### ELIMINATING SKEW BETWEEN VOLTAGE AND CURRENT PROBES

To make power measurements with an oscilloscope, it is necessary to measure voltage across and current through the device under test. This task requires two separate probes: a voltage probe (often a high voltage differential probe) and a current probe. Each voltage and current probe has its own characteristic propagation delay and the edges produced in these waveforms will probably not be aligned. The difference in the delays between the current probe and the voltage probe, known as skew, causes inaccurate amplitude and timing measurements.

Since skew creates a timing delay, it can cause inaccurate measurements of timing differences, phase, and power factor. Many measurement systems can "auto-calibrate" for delays internal to the instrument, but when you add probes to your system you must compensate for differences in probe amplifiers and cable lengths.

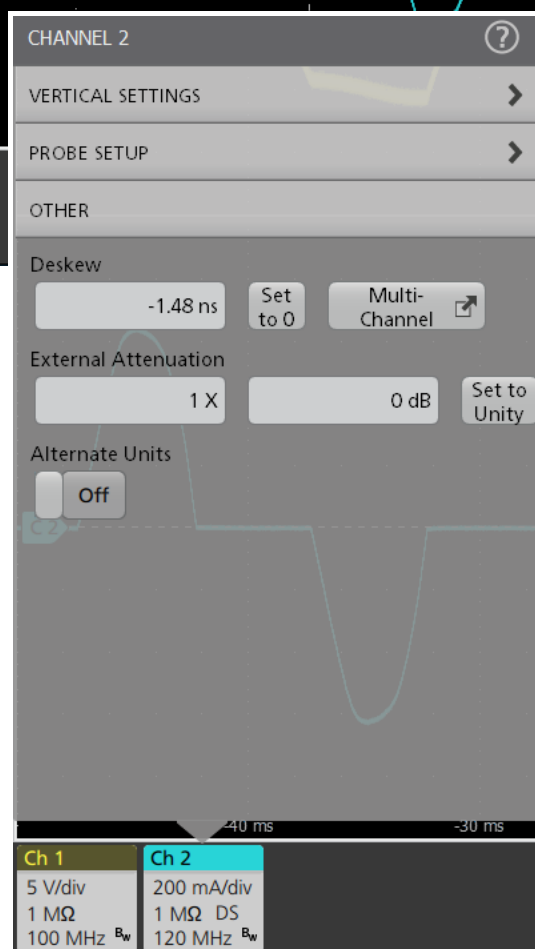
The Tektronix 5 Series MSO allows you to compensate for the delays from your probe tips to the measurement system to ensure you make the most accurate timing measurements. You can manually deskew the probes by connecting your probes to the same waveform source, and adding delay to the signal path of the faster signal. This allows the signals to be aligned in time without having to physically add cable length to the shorter probe cable.



**FIGURE 1.** Static skew compensation between a differential voltage probe and current probe BEFORE Adjustment. These probes have onboard memory that stores their nominal propagation delays.

The 5 Series MSO also provides a one-button "static" deskew feature. Figure 1 shows an example of skew between two TekVPI® power probes. The oscilloscope reads the nominal propagation delays from the probes and calculates that there is a difference of about 1.48 ns of delay between the two probes. Simply pressing the OK, Deskew button adjusts the relative timing between the signals.

Figure 2 shows the same test setup used in Figure 1 after the static deskew function has been run. If non-Tektronix probes are used, you will need to manually deskew the voltage and current waveforms, and configure the current probe settings.



**FIGURE 2.** Static skew compensation AFTER Adjustment. Note that -1.48 ns of deskew has been added, based on the propagation delays stored in the probes.

## ELIMINATING PROBE OFFSETS

Differential probes may have a slight voltage offset. This offset can affect accuracy and should be removed before proceeding with measurements. Most differential voltage probes have built-in DC offset adjustment controls, which makes offset removal a relatively simple procedure.

Similarly, it may be necessary to adjust offset on current probes before making measurements. Current probe offset adjustments are made by nulling the DC voltage to a mean value of 0 amperes or as close as possible. TekVPI probes, such as the TCP0030A AC/DC current probe, have an automatic Degauss/AutoZero procedure built in that's as simple as pressing a button on the probe compensation box, as shown in Figure 3.

## DEGAUSSING YOUR CURRENT PROBE

A current probe should also include an easy to use degaussing feature. Degaussing removes any residual DC flux in the core of the transformer, which may be caused by a large amount of input current. This residual flux results in an offset error that should be removed to increase the accuracy of the measurements being made.

Tektronix TekVPI current probes offer a degauss warning indicator that alerts the user to perform a degauss operation. A degauss warning indicator is important since current probes may have significant drift over time, which can significantly affect measurements.

## Addressing wide bandgap testing challenges

Until recently, switching measurements on the high side of half-bridge switching stages were almost impossible. Any measurement relative to the switching node, including high-side  $V_{DS}$  and voltages across current shunts, suffered from distortion due to the significant common mode voltage signal impinging on the differential signal. This problem is worse with wide bandgap devices, such as GaN and SiC transistors, as switching frequencies increase and the need to optimize brand new designs becomes imperative. The unmatched common mode rejection of IsoVu probes and the automation of Advanced Power Measurement and Analysis make an unbeatable combination for optimizing the latest GaN and SiC designs.



FIGURE 3. Tektronix TCP0030A AC/DC Current Probe with Degauss/AutoZero.

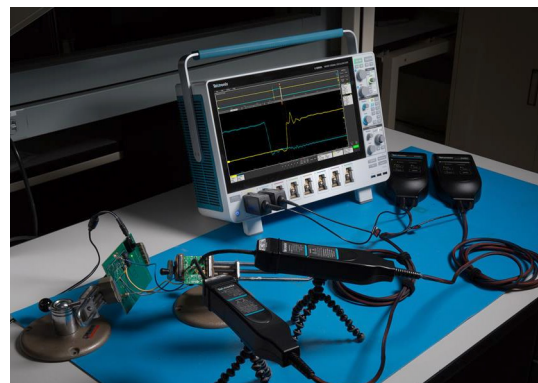
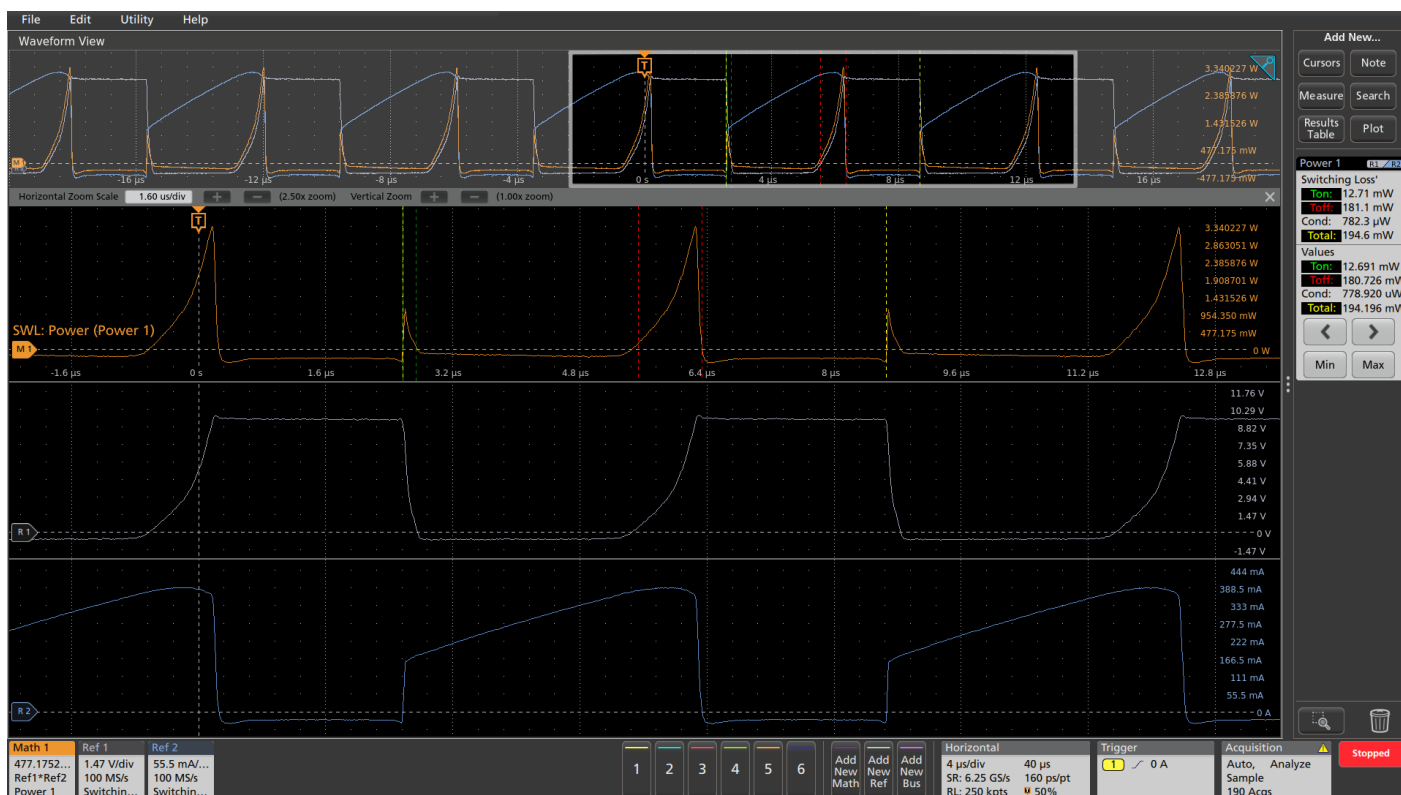


FIGURE 4. Many power supply topologies require measurements of small differential voltage in the presence of high common mode signals. For example,  $V_{GS}$  and  $V_{DS}$  on the high side of a half-bridge switching stage often move up and down 100s or 1000s of volts relative to ground. IsoVu™ Isolated Measurement Systems can be used with the 5 Series MSO and offer extremely high common mode rejection.



**FIGURE 5.** Switching Loss Measurements Using 5-PWR. The upper trace (orange) is calculated by multiplying current and voltage for instantaneous power. Loss measurements are performed on the instantaneous power waveform. Each loss region is annotated with colored markers that correspond to measurement labels. The bottom waveforms are the voltage across the switch and current through the switch.

## Switching Analysis

Measurements in the switching stages of the power supply confirm that the converter is functioning correctly, quantify sources of loss, and confirm that devices are operating within normal ranges.

### SWITCHING LOSS MEASUREMENTS

Turn-on losses occur as various physical and parasitic capacitors are charged, inductors generate magnetic fields, and related transient resistive losses occur. Likewise, when the switching supply turns off there is energy still available to discharge and interact with various components even though the main power has been removed, and so losses occur here too.

#### Making the measurement

To make a switching loss measurement, the oscilloscope must measure voltage across the switching device and current through the device. The switching loss results are presented as shown in Figure 5.

#### Measurement results

- **Ton:** The mean of the Turn On power and energy loss values for each cycle
- **Toff:** The mean of the Turn Off power and energy loss values for each cycle
- **Total:** The mean of the Total Average Power Loss and Average Energy values for each cycle
- Left and right arrow buttons let you traverse through the switching cycles and zero-in on problem areas
- Measurements can also be viewed in a Results Table. The table shows accumulated measurement results for all switching cycles for quick review.

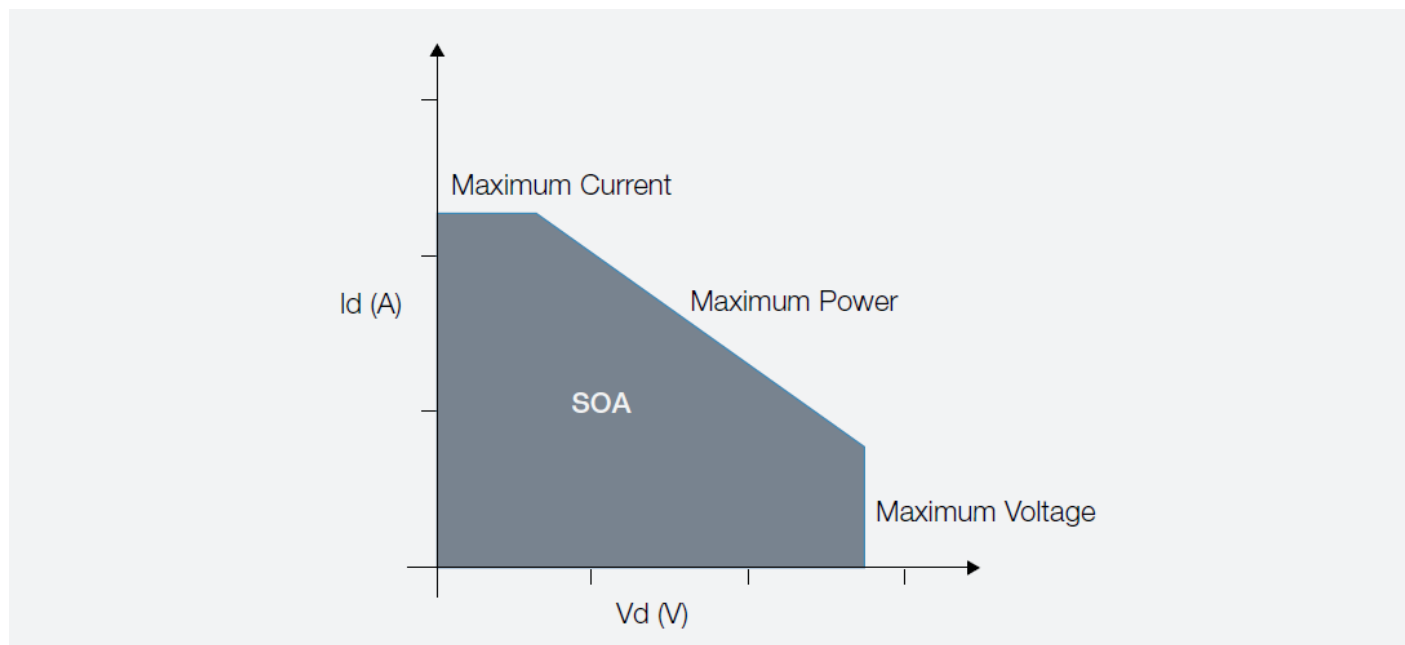


FIGURE 6. Safe Operating Area (SOA) graph of a transistor.

### SAFE OPERATING AREA

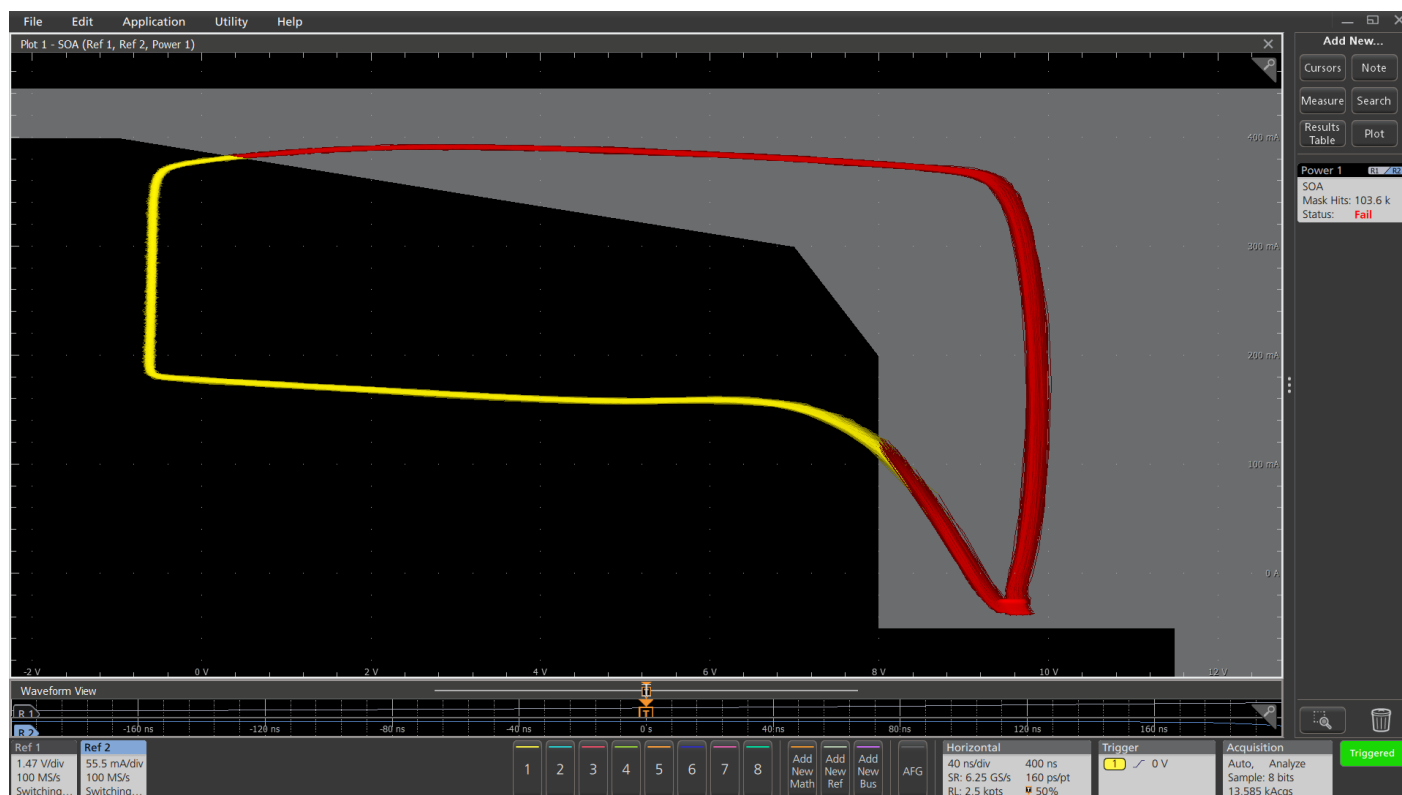
The safe operating area (SOA) of the switching transistor in a switch-mode power supply defines the current that can safely run through the transistor at a given voltage. The SOA is usually defined in the datasheet of BJT, MOSFET, or IGBT switching transistors. It is given as a plot of  $V_{CE}$  (or  $V_{DS}$  for a FET) versus  $I_{CE}$  (or  $I_{DS}$ ), and describes the ranges over which the transistor can operate without degradation or damage.

Power analysis software lets you transfer the SOA from the device datasheet into the 5 Series MSO. Then you can measure voltage and current on the actual, in-circuit device as you vary the operating conditions of your power supply design. The oscilloscope records the V-I plots and can indicate whether any parameters go outside the SOA.

### Making the measurement

One of the main challenges with determining the SOA of a transistor while operating in a power supply is accurately capturing voltage and current data under a variety of load scenarios, temperature changes and variations in line input voltages. 5-PWR simplifies this task by automating data capture and analysis. The measurement setup requires probing the voltage across and the current through the switching transistor.





**FIGURE 8.** SOA using 5-PWR. If the data points fall inside the mask zone, they are yellow to indicate ‘pass’ and if they fall outside the mask zone, they are red to indicate ‘fail’. In this example, the V-I curve has gone outside the SOA, subjecting the switching device to excessive stress.



**FIGURE 7.** SOA Mask Editor window. The mask is defined by a set of (voltage, current) coordinates taken from the switching device datasheet, or may be user-defined.

The next step is to set up the SOA mask. As shown in Figure 7, the SOA Mask editor lets you enter the SOA limits for the transistor, as defined in its datasheet or by your own standards.

### Measurement results

After completing the setup, the SOA test results are presented as shown in Figure 8. The voltage and current waveforms are plotted in a single record in XY mode. The plot shows all the data for a single acquisition cycle.

The results badge shows the number times the device went outside the SOA mask and gives a pass/fail verdict.

## Input Analysis

Line measurements characterize the design's reaction to changing inputs, the design's current and power draw, and the design's distortion of the line current. Some measurements, such as power consumption, are critical specifications. Others, such as power factor and harmonics, may be limited by regulations.

### POWER QUALITY MEASUREMENTS

In 5-PWR, Power Quality measurements are a set of standard power measurements. They are often performed on AC line inputs, but can also be applied to AC outputs of devices such as power inverters. These measurements include:

- Frequency
- RMS voltage and current
- Crest Factor (voltage and current)
- True, reactive, and apparent power
- Power factor and phase

### Making the measurement

Power quality measurements are easily made by using a differential probe to measure the line voltage of the system and a current probe to measure the line current of the system. This same setup may be used to measure current harmonics as well.



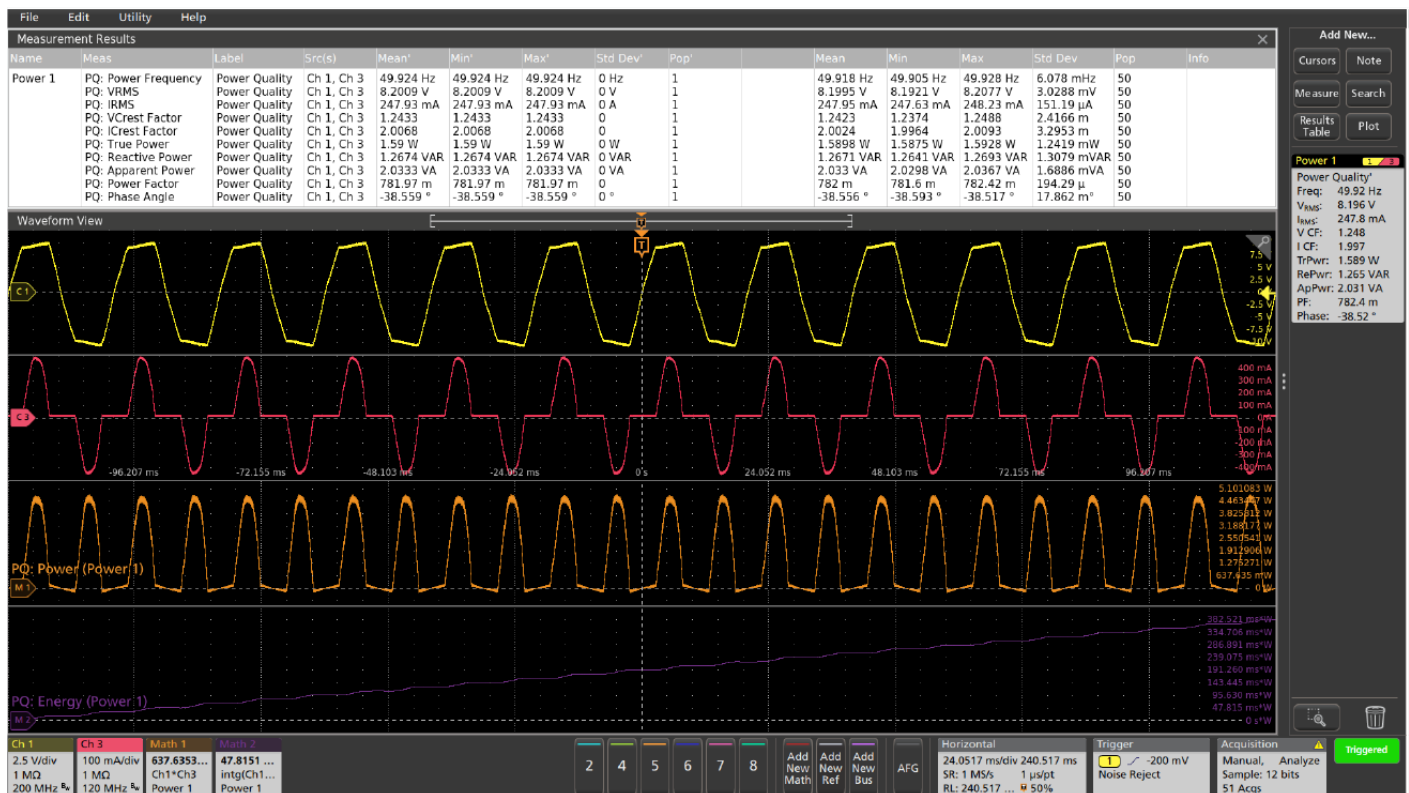


FIGURE 9. Power quality measurements paint a rich picture of the AC line. Line voltage is the upper waveform. Current is the red waveform. Instantaneous power is the orange waveform. The results badge (upper right) shows a summary of the line characteristics, and the results table in the upper section can be activated for more detailed data and statistics.

### Measurement results

- Frequency: The frequency in Hertz of the voltage waveform
- $V_{RMS}$ : The Root-Mean-Square value of the displayed voltage waveform
- $I_{RMS}$ : The Root-Mean-Square value of the displayed current waveform
- V Crest Factor: The peak amplitude of the voltage divided by the RMS value of the voltage
- I Crest Factor: The peak amplitude of the current divided by the RMS value of the current
- True Power: The real power of the system measured in Watts (W)
- Reactive Power: The imaginary power temporarily stored in inductive or capacitive elements, measured in Volt-Amperes-Reactive (VAR)
- Apparent Power: The absolute value of the complex power measured in Volt-Amperes (VA)
- Power Factor: Ratio of the True Power to the Apparent Power
- Phase: The angle between the True and Apparent Power vectors, in degrees

## HARMONICS

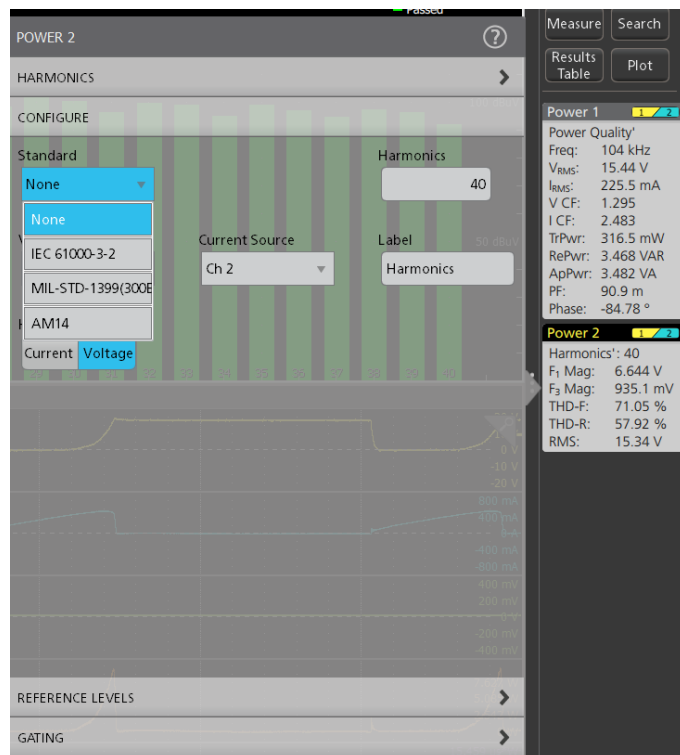
Current harmonics occur when non-linear devices distort the flow of current into the circuit. Linear circuits draw current only at the fundamental line frequency, but non-linear circuits draw current at multiples of the fundamental frequency, with a different amplitude and phase for each harmonic.

When currents with harmonics flow through the impedance of the electrical distribution system voltage distortion can result. Heat can build-up in cabling and transformers. And as the number of switching supplies connected to the grid increases, the harmonic distortion on the grid also increases. It therefore becomes important to control the harmonics of power system.

Thus, standards have been designed to limit the impact on power quality from non-linear loads. Standards such as IEC61000-3-2 and MIL-STD-1399 have been developed to limit harmonics.

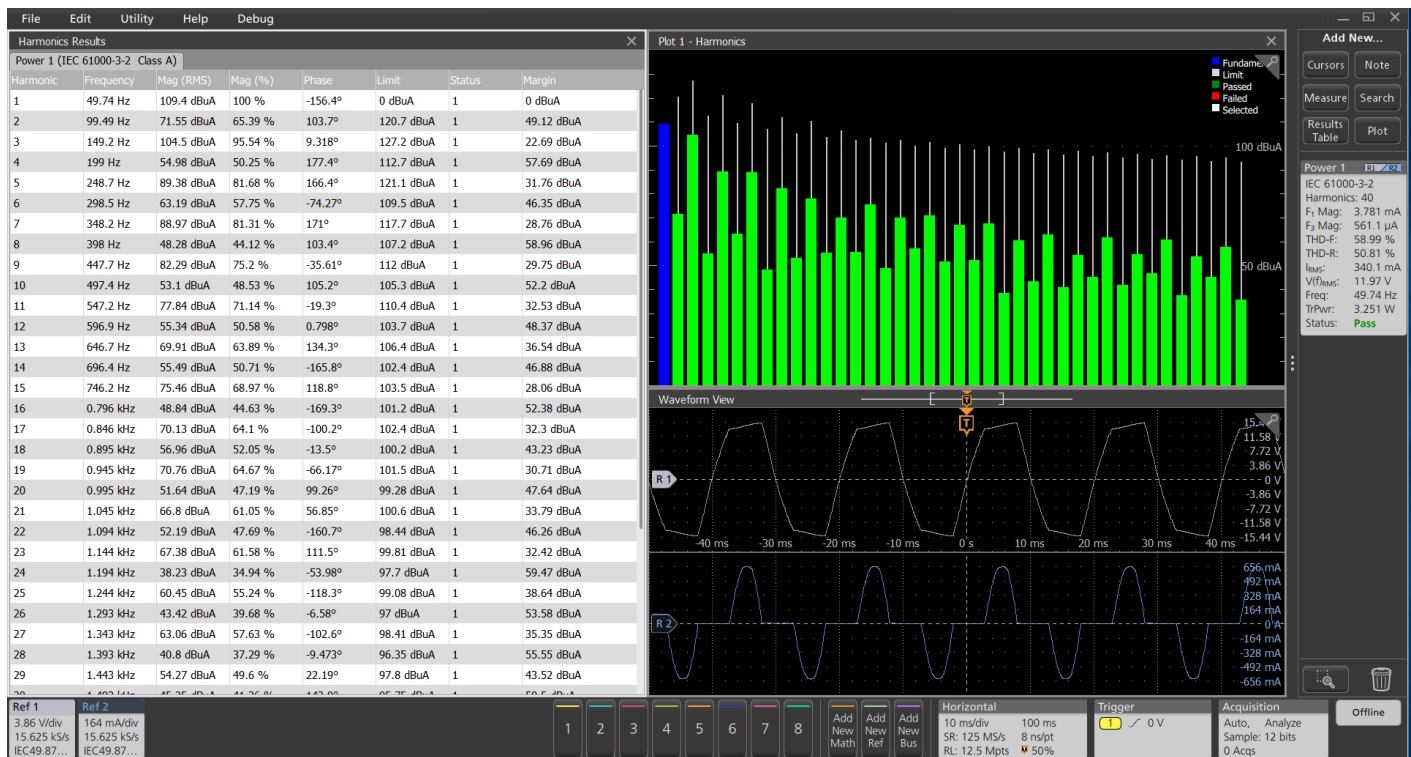
The IEC61000-3-2 standard limits the current harmonics injected into the public mains power supply system. It applies to all electrical and electronic equipment that has input current up to 16A per phase that will be connected to public low voltage distribution systems (230V AC or 415V AC 3 phase). The standard is further divided into Class A (balanced 3-phase equipment), Class B (portable tools), Class C (lighting equipment and dimming devices) and Class D (equipment with unique current waveform requirements).

MIL-STD-1399 lays out specifications and testing requirements for equipment (loads) to maintain compatibility with shipboard AC power systems, from computers and communications equipment to air conditioners.



**FIGURE 10.** Setting up a basic current harmonics analysis requires just a few settings. This example shows settings for a pre-compliance check against industry standards.

The 5-PWR analysis application easily provides measurements of current harmonics. It can display the measurement results in both tabular and graphical formats. It also enables designers to quickly compare performance of their devices against compliance standards before going through certification -- an often time-consuming and expensive process. Having these measurement capabilities available in the oscilloscope, not speeds up debugging, but can help avoid last minute design changes to meet regulatory requirements.

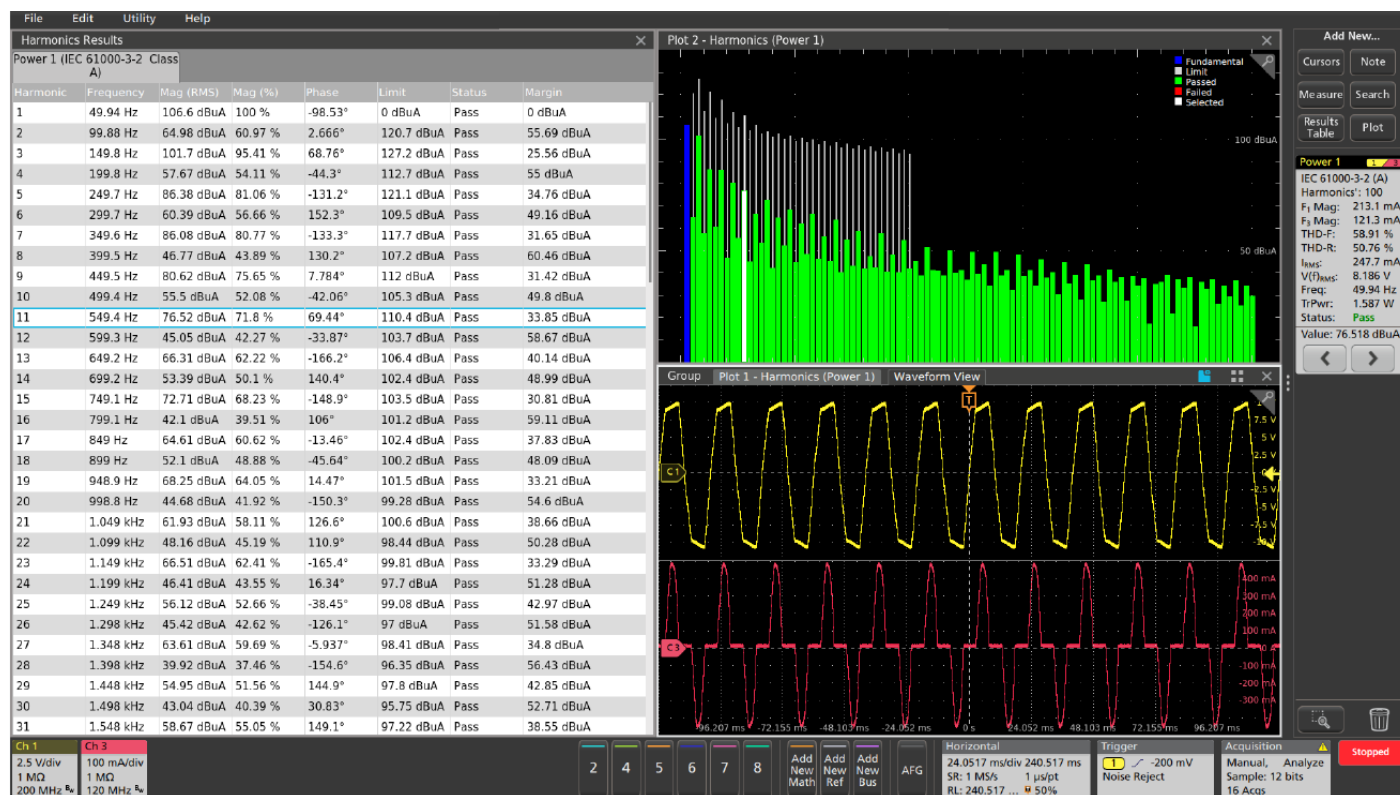


**FIGURE 11.** Harmonics results using 5-PWR. The non-sinusoidal current waveform with can be seen in the lower right. The harmonics bar chart shows harmonic content on a decibel scale. The odd harmonics are most significant, but well within the IEC 61000-3-2 limits.

## Making the measurement

Use a differential voltage probe to measure the line voltage. Use a current probe to measure the line current.

If you want to compare the harmonics in your design against limits in the IEC 61000-3-2 standard, line frequency and must be defined, and the class type needs to be selected. In the case of Class C or D standards, the input power, power factor and fundamental current will also need to be entered. The analysis package will load a pre-defined limit table and make comparisons between measured harmonics and limits. The pre-compliance results will be presented as shown in Figure 12.



**FIGURE 12.** Up to 100 Harmonics may be displayed in graphical form. The table shows IEC 61000-3-2 Pre-Compliance Testing results. Based on your settings the analysis package will load a pre-defined limit table and make comparisons between each measured harmonic and limits.

### Measurement results

- The Results badge shows the Harmonics standard selected, Fundamental Harmonic and 3rd Harmonic magnitude, THD-F, THD-R, RMS value and Pass/Fail status.
- Individual harmonics can be selected and measurement values are linked between the results badge, bar graph, and results table.
- Harmonics Results Table includes:
  - Harmonic standard selected
  - Harmonic number and frequency
  - Magnitude (RMS): The measured RMS amplitude values of the harmonics, in dBμA or A
  - Magnitude (%): The measured amplitudes of the harmonics relative to the fundamental
  - Phase: The phases of the harmonics relative to the frequency reference, in degrees
  - Limit: The harmonic limits per the specified standard
  - Status: The Pass/Fail status of the pre-compliance test
  - Margin: The difference between the Value and Limit
- Current harmonics may be shown in units of decibel microamperes (dBμA) or amperes (A)

## Output Analysis

The output of any DC power supply must be evaluated for regulation and noise. 5-PWR Advanced Power Measurement and Analysis software includes tools for quantifying and classifying ripple.

### Line and Switching Ripple

Simply stated, ripple is the AC voltage that is superimposed onto the DC output of a power supply. It is expressed as a percentage of the normal output voltage or as peak-to-peak volts.

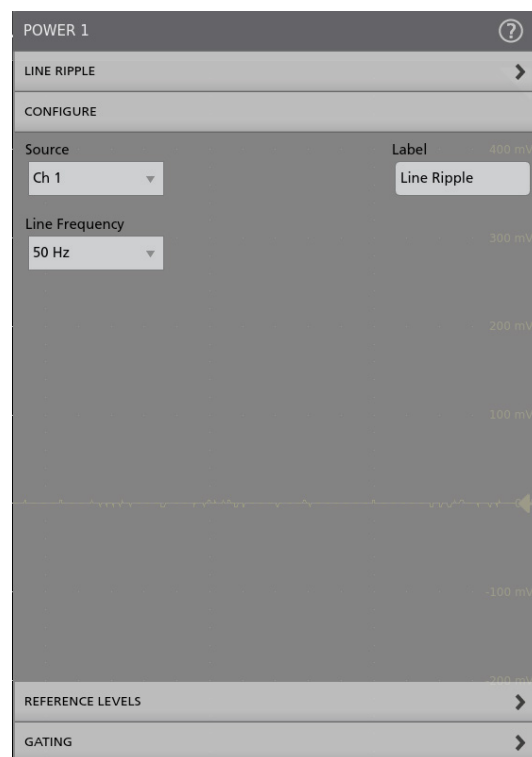
There are two kinds of ripple that show up at the output of a power supply. Line ripple measures the amount of ripple related to the line frequency. On the other hand, switching ripple measures the amount of ripple detected from the switching supply output based on the switching frequency that you identify.

The output line ripple is usually twice the line frequency; whereas the switching ripple is typically coupled with noise and in the kHz frequency range. Separating line ripple from switching ripple is one of the biggest challenges in power supply characterization. Power analysis software greatly simplifies this task.

### Making the measurement

To measure the ripple of the system, only a voltage probe is needed. The differential probe must be connected to the output of the system to measure the output line and switching ripple voltages.

The configuration tabs (see Figure 13) for line and switching ripple are very similar. Both ripple measurements require the selection of input coupling (AC or DC) mode, bandwidth limit required (20MHz, 150/250MHz or Full) and the oscilloscope's acquisition mode – Sample, Peak Detect or High Resolution (High Res). In the case of a line ripple measurement, the line frequency of the system, 50 Hz or 60 Hz or 400 Hz, needs to be defined. Switching ripple measurements require specification of the switching frequency.



**FIGURE 13.** Line Ripple configuration tab for 5-PWR.

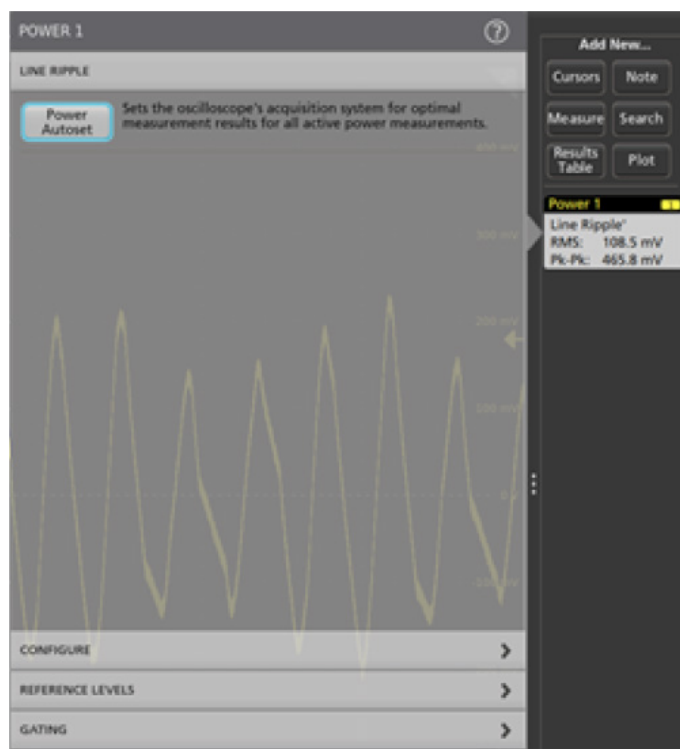


FIGURE 14. Switching Ripple results using 5-PWR.

## Power Measurements Report

Thursday October 26 2017 14:03:53

## Setup Configuration

Scope Details			
Scope Model Number	Scope Serial Number	TekScope Version	Scope Calibration Status
MSO58	PQ300015	1.4.6	Pass
Probe Details - CH1			
Probe Type	Probe Serial Number	Probe Cal Status	
THDP0100	C000079	Default	
Probe Details - CH2			
Probe Type	Probe Serial Number	Probe Cal Status	
TCP0050A	C007428	Default	

## Power Measurement Summary Results

Power1 - PowerQuality											
Measurement	Source	Power Frequency	V <sub>RMS</sub>	I <sub>RMS</sub>	V <sub>Crest</sub> Factor	I <sub>Crest</sub> Factor	True Power	Reactive Power	Apparent Power	Power Factor	Phase Angle
Power Quality	Ch1 Ch2	103.9kHz	15.34V	224.9mA	1.288	2.454	293.2mW	3.436VAR	3.449VA	85.03m	85.12Degrees
Power2 - Harmonics											
Measurement	Source	Standard	Harmonics	F1 mag	F3 mag	THD-F	THD-R	I <sub>RMS</sub>			
Harmonics	Ch1 Ch2	NONE	40	6.617A	893.4mA	70.7%	57.73%	15.25A			
Power3 - CycleAmp											
Measurement	Source	Amplitude									
Cycle Amplitude	Ch1	18.56V									
Power4 - CyclePkPk											
Measurement	Source	Cycle Peak-to-Peak									
Cycle Peak-to-Peak	Ch1	20.03V									
Power5 - CycleTop											
Measurement	Source	Top									
Cycle Top	Ch1	18.47V									
Power6 - CycleMax											
Measurement	Source	Cycle Maximum									
Cycle Maximum	Ch1	19.56V									
Power7 - CycleBase											
Measurement	Source	Base									
Cycle Base	Ch1	-92.16mV									
Power8 - CycleMin											
Measurement	Source	Cycle Minimum									
Cycle Minimum	Ch1	-471.1mV									
Power9 - Period											
Measurement	Source	Period									
Period	Ch1	9.526us									
Power10 - Frequency											

FIGURE 15. Reports are available in .MHT or .PDF file formats.

Once the measurement has been configured, the results are presented as shown in Figure 14.

### Measurement Results

Peak to Peak and RMS Ripple values: These are the peak to peak and RMS voltage values of the Line or Switching ripple of the system.

### Report Generation

Data collection, archiving and documentation are often tedious but necessary tasks in the design and development process. 5-PWR is equipped with a report generation tool that makes the documentation of measurement results practically effortless.

By pressing the Generate Report button, a finished report with the specified layout is generated and displayed on the oscilloscope screen.







### Summary

By using the 5-PWR application with 5 Series MSO oscilloscopes, engineers can make accurate and repeatable measurements quickly and with very little setup time. Best of all, they don't need to do manual calculations! The oscilloscope application does the work, and by using screen captures and reporting, engineers can easily provide complete documentation of how the instrument was set up, waveforms, and measurement results.

### Which probes are right for your application?

5 Series MSO oscilloscopes achieve the best power measurement performance when combined with the right power probes. The 5 Series MSO is equipped with the TekVPI probe interface which enables communication between the oscilloscope and probes. Please refer to [www.tek.com/accessories](http://www.tek.com/accessories) for specific information on recommended models of differential and current probes, including IsoVu isolated probes and Rogowski probes, and any necessary probe adapters.



PROBE TYPE	DESCRIPTION	
High Voltage Differential Probes	The THDP0100/THDP0200/TMDP0200 high-voltage differential probes are the best choice for making non-ground referenced, floating measurements. These probes provide bandwidths to 200 MHz and voltage ranges up to 6000 V.	
	The P5200A/P5202A/P5205A/P5210A high-voltage differential probes are an excellent choice for making non-ground referenced, floating or isolated measurements. These probes provide bandwidths to 100 MHz and voltage ranges up to 5600 V.	
Optically Isolated Differential Probes	<p>The TIVM1, TIVH08, TIVH05, and TIVH02 optically-isolated differential probes are the best choice for accurately resolving high bandwidth, differential signals -- ideal for testing wide bandgap designs. The probes are available in 3 m and 10 m lengths.</p> <p>The TIVM1 provides 1 GHz bandwidth and can measure differential signals up to <math>\pm 50</math> Vpk in the presence of common mode voltages up to 60 kV. The TIVH08, TIVH05, and TIVH02 provide 800 MHz, 500 MHz, and 200 MHz, respectively, and can measure differential signals up to <math>\pm 2500</math> Vpk in the presence of common mode voltages up to 60 kV.</p>	
Current Probes	Tektronix offers a broad portfolio of current probes, including AC/DC current probes that provide bandwidths up to 120 MHz and best-in-class current clamp sensitivity down to 1 mA.	
	AC-only Rogowski probes include the TRCP300 (9 Hz to 30 MHz, 250 mA to 300 A peak), TRCP600 (12 Hz to 30 MHz, 500 mA to 600 A peak), and TRCP3000 (1 Hz to 16 MHz, 500 mA to 3000 A peak).	
Mid-Voltage Differential Probes	The TDP0500/TDP1000 medium-voltage differential probes are the best choice for making non-ground referenced, floating or isolated measurements. These probes provide bandwidths to 1 GHz and voltage ranges up to $\pm 42$ V (DC + pk AC).	



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