Tektronix

Application Note

Power-Electronics Measurements Made Easy with TDS Oscilloscopes

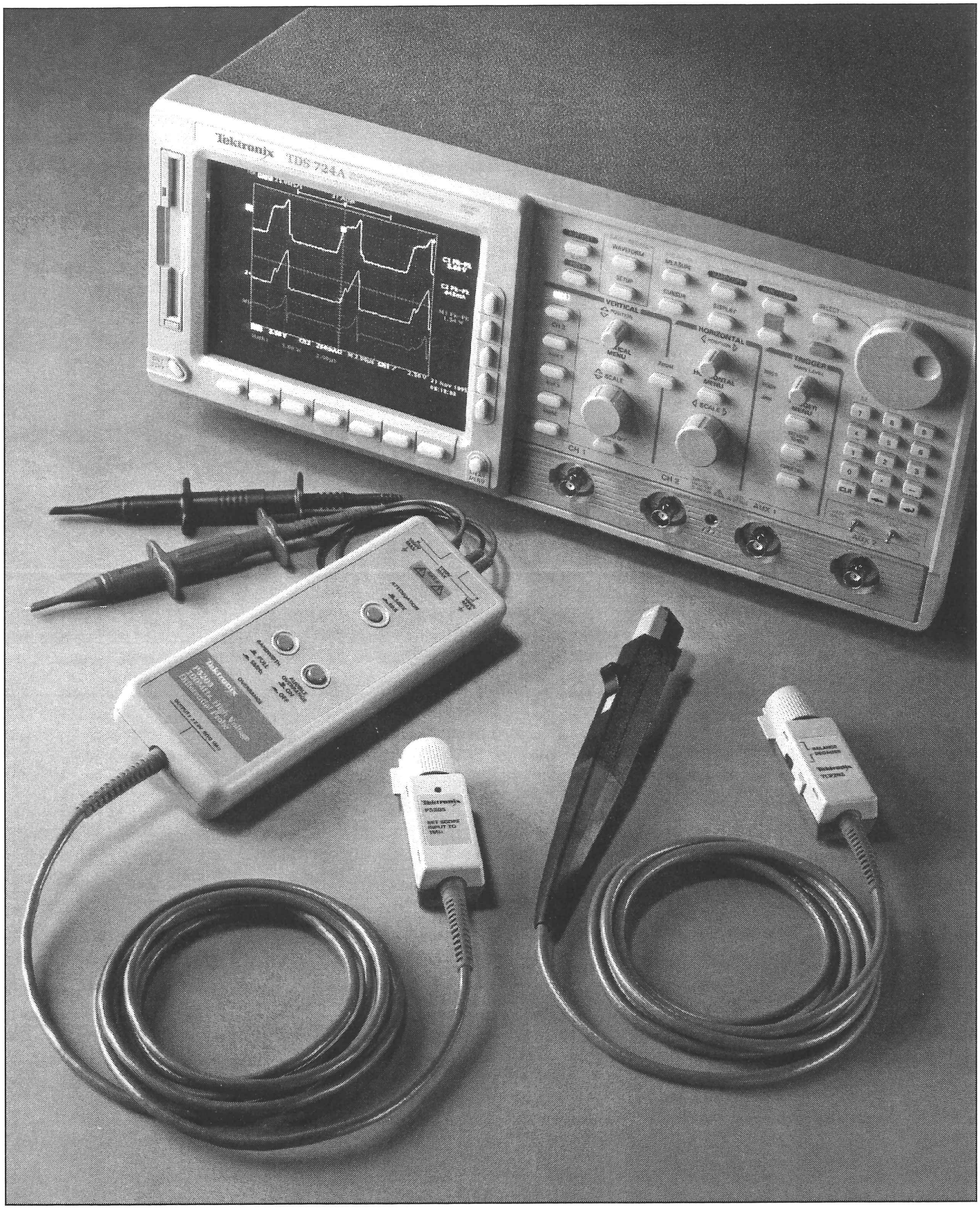

Table of Contents

Solutions

Appendices

WARNING

Power-electronics measurements involve exposure to potentially lethal voltages. Please review the operating instructions and safety guidelines provided with each instrument and probe system. In particular, never float instruments by cutting or defeating their third-wire protective ground connection.

Introduction

Accurate and insightful analysis of power-converter performance is a challenging task. This application note illustrates several measurement techniques for designing and evaluating line-operated, battery-operated, and DC-DC power supplies. We'll address measurements at the input stage, in the switch-mode converter itself, and at the load connection.

Tektronix offers a broad selection of instrumentation for power-electronics applications. In this application note, we've selected three instruments that provide a well-balanced set of features suitable for most applications. The TDS digital oscilloscopes provide the advanced signal acquisition, analysis, and display functions required in power-electronics measurements. The TDS family offers a true next step beyond the storage and documentation features of the basic digital oscilloscope.

The second tool is the TCP202 Current Probe. The TCP202 enables both DC and AC current measurements using a convenient clip-on probe so you don't have to break circuit connections.

The third tool is the P5205 Differential Probe. The P5205 enables safe probing of floating voltages where one side of the signal is not ground. The P5205 supplants the dangerous practice of floating your scope by cutting the third-wire ground connection.

The TCP202 and P5205 probes use the TekProbe™ interface system to provide the next step in performance and ease of use for power-electronics measurements. TekProbe directly powers the TCP202 and P5205 probes through the input connectors on TDS oscilloscopes. This eliminates external power modules, wall-adapters, or frequent battery replacement. TekProbe integration also means that the probes can take advantage of the TDS scope's precision input amplifiers. Gain and attenuation control are retained within the TDS and are not duplicated in external probe electronics. The results are high-performance, wide dynamic range current and differential-voltage measurements in a compact package.

Finally, TekProbe enables direct on-screen readout and measurement of each probe's scale factor. The scale factor of a TCP202 current waveform is displayed in Amps per division and resulting power waveforms are directly displayed in Watts per division. Automatic measurements such as RMS current or true power are properly scaled in Amps or Watts. Scale factors also apply to the triggering system, which means that trigger levels on current waveforms are directly settable in milliamps or Amps.

1. Measuring True and Apparent Line Power

Problem: Erroneous results in AC power measurements due to inadequate sample rate and record length.

Key TDS Features: Decimal record length, waveform multiplication, and automatic measurements.

Benefits: The TDS decimal record length simplifies the measurement of line-power parameters.

Quantifying AC line-power components is a basic requirement in every off-line power converter application. The digital scope is an ideal tool for this task, but some subtle traps can turn this straightforward measurement into a tedious exercise. The first step is to acquire the voltage and current waveforms (Figure 1). A standard 10X passive probe can safely sense the line voltage.[1] The TCP202 can readily sense the line current. Figure 2 shows the results for a typical switch-mode converter. The upper waveforms show the distorted current and sinusoidal voltage waveforms. The TDS calculates the individual RMS values of 121 Volts and 1.11 Amps. The apparent power is 134 VA or the product of the individual RMS values. True power is the mean value of the instantaneous product of voltage and current. The TDS multiplies the voltage and current waveforms to create the instantaneous power waveform. The TDS then calculates the mean value of the entire power waveform which yields a true power of 88 W. The ratio between the true and apparent power values yields the power factor of 0.66.

$$\text{Apparent Power } (P_A) = 120.8\text{ V} * 1.108\text{ A} = 133.8\text{ W}$$

$$\text{True Power} = (P_t) = 88.0\text{ W}$$

$$\text{Power Factor (pf)} = \frac{88.0\text{ W}}{133.8\text{ W}} = 0.66$$

Several system features simplify this technique as well as guard against measurement errors. For current sensing, the TCP202 is ideal because it provides a flat frequency response across the relevant measurement range. Contrast this with AC current transformer (CT) clamps. Many CT devices are not suitable for sensing the complex waveshapes at switching converter inputs. While rated for 50 or 60 Hz operation, their low-frequency roll-off can induce phase shift with respect to the voltage measurement. This phase shift will cause errors in the true power measurement since the two waveforms are multiplied in time. It's important to note that CT devices will very accurately sense the current's fundamental frequency component, but they're not necessarily designed to sense the higher frequency harmonics (up to several kHz) found in contemporary power waveforms.

Several TDS features also simplify this technique. As with any measurement of a periodic signal, a rule is to record and measure over complete events. In the case of AC waveforms, this means selecting a measurement interval that includes an integral number of line cycles. With some planning, you can set your TDS to cap-

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[1] This assumes your AC neutral and ground are at the same potential. If your building's ground wiring has a "power-quality" problem, or if you need to actually measure the line-to-neutral voltage, use the P5205 differential probe. Do not connect the ground clip of your standard 10X passive probe to the AC neutral. Under no circumstances should you "float" your scope by cutting or defeating the ground connection. For further information, please read the publication 51W-10640-0, "Floating Oscilloscope Measurements... And Operator Protection."

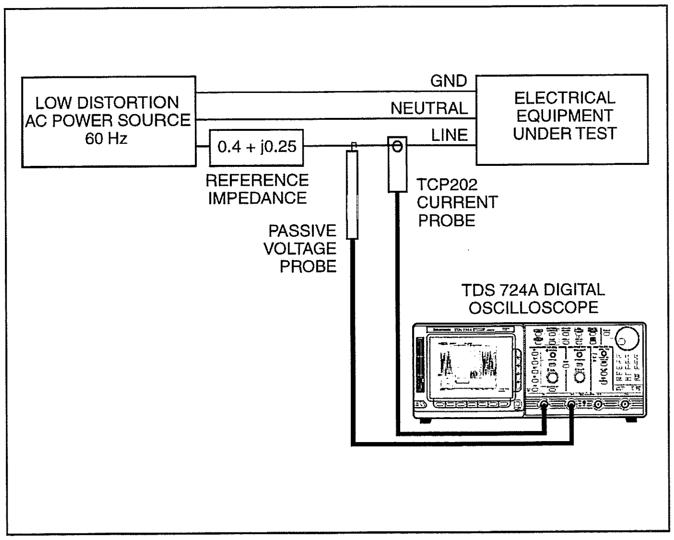


Figure 1. A standard 10X passive probe senses the line voltage while the TCP202 current probe clips on to the line lead. The scope implicitly provides the ground return for the voltage probe. NOTE: Do not hook the probe's ground clip to the neutral wire.

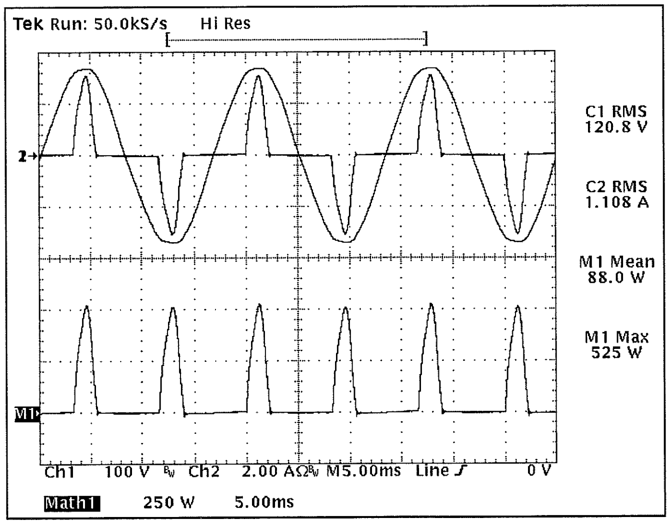


Figure 2. The upper waveforms are the voltage and current scaled at 100 V per division and 2 A per division. The TDS multiplies the voltage and current to create the instantaneous power waveform (lower) scaled at 250 W per division. The TDS then calculates the power parameters. The true power is 88 W and the peak power is 525 W.

ture integral numbers of 60 Hz (or 50 Hz) cycles. In Figure 2, the waveforms are exactly 50 milliseconds long or three complete line cycles. This results from a sampling rate of 50 kS/s (i.e., 20 µs between samples) and a record length of 2500 samples. Unlike the TDS, many digital scopes only offer record lengths that are powers of 2 such as 1024 samples. When combined with a limited selection of sample rates (e.g., 10 kS/s, 20 kS/s), this yields recording times that don't capture an integral number of line cycles. For example, a sample rate of 20 kS/s and a record length of 1024 samples results in 3.07 line cycles (instead of 3.00 cycles), which translates to a calculation error of greater than 2%.

In some cases, you can obtain acceptable results by using a digital scope's cycle-based measurement functions. The scope scans the selected waveform for a complete cycle of data and performs the measurement only on a complete cycle of the waveform. This technique works well with simple sinusoidal signals such as measuring the RMS value of the line voltage, but it can lead to erratic results with complex current and true power waveforms. In addition, a single cycle measurement of the 120 Hz instantaneous power waveform, shown in Figure 2, only represents half of a 60 Hz line cycle.

Of course there are applications where you want to directly control the measurement interval. You may want to measure the difference between the power delivered on the two halves of the line cycle or test your converter's power consumption at 47 Hz using a programmable AC source. In these cases, you would use the TDS gated measurement capability to directly set the time interval for a calculation. This capability is illustrated separately in this note.

2. Measuring Line-current Harmonics

Problem: Harmonic measurements on most digital scopes are confusing and often inaccurate.

Key TDS Features: Decimal record length, FFT, and automatic measurements.

Benefits: The TDS decimal record lengths and Fast Fourier Transform (FFT) implementation bypass the limitations of traditional scope calculations of line frequency harmonics.

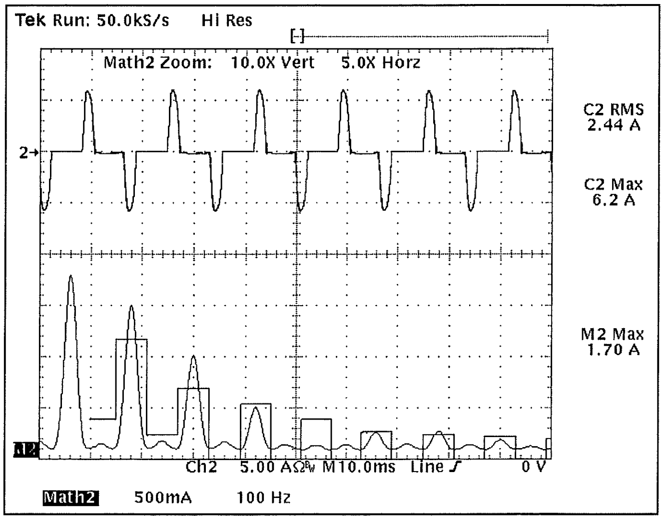


Figure 3. The upper waveform is the 60 Hz line current from the TCP202 current probe displayed at 5 Amps per division. The TDS calculates the RMS current of 2.44 A and peak current of 6.2 A. The lower waveform shows the FFT of the current waveform. The vertical scale is Amps RMS with a factor of 0.5 A/div. The horizontal scale factor is 100 Hz/div. The TDS calculates the maximum harmonic component – the 60 Hz fundamental – of 1.70 A. Unlike most other FFTs which are sluggish, the TDS FFT display is extremely lively due to the dedicated Digital Signal Processor (DSP).

Regulatory standards such as IEC 555 governing disturbances in power systems have brought current-distortion measurements of line-connected equipment into the mainstream of analysis. In simple terms, electrical equipment manufacturers need to measure and characterize how their equipment affects the power system. The most useful technique for characterizing line-current distortion is to plot the relative levels of the harmonic components. This has traditionally required specialized frequency analysis instrumentation, but the TDS equipped with the Fast Fourier Transform (FFT) function makes this a readily accessible measurement. Once again, the current sensing task is handled by the TCP202.

Figure 3 illustrates the type of results you can expect from the measurement system. The current waveform is captured by the TCP202. The distortion in the waveform is obvious but the conventional measurements of RMS current (2.44 A), peak current (6.2 A), or even the crest factor ratio of 2.5 (6.2/2.44) are only part of the story. The TDS uses the FFT to display the frequency components of the current waveform in a clear and understandable format. The vertical axis is scaled in Amps RMS. In this case, the vertical scale factor is 500 mA/div. The horizontal axis is 100 Hz/div starting with 0 Hz (DC) on the left.

Depending on your application, you may have limits on the permissible level of each harmonic component. In this case, another "waveform" representing the absolute current limits for equipment under the IEC 555-2 guidelines is displayed. This additional waveform was created as a string of numbers on a PC and transferred into the TDS. For example, the third harmonic at 180 Hz clearly exceeds the 1.08 A limit.

The FFT often confuses the first-time user of this powerful function. But a key feature of the TDS profoundly simplifies the application of the FFT to line-current harmonic measurements. In particular, the FFT results directly include 60 Hz (or 50 Hz) and their harmonics. The frequency domain result in Figure 3 is a set of data samples equally spaced in frequency instead of time. The spacing between points is set by the ratio of the sample rate and the record length of the original time-domain waveform. In this case the sample rate was 50 kS/s and the record length was 5000 samples yielding a frequency spacing of 10 Hz per point. This means that the FFT results implicitly include 60 Hz, 120 Hz, 180 Hz – or all of the 60 Hz harmonics.

This simple relationship can confound users of scopes that store waveforms and calculate FFT results based on record lengths that are powers of 2. For example, with a 10 kS/s sample rate and a 1024 sample record length, the frequency domain points would be spaced 9.766 Hz apart. No point falls on 60 Hz; the closest points are 58.6 Hz and 68.4 Hz. If you simply take nearby points as proxies for the harmonic levels, your measurements can be off by more than 10%.

In fact, the results can be quite confusing since some points fall closer to an actual harmonic than others. While there are techniques to reduce this error source, the TDS implementation of the FFT bypasses this issue. For more detailed information refer to the Tektronix publication 55W-8815-0, ***FFT Applications for TDS***.

3. Measuring Line-voltage Distortion

Problem: Visual inspection of simple parametric relationships such as crest factor are inadequate for line-voltage distortion.

Key TDS Features: FFT, automatic measurements, and cursor readout.

Benefits: The FFT can quantify distortion levels that are masked by traditional measurement techniques.

The companion measurement to line-current distortion is line-voltage distortion. This is often overlooked because the voltage waveform generally appears to be a textbook sinusoid. But manufacturers of AC inverters or uninterruptible power sources (UPS) need to characterize the output characteristics of their equipment. Once again, a task that used to require specialized distortion-analysis equipment has become more accessible through the digital processing capabilities of the TDS.

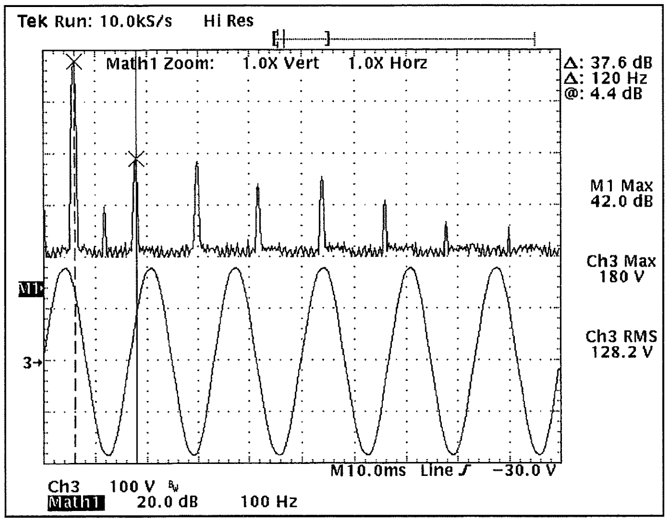


Figure 4. The lower waveform is the line voltage. The maximum and RMS voltages are automatically calculated at the right. The upper waveform is the FFT of the voltage waveform. The vertical scale is 20 dBV/div and the horizontal scale is 100 Hz/div. The principal component is the 60 Hz fundamental at 42.0 dBV (126 V).

The lower waveform in Figure 4 shows the line voltage. The TDS calculates the 180 V peak and 128 V RMS values of the waveform. The crest-factor ratio is 1.42, which matches that of an ideal sinusoid. But the FFT results on the upper waveform uncover much more information. Unlike the current-harmonic measurement, the harmonic content of the voltage waveform is much smaller. In this case, it's more appropriate to set the TDS to display the results in dBV or on a log scale where 1 V (RMS) equals 0 dBV. You can convert between a value V(x) in Volts and its equivalent dBV(x) in dBV using:

$$V(x) = 10^{(dBV(x)\ /\ 20)}$$

and

$$dBV(x) = 20 \log V(x)$$

The peak harmonic component is the 60 Hz fundamental at 42.0 dBV or 126 V (i.e., $10^{2.1}$). The TDS cursor function lets you quickly scroll through the harmonics to measure relative levels. For example, the 3rd harmonic, which is 120 Hz from the fundamental, is 4.4 dBV (1.7 V) and is 37.6 dB below the fundamental. You can insert −37.6 dB into the formula above (yielding 0.013) to conclude that this component is 1.3% of the fundamental. Table 1 summarizes the results. You can calculate the total harmonic distortion (THD) by taking the square root of the sum of the squares of each value in the last column. In this case the THD is 1.9%. For line voltages, the total distortion is typically dominated by the first few odd harmonics so you only need to tabulate three or four values.

The TDS cursor function can directly display the level of each harmonic relative to the fundamental. This simplifies THD calculations since distortion components are normalized to the fundamental amplitude. THD is obtained

Table 1

Harmonic	Frequency	Relative to Fundamental	Percent of Fundamental
2nd	120 Hz	–56.4 dB	0.15%
3rd	180 Hz	–37.6 dB	1.32%
5th	300 Hz	–38.8 dB	1.15%
7th	420 Hz	–47.2 dB	0.44%
9th	540 Hz	–45.2 dB	0.55%
11th	660 Hz	–54.8 dB	0.18%

by taking the square root of the sum of the squares of the last column. In this case, the total is 1.9%, but the 3rd and 5th harmonic alone would have yielded a THD of 1.8%.

4. Measuring Line Phase

Problem: The distortion or harmonic content in modern line waveforms can cause errors when applying the conventional phase measurement function of digital oscilloscopes.

Key TDS Feature: FFT phase.

Benefits: The FFT phase function can provide more accurate phase measurements for complex or distorted voltage and current waveforms.

Phase angle between line voltage and current is a commonly measured relationship since the angle indicates the reactive characteristic of the source-load connection. The upper two waveforms in Figure 5 show the line voltage and current waveforms to a slightly reactive load. The phase-measurement function reports that the voltage leads the current by 11.4 degrees. This phase measurement was derived by measuring the relative time delay between the zero-crossings of the signals, and then dividing it by the period.

This technique works well for pure sinusoids, but it can lead to errors for distorted signals. Phase is a frequency-dependent parameter and the actual objective is to measure the phase at the fundamental frequency, which in this example is 60 Hz. The lower two waveforms illustrate a better solution. The FFT phase function is used to display the phase vs. frequency relationship for the voltage and the current. This means that we can look at the relative phase of the two signals at 60 Hz. The TDS was set to only display the phase at frequencies where there was a significant signal level. The display threshold is programmable and in this case it was set to only show phase results at the dominant component of 60 Hz. The TDS was also set to report the 60 Hz phase for the two waveforms. We're only interested in the relative phase between the two signals, which is 8.1 degrees (the difference between the two displayed values).

The key point is that the phase angle between signals is a frequency-dependent parameter. And while you can display the phase vs. frequency results for the voltage and current independently, it's the difference between the two that yields the relevant information.

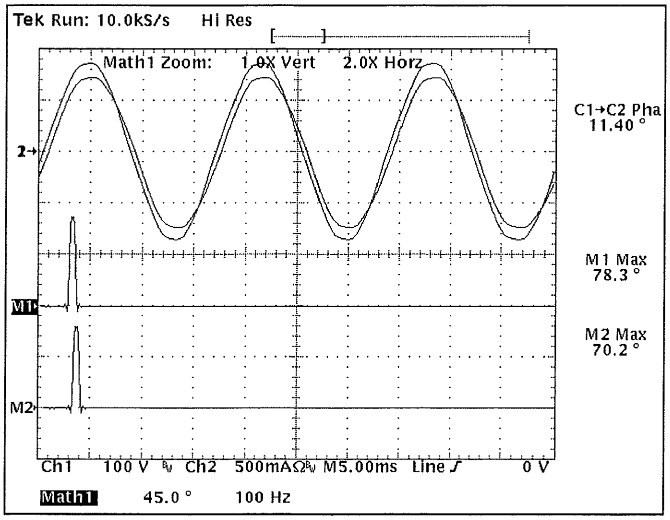


Figure 5. The line voltage (100 V/div) leads the line current (displayed at 500 mA/div). The conventional zero-crossing phase measurement reports an inaccurate phase lead of 11.4°. The TDS FFT function generates the lower two phase vs. frequency waveforms for the voltage and current. At 60 Hz, the voltage only leads the current by 78.3° – 70.2° = 8.1°. The distortion in the current waveform rules out the use of a conventional time-domain zero-crossing phase measurement.

5. Triggering on Line-voltage Aberrations

Problem: Traditional scope triggering modes do not detect line-voltage aberrations.

Key TDS Feature: Limit template triggering.

Benefits: The TDS pass/fail limit test function enables triggering on deviations from a user-definable reference template.

A common need in analyzing line-power waveforms is to capture aberrations. Some aberrations are easily defined by an absolute magnitude such as when the line voltage exceeds a threshold. However, when the objective is to capture a deviation from a reference, it's more difficult to trigger or capture the relevant event. The TDS limit template triggering capabilities simplify the capture of aberrations by continually comparing acquired waveforms to a stored reference or template. If and when an acquired waveform exceeds a user-defined envelope around the reference, you can trigger actions ranging from a simple audible alarm to the storage and print-out of the event data.

Figure 6 shows the creation of the reference template for the line-voltage waveform. First, the line voltage itself is captured. In this case, six cycles are used which represents a tenth of a second.

Then the limit boundaries are defined. In this case, we want to trigger whenever an acquired waveform deviates by more than 10 Volts from our reference waveform. Thus, since the voltage was acquired at 50 V/div, we set vertical limits of ±0.2 divisions. The TDS is then set to continually acquire the line-voltage signal but to stop when an acquired waveform falls outside the template.

Figure 7 shows a typical result. An acquired waveform had a glitch near the negative peak. The TDS captured this event and stopped. Note that this is a triggering function and other channels could have been active to capture other signals. In this case, just the voltage is shown for clarity.

On an operational note, there is a slight "dead" time between successive waveform captures. In this example, the TDS captures six cycles and then processes the measured signal against the reference template. During the processing time, a line cycle will be missed. For this reason, the template was chosen to cover more than one complete cycle; otherwise, no more than 50% of the cycles would be tested.

NOTE: The TDS scopes can be set up to provide a hardcopy on the presence of an aberration; this is a useful capability in manufacturing test and quality departments. Waveforms and screen data can be stored in any of 14 formats.

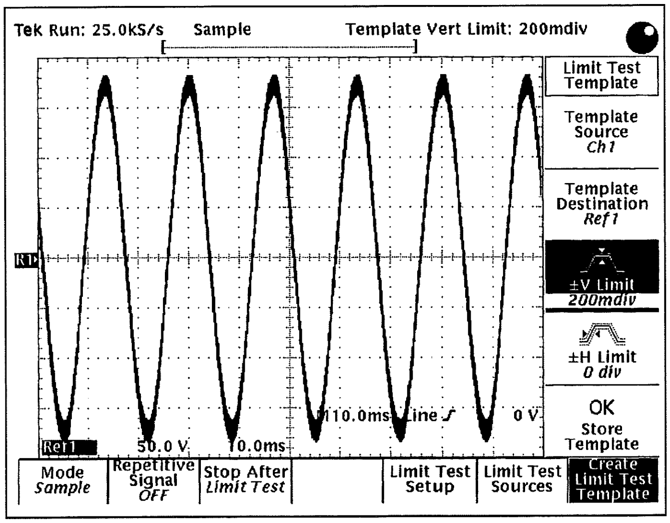


Figure 6. The trigger template is based on an actual line voltage waveform. The upper and lower limits are defined to be 0.2 divisions above and below the reference waveform. Since the voltage was acquired at 50 V/div, this is a range of ±10 V around the reference waveform.

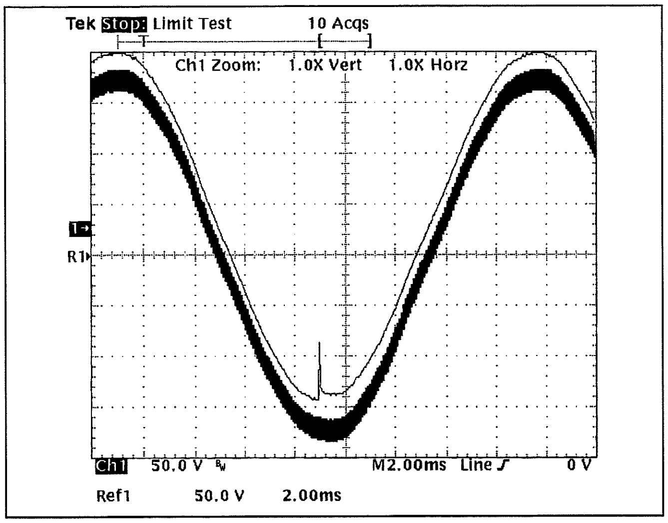


Figure 7. The TDS is set to capture deviations from the reference template. In this case, the aberration near the negative peak of the line cycle exceeded the template.

6. Low-level Current Measurements

Problem: The usefulness of digital multimeters is limited as they provide only static measurement results.

Key TDS Features: Hi-Res acquisition and zoomed display.

Benefits: The stability and signal processing capability in the TCP202/TDS combination provide a new way to characterize low-level current dynamics.

The goal of increasing battery life in handheld electronic gadgets requires thorough knowledge of how current is drawn by the load components. Microampere current measurements are readily made using digital multimeters, but they don't provide more than a steady-state or DC measure of current flow. How do you measure micropower switching dynamics as loads switch from active to shutdown states?

The TCP202 provides a simple technique for multiplying the sensitivity of current measurements in this application. By looping 'n' turns of the sensed-current conductor through the current probe (Figure 8), you can multiply the effective sensitivity by n. The waveform in Figure 9 (lower screen) is the battery-current waveform of a clock sensed at the maximum TCP202 sensitivity of 10 mA/div. However, the sensed current conductor was looped through the current probe ten times, so the sensitivity is actually ten times larger (1 mA/div). The TDS calculates the mean multiplied current of 620 µA which is equivalent to 62 µA. Note that the current pulses occur once per second as the clock advances the second hand. Many multimeters cannot provide a meaningful current measurement in this application. In addition, the TDS zoom function can expand the pulse (upper screen) to reveal the current dynamics. Note that the TDS displays a box around the area that's magnified into the upper screen.

You can readily duplicate these results by following these recommendations. Since you're taking advantage of the excellent stability of the TDS and TCP202 amplifiers, be sure that both are calibrated and have passed their warm-up periods. Before powering up the circuit under test, use the TDS mean measurement function to calculate the average value of measured current. With the current probe attached to the multi-turn loop, use the TCP202's DC level adjust to null the mean output voltage to 0 mA. Finally, since the multi-turn technique multiplies the noise as well as the signal, you'll need to use the TDS Hi-Res acquisition mode to filter the waveform.

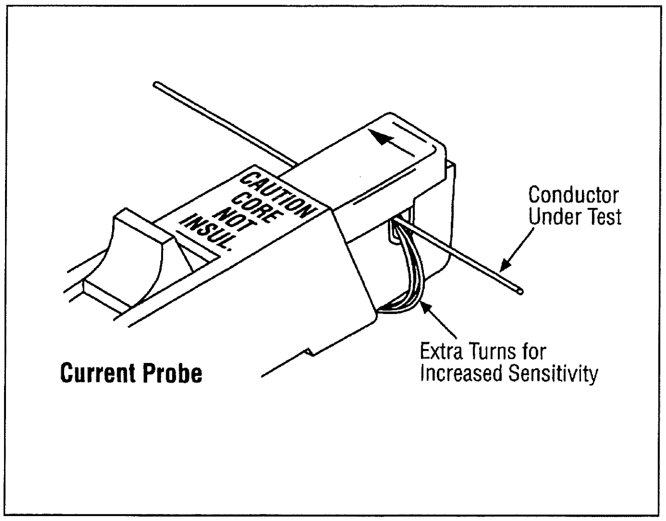


Figure 8. Looping 'n' turns of the sensed-current conductor through the current probe multiplies the effective sensitivity by n.

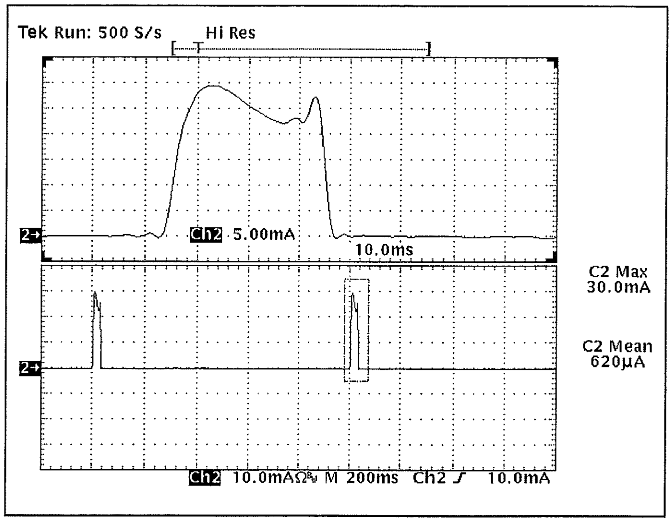


Figure 9. The TCP202 was set to its maximum sensitivity of 10 mA/div, but the sensed current was looped through the current probe ten times. Therefore, the TDS calculation of 30 mA (peak) and 620 µA (mean) must be scaled by 1/10. Since the period of the event is one second, the record interval of two seconds captures an integral number of events. Thus, the mean measurement function over the entire record interval can be used to determine the average DC current.

7. Measuring Battery Power Consumption

Problem: There are no convenient methods to measure power consumption in battery-powered devices.

Key TDS Features: Waveform multiplication, and area measurements.

Benefits: The TDS waveform processing functions also apply to slow DC events often associated with chart recorders.

A critical specification of all portable electronic gadgets is battery life. It's easy to measure the steady-state DC power consumption with a traditional multimeter – just measure the DC current drain and battery voltage and multiply the two results. But most electronic devices switch between a multitude of operating modes. Hence, you need to measure the dynamic power characteristics of the various modes over time to truly understand system performance.

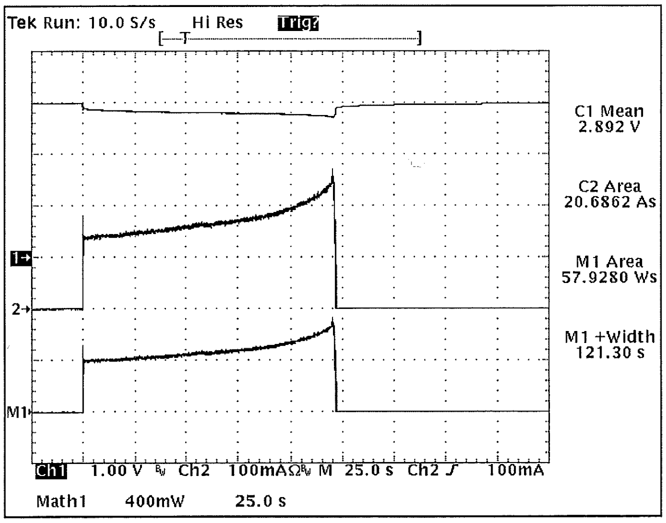


Figure 10. Upper waveform is 3 V battery voltage. Center waveform is the battery current (100 mA/div). Lower waveform is the calculated instantaneous power waveform. The width of the power waveform measures the total rewind time of 121 seconds.

Figure 10 shows various power measurements for the "rewind" mode of a portable tape player. The top two traces are the battery voltage and current. The TDS calculates the power waveform by multiplying the voltage and the current. The waveform signatures are easily understood. The battery voltage dips as the motor starts drawing current. The current surges to start the motor. The power remains relatively constant until the rewinding finishes; then the motor stalls and the current surges again. The motor then shuts off.

The TDS calculates the area under the current waveform as 20.7 A-sec. This is converted to 5.8 mA-h by dividing by 3600 s/h You can then compare this result to the mA-h capacity of your selected battery type to estimate operating times.

On the other hand, if you choose to calculate true energy consumption, you need to multiply the battery voltage and current, then measure the area under the power curve. The TDS calculates the instantaneous power waveform (400 mW/div) and measures the area under the curve. In this case the result is 58 W-s or 58 joules. While this seems like a large number, it's equivalent to running a 60 Watt light bulb for about one second! Finally, the TDS calculates the width of the power curve which measures the total event time of just over two minutes.

8. Measuring Instantaneous AC Resistance

Problem: In AC signals, a relevant parameter is often measurable only at a specific portion of the line cycle. It's difficult to interpret a cycle-location dependent parameter over many cycles of a continuous AC waveform.

Key TDS Features: Waveform division, FastFrame acquisition, and gated measurements.

Benefits: The FastFrame acquisition mode simplifies analysis of complex AC events by capturing only selected segments of successive cycles.

Several types of power electronics components exhibit time-varying resistance. For example, current limiting devices exhibit large resistance changes by design as a function of temperature variations due to resistive heating. The time constant associated with the variations may be a few seconds or even less than a second. Multimeters don't work because you can't use the meter's ohms mode with a live circuit. And while you could independently measure and divide the AC voltage and AC current levels through the component, you can't obtain dynamic information.

At first glance, the conventional digital scope might be the solution. By capturing both the AC voltage and AC current waveforms, you can divide the two waveforms and obtain the instantaneous resistance. This is shown in Figure 11 for the best known time-varying AC resistance – the incandescent filament. The two sinusoidal waveforms are the AC voltage (larger) and AC current; the TCP202 was set to 1A/div. The third waveform is the derived instantaneous resistance calculated using the TDS waveform division function. The problem is obvious. At the zero crossings of the AC waveform, the current goes to zero. This leads to a divide-by-zero condition twice per cycle. While this by itself is not a problem, it

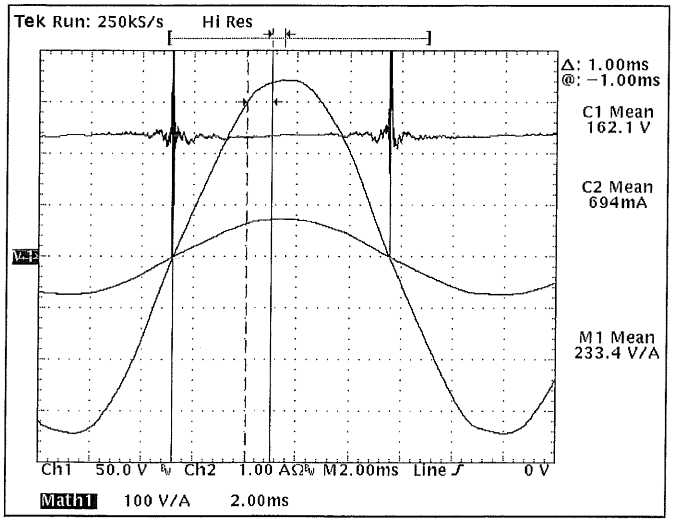


Figure 11. The two sinusoids show the line voltage and current to an incandescent filament. The TCP202 was set to 1 A/div. The third waveform is the instantaneous resistance calculated by dividing the voltage waveform by the current waveform (100 V/A or 100 Ω per div). The large excursions near the zero crossings result from the divide-by-zero condition. The cursors define a gated measurement interval of 1.0 milliseconds.

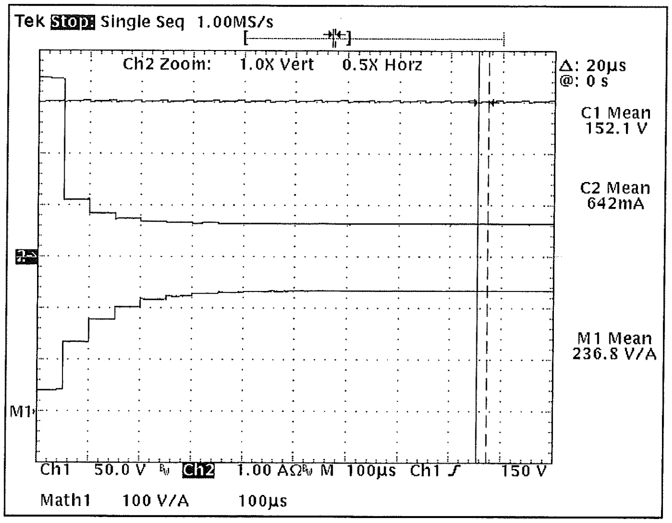


Figure 12. FastFrame was used to capture 50 point segments at the positive line peaks. Each segment was defined to start when the line voltage reached 150 V. Since the sampling rate was 1 MS/s, each segment represents a 50 microsecond sliver of a total line cycle. The twenty segments shown, requiring 1,000 total points, represent the information portion of a real-time interval of over 330 milliseconds (20 cycles / 60 Hz). The same information captured without FastFrame would have required a record length of 330,000 points.

makes interpretation much more difficult. In this case, we're only looking at about one line cycle. But if we had captured ten cycles, the display would be cluttered with these excursions to ±∞.

The TDS gated measurement function provides one approach to extracting the relevant information. We can choose to measure the voltage and current waveforms within a user-settable zone defined by the vertical cursors. In this case, we're near the positive peak of the cycle and the mean voltage (Ch 1) in the zone is 162 V and the mean current (Ch 2) is 694 mA. The TDS calculates the mean value of the divided waveform in the same zone as 233 Ω. Of course, you could obtain the same results by manually dividing the mean voltage and current values.

But this somewhat tedious process is greatly simplified by the TDS 500's FastFrame capability. Recall that the objective is to capture information only when it's valid. In this case, we'd ideally capture snapshots of the voltage, current, and resistance waveforms at the line peaks. Figure 12 shows the result for the lamp turn-on interval. The TDS was set to capture 50 μs snapshots when the line voltage reached 150 V. The sampling is then "disabled" until exactly one cycle or 16.7 ms later. The voltage waveform now appears as a straight line with a level of ≈150 V. The current snapshots change rapidly during the first few cycles and settle out to 642 mA. Since the voltage is constant in this example, the resistance waveform is proportional to the reciprocal of the current waveform and settles to a steady-state value of 237 Ω in less than 10 line cycles. You can still use the TDS gated measurement capability to scroll through the start-up waveform and measure values at different points in time. Of course, you need to keep in mind that each 50 μs line segment or frame is separated by one line cycle period.

One way to think of FastFrame is as a record-length multiplier. Power electronics is filled with measurement applications where the relevant information occurs at well defined instants of consecutive-line or switch-mode cycles. Rather than filling digital scope memory with extraneous information, FastFrame lets you apply your waveform memory only when it's needed. For further information on FastFrame, including an example of measuring the instantaneous cycle-by-cycle turn-on power in a switch-mode transistor, refer to Tektronix publication 55W-8861-0, ***FastFrame TDS 500A Segmented Memory***.

9. Capturing and Analyzing Power Converter Start-up Modes

Problem: Your digital scope doesn't have enough memory to capture an entire start-up event at a reasonable sampling rate.

Key TDS Features: Long record length and zoom.

Benefits: The TDS memory options enable both fast sampling rates and long recording times across all active channels.

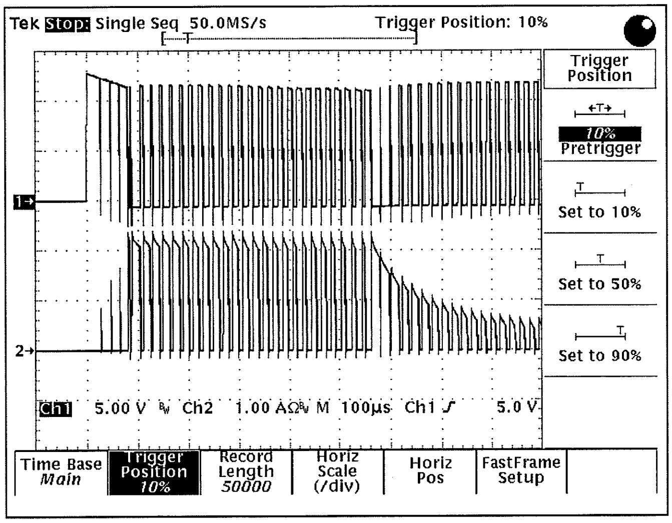
One of the most common applications for digital scopes in power electronics applications is to capture the start-up waveforms in a power converter. This is because the start-up interval often places the greatest electrical stress on circuit components. The single-sequence mode of the digital oscilloscope is required since you only get one chance to capture the entire event. That is, no two start-up events are exactly alike. The basic trade off in capturing single-sequence or single-shot events is controlled by the relationship:

$$\textbf{Record time (seconds)} = \frac{\textbf{Record length (samples)}}{\textbf{Sample rate (samples/sec)}}$$

The record time is a requirement set by your application. The sample rate and record length are specifications of the digital scope. The sample rate must be fast enough to capture the significant details of your waveforms. There is no absolute rule, but you should sample at least five times the bandwidth of your fastest signal. For line waveform measurements, sampling rate is usually not the limiting factor. A sampling rate of 10 kS/s is typically more than adequate. A record length of 5,000 points, for example, yields a record time of 0.5 seconds or 30 consecutive line cycles.

On the other hand for switch-mode electronics measurements, you must often trade off sample rate and record length to meet your record time requirement. Since bandwidth is not a typical specification in a power circuit, it's left to the scope user to select a sample rate based on experience and trial and error. For example, at first you should set all the instruments (TDS, TCP202, P5205) to their maximum bandwidth settings. Then you can observe if your signals appreciably change when you enable the various bandwidth limiting functions (e.g., 20 MHz bandwidth limit). In the same way, you can lower the TDS sampling rate and determine if you're losing high-frequency waveform detail or measurement resolution. Any loss of resolution is given back as an increase in the record time. This is generally an iterative process.

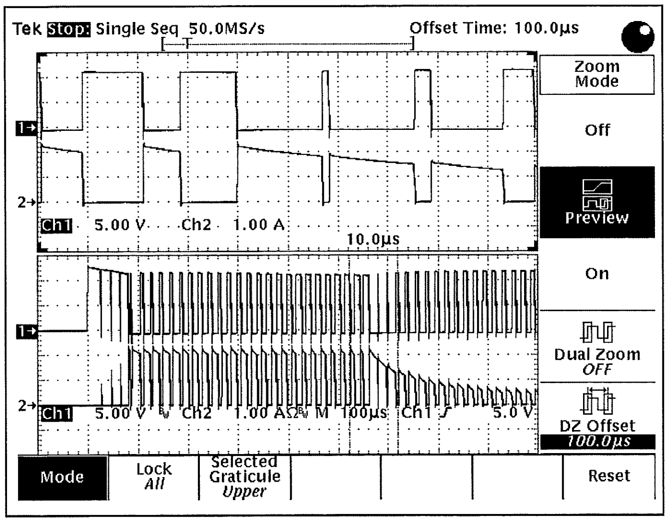
This trade off has become less of an issue as each digital scope generation brings longer standard and optional record lengths. Figure 13 illustrates a typical result. The upper waveform is the reverse voltage on a Schottky catch diode in a switch-mode converter. The lower waveform is the diode forward current. The start-up interval is about eight horizontal divisions or 800 µs. In this case, we set the TDS to a record time of 1 ms and a record length of 50,000 samples. This enables a sampling rate of 50 MS/s. After the entire event is captured, you can use the TDS zoom function to expand the waveform to view the long forward-current pulse about 550 µs into the start-up interval. Figure 14 shows the original waveforms expanded horizontally 10 times (upper


Tek Stop: Single Seq 50.0MS/s Trigger Position: 10%

Ch1 5.00 V ∿ Ch2 1.00 AΩ∿ M 100µs Ch1 ∫ 5.0 V

Time Base Main | Trigger Position 10% | Record Length 50000 | Horiz Scale (/div) | Horiz Pos | FastFrame Setup

Figure 13. The upper waveform is the reverse voltage on a Schottky diode in a switch-mode converter. The lower waveform is the diode's forward current from the TCP202. The entire ≈1 millisecond start-up event is captured using a 50,000 sample record length. The 50,000 sample record length enables a sampling rate of 50 megasamples per second on each channel.


Tek Stop: Single Seq 50.0MS/s Offset Time: 100.0µs

Ch1 5.00 V Ch2 1.00 A 10.0µs

Ch1 5.00 V ∿ Ch2 1.00 AΩ∿ M 100µs Ch1 ∫ 5.0 V

Mode | Lock All | Selected Graticule Upper | Reset

Figure 14. After capturing the start-up event, the zoom function permits both horizontal and vertical expansion of the record. At a horizontal expansion of 10X, we can more carefully study the long turn-on pulses two-thirds of the way through the start-up interval. Note that the dotted vertical lines 62 and 72 µs into the lower screen. This identifies the 10 µs zoom window displayed in the upper screen.

screen) and the original waveforms (lower screen). In other words, we're now viewing 100 microseconds of data or 5,000 samples. We have enough horizontal timing resolution to analyze individual pulses. In fact, there are 500 samples of data in each of the ten horizontal divisions.

10. Separating Switching Ripple from Line Ripple

Problem: Output ripple in switch-mode converters masks the measurement of line-ripple feedthrough.

Key TDS Feature: Hi-Res acquisition.

Benefits: The TDS Hi-Res acquisition mode can attenuate switching ripple so the isolated line ripple can be quantified.

Measuring output ripple in traditional linear converters was simple because you could trigger your scope on the line voltage and the display would be locked on the line-frequency feedthrough. Switch-mode converters have confounded this measurement because the converter's output is swamped with switching frequency noise. Measuring the characteristics of the switching-frequency ripple is usually simple since you can readily trigger on the ripple voltage either at the output or at another node in the switch-mode circuit. But measuring the line-frequency ripple is a separate problem. This may be the more important measurement since the lower frequency ripple can introduce hum or close-in sidebands in audio or communications applications.

The upper waveform in Figure 15 shows the 120 Hz rectified line-frequency ripple into a DC-DC converter. The TDS calculates the 1.08 V peak-to-peak voltage of this signal. The middle waveform is the 5 V output voltage using conventional digital scope sampling. At a time base setting appropriate for viewing line ripple, the ≈50 kHz switching noise at 88 mV peak-to-peak dominates the display. There's no indication of any 120 Hz feedthrough voltage. But the lower waveform captures the same signal by using the TDS Hi-Res acquisition mode which unmasks the elusive ripple component! The switching noise is rejected and the 120 Hz ripple can be measured. The peak-to-peak feedthrough is 6 mV, representing an attenuation of 180-to-1 or 45 dB (i.e., 20 * log (1.08 V / 6 mV)).

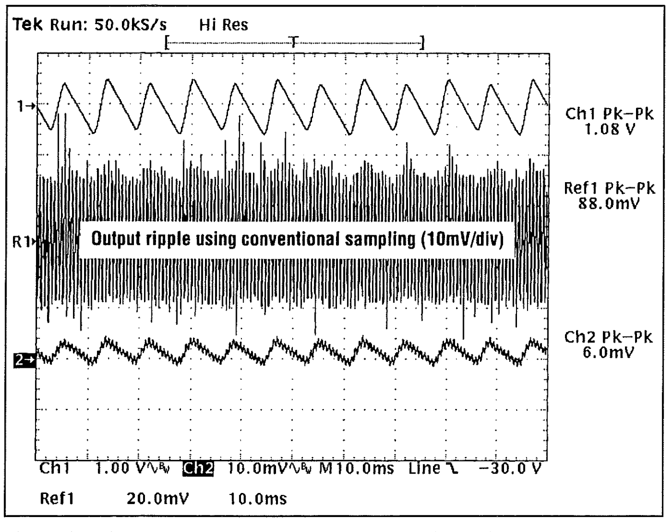


Figure 15. The upper waveform shows the 120 Hz input ripple to the DC-DC converter. The center trace shows the output ripple using conventional digital sampling. The switching frequency noise at about 50 kHz dominates the waveform. The lower waveform is the same signal acquired using the TDS Hi-Res acquisition mode. The switching ripple is rejected which reveals the 120 Hz feedthrough.

The TDS Hi-Res acquisition mode represents a breakthrough in power conversion measurements because it provides signal filtering capabilities beyond the traditional 20 MHz bandwidth limit. The relevant result of Hi-Res acquisition is that your signal is low-pass filtered in a manner consistent with your selected sampling rate. In Figure 15, the sampling rate of 50 kS/s is clearly inadequate (middle waveform) for acquiring the ≈50 kHz switching noise. But this is an appropriate rate for the 120 Hz component (upper waveform). The TDS filters the 50 kHz switching component using digital processing before displaying the result (lower waveform).

It's important to understand why waveform averaging wouldn't work in this application. For example, one might trigger the scope on the line voltage to synchronize acquisition to the line ripple and then enable waveform averaging to filter out the switching "noise." In principle, this would work if the switching ripple was random noise. Instead, it's a ripple voltage at the switching frequency. Since the switching frequency is asynchronous to the line frequency, the averaged waveform will exhibit a curious modulation with characteristics that vary over time.

11. Measuring Converter Output Impedance

Problem: Switching ripple at the DC output of a converter complicates output impedance measurements.

Key TDS Features: Hi-Res acquisition, FFT, and Calibrated DC offset.

Benefits: The TDS Hi-Res acquisition mode in conjunction with the FFT enable frequency-dependent output impedance measurements.

A power converter's output impedance is a useful indicator of stability and of compatibility with your specific load characteristics. There are many techniques for measuring impedance, but this technique specifically addresses the problem of measuring impedance in the presence of line and switching ripple. A signal generator is AC-coupled (e.g., 100 µF capacitor) into the loaded converter output. The TCP202 senses the current into the converter output while a standard passive probe senses the output voltage. The TDS measures the magnitude of the voltage and the current at the generator frequency. The ratio is the impedance.

Figure 16 illustrates this measurement at 100 Hz. The upper waveform is the +5 V output of the converter. The TDS DC offset capability was used to enable DC coupling of its input amplifier. Since there's a steady-state DC load at the output, the TDS calibrated DC offset was used to retain DC measurement information. The mean output voltage is +4.98 V. The second waveform is the current into the converter sensed with the TCP202 displayed at 50 mA/div. Once again, the TDS DC offset was used and the mean (DC) current is 320 mA into the resistive load. While the induced 100 Hz current is readily measurable, the 100 Hz voltage component is more complex. This is because the 120 Hz line feedthrough and noise are also present at the converter output. The TDS Hi-Res acquisition mode was used to attenuate the ≈50 kHz switching frequency ripple. The lower two waveforms are the FFT waveforms of the voltage and current. The FFT of the voltage clearly separates the 100 Hz induced voltage from the 120 Hz ripple. The TDS automatically measures just the 100 Hz component which is 2.24 mV (RMS). The same technique applied to the current yields a 100 Hz component of 14 mA (RMS). Thus, the impedance at 100 Hz is about 0.16 Ω.

Figure 16 shows the results at 10 kHz. The FFT of the voltage clearly separates the 10 kHz from the ≈50 kHz switching ripple. The induced voltage at 10 kHz is 17 mV while the current is 58 mA. In this case, the impedance is about twice as large or 0.3 Ω.

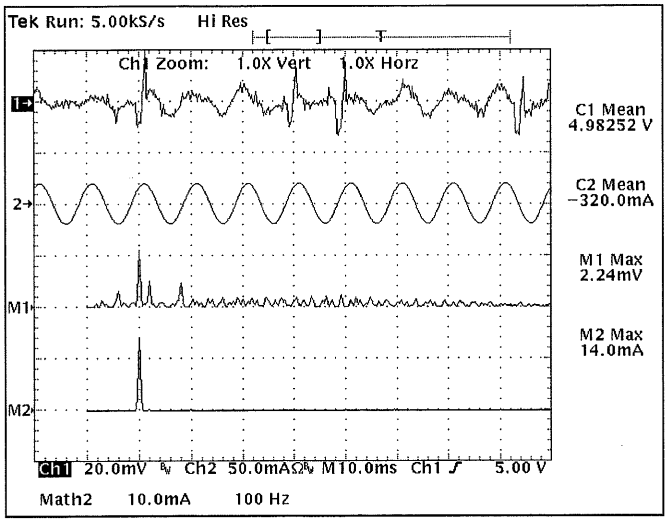


Figure 16. Upper two waveforms are the voltage and current at the +5 V output terminal. Horizontal scale is 10 ms/div. Lower two waveforms are the FFT of the voltage (2.0 mV/div) and the current (10 mA/div). The horizontal scale for the FFT waveforms is 100 Hz/div. The 100 Hz signal source induces a current of 14 mA and a voltage of 2.24 mV. The impedance at 100 Hz is ≈0.16 Ω (2.24 mV / 14 mA).

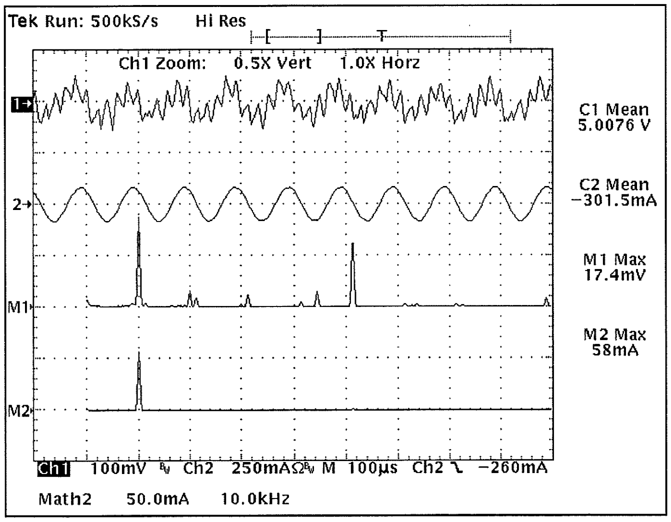


Figure 17. Upper two waveforms are the voltage and current at 100 µs/div. Lower two waveforms are the FFT of the voltage (10 mV/div) and current (50 mA/div). The horizontal scale for the FFT waveforms is 10 kHz/div. The 10 kHz signal source induces a current of 58 mA and a voltage of 17.4 mV. The impedance at 10 kHz is ≈0.3 Ω (17.4 mV / 58 mA).

12. Measuring Instantaneous Power in Switching Transistors

Problem: Displaying only the voltage and current waveforms in a switch-mode transistor doesn't characterize the instantaneous power dissipation in the device.

Key TDS Features: Waveform multiplication and automatic measurements.

Benefits: The TDS waveform processing and display capabilities readily translate the raw voltage and current waveforms into more meaningful power switching parameters.

Proper selection of switch-mode transistors in power converters requires a detailed understanding of both the steady-state and transient modes of operation. In particular, the start-up mode often places the greatest stress on devices. Dynamic measurements include verification of V_{gs} or V_{be} drive levels and corresponding V_{ds} or V_{ce} transitions. But the most useful dynamic measurement is the power dissipation during switching transitions. In particular, this is the relationship between V_{ds} and I_d or between V_{ce} and I_c.

Figure 18 illustrates the start-up cycle of a 40 kHz converter. The upper waveform is the drain-to-source voltage measured through the P5205. This is a floating measurement since neither terminal is at ground. The TCP202 senses the drain current at 500 mA/div. The TDS waveform multiplication function was used to generate the lower waveform representing instantaneous power. The displayed vertical scale factor for the power waveform is 25 W/div. The TDS calculates a peak power of 30 W during this initial turn-on transition. This was by far the worst case dissipation for the device. For example, the initial turn-off transition power near the end of the waveform was negligible.

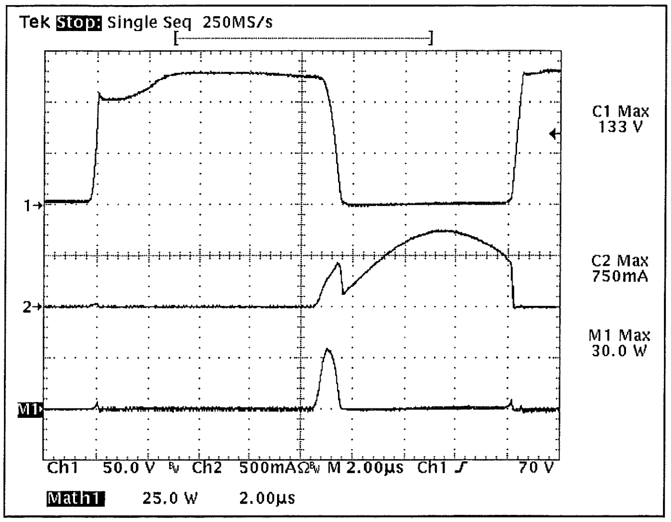


Figure 18. The upper waveform is the floating drain-to-source voltage measured with the P5205. The center waveform is the drain current measured with the TCP202 (500 mA/div). The TDS multiplication function generates the lower waveform showing the instantaneous power (25 W/div).

Calculating the instantaneous power waveform in switch-mode converters is a classic example of the big number/small number relationship. The blocking voltage is large during cut-off when no current flows. Conversely, there's a small saturation voltage when the device conducts the maximum current. This means that any small DC offsets in the voltage or current measurements can lead to gross numerical errors. Typical symptoms of offset problems include excessive power during cut-off or negative power measurements. When you use the TCP202 and the P5205 with the TDS, perform the following simple step before any instantaneous power measurement. Set the TDS to measure the mean of both the voltage and current waveforms. Set the TCP202 and P5205 to the sensitivity settings that will be used for the measurement. Then, with the device-under-test turned off, use the DC offset adjustment on the TCP202 and the P5205 to null the mean level for each waveform. Always be sure that all three instruments have passed their warm-up interval.

13. Monitoring Core Saturation

Problem: Display of only the voltage and current waveforms in an inductor do not directly reveal core saturation activity.

Key TDS Features: Waveform integration, X-Y display, and zoom.

Benefits: The TDS waveform processing and display functions enable the direct display of an inductor's cycle-by-cycle saturation activity.

Component analyzers readily characterize the out-of-circuit parameters of magnetic elements such as inductors and transformers. Measuring in-circuit dynamics is more challenging but offers valuable insight for start-up and other transient operating modes. One particularly useful measurement is the relationship between a magnetic core's flux density (B) and its field intensity (H). For example, this parametric relationship graphically indicates magnetic saturation which can lead to excessive current flow and thermal runaway in switching transistors. Measuring this relationship in-circuit helps to verify that the core parameters were properly selected for start-up operation where the likelihood of saturation is generally the greatest.

Figure 20 shows the first step of the two-step process for a toroidal inductor during start-up in a 40 kHz converter. The field intensity in the core is directly proportional to the winding current. The TCP202 senses the current (2.84 A pk-pk). The flux density is proportional to the integral of the voltage across the inductor. The P5205 senses the floating voltage since neither side of the voltage is ground. The TDS waveform integration function is used to generate the center waveform which is the time integral of the voltage. Notice from the pk-pk measurement that the units of the integrated waveform are Volt-seconds. The next step (Figure 21) is to plot the integral of the voltage against the current. The TDS X-Y display mode is used to plot this parametric relationship. The onset of saturation – or the point where flux density no longer increases linearly with field intensity – is now evident. In Figure 20, the '[ ]' brackets above the display show that this X-Y plot is displaying only 20% or 50 µs of the information of the total 250 µs waveform record. In the X-Y mode, you can use the TDS Zoom function to scroll through a reduced time segment of the total waveform. In other words, you can follow the B-H loop as the circuit drives the core.

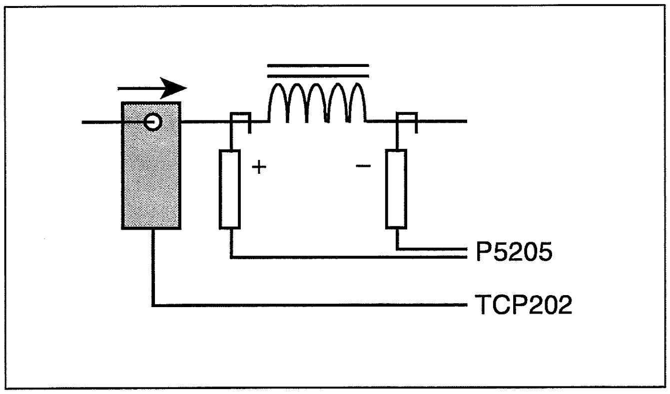


Figure 19. Connecting the P5205 and the TCP202 probes to the inductor under test.

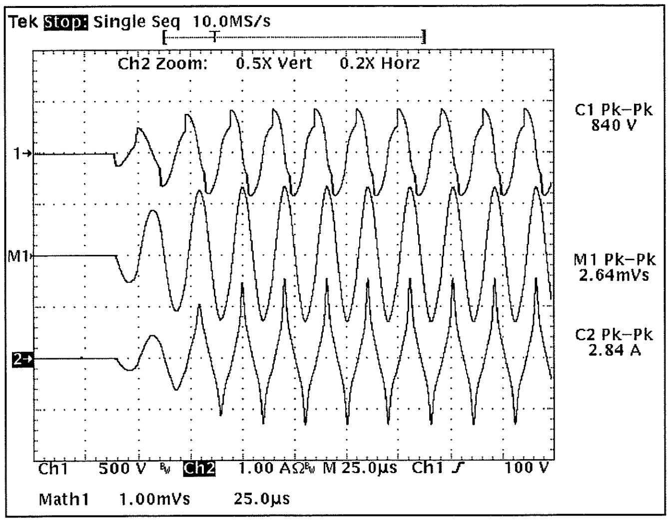


Figure 20. Upper waveform is the floating voltage across the inductor measured with the P5205. The peak-to-peak voltage is 840 V. Center waveform is the integral of the voltage. This is scaled directly with the voltage waveform so the peak-to-peak value is 2.64 mV-sec. Lower waveform is the inductor current. The TCP202 current waveform is displayed at 1.0 A/div. The peak-to-peak current is 2.84 A.

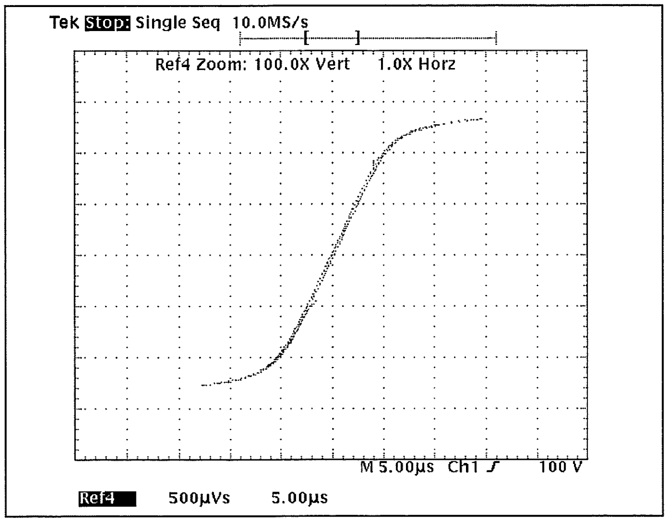


Figure 21. The flux density (integral of the voltage) is plotted against the current. The flux density is 0.5 mV-sec/div, the field intensity is 0.5 A/div. You can use the TDS zoom function to scroll through slices of the start-up waveform to watch how the core enters and exits saturation.

Glossary

Apparent Power – The product of the RMS voltage and RMS current values expressed in Volt-Amps. The ratio of the apparent power to the true power is the power factor.

Crest Factor – The ratio of a signal's peak value to its RMS value. The crest factor of a pure sine wave is $\sqrt{2}$.

FastFrame – A waveform recording technique available in TDS scopes that enables only selected segments of a complex waveform to be saved into record memory. This simplifies the analysis of complex waveforms and multiplies the effective record length of the scope. FastFrame is particularly useful in power electronics since critical measurements often occur at a fixed point in the power-line or switch-mode cycle. Refer to Tektronix publication 55W-8861-0, ***FastFrame TDS 500A Segmented Memory***.

FFT – Fast Fourier Transform. An algorithm which transforms a sequence of values spaced in time to or from a sequence of values spaced in frequency. This is particularly useful in power measurement applications for calculating the harmonic content of line signals. Refer to Tektronix publication 55W-8815-0, ***FFT Applications for TDS***.

Hi-Res Acquisition – A TDS sampling technique that provides inherent low-pass filtering and can improve measurement resolution. If an application only requires a sample rate of 10 Megasamples per second, the TDS nevertheless samples at the full rate of 1 Gigasample per second and averages 100 samples to obtain a 10 Megasample per second result. The extra 99 samples yields a higher resolution result. This acquisition technique is particularly useful in power-electronics applications. First, most applications don't require the maximum sampling rate of the scope so Hi-Res provides waveforms with higher resolution. The basic 8-bit resolution of the TDS family can be increased to more than 12-bits. Second, the traditional 20 MHz bandwidth limit capability is often not low enough in power applications. The Hi-Res mode effects a low-pass filter that is a function of the selected sample rate. The roll off is not monotonic (it follows a (sin x) / x function), but it provides less than 2% (0.17 dB) attenuation for signals less 10% of the sampling rate. The 3 dB attenuation occurs at about 45% of the sample rate. There will be >20 dB of attenuation at three times the sampling rate and >30 dB of attenuation at 10 times the sampling rate.

Instantaneous Power – The product of the voltage and current at any point in time expressed in Watts. Instantaneous power can be negative. In a digital scope, the instantaneous power waveform can be calculated by multiplying each voltage sample with its corresponding current sample.

Power Factor – The ratio of the true power to the apparent power. Power factor is between 0 and 1. For a sinusoidal voltage and current pair, the power factor is the cosine of the phase angle between the two waveforms.

RMS – Root mean squared value. The RMS value of an AC voltage equals the DC voltage that would cause identical heating in a resistive load. Digital scopes calculate the RMS value of a series of samples over a user-defined interval. First, all the sample values are squared. Then the square root of the average squared value is calculated. RMS is never negative. The most common RMS measurements are for current and voltage.

True Power – The average instantaneous power in Watts. In digital scopes this is calculated by taking the average value of the instantaneous power waveform over a user-defined interval.

Helpful Reminders on Optimizing Measurements

For the most accurate results when using the TCP202 and/or the P5205 with the TDS digital scope, follow these guidelines.

- Always use calibrated instruments and allow the instruments to pass their specified warm-up intervals.
- Degauss the TCP202 probe before each critical current measurement.
- Twist the input leads of the P5205 together to maximize rejection of common-mode signals. Twisting the input leads helps to cancel noise that is induced into the input leads and to improve the high-frequency response of the inputs.
- Carefully determine the effect of probe impedance on your circuit. While the TCP202 employs clip-on probes that sense current with galvanic isolation, it presents a complex impedance to the measured circuit. Likewise, the impedance of voltage probes decreases with frequency. The data sheets for Tektronix probes provide impedance vs. frequency information.
- Trim DC offsets using the TCP202's zero-adjust control before critical measurements. With no current flowing through the circuit-under-test, use the TDS "Mean" measurement function to measure the output level of the TCP202. Use the zero-adjust control to adjust the measured level to 0 Volts. The same technique applies to the P5205. In both cases, the DC offset control is an adjustment on the probe's compensation box.
- Insure that the input levels don't exceed the measurement range of the scope and/or probe. The TDS displays a "clipping" message if signals exceed the scope channel's input range. If this message is displayed, any automatic measurements should be ignored. The P5205 has an audible indicator when an overrange is detected.
- Understand the insertion delay characteristics of the TCP202 and the P5205. There's a signal delay from the current probe or differential probe to the scope. The TCP202 delay is ≈ 17 ns. The P5205 delay is also ≈ 17 ns. However, the delay of a conventional 10X passive probe will be smaller. Differences in insertion delay for two signal channels supposedly measuring the identical event lead to a time skewing of the displayed waveforms. When the relative delay is large compared to the transition times of the current and voltage waveforms, this can lead to errors in calculating the instantaneous power waveform. This is particularly true when calculating the turn-on and turn-off switching losses in switch-mode power transistors. In these cases, you may need to use the TDS's built-in waveform deskewing function.

***NOTE:** This application note is written around the P5205 Differential Probe, the TCP202 Current Probe, and the following oscilloscopes*

- *TDS 520B*
- *TDS 540B*
- *TDS 724A*
- *TDS 744A (S/N B040100 and higher)*
- *TDS 784A (S/N B040100 and higher)*

If these probes are used with other TDS scopes in the Tektronix 400, 500, 600, or 700 series, the values displayed on the screen will be correct but the units-of-measure will show V instead of A and VV instead of W.

Related Publications

For additional information on the products and measurements referenced in this application note, refer to the following publications:

A6905S Data Sheet, Tektronix literature number 51W-8987-0.

A6906S Data Sheet, Tektronix literature number 51W-9086-0.

A6907/A6900 Data Sheet, Tektronix literature number 51W-10376-0.

ADA 400A Differential Preamplifier Data Sheet, Tektronix literature number 60W-10387-1.

Differential Oscilloscope Measurements Application Note, Tektronix literature Number 51W-10540-0.

Floating Measurements Solution Guide, Tektronix literature number 51W-10457-1.

P5200 Data Sheet, Tektronix literature number 51W-10388-1.

P5205 Data Sheet, Tektronix literature number 51W-10712-0.

Power Electronics System Data Sheet, Tektronix literature number 51W-10795-0.

TCP202 Data Sheet, Tektronix literature number 51W-10736-0.

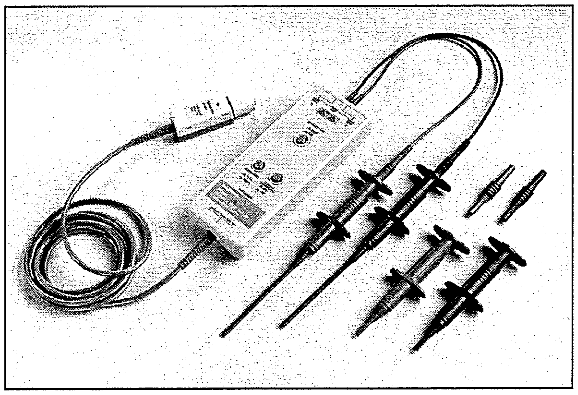
TDS 400/500/600/700 Options Brochure, Tektronix literature number 55W-10794-0.

TDS 500B/600A/700A Digitizing Oscilloscope Series Brochure, Tektronix literature number 55W-10333-1.

TDS 500B/600B/700A Series Digitizing Oscilloscopes (500 MHz) Data Sheet, Tektronix literature number 55W-10336-2.

TDS 680B/684B/784B Digitizing Oscilloscopes (1 GHz) Data Sheet, Tektronix literature number 55W-10065-2.

Product Specifications

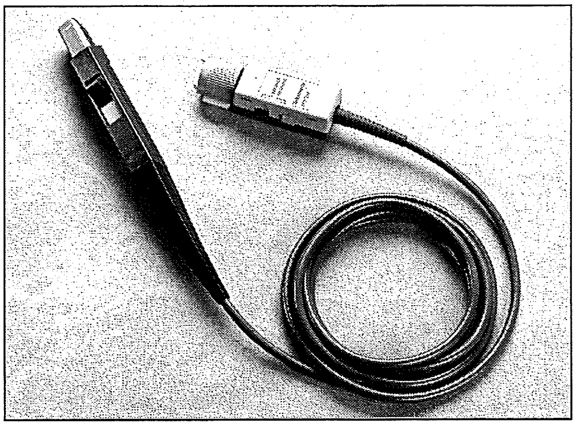


P5205 High Voltage Differential Probe

The P5205 provides exceptional differential measurement capability and can measure floating signals to 1300 V. The probe is well suited for making floating measurements on switched power supplies and motor drives.

P5205 Features

- 100 MHz bandwidth
- 1300 V maximum tip-to-tip
- ±1000 V tip-to-ground
- 80 dB CMRR @ 60 Hz
- 17 ns propagation delay

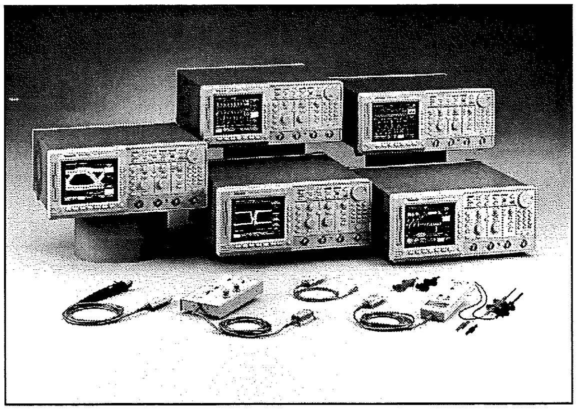


TCP202 DC-coupled Current Probe

The TCP202 provides simultaneous AC/DC measurements from DC to 50 MHz. This probe has a 500×10^{-6} Amp∗Sec product rating and is ideal for measuring currents in switching power supplies, motor controllers, and other power-conversion products.

TCP202 Features

- DC to 50 MHz bandwidth
- 50 A maximum pulse current
- 15 A maximum DC + pk AC
- 1% accuracy with calibrator
- 17 ns propagation delay



TDS Series Digitizing Oscilloscopes

The TDS 520B, TDS 540B, TDS 724A, TDS 744A, and the TDS 784A digitizing oscilloscopes, with bandwidths ranging from 500 MHz to 1 GHz, all incorporate the InstaVu™ acquisition system. They provide a host of precision testing, automatic measurements, differentiation, and integration.

TDS Series Features

- 500 MHz to 1 GHz bandwidths
- InstaVu acquisition
- 2 and 4 channels
- 500 MS/s to 4 GS/s sample rates
- TekProbe interface
- Monochrome and color displays
- 25 auto measurements
- ±25 ns deskew

For further information, contact Tektronix:

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