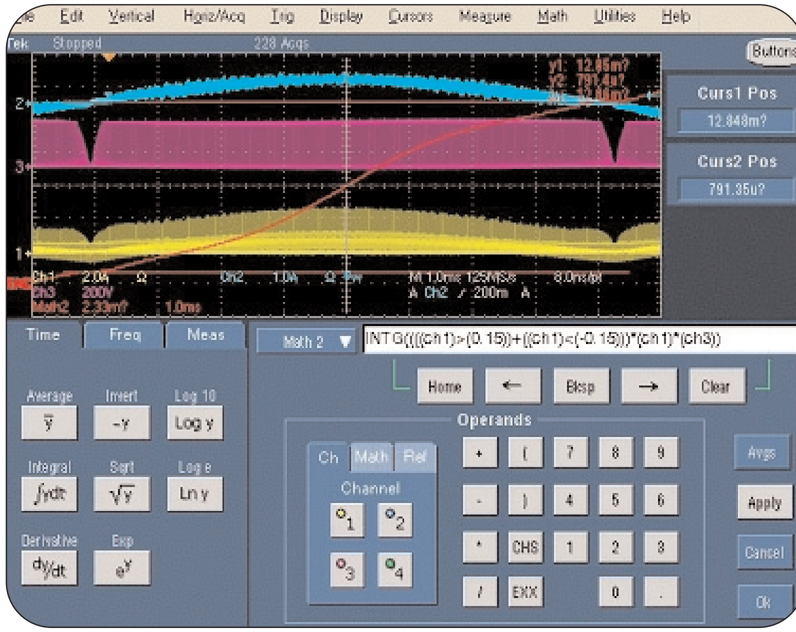


COMPUTING

COMMUNICATIONS

VIDEO

Using Real-time Oscilloscopes To Make Power Electronics Measurements

TDS7000 Series digital phosphor oscilloscopes enable the measurement and analysis of waveforms of power electronics devices and systems in ways that traditionally were not practical.

Introduction

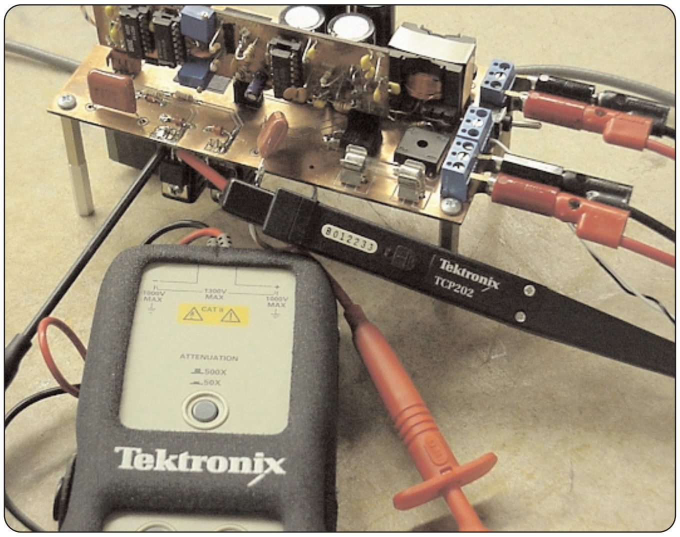
Real-time oscilloscopes with long record length can capture and display details of the switching transitions of high-frequency switched-mode power supplies, even through transients lasting many milliseconds. High-resolution details of up to four waveforms can be recorded during start-up or protection modes, or over the entire AC line period of a power-factor-corrected off-line rectifier system. Some real-time oscilloscopes have powerful built-in waveform math features that allow the performance of computations, such as instantaneous or average power loss, or harmonic spectrum, with the results displayed directly on the oscilloscope screen. Waveform math can also be used to improve the accuracy of measurements.

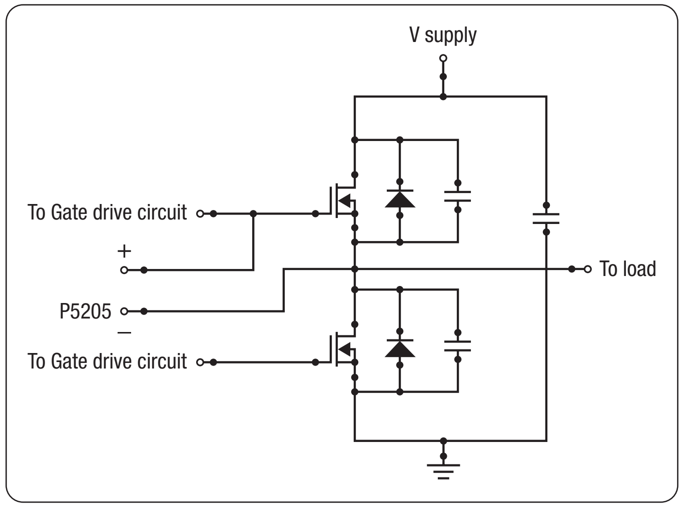
High-voltage differential probes, as well as DC current probes, plug directly into the front panel of some real-time oscilloscopes, allowing floating measurements of switched-mode power supply waveforms. A calibration test fixture can allow automatic calibration and setting of zero levels for all probes.

Some real-time oscilloscopes have a built-in, Windows-based PC system that simplifies the transfer of data from the oscilloscope to a personal computer (PC). Waveforms can be exported as bitmapped files and used directly in text-editing or presentation programs. Numerical data can be exported to the PC for further analysis using spreadsheet or mathematical programs. These files can also be transported to other computer systems using the built-in floppy disk drive or the built-in Ethernet connection. These features can be used to document transient and protection modes of two converter systems, or to analyze core loss.

This application note discusses the use of the TDS7000 Series oscilloscope in power electronics applications, enabling you to unleash the full power of this instrument to measure things such as ripple, average power loss, AC current line harmonics, and *B-H* characteristics.

Table of Contents





▶ ***Figure 1.*** *Half-bridge circuit.*

Capturing and Analyzing High-Side Gate Drive Waveforms

In switching converters that contain transistors that are not referenced to ground, it is difficult to capture the waveforms of the gate driver circuit. For example, Figure 1 illustrates a half-bridge circuit whose high-side MOSFET is not referenced to ground. Measurement of the gate-to-source voltage produced by the high-side driver is needed to verify correct operation.

A standard voltage probe cannot be connected to directly measure the gate-to-source voltage because the ground terminal of the probe is connected to earth ground through the oscilloscope and its power supply. "Floating" the oscilloscope by disconnecting its safety ground is an unsafe practice; furthermore, such a practice would yield an incorrect measurement here because common-mode capacitors within the oscilloscope power supply would disrupt the operation of the circuit being measured.

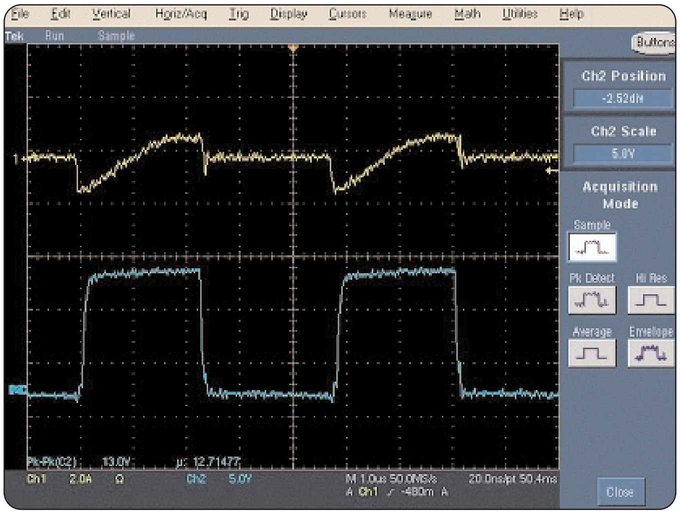
Two standard voltage probes can be used to measure the gate-to-ground and source-to-ground voltages, respectively. The gate-to-source voltage is then found by subtracting the channels, removing the common-mode signal (i.e., the source-to-ground voltage). This approach is unsatisfactory when the gate-to-source voltage is much smaller than the supply voltage due to inadequate common-mode rejection and the tendency of the common-mode signal to saturate the input amplifiers.

The TDS7000 Series can be used to capture and analyze high-side gate drive waveforms in a half-bridge circuit by measuring high-frequency floating voltages using the P5205 high-voltage differential probe. The P5202 probe allows safe, highly accurate measurements of floating voltage signals. It also enables clear and accurate measurement of high-speed transitions while providing excellent common-mode rejection. Its high input impedance and low capacitance at both inputs allows it to safely measure floating voltages in switching power supplies (up to a maximum of 1300 V between the inputs for the P5205 probe).

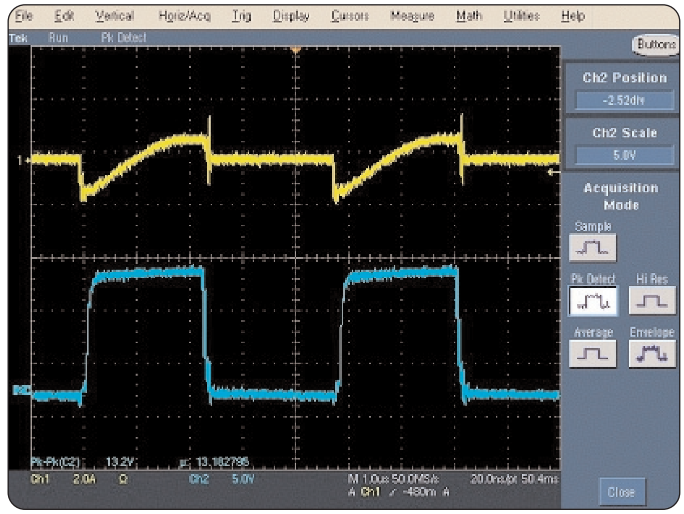
Setup

Before taking any measurements, the TCP202 current probe must be calibrated using the probe calibration fixture. In addition, the P5205 high-voltage differential probe output must be adjusted to zero using the procedure given in its instruction manual.

1. Set P5205 high-voltage differential probe to measure the high-side gate-to-source voltage waveform (see Figure 1).
2. Set TCP202 current probe to measure the drain current of the same device.
3. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
4. Select "Acquisition" and set as necessary to "Sample" or "Peak Detect" (see Figure 2).
5. Select "Horizontal" and set the "Sample Rate" to 50 MS/s.
6. Set trigger as "Auto Trigger" and press the "EDGE" and "POS" slope (rising edge) buttons on the oscilloscope front panel.



▶ ***Figure 2a.*** *Measured signals using sample mode. Channel 1 (yellow trace): drain current, 2 A/div. Channel 2 (blue trace): gate-to-source voltage, 5 V/div.*



▶ ***Figure 2b.*** *Measured signals using peak detect mode. Channel 1 (yellow trace): drain current, 2 A/div. Channel 2 (blue trace): gate-to-source voltage, 5 V/div.*

Figure 2 illustrates the measured waveforms. Channel 1 (yellow trace) displays the MOSFET drain current at 2 A per division. Channel 2 (blue trace) displays the high-side gate-to-source waveform at 5 V per division. For these measurements, the supply voltage was approximately 200 V. The attenuation range of the probe was set on 50X for better signal resolution. The audible overrange was kept "ON" and the bandwidth set to "FULL".

Figure 2a shows that the maximum gate-to-source voltage is 14.75 V and minimum is – 1.3 V, which is sufficient to ensure proper turn-on and turn-off of the device. These waveforms employ the default sample mode in which the waveforms are sampled at the selected rate.

As a further check of the gate drive waveform, the peak detect mode can be employed, as in Figure 2b. In this mode, the waveforms are sampled at a 2.5 GS/s sample rate, and the extreme (maximum and minimum) values are alternately stored. For example, at the 50 MS/s rate selected in Figure 2b, waveform data is stored every 20 ns. Each stored data point represents the maximum or minimum value of the (2.5 GS/s) / (50 MS/s) = 50 samples taken over the 20 ns period. The resulting display provides an additional check on whether noise or ringing is being missed in the sampling process. Figure 2b illustrates that the gate drive waveform appears to be sufficient to properly switch the MOSFET. The sample, peak detect, and other acquisition modes are further discussed in the section titled *Separating Switching Ripple from Line Ripple*.

To save the measured waveforms in a file usable by PC applications, use the following export commands under the File menu. The Select for Export command allows you to specify whether to export numerical waveform and measurement data, or bitmapped images of the graticule or entire screen area. The Export Setup command allows you to choose the file format; bitmap (.bmp) and jpeg (.jpg) formats are available for bitmapped images, while .txt, .csv, and .dat formats are available to export numerical data to applications including word processors, spreadsheets (Excel, Lotus 1-2-3, Quattro Pro), and mathematical applications (MATLAB, Mathcad). Finally, the Export command allows you to save the file to disk.

Capturing and Analyzing Protection Modes in a Current-Mode Controlled DC-DC Converter

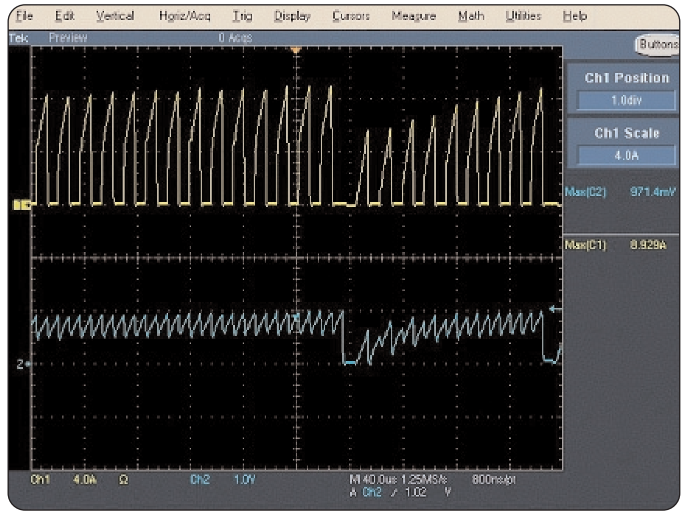
The TDS7000 Series' high-resolution acquisition, long record length and high sample rate makes it the ideal tool to capture and analyze protection modes in a current-mode controlled DC-DC converter to determine whether cycle-by-cycle current limiting circuitry functions correctly. This instrument allows easy capture of transients with exceptional resolution, ideal for viewing the operation of cycle-by-cycle current limiting in a current-mode controlled converter.

Setup

The TCP202 current probe and P6139A voltage probe must be calibrated using the probe calibration fixture before taking any measurements.

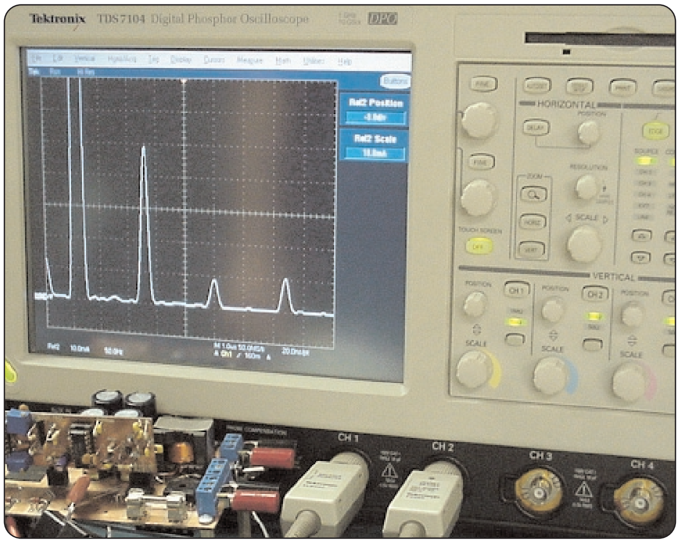
1. Set P6139A voltage probe to measure the voltage waveform input to the overcurrent comparator.
2. Set TCP202 current probe to measure the drain current of the MOSFET.
3. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
4. Select "Acquisition" and set to "Hi Res".
5. Set trigger as "Single Trigger" in "Normal" mode and press the "EDGE" and "POS" slope (rising edge) buttons on the oscilloscope front panel.
6. Adjust the record length long enough to capture the current protection mode waveform.

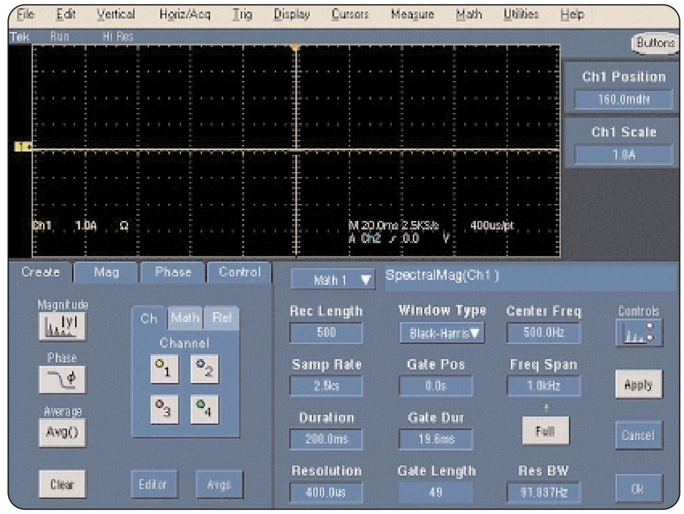
In Figure 3, Channel 1 (yellow trace) is the drain current of the device set on 4.0 A per division and Channel 2 (blue trace) is the waveform at one of the inputs of the overcurrent comparator set on 1.0 V per division. The trigger is set on Channel 2 at 1.02 V level.



▶ ***Figure 3.*** *Overcurrent protection in a current-mode controlled converter. Channel 1 (yellow trace): MOSFET drain current, 4 A/div. Channel 2 (blue trace): voltage input to overcurrent comparator, 1 V/div.*

The voltage at this input of the comparator is directly proportional to the drain current of the device. The comparator has a reference of 1.0 V. Hence as the drain current increases beyond the user-selected reference limit (1.0 V in this case), the voltage at Channel 2 increases. As soon as this voltage crosses the reference of 1.0 V, the overcurrent comparator sets a latch such that the gate drive signal to the device becomes low (i.e. turned off). Hence the drain current becomes zero and the whole process of soft-starting the converter is repeated again. The overcurrent comparator also ensures a complete discharge of the soft-start capacitor before allowing the restart process. The oscilloscope's long record length makes it easy to observe the circuit behavior exactly before and after the current protection mode action starts.





▶ ***Figure 4.*** *Spectral analysis setup window.*

Measuring Line Current Harmonics in a Power-Factor Corrected (PFC) AC-DC Rectifier

Equipped with decimal record length, Fast Fourier Transform (FFT) math and automatic measurements, the TDS7000 Series is a superior tool to measure AC line current harmonics in a power-factor corrected (PFC) AC-DC switched-mode rectifier.

The oscilloscope's math capabilities include spectral analysis of the waveform in both the time and the frequency domains. The frequency domain controls resemble those of traditional spectrum analyzers, with the ability to set the center frequency, span and resolution bandwidth. The oscilloscope uses the FFT function to plot the magnitude and phase spectra of a measured waveform. Here we plot the harmonic magnitudes of the measured AC line current waveform.

Setup

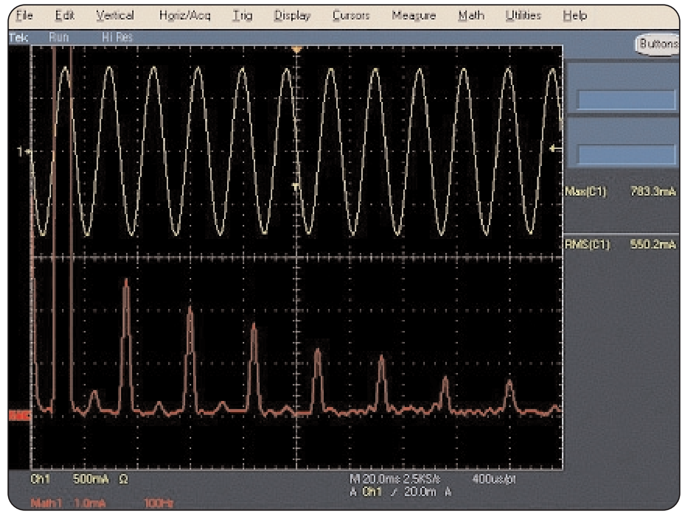
The TCP202 current probe must be calibrated using the probe calibration fixture before taking any measurements.

1. Set the TCP202 current probe to measure the input line current. Accuracy of the measurement is maximized when the vertical scale is adjusted so that the waveform fills the screen without saturating the input amplifier and A/D converter. See Step 4 of the section titled *Separating Switching Ripple from Line Ripple* for a way to adjust the vertical scale using peak detect mode.
2. From the "Math" menu, select "Math Setup" and then "Spectral Analysis Setup" (see Figure 4).
3. In "Window Type", select "Black Harris". There are 8 different spectral analyzer window types. Each window type affects the shape of the spectral analyzer response in the frequency domain. Therefore, this selection is made based solely on the characteristic of each window type.
4. Set "Frequency Span" to 1 kHz.
5. Set "Center Frequency" to 500 Hz. This will cause the horizontal scale to become 100 Hz/div.
6. Select "Mag" and set to "Linear".
7. Set the Math 1 function as SpectralMag(Ch1), as follows: from the "Create" palate, click on "Magnitude" and then "Ch1".
8. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
9. Select "Acquisition" and set to "Hi Res".
10. Set trigger as "Auto Trigger" and press the "EDGE" and "POS" slope (rising edge) buttons on the front panel.
11. Click "Apply".

Figure 5 illustrates the results. Channel 1 (yellow trace) is set to measure the input current at 500 mA per division. M1 is the Math 1 waveform (red trace) showing the current harmonic magnitudes produced by the converter. The FFT includes the 60 Hz AC line frequency and its harmonics.

The horizontal scale for the Math 1 waveform is measured in units of Hz, and is adjusted to 100 Hz per division, starting at 0 Hz (DC) on the left of the screen. The vertical units for this measurement are set to 1 mA per division. This choice causes the fundamental amplitude to be off scale, but it allows the harmonic magnitudes to be read with greater accuracy. Note that Math waveforms can be off scale without compromising the integrity of the original waveform acquisition.

Note that the FFT algorithm requires that the horizontal scale of the current waveform be set such that many cycles (approximately 10) are displayed on the screen. If desired, a magnified view of the current waveform can still be obtained using the zoom function.



▶ ***Figure 5.*** *Measured line current waveform and its spectrum. Channel 1 (yellow trace): line current, 500 mA/div vertical scale, 20 msec/div horizontal scale. Math 1 (red trace): magnitude spectrum, 1.0 mA/div vertical scale, 100 Hz/div horizontal scale.*

Monitoring Core Saturation and Displaying *B-H* Characteristics

The TDS7000 Series can be employed to monitor core saturation and to display *B-H* characteristics under both test and operating conditions by using its waveform integration math function and exporting the waveform numerical data into an Excel spreadsheet or other data analysis tool.

This high-performance oscilloscope can be used to export waveforms, images and measurements in several formats, which can then be used for further analysis with other application tools. For this particular measurement, the .csv format (comma separated value) is used; this format can be directly imported into an Excel spreadsheet. The waveforms exported by the .csv format do not contain timing and scaling information; instead, the waveform is exported as values with amplitudes but without units. The data is written to the file in sequence, from the first sample of the waveform to the last sample.

The relationship between the flux density *B* and the magnetic field intensity *H* of the core material is important to the design of an inductor or transformer. The slope of this characteristic is the permeability μ of the core material, which influences the inductance. The core material saturates at high flux densities, leading to greatly reduced permeability and inductance. The area contained within the *B-H* loop is equal to the energy lost per cycle (core loss) in a unit volume of core material. Measurement of *B* vs. *H* allows verification of the core loss and saturation (or lack thereof) of the magnetic elements in a switching converter. Such measurements can even be performed on an inductor within an operating converter.

Faraday's law relates the flux density *B* to the integral of the voltage applied to a winding. Hence, we can measure *B(t)* by acquiring and integrating the winding voltage waveform. Ampere's law relates the magnetic field strength *H* to the winding current (or, in a multiple-winding element, to the total ampere-turns of all windings). We can measure *H(t)* by acquiring the current waveform using a DC current probe. For a multiple-winding device, the current probe can be clipped onto all of the windings at once (if there is a turns ratio other than 1:1, then multiple turns must be put through the current probe, according to the turns ratio).

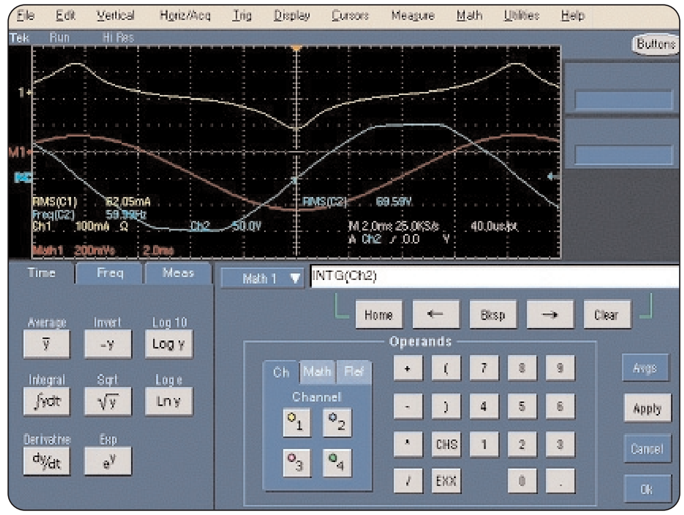


Figure 6. *The waveform integration window.*

Setup

Before taking any measurements, the TCP202 current probe must be calibrated using the probe calibration fixture, and the P5205 high-voltage differential probe output must be adjusted to zero.

1. Set the TCP202 current probe to measure the primary winding current of transformer.
2. Set the P5205 voltage probe to measure the secondary side voltage.
3. Select "Acquisition" and set to "Hi Res". Adjust the record length to fit one complete input cycle in the screen.

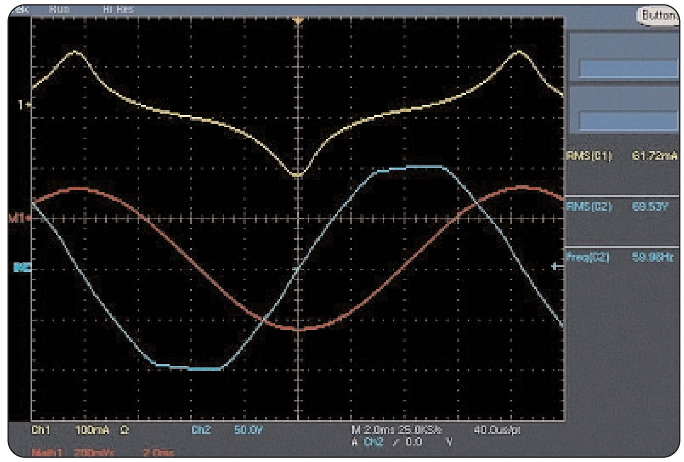
Integration of the voltage waveform:

4. From the menu bar, select "Math", then select "Equation Editor" control window.
5. In this window, select "Time" and select "Integral".
6. Then from the "Math" menu, select "Math 1". In the space next to "Math 1" you should see "INTG(Math 1)" (see Figure 6). Click "Apply".
7. Set trigger as "Single Trigger" in "Normal" mode and press the "EDGE" and "POS" slope (rising edge) buttons on the oscilloscope front panel.

To export the waveform data to a file readable by Excel, follow the sequence below:

8. From the menu bar select "File", then select "Select For Export" and select "Waveform(data)".
9. From the menu bar select "File", then select "Export Setup" control window.
10. From the "Export Setup" control window, select "Waveforms".
11. Within the "Data Destination" field, select "Spreadsheet CSV".
12. From the "Source" select the channel/math waveform which needs to be exported (e.g., in this measurement select Channel 1 for the current waveform and Math 1 for the integrated voltage waveform).
13. From the "Waveform Curve Data Slope" select "All".
14. Finally, select "Export".

Figure 7 illustrates the measured waveforms for a transformer. Channel 1 (yellow trace) is the primary winding current set at 100 mA per division. Channel 2 (blue trace) is the secondary voltage set at 50 V per division and Math 1 (M1 – red trace) is the integral of the voltage waveform set at 200 mV per division.



▶ ***Figure 7.*** *Measured transformer waveforms. Channel 1 (yellow trace): primary winding current, 100 mA/div. Channel 2 (blue trace): secondary-side voltage, 50 V/div. Math 1 (red trace): integrated voltage waveform.*

The plotting of *B-H* characteristics is a two-step process. First, the current and voltage are measured and the integral of the voltage is generated using the built-in math waveform integration function. The P5205 probe is used to measure the differential voltage across the winding; in many applications neither side of the winding is grounded. In step two, the waveform data of current and integrated voltage is exported to an Excel spreadsheet. The current and integrated voltages are multiplied by scale factors to obtain MKS units of Tesla and Amperes/meter. Integration of Faraday's law yields

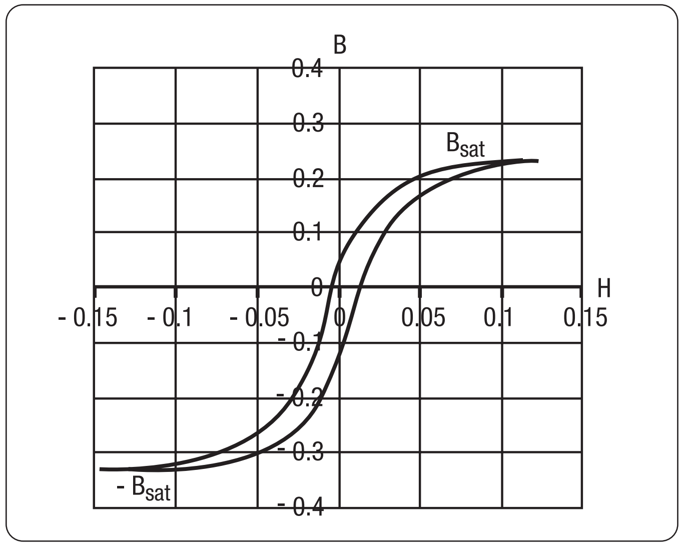
$$B(t) = B(0) + \frac{1}{nA_c}\int_0^t v(t)dt \qquad (1)$$

where *v(t)* is the voltage induced in the winding, *n* is the number of turns of the winding, A_c is the core cross-sectional area, and *B(t)* is the average flux density in the core. We can obtain *B(t)* by dividing the integrated voltage waveform by nA_c. Since the integration function may contain an arbitrary constant *B(0)*, it may be desirable to subtract the average value from the data. Ampere's law relates the magnetic field strength *H(t)* to the winding current *i(t)* as follows:

$$H(t) = \frac{ni(t)}{l_m} \qquad (2)$$

where l_m is the mean magnetic path length of the core. So we can obtain *H(t)* by multiplying the current waveform by n/l_m.

Next, the *B-H* loop is plotted using Excel's plotting features. Figure 8 illustrates the result. It can be seen that the characteristic is nonlinear and exhibits both hysteresis and saturation. The core saturates when the magnitude of the flux density *B* exceeds the saturation flux density B_{sat}.



▶ ***Figure 8.*** *B-H loop, plotted by Excel.*

Measurement of Startup and Run Modes of an Electronic Ballast for Fluorescent Lamps

An electronic ballast includes a high-frequency inverter that drives the lamp with AC having a frequency typically in the 50 to 100 kHz range. The ballast must provide a high voltage to start the lamp; the starting process may require tens of milliseconds. After the lamp has started, the inverter must provide a regulated current (at lower voltage) to run with stabilized light intensity and power. It is important to measure the voltage and current waveforms during the startup transient to ensure reliable operation.

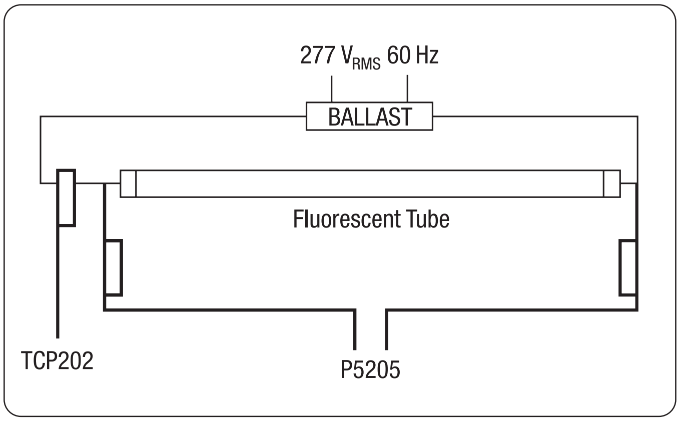
The transistor switching times are typically tens of nanoseconds in duration, while the switching period is ten or twenty microseconds, and the startup transient may last for tens of milliseconds. Capturing all of these events requires sampling rates of tens or hundreds of Megasamples per second, with record lengths of tens of milliseconds.

The performance of the TDS7000 Series is equal to this task, allowing the user to record the entire startup transient, and then zoom to view the transistor switching times and other detailed features at any point in time.

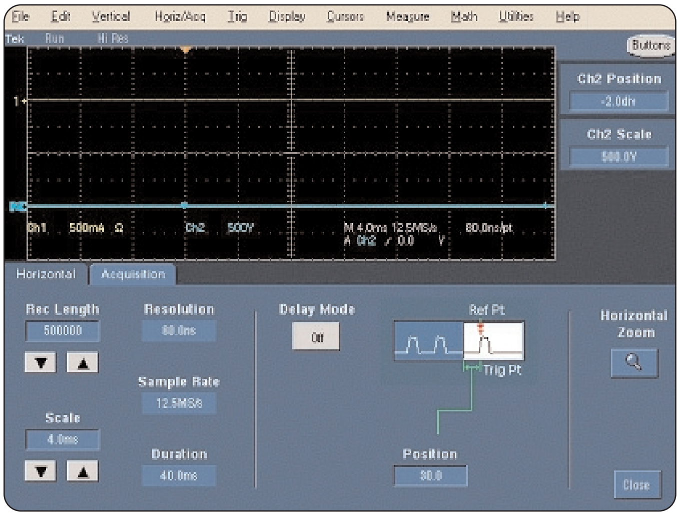
Set Up

The TCP202 current probe must be calibrated using the probe calibration fixture, and the P5205 high-voltage differential probe output must be adjusted to zero before taking any measurements.

1. Connect the P5205 voltage probe across the fluorescent lamp (see Figure 9).
2. Connect the TCP202 current probe to measure the input current of the fluorescent lamp (see Figure 9).
3. Set the trigger mode to "Single Trigger" in "Normal" mode and press the "EDGE" and "POS" (rising edge) buttons on the oscilloscope front panel.
4. From the "Horiz/Acq" menu select "Horizontal/Acquisition".
5. Select "Horizontal" and keep "Sample Rate" as high as possible (see Figure 10).
6. Select "Acquisition" and set to "Hi Res".
7. Adjust the record length suitably to capture the STARTUP and RUN Modes in a single screen.



▶ ***Figure 9.*** *Voltage and current probes connected to the lamp.*



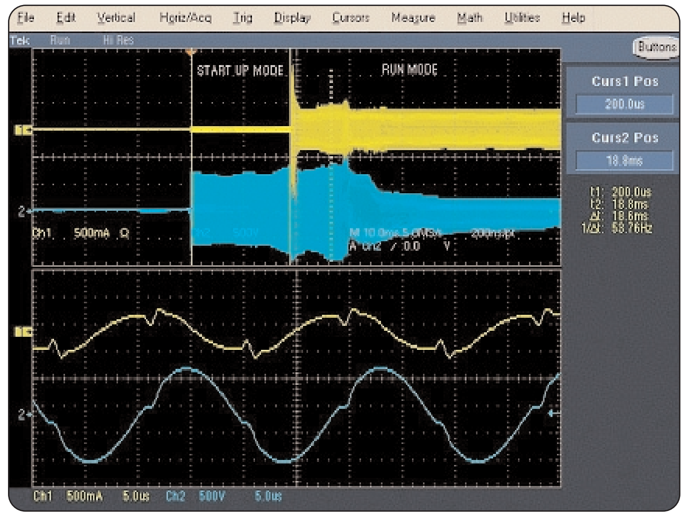
▶ ***Figure 10.*** *Horizontal set-up window used to control the sample rate and record length.*

Figure 11 illustrates the resulting waveforms. Channel 1 (yellow trace) is the lamp current, and Channel 2 (blue trace) is the lamp voltage. The selected sample rate is high enough (12.5 MS/s) to avoid aliasing of the MOSFET switching waveforms. The trigger position is kept at 30% of the screen and the trigger source is Channel 2, the lamp voltage.

The startup and run modes are clearly visible and are labeled on the screen. Initially a high voltage is required to start the lamp; in this case, 650 V peak. After 18.6 ms, the current increases as the arc is established. Eventually the voltage and current waveforms settle to a steady-state run mode.

To zoom the waveform, touch and drag across the desired portion of the waveform. Then select zoom from the drop-down list (right-click with the mouse) to magnify the highlighted waveform segment. The lower half of the screen is the magnified waveform.

The same waveforms can also be acquired in a similar manner using the peak detect mode, allowing capture of the peak values of the waveforms with sub-nanosecond resolution.



▶ ***Figure 11.*** *Captured startup and run modes. Channel 1 (yellow trace): fluorescent lamp current, 500 mA/div. Channel 2 (blue trace): voltage across the fluorescent lamp, 500 V/div. Bottom half of the screen shows the zoomed area.*

Separating Switching Ripple from Line Ripple

In linear power supplies, the measurement of twice-line-frequency (120 Hz) output ripple is relatively easy, since one can trigger the oscilloscope on the line voltage and the oscilloscope then displays the line frequency ripple. But in switched-mode power supplies, the output signal is dominated by switching ripple of hundreds of kHz, as well as other noise. It becomes difficult to measure the component of output voltage ripple that is induced by AC line rectification ripple. Similar issues arise when measuring the input current waveform quality in a power factor corrected off-line rectifier.

The TDS7000 Series' various acquisition modes – sample, envelope, average, high-resolution (Hi Res) and peak detect – make it the ideal tool to determine the quality of the DC output voltage of a switching converter, specifically the determination of output noise and switching ripple. This task is accomplished by separating switching ripple from line ripple to display the low-frequency components of a waveform containing substantial switching harmonics.

Sample mode is the default mode in which the oscilloscope displays samples of the waveforms with no additional processing. Envelope and average modes accumulate data over multiple sweeps.

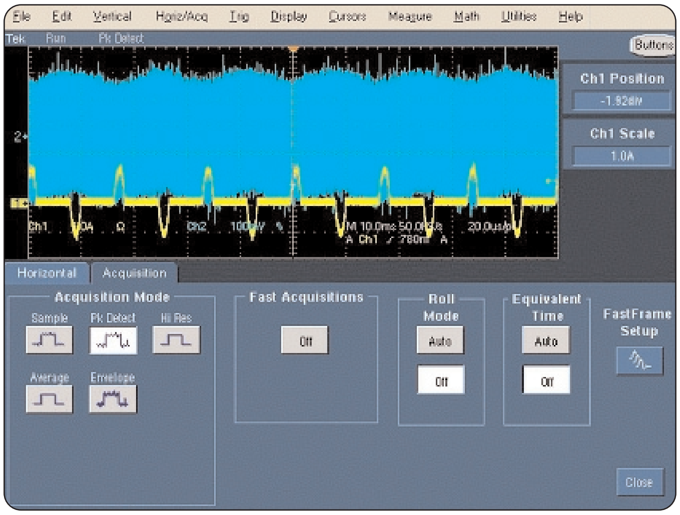
High-resolution (Hi Res) mode performs a fast averaging of the waveform that can be used to filter out noise and switching ripple, and also improves the effective resolution of the analog-to-digital conversion. In the Hi Res mode, the TDS7000 Series oscilloscopes sample the waveform at a 2.5 GS/s rate. Waveform data points are saved at a lower sample rate, set in the horizontal acquisition window. Each record data point is generated by averaging all samples taken during that acquisition interval. Key advantages of the Hi Res mode are to increase resolution regardless of the input signal, and to average the waveforms over the acquisition interval. The effective resolution is given by Equation 13 (see the section titled *Measurement of Transistor Losses in a PFC Boost Converter*), up to a maximum of 16-bit resolution. The averaging process effectively low-pass filters the waveform, with cutoff frequency dependent on the horizontal sample rate. For this measurement, the averaging property is exploited to attenuate the switching ripple by selecting a sample rate slower than the switching frequency. The oscilloscope then displays the low-frequency AC line ripple.

Peak detect mode is similar to Hi Res mode, but records the data points that are the extreme values of the waveform, including noise and switching ripple – in this case, 2.5 GS/s samples (maximum and minimum values are alternately stored) – enabling the oscilloscope to record peak noise levels. This mode can also be used to adjust the channel vertical scales to avoid saturation of the input amplifiers and analog-to-digital converters (ADCs).

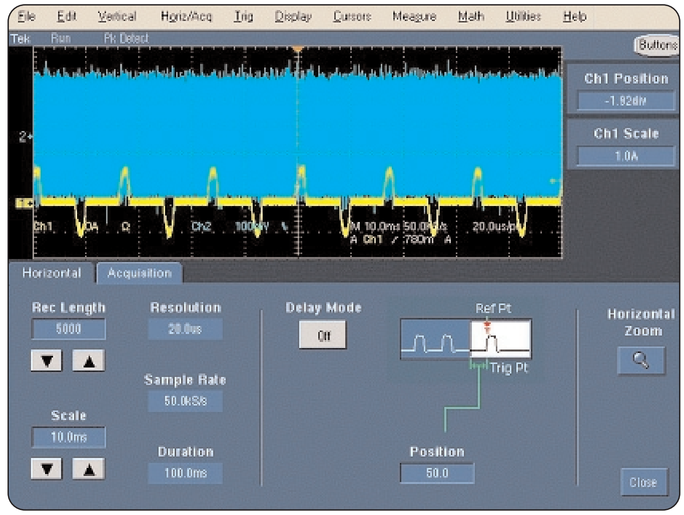
Set Up

Before taking any measurements, the TCP202 current probe must be calibrated using the probe calibration fixture. In addition, the P5205 high-voltage differential probe output must be adjusted to zero using the procedure given in its instruction manual.

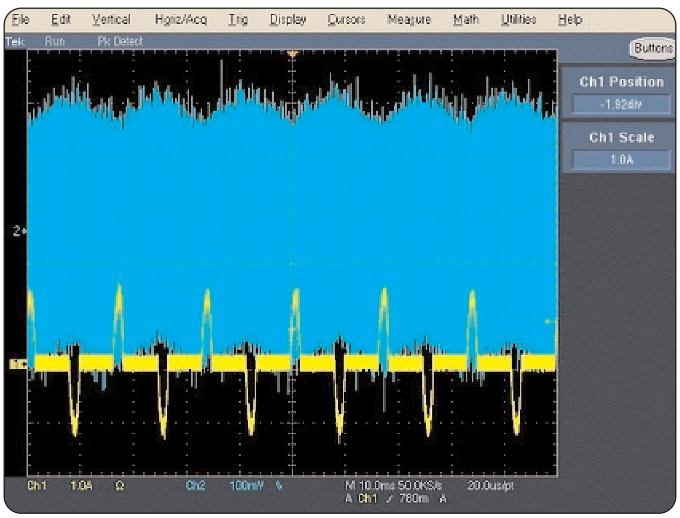
1. Connect the P5205 voltage probe to measure the output voltage with AC coupling.
2. Connect the TCP202 current probe to measure the input current of the converter.
3. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
4. Select "Acquisition" and set to "Peak Detect" (see Figure 12). For maximum resolution of the analog-to-digital conversion, the vertical scale should be set to the highest sensitivity possible. However, the input channel ADCs have a linear range of 10.24 divisions (± 5.12 divisions from the centerline of the display, or 1.12 divisions above and below the top and bottom of the display respectively). To avoid saturation, the waveform display in peak detect mode should remain within these limits.
5. Select the Horizontal menu and set the "Sample Rate" to a value that is sufficiently less than the switching frequency, and much greater than the frequency of the (100 Hz or 120 Hz) rectification ripple (see Figure 14).
6. Select "Acquisition" and set to "Hi Res" (see Figure 15).
7. Set the trigger mode to "Auto Trigger" and press the "EDGE" and "POS" slope (rising edge) buttons on the oscilloscope front panel.
8. If desired, the waveform can now be examined with greater magnification using the zoom function.



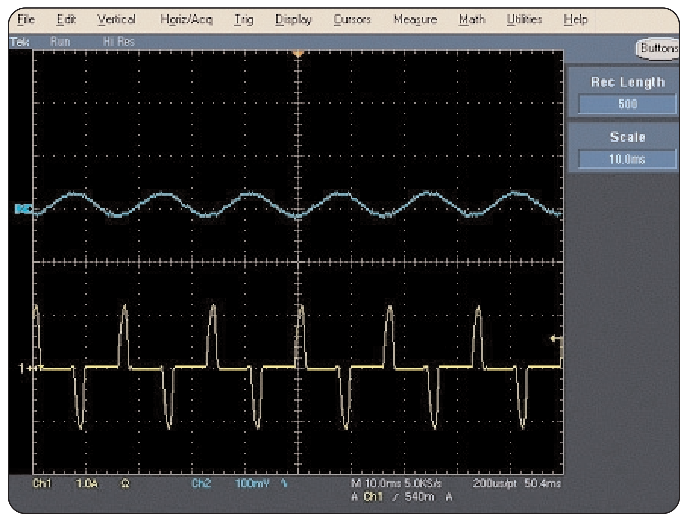
▶ ***Figure 12.*** *Configuring the peak detect mode.*



▶ ***Figure 13.*** *Configuring horizontal acquisition.*

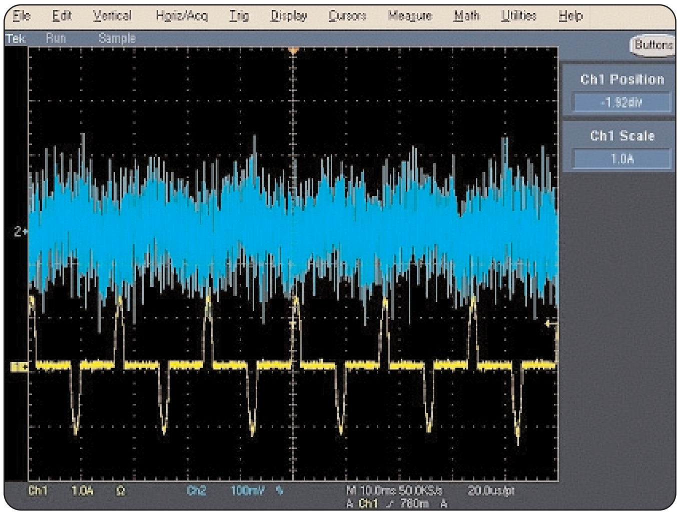


▶ ***Figure 14.*** *Peak detect mode. Channel 1 (yellow trace): input line current, 1 A/div at 60 Hz. Channel 2 (blue trace): output voltage ripple, 100 mV/div. Note the blue trace is adjusted to get maximum output ripple on the screen without saturating the oscilloscope.*

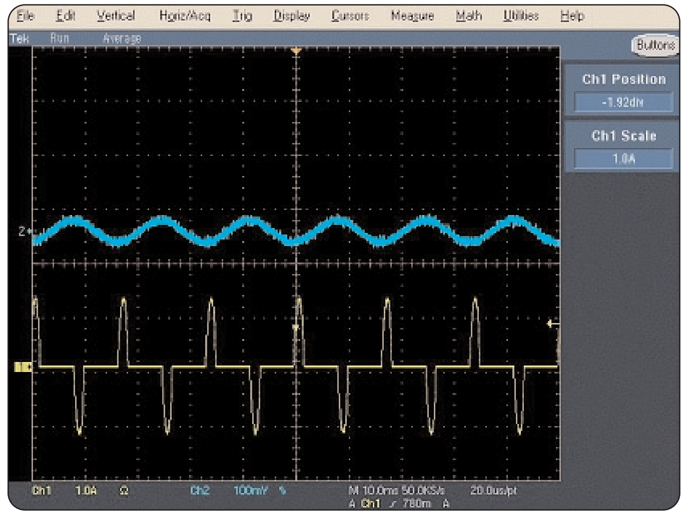


▶ ***Figure 15.*** *High-resolution mode. Channel 1 (yellow trace): input line current, 1 A/div at 60 Hz. Channel 2 (blue trace): output voltage ripple, 100 mV/div.*

In Figures 14 to 17, the uppermost waveform (Channel 2, blue trace) is the converter output ripple voltage, AC coupled at 100 mV per division. Channel 1 (yellow trace) is the 60 Hz input current waveform, at 1 A per division. Figure 14 shows the results obtained using the peak detect mode, and Figure 15 illustrates the same waveforms measured with Hi Res mode. The same waveforms measured with the sampled and averaged modes are illustrated in Figures 16 and 17, respectively. Figure 18 demonstrates the use of the zoom function to display details of the Hi Res waveform. The switching frequency of the converter is approximately 60 kHz.

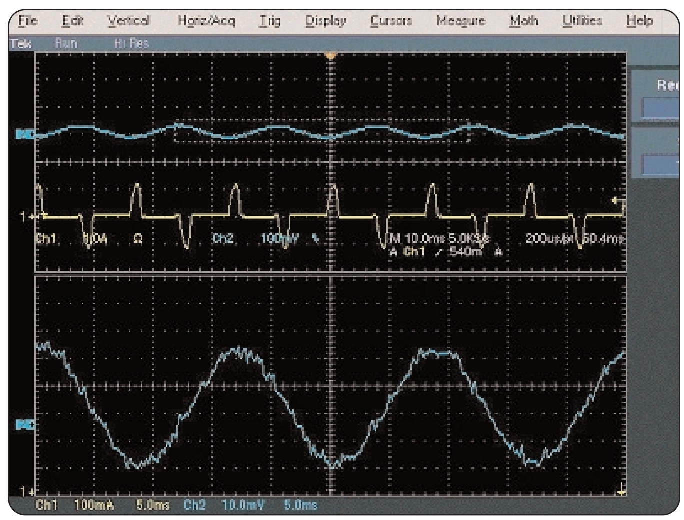


▶ ***Figure 16.*** *Sample mode. Channel 1 (yellow trace): input line current, 1 A/div at 60 Hz. Channel 2 (blue trace): output voltage ripple, 100 mV/div.*



▶ ***Figure 17.*** *Average mode. Channel 1 (yellow trace): input line current, 1 A/div at 60 Hz. Channel 2 (blue trace): output voltage ripple, 100 mV/div.*

The 60 kHz switching ripple can be removed through averaging because the oscilloscope provides signal filtering capability beyond the traditional 20 MHz bandwidth. The filtering achieved by Hi Res acquisition is determined by the sample rate. In this example, the sample rate of 5 kS/s is inadequate to acquire 60 kHz switching noise, but it is more than fast enough to acquire the 120 Hz line ripple component. The averaging process of the Hi Res mode effectively low-pass filters the switching harmonics of the signal, thus eliminating the switching ripple. The sample rate should be chosen to adequately filter the switching ripple while retaining the significant harmonics of the AC line frequency.



▶ ***Figure 18.*** *Magnification of the 120 Hz output voltage ripple using the zoom function.*

Measurement of Instantaneous and Average Power in Switching Transitions

In a switching converter, conduction loss is induced in the power transistor when current flows through its on-state forward voltage drop. During the turn-on and turn-off switching transitions, large instantaneous voltages and currents may be observed in the power transistor, which lead to switching loss. Typical sources of switching loss include diode reverse recovery and MOSFET drain-to-source capacitance. Even though the transistor switching times are short, the average power loss induced by switching can be significant.

This is traditionally a very difficult measurement to make by electrical means because of the complexity of the voltage and current waveforms during the switching transitions, and because of the large change in the transistor voltage during its on and off states. Total MOSFET loss can be measured using thermal methods, but these methods can present mechanical and accuracy difficulties. The ability to make an accurate measurement of average loss in a switched-mode transistor by electrical means provides a useful and fundamental tool to the design engineer.

The average power dissipated by a MOSFET is given by:

$$P = \frac{1}{T_S}\int_0^{T_S} v_{DS}(t)\, i_D(t)\, dt \qquad (3)$$

where $v_{DS}(t)$ is the drain-to-source voltage, $i_D(t)$ is the drain current, and T_S is the switching period. This quantity can be computed by first multiplying the voltage and current waveforms to find the instantaneous power:

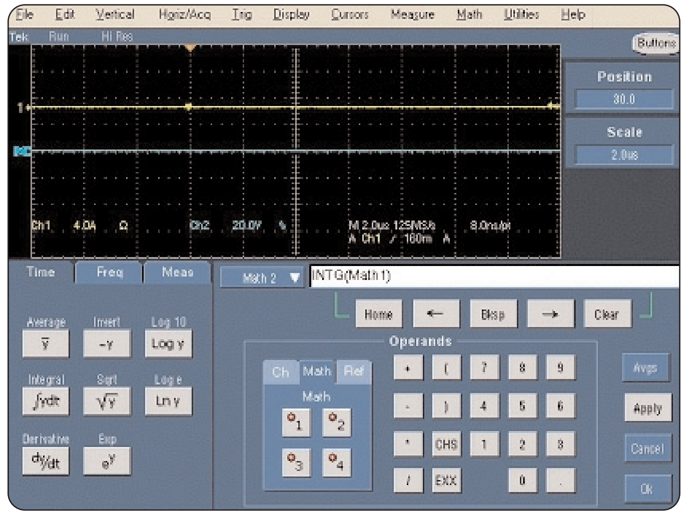
$$p(t) = v_{DS}(t)\, i_D(t) \qquad (4)$$

Integration of the instantaneous power $p(t)$ yields the energy $W(t)$ consumed by the MOSFET:

$$W(t) = \int_0^{t} v_{DS}(t)\, i_D(t)\, dt \qquad (5)$$

The waveform multiplication and integration functions of the TDS7000 Series oscilloscopes can be used to evaluate Equations 3 to 5 above. The average power loss is then given by:

$$P = \frac{W(T_S) - W(0)}{T_S} \qquad (6)$$



▶ ***Figure 19.*** *Applying waveform math.*

Setup

Before taking any measurements, the TCP202 current probe must be calibrated using the probe calibration fixture and the P5205 high-voltage differential probe output must be adjusted to zero.

1. Set the P5202 voltage probe to measure the drain-to-source voltage of the MOSFET.
2. Set the TCP202 current probe to measure the drain current of the device.
3. From the Math menu (see Figure 19), select the multiplication function "Ch1*Ch2" as Math 1 function M1.
4. From the Math menu, select "Equation Editor". In the equation editor, click "Integral" and then click "Math" and select "Math 1".
5. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
6. Select "Acquisition" and set to "Hi Res".
7. Adjust the record length suitably to display one cycle of the switching period.

8. Set trigger mode as "Single Trigger" in "Normal" mode and press the "EDGE" and "POS" slope (rising edge) buttons on the oscilloscope front panel.
9. Click "Apply".

Figure 20 illustrates waveforms obtained using the above procedure. The measurements are taken from a push-pull current-mode controlled DC-DC converter with a switching frequency of 60 kHz. Channel 1 (yellow trace) shows the drain current at 4 A per division, and Channel 2 (blue trace) shows the drain-to-source voltage at 20 V per division.

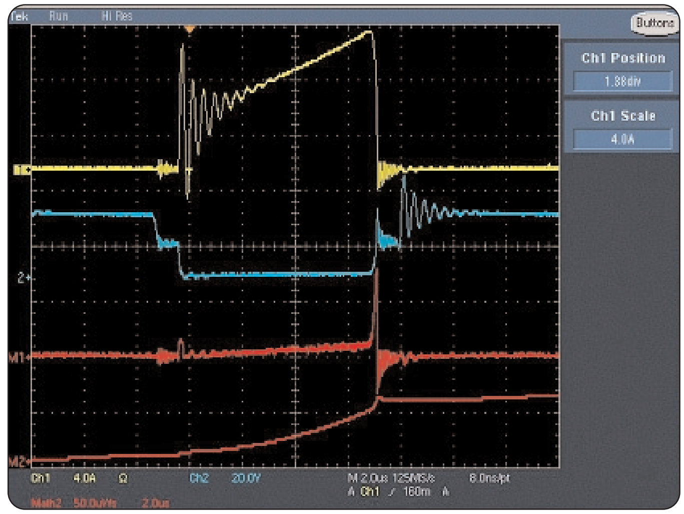
The waveform M1 (red trace) is the instantaneous power loss *p(t)* given by Equation 4. The instantaneous power loss is zero while the MOSFET is off, since the drain current is zero. During the switching transitions, spikes are observed in *p(t)* that represent switching losses. While the transistor is on, conduction losses are observed in *p(t)*.

The waveform M2 (red trace) is the energy loss given by Equation 5. The display indicates that the vertical scale for this trace is 50 microwatt-seconds (i.e., 50 μJ) per division. During the switching transitions and on-time, trace M2 increases by a total of 1 division, or 50 μJ. Hence, the total loss in the MOSFET (switching loss plus conduction loss) is given by Equation 6 as:

$$P = (50\ \mu J)\ (60\ kHz) = 3W \quad (7)$$

Switching loss alone can be computed in a similar manner using the cursors to determine the change in trace M2 that occurs during the switching transitions, and then dividing the result by the switching period T_S.

Because small DC offsets can lead to errors in integration, it is important to zero the probes and channels before taking any measurements. While the transistor is off, trace M2 should remain constant. See the section titled *Measurement of Transistor Losses in a PFC Boost Converter,* for a more detailed discussion of this technique and its limitations.



▶ ***Figure 20.*** *Measured transistor-switching waveforms. Channel 1 (yellow trace): MOSFET drain current. Channel 2 (blue trace): MOSFET drain-to-source voltage. Math 1 trace (red): instantaneous power dissipation, found by multiplying Channels 1 and 2. Math 2 trace (red): energy consumed by MOSFET, found by integrating the Math 1 trace.*

Measurement of Transistor Losses in a PFC Boost Converter

Measurement of conduction and switching losses in switched-mode converters is traditionally very difficult. During the switching transitions, high instantaneous voltage and current are simultaneously applied to the transistor, which can lead to significant energy loss. Measurement of this loss requires that the instantaneous voltage and current waveforms be multiplied and integrated. In addition, conduction loss occurs during the transistor on-time, equal to the forward voltage drop multiplied by the on-state current. Hence, it is necessary to multiply the transistor instantaneous voltage and current, and integrate the resulting instantaneous power waveform over the switching period (as described in Equations 3 to 7 – see the section titled *Measurement of Instantaneous and Average Power in Switching Transitions*). Division by the switching period yields the average power loss.

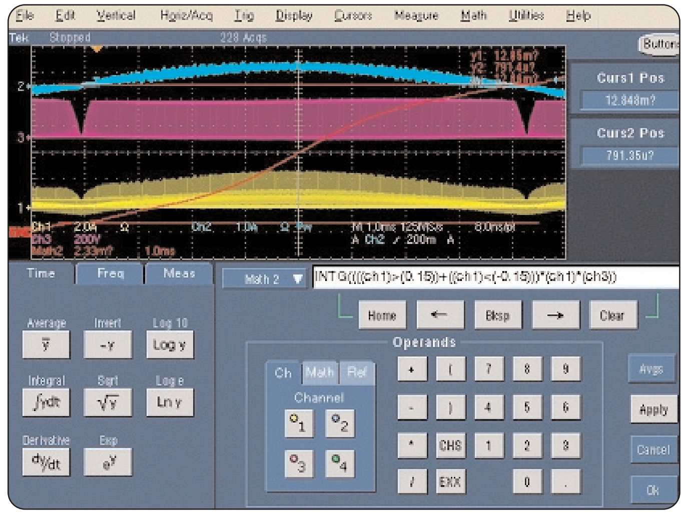
Power-factor corrected rectifiers, such as the well-known PFC boost converter, control their input current waveforms to follow the applied AC line voltage. In these converters, the switch duty cycle typically varies along the AC line cycle. Loss calculations in these converters are further complicated by the fact that the loss varies along the AC line cycle. To compute the average loss in the transistor, it is necessary to integrate over a half line-period (8.33 milliseconds in a 60 Hz system) while accurately integrating the instantaneous power during the fast (tens of nanoseconds) switching transitions.

High sample rate, long record length, high-resolution acquisition, built-in math functions, and the zoom function of the TDS7000 Series makes these instruments superior tools for these types of measurements. These oscilloscopes can be used to measure MOSFET switching and conduction losses in a PFC boost converter, and their gating function can be employed to increase the accuracy of DC current probe measurements.

Setup

The TCP202 current probe must be calibrated using the probe calibration fixture and the P5205 high-voltage differential probe output must be adjusted to zero before taking any measurements.

1. Set the P5202 voltage probe to measure the drain-to-source voltage of the MOSFET. Adjust the vertical scale so that the trace fills the entire screen.



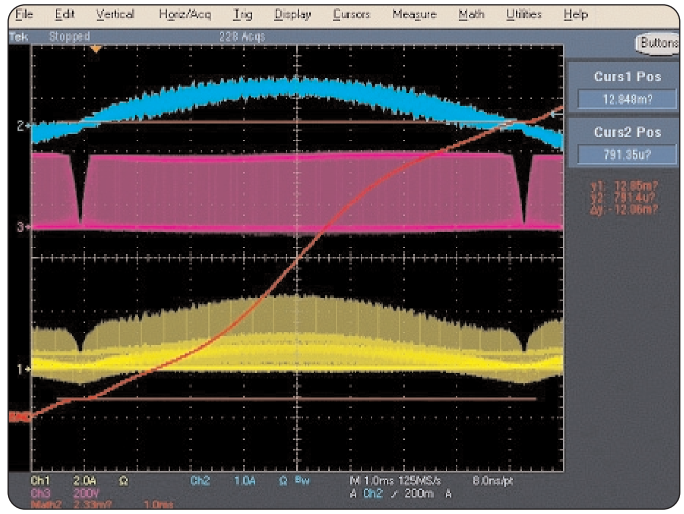
▶ ***Figure 21.*** *Applying waveform math and creating the logical function.*

2. Set the TCP202 current probe 1 to measure the drain current of the device. Adjust the horizontal scales so that the trace fills the entire screen.
3. Set the TCP202 current probe 2 to measure the input line current.
4. Adjust the record length suitably to capture a half-cycle of the input line current on the oscilloscope screen.
5. Set the trigger as "Single Trigger" in "Normal" mode and press the "EDGE" and "POS" (rising edge) buttons on the oscilloscope front panel.
6. From the "Horiz/Acq" menu, select "Horizontal/Acquisition".
7. Select "Horizontal" and set "Sample Rate" as high as possible.
8. Select "Acquisition" and set to "Hi Res".
9. From the Math menu, select "Equation Editor". In the equation editor, click "Math 2" (refer to Figure 21).
10. From the Equation Editor menu, click "Integral" and then write the following logical expression as

    INTG((((ch1)>(0.15))+((ch1)<(-0.15)))*(ch1)*(ch3))
11. Click "Apply".

Figure 22 illustrates the measurement of a PFC boost converter at an AC line voltage of 150 $V_{RMS.}$ The DC output is 75 W at 255 V, and the vertical scales have been adjusted to easily view the waveforms. Channel 1 (yellow trace) is the MOSFET drain current at 2 A per division, Channel 2 (blue trace) is the input line current at 1 A per division, and Channel 3 (pink trace) is the MOSFET drain-to-source voltage at 200 V per division. The selected sample rate is high enough (125 MS/s) to accurately capture the switching loss.

Figure 23 illustrates the measurement at an operating point of 150 $V_{RMS.}$ The total energy lost in the transistor over a half-cycle of the input line is measured with the cursors to be 12.06 mJ. Multiplication by the period of 8.33 ms leads to an average power loss of 1.44 W. Similarly, Figure 24 illustrates the measurement at an input voltage of 110 $V_{RMS,}$ where the measured energy loss over a half-cycle of the input line is 14.6 mJ. The average power loss is 1.75 W. These results correlate to theoretical expectations.

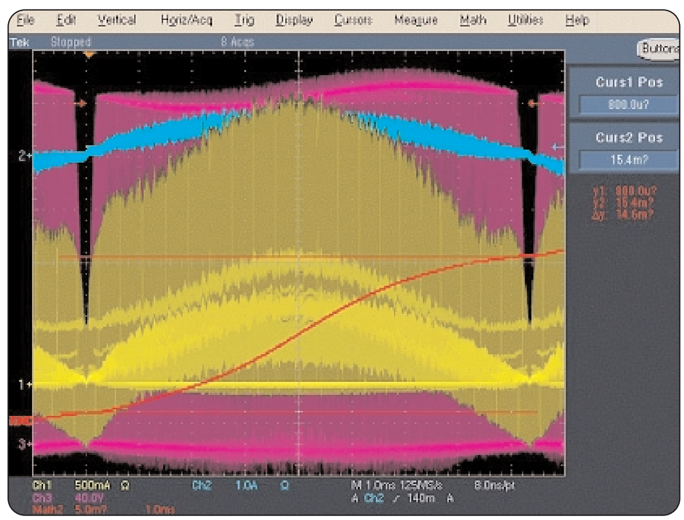


▶ ***Figure 22.*** *Captured waveforms over half input line cycle for input voltage of 150 $V_{RMS.}$ Channel 1 (yellow trace): MOSFET drain current, 2 A/div. Channel 2 (blue trace): input line current, 1 A/div. Channel 3 (pink trace): MOSFET drain-to-source voltage, 200 V/div. Math 2 (red trace): Losses over half line cycle, 2.33 mJ/div.*

Maximizing Accuracy

To obtain measurements of total transistor loss with acceptable accuracy, the transistor voltage and current waveforms must be captured with high accuracy. First, care must be taken before measurements are taken by warming up the oscilloscope and probes for twenty minutes, and then calibrating the probes using the calibration test fixture. Second, it is important that the current probe be accurately adjusted to introduce zero offset to the measured current waveform. A gating function can be employed to mitigate the offset problem. Third, it is important to set up the measurement of the transistor voltage so that the on-state forward voltage drop is accurately measured. These issues are discussed in detail below.

Traditionally, it is very difficult to accurately null the DC offset of a DC current probe. While the calibration test fixture considerably simplifies this procedure, some small offset will still remain after the probe has been disconnected from the test fixture and inserted into the converter. This small offset leads to the prediction of power loss while the transistor is off – although the off-state current of the transistor is exactly zero, the offset causes prediction of substantial power loss equal to the (large) off-state voltage multiplied by the (small) current offset.



▶ ***Figure 23.*** *Accurate measurement of the total energy lost in the transistor over one half-cycle AC line input, at an RMS input voltage of 110 VAC. The vertical scales of the transistor voltage and current waveforms are adjusted to fill the screen. A gating function is applied to zero the DC current probe measurement. Horizontal cursors are used to measure the net energy lost in the transistor over the half-cycle AC line input.*

The math capabilities of the TDS7000 Series provide a solution to overcome this problem. A logical gating function is generated, which is equal to exactly zero while the transistor is fully off. The gating function is equal to exactly one during the switching transitions and the on time of the transistor. Multiplication of the measured current by this gating function eliminates the offset.

Such a gating function can be generated using the comparison operators of the oscilloscope. This comparison is a binary expression that returns a logical value of zero when the comparison is false, and a logical value of one when the comparison is true. The result can be used in other expressions, and in particular, can be multiplied by the current waveform. The syntax is:

<Expression> := <Term> <ComparisonOperator> <Term> **(8)**

where <Term> can be a reference to a waveform, such as Ch1, or can be another expression enclosed in parentheses. Also, <ComparisonOperator> is one of the following:

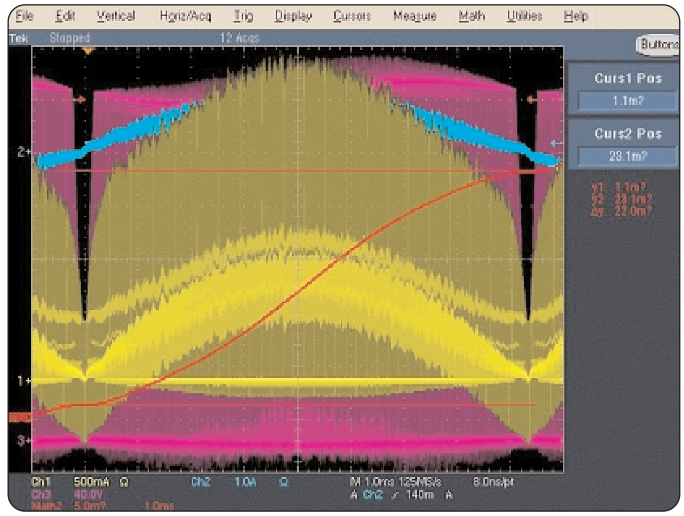
==	**Equal**
=!	**Not Equal**
>	**Greater Than**
<	**Less Than**
>=	**Greater Than or Equal**
<=	**Less Than or Equal**

(9)

In addition, the operators "+" and "*" can be used to implement logical OR and AND functions. For example, if A and B are variables having values of 0 or 1, then A*B implements the logical AND function. The expression ((A+B) > 0.9) implements the logical OR function.

For example, if the controller circuit contains a waveform that is high (greater than 3 V) while the transistor is off, and is low (less than 1 V) during the switching transitions and transistor on time, then this signal could be acquired using Channel 4, and a suitable gating signal could be generated using the following math expression:

Ch4 < 2 **(10)**



▶ ***Figure 24.*** *Accurate measurement of the total energy lost in the transistor over one half-cycle AC line input, at an RMS input voltage of 150 VAC. The vertical scales of the transistor voltage and current waveforms are adjusted to fill the screen. A gating function is applied to zero the DC current probe measurement. Horizontal cursors are used to measure the net energy lost in the transistor over the half-cycle AC line input.*

This comparison is done on a waveform point-by-point basis, and produces a point-by-point result. Let's assume that the current is acquired by Channel 2. Multiplication of Channel 2 by the above gating function is accomplished by the following expression:

(Ch4 < 2)*Ch2 **(11)**

The result follows the measured current during the transistor switching times and on time, and is exactly zero during the transistor off time. This approach considerably improves the accuracy of average power measurements in switched-mode applications.

When a suitable signal is not present within the controller circuitry, it is still possible to apply the above approach using only the measured current waveform by multiplying the transistor current waveform by a gating function that is equal to zero when the current itself is close to zero. This effectively introduces a dead-band into the current measurement. The threshold is chosen to be larger than the maximum offset of the current probe, but otherwise as small as possible. An expression that accomplishes this use of a dead-band of 0.15 A, with the current acquired in Channel 2, is:

(Ch2)*((Ch2>0.15)+(Ch2<(-0.15))) **(12)**

This approach is used in the measurements of Figures 21 to 24. Note that when comparison operators are used, the oscilloscope displays the units of the waveform as "?".

When attempting to measure the conduction losses of a transistor in a switched-mode converter, accuracy of the transistor voltage measurement is another traditional problem. First, the vertical scale must be adjusted so that the input amplifier and analog-to-digital converter (ADC) do not saturate while the transistor is off. Then, the small forward voltage drop of the transistor must be measured while the transistor is on. These issues can be addressed with the TDS7000 Series by properly adjusting the vertical scale and using the high-resolution mode, as discussed below.

The ADC within each channel of the oscilloscope operates with eight-bit raw resolution. Each division of the display represents 25 levels, and 10.24 divisions lie within the linear range of the ADC (8 of these 10.24 divisions are displayed on the screen). Therefore, it is highly advantageous to adjust the vertical scale of the channel used to measure the transistor voltage so that the measured waveform fills the screen. Of course, the zoom function can later be used to increase or decrease the size of the display, without compromising the accuracy of the measurement.

The resolution of the acquisition can be further improved with the high-resolution (Hi Res) mode. The ADCs sample the waveforms at the specified sample rate of the oscilloscope (i.e., 10 GS/s). The Hi Res mode is able to operate at sample rates up to 2.5 GS/s. When operating in Hi Res mode with a selected sample rate slower than 2.5 GS/s, the extra samples are averaged, which improves the effective resolution of the acquisition. Ideally, the enhancement of resolution is given by:

$$\text{Enhanced resolution bits} = 0.5 \log_2(N) \qquad (13)$$

where N is the number of averages. Effective ten-bit resolution is obtained when sixteen averages are employed, i.e., when the selected sample rate is (2.5 GS/s)/16 = 156 MS/s. Twelve-bit effective resolution requires 10 MS/s, and the maximum allowable resolution is limited to 16 bits by the hardware architecture. The number of effective levels is given by

$$256 \sqrt{N} \qquad (14)$$

Hence, we should set the horizontal time/point to be as long as possible without compromising the acquisition of the switching transitions and the measurement of the switching loss. At 8 ns/point, the waveform sample rate is set to 125 MS/s, and (2.5 GS/s)/(125 MS/s) = 20 samples are averaged into each point of the stored waveform, yielding an effective resolution slightly better than 10 bits. If the vertical scale is set so that the measured voltage waveform is as large as possible without saturating the ADC (i.e., 10.24 divisions), Equation 14 predicts that the voltage will be digitized into 1145 levels. For a 400 V peak-to-peak waveform, this corresponds to a resolution of 0.35 V. The resolution could be further improved by increasing the number of averages per point; at 40 ns/point, a resolution of 0.15 V could be obtained.

It should be noted that, owing to the non-synchronous relationship between the measured signal and the sample clock, the averaging process introduces an amplitude roll-off in addition to the inherent amplifier frequency roll-off.

Conclusion

Some high-performance, real-time oscilloscopes, such as the TDS7000 Series, enable the measurement and analysis of waveforms of power electronics devices and systems in ways that traditionally were not practical. Their long record length can be applied to capture, display and record details of signal transitions lasting many milliseconds. Their powerful, built-in math features enable complex computations, such as instantaneous or average power loss, or harmonic spectrum. Some of these instruments like the TDS7000 Series also have a built-in, Windows-based PC system that simplifies the transfer of data from the oscilloscope to a PC for further processing and analysis. Whether capturing and analyzing high-side gate drive waveforms, measuring transistor losses in a PFC boost converter, or making a full range of other electronics power measurements, the high-performance, real-time oscilloscope is an ideal tool to solve your measurement challenges.

Written by:

Robert Erickson
University of Colorado at Boulder

Aditya Sathe
University of Colorado at Boulder

Dragan Maksimovic
University of Colorado at Boulder

The Integrated Tool Set for Power Measurements

▶ **TDS7000 Series Digital Phosphor Oscilloscopes**
The TDS7000 Series oscilloscopes, with bandwidth from 500 MHz to 4 GHz and up to 20 GS/s real-time sample rate, are high-performance real-time oscilloscopes for verification, debug and characterization of sophisticated electronic designs.

▶ **Active, Differential, Passive and Current Probes**
A dependable probe is an integral part of your measurement system because even the most advanced oscilloscope can only be as precise as the data that goes into it. Tektronix offers a wide selection of probes and devices which enable you to safely and accurately capture current, high voltage and floating signals - all converted to voltage inputs acceptable to your oscilloscope.

Contact Tektronix:
ASEAN Countries & Pakistan (65) 6356 3900
Australia & New Zealand (65) 6356 3900
Austria +43 2236 8092 262
Belgium +32 (2) 715 89 70
Brazil & South America 55 (11) 3741-8360
Canada 1 (800) 661-5625
Central Europe & Greece +43 2236 8092 301
Denmark +45 44 850 700
Finland +358 (9) 4783 400
France & North Africa +33 (0) 1 69 86 80 34
Germany +49 (221) 94 77 400
Hong Kong (852) 2585-6688
India (91) 80-2275577
Italy +39 (02) 25086 1
Japan 81 (3) 3448-3111
Mexico, Central America & Caribbean 52 (55) 56666-333
The Netherlands +31 (0) 23 569 5555
Norway +47 22 07 07 00
People's Republic of China 86 (10) 6235 1230
Poland +48 (0) 22 521 53 40
Republic of Korea 82 (2) 528-5299
Russia, CIS & The Baltics +358 (9) 4783 400
South Africa +27 11 254 8360
Spain +34 (91) 372 6055
Sweden +46 8 477 6503/4
Taiwan 886 (2) 2722-9622
United Kingdom & Eire +44 (0) 1344 392400
USA 1 (800) 426-2200
USA (Export Sales) 1 (503) 627-1916
For other areas contact Tektronix, Inc. at: 1 (503) 627-7111
Updated 18 April 2002

For Further Information
Tektronix maintains a comprehensive, constantly expanding collection of application notes, technical briefs and other resources to help engineers working on the cutting edge of technology. Please visit **www.tektronix.com**

05/02 FLG5618/BT 55W-12447-1

Tektronix
Enabling Innovation