ISSUE: March 2017

A Practical Primer On Motor Drives (Part 14): Power Measurements On Distorted Signals

by Ken Johnson, Teledyne LeCroy, Chestnut Ridge, N.Y.

In an earlier section, single-and three-phase sinusoidal ac line systems were described as rotating vector systems with one set (single-phase) of voltage and current vectors or three sets (three-phase) of voltage and current vectors. However, power conversion systems and drives do not output sinusoidal signals—they are PWM signals and they have high harmonic content.

This high harmonic content can be thought of as a multi-vector system, with one rotating voltage vector and one rotating current vector (for each phase) for "N" harmonics, with each voltage and current vector system associated with a given harmonic having a unique phase angle. As described previously in part 6, we cannot directly measure the phase angle between distorted voltage and current waveforms. We must use a digitally sampled waveform technique, as described previously, for accurate calculation of the power values for these waveforms.

We will not repeat the previous description of the digitally sampled waveform technique. However, understanding of some additional considerations will aid in correct measurement of power on these types of signals. These considerations are:

- Advanced cyclic period detection and display
- Harmonic filtering of power measurements
- Impact of line-to-reference voltage probing.

These issues will be explained and demonstrated using measurements taken on Teledyne LeCroy's Motor Drive Analyzer, which contains certain built-in functions specifically geared toward distorted waveform measurements as found on motor drive pulse-width modulated (PWM) outputs.

Advanced Cyclic Period Detection and Display

As described previously, we use a signal to determine the cyclic period for the measurement calculations. Ideally, the signal chosen (what Teledyne LeCroy refers to as the Sync signal) to determine the cyclic period is highly sinusoidal, or could be made sinusoidal through low-pass filtering.

When measuring power in distorted waveforms, proper selection of a suitable signal, understanding how to optimize settings for the desired results, and learning how to use viewable "feedback" of the settings is critical to ensuring accurate power measurements. With a thorough understanding of how to choose, filter, and set hysteresis for the Sync signal, one will obtain accurate measurements with Teledyne LeCroy's Motor Drive Analyzer or a power analyzer under most or all conditions.

Fig. 1 shows the setup for the Sync signal in the Motor Drive Analyzer. Power analyzer instruments have similar setups, though they usually do not allow a hysteresis band setting. Moreover, we cannot view the filtered signal, with cyclic period determination, on a power analyzer instrument as we can on the Motor Drive Analyzer.

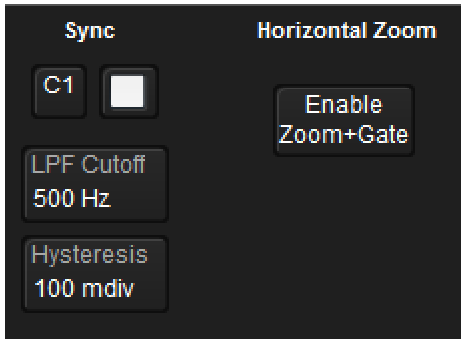

Fig. 1 Setup for the Sync signal in the Teledyne LeCroy's Motor Drive Analyzer.

Choosing A Sync Signal

The highest amplitude, least distorted signal is best for cyclic period determination. Use any acquired periodic signal with a period representing the interval for performing cyclic measurements. In general, the ideal Sync signal has these characteristics:

- Low or predictable distortion (e.g., a pure or nearly-pure sine wave, or one that could be made as such with low pass filtering)
- Constant amplitude (e.g., a constant-amplitude current signal during steady-state load, or constant-amplitude PWM drive voltage output)
- Low noise
- Variation around a zero crossing (e.g., line-to-line voltages, or sinusoidal current signals.)

If a signal with the above characteristics is not naturally present in the acquisition, then adjust the low-pass filter (LPF) cutoff and hysteresis band (zero-crossing filter) settings to improve the 50% (zero) crossing determination and/or to reduce the noise and distortion on the signal. In the case of severely distorted waveforms (e.g., six-step commutated voltage or current waveforms), it may be necessary to adjust both.

If no signal has the ideal characteristics described above, use a math function as the Sync signal. An example where this might be useful is if the voltage probing is line-to-reference (no variation around a zero crossing) and the current signals have a very wide dynamic range. In this case, one may define a math function as the difference in two line-to-reference probed voltages to obtain a line-to-line voltage to use as a Sync source.

LPF Cutoff Settings

The low-pass filter (LPF) applies a digital filter with a -3-dB cutoff at the specified frequency. The default value in the Motor Drive Analyzer is 500 Hz. There is significant attenuation of Sync source signals with significant high-frequency content (e.g., a PWM voltage signal) when filtered to the default frequency, but they may still be suitable Sync signals if they are sinusoidal with low (post-filtered) distortion.

Signals with very high harmonic content (e.g., six-step commutated voltage signals) will have significant attenuation when the low-pass filter is applied. Therefore, filtering may render such signals unsuitable for synchronizing unless care is taken in setting the hysteresis level. Signals that experience wide dynamic ranges, such as load current signals in acquisitions under highly dynamic loading conditions, may also be unsuitable.

Be careful when setting the LPF filter value to a value that is lower than the default setting, and view the Sync signal to ensure that the chosen filter setting is providing the desired result. The LPF cutoff may be set to a lower or higher frequency than the default 500 Hz to improve the quality of the Sync signal:

- Lower values improve the noise and distortion rejection, but may overly attenuate the signal, requiring undesirable hysteresis settings, or result in no cyclic detection at all.

- Higher values may improve the signal amplitude, but pass too much high-frequency content, leading to a distorted signal and incorrect 50% (zero) crossing determination.

Hysteresis Band Settings

The hysteresis band setting defines an amplitude "band" which the Sync signal must exceed before the Sync signal slope is deemed acceptable for use in the 50% (zero) crossing determination. The default value is 100 millidivisions (mdiv), with the unit "divisions" being equal to oscilloscope vertical grid divisions.

- Lower hysteresis values improve the ability to detect a 50% (zero) crossing on a smaller amplitude signal but with risk of detecting false 50% (zero) crossings.
- Higher hysteresis values improve the ability to reject the impact of signal distortion or noise in determination of the 50% (zero) crossing but with risk of reduced accuracy of 50% (zero) crossing detection.

Some non-zero hysteresis value is required to prevent false 50% (zero) crossing determination. However, this also means that the Sync signal must meet a minimum amplitude requirement, and be relatively noise-free at lower amplitudes. Signals with very wide dynamic ranges and very high distortion (e.g., a six-step commutated current signal with very high dynamic range) likely require more care when setting the hysteresis band.

To understand how the hysteresis-band setting works, consider the Fig. 2 example of a perfect sinusoid. In this case, it is simple to detect the zero or 50% crossing level and to determine the measurement intervals.

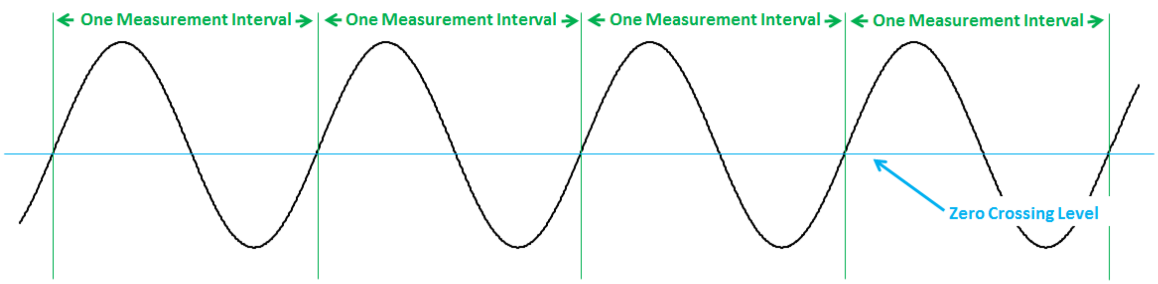

Fig. 2. Cyclic period measurement intervals on a sinewave signal. Determining the measurement interval is simple in this case.

Now, consider the example in Fig. 3 where there is a non-monotonicity near the zero or 50% crossing level. The non-monotonicity results in an incorrect period determination because it is detected as a measurement interval, which results in incorrect calculations.

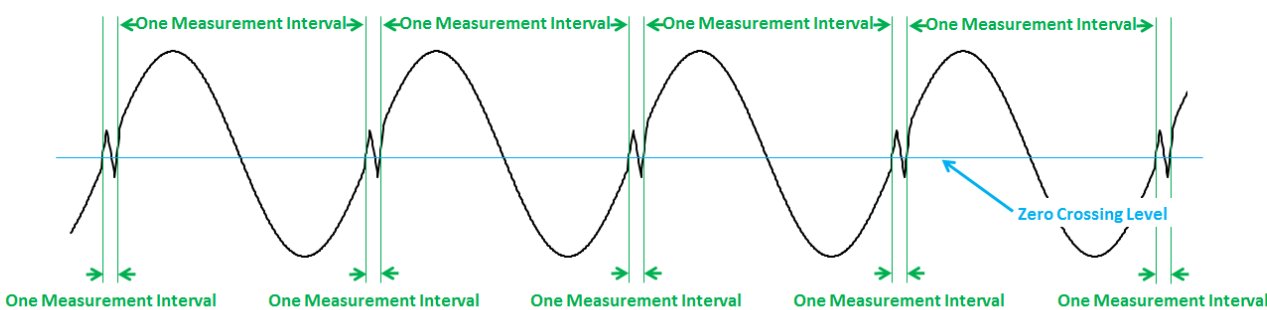

Fig. 3. A non-monotonic signal produces "false" measurement intervals.

Using the hysteresis band controls, set a hysteresis band level of greater than the amplitude of the non-monotonicity to avoid false measurement interval calculations as illustrated in Fig. 4.

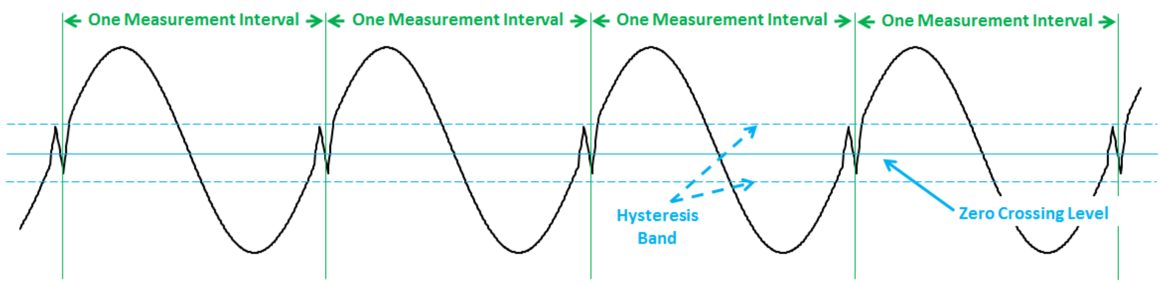

Fig. 4. Setting a hysteresis band corrects for non-monotonicity when measuring intervals.

Sync Signal Display + Zoom

Visual feedback on the Sync signal settings provides confidence that we have calculated a correct cyclic period. If the cyclic period calculation is wrong for some reason, all power values will be incorrect. Therefore, the Motor Drive Analyzer provides the ability to view the filtered Sync signal with a transparent, color-coded overlay to indicate the exact locations of measurement period (cyclic) determination (Fig. 5.)

Use these locations to verify that the Sync signal is performing as would be expected. If the acquisition contains many Sync signal cycles, zoom the display to see cyclic period details using the Motor Drive Analyzer's Zoom+Gate feature.

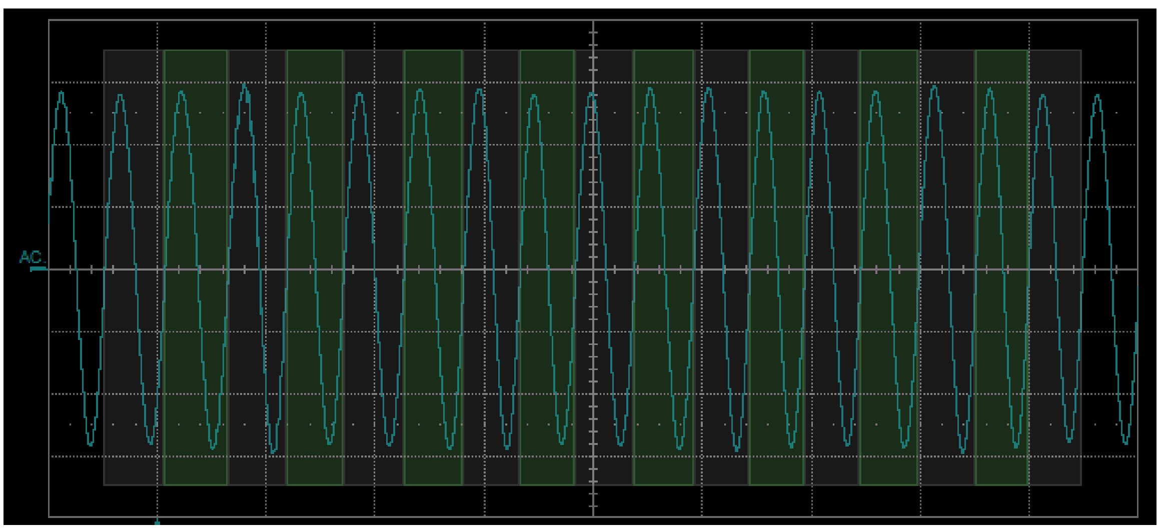

Fig. 5. Colored overlays mark the measurement cycles on Sync signal.

Simple Examples Of Distorted Waveforms

To illustrate how to use a combination of the settings to obtain or verify an accurate cyclic period determination, we will show a number of examples. For simplicity, we show just a single phase of a three-phase system, but the examples are generic and apply to single- or three-phase systems.

Fig. 6 presents a single line-to-line voltage (Z3, light blue, upper left) and line current output (Z6, purple, lower left) of a low-voltage vector FOC (sine-modulated PWM) drive. We have chosen the Sync as the line-to-line voltage signal and are using the default low-pass filter and hysteresis settings. The filtered Sync signal with cyclic period overlays appears as DrvOutSyncZ (green, upper right.)

Fig. 6. A single line-to-line voltage (Z3, light blue, upper left) and line-current output (Z6, purple, lower left) of a low-voltage vector FOC drive. The filtered Sync signal with cyclic period overlays appears as DrvOutSyncZ (green, upper right.)

While low in amplitude, the filtered line-to-line voltage signal is still of sufficient amplitude to determine the cyclic period, which is shown by the transparent overlays showing three cyclic periods.

If we choose the line current signal—a much more sinusoidal signal without filtering—as the Sync signal, the image in Fig. 7 shows that we can make the same cyclic period determination as when we used the line-to-line voltage signal as the Sync signal.

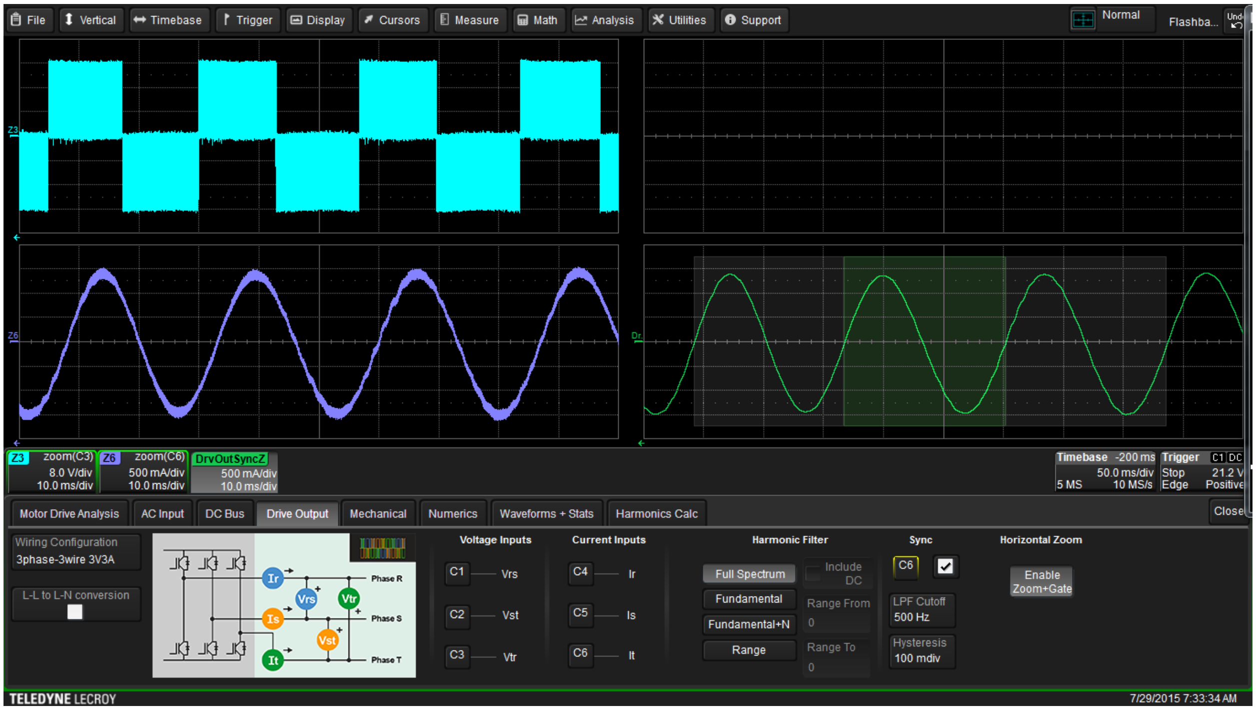

Fig. 7. Using the line current signal (Z6, purple, lower left) as the Sync signal, we can make the same cyclic period determination as when we used the line-to-line voltage signal but filtering is not required. The Sync signal appears on the lower right.

Fig. 8 shows a single line-to-line voltage (Z3, light blue, upper left) and line-current output (Z6, purple, lower left) of a low-voltage BLDC six-step commutated drive output. We have chosen the Sync signal as the line-to-line voltage signal and are using the default low-pass filter and hysteresis settings. The filtered Sync signal with cyclic period overlays appears as DrvOutSyncZ (green, upper right).

While we might expect that this waveform would challenge the cyclic period detection algorithm, in fact, the default settings for low-pass filter and hysteresis band are acceptable, though this may not be the case with different but similar waveforms. Note that there are non-monotonicities present in the filtered signal, and some adjustment of the hysteresis band setting or low-pass filter may be necessary on other similar waveforms.

If we choose the line-current signals as the Sync signal, Fig. 9 shows that the resulting cyclic period determination is the same as that made with the line-to-line voltage signal. The same cautions apply as in the line-to-line voltage example shown in Fig. 8.

For instance, for the same example above, a waveform with a little more distortion or noise at the zero crossing results in a false cyclic period determination with the default hysteresis band setting as illustrated in Fig. 10. In this case, the half period was determined instead, which would lead to incorrect power calculations.

Fig. 8. Even with the low-voltage BLDC six-step commutated drive output line-to-line voltage (Z3, light blue, upper left) measured here, we can still obtain an accurate Sync signal from this line-to-line voltage signal using the default settings for the low-pass filter and hysteresis. The filtered Sync signal with cyclic period overlays appears as DrvOutSyncZ (green, upper right).

Fig. 9. Choosing the line-current signals as the Sync signal for the low-voltage BLDC six-step commutated drive output produces similar results to those obtained in Fig. 8.

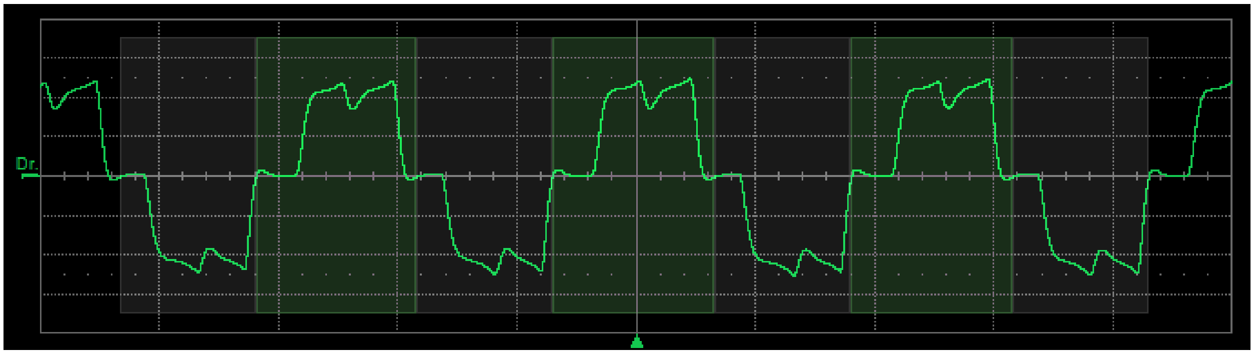

Fig. 10. This line current signal is essentially the same as in Fig 9, but the presence of slightly more noise causes the MDA to determine the cyclic period to be just half of the actual period as the overlays indicate when the default setting for hystersis band is used.

We identified this problem by viewing the Sync signal with the cyclic period overlays. Correcting it requires only a minor change in the hysteresis band setting.

Fig. 11 shows a single line-to-reference voltage (Z3, light blue, upper left) and line-current output (Z6, purple, lower left) of a low-voltage, BLDC, six-step commutated drive output. We have chosen the Sync signal as the line-to-reference voltage signal and are using the default low-pass filter and hysteresis settings. The filtered Sync signal with cyclic period overlays appears as DrvOutSyncZ (green, upper right). In this case, the software algorithm cannot correctly determine the cyclic period. While not shown, it might be possible to adjust the filter or hysteresis settings and obtain a good Sync period.

Fig. 11. A line-to-reference voltage (Z3, light blue, upper left) of a low-voltage, BLDC, six-step commutated drive output is chosen as the Sync signal, but the MDA software cannot accurately determine the cyclic period.

In this particular case, substituting the line-current waveform creates a more suitable signal, as shown in Fig. 12.

Fig. 12. When the line-current waveform is selected as the Sync signal, the MDA is able to correctly determine the cyclic period using default settings.

Perhaps the best Sync signal is a Math waveform defined as the difference between two line-to-reference waveforms, or a line-to-line voltage. Doing so produces results similar to those obtained with direct acquisition of the line-to-line voltage waveform.

Fig. 13. A Math function within the MDA takes the difference between the two line-to-reference waveforms shown on the left and uses this difference waveform as the Sync signal shown on the lower right.

Long Acquisitions With Distorted Signals

As previously described in this section, long acquisitions of signals with wide dynamic ranges and distortion require care in setting the Sync signal to achieve accurate results. Additionally, on longer acquisitions, especially those with dynamic load conditions, it may be necessary to zoom the Sync signal to verify a good cyclic period determination. This is where the Motor Drive Analyzer's Zoom+Gate capabilities shine.

Consider a two-second acquisition of a sine-modulated, three-phase drive that ultimately shuts down due to an overcurrent condition, incurring a substantial output-current change (i.e., wide dynamic current range) and significant signal distortion at the shutdown event. The three-phase, line-to-line voltage waveforms appear in the top grid of Fig. 14, while the three-phase line currents appear in the bottom grid.

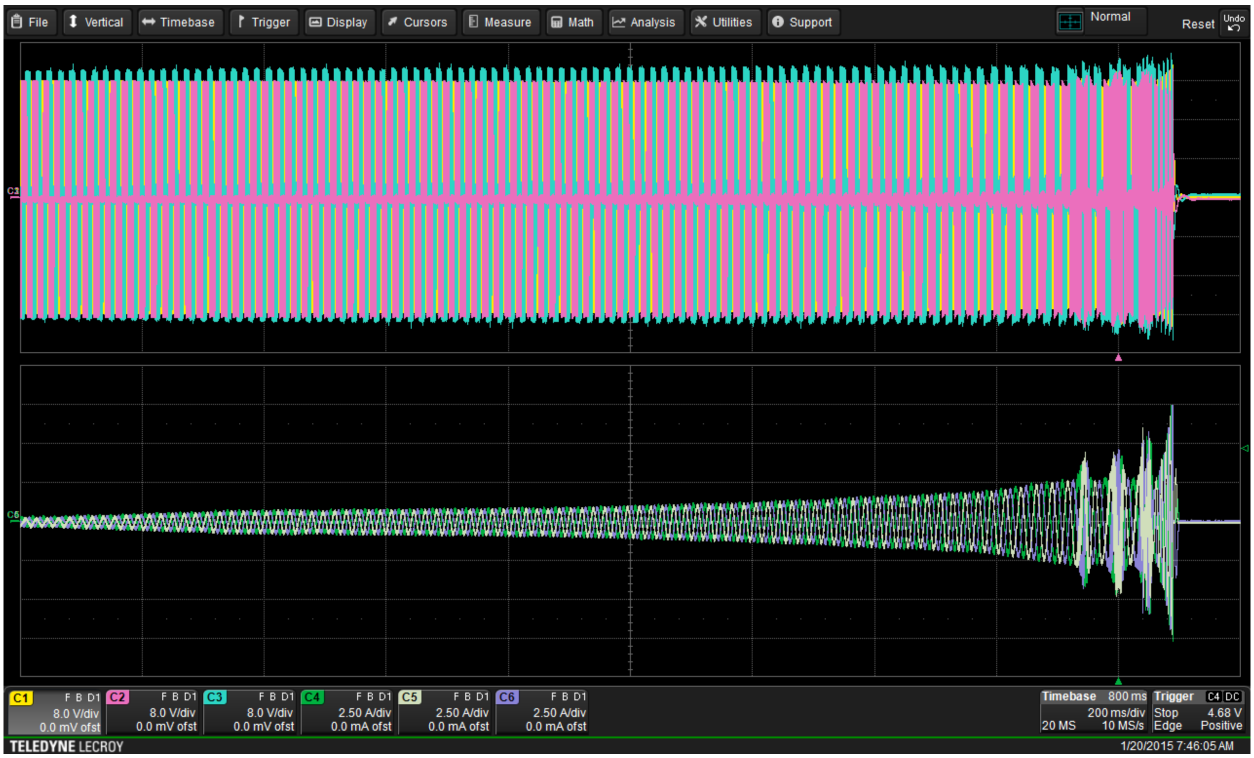

Fig. 14. Initial display of input source waveforms for a sine-modulated, three-phase drive.

In Fig. 15 we have enabled Zoom+Gate for the same line-to-line voltage waveforms. The original, (2-s- long acquisitions appear on the left side of an octal grid with the zoomed waveforms shown on the right. Then, for illustrative purposes, C4 (a current signal on Channel 4) is assigned as the Drive Output Sync signal (named DrvOutSyncZ and shown as a green trace.) C1 (a voltage signal on Channel 1) is assigned as the ac input Sync signal (named ACInSyncZ and shown as a blue trace.) We have retained the default LPF Cutoff (500 Hz) and Hysteresis (100 mdiv) settings.

Both signals display nearly the same amplitude. If we change the horizontal zoom ratio to encompass nearly half the waveform and change the zoom position location to the beginning of the acquisition, the transparent overlays show us that the Sync signal seems to have a well-defined period in both cases.

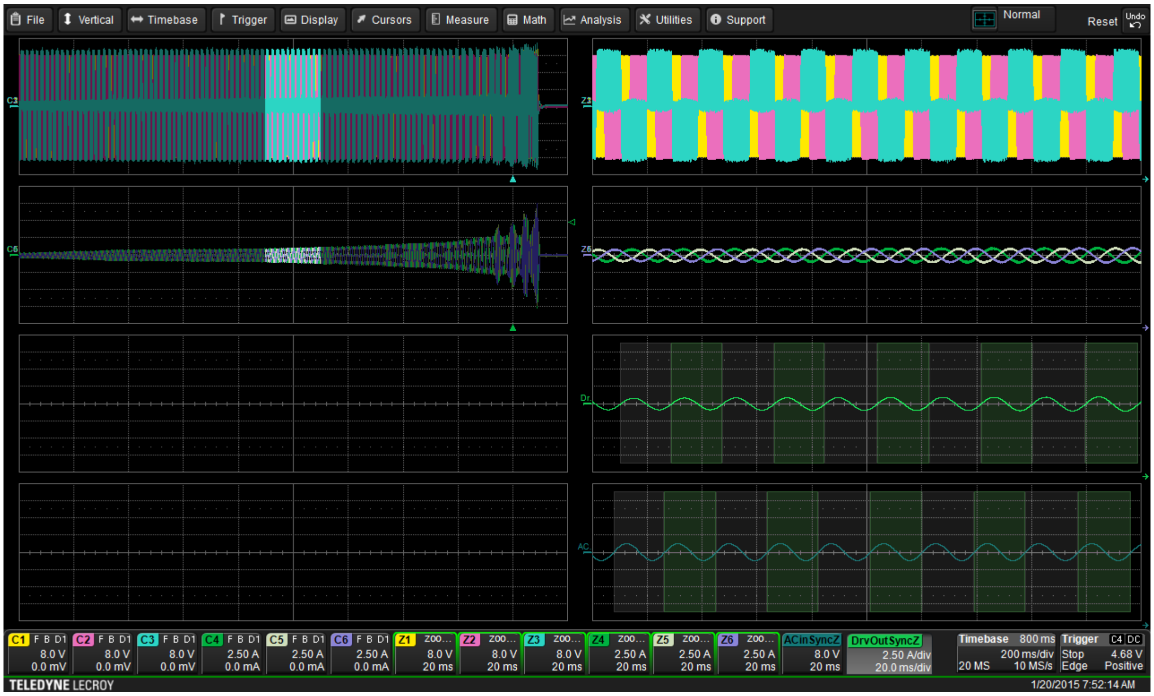

Fig. 15. Sync signal display after Zoom+Gate is enabled (lower right).

If, as in Fig. 16, we change the zoom position to the end of the acquisition, the voltage and current signals display different behaviors near the end of the acquisition (where the overload condition is occurring). The voltage and current signals have different behaviors with identical LPF cutoff and hysteresis settings, but neither of them achieves a good period determination in this location.

Fig. 16 Changing zoom position changes display of all zoomed waveforms, including Sync signals.

Zooming further to the end of the acquisition and adjusting LPF cutoff to 160 Hz and hysteresis to 20 mdiv on both Sync signals as done in Fig. 17 shows that the voltage source (green trace, used in DrvOutSyncZ) is the better source. With these changes, it would be wise to review the entire waveform (using the Zoom+Gate capabilities) to ensure that a good Sync period is found throughout the entire acquisition. This review (not shown in an image) reveals that maintenance of proper period determination of the C1 line-to-line voltage signal reaches back to the beginning of the acquisition.

Fig. 17. Adjusting filters reveals DriveOutSyncZ (C4, second waveform from the bottom on the lower right) is the better choice as the Sync signal.

Conclusion

In this section, we demonstrated the importance of waveform selection for the Sync signal and of filtering and hysteresis bands in determining the cyclic period of a motor drive waveform. In part 15, we'll delve further into filtering as it applies to measuring the power of distorted motor drive waveforms, including the use of discrete fourier transforms (DFTs) for selectively filtering specific waveform harmonics. For a full list of topics that will be addressed in this series, see part 1.

About The Author

Kenneth Johnson is a director of marketing and product architect at Teledyne LeCroy. He began his career in the field of high voltage test and measurement at Hipotronics, with a focus on <69-kV electrical apparatus ac, dc and impulse testing with a particular focus on testing of transformers, induction motors and generators. In 2000, Ken joined Teledyne LeCroy as a product manager and has managed a wide range of oscilloscope, serial data protocol and probe products. He has three patents in the area of simultaneous physical layer and protocol analysis. His current focus is in the fields of power electronics and motor drive test solutions, and works primarily in a technical marketing role as a product architect for new solution sets in this area. Ken holds a B.S.E.E. from Rensselaer Polytechnic Institute.

For further reading on motor drives, see the How2Power [Design Guide](), locate the "Power Supply Function" category, and click on the "Motor drives" link.