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A Practical Primer On Motor Drives (Part 15): Low-Pass And Harmonic Filtering Of Power Measurements

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As described earlier, the Motor Drive Analyzer and most power analyzers utilize an analog-to-digital conversion system to digitize the voltage and current waveforms, and then perform power calculations on each acquired cycle. By default, the instrument's analog bandwidth and digital sample rate combine to determine the maximum (full-spectrum) frequency of the acquired voltage and current signals, and thus the number of harmonic orders present in the power calculations.

One may employ analog or digital low-pass filters, complex harmonic filters, or any combination of these, to achieve filtering of the acquired full-spectrum signals. This part explains how these different filtering options work and shows how they are configured on Teledyne LeCroy's Motor Drive Analyzer. Measurement examples of motor drive waveforms that have been processed using a discrete Fourier transform (DFT) digital harmonic filter demonstrate the impact of filter settings on calculated power values. Finally, the last section in this part discusses the impact of line-to-reference voltage probing of PWM signals on drive outputs and how the analyzer's harmonic filtering can be used to remove the high common-mode voltage present on such measurements.

Analog Low-Pass Filter

Analog low-pass filters limit the frequency content prior to the analog-to-digital conversion. This method requires no post-processing time, but it permanently removes frequency information from the acquired signals, and typically, there is little flexibility in the low-pass filter cutoff settings. Additionally, we base filtering on a constant frequency limit, and thus may include more or fewer harmonic orders depending on the VFD's output frequency.

Fig. 1 shows an example from Teledyne LeCroy's Motor Drive Analyzer in which an analog filter may be set (in this case, to 20 MHz) in the Channel setup dialog.

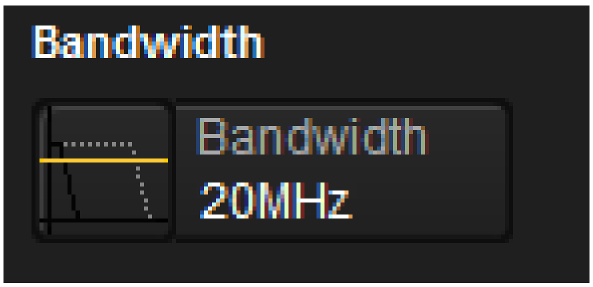


Fig. 1. Analog filter setting on Motor Drive Analyzer.

Digital Low-Pass Filter

Application of a post-acquisition digital low-pass filter comes after the analog-to-digital conversion. This method requires post-processing time to apply the digital low-pass filter, but retains the original data and provides much more flexibility in the low-pass filter cutoff settings. In some cases, this digital filter may be dependent on the digital sample rate, so if the digital sample rate is changed, the low-pass filter cutoff settings will change as well. Like the analog low-pass filter, this filter also may include more or fewer harmonic orders depending on the output frequency of the variable frequency drive.

Fig. 2 presents an example from the Teledyne LeCroy Motor Drive Analyzer in which a simple (digital) noise filter may be set (in this case, to improve noise by 1 bit, with a 3-dB cutoff at ~300 MHz) in the Channel setup dialog. Other types of digital filters are also available.

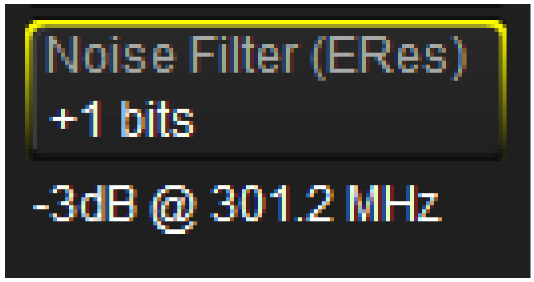


Fig. 2. Digital filter settings on Motor Drive Analyzer.

Selective Hardware PLL-Based Harmonic Filter

Power analyzer instruments often utilize a hardware PLL to recover the cyclic period in real time and dynamically adjust the sample rate to obtain a fixed number of samples per cyclic period upon which to perform an FFT for selective harmonic inclusion/exclusion from the power calculations. This method works well when the frequency is relatively stable and within the narrow loop-bandwidth constraints of the PLL (i.e., an ac 50-/60-Hz line input, or a variable-frequency drive output under constant load, speed, and torque conditions.) It will not perform properly under highly dynamic operating conditions.

Selective Software-Based FFT Digital Harmonic Filter

The Motor Drive Analyzer's fixed-frequency harmonics table calculation assumes a constant cyclic period (detected automatically or fixed by the operator.) The calculation involves a fast-Fourier transform on the full acquisition length to selectively include the fundamental and a user-settable number of harmonic orders in the harmonics calculation table.

This method requires digital post-processing of the acquired data, and takes longer to compute than a hardware-based PLL method. However, it provides the ability to set the frequency limit based on a per-cycle harmonic order, and not a fixed bandwidth limit. In addition, because we perform digital filtering as a post-processing operation, one may change the settings to obtain a different result without having to reacquire the voltage and current data. This method only works well with a 50-/60-Hz ac line input, or a variable-frequency drive output under constant load, speed, and torque conditions, because it requires a constant frequency for correct calculations.

Selective Software-Based DFT Digital Harmonic Filter

The Teledyne LeCroy Motor Drive Analyzer's harmonic filter utilizes a complex Fourier sum (term of a DFT) for each of the specified harmonic frequencies. The analyzer calculates Fourier sums on the acquired (sampled) voltage and current data over the cyclic period defined by each Sync period. For each cyclic period, it uses the resulting complex results to reconstruct the current and voltage waveforms composed of only the specified harmonics. Then, it makes power calculations only on the fundamental and the specified harmonic waveforms, with an option to include or exclude the dc component in the calculations. Thus, this method permits inclusion or exclusion of selective harmonics from the power calculations.

This filter requires digital post-processing of the acquired data, and takes the longest time to compute. However, it provides the ability to set the frequency limit based on a per-cycle harmonic order and not a fixed bandwidth limit, and because the filtering operation takes place digitally with a software-recovered cyclic period, this type of filter provides accurate power calculations by harmonic order under widely varying drive-output frequencies.

These two capabilities are highly advantageous when the cyclic period changes constantly during the acquisition (as would normally be the case with a variable frequency drive.) In addition, because we perform digital filtering as a post-processing operation, one may change the settings to obtain a different result without having to reacquire the voltage and current data. This brings a significant advantage if an operator wishes to compare a single acquisition with multiple different settings, e.g., power calculated on the fundamental only compared to fundamental through the 50^{th} harmonic (to understand power lost to heat in the windings.)

Fig. 3 shows an example from the Teledyne LeCroy Motor Drive Analyzer in which we apply a harmonic filter to power calculations made on the ac input or drive output signals, including the fundamental per-cycle frequency through the 50th harmonic.

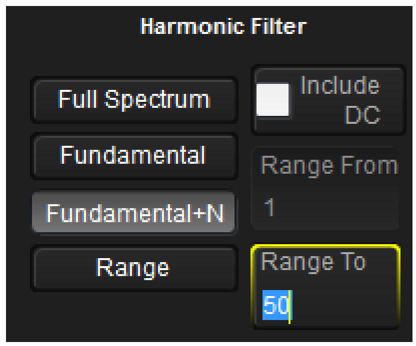


Fig. 3. Harmonic filter settings for a Motor Drive Analyzer configured to apply filtering to the acquired motor drive waveforms up to the 50^{th} harmonic.

One may make a similar selection in the harmonics table and spectral display setup in the Teledyne LeCroy Motor Drive Analyzer as shown in Fig. 4.

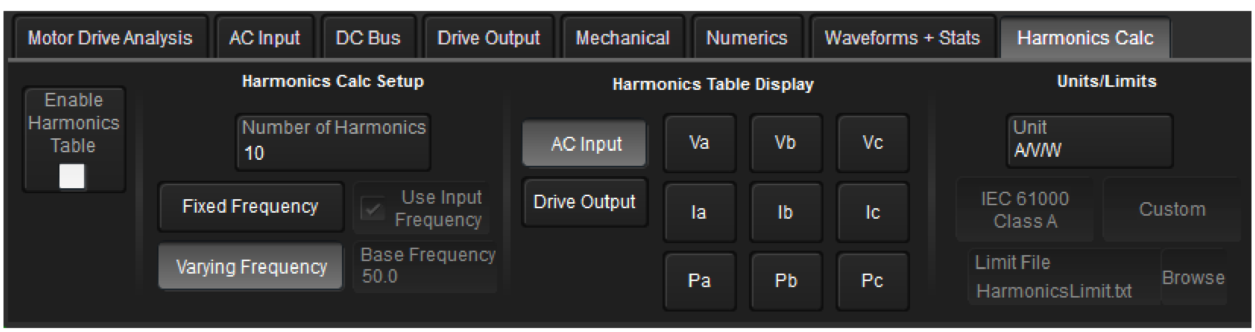


Fig. 4. The number of harmonics can also be specificied in the analyzer's harmonics table and spectral display setup.

Examples Using A Selective Software-Based DFT Digital Harmonic Filter

Consider the example in Fig. 5 of a three-phase, sine-modulated motor drive output. The acquisition is the three-phase, line-to-line voltage waveforms (all shown in the top grid) and the three-phase line currents (all shown in the bottom grid). The analyzer performs a line-to-line to line-to-neutral conversion. The Numerics table displays data for each of the three phases, and the sum total of all three phases with the harmonic filter "off" (or set to Full Spectrum), which indicates that no harmonic filtering should be performed on the data reported in the Numerics table.

Fig. 5. Numerics data calculated for the Full Spectrum of the captured waveform.

Note that the reported apparent power (S) and the reactive power (Q) values are very high. Therefore, the calculated power factor (PF) is very low and the phase angle value (φ) is correspondingly high.

Changing the Harmonics filter setting to Fundamental and unchecking the Include DC checkbox results in very different calculated data in the Numerics table, as shown in Fig. 6.

Fig. 6. Numerics data calculated for only the fundamental. Note that only the table changes.

Notice that the displayed waveform data did not change—only the Numerics table values changed. With the Include DC checkbox checked, the calculation of Numerics data takes place on that basis, as shown in Fig. 7.

Numerics		Vrms	Irms	P	S	Q	PF	φ
Vr:Ir	LL to LN	1.361 V	1.0143 A	1.331 W	1.3803 VA	364 mVAR	965e-3	15.3024 °
Vs:Is	LL to LN	1.355 V	1.0133 A	1.319 W	1.3728 VA	382 mVAR	961e-3	16.1264 °
Vt:It	LL to LN	1.364 V	995.9 mA	1.306 W	1.3582 VA	371 mVAR	962e-3	15.8574 °
Σrst	LL to LN	1.360 V	1.0078 A	3.956 W	4.1113 VA	1.118 VAR	962e-3	15.7666 °

Fig. 7. Numerics data calculated for fundamental including the dc component.

Note that now in both cases, the calculated reactive power (Q) values are now much lower, and therefore, the calculated power factor (PF) is very high and the phase angle value (φ) is correspondingly low. This is expected. PWM waveforms will produce power calculations with very high levels of reactive power but when filtered to the fundamental only, the reactive power values are greatly reduced.

Line-To-Reference Voltage Probing Of PWM Signals On Drive Outputs

As described previously, the power electronics inverter subsection of any type of drive has no direct connection to earth ground or ac line input neutral. Therefore, voltage sensing typically is performed line-to-line, which requires one of the following:

- A high-voltage, isolated differential voltage probe
- A high-voltage isolated input (channel-channel and channel-ground) to the measurement instrument.

The Teledyne LeCroy Motor Driver Analyzer requires the former, while dedicated power analyzers generally provide the latter. Probes offer flexibility: one may use any input channel for multiple purposes while slightly reducing the accuracy of the measurement (the additional inaccuracy of the probe is additive to that of the channel) and increasing cost. Isolated inputs have the advantage of lower cost. However, at high input voltages or currents, additional stepdown devices become necessary, which increases cost, and the non-shielded cable connections from the isolated input to the DUT can result in significant noise pickup.

However, some users also measure voltages from each line to a common "reference" plane, which could be a common reference location on a printed circuit board or simply three (single-ended) probe ground leads or (differential) probe negative leads connected together. While this is not the same as a line-to-neutral connection, it does eliminate the need to use a differential probe with the Motor Drive Analyzer. If the drive output peak voltage is less than ~400 V, inexpensive, single-ended passive probes suffice for the voltage measurements.

As an example, see the image in Fig. 8 of a low-voltage, six-step commutated brushless dc drive output. Z1 (yellow) is the line R-reference voltage signal, Z2 (magenta) is the line S-reference voltage signal, and Z3 (blue) is the line T-reference voltage signal. The nature of the six-step voltage commutation clearly reveals the "reference" where no PWM activity is occurring.

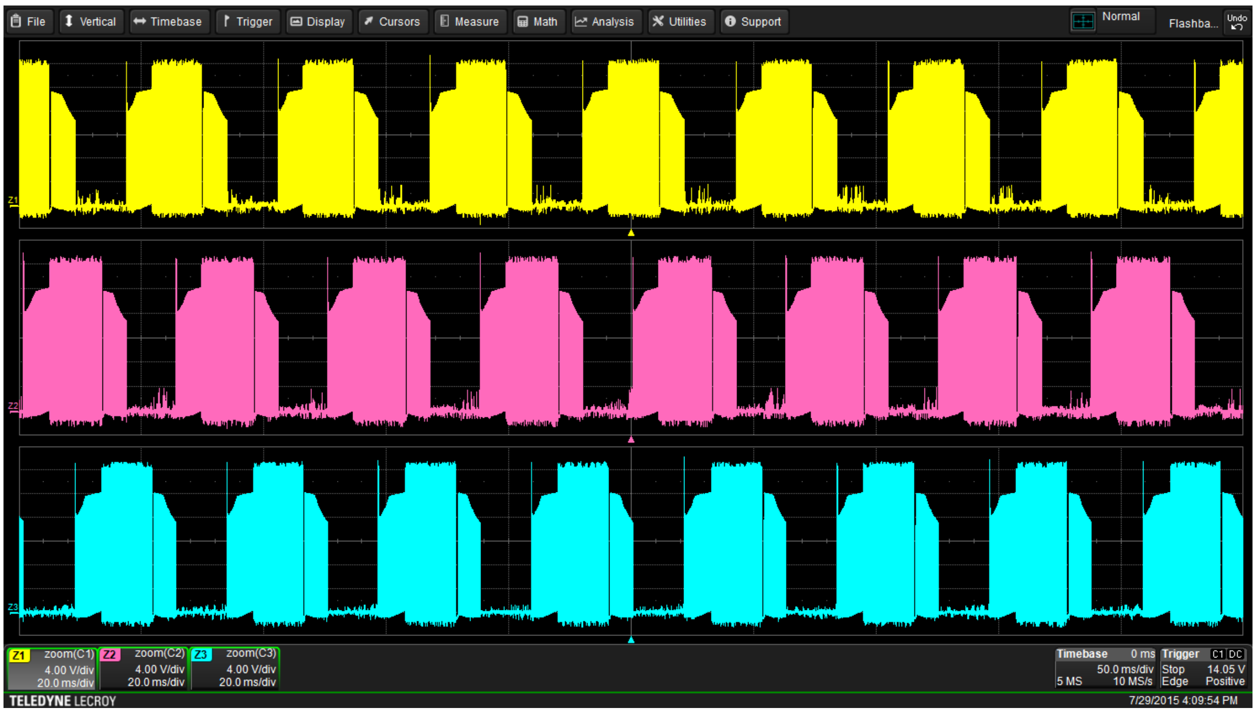


Fig. 8. Waveforms produced by a low-voltage, six-step commutated brushless dc drive output as measured by a Motor Drive Analyzer.

Note that in the Motor Drive Analyzer Drive's output setup, we have used the three-phase, four-wire (3V3A) wiring configuration, which shows a connection to "neutral" as indicated in Fig. 9. This can also be a "reference" and not true neutral connection point.

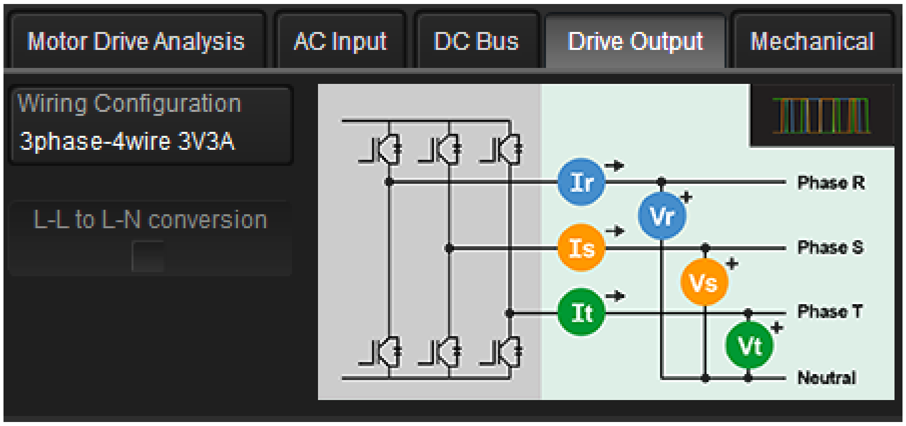


Fig. 9. Drive's output setup in the Motor Drive Analyzer.

The practical impact of using a line-to-reference probe connection instead of line-to-true neutral is that the Motor Drive Analyzer or power analyzer instrument measures the voltage signal as pulse-width modulated from 0 V to some positive voltage value, and therefore the PWM signal exhibits a very high overall common-mode (dc, or average) value. A line-to-line or true line-to-neutral measured voltage signal alternates around 0 V, leaving the PWM signal's common-mode (dc, or average) value near 0 V. This high measured common-mode voltage will not have practical impact on the calculated real power (P), but does have two other impacts:

- The high common-mode RMS voltage increases the value of the apparent power (S), which then increases the value of the reactive power (Q) and phase angle (φ), and decreases the power factor (λ).

- The high common-mode RMS voltage increases the measurement error due to residual offsets in the RMS current measurement, due to either the current probe/sensor or the acquisition system. The I_{DC} parameter can be used to measure the residual offset. If this is a significant portion of the I_{RMS}, then measurement errors will increase.

Consider the line-to-reference voltage probed acquisition in Fig. 10 from a three-phase, six-step commutated brushless dc motor. C1 (yellow) is the R-reference voltage and C4 (green) is the R current. C2 and C5, and C3 and C6 are the corresponding S and T phase line-reference voltage and current pairs. The Numerics table with various voltage, current, and power calculations appears at the bottom. Note that we set the Harmonic Filter to Full Spectrum.

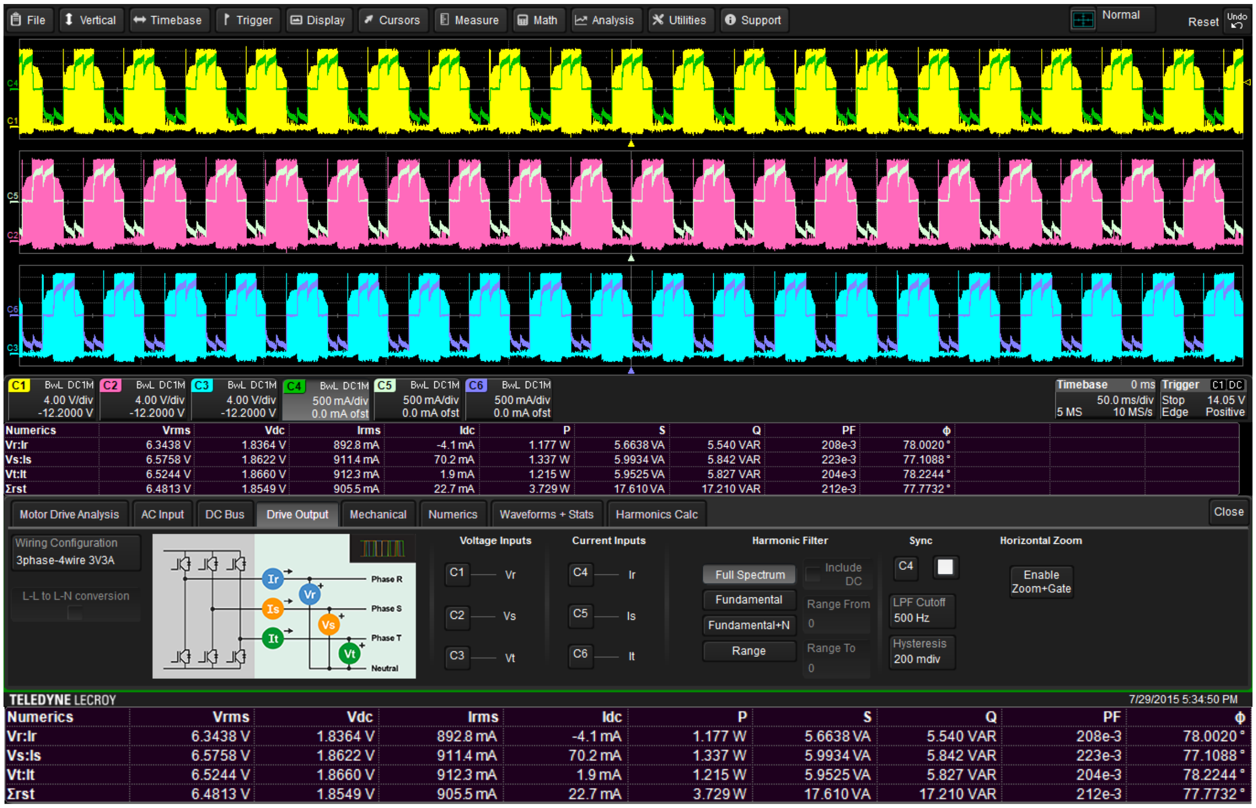
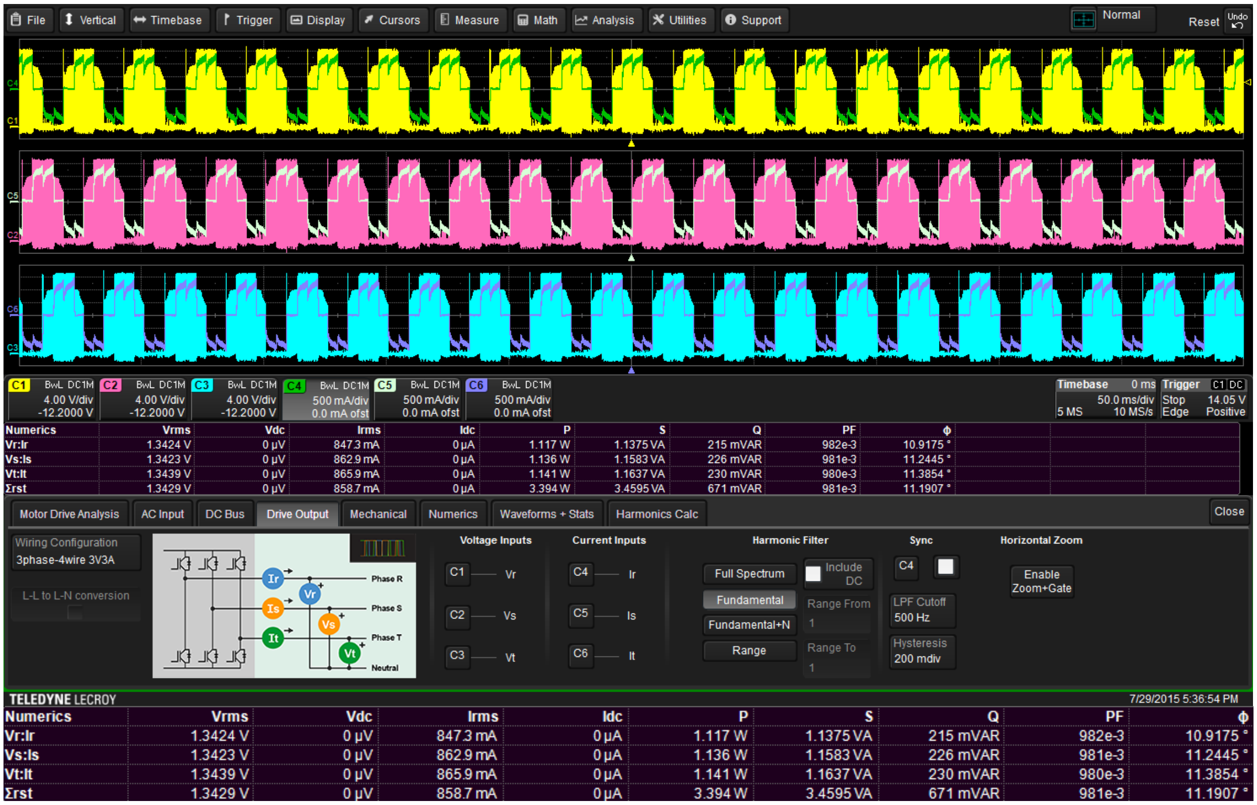


Fig. 10. Waveforms produced by a three-phase, six-step commutated brushless dc motor probed from line to reference with Harmonic Filter set to Full Spectrum.

Visually the R, S, and T phase voltage and current pairs seem to be in-phase, so one would expect a very high calculated power factor (PF) and low calculated phase angle (φ). However, the opposite is true—the calculated power factor is very low, and phase angle is subsequently very high. This is a result of a very large calculated apparent power (S, refer to the earlier section regarding power calculations using a digital sampling technique for more details) due to the high common-mode voltage (observable in the large V_{DC} measurement).

If we change the harmonic filter to fundamental (as shown in Fig. 11) and uncheck the “Include DC” checkbox (excluding the dc value from the measurement), a change in calculated power values becomes evident. Note that no new set of acquisition data was required because this is a software post-process calculation.

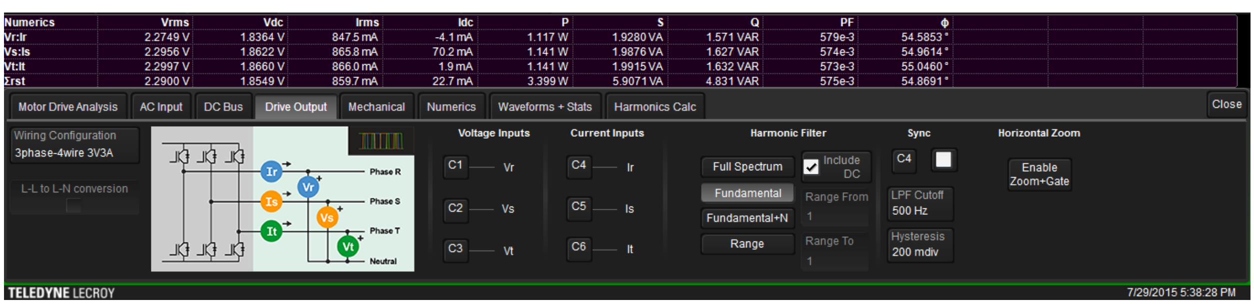


Numerics	Vrms	Vdc	Irms	Idc	P	S	Q	PF	ϕ
Vr:Ir	1.3424 V	0 µV	847.3 mA	0 µA	1.117 W	1.1375 VA	215 mVAR	982e-3	10.9175 °
Vs:Is	1.3423 V	0 µV	862.9 mA	0 µA	1.136 W	1.1583 VA	226 mVAR	981e-3	11.2445 °
Vt:It	1.3439 V	0 µV	865.9 mA	0 µA	1.141 W	1.1637 VA	230 mVAR	980e-3	11.3854 °
Σrst	1.3429 V	0 µV	858.7 mA	0 µA	3.394 W	3.4595 VA	671 mVAR	981e-3	11.1907 °

Fig. 11. Waveforms produced by a three-phase, six-step commutated brushless dc motor as in Fig. 10, but with Harmonic Filter set to Fundamental.

In this case, the V_{DC} and I_{DC} values are zero, as expected (dc was not included in the measurement.) There is a great reduction in apparent power (S), which is now nearly equal to the real power (P). Therefore, the power factor (PF) is increased to nearly 1.0 (as would be expected from visual inspection of the voltage and current pairs for each phase), and the phase angle (φ) is much smaller.

Had we checked "Include DC" in the calculation of values with harmonic filter = fundamental, we would have measured high V_{DC} values, and the power factor and phase angle would have fallen from the expected values. However, they would not drop to the values in the harmonic filter = full spectrum case, because the V_{RMS} value is lower due to the imposed harmonic filtering (see Fig 12.)



Numerics	Vrms	Vdc	Irms	Idc	P	S	Q	PF	ϕ
Vr:Ir	2.2749 V	1.8364 V	847.5 mA	-4.1 mA	1.117 W	1.9280 VA	1.571 VAR	579e-3	54.5853 °
Vs:Is	2.2956 V	1.8622 V	865.8 mA	70.2 mA	1.141 W	1.9876 VA	1.627 VAR	574e-3	54.9614 °
Vt:It	2.2997 V	1.8660 V	866.0 mA	1.9 mA	1.141 W	1.9915 VA	1.632 VAR	573e-3	55.0460 °
Σrst	2.2900 V	1.8549 V	859.7 mA	22.7 mA	3.399 W	5.9071 VA	4.831 VAR	575e-3	54.8691 °

Fig. 12. Numerics table values for the three-phase, six-step commutated brushless dc motor with Harmonic Filter set to Fundamental and dc included.

Conclusion

In this section, we described the different types of filtering that can be applied by the Motor Drive Analyzer to motor drive waveforms and looked at some examples of how they affect power calculations. In the upcoming part 16, we introduce the different types of sensors and sensing techniques that can be applied when motor drives are operated under closed-loop control. 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.