



Instruction Manual

Motor Drive Analyzer Software

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November, 2015





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Introduction

The Teledyne LeCroy MDA800 Series Motor Drive Analyzer (MDA) is a precision instrument based on an 8-channel, 12-bit acquisition system that uses Teledyne LeCroy's HD4096 technology. It acquires single or three-phase motor drive AC input, drive output and DC bus waveforms and performs a variety of static and dynamic voltage, current, power and other calculations. A variety of different speed (analog and digital, Quadrature Encoder, brushless DC Hall sensor, and resolvers) and torque measurement sensors are used to calculate motor mechanical shaft speed, direction, rotor (or electrical) shaft angle, torque, and mechanical output power. Various conversion efficiencies may also be calculated and displayed.

Calculations can be performed in a static (steady-state) or dynamic (transient) drive or motor operating condition, with results displayed in a Numeric table, Statistics table, or as synthesized per-cycle Waveforms that are time correlated to the originally acquired data. Zoom+Gate functionality is included to permit calculations on a smaller portion of a larger acquisition record. As the zoom window is changed, the Numerics table results are updated instantly without the need to reacquire the waveforms.

MDA800 Series Motor Drive Analyzers are available with up to 1 GHz bandwidth, with optional mixed-signal (MSO) and serial trigger/decode capabilities. Standard 50 Mpts/ch of acquisition memory (up to 250 Mpts/ch optional) in Single or Normal (continuous) trigger modes enables capture of long periods of time (hundreds or thousands of seconds). Traditional mixed-signal oscilloscope acquisition and analysis capabilities are included, so a complete range of serial data, digital logic, analog sensor, microprocessor, power supply and other signals can be acquired to permit complete embedded system and control debug and validation, including cross-correlation of abnormal drive power system behaviors with embedded and control system behaviors and activities.

Acquisition sample rates from 1 kS/s to 2.5 GS/s are provided, with acquisition Roll Mode supported up to 5 MS/s. Sample rates can be set very low for power analysis (~1 MS/s), at higher sample rates suitable for detailed drive analysis (10 to 25 MS/s or more), or yet higher for embedded control debug (up to 2.5 GS/s). The combination of high sample rates and long acquisition memory permits long captures in systems that combine low speed (power) and high speed (control) events—ideal for correlating high-frequency control system behaviors with lower frequency drive system behaviors. An extensive array of triggers that can isolate analog, digital, serial data, or combination events in long acquisitions supports debug of common problems that are a result of the coupling or interactions of low-frequency and high-frequency signals.

In summary, the MDA800 Series Motor Drive Analyzers combines power analyzer instrument measurement capability with traditional oscilloscope capabilities:

- Short duration steady-state (static) operating condition voltage, current, power, torque, speed, and other measurements on the motor drive input, output, DC bus, or motor mechanical shaft output.
- Long duration transient (dynamic) operating condition voltage, current, power, torque, speed and other measurements on the motor drive input, output, DC bus, or motor mechanical shaft output.
- Short or long duration capture of other signals coincident to drive signals (such as drive control feedback signals, microprocessor signals, semiconductor device gate-drive signals, etc.) to enable debug of the complete drive system isolation and debug of abnormal events or operating conditions.

Operational Overview

The MDA utilizes a high-resolution acquisition system controlled by a core operating software program (Teledyne LeCroy X-Stream™) running under Windows OS, with the Motor Drive Analysis application embedded into the core operating software program.

Signals are input to any of the eight analog channels through simple BNC/cable connection with 50Ω or 1MΩ coupling, passive probe connection with 1MΩ coupling, or Teledyne LeCroy-compatible voltage or current probes. Digital signals may also be input with the addition of a Mixed Signal option (HDO8k-MSO). Adapters are available to conveniently rescale current signals from other devices (e.g., current transformers, current transducers, Rogoswki coils, etc.) to Ampere units and values when connected to the analog channels.

As drive voltage and current and motor torque and speed signals are acquired, the Motor Drive Analyzer automatically performs cyclical analysis of the acquired signals using a user-specified “Sync” signal. This determines the measurement interval (period of time) that voltage, current, power, efficiency, speed, torque, etc. values will be computed. Figure 1 is an example of a three-phase set of drive output line-line voltage and line current signals with the “Sync” signal defined to be the blue sinusoidal current trace.

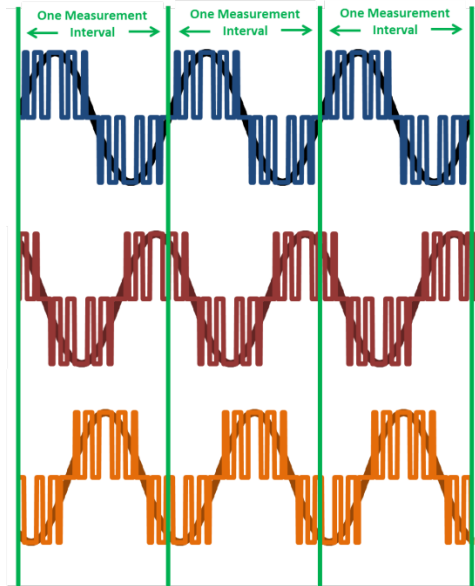


Figure 1: Sinusoidal “Sync” signal determines measurement interval for three-phase set of signals.

Once measurement intervals are defined and applied across all waveforms in an acquisition, mathematical calculations are then performed for each measurement interval as defined by the selected Sync source signal, with mean or average values calculated over N cycles for cycles $i = 1$ to N in the full or gated acquisition.

Mathematical operations are valid for both sinusoidal voltage and current waveforms and for non-sinusoidal (e.g., PWM or non-linear) waveforms typical of motor drive outputs. Voltage and Current values are calculated per IEEE definitions. See the Appendix (p.77) for more detailed descriptions of power and other measurement calculations.

The mean or peak value (depending on the measurement) for a single acquisition is displayed in a user-defined Numerics table.

Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir	12.0815 V	598.7 mA	703 mW	7.2333 VA	7.199 VAR	97e-3	84.4201 °
Vs:Is	12.2929 V	599.4 mA	700 mW	7.3683 VA	7.335 VAR	95e-3	84.5459 °
Vt:It	11.9865 V	601.3 mA	707 mW	7.2069 VA	7.172 VAR	98e-3	84.3680 °
Σ rst	12.1203 V	599.8 mA	2.111 W	21.809 VA	21.706 VAR	97e-3	84.4454 °

Figure 2: Numerics table shows measurement values.

You can display statistical data and a synthesized per-cycle Waveform tracking the variation of this data over time simply by selecting a Numerics table cell. Each cell represents a motor parameter, a specific measurement on a single input source:

Statistics	P(Σ rst)	S(Σ rst)	PF(Σ rst)	Q(Σ rst)	Irms(Vr:Ir)	Irms(Vs:Is)	Irms(Vt:It)
value	10.3054 W	28.481 VA	362e-3	26.5514 VAR	1.80025 A	1.73721 A	1.73604 A
mean	10.1781 W	28.2021 VA	360.8882e-3	26.3014 VAR	1.78434 A	1.72494 A	1.732681 A
min	10.0507 W	27.923 VA	360e-3	26.0514 VAR	1.76844 A	1.71267 A	1.72932 A
max	10.3054 W	28.481 VA	362e-3	26.5514 VAR	1.80025 A	1.73721 A	1.73604 A
sdev	127.4 mW	279.1 mVA	945.3e-6	250.0 mVAR	15.90 mA	12.27 mA	3.362 mA
num	2	2	2	2	2	2	2
status	✓	✓	✓	✓	✓	✓	✓

Figure 3: Statistics table shows measurement statistics for selected motor parameters.

The per-cycle Waveforms may then be correlated with other acquired signals, or gated to a specific portion of the acquisition, providing valuable capability to debug complex drive behaviors under long duration, transient operating conditions.

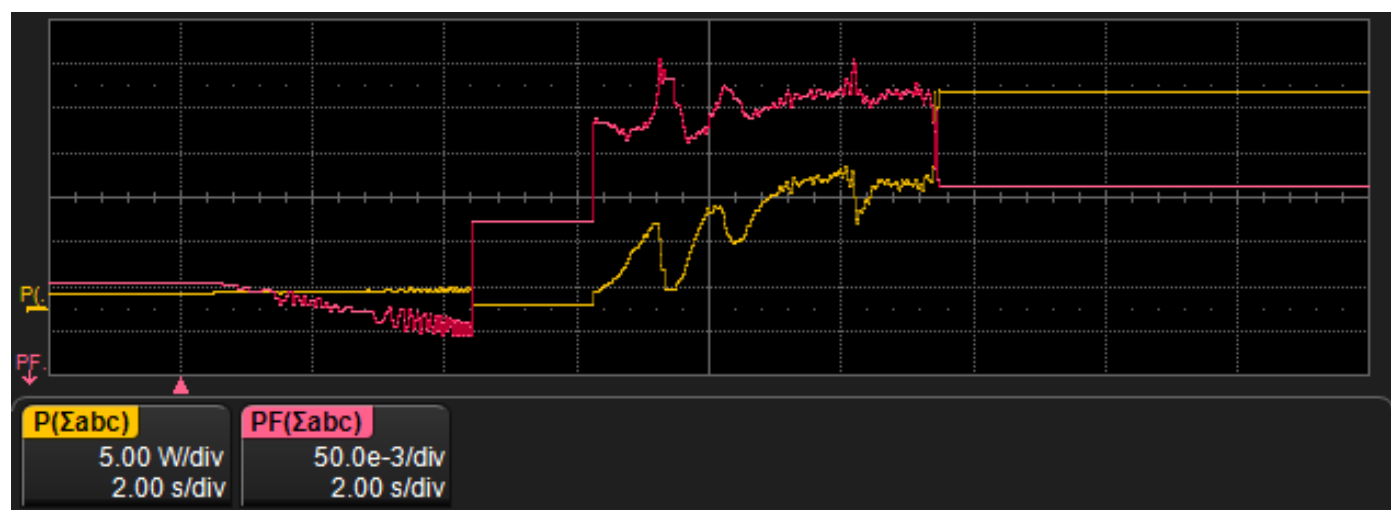


Figure 4: Synthesized per-cycle Waveforms plot motor parameter values over the course of the acquisition.

Supported Inputs

The MDA analog channels utilize a ProBus™ interface that consists of a BNC and a 6-pin connector. The ProBus interface:

- Identifies and sets attenuation for passive probes
- Powers and identifies ProBus-compatible probes, making correct selection of probe input coupling, attenuation, etc.

A variety of standard Teledyne LeCroy ProBus-compatible voltage and current measurement probes are supported for use with Motor Drive Analyzers. Differential voltage probes are available with high voltage isolation, excellent noise and flatness performance, and high common-mode rejection ratio (CMRR). Current probes are available with ratings up to 700A (RMS, peak) ratings.

A wide variety of third-party voltage and current transformers/transducers may be integrated into the MDA and Motor Drive Analyzer software by using a direct BNC connection to the instrument and a rescale operation. A Current Adapter may be purchased from Teledyne LeCroy and programmed so that a third-party current measurement device is automatically re-scaled whenever it is plugged-in to the MDA. Built-in support is provided for the widest variety of angular speed, direction and absolute position sensing mechanisms, including simple analog and digital (pulse) tachometers, quadrature encoder interfaces (QEI), resolvers, and Hall effect sensors. To conserve high-resolution (12-bit) analog input channels, digital (MSO) inputs may be used for speed sensors with digital signal outputs. Torque transducers may also be integrated.

See Choose the Correct Input Method for Your Signals (below) for guidance on selecting the best input device.

Choose the Correct Input Method for Your Signals

Direct BNC/Cable Connections

BNC/cable connections are commonly used to connect current transducers/transformers (CT), Rogowski coils, voltage (potential) transformers (PT), or other sensor units to the input channels. A CT should have a resistor installed across the output so as to create a voltage which can be input to the MDA.

Input signals can be manually rescaled and converted to new units directly in the software using the input channel dialog (Cx). Select a new unit and Unit/V conversion ratio (and an Add value, if appropriate). You can also select the coupling (DC50Ω, DC1MΩ, or AC1MΩ).

NOTE: The maximum input voltage rating on a channel when using 50Ω coupling is 5Vrms. Many current and voltage sensing devices may not provide frequency response to DC, and therefore cannot be DC-coupled to the instrument. Depending on the input signal, this may impact voltage, current, and power measurement accuracy.



Figure 5: Define input signal characteristics on the Channel (Cx) dialog.

Passive Voltage Probes

Passive probes utilize an attenuation-sense pin that identifies to the input channel the appropriate attenuation (and coupling) settings. Passive probes are single-ended, and the ground lead on a passive probe is connected directly to the instrument chassis ground. Therefore, the probe connection to the device under test (DUT) is also connected to instrument chassis ground.

The passive probes (qty. 4) supplied with the MDA are rated for up to 500 MHz bandwidth with 10 MΩ input resistance, DC coupled to the input channel with 1 MΩ input resistance, resulting in a 10:1 attenuation. This high input resistance means that passive probes are the ideal tool for low-frequency signals, since circuit loading at these frequencies is minimized. However, the maximum voltage at the probe tip cannot exceed 600V (DC + peak AC, with a frequency de-rating beyond 30 kHz), and the maximum voltage at the input channel (after 10:1 attenuation) cannot exceed 400V max (DC + peak AC, ≤10 kHz, when DC coupled to 1 MΩ input resistance). Thus, passive probes are ideal for measuring lower voltage signals referenced to ground. A common application for passive probes is measuring drive output voltages on a battery-powered device (within the limitations described above) where the drive output is effectively referenced to an earth ground. At higher voltages (>50V), common-mode interference may introduce unwanted noise to the measurement. In these cases, a suitable differential voltage probe is usually recommended.



CAUTION: Do not use passive probes with the probe ground attached to a three-phase system Neutral connection, as the Neutral voltage may not be the same as Ground, and significant currents could travel from the passive probe neutral to instrument ground—a hazardous situation that could result in shock or damage to the DUT or MDA (or both). In this case, an HV-isolated, differential voltage probe is recommended.

High-Voltage (HV) Passive Voltage Probes

These probes are similar to low-voltage passive voltage probes except they have a higher voltage rating at the probe tip and may require that you manually set the attenuation and coupling for the input channel. The same cautions about ground connections that apply to passive voltage probes apply to HV passive voltage probes. Two HV passive voltage probes may be used in a pseudo-differential mode if the probe grounds are connected together (but not to ground) and connected to two separate input channels using a math subtraction of the two input channels to achieve the differential result. While this may be the only suitable method for very high voltages, there can be significant common-mode interference when using this technique.

Active (Single-Ended) Voltage Probes

Active probes utilize a Teledyne LeCroy ProBus interface connection to identify the probe to the input channel so that the correct attenuation and coupling are set automatically. These probes typically have less voltage range than a passive probe. The same cautions about ground connections that apply to passive voltage probes apply to active single-ended voltage probes as well, but these types of probes typically have much less voltage range and peak voltage capability than passive probes.

Active (Differential) Voltage Probes

Differential voltage probes sense the voltage difference that appears between + and – inputs. The voltage component that is referenced to earth (the common mode voltage) is identical on both inputs and is rejected by the amplifier. These types of probes are ideal for measuring low voltages in control systems, drive inputs/outputs, and gate drive voltages as long as the voltages are not “floating” more than the common-mode voltage rating of the probe. In drives, very often the common-mode voltage is “floating” by a large amount, so typically a high-voltage differential voltage probe is used.

High-Voltage (Differential) Probes

High-voltage differential voltage probes operate the same as “normal” differential voltage probes, but they have the added benefit of HV isolation with respect to ground and wider differential voltage ranges. They are also very cost effective, making them a good, general-purpose differential voltage probe for a variety of power electronics inverter subsystem, drive input/output, and control system probing. Since these probes are rated for higher voltages, the tips are HV insulated and larger than normal differential voltage probes, so they are not suitable for fine pitch probing. Also, bandwidths are usually lower (~100 MHz).

Current Probes

Current probes use a combination of Hall effect and transformer technology, which enables measurements to be made on DC, AC and impulse currents at very high bandwidths. These probes are available with ratings up to 500A continuous (700A peak). They are designed to be used on insulated conductors, as the core and shield are grounded and voltage applied to the probe may damage the probe or the circuit under test. Note that in the presence of strong magnetic fields, accurate measurements may not be possible, so it is good operating practice to locate these probes as far away from strong magnetic fields as possible.

CA10 ProBus Current Adapter

The CA10 ProBus Current Adapter is a programmable and customizable interface device that seamlessly incorporates third-party current transducers/transformers into the MDA. It allows the third-party device to be recognized and operate as if it were a Teledyne LeCroy probe, replacing the need to manually rescale and convert units each time the device is connected to the MDA. Examples of devices that can be used with the CA10 include Pearson Current Transformers, Danisense/LEM Current Transducers, PEM-UK Rogowski Coils, or any conventional turns-ratio current transformers.

When using the CA10 ProBus Current Adapter to connect the current measuring device to the instrument, coupling and rescale settings will appear on the CA10 dialog immediately behind the input channel dialog. Once the CA10 is programmed, the third-party transducer/transformer will be recognized and operate like a Teledyne LeCroy probe.

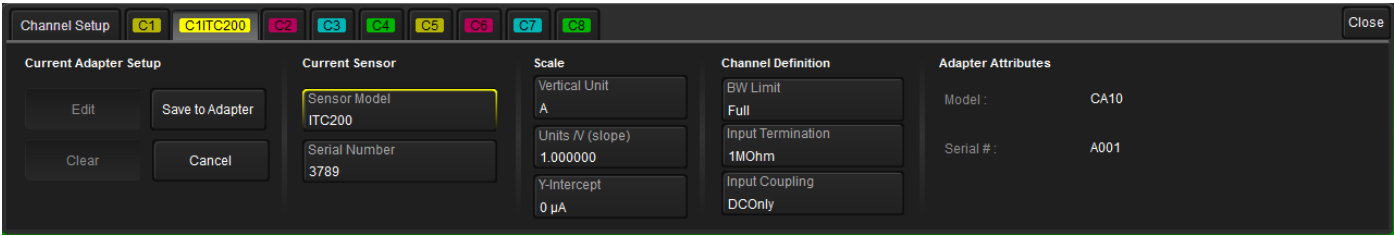


Figure 6: When using the CA10, define current measuring device inputs on the CA10 dialog.

Using the Motor Drive Analysis Software

Accessing the Motor Drive Analysis Setup Dialogs

The Motor Drive Analysis software package employs a multi-tabbed user interface. The tabs are referred to as “setup dialogs”. These dialogs enable you to define the connection of signals for proper analysis and to create numeric tables and specialized per-cycle voltage, current, power and mechanical waveforms.

From the menu bar along the top of the display, choose Analysis > Motor Analysis.



Figure 7: Motor Drive Analysis Software option on Analysis menu.

The following Motor Drive Analysis dialogs appear (from left to right):

- **Motor Drive Analysis**—A summary of the current setup and quick access buttons to all the other dialogs
- **AC Input, DC Bus, Drive Output, and Mechanical**—Setup dialogs used to characterize sections of the drive or motor and to select a measurement Sync signal
- **Numerics**—Used to configure the Numerics table that displays the mean or peak measurement values for a given source and measurement
- **Waveforms + Stats**—Used to turn on/off the Statistics table, and to provide descriptions of per-cycle Waveforms created and other configuration controls

When first entered from Analysis > Motor Analysis, the Motor Drive Analysis setup dialog is displayed on top. Other setup dialogs may be accessed by touching the labeled blocks or the tabs.

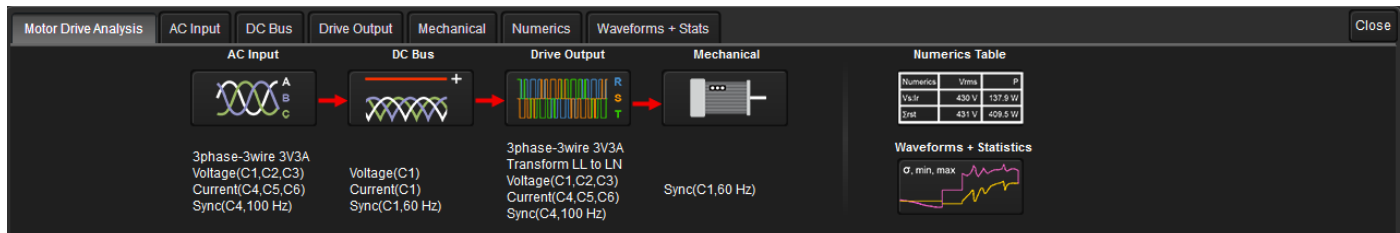


Figure 8: Motor Drive Analysis dialog group.

Using the Shortcut Buttons

Beneath the touch screen display are six shortcut buttons, four of which (**Drive Setup**, **Numerics**, **Waveforms**, and **Zoom+Gate**) are colored gray and perform actions specific to the Motor Drive Analysis program.



Figure 9: Motor Drive Analyzer shortcut buttons on front panel of MDA.

The table below describes how these buttons work.

Table 1: MDA Shortcut Button Functions

Button Press	Drive Setup	Numerics	Waveforms	Zoom+Gate
First	1) If setup dialogs are closed, then opens the Motor Drive Analysis dialog. OR 2) If setup dialogs are open, closes all dialogs.	1) Turns on the Numerics table (Show Numeric Table checked) provided at least one row (source) and one column (measurement) are defined. OR 2) If table defined and displayed, turns off Numerics table (Show Numeric Table unchecked). OR 3) If table not sufficiently defined, opens the Numerics setup dialog to allow table definition.	1) Shows per-cycle Waveforms and Statistics table if they are defined but turned off. OR 2) If no per-cycle Waveforms have been defined, opens the Waveforms + Stats setup dialog.	Creates zoom (Zx) traces (at 10:1 horizontal zoom ratio) for all acquired analog and digital channels. Creates a time-synchronized multi-zoom group that includes all per-cycle Waveforms and Sync signals. Activates Vertical and Horizontal front panel knobs for zooming (Zoom button is lit). Numerics and Statistics table data "gated" to the zoomed area.
Second	Reverses action of first button press.	1) If Numerics table is displayed, turns it off (Show Numeric Table unchecked). OR 2) If Numerics table is not displayed, then performs same actions as first button press.	1) If per-cycle Waveforms and/or statistics are on (Waveforms and/or Show Statistics Table checked), they are turned off (unchecked). OR 2) If no per-cycle Waveforms have been defined, closes the Waveforms + Stats setup dialog.	Turns off channel zooms (Zx traces). Resets per-cycle Waveforms and Sync signals to 1:1 (same time scale as acquired channels).
Third	Same as First.	Same as First.	Same as First.	Same as First.

The other two shortcut buttons (**LabNotebook**, **Q-Scope**) perform the same functions as on the HDO8000 oscilloscopes. See the *MDA/HDO8000 Oscilloscopes Operator's Manual* for a description. See the instructions for using the Numerics Table (p.45) and Zoom+Gate (p.52) features later in this manual.

Motor Drive Analysis Dialog

The Motor Drive Analysis dialog is the entry point to the Motor Drive Power Analysis software. The dialog shows a block flow diagram of the electrical signal path of a Motor Drive and Motor, and provides a visual and textual summary of the wiring configuration, channel assignments, and Sync signal selection for each motor drive “block”.

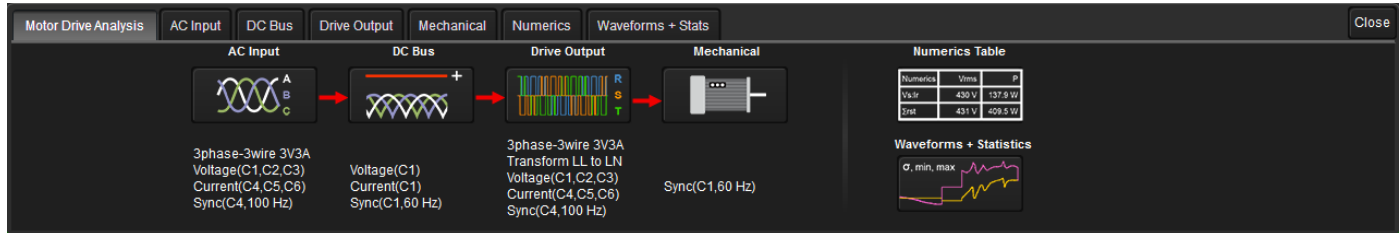


Figure 10: Motor Drive Analysis dialog provides visual and textual summary of motor drive “block” configurations.

The icon shown on the AC Input, DC Bus and Drive Output blocks changes based on the wiring configuration selected on the respective dialog. For instance, if the AC Input wiring configuration is “3phase-3wire 3V3A”, then the AC Input block icon shows three sinusoidal signals labeled A, B, and C to evoke a 3-phase / 3-wire configurations.

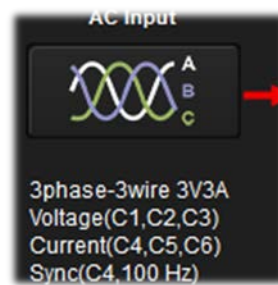


Figure 11: Icons show wiring configuration selected for that block.

If “None” is selected for a specific wiring configuration, the block shows the icon for the previous wiring configuration selection so as to maintain a visual “cue” of what the block represents.

Each block has a distinctive, application-specific set of icons so as to clearly differentiate the AC Input, DC Bus and Drive Output, and the icons are repeated in the larger wiring configuration diagrams shown on the respective setup dialogs.

Below the block is a summary description of the wiring configuration selected, the channel assignments, and Sync signal selections made for the various drive power sections (AC Input, DC Bus, and Drive Output) so as to facilitate understanding of the complete setup definition. The Mechanical (Motor) block indicates the torque and speed configurations, the channel assignments for them, and the Sync signal selection. All summaries are shown at all times, whether or not there is an active acquisition, measurement or waveform for the section.

The blocks in the flow also serve as buttons to open the corresponding setup dialogs. You may use either the setup dialog tab or the button to open the dialog. Detailed setup instructions for each setup dialog follow in separate sections.

Two additional buttons, Numerics and Waveforms + Stats, open their respective setup dialogs. Use these dialogs to configure the measurement parameters shown in the Numerics or Statistics measurement tables. No summary information is provided for these blocks.

AC Input and Drive Output Dialogs

The AC Input and Drive Output dialogs contain essentially the same setup information (although each group of settings is used independent of the other), therefore, they are described together here. The main differences between the two dialogs are:

- The line (phase) nomenclature for AC Input is A, B, and C, while for Drive Output is R, S, and T
- The single-phase wiring configurations differ

In general, on either AC Input or Drive Output setup dialog, you will select:

- A single or three-phase wiring configuration, or “None”
- Sources to be assigned to the voltage or current inputs shown in the selected wiring configuration
- A Sync signal to determine the measurement interval cycle (period) over which all calculations are made

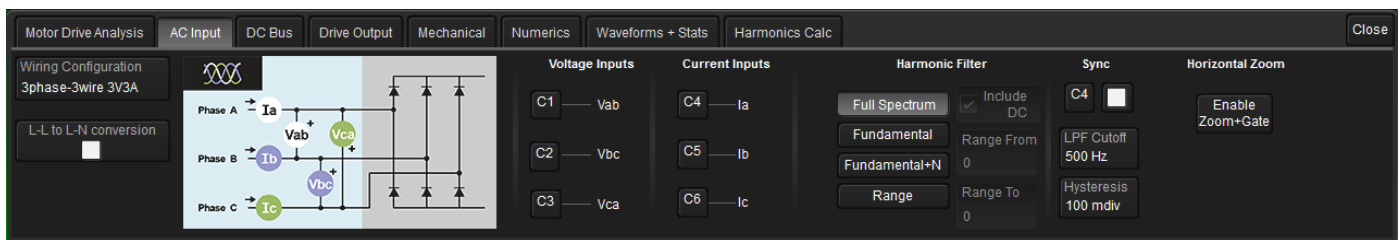


Figure 12: AC Input setup dialog.

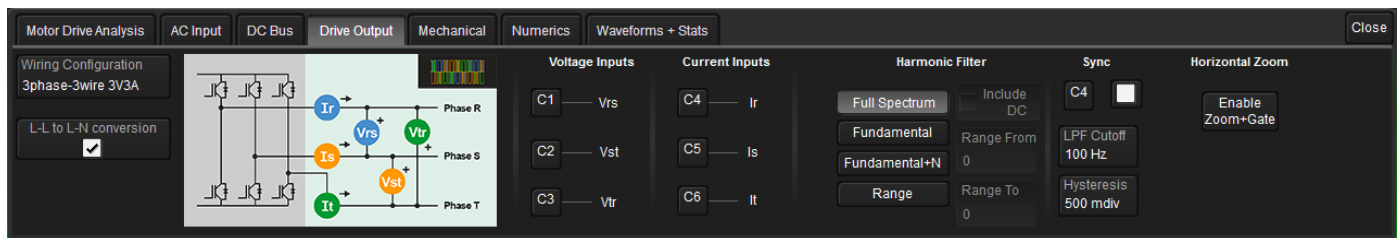


Figure 13: Drive Output setup dialog.

Wiring Configuration

To correctly calculate power values, identify the **Wiring Configuration** used by the drive power section and assign sources to each voltage and current input.

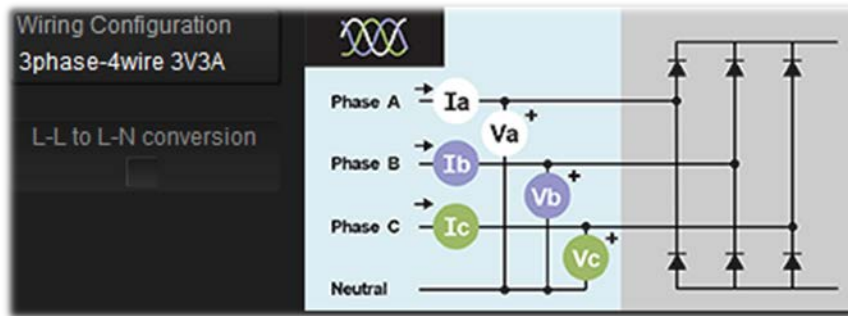


Figure 14: AC Input 3-phase/4-wire wiring configuration.

AC Input and Drive Output each has five available wiring configuration selections (plus “None”):

- 3-phase/3-wire (2 Voltages, 2 Currents)–Use Line-Line voltage probing and 2 wattmeter method. This method is ideal for measuring drive input/output efficiency since, if selected for both the AC Input and Drive Output, it requires only eight total (4 voltage and 4 current) analog input channels.
- 3-phase/3-wire (3 Voltages, 3 Currents)–Use Line-Line voltage probing.
- 3-phase/4-wire (3 Voltages, 3 Currents)–Use Line-Neutral or Line-Reference voltage probing.
- 1-phase/2-wire (1 Voltage, 1 Current)–AC Input setup dialog only.
- 1-phase/3-wire (2 Voltages, 2 Currents)–AC Input setup dialog only.
- 1-phase (Half Bridge)–Drive Output setup dialog only.
- 1-phase (Full Bridge)–Drive Output setup dialog only.
- None–This selection is equivalent to de-activating any voltage and current assignments to the right of the Wiring Configuration setup.

NOTE: The wiring configuration is not the same as the motor *winding configuration*. A three-phase motor winding may be either a Wye (Y, or Star) or Delta (Δ), and while a Delta motor winding will naturally encourage a three-wire wiring configuration (there is no neutral present in a Delta winding), a Wye winding may provide ability to probe voltage line-line (three-wire) or line-neutral or line-reference (four-wire). Some users, especially those testing high voltage motors (>600V class) may probe voltage line to “reference” (an artificial floating neutral) and this may provide acceptable results, through voltage waveforms may show artifacts of this approach. Users testing very low voltage motors (<50V) may prefer standard low voltage passive probes in a line to “reference” configuration with the probe ground connected to control reference. In this case, the oscilloscope will force the control “reference” to ground. This may or may not be acceptable, depending on the controls and motor.

AC Input and Drive Output may each use a different wiring configuration (e.g., the AC Input may use a single-phase, two-wire wiring configuration while the Drive Output may use a three-phase, three-wire (3V3A) wiring configuration). Therefore, the connection diagram that appears on the dialog will dynamically change depending on the wiring configuration selected. The wiring configuration diagram shown in Figure 14 is for a three-phase, four-wire (3V3A) selection made in the AC Input setup dialog. The wiring configuration diagram shown in Figure 15 is for a three-phase, three-wire (3V3A) selection made on the Drive Output setup dialog.

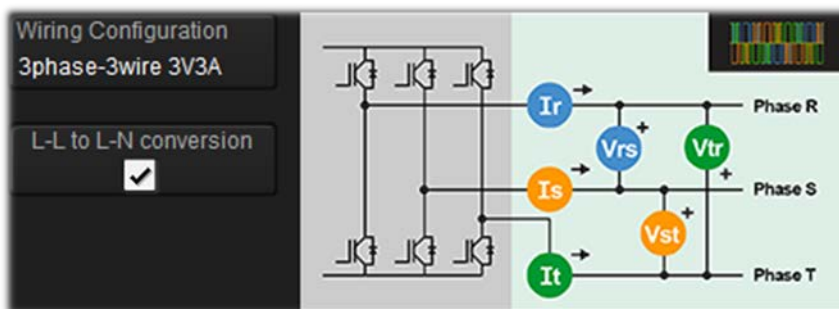


Figure 15: Connection diagram changes for each drive section and wiring configuration.

These diagrams provide important information on how to connect the probes for each phase. For example, current probes must be connected with current flow into the load (i.e., into the drive or into the motor) and voltage probes must be connected as indicated with the plus sign indicating the positive connection of the probe. If you are using differential voltage probes (as would be required in the case of line-line voltage probing), you must connect the positive and negative leads of the differential probes as shown in the diagram. Failure to do so will result in incorrect values for total and per-phase power. These incorrect results may not be obvious in three-phase, three-wire (3V3A) wiring configurations where a line-line to line-neutral conversion is not performed and individual phase values are not shown.

NOTE: The voltage connection and nomenclature in the diagram follows the utility industry convention of indicating voltage polarity (i.e., VAB indicates a voltage made with reference from A phase to B phase) and not the mathematical vector convention (i.e., $\vec{AB}$ indicating a vector drawn from A to B).

The AC Input/Drive Output wiring configuration selection impacts the display of data in the Numerics table. Figure 16 shows the Numerics table display for a three-phase, four-wire (3V3A) Drive Output wiring configuration in which voltage is sensed line-reference. The table contains rows for the line-reference voltages and the corresponding line currents for the Drive Output (R, S, T) setup. In this case, voltage, current and power values for each phase are displayed, as well as the sum value for the three-phase total (see the Appendix (p.77) for measurement definitions).

Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir	12.0815 V	598.7 mA	703 mW	7.2333 VA	7.199 VAR	97e-3	84.4201 °
Vs:Is	12.2929 V	599.4 mA	700 mW	7.3683 VA	7.335 VAR	95e-3	84.5459 °
Vt:It	11.9865 V	601.3 mA	707 mW	7.2069 VA	7.172 VAR	98e-3	84.3680 °
Σ rst	12.1203 V	599.8 mA	2.111 W	21.809 VA	21.706 VAR	97e-3	84.4454 °

Figure 16: Leftmost source column shows values will be line-reference (Vr, Vs, and Vt).

Line-Line to Line-Neutral Conversion

For wiring configurations that require voltage sensing line-line, the Numerics table will display line-line per-phase voltage and current values, but it will not display per-phase power values due to the voltage being sensed to a different reference (line-line) than the current (line). In Figure 17, the leftmost column of the table indicates voltage as line-line (Vrs, Vst, and Vtr) and currents as line currents (Ir, Is, and It).

Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vrs:Ir	7.387 V	1.0159 A	—	—	—	—	—
Vst:Is	7.436 V	1.0148 A	—	—	—	—	—
Vtr:It	7.469 V	1.0113 A	—	—	—	—	—
Σ rst	7.431 V	1.0140 A	4.046 W	15.135 VA	14.584 VAR	267e-3	74.4976 °

Figure 17: Leftmost source column shows values will be line-line (Vrs, Vst, and Vtr).

However, it is possible to convert the voltage reference to a Line-Neutral basis, which then permits per-phase power calculations. Simply select the L-L to L-N conversion checkbox immediately below the Wiring Configuration (this checkbox is disabled when voltage is already sensed line-neutral or line-reference).

When conversion is selected, the Numerics table data will change as shown in Figure 18.

Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir LL to LN	4.275 V	1.0159 A	1.358 W	4.3427 VA	4.125 VAR	313e-3	71.7853 °
Vs:Is LL to LN	4.274 V	1.0148 A	1.345 W	4.3382 VA	4.124 VAR	310e-3	71.9417 °
Vt:It LL to LN	4.303 V	997.4 mA	1.328 W	4.2918 VA	4.081 VAR	309e-3	71.9820 °
Σ rst LL to LN	4.284 V	1.0094 A	4.030 W	12.973 VA	12.331 VAR	311e-3	71.9027 °

Figure 18: Leftmost source column shows values have undergone L-L to L-N conversion.

Now, the voltage magnitude is in a Line-Neutral basis, and the phase has been corrected as well, which allows per-phase power values to be calculated. The leftmost column of the table now indicates voltage as line voltage (Vr, Vs, and Vt) and there is an **LL to LN** notation next to each indicating that these values were calculated using a mathematical conversion and not via direct measurement.

Conversion has the benefit of allowing you to configure the Numerics table to display the per-phase power (P, S, Q, λ , and ϕ) values for each phase and converted line-neutral V_{RMS} value (and other voltage values calculated on a line-neutral basis).

NOTE: The line-neutral conversion assumes a balanced three-phase system in which the vectoral sum of all voltages is zero and the vectoral sum of all currents is zero. To perform the conversion, it enforces this assumption as a requirement, and the C (AC input) or T (Drive Output) current value will be adjusted to ensure that the vector sum of all currents is zero. Depending on the amount of adjustment to the C or T phase current reading, the total P (and S and Q) values will change slightly, as can be seen Figure 18). If the Idc measurement parameter was displayed in the Numeric table, the adjustment could be quantified.

See Numerics Setup Dialog (p.45) for more information on configuring the Numerics table.

Voltage and Current Assignments

A unique voltage and current input assignment section appears on the AC Input, DC Bus, and Drive Output dialogs, depending on the wiring configuration chosen. Figure 19 shows the voltage and current input assignment on the Drive Output dialog for a three-phase, three-wire (3V3A) wiring configuration.

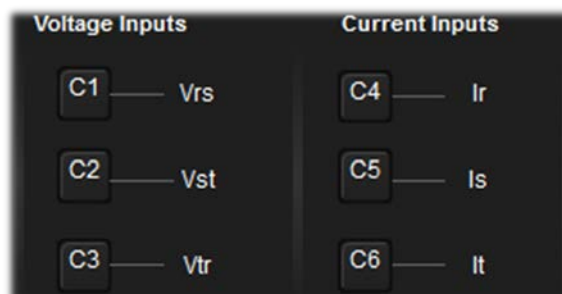


Figure 19: Voltage and Current assignments.

Two columns appear—one for Voltage Inputs and one for Current Inputs. In this case, each has three assignments. The input source is shown at the left of each assignment, with the voltage or current to which it is assigned shown to the right. By default, C1 is the source for all voltages and currents.

To make assignments, simply touch or click the source button, and from the pop-up, choose the channel (Cx) or memory (Mx) that is the correct source for that voltage or current.

NOTE: Use care when changing from a three-phase, three-wire (3V3A) wiring configuration to a three-phase, three-wire (2V2A) wiring configuration. The input assignments look very similar, but the polarity of the CA or TR voltage is now reversed (by definition of the two wattmeter method) to AC or RT. This requires that you physically reconnect the differential voltage probe or Invert the input channel on the channel dialog (and swap the selection of inputs) to switch the signal polarity and reassign a voltage. Failure to do this will result in an incorrect result.

Harmonic Filter

The AC Input and Drive Output setup dialog contains selections for setting a Harmonic filter on the drive output.

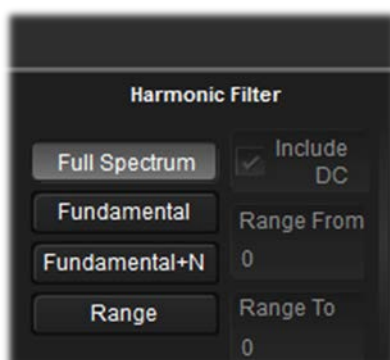


Figure 20: Harmonic filter setup.

Motor Drive Analyzer Software

Up to four selections could appear:

- Full Spectrum
- Fundamental
- Fundamental+N
- Range

Only two selections (Full Spectrum and Fundamental) are standard with the Motor Drive Analyzer and available with the initial software release (7.7.x.x). The Fundamental+N and Range selections are enabled with the purchase of the Harmonics Calculation option (p.60). This option requires that firmware version 7.9.x.x or greater be installed on the Motor Drive Analyzer.

Consider this example of a three-phase sine-modulated motor drive output. The acquisition is the three-phase line-line voltage waveforms (all shown in the top grid) and the three-phase line currents (all shown in the bottom grid). A Line-Line to Line-Neutral conversion is performed, and 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.



Figure 21: Numerics data calculated for the Full Spectrum.

You can see that the reported apparent power (S) and the reactive power (Q) values are very high, therefore the calculated power factor (PF) and phase angle values (ϕ) are very low.

If the Harmonics filter setting is changed to Fundamental and the Include DC checkbox is left unchecked, then the calculated data in the Numerics table is very different, as shown in Figure 22.



Figure 22: Numerics data calculated for only the Fundamental Harmonic. Note that only the table changes.

Notice that the displayed waveform data did not change—only the Numerics table values changed. If the Include DC checkbox is checked, then the Numerics data is now calculated on that basis, as shown in Figure 23.

Numerics	Vrms	Irms	P	S	Q	PF	Φ
Vr:lr LL to LN	1.361 V	1.0143 A	1.331 W	1.3803 VA	364 mVAR	965e-3	15.3024 °
Vs:ls LL to LN	1.355 V	1.0133 A	1.319 W	1.3728 VA	382 mVAR	961e-3	16.1264 °
Vt:lt 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 °

Figure 23: Numerics data calculated for Fundamental Harmonic including the DC component.

The Fundamental+N setting is available with the MDA Harmonics Calculation option. If this selection is made, then the calculated data in the Numerics table is based on only the harmonics from the fundamental to the specified Nth harmonic. For example, if Fundamental+N is selected and the Range to field is set to 10, then the Numerics table will only calculate data based on the fundamental to the 10th harmonic, as shown in Figure 24.

Numerics	Vrms	Irms	P	S	Q	PF	Φ
Vr:lr LL to LN	1.357 V	1.0143 A	1.331 W	1.3768 VA	351 mVAR	967e-3	14.7611 °
Vs:ls LL to LN	1.355 V	1.0133 A	1.319 W	1.3736 VA	384 mVAR	960e-3	16.2024 °
Vt:lt LL to LN	1.361 V	995.3 mA	1.305 W	1.3548 VA	362 mVAR	964e-3	15.4959 °
Σrst LL to LN	1.358 V	1.0076 A	3.956 W	4.1053 VA	1.098 VAR	964e-3	15.4981 °

Figure 24: Numerics data calculated for Fundamental to the 10th harmonic.

The Range setting (also made available with the MDA Harmonics Calculation option) is very similar to the Fundamental+N setting, except it allows a starting harmonic order to be specified. This provides a method to make measurements on a range of harmonic orders that don't necessarily include the fundamental.

Sync Signal

In order to perform power, voltage and current measurements over individual cycles, a measurement interval must first be determined for the acquired voltage and current data. For each drive power measurement section, you will choose a Sync signal that determines the measurement interval (the default is the signal on C1). This Sync signal can be filtered to remove high-frequency content and obtain better periodicity.



Figure 25: Sync signal setup.

HOW THE SYNC SIGNAL IS USED

The software determines a 50% amplitude value for the Sync signal waveform (the 50% amplitude value equals approximately 0V for a voltage signal probed line-line, or a line current signal). It then determines a 50% (or zero) crossing point for each individual cycle, and a time measurement for the start and end of each full cycle present in the acquisition. The 50% (zero) crossing point determination is made with high precision using a proprietary software algorithm that combines the following measurement techniques:

- User-settable high-frequency filtering via low pass filter cutoff setting
- Localized interpolation/oversampling at the 50% (zero) crossing point
- Elimination or minimization of the effects of non-monotonicities at the 50% (zero) crossing point with a user-defined hysteresis band control

Once the 50% (zero) crossing point times are determined, the various measurement parameters are calculated in the defined measurement time period for any waveform that uses that Sync signal. The Sync signal may be unique to the AC Input, DC Bus, Drive Output and Mechanical, or it may be shared among power or mechanical sections.

CHOOSING A SYNC SIGNAL

Choose the Sync signal so as to obtain the highest amplitude, least distorted signal for cyclical determination. Any measured periodic signal may be used with a time period representing the interval at which cyclic measurements should be performed. In general, the ideal Sync signal has the following characteristics:

- Low distortion (e.g., a pure sine wave or very close to it)
- 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-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), you will likely find that it is necessary to adjust both. See the following sections on LPF Cutoff and Hysteresis for recommendations. If no signal has the ideal characteristics described above, you can define a math function to use as the Sync signal. An example where this might be useful is if the voltage probing was line-reference (no variation around a zero crossing) and the current signals had a very wide dynamic range. In this case, a math waveform could be defined as the Difference in two line-reference probed voltages to obtain a line-line voltage that might be a better Sync source.

NOTE: LPF cutoff is accomplished with a digital (software) filter. This digital filter will result in a small phase-shift of the filtered signal when referenced to the non-filtered signal. This is normal and does not impact the accuracy of the measurement. Note also that changing the Sync signal source, LPF cutoff frequency, or hysteresis will result in a recalculation of the Numerics table results. It is therefore recommended that all these settings first be made and verified on a shorter acquisition record before acquiring longer records.

SYNC SOURCE SELECTION

You may select a different Sync signal source for each drive power measurement section. Each selection is used the same way but functions independently, providing maximum flexibility to achieve the most accurate results. This is typically necessary since the drive (line) input is usually fixed frequency whereas the drive output is variable frequency. Thus, two Sync sources assignments appear for AC Input and Drive Output, and the DC bus/link usually shares a Sync source with either the AC Input or Drive Output. Per-cycle voltage and current measurements are made for each identified measurement period (cycle), and power is calculated from those values.

Any analog or digital channel, math or memory waveform can be the Sync signal source. Simply touch or click the input button below **Sync** on each setup dialog, and select the source from the pop-up. The default is C1. Given that you have unlimited ability to assign C1 to a voltage, current, torque, speed or other signal, you should first use the guidelines above to determine whether C1 is an appropriate Sync signal source, and if not, select a more suitable source.

VIEWING THE SYNC SIGNAL

The filtered Sync signal can be viewed. When viewed, a good understanding can be quickly gained as to whether the signal is periodic enough to determine the 50% (zero) crossing period times. In general, it is good practice to display the Sync signal waveform so as to ensure that the cyclic determination algorithm has been provided with a near-sinusoidal signal. Otherwise, incorrect cyclic voltage, current and power measurements will result. The checkbox to the right of the Sync source control displays the Sync signal waveform (when checked). When displayed, a unique descriptor box for each Sync signal is placed on the display grid:

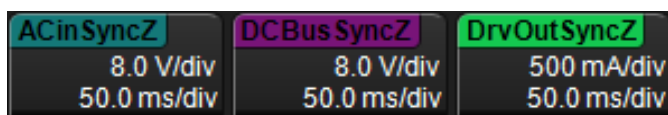


Figure 26: Sync signal descriptor boxes ("*SyncZ").

When viewing the Sync signal, a transparent, color-coded overlay is present to indicate the exact locations where measurement period (cyclic) determination is made (Figure 27). This can be used to verify that your Sync signal is performing as would be expected. If the acquisition contains many Sync signal cycles, you may need to zoom this

signal to see the detail. Use the Zoom+Gate feature to zoom the Sync signal in in a time-correlated way to the original channel acquisitions and any per-cycle Waveforms that were defined.

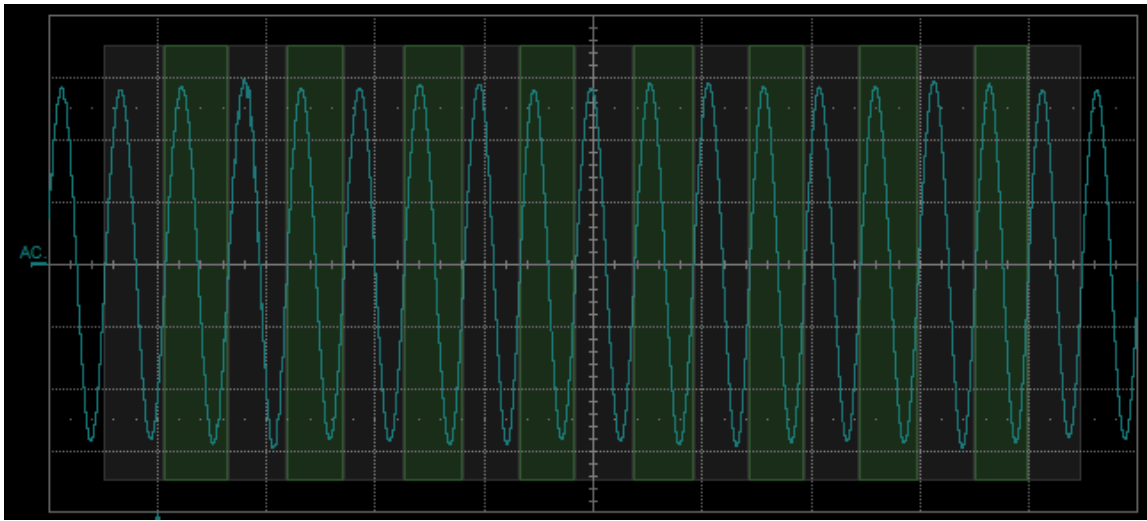


Figure 27: Colored overlays mark measurement cycle on Sync signal.

NOTE: The transparent overlay on the displayed Sync signal does consume processing overhead. You may notice less responsiveness in Numeric table calculation time or Zoom+Gate window changes, especially on longer acquisitions. Once you have determined that the Sync signal is suitable for accurate measurements, it is recommended that it be turned “off”.

LPF CUTOFF

The low pass filter (LPF) applies a digital filter with a -3dB cutoff at the specified frequency. The default value is 500 Hz. Sync source signals with significant high-frequency content (e.g., a PWM voltage signal) will be significantly attenuated in amplitude when filtered to the default frequency, but 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 and may therefore be 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. Use care in setting the LPF filter value to lower than the default setting, and view the Sync signal to ensure that the chosen filter setting is providing the desired result.

Set **LPF Cutoff** 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 resulting 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.

In Figure 28 we see a capture of a sine-modulated line-line drive output voltage waveform (Z1, or the Zoom of C1, which is not shown) and the corresponding drive output line current waveform (Z4, or the zoom of C4, which is not shown). The ACinSyncZ signal (upper right, based on the zoomed and filtered filtered C1 line-line voltage waveform) and DrvOutSyncZ signal (lower right, based on zoomed and filtered C4 line current waveform) are displayed with the default 500 Hz LPF cutoff.

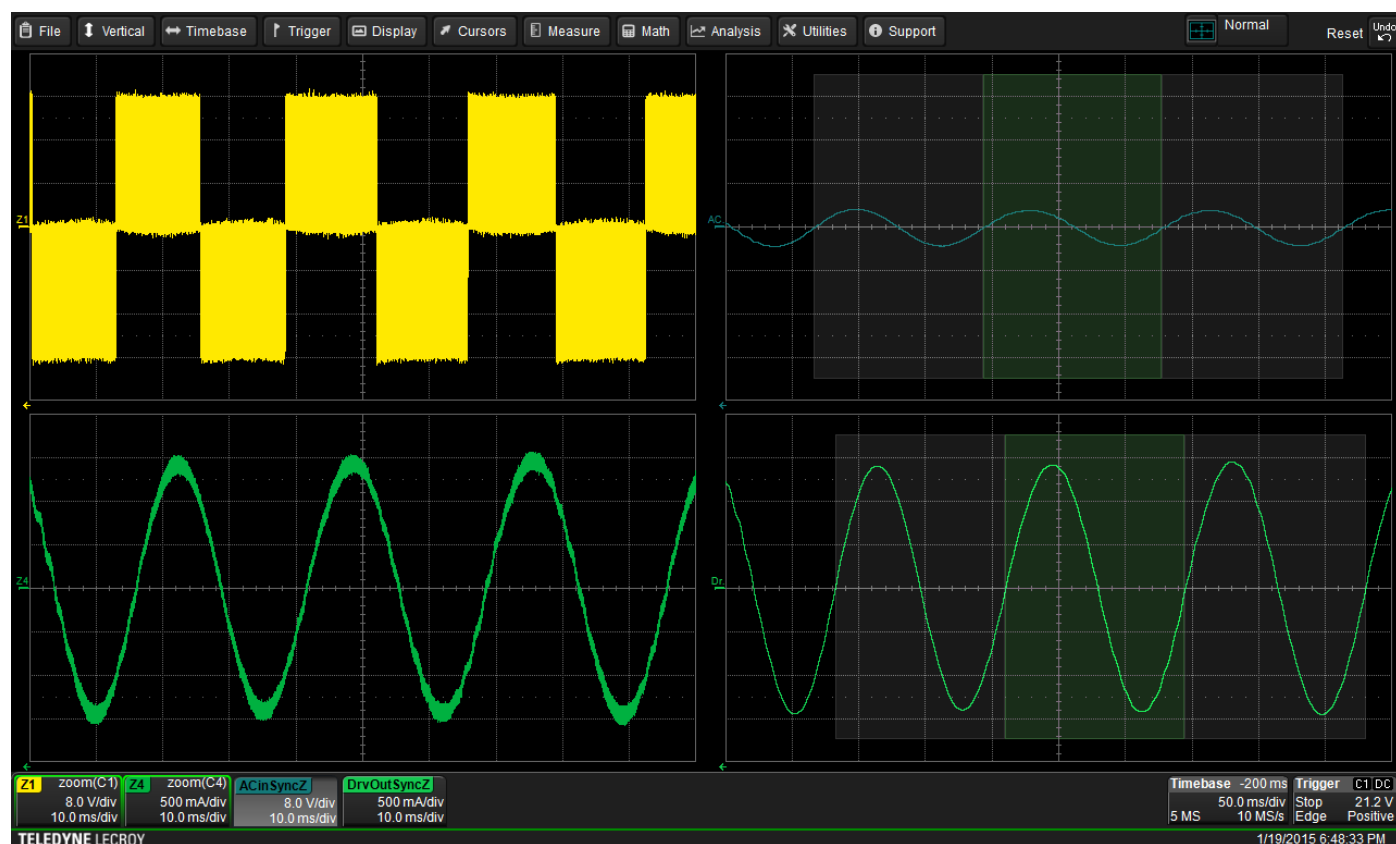


Figure 28: Sinusoidal Sync signals displayed with default 500 Hz LPF Cutoff.

NOTE: Only one Sync signal is required for proper measurements, and the Sync signal associated with the drive power section (ACinSync for AC Line Input or DrvOutSyncZ for Drive Output) should be used for measurements on that power section. Two Sync signals are shown in these examples only to show the difference between using a voltage or current signal for the Sync, or to show the effects of different LPF Cutoff filter or Hysteresis band settings.

The voltage signal is significantly attenuated in amplitude when filtered (upper right), but still suitable as a Sync signal with the default 100mdiv hysteresis setting. The current signal (lower right) is an ideal Sync signal since it is highly sinusoidal with high amplitude and fast slew rates, before (and after) filtering.

NOTE: Highly distorted waveforms (e.g., six-step commutated voltage and current waveforms) might require significantly lower LPF cutoff settings than provided by the default 500 Hz setting. See Figure 29.

Figure 29 shows a capture of a six-step commutated line-line drive output voltage waveform (again, Z1 or the Zoom of C1, which is not shown) and the corresponding drive output line current waveform (again, Z4, or the zoom of C4, which is not shown).

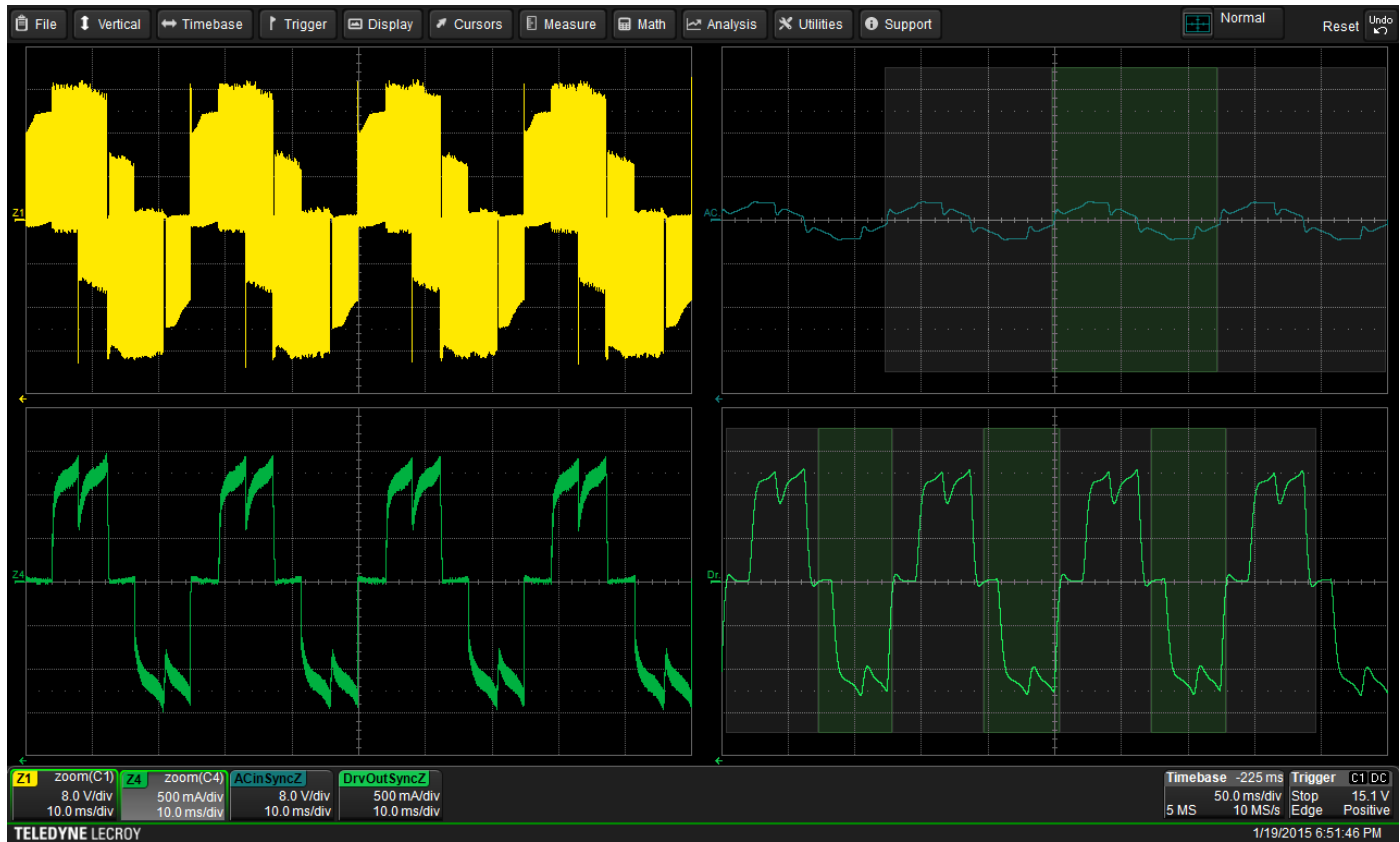


Figure 29: Non-sinusoidal Sync signals that would benefit from lowering the LPF Cutoff.

The ACinSyncZ signal (upper right, based on the zoomed and filtered C1 line-line voltage waveform) and DrvOutSyncZ signal (lower right, based on the zoomed and filtered C4 line current waveform) are displayed with the default 500 Hz LPF cutoff. The voltage signal (upper right) is significantly attenuated in amplitude and has high distortion near the zero crossing, so careful setting of the Hysteresis value would be necessary, likely higher than the default 100 millidivision hysteresis band. The current signal (lower right) incorrectly determines the measurement period to be a half period. Additional LPF Cutoff filtering or Hysteresis setting changes are necessary in this case.

Figure 30 shows the same Sync signals with an LPF Cutoff filter setting of 100 Hz (as opposed to the 500 Hz used in Figure 29).

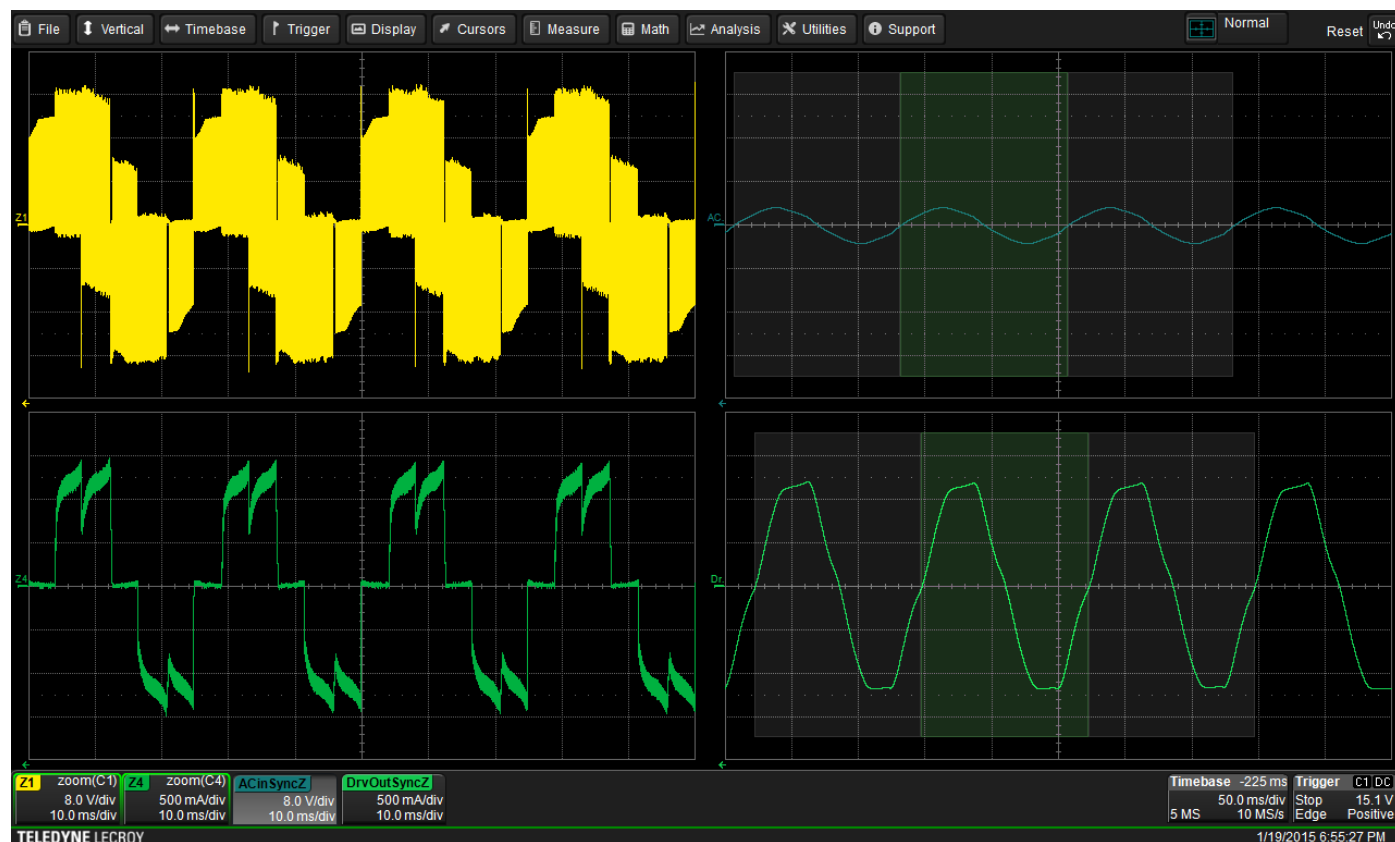


Figure 30: Non-sinusoidal Sync signals corrected by adjusting LPF Cutoff filter.

HYSTERESIS BAND

The **Hysteresis** band setting defines an amplitude “band” through which the Sync signal must exceed before Sync signal slope will be determined to be 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 that false 50% (zero) crossings will be detected.
- 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 that accuracy of 50% (zero) crossing detection will be reduced.

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) are therefore likely to be bad Sync signals since the low signal amplitude portions of the Sync waveform might be smaller than the hysteresis setting that is required. In this case, it is best to choose a different signal that has more constant amplitude or a smaller dynamic range.

To understand how the hysteresis band setting works, consider the example in Figure 31 of a perfect sinusoid. In this case, the zero or 50% crossing level is simple to detect and the measurement intervals are easily determined.

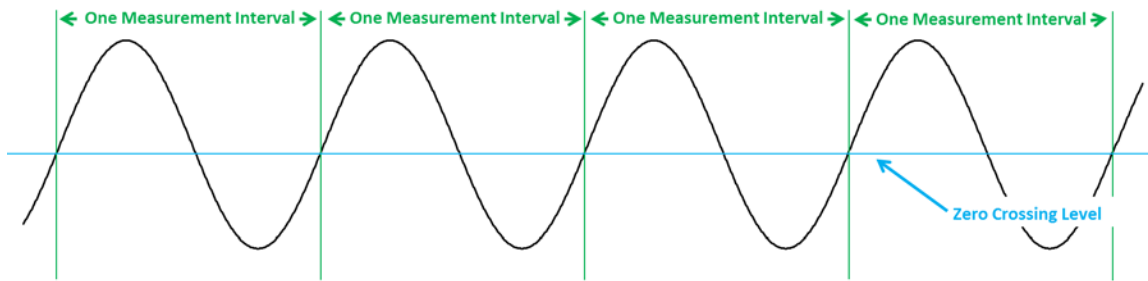


Figure 31: Measurement intervals on monotonic signal.

Now, consider the example in Figure 32 in which there is a non-monotonicity near the zero or 50% crossing level. The non-monotonicity period is detected as a measurement interval, resulting in an incorrect period determination, which will result in incorrect calculations.

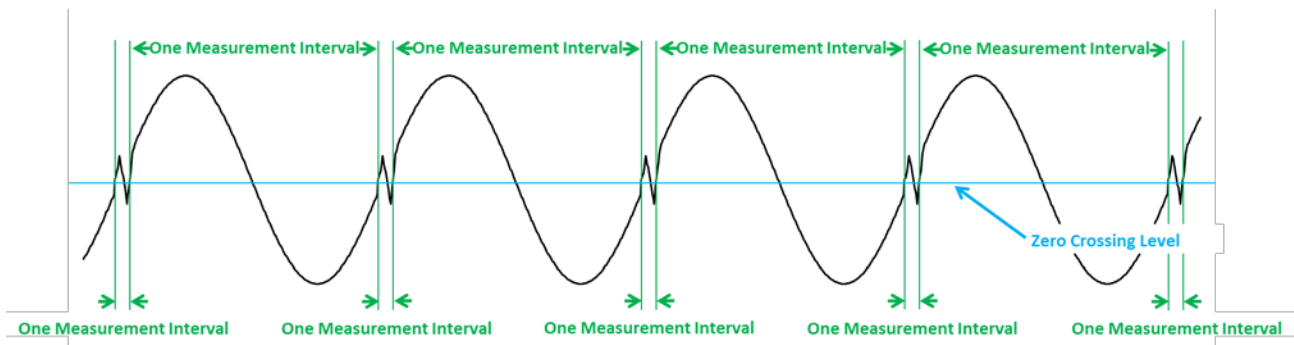


Figure 32: Non-monotonic signal produces "false" measurement intervals.

By using the Hysteresis Band controls, you can set a hysteresis band level that is greater than the amplitude of the non-monotonicity and avoid false measurement interval calculations.

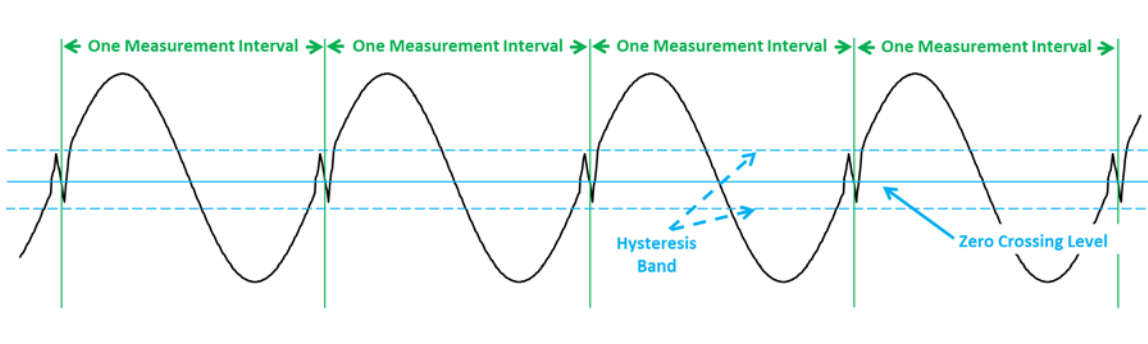


Figure 33: Hysteresis Band corrects for non-monotonicity.

ZOOM SYNC SIGNAL

On longer acquisitions, especially those with dynamic load conditions, it may be necessary to zoom the Sync signal to verify that a good cyclic determination is achieved. Press the Zoom+Gate button to create new zoom traces of each source waveform time-correlated to a zoom of the Sync signal. If undesirable results are obtained, adjust LFP cutoff and Hysteresis settings, as necessary, or choose a different signal to use as the Sync source. See Zoom+Gate Mode (p.52) for more information.

EXAMPLE SYNC SIGNAL SETUP – LONG ACQUISITION WITH WIDE DYNAMIC RANGE AND OVERLOAD

As described earlier in this section, long acquisitions of signals that have wide dynamic ranges and distortion require care in setting the Sync signal in order to achieve accurate results.

Consider this example of a long acquisition (two seconds of time) 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 distortion of the signal at the shutdown event. The three-phase line-line voltage waveforms are shown in the top grid, and the three-phase line currents are shown in the bottom grid.



Figure 34: Initial display of input source waveforms for sine-modulated three-phase drive.

Then, Zoom+Gate is enabled, and the original (two second long) acquisitions are kept on the left side of an octal grid, and the zoomed waveforms are located to the right. Then (for illustrative purposes) C4 (channel 4, a current signal) is assigned as the Drive Output Sync signal (named DrvOutSyncZ and shown as a green trace). C1 (channel 1, a voltage signal) is assigned as the AC Input Sync signal (named ACInSyncZ and shown as a blue trace). The default LPF Cutoff (500 Hz) and Hysteresis (100 mdiv) settings are retained.

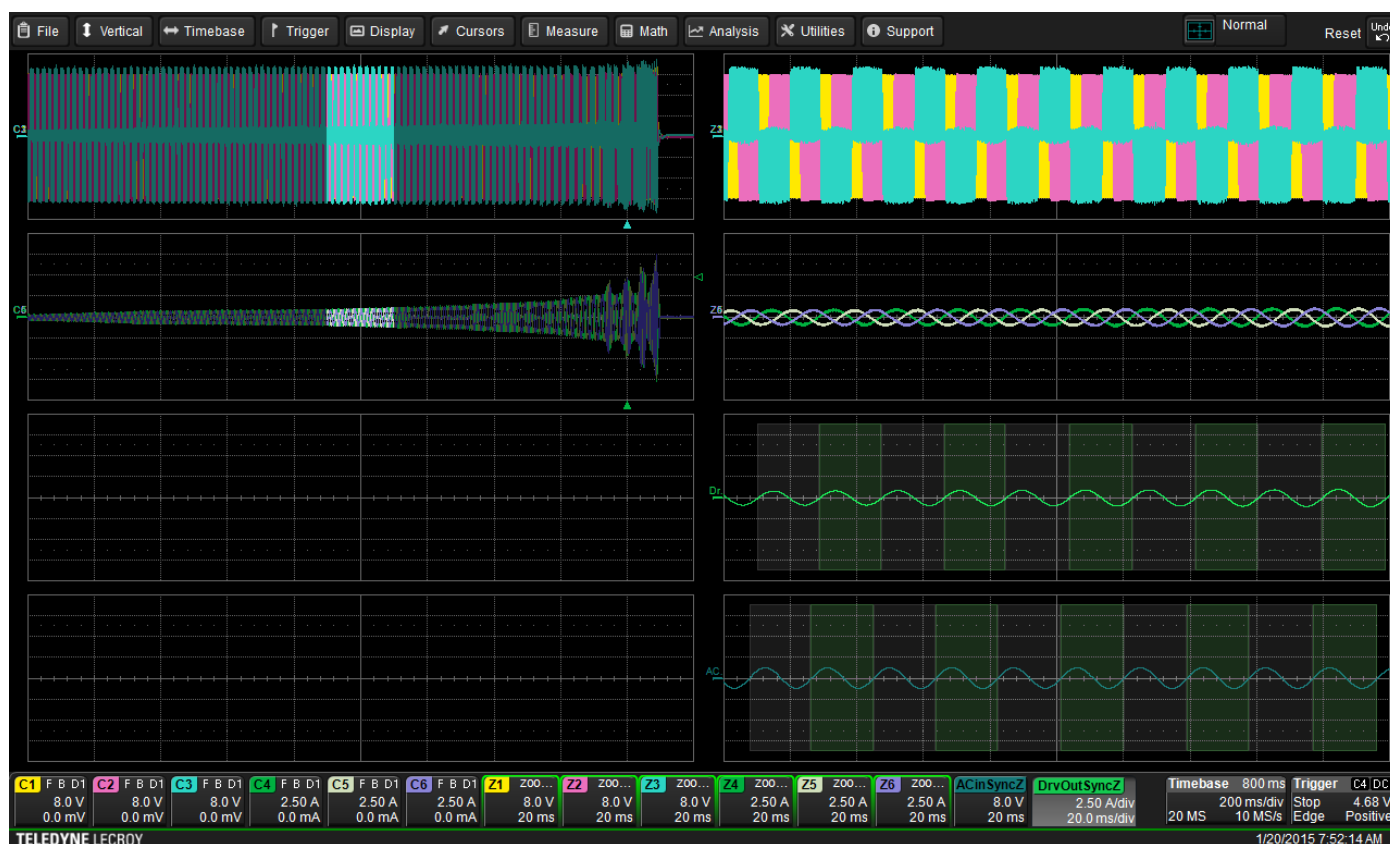


Figure 35: Sync signal display after Zoom+Gate enabled (lower right).

NOTE: Only one Sync signal is required for proper measurements, and the Sync signal associated with the drive power section (e.g., ACInSyncZ for AC Line Input or DrvOutSyncZ for Drive Output) should be used for measurements on that power section. Two Sync signals are shown in these examples only to illustrate the difference between using a voltage or current signal for the Sync, or to show the effects of different LPF Cutoff filter or Hysteresis band settings.

Both signals look nearly the same amplitude. If the horizontal zoom ratio is changed to encompass nearly half the waveform, and the zoom position location is changed to the beginning of the acquisition, it can be seen that, based on the transparent overlays, the Sync signal seems to have a well-defined period in both cases.

Now, if the zoom position is changed to the end of the acquisition, as in Figure 36, it can be seen that 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 achieve a good period determination in this location.

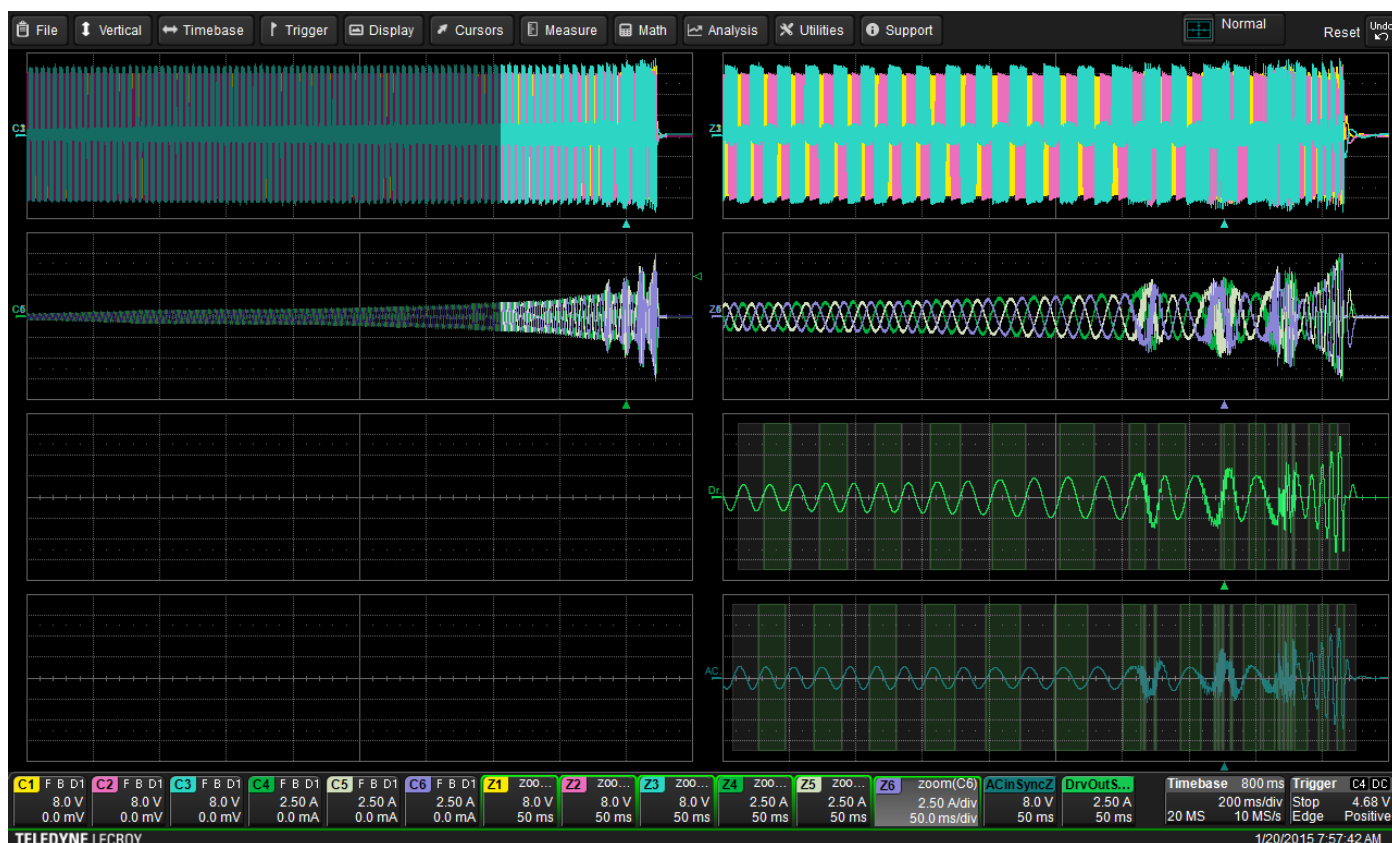


Figure 36: Changing zoom position changes display of all zoomed waveforms, including Sync signals.

Zoom further to the end of the acquisition, and adjusting LPF Cutoff to 160 Hz and Hysteresis to 20 mdiv on both Sync signals shows that the voltage source (green trace, used in DrvOutSyncZ) is the better source. A quick review of the Sync signal shows that proper period determination of the C1 line-line voltage signal is maintained back to the beginning of the acquisition.



Figure 37: Adjusting filters reveals DriveOutSyncZ is the better choice Sync signal.

EXAMPLE SYNC SIGNAL SETUP – LINE-REFERENCE VOLTAGE WAVEFORMS WITH A SIX-STEP COMMUTATED BRUSHLESS DC MOTOR

Six-step commutated waveforms can present special challenges for Sync signal setup since they are highly distorted, and since, due to common low voltage levels (<50V), voltage is often probed line-reference using common passive voltage probes.

Consider the short acquisition (500ms) in Figure 38 in which a BLDC motor is operating under steady-state conditions. The three line-reference voltage signals are shown in the top grid; the line current signals are shown in the bottom grid.

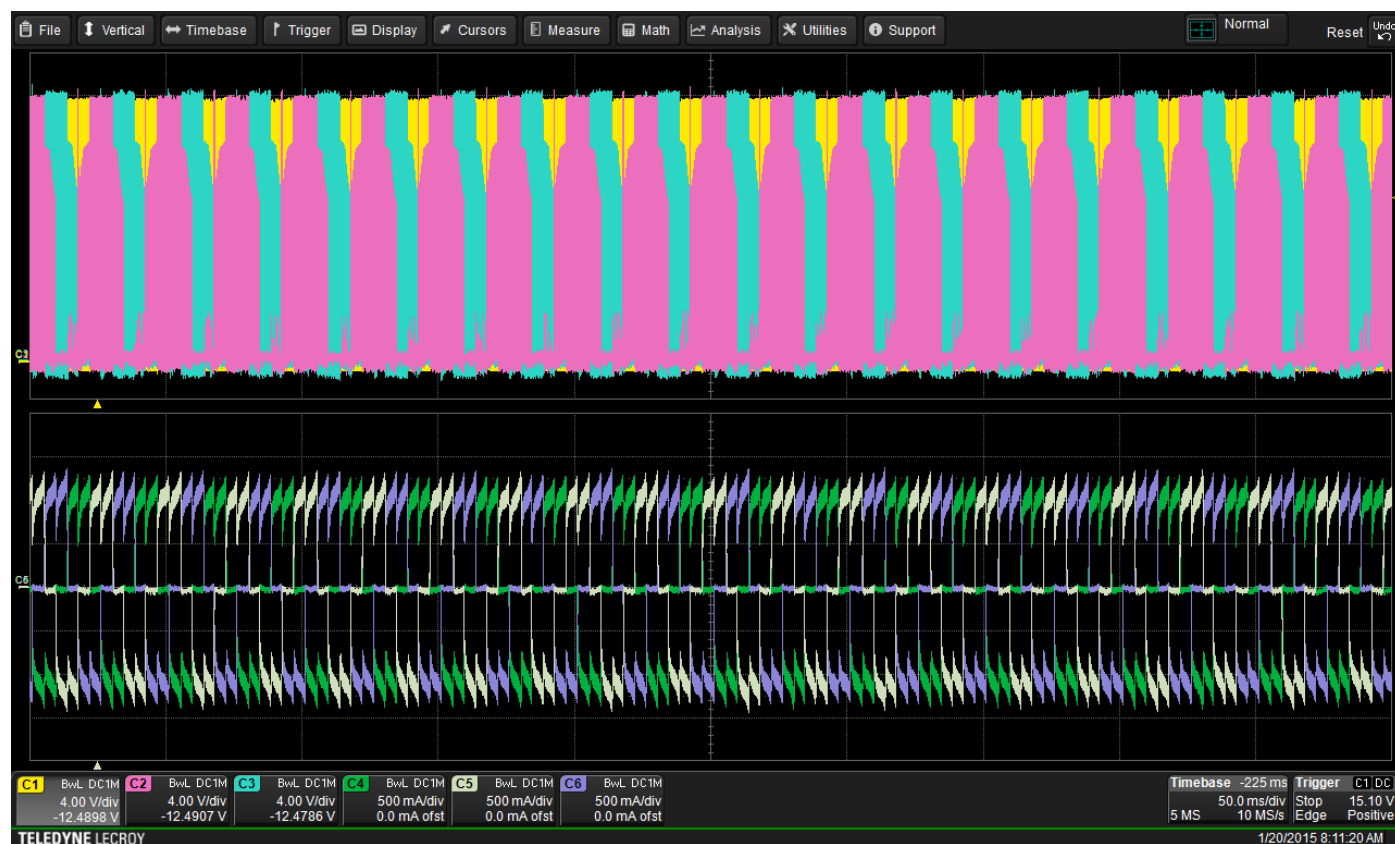


Figure 38: Initial display of input source waveforms for six-step commutated brushless DC motor.

Then, as in the previous example, Zoom+Gate is enabled, and the original (half second long) acquisitions are kept on the left side of an octal grid, while the zoomed waveforms are located to the right. C4 (channel 4, a current signal) is assigned to the Drive Output Sync signal (named DrvOutSyncZ and shown as a green trace), while C1 (channel 1, a voltage signal) is assigned to the AC Input Sync signal (named ACInSyncZ and shown as a blue trace). The default LPF Cutoff (500 Hz) and Hysteresis (100 mdiv) settings are retained.

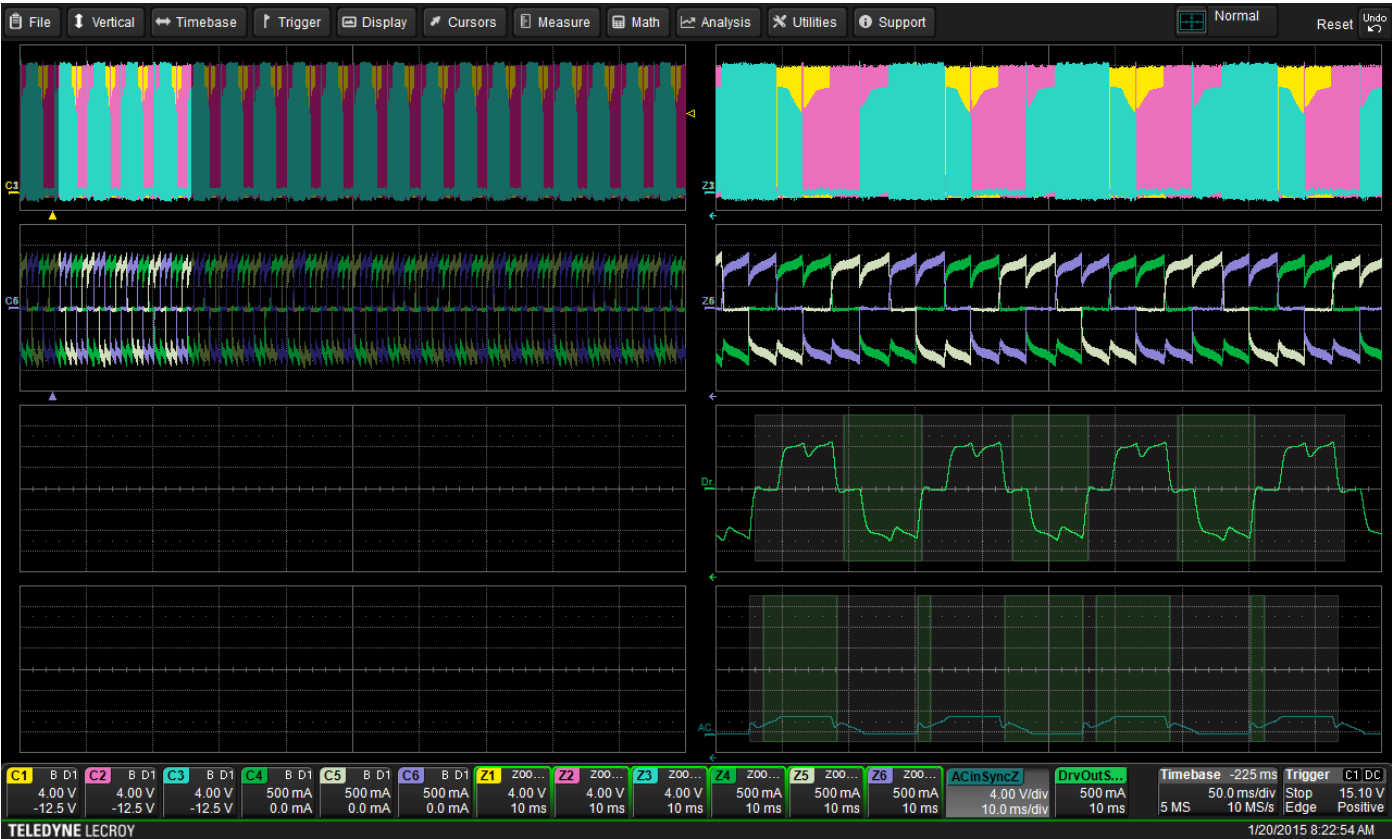


Figure 39: Sync signal display after Zoom+Gate enabled (lower right).

It can be immediately seen that the settings used in the DrvOutSyncZ are resulting in a half-period measurement cycle determination, instead of a full period. Also, the ACinSyncZ signal (using source C1, or the line-neutral voltage signal) has too low an amplitude and poor zero crossings to be effective as a Sync signal. A better approach would be to create a line-line voltage waveform using a Math function, and make that the Sync signal source instead. Figure 40 shows the new F1 trace (C1 minus C2, a line-line voltage), with the ACinSyncZ source changed from C1 to F1, but otherwise the same.



Figure 40: Changing ACinSyncZ source to math function improves periodicity (blue, lower right).

The ACInSyncZ signal amplitude remains low, but the quality of the measurement period determination has improved. Closer inspection of many cycles (using the Zoom controls) indicates that all periods are properly determined. The DrvOutSyncZ signal amplitude is suitable, but lowering the LFP Cutoff filter to 200 Hz, shown in Figure 41, results in correct determination of the full measurement period.

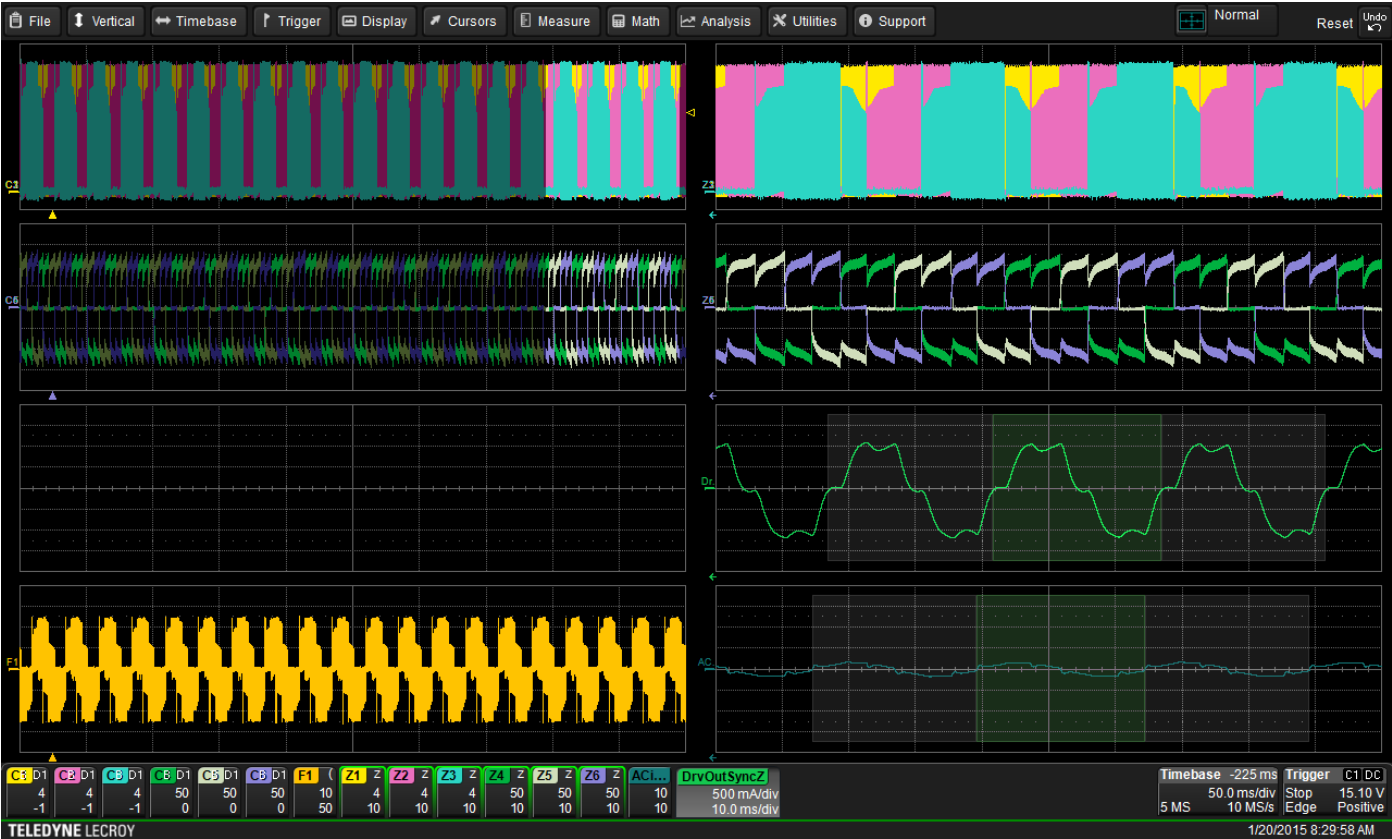


Figure 41: Lowering LPF Cutoff improves crossings period determination of (green) DriveOutSyncZ.

DC Bus Setup Dialog

To correctly calculate power values, identify the wiring configuration used by the DC Bus power section and assign input channels to each voltage and current. Choose from either:

- 1-phase/2-wire (1 Voltage, 1 Current)–This is equivalent to activating the voltage and current assignments to the right of the Wiring Configuration setup.
- None–This selection is equivalent to de-activating any voltage and current assignments to the right of the Wiring Configuration setup.

Voltage input assignments are performed the same as for AC Input and Drive Output, as is the Sync signal selection and adjustment. See the previous sections on Voltage and Current Assignments, Sync Signal, and Zoom+Gate for instructions on using these controls.

The Sync signal source can be the same as or different than that selected for AC Input and Drive Output. Since the DC Bus signals are non-periodic, measurement periods must be made consistent with the AC Input or Drive Output measurement periods.

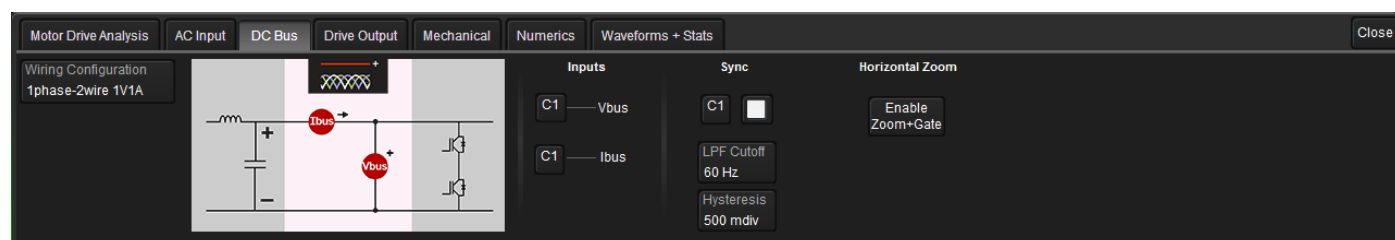


Figure 42: DC Bus setup dialog.

Mechanical Setup Dialog

The Mechanical setup dialog allows you to incorporate outputs from motor torque and (shaft) angular speed/direction/position sensors into the MDA. Once incorporated, these sensor values can be displayed as measurements and per-cycle waveforms in user-defined units of measure (N·m, lb·ft, RPM, radians/second, etc.). They can further be used to calculate Mechanical power and, for an AC induction motor, Slip. By doing so, you can gain detailed information about overall drive operation and efficiency through the motor output.

The complete (default state) dialog is shown in Figure 43.



Figure 43: Mechanical setup dialog.

There are independent settings for:

- **Torque**—Analog 0-Vdc, Analog mV/v, None.
- **Speed & Angle**—Quadrature Encoder, Analog Tachometer, Resolver, Hall Sensor, Pulse Tachometer, None.

Common Settings

The different Torque and Speed & Angle sensors share many common settings, although the exact setup will depend on the sensor. Common settings for many sensors include:

Method—The type of sensor to be integrated, or “None” to de-activate the setup.

Input Source(s)—An analog channel, digital line, or memory trace that is the measured sensor signal. The type and the number selected will vary by sensor.

Units—The desired display units for the sensor values.

LPF Cutoff—The low pass filter setting, used to reduce the bandwidth (and eliminate noise and/or interference) from the sensor signal. This setting is available only when the source is an analog input.

Range Settings—Depending on sensor type, selections to equate a high and low sensor unit value with a high and low input value (Figure 43 shows Low Torque and High Torque). These settings are enabled only when the source is an analog input.

Sync Signal—As with the AC Input, DC Bus and Drive Output, the mechanical torque and speed values are computed over a given signal period defined by the Sync signal. Low Pass Filter (LPF) and Hysteresis settings operate as described earlier. The Sync source can be a captured channel signal, a math waveform, or a (stored) memory trace. The Sync source is common to both the Torque and Speed setups.

+Rotation—Defines the positive rotation direction for the motor shaft from the perspective of a person looking down the shaft towards the motor. Selection of “CW” defines rotation as positive when the shaft rotation is clockwise, and selection of “CCW” defines rotation as positive when the shaft rotation is counter-clockwise.

Gear Ratio—The motor shaft may turn at a different speed if it is geared up or down. Use this setting to indicate a gear ratio to reduce motor shaft speed compared to rotor field speed. Gear ratio >1 indicates gearing down, whereas gear ratio <1 indicates gearing up. Speed & Angle methods that include a (Rotor) Pole Pairs selection take into account the faster electrical speed with rotor pole pairs.

The Numerics dialog (p.45) includes parameters for Torque, Speed and (Rotor Field) Angle that you can add to the Numerics table display.

Torque Setup (Analog 0-Vdc)

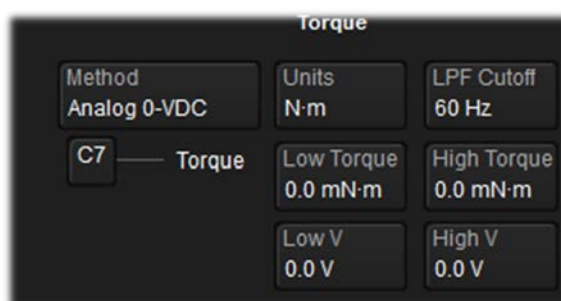


Figure 44: Analog 0-VDC torque setup.

All settings required for this torque sensor type are described above in common settings (p.34).

Torque Setup (Analog mV/V)

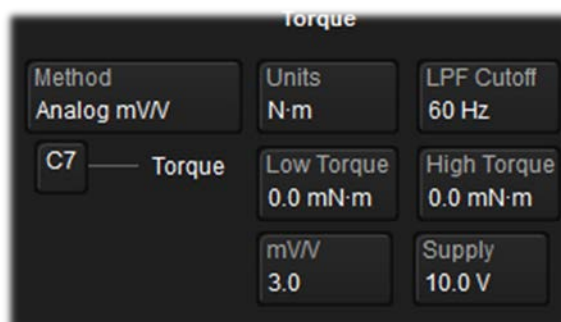


Figure 45: Analog mV/V torque setup.

The settings are described above in common settings (p.34), with the exception of:

mV/(excitation)V—Full scale torque output.

Supply—DC excitation voltage to the sensor.

Due to the low output voltage of this sensor, the accuracy of a measurement will likely not be as good as in the previous case. For instance, if the mV/V full scale output is 3mV/V, and 10V excitation is applied to the torque sensor, then the maximum output is 30mV at full scale torque. Realistically, inputting 30mV into the MDA channel will result in a 4-5mV/div gain setting for the channel, and the measured signal will likely be much smaller in many cases, so more error will be introduced into the measurement than if the torque sensor had a larger output signal.

Speed Setup (Analog Tachometer)

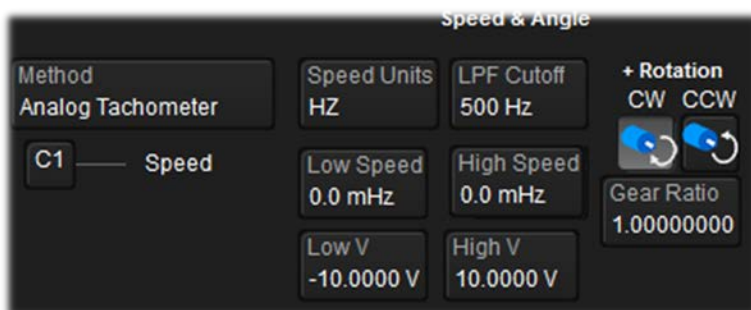


Figure 46: Analog Tachometer speed setup.

The settings are described above in common settings (p.34).

Speed Setup (Pulse Tachometer)

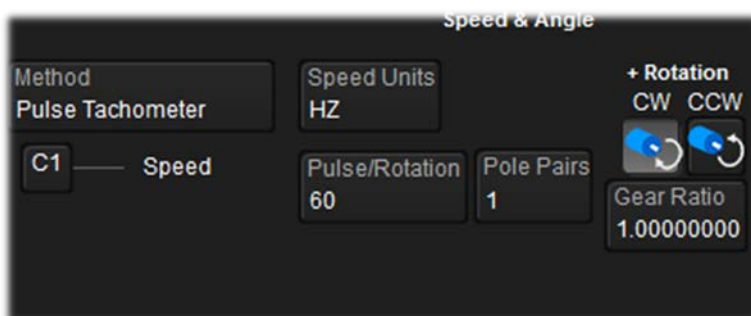


Figure 47: Pulse Tachometer speed setup.

In this case, the input is a pulse train with N pulses/revolution. In addition to the common settings (p.34), define:

Pulse/Rotation—The number of pulses for one rotation of the motor shaft. The minimum value is 1, and the maximum value is 2000.

Speed and Direction Setup (Hall Sensor)

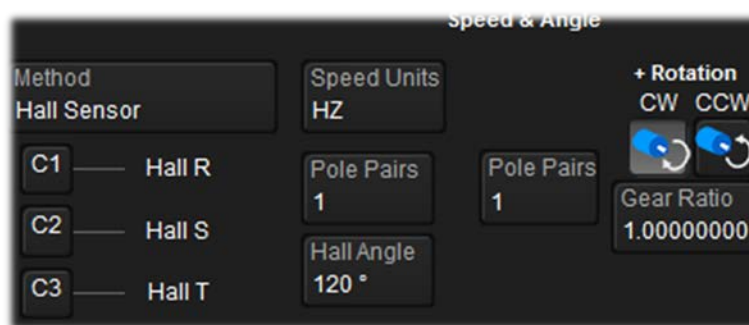


Figure 48: Hall sensor setup.

In addition to the common settings (p.34), define the following:

Pole Pairs—The number of rotor (magnetic) pole-pairs is entered in the Pole Pair selection. For each rotor Pole Pair, there is one complete set of six transitions per shaft revolution. A two pole rotor would have one mechanical shaft rotation for two sets of six transitions each. Therefore, this is an important value to enter to correctly gauge the shaft speed. Minimum value is 1 and maximum value is 6.

Hall Angle—Either 60° or 120°, representing the angular separation of the three Hall sensors around the rotor. In both cases, there are six unique transitions for one shaft revolution when there is one rotor (magnetic) Pole Pair.

HALL SENSOR INPUTS

While the inputs for Hall R, Hall S, and Hall T can be either analog channels (C1-C8) or digital logic lines (D1-D15), as Hall effect sensor signals are digital, digital inputs are typically used to conserve analog channels for other uses.

NOTE: It is good practice to first verify the Hall sensor signal levels using a passive probe and an analog channel before using the digital channels, as this will help ensure that the digital logic calculation threshold and hysteresis settings are appropriate.

POLE PAIRS AND HALL ANGLE

Brushless DC (BLDC) motors using six-step commutation most often utilize Hall effect sensors embedded in the rotor to provide a non-contact signal output to a pickup on the stator. These sensors are used to sense rotor position and then directly control the electrical commutation of voltage in the stator. The Hall sensor signals can be used to indicate rotor speed, from which shaft speed can be calculated.

The three Hall sensors provide pulse outputs that, when taken as a 3-bit binary string, provide 6 different values that repeat in a defined order. One repetition of the six values corresponds to one rotation of the rotor for a motor with one rotor pole pair, or two repetitions corresponds to one rotation of the rotor for a 2-pole pair rotor. The sequence of the repetition indicates either clockwise (+RPM) or counter-clockwise (-RPM) rotation. Figure 49 shows Hall effect sensor signals for a three Hall effect sensor configuration with the sensors placed 120° apart on the stator (equally spaced) and one rotor pole pair. At every 120° one of the Hall effect sensors makes a positive transition (the figure shows 60°/horizontal division) and one electrical cycle completes in the same time as one mechanical shaft revolution.

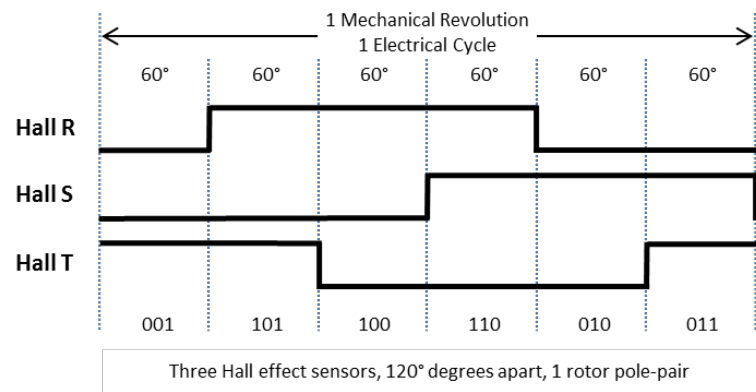


Figure 49: Hall sensors placed 120° apart on the stator (equally spaced) with one rotor pole pair.

Three sensors each 60° apart means that the three Hall sensors are all placed on one side of the stator. There are still six, unique three-bit transitions, so the operation is essentially the same, but the rising edges of the Hall sensor signals are separated by 60° at the beginning of the Hall cycle.

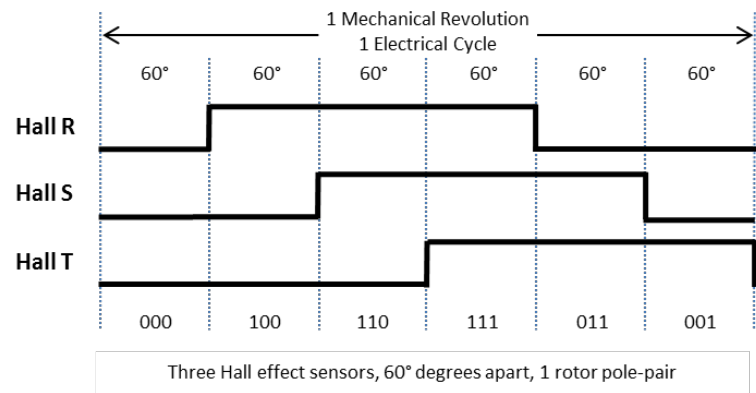


Figure 50: Hall sensor signals on a motor with one rotor pole pair.

When there are “N” rotor pole pairs, there are “N” electrical cycles per mechanical shaft revolution.

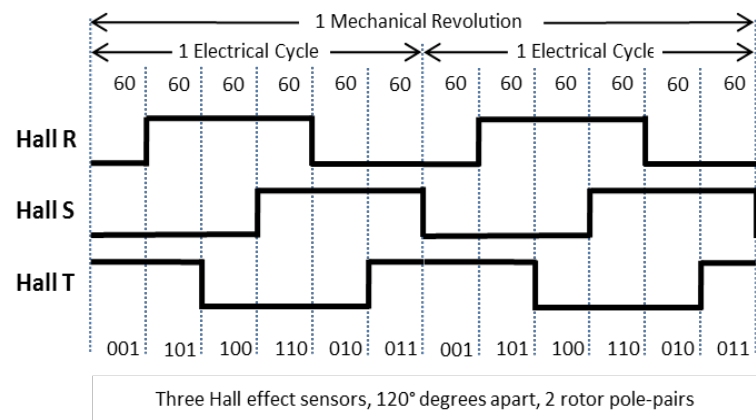


Figure 51: Hall sensors placed 120° apart on a motor with two rotor pole pairs.

Speed is calculated from edge-to-edge timing measurements between the Hall A, B and C signals, with the edge-to-edge time inversely proportional to frequency, from which rotational speed is derived. Internally, the software calculates the transition time between each Hall state (000, 100, 110, etc.), and then averages these time periods over the Mechanical Sync period to report one average speed value per Mechanical Sync period.

NOTE: Hall effect sensor signals timing with reference to other Hall effect sensor signals is directly related to the accuracy of placement of the Hall sensors on the rotor. This placement accuracy is relatively low. Additionally, Hall sensors can exhibit small movements based on thermal effects in the motor, and this can further impact the signal timing accuracy over time. Therefore, it is recommended that the Sync signal used in the Mechanical dialog include several Hall transitions, or about one complete Hall six-step transition event. If you select a Drive Output voltage or current signal as your Sync, then you will meet this recommendation.

HALL SENSOR SYNC SIGNAL

A Sync signal must be chosen in the Mechanical dialog in order to define the time period over which to make the speed measurement using the Hall sensor signals. The number of edge-to-edge timing measurements per calculation (and thus the time duration for each calculated speed value) depends on the Sync signal chosen in the Mechanical dialog. More edge-to-edge (Hall sensor) timing signals per calculation results in a more average speed value but fewer speed results. If the Sync signal is one of the Drive Output voltage or current signals, then the number of speed values returned per shaft rotation will be directly related to the number of stator poles and rotor pair poles in the motor.

Speed, Direction, and Absolute Position Setup (Resolver)

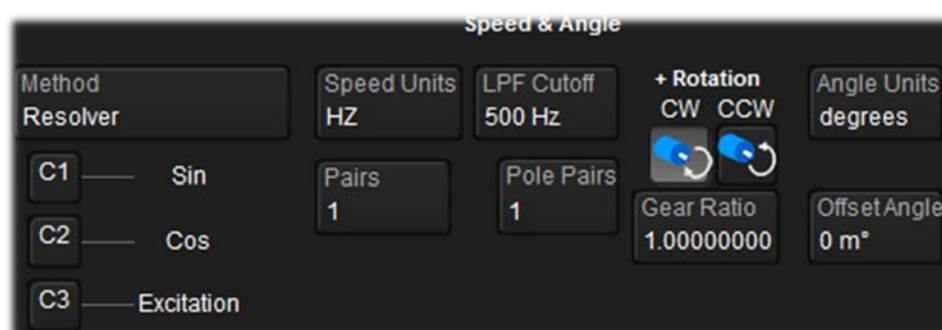


Figure 52: Resolver setup.

In addition to the common settings (p.34), define the following:

Pairs—The number of resolver pole pairs is entered in the Pairs selection. An “N” pole-pair resolver would have “N” mechanical shaft rotations per sine/cosine signal period. Therefore, this is an important value to enter to correctly gauge the shaft speed. Minimum value is 1 and maximum value is 100.

Offset Angle—It is unlikely that the Resolver is mounted to the rotor shaft so that sine/cosine signals are aligned with the motor rotor magnetic field. An offset angle can be entered to compensate for the resolver misalignment so that the Angle measurement parameter represents the rotor flux field angle or some other angle of interest.

Angle Units—Selects the units in which offset angle is entered and Angle measurement values are displayed.

RESOLVER INPUTS

In this case, the input is a set of analog sine and cosine signals that (by definition) are 90 degrees out of phase. These are referred to as the sine and cosine signals and they provide speed and direction information. The excitation signal (reference) defines the frequency by which the sine and cosine signal amplitude alternates within the sine and cosine envelopes. One full period of the sine or cosine signal represents “N” rotations of the rotor shaft for an “N” pole-pair resolver.

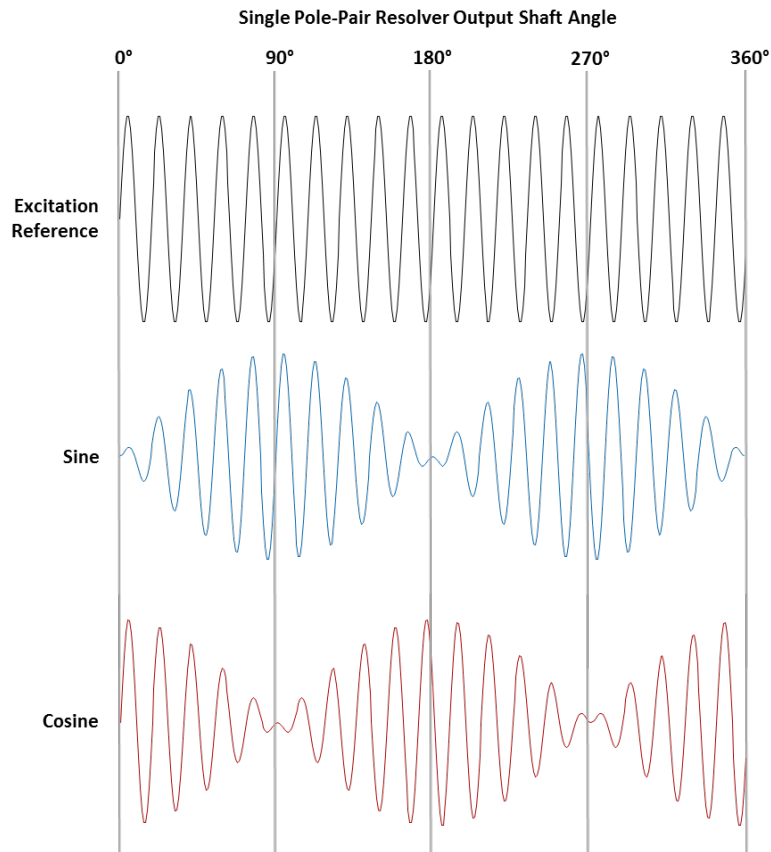


Figure 53: 1 speed (1 pole-pair) resolver inputs.

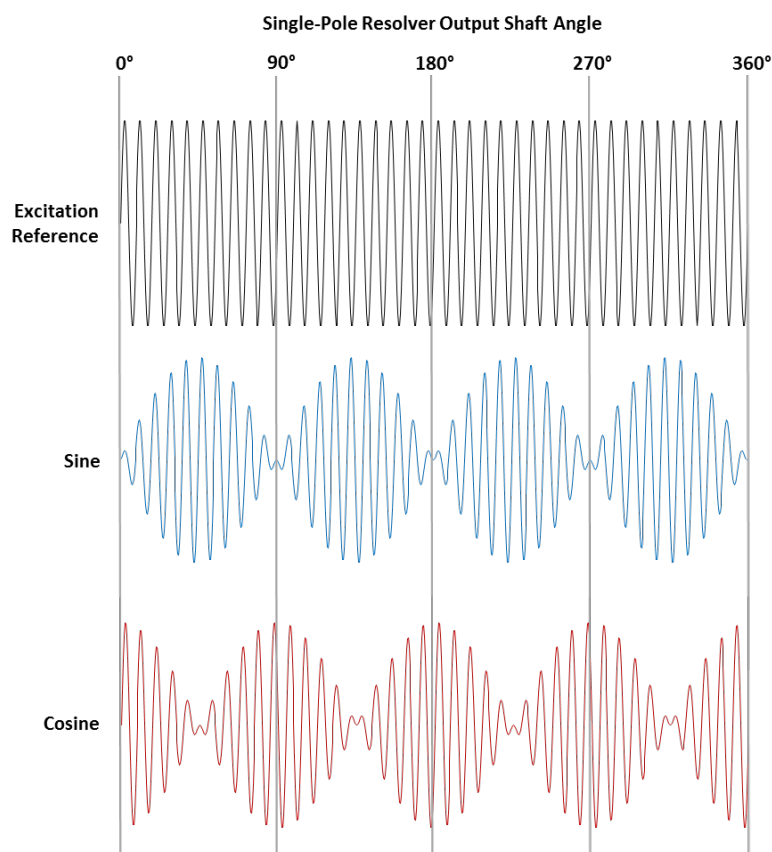


Figure 54: 2 speed (2 pole-pair) resolver inputs.

The Excitation Reference signal is usually used to define the Mechanical Sync period for the calculation of rotor speed and angle from the sine and cosine signals. During each Sync period, a calculation of speed and angle is made from the corresponding peak values of the sine and cosine signals.

OFFSET ANGLE AND ANGLE UNITS

The calculated Angle parameter value is arbitrary depending on the mechanical placement of the resolver around the shaft, but this Angle parameter can be adjusted to represent the rotor flux field angle or some other angle through use of the Offset Angle setting. Angle units for the Offset Angle adjustment are selected with the Angle Units selection.

Speed, Direction, and Absolute Position Setup (Quadrature Encoder Interface, or QEI)

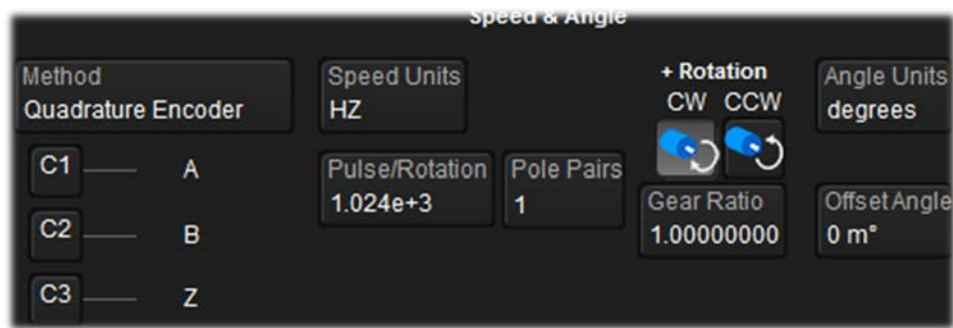


Figure 55: QEI setup.

In addition to the common settings (p.34), define the following:

Pulse/Rotation—Enter the total number of AB phase sequences per single shaft rotation. The default value is 1024, the minimum value is 1, and the maximum value is 1×10^{12} .

+Rotation—Even though the QEI signals include direction information, the default direction as installed or defined by the QEI signals may not be what you desire. Simply make a selection here to change the rotation sign from one direction to another.

Offset Angle—The calculated QEI motor shaft angle can be converted to a rotor magnetic pole field electrical angle by entering a value for the Offset Angle (offset of the rotor magnetic pole field electrical angle compared to the QEI shaft angle). Knowledge of the rotor electrical field angle is useful for analyzing advanced Vector FOC control systems, but is not needed for speed or direction sensing. Enter the offset in degrees of the QEI "Z" pulse in relation to the rotor magnetic flux field.

Angle Units—Select the units in which the offset angle is entered and in which the Angle measurement values are displayed.

QEI INPUTS

In this case, three digital pulses (A, B and Z, or the Index pulse) are used to define speed, direction and absolute position. The inputs for A, B, and Z can be either analog (C1-C8) or digital logic lines (D1-D15). Typically, digital inputs would be used to conserve analog channels for other uses.

The QEI utilizes two digital signals (A and B) that are 90° out of phase to communicate a two-bit pulse sequence N times per shaft revolution. A third digital signal is used to communicate position information once per revolution. This third signal is the "Z" index pulse signal. This type of sensor is also referred to as an "incremental encoder" since it provides information on incremental, but not absolute, rotor shaft position.

Rotation speed and direction are communicated via the sequence of the A and B signals, which are 90° out of phase with each other. The A and B signals together form four unique binary AB pulse patterns, and the sequence of pulse patterns is different for different rotation directions. The QEI can be constructed so that the "A" signal rising edge can lead the "B" signal, or vice-a-versa. Rotation direction can be conveyed based on the order of the digital AB sequence (for A leading B they are, in order, 00, 10, 11, 10, for a "positive" rotation direction). However, rotation

direction is arbitrary, so the user must also define in the QEI setup interface which rotation direction represents positive.

There are multiple AB pulse pattern sequences per shaft rotation. The Z index pulse occurs once per revolution and, while it could be used directly for speed measurements, it lacks enough resolution, especially at low speeds, to be useful.

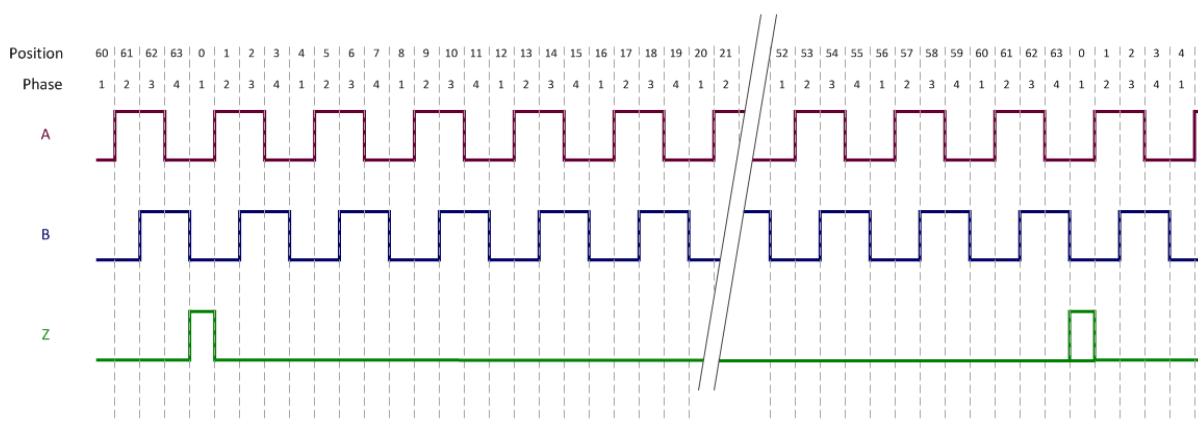


Figure 56: QEI signal set with A leading B.

The unique two-bit (AB) pulse patterns are referred to as the QEI phases, which proceed through the binary sequence 00, 10, 11, 01 for positive shaft rotation. In this hypothetical encoder, there are a total of 16 repetitions of the phase sequences, or 64 pulses/revolution (ppr). The Z “index” pulse occurs once per shaft revolution (once every 64 pulse transitions).

The Motor Drive Analyzer utilizes the A, B, and Z signals to calculate speed, direction and absolute shaft angle in the following manner:

- The time between any A and B transitions (positive or negative) is internally calculated by the software.
- Speed is calculated through knowledge of the average time between A and B transitions, and the knowledge of number of pulses per revolution, and values are returned to the user as an average speed value during on Mechanical Sync period.
- Direction is calculated from the sequence of binary transition codes during the Mechanical Sync period.
- Position is obtained through measurement in time of the rising edge of the Index (Z) pulse, and establishing that as Angle = 0°, and the angle increment would be as follows:
 - o $360/(4 * \text{QEI pulse/rotation value})$ in the case of degree units
 - o $2*\pi/(4 * \text{QEI pulse/rotation value})$ in the case of radian units

The calculated QEI shaft Angle can be converted to a rotor magnetic pole field electrical angle by entering a value for the Offset Angle (offset of the rotor magnetic pole field electrical angle compared to the QEI shaft angle). Knowledge of the rotor electrical field angle is useful for analyzing advanced Vector FOC control systems, but is not needed for speed or direction sensing.

The QEI A, B, and Z signals are digital; therefore, digital inputs (D0, D1, D2, etc., available with MSO) can probe these signals, conserving analog channels for other uses.

QEI SYNC SIGNAL

A Sync signal must be chosen in the Mechanical setup dialog in order to define the time period over which to make the speed measurement using the A and B QEI signals. The maximum number of speed calculations that could be made would be equal to the pulses/revolution divided by four if the Sync signal chosen in the Mechanical dialog had the same period as the A or B signal. If the Sync signal period is longer, then the speed is calculated on the average of multiple four AB phase long periods. If the Sync signal is one of the Drive Output voltage or current signals, then the number of speed values returned per shaft rotation will be directly related to the number of stator poles in the motor and the number of QEI pulses/rotation.

Slip Setup

For an AC induction motor, the load on the rotor shaft serves a purpose to slow the angular speed of the rotor magnetic flux field and permit the motor to develop torque. The ratio between the rotor angular speed and stator magnetic flux angular speed is called slip. Percent slip is the percent difference between the Synchronous speed and the base speed. Thus, an ACIM is never operating at its rated (no-load, or 100%) speed but some lower speed. Slip may also be expressed as a percentage of one revolution, or in radians or degrees.

Mechanical Sync Signal

The Mechanical Sync signal setup is identical to that for AC Input, DC Bus, and Drive Output. One Sync source applies to all mechanical values. The Sync source can be different from that of the electrical sections or the same. See Choosing a Sync Signal (p.18) for more information on choosing a good Sync signal for this measurement.

Numerics Setup Dialog and Table

Once proper voltage, current and mechanical signal assignments are made to analog or digital channels, and appropriate Sync signal selections are made, the Numerics setup dialog provides the ability to quickly and easily create a customized measurement table with up to 10 **Table Rows** representing sources (or combinations of sources) and 12 **Table Columns** consisting of voltage, current, power, torque, speed, and other measurements. These measurement parameter values are mean or peak values (depending on the measurement parameter) as described in the Appendix. The intersection of a row and column results in a **motor parameter (MP)**, which represents a specific measurement made on a specific source.

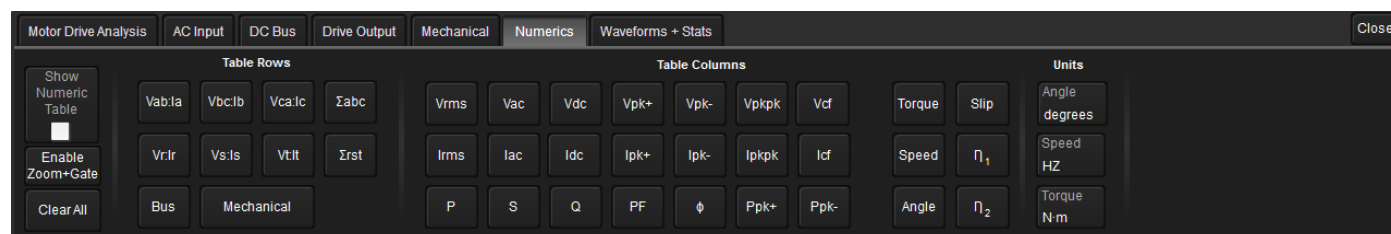


Figure 57: Default Numerics dialog before defining table. This image shows only standard capability. Additional Numerics are available with add-on options.

Table Rows

Table rows are the sources that are available to display, corresponding to the wiring configuration inputs, and these selections change dynamically based on selections made for the AC Input, DC Bus, and Drive Output wiring configurations and the Mechanical torque and speed/direction methods. In Figure 57, the AC Input wiring configuration is a 3-phase/3-wire (3V3A) resulting in V_{AB} , V_{BC} , and V_{CA} (line-line) voltages paired with I_A , I_B , and I_C line currents, whereas the Drive Output wiring configuration is a 3-phase/4-wire (3V3A) resulting in V_R , V_S , and V_T (line-neutral or line-reference) voltages paired with I_R , I_S , and I_T line currents. In both cases, there is a Σ three-phase value. The (DC) Bus selection will appear or not based on whether the “None” or “1-phase/2-wire (1V1A)” selection is made. The Mechanical selection will appear as long as there is one method selection made for torque or speed/direction.

For instance, if the AC Input wiring configuration was selected to be 1-phase/3-wire (2V2A) and the Drive Output wiring configuration was selected to be 3-phase/3-wire (3V3A), then the Table Row selections would change as shown in Figure 58:



Figure 58: Table Rows options change depending on the wiring configuration. Incompatable sources are disabled.

From 1 to 10 rows, depending on need, may be added to the table by selecting the source on the dialog. If the wiring configuration or selections made dictates that fewer than 10 sources are possible, then the number of rows will be restricted to the maximum possible number of sources. If a source is selected as a Table Row, it will indicated by a gray color highlight on the source button.

Motor Drive Analyzer Software

Before configuring the table, ensure that your voltage and current sources are assigned correctly, that current probes are placed in the correct direction for current flow, and that voltage probes are connected with the correct polarity. Otherwise, measurement parameters will calculate incorrectly for a given source.

Table Columns

Table columns are the actual measurements that are performed on the selected sources (rows). The superset of all measurements is always displayed. Those measurements selected are indicated by a gray color highlight on the Table Columns button. If a measurement (column) is incompatible with a source (row), then “---” is displayed in the table cell where the measurement value would normally appear.

When the maximum number of measurements (12) is reached, the remaining measurements are disabled to indicate that no more selections may be made, and the Table Column heading will say “Full”.

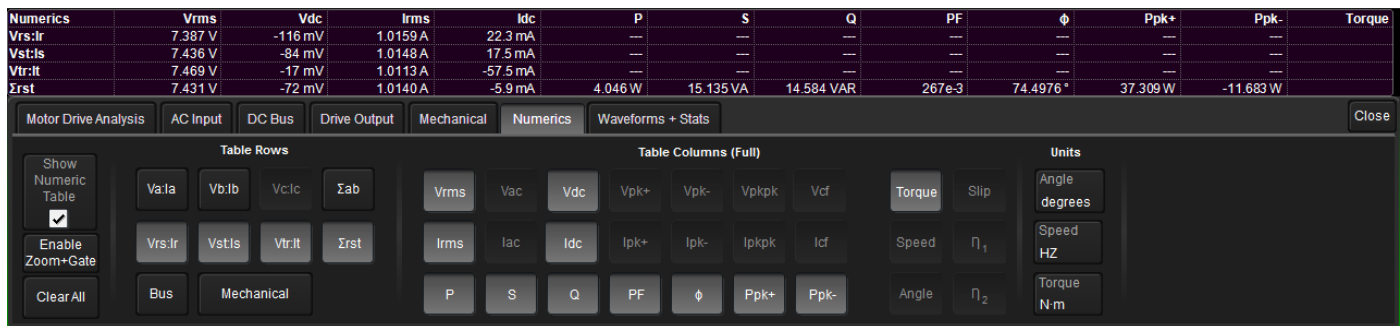


Figure 59: Highlighting indicates selected sources and measurements. Disabled Table Columns options indicate table is full.

To change the measurement set at this point, deselect unwanted measurements under Table Columns to re-enable the desired options. To quickly clear all row and column selections, simply press the Clear All button in the lower left of the Numerics dialog.

See the Appendix (p.77) for a complete description of what information appears for each measurement, depending on the source wiring configuration. In general, the value displayed is a mean or peak value for the entire acquisition.

Unit Selection

Voltage, current, power (real, apparent, reactive), power factor and phase angle have pre-defined units assigned to them and these cannot be changed. However, mechanical units related to the torque and speed/direction/position sensing can be changed. The following selections are supported:

- Angle—Units may be degrees, radians, or cycles.
- Speed—Units may be in degrees/s, radians/s, or revolutions per minute (RPM).
- Torque—Units may be in Newton Meters (N·m), foot pounds (ft·lb), inch ounces (in·oz), or inch pounds (in·lb).

Selections made on this setup dialog will override selections made in the Mechanical setup dialog, and vice versa.

Creating Per-Cycle Waveforms from the Numerics Table

The Numerics table is interactive. Touching or clicking a table cell creates a new, per-cycle Waveform of that measurement parameter, and (provided Show Statistics Table is checked on the Waveforms + Stats setup dialog) statistics for that mean or peak value are displayed in a separate Statistics table.

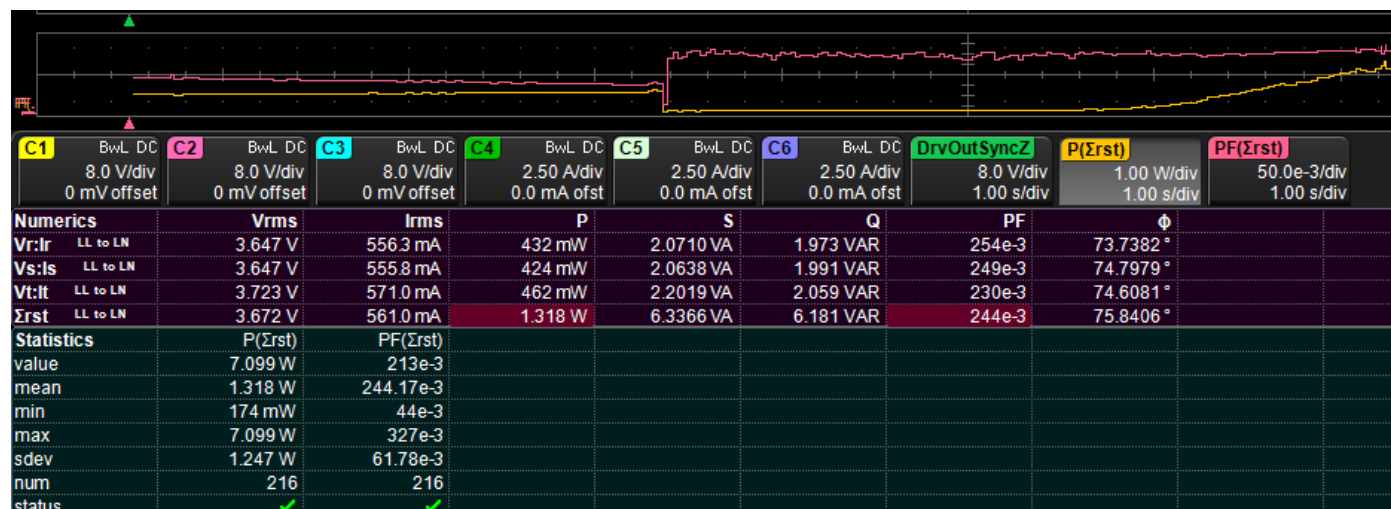


Figure 60: Numerics table cells indicate which motor parameters have per-cycle Waveforms.

The per-cycle Waveform is a synthesized waveform tracking the per-cycle values versus time, time-correlated to the original acquisition waveforms. When displayed, the waveform has a unique color and descriptor box showing the waveform name (e.g., P(Σrst)) and vertical and horizontal scale information. The default location for the waveform trace is Grid 1 (Grid 1 of Tab1 if in Q-Scape display mode); from there it may be moved to any desired grid, just like any other trace.

The per-cycle Waveform may be used as the source of a zoom, math function, measurement parameter, memory, etc. using the standard Teledyne LeCroy oscilloscope tools incorporated into the MDA. You can create up to 12 of these per-cycle Waveforms at any given time, with corresponding statistical information displayed in the Statistics table below the Numerics table.

When a Numeric table value has a per-cycle Waveform displayed, the color of the corresponding Numerics table cell will change, as shown in Figure 60.

To turn off the synthesized per-cycle Waveform, simply touch or click the cell again, and the trace is removed from the display, the same as if you had turned off the waveform by clearing the checkbox on the Waveforms + Stats dialog.

Waveforms + Stats Setup Dialog and Statistics Table

As described above, waveforms can be created from the per-cycle measurement values by selecting any Numerics table cell. This waveform represents a per-cycle measurement value vs. time, time-correlated to the original acquired voltage and current waveforms, with one discrete vertical level (measurement value) in the waveform for each measurement period, as defined by the Sync signal. These waveforms are thus time-correlated with any other signal input to an MDA channel, and can be used to understand and debug complex behavioral interactions in the AC input, DC bus, drive output, or mechanical section that would be otherwise difficult to understand. Up to 12 per-cycle Waveforms can be created and viewed at any one time.

When a per-cycle Waveform is created, an additional Statistics table is displayed by default. The values in this table are the statistical data values that comprise the per-cycle Waveform. Thus, if there are 500 unique measurement periods in the acquisition (and therefore 500 measurement values), the Statistics table will provide the statistical mean, minimum, maximum, standard deviation, number of measurements, and last value in the acquisition, as shown in Figure 61.

Statistics	P(Σ rst)	S(Σ rst)	PF(Σ rst)	Q(Σ rst)	Irms(Vr:Ir)	Irms(Vs:Is)	Irms(Vt:It)
value	4.084 W	12.864 VA	317e-3	12.199 VAR	990.4 mA	990.5 mA	974.2 mA
mean	4.0303 W	12.9727 VA	310.627e-3	12.3306 VAR	1.01588 A	1.01482 A	997.42 mA
min	3.795 W	12.445 VA	300e-3	11.852 VAR	990.4 mA	990.4 mA	974.2 mA
max	4.265 W	13.540 VA	320e-3	12.892 VAR	1.0538 A	1.0506 A	1.0233 A
sdev	133.1 mW	298.8 mVA	4.861e-3	275.6 mVAR	16.96 mA	17.46 mA	13.99 mA
num	17	17	17	17	17	17	17
status	✓	✓	✓	✓	✓	✓	✓

Figure 61: Statistics table display.

The definition of the values displayed is as follows:

- Value = last value calculated in the acquisition set
- Mean = mean value for all “N” values in the statistical set
- Min = minimum value for all “N” values in the statistical set
- Max = maximum value for all “N” values in the statistical set
- Sdev = standard deviation value for all “N” values in the statistical set
- Num = number of values in the statistical set
- Status = indicates whether the measurement was performed correctly or not

You can show or hide this table by selecting/deselecting the “**Show Statistics Table**” checkbox on the Waveforms + Stats setup dialog.

There are a maximum of 12 **motor parameters** (MP1, MP2,...MP12) representing a specific measurement on a specific source (i.e., a “cell” of the Numerics table) that may be displayed at once in the Statistics table. Although the default is to display the table with the corresponding per-cycle Waveform, you can hide the waveform while retaining the MP in the table by clearing the **Waveform** checkbox next to the MP.

The Waveforms + Stats setup dialog provides a summary of the 12 motor parameters and per-cycle Waveforms, as well as an alternative method for creating and modifying them.

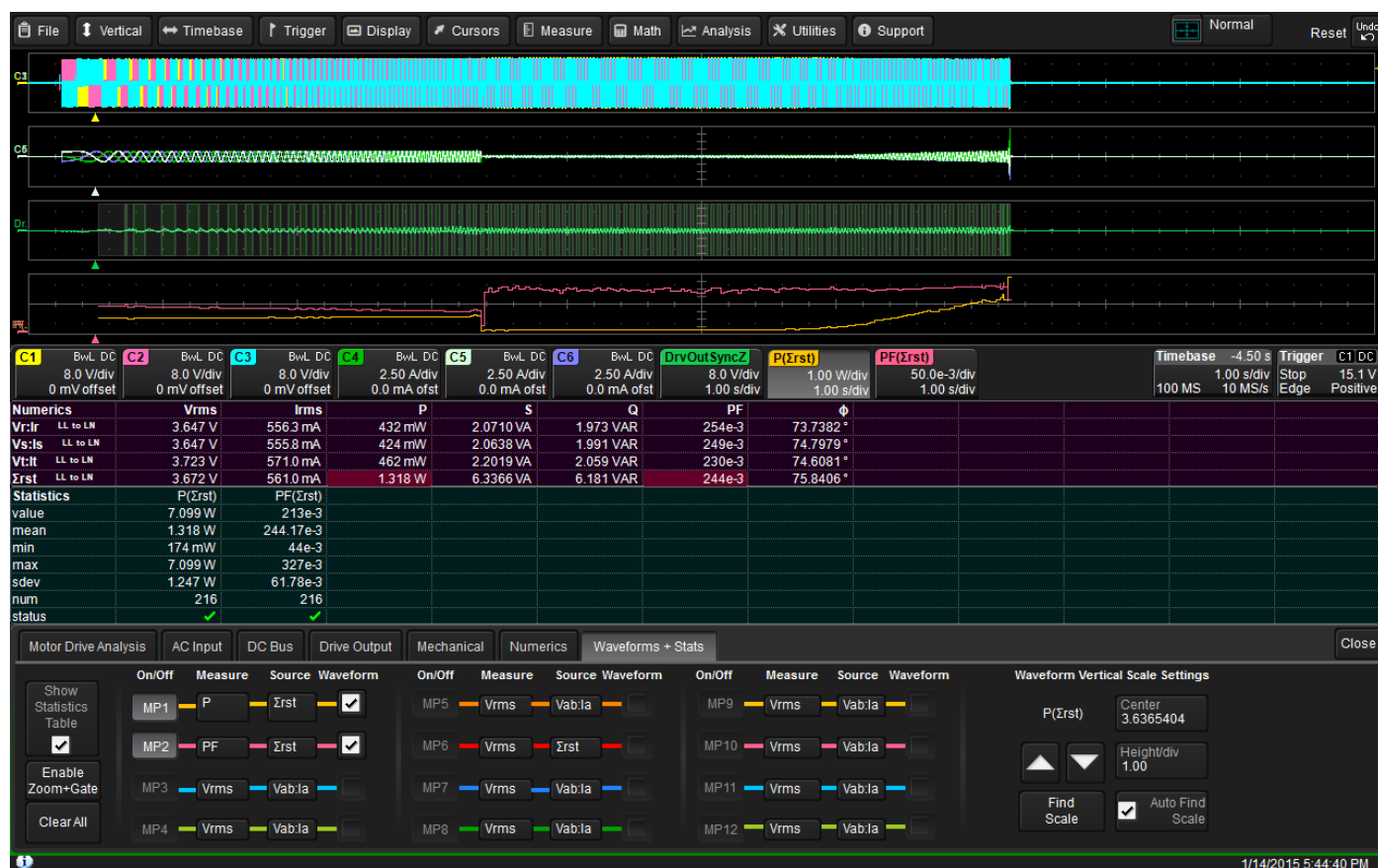


Figure 62: Waveforms + Stats dialog with Statistics table and per-cycle Waveforms displayed.

To quickly empty the Statistics table, touch the **Clear All** button at the bottom left of the Waveform + Stats dialog.

Motor Parameter Definitions

For each of these 12 possible MPs, the Waveforms + Stats dialog shows its current status and may be used to change the MP definition.



Figure 63: Single MP definition as it appears on the Waveforms + Stats dialog.

On/Off shows or hides the MP in the Statistics table. When On (light gray), the MP is shown on the table, when Off (black), the MP is hidden.

Measure indicates the measurement chosen (e.g., Vrms). You can change the measurement shown on the table by selecting this button and choosing a new measurement.

Source indicates the source for the measurement (e.g., Vrs). As with Measure, you can change the table by selecting the Source button and choosing a new source.

The **Waveform** checkbox shows/hides the per-cycle Waveform that corresponds to this MP.

Per-Cycle Waveform Vertical Scale Settings

When a per-cycle Waveform is displayed, a corresponding descriptor box appears below the grid.



Figure 64: Per-cycle Waveform descriptor box.

Selecting the descriptor box (it will appear highlighted, as in Figure 64) activates that trace and the following Waveform Vertical Scale Settings on the Waveforms + Stats dialog.

Height/div or the arrow buttons adjusts the trace amplitude.

Center shifts its horizontal position so it is centered on the grid.

Find Scale automatically detects and sets the scale based on waveform mean amplitude.

Auto Find Scale checkbox indicates whether a new scale should be found automatically whenever the values change enough to warrant it a scale change.

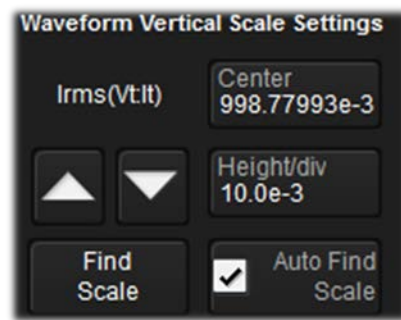


Figure 65: Synthesized per-cycle Waveform vertical scale settings.

By definition, the per-cycle Waveforms don't have horizontal rescale capability and are always locked to the same timebase setting as the original input source traces or to the zoom scale when Zoom+Gate is enabled. However, if desired, you can create a zoom trace of the per-cycle Waveform using the standard zoom controls, which can be adjusted horizontally. Select the per-cycle Waveform by name (e.g., $\phi(\Sigma rst)$) from the "Motor" category on the Select Source pop-up dialog (Figure 66). These selections automatically change depending on the MP setup.

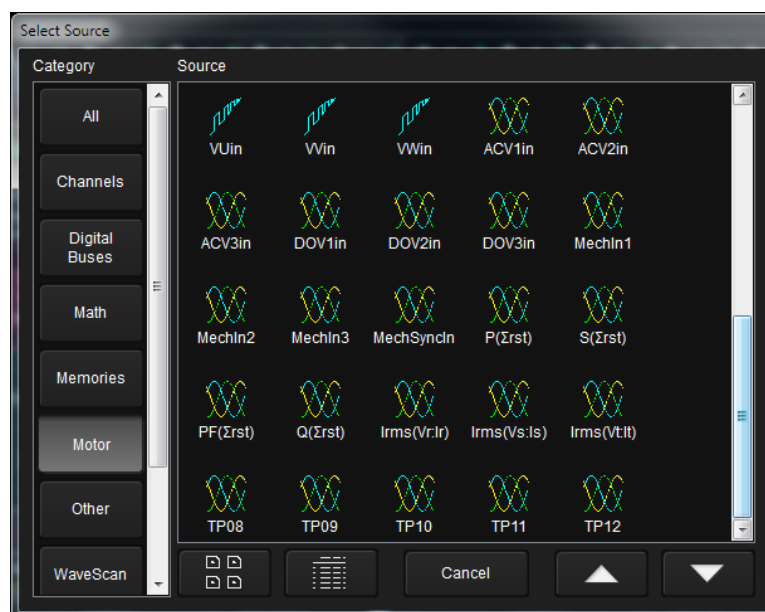


Figure 66: Select Source pop-up dialog.

NOTE: When the zoom of the per-cycle Waveform is created, the source shown on the zoom descriptor box will appear as TPxx, with xx being the MP number (01-12) that corresponds to the waveform.

Zoom+Gate Mode

The Motor Drive Analyzer combines the best capabilities of power analyzer instruments with very long record captures (up to 250 Mpts, or minutes of acquisition data), and consequently is able to perform numerical calculations and display per-cycle Waveforms for hundreds or thousands of power cycles. This provides a unique ability to validate and debug drive, control and mechanical system behaviors that is not possible using a traditional power analyzer or oscilloscope.

However, such long records and large datasets are difficult to analyze. The Zoom+Gate feature provides a simple method for zooming all input sources (analog and digital), per-cycle Waveforms, and Sync signals together, positioning the zoom window on any portion of the trace. The common zoom window then acts as the measurement gate for the Numerics and Statistics tables. Thus, it is possible to push one button (Zoom+Gate), turn a couple knobs to adjust zoom ratio and position, and quickly compare the acquired waveforms to per-cycle Waveforms, while automatically and instantly recalculating the measurements for only the zoomed area.

Accessing Zoom+Gate

Zoom+Gate may be enabled by pushing the Zoom+Gate shortcut button on the front of the MDA (Figure 9) or by touching the Enable Zoom+Gate button on the AC Input, DC Bus, Drive Output, and Mechanical dialogs.

Both the hardware and software buttons perform the same actions:

- Creates zoom traces (Zx) of all displayed input sources. These new Zx waveforms will likely not be located in the grid you desire, so select a new grid style and/or drag the trace descriptor box for each Zx trace to a different grid to position them appropriately.
- Includes all Zx traces in a multi-zoom so that all Zx traces are zoomed with the same ratio and positioned in a time-correlated fashion.
- Includes any per-cycle Waveforms and Sync signal traces in the multi-zoom with the Zx traces so that all are zoomed and positioned in a time-correlated fashion.
- Adds per-cycle Waveforms and Sync signals that are displayed *after* Zoom+Gate is enabled to the multi-zoom group.
- Permits other math (Fx) or memory (Mx) traces to also be added to the multi-zoom, as desired. To do this, from File toolbar, select Math > ZoomSetup, then select MultiZoom tab, and include additional Fx or Mx traces in the multi-zoom.

Although there are several instances of the control, activating/deactivating Zoom+Gate in any one way serves for the entire application. When Zoom+Gate is enabled, the LED on the Zoom+Gate button is lit, and the Enable Zoom+Gate software button is highlighted light gray. The front panel Zoom button (between the Vertical and Horizontal scale controls) is also lit, indicating that these controls may be used to control the zoom ratio and position, and thus also control the gating location and size.

Zoom+Gate Example

In this example, a Drive Output is captured and measurement parameters are calculated in the Numerics and Statistics tables, and several per-cycle Waveforms are created. The current signal undergoes a wide dynamic range—it is not necessarily the best Sync signal—so the voltage signal is chosen instead and appropriately filtered with a Hysteresis band setting of 500 mdiv to avoid bad cyclic calculations. Nonetheless, the overload condition just before drive shutdown shows a lot of ringing, making it difficult to determine cyclic values in this area.

Q-Scape display mode is used to show the full acquisition on the left and the Zoom+Gate area on the right. Q-Scape is configured for Q-Dual mode.

Cursors are placed on the waveforms and values can be read on the descriptor boxes at each cursor location. The Statistics table indicates that the Zoom+Gate area has a total of 12 measurement cycles (you can count the cycles on the zoomed DrvOutSync waveform). The stress on the drive as it reaches overload conditions can be seen in the zoomed voltage and current waveforms. The P(SumRST) and PF(SumRST) Waveforms show the Power and Power Factor values during the overload, and the values are represented in the Statistics table.

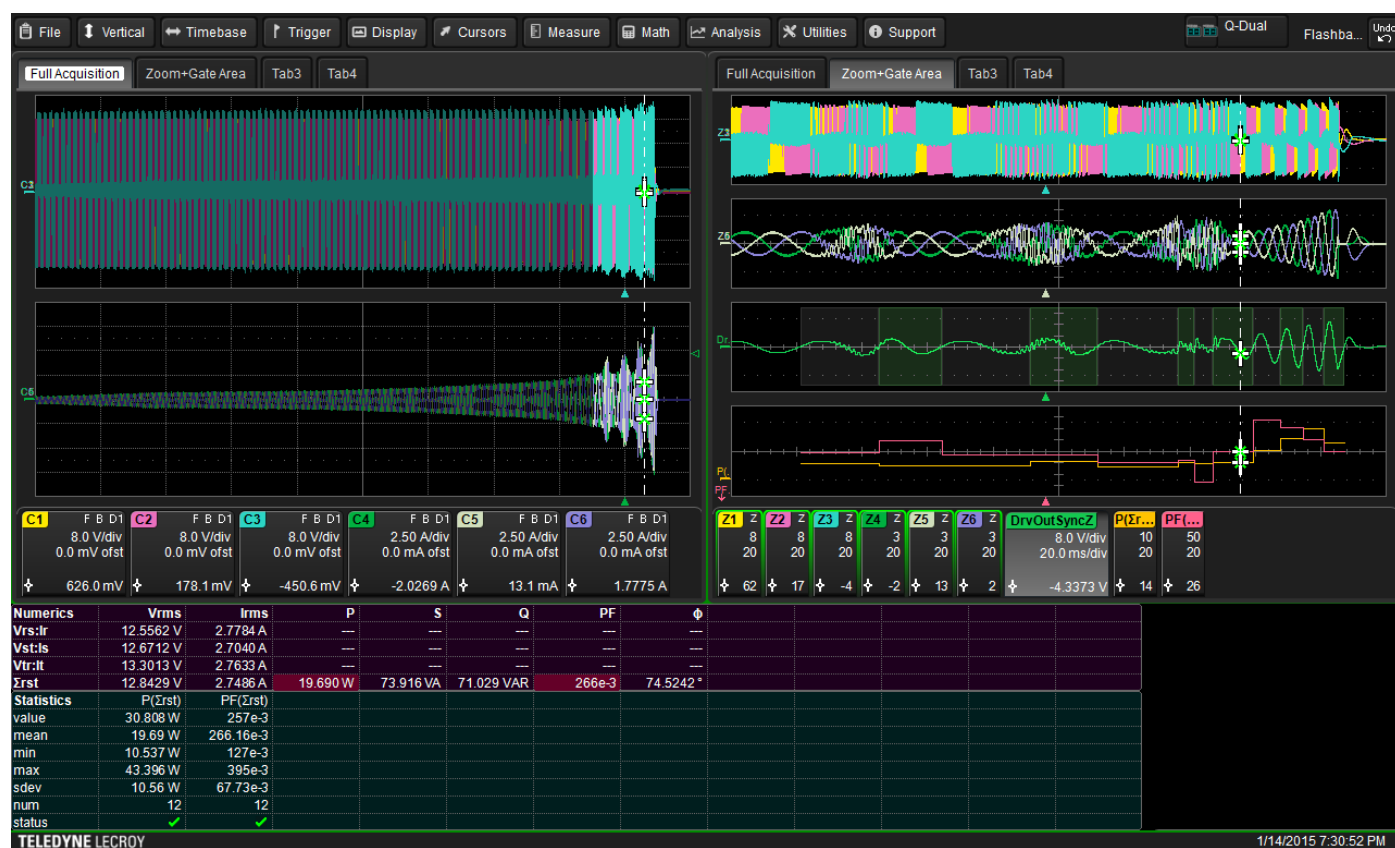


Figure 67: Zoom+Gate on a drive output undergoing an overload condition.

X vs. Y Displays

The MDA800 Series provides advanced capability to display up to twelve XY plots. The XY plots can be comprised of any two waveforms, such as channel acquisitions, zooms, math traces, memory traces, or per-cycle Waveforms.

Six specialized grid modes display just the XY plots on XY type (8-division wide by 8-division high) grids, as many as eight grids at once. Five additional grid modes display the XY plots in combination with other waveforms displayed on standard (10-division wide by 8-division high) grids.

Accessing XY Setup

The XY setup dialog can be accessed by selecting XY Setup from the Display setup dialog or from the Math drop-down menu, as shown in Figure 68.



Figure 68: Accessing the XY setup dialog.

The XY setup dialog, shown in Figure 69, contains controls for assigning the X and Y inputs of plots XY1 through XY12, changing plot colors, and turning on/off the plot display (using the checkbox).

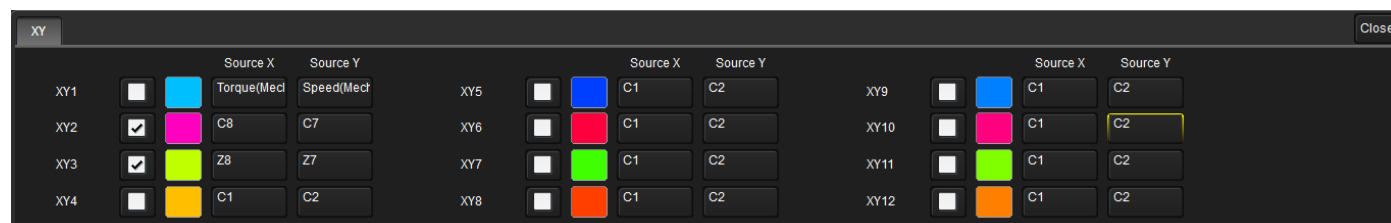


Figure 69: XY setup dialog.

Note that the displayed XY plots will have a descriptor box like that of a channel, math, memory, zoom or per-cycle Waveform trace. However, no additional post-processing can be performed on these XY plots, so plots XY1 through XY12 cannot be selected as sources for measurements or math. As elsewhere, touching the descriptor box opens the XY setup dialog, and dragging the descriptor box to a new grid moves the XY plot to that grid.

X vs. Y (8 division by 8 division) Grid Modes

The advanced XY capability includes specialized grid modes to display XY only or combined XY+standard grids. The selections are:

- XY—single XY grid
- DualXY—two XY grids
- TripleXY—three XY grids
- QuattroXY—four XY grids
- HexXY—six XY grids
- OctalXY—eight XY grids
- XYSingle—a single XY grid and a single standard grid
- XYDual—a single XY grid and two (dual) standard grids
- DualXYSingle—two XY grids and a single standard grid
- DualXYDual—two XY grids and two (dual) standard grids
- HexXYDual—six XY grids and two (dual) standard grids

Any of these grid modes may be selected in Normal display mode or in Q-Scape tabbed display modes.

Example 1: Torque vs. Speed plot

In this example, analog torque (channel 7, or C7) and speed (channel 8, or C8) signals are acquired from a dynamometer torque load cell and speed sensor output, then scaled and unitized in the MDA mechanical setup dialog. The XY2 plot is defined with Source X = C7 (Torque) and Source Y = C8 (Speed). The XY3 plot is defined with Source X = Z7 (the zoom of Torque) and Source Y = Z8 (the zoom of Speed).

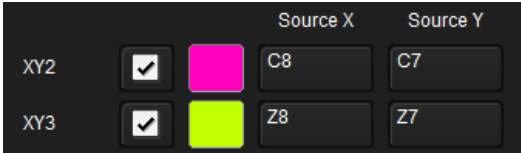


Figure 70: XY plot definition.

The MDA display is set up in Q-Scope display mode, and one of the tabs is renamed Torque vs. Speed. The grid mode selection made for this Q-Scope tab is XYDual (Figure 71) to allow a mix of signals to be easily viewed.



Figure 71: XYDual grid mode selection in tabbed Q-Scope display mode.

The location and size of zooms Z7 and Z8 are highlighted in the screen capture. XY2 displays the full acquisition torque vs. speed plot of all 25 million acquisition points. XY3 displays the torque vs. speed plot of only the zoomed area, many fewer points.

Use the front panel zoom controls or the Auto-Scroll (playback) controls on the MultiZoom setup dialog to change the zoom location and better understand the zoomed torque vs. speed plot relative to the full acquisition.

NOTE: In this example, the XY3 plot is laid over the XY2 plot. This is because XY3 was defined and turned on after XY2. The plot turned on last will be displayed at the forefront of other plots.

Example 2: Torque vs. Speed plot using per-cycle Waveforms

In this example, torque vs. speed is plotted using the per-cycle Waveforms. The waveforms were created by touching the Torque(Mechanical) and Speed(Mechanical) cells in the Numerics table, and the plot was defined by selecting Torque(Mechanical) and Speed(Mechanical) from the Motor sub-category of the Sources pop-up dialog.

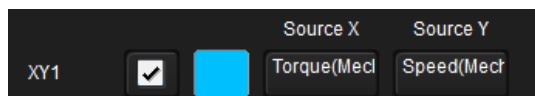


Figure 72: XY plot defined using per-cycle Waveforms.

There are only 372 measured values in these waveforms (instead of 25 million sample points), so the resulting display (Figure 73) is more granular than in the previous example.

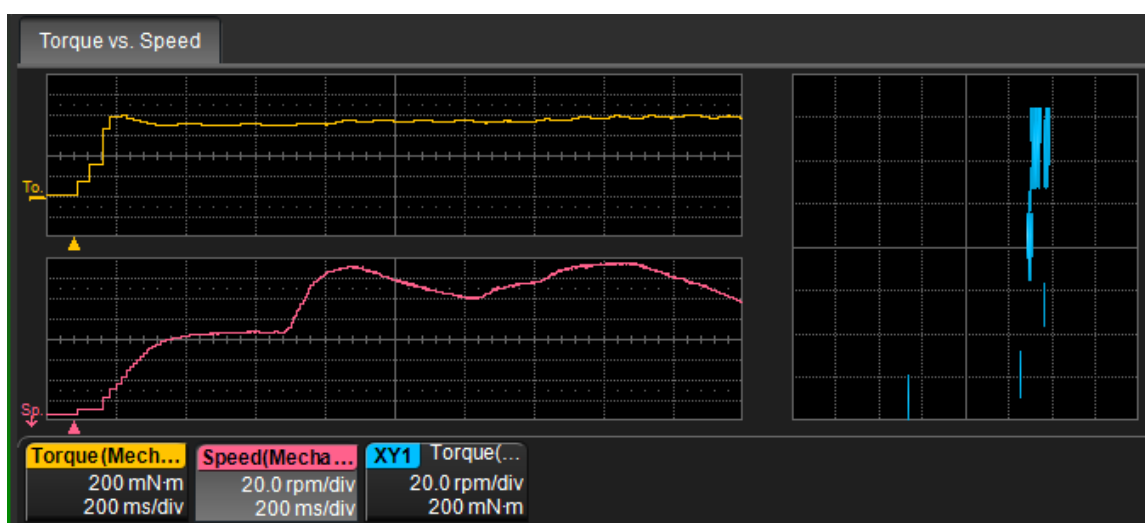


Figure 73: Per-cycle Waveforms displayed next to their XY plot.

Example 3: Six X vs.Y plots using vertical zooms

In this example, vertical zoom traces are used as the sources for the XY plots. The reasons for this are twofold:

- If the zoom ratio is 1:1 (the default), the XY display is for the full acquisition, but if the zoom ratio is changed to >1:1, and the zoom position is moved, the XY plots are calculated for the zoomed areas only.
- Vertical zooming increases the magnitude of vertical height of the DC bus, speed and torque signals so as to provide a “larger” XY plot that uses more of the 8 x 8 division grid.



Figure 74: Multiple XY plot definitions using vertical zooms as sources.

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Six XY plots are created using different combinations of seven zoom traces: Z1, Z3, Z4, Z5, Z6, Z7, and Z8:

- XY1 is Z3 (vertical zoom of the DC bus voltage) vs. Z8 (vertical zoom of the analog speed signal)
- XY2 is Z6 (vertical zoom of the DC bus current) vs. Z8 (vertical zoom of the analog speed signal)
- XY3 is Z3 (vertical zoom of the DC bus voltage) vs. Z7 (vertical zoom of the analog torque signal)
- XY4 is Z3 (vertical zoom of the DC bus voltage) vs. Z6 (vertical zoom of the DC bus current)
- XY5 is Z6 (vertical zoom of the DC bus current) vs. Z7 (vertical zoom of the analog torque signal)
- XY6 is Z1 (LineR-LineT voltage) vs. Z4 (LineT current)

Figure 75 shows the XY plots and their source waveforms in Q-Single display mode with HexXYDual grid mode selected and the tab relabeled “X vs. Y Plots”. The source waveforms are in the two standard grids to the left of the six XY grids.

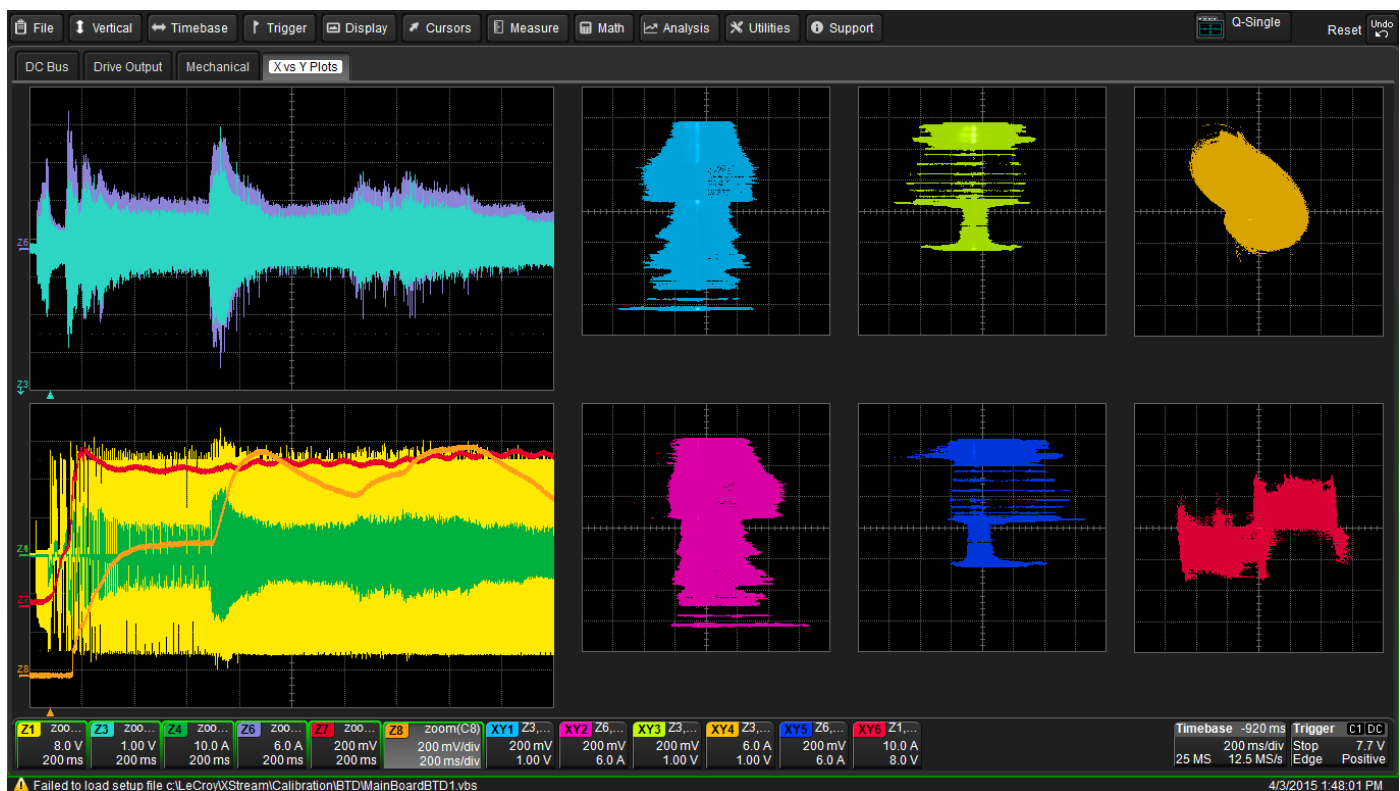
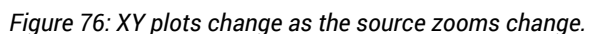


Figure 75: HexXYDual display of six XY plots and their source waveforms.



Harmonics Calculation Option

Harmonics Calculation is an optional software package for use with the Teledyne LeCroy MDA800 Series Motor Drive Analyzer. It adds the following capabilities to the standard Motor Drive Analyzer tools:

- Advanced harmonic filtering of AC Input and Drive Output for voltage, current, and power measurements
- Total Harmonic Distortion (THD) measurement parameters for voltage, current, and power
- A Harmonic Calc(ulations) tab for setting up per-order harmonic measurements, which are displayed in a new Harmonic Order table
- Spectral waveform displays

Harmonics Calculation Overview

The Motor Drive Analysis software includes standard capabilities to filter Numerics table measurements to include all acquired harmonics (Full Spectrum) or only the Fundamental. However, it can be helpful to more precisely limit the harmonic content of the acquired waveforms when calculating Numerics table measurement parameters. The Harmonics Calculation option provides a method to harmonically filter input waveforms using either a Fundamental+N or Range filter. Fundamental+N allows you to specify how many (N) harmonics from the fundamental to include in the Numerics table calculations. The Range filter is very similar, except it allows you to specify a starting point for the range other than the fundamental, including the ability to filter to a single harmonic order.

Additionally, the Harmonics Calculation option provides per-order harmonic measurement results for up-to-nine waveforms: voltage, current, and power for each phase of a three-phase system. The method used allows for both steady-state (Fixed Frequency) and dynamic (Varying Frequency) operating conditions. The steady-state method is similar to that found in a typical power analyzer. The dynamic method provides maximum flexibility for variable frequency drive outputs. This is made possible by a flexible, per-cycle period detection technique far more advanced than what is typically found in power analyzers, which can only perform steady-state harmonic analysis.

NOTE: As Varying Frequency calculations are done on a per-cycle basis, processing time will increase for a large number of harmonic orders and/or many cyclic periods within an acquisition. Gain experience first with shorter acquisitions at lower sample rates to understand the processing time required for these complex calculations, and ensure that input waveforms are not unnecessarily oversampled. At a minimum, the sample rate should be at least ten times the switching frequency of a pulse-width-modulated signal, with appreciably more sample rate used only if non-harmonic behaviors are also to be investigated at the same time.

Lastly, per-cycle THD measurement parameters for voltage, current and power are available for selection and inclusion in the Numerics table display. Per-cycle synthesized waveforms for THD can be created by touching a THD measurement parameter cell in the Numerics table —a capability unique to the Motor Drive Analyzer.

Harmonic Filtering – AC Input and Drive Output Setup Dialogs

The Harmonics Calculation option activates the (normally disabled) **Fundamental+N** and **Range** Harmonic Filter selections on the AC Input and Drive Output setup dialogs. The Harmonic Filter is used to calculate the measurement results shown in the Numerics table. (This filter selection is not used for the Harmonic Order table measurements, which are set up separately as explained on Page 64.)

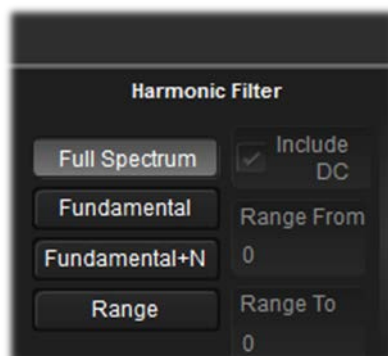


Figure 77: Harmonic Filter controls.

The Fundamental, Fundamental+N, and Range Harmonic Filter selections perform a mathematical operation on the acquired voltage and current waveforms using a Discrete Fourier Transform (DFT). This mathematical operation transforms the acquired waveform sample points to the frequency domain for each cyclic period calculated from the Sync source signal. For each cyclic period, there is a unique DFT, and therefore typically multiple DFTs per acquisition. For each DFT, the inverse of the cyclic period is defined to be the Fundamental frequency, and integer multiples of the Fundamental are the harmonic orders. The total frequency content of the DFT is then "binned" into the various harmonic orders.

The Harmonic Filter selection is the user input to this calculation, determining the relevant harmonic orders. Based on this setting, unwanted harmonic orders are discarded from the DFT, while desired harmonic orders are retained. An inverse DFT is then performed on each DFT to convert the remaining frequency-domain waveform back to a time domain waveform that represents only the desired harmonic orders. The process is repeated for each cyclic period for all acquired voltage and current waveforms, using the harmonically filtered waveforms to calculate the measurement results shown in the Numerics table. This technique works on waveforms with constant or highly variable cyclic periods.

NOTE: Although used for Numerics table calculations, the harmonically filtered waveforms are not displayed, and the originally acquired channel waveforms remain the same.

An example of what the harmonic filter does is shown in Figure 78 and Figure 79. The images show a width-modulated waveform (thick red trace) that is not harmonically filtered. This waveform is made up of many sinewaves (harmonic orders) that when added together result in the shape shown. The multi-colored harmonic order sinewaves are shown in the figures, as well.

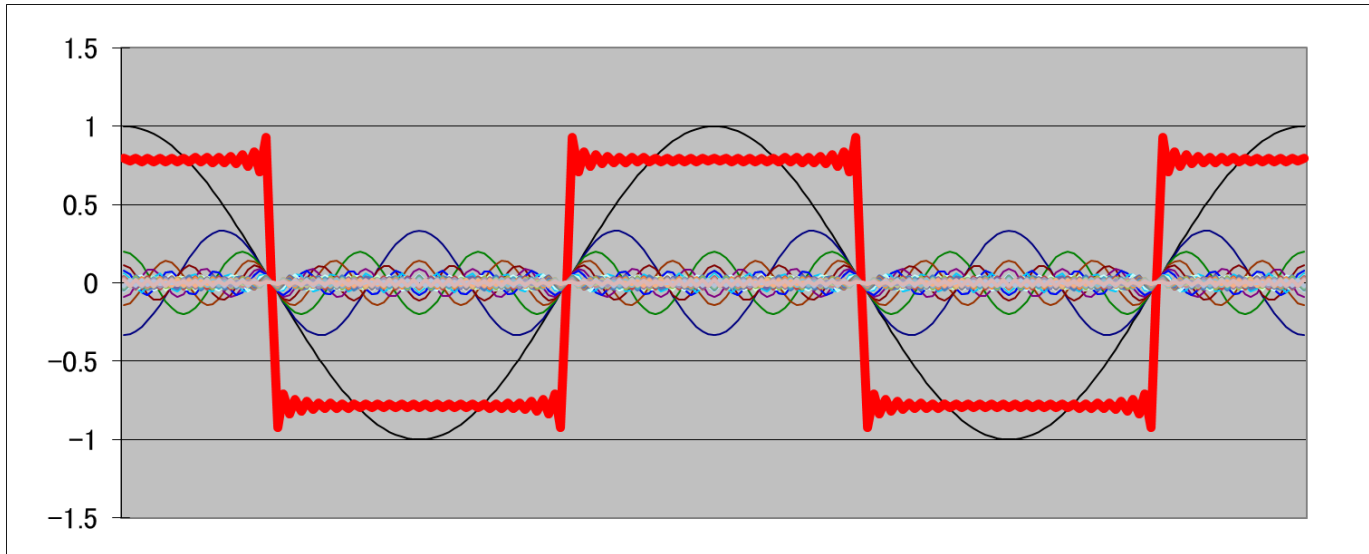


Figure 78: Non-Filtered square wave displayed with 50 harmonic order waveforms.

When a harmonic filter is applied to show only the fundamental through the 5th harmonic order, the width-modulated waveform looks much different, as shown in Figure 79. The harmonically filtered waveform would yield much different power measurement results than the non-filtered waveform.

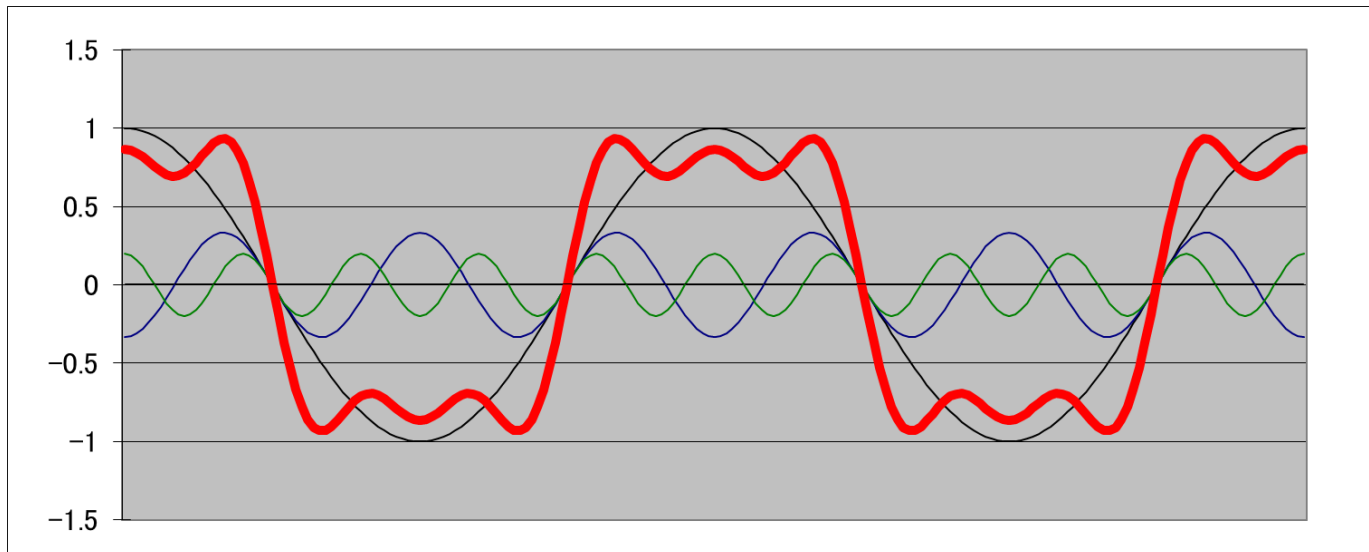


Figure 79: Filtered fundamental through 5th harmonic square wave displayed with harmonic order waveforms.

Numerics Table THD Measurement Parameters

The MDA Harmonic Calculation option adds the ability to display THD voltage, current, and power parameters in the Numerics table. As with other Numerics table parameters, synthesized per-cycle Waveforms can be created simply by touching a THD measurement cell, and the Zoom+Gate feature can also be used with THD synthesized per-cycle Waveforms.

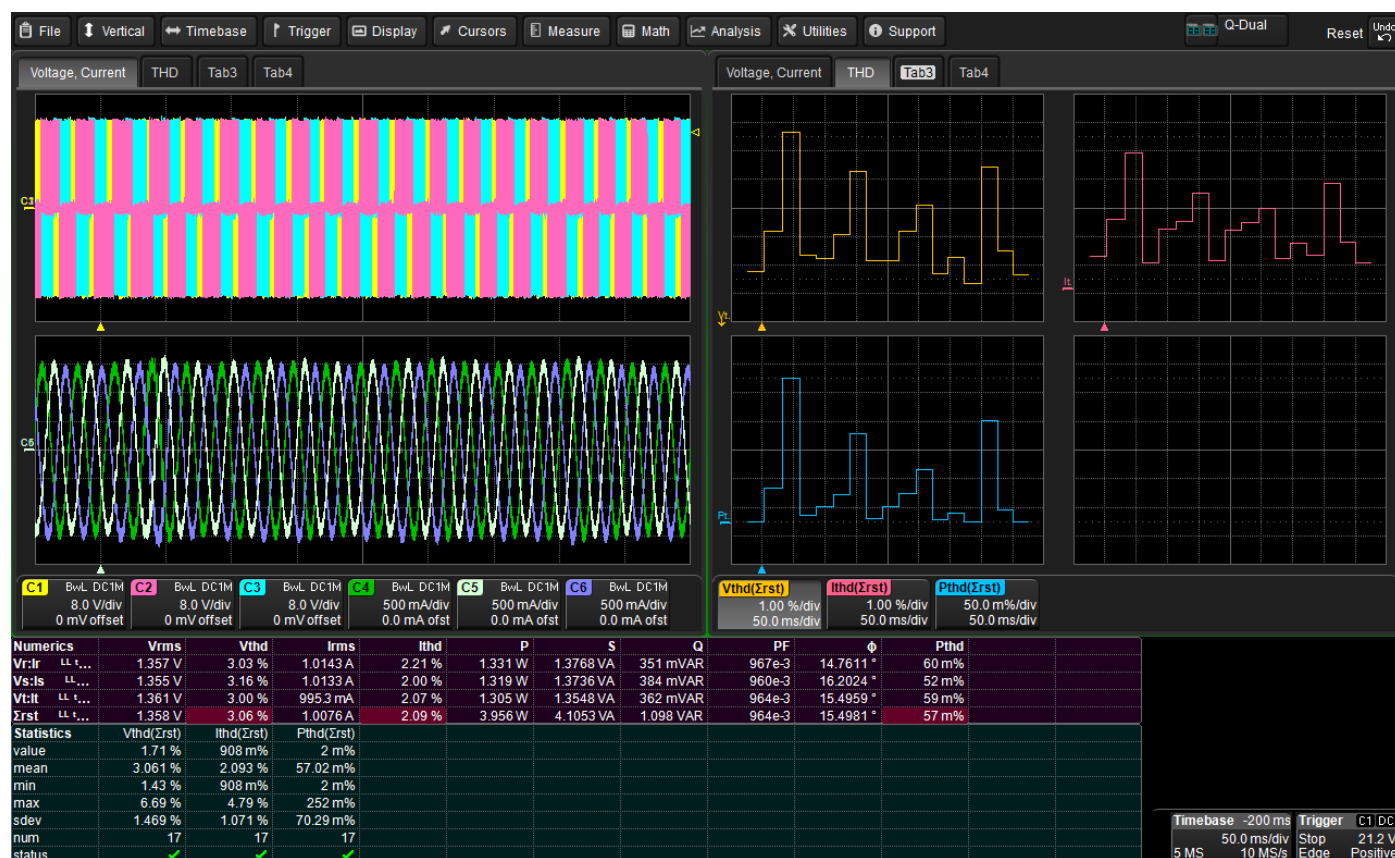


Figure 80: Example of THD measurement parameters in Numerics table and THD per-cycle Waveforms.

NOTE: THD is always calculated as a percentage of the fundamental. See the Appendix for complete formulas.

The THD measurement parameters are available for selection only if the Harmonic Filter is either Fundamental+N or Range, because the DFT calculation method must be performed in order to understand the harmonic content of the waveform. Providing THD measurements for the Full Spectrum selection would increase processing times for all Numeric table measurements, even when THD is not of interest. THD measurements cannot be provided when the Fundamental selection is made since, by definition, there is no harmonic content in the fundamental waveform.

Harmonics Calc Setup Dialog

Once the proper voltage and current signal assignments have been made on the AC Input or Drive Output dialogs, the Harmonics Order table may be set up and displayed using the Harmonics Calc(ulation) dialog. These harmonic calculations can be performed on any phase of either the AC Line Input or Drive Output voltage, current, and power waveforms. Spectral waveforms showing the result of the selected calculations are displayed, along with harmonic order measurement values in a new Harmonic Order table.

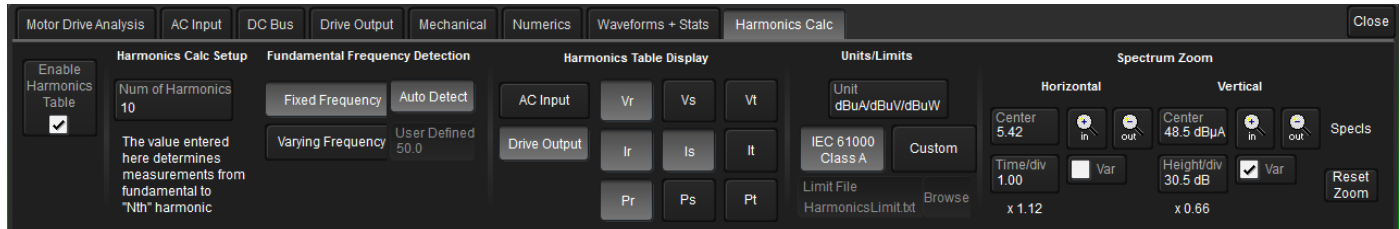


Figure 81: Harmonics Calc setup dialog.

Harmonics Calc Setup and Fundamental Frequency Detection

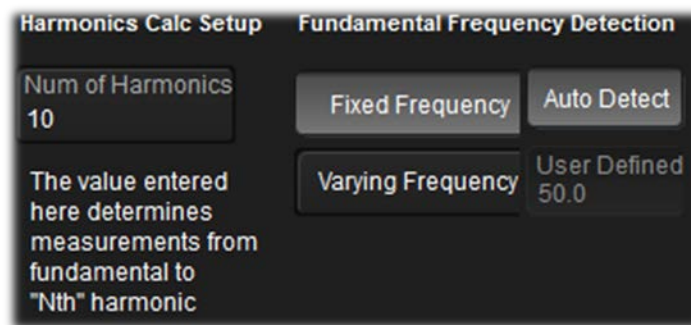


Figure 82: Harmonics Calc Setup and Fundamental Frequency Detection controls.

Enter the **Num(ber) of Harmonics** orders of interest to be measured. This setting determines measurements from the fundamental to the Nth harmonic.

NOTE: This is different from the Harmonic Filter setting on the AC Line and Drive Output dialogs, which only applies to the Numerics table measurements. The Num of Harmonics setting is only used to calculate results in the Harmonics Order table.

Under Fundamental Frequency Detection, choose the method for detecting the fundamental frequency:

- **Fixed Frequency** allows the Num(ber) of Harmonics to be set up to 100, but does not allow the use of the Zoom+Gate feature. By default, the input current signal is used to **Auto Detect** the frequency, but you may enter a **User Defined** base frequency as an alternative to using the input current signal frequency.
- **Varying Frequency** uses the Sync signal defined for the AC Input or Drive Output to determine the proper period of each cycle. The Num(ber) of Harmonics is limited to 50 with this setting, and the harmonic calculations are done on a per-cycle basis. Since the harmonics are calculated per-cycle, the processing times may be significantly longer when compared to the fixed frequency mode. However, the Varying Frequency method can be used with the Zoom+Gate feature.

The Fixed Frequency setting should only be used with a fixed frequency input, such as an AC Line Input (50 or 60 Hz) or a (Variable Frequency) Drive Output signal operating under steady-state conditions (constant speed, torque, load) that result in a steady-state frequency (fixed, but not necessarily 50 or 60 Hz) during the entire acquisition. In both cases, the average frequency throughout the entire acquisition would be determined by the software using mean cyclic information obtained from input current waveforms. Alternatively, you could define what this mean cyclic period should be.

The Varying Frequency setting will increase the processing since it does perform per-cycle measurements. A variable frequency drive output can change very quickly from cycle to cycle, especially during drive startup or during large speed, torque, or load changes. The cyclic period determination method (using the filtered Sync signal) is very robust and is able to respond instantaneously to the changing cyclic period. Also, the use of a Discrete Fourier Transform (DFT) instead of a Fast Fourier Transform (FFT) permits the sample rate to remain fixed throughout the acquisition, regardless of the change in cyclic period. An instrument that uses an FFT for harmonic order analysis (e.g., many dedicated power analyzers) requires a constant number of sample points in each cyclic period, which in turn necessitates a hardware phase-locked loop (PLL) to track the varying frequency of the input signal and adjust the sample rate to maintain a constant number of samples. The hardware PLL may not be able to track the rapid frequency changes present under the widely dynamic operating conditions of a variable frequency drive, making it unable to perform harmonic order analysis during drive operation. Using a hardware PLL to adjust sample rate may also limit the ability to calculate harmonic orders and power values simultaneously. The Motor Drive Analyzer has no such limitations. Because the Motor Drive Analyzer uses a software algorithm to determine the cyclic period, you may change settings post-acquisition, and new results will be calculated from these changed settings, something not possible with most power analyzers.

Harmonics Table Display

Use the Harmonics Table Display settings to choose on which phases of which waveforms to perform harmonic calculations. Select either the **AC Input** or **Drive Output** waveforms; the options to the right are updated to reflect the wiring configuration selections that were made on the AC Input or Drive Output setup dialogs. Choose all you wish to display from this list. Up-to-nine selections may be made at one time (voltage, current, and power for each phase of a three-phase system).

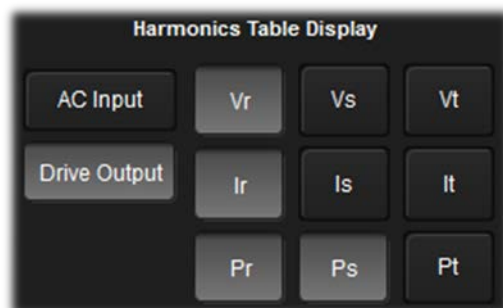


Figure 83: Harmonics Table Display controls.

NOTE: The AC Input or Drive Output selection determines which Sync signal (set up on the AC Input and Drive Output dialogs) is used to find the cyclic period when in Varying Frequency mode. In Fixed Frequency mode, the Sync signal is not used to determine the frequency.

Units/Limits

Choose the **Unit** in which to display harmonics calculation results: amperes (A), volts (V), watts (W), percent (%), or decibels (dB). When using percent, THD results are given as a percentage of the fundamental component.

$$THD_{\%} = \frac{Each\ harmonic\ order}{Fundamental\ component} \times 100$$

In Fixed Frequency mode, you may optionally compare the measured current harmonics to the limits set by the **IEC 61000 Class A** specifications. Convenient Pass/Fail indicators are posted next to the measured current values in the Harmonics Order table.



Figure 84: Units/Limits controls.

Alternatively, you may compare to a **Custom** limit set. When using this option, **Browse** to and select your user-defined **Limit File**.

Limits are defined in a .txt file in the format shown in Figure 85. The first column represents the harmonic order. The second column (separated by a tab from the first column) represents the current limit in amps, or in percent if using percent as the unit. If the unit is decibels, enter the current limit in amps in the limits file, and it will be converted to dBuA automatically.

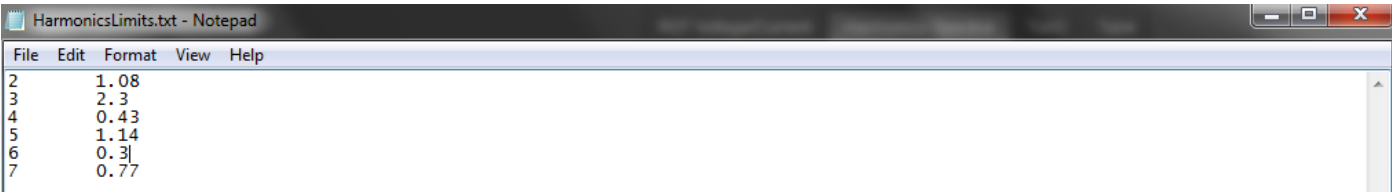


Figure 85: Example custom harmonic limits file.

Spectrum Zoom

A Spectral waveform is displayed for each input waveform selected under Harmonics Table Display. Each Spectral waveform may be zoomed independently. As the Spectrum Zoom controls can only control one Spectral waveform at a time, first activate the waveform of interest by selecting its descriptor box (Spec**).

TIP: The active Spectral waveform is shown next to the Vertical Spectrum Zoom controls.

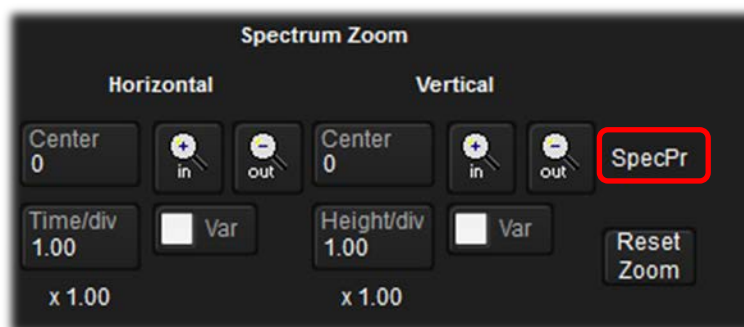


Figure 86: Spectrum Zoom controls.

Harmonics Order Table

The Harmonics Order table is an additional display only available with the Harmonics Calculation option. It is separate from the standard Numerics table. The values displayed are always presented as Line-Neutral or Line-Reference values. If the signals are probed Line-Line, a Line-Line to Line-Neutral conversion is automatically performed to calculate the values for this table. Figure 87 shows an example Harmonics Order table display.

Order(RST)	Freq [Hz]	Vr [dBuV]	Pr [dBuW]	Ps [dBuW]	Ir [dBuA]	Limit[dBuA]	Pass/Fail					
1	38.0	122.52	119.36	119.36	120.00							
2	76.0	88.83	63.88	76.07	84.44	120.7	Pass					
3	114.0	70.64	67.36	70.59	70.45	127.2	Pass					
4	151.9	67.99	71.72	70.13	61.94	112.7	Pass					
5	189.9	68.56	51.88	47.75	68.56	121.1	Pass					
6	227.9	60.65	63.24	53.45	55.01	109.5	Pass					
7	265.9	74.32	61.11	63.11	65.40	117.7	Pass					

Figure 87: Example Harmonics Order table.

The measurement values in the Harmonics Order table are “per-order”, but not per-cycle—they are the mean value for all the cycles.

Figure 88 shows a Harmonics Order table and its related Spectral waveforms (to the right side of the image).



Figure 88: Harmonic Order table and Spectral waveform example.

You cannot generate a per-cycle Waveform by selecting an individual cell of the Harmonics Order table as you can with the Numerics table. The Harmonics Order table displays the mean value for each order.

If a per-cycle Waveform is required, do the following to generate it:

1. Use the Range harmonics filter in either the AC Input or Drive Output setup, selecting a range that covers one harmonic order (i.e., from 3 to 3 for harmonic order 3).
2. Turn on the THD measurement parameter in the Numerics tab, then select the cell of interest to create the per-cycle Waveform for that order.

Spectral Waveform Display

Spectral waveforms are displays that contain bars representing the harmonic order value for each harmonic order specified. The Spectral waveforms bin the surrounding frequency components to the harmonic orders, which results in an easy-to-read display, unlike a simple FFT math calculation. These Spectral waveforms vary in thickness based on the number of harmonics specified, giving the appearance of a bar graph as shown in Figure 89.

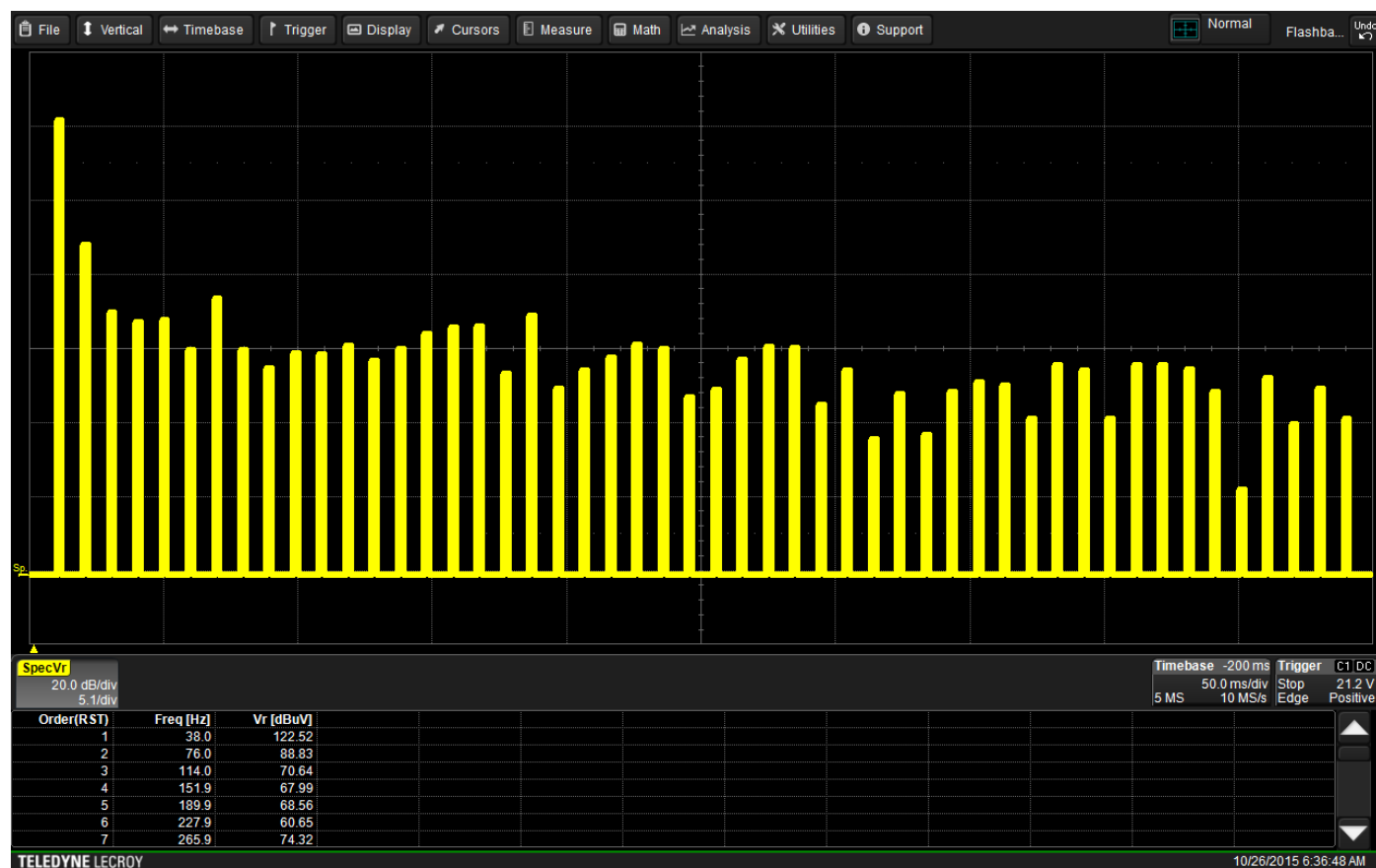


Figure 89: Spectral waveform display.

Cursors can be placed anywhere on the Spectral waveforms to read out the harmonic order values.

In some cases, the Spectral waveform may have the appearance of gaps within the bars (see Figure 90). This occurs when the specified number of harmonics is low and/or when the display grid is elongated (i.e., Single grid mode).

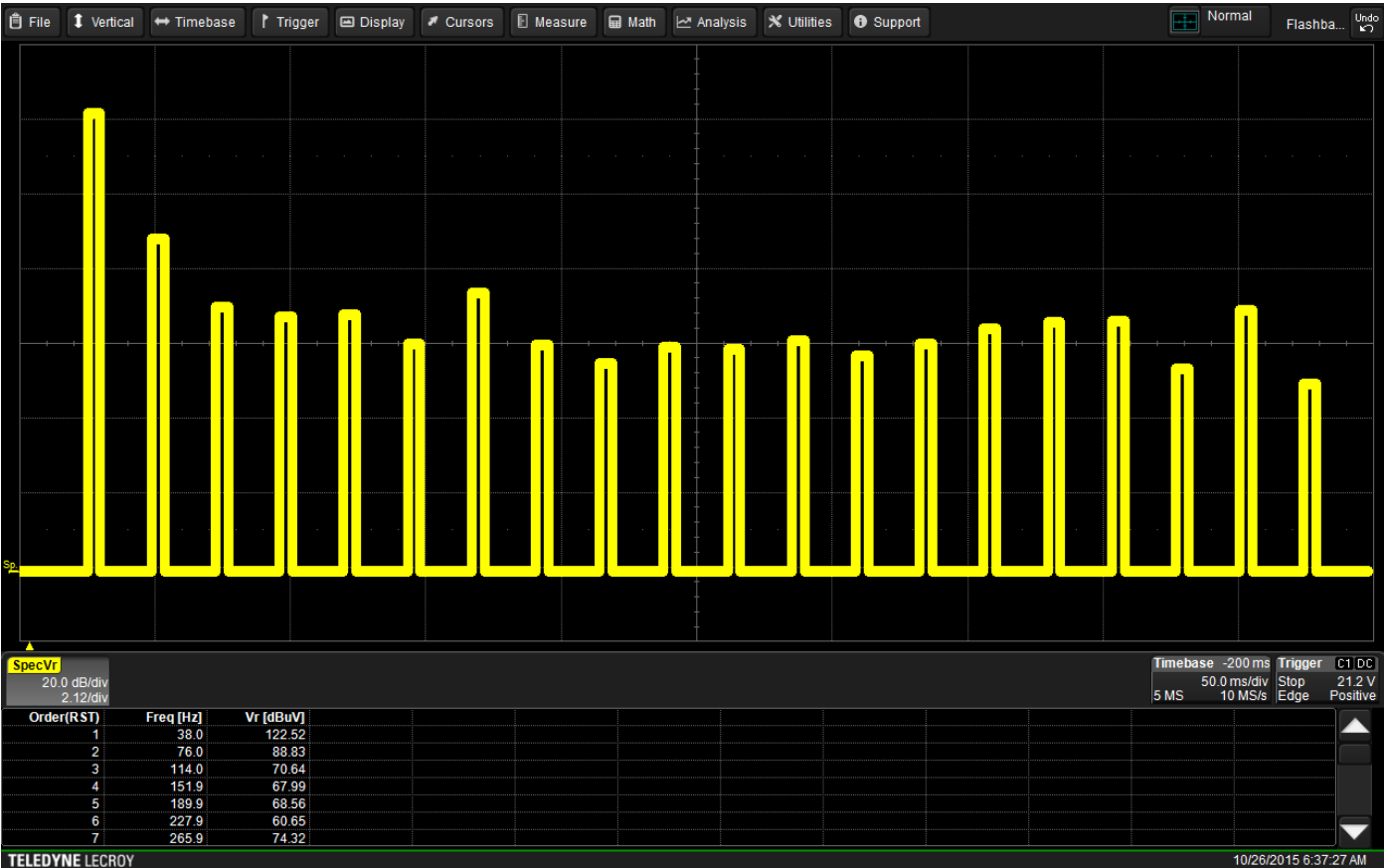


Figure 90: Spectral Waveforms with gap appearance in bars.

The Units/Limits selection also influences the Spectral waveform display. When using A, W, V or dB, the Spectral waveforms display all harmonic orders out to the specified number of harmonics (N), including the fundamental. When using %, Spectral waveforms do not display the fundamental, but do display orders 2 through N. This is because the percent selection treats the fundamental as the total value to which all the other harmonic orders are compared to compute their values as percentages. Removing the fundamental from the Spectral waveform allows the other harmonic orders to expand vertically, resulting in a more readable display.

Measurement Best Practices

A variety of measurement “best practices” should be followed when making three-phase voltage, current and power measurements that require the highest accuracies. If these practices are not followed, measurement accuracy will be reduced. We have provided enough background description of each “best practice” that the best decision can be made about whether it is necessary to follow or not, based on the degree of measurement accuracy desired.

Highest Importance for Achieving Best Accuracy

- Allow for recommended warm-up times (p.71)
- Auto Zero differential probes (p.71)
- Degauss current probes (p.72)
- Deskew non-Teledyne LeCroy current or voltage measurement devices (p.73)
- Choose the correct Sync signal for measurements (p.74)

Medium Importance for Achieving Best Accuracy

- Avoid use of non-zero offset values (p.74)
- Maximize use of vertical grid (p.74)

Lowest Importance for Achieving Best Accuracy

- Compensate passive probes (p.75)
- Apply filters to lower noise (p.75)
- Deskew Teledyne LeCroy voltage and current probes (p.76)

In addition to the instructions below, see the *MDA/HDO8000 Operator's Manual* or the pertinent probe manual for more information about performing each practice.

Allow for Recommended Warm-up Times

To ensure accurate measurements, allow active probes to warm-up the recommended amount of time before autozeroing, degaussing or performing critical measurements. 20 minutes is the recommended warm-up time for most Teledyne LeCroy instruments and probes.

Auto Zero Differential Probes

Auto Zero removes DC offset from the probe measurement. Perform an Auto Zero on a differential voltage or current probe after initial warm-up, at the beginning of critical measurements, or when the ambient temperature has changed by more than 5°C.

Probes that require Auto Zero have an Auto Zero button on the probe dialog that appears next to the input channel dialog when the probe is connected. Invoke Auto Zero by pressing the button.



Figure 91: Auto Zero button on Probe dialog.

NOTE: To ensure an accurate Auto Zero on a differential probe, follow the instructions in the probe user manual. Some voltage probes (e.g., HVD310x models) must be disconnected from the device under test (DUT) before Auto Zero is performed.

Failure to Auto Zero a probe will likely result in a DC bias applied to the voltage measurements, leading to inaccurate results. This step should not be skipped when taking a critical measurement, particularly a power measurement.

Degauss Current Probes

Teledyne LeCroy current probes use a combination of Hall effect and ferrite-core transformer technology to measure AC, DC, and impulse currents. To ensure the most accurate measurements, the current probes must be periodically demagnetized to remove any residual magnetic field from the transformer core caused by excessive input currents (e.g., peak current that exceeds the probe rating or sensitivity setting) or strong external magnetic fields. This process is referred to as “Degaussing.” The Degauss process takes about 5 seconds and should always be performed during initial setup (after probe warm-up), when peak currents exceed the probe rating for a given sensitivity setting, or (recommended) at the beginning of a day. This step should not be skipped when taking a critical measurement, particularly a power measurement.

To degauss a current probe:

3. Remove the probe from the conductor.
4. Slide the opening lever to close and lock the probe.
5. Press the Degauss button on the probe dialog.

An Auto Zero is automatically performed as part of the degauss cycle and does not need to be performed again.

NOTE: Use care when attaching current probes around an insulated wire. Ensure that the current probe slider does not rub on the insulated wire as it is closed. If it requires force to move the slider over the insulated wire, the accuracy of the measurement will likely be reduced.

Deskew non-Teledyne LeCroy Current or Voltage Measurement Devices

A variety of measurement devices (current transformers, Rogowski coils, potential transformers, torque load cells, long BNC cables, etc.) may be integrated to the MDA. Cables, probes and other measurement devices introduce a propagation delay from the measurement point back to the input channel of the MDA. In general, Teledyne LeCroy voltage and current probes introduce propagation delays in the range of 1 to 15 ns. Other measurement devices may introduce more (or less) propagation delay. RG58 coaxial cable has a propagation delay of ~3 to 5ns/m (depending on construction). For precision timing measurements or best accuracy when two signals are used in a math operation (e.g., a multiplication to achieve a power value), correction for the propagation delays *may* be necessary *depending* on the signal speed(s) and necessary precision required.

“Deskew” is the process by which various propagation delays are corrected for at the input plane of the MDA. To perform a deskew:

1. Measure voltage and current signals coincidentally using the same signal source.
2. Enter the deskew adjustment (plus or minus) on the input channel dialog.

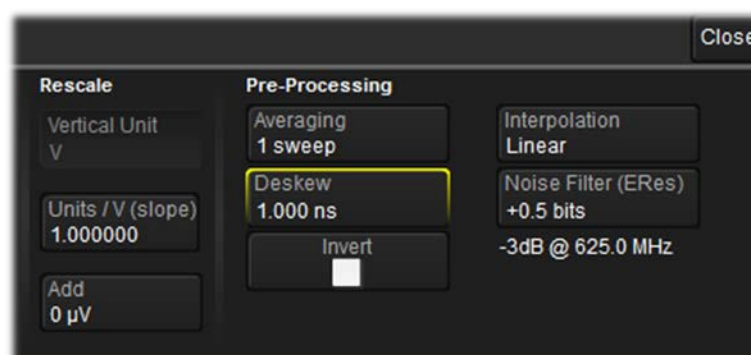


Figure 92: Deskew entry field on channel setup (Cx) dialog.

Teledyne LeCroy’s DCS015 Deskew Calibration Source connects to the AUX IN connector of the MDA and produces a set of signals that allow voltage and current probe deskew (within limitations of the current loop size). You could also use a similar device of your own construction.

The propagation delays of non-Teledyne LeCroy measurement devices should be understood so that a sensible decision can be made as to whether the propagation delays should be adjusted for (deskewed). AC input (line frequency) or drive output PWM periods typically have frequencies in the range of 1 to 300 Hz, and the propagation delay errors between different voltage and current measurement devices may be so small compared to the speed of the signal being measured that rigorous deskew of input signals is unlikely to result in improved power measurement accuracy. For instance, a 10ns error between a voltage and a current signal that is contained within a 10ms (100 Hz) period would result in a miniscule measurement error – the propagation delay is 0.0001% of the measurement period. Therefore, most users do not bother to deskew probes for power measurements unless the propagation delays are much larger than what is described above.

Choose the Correct Sync Signal for Measurements

Sync signal selection is critical to the correct operation of the Motor Drive Power Analyzer software, as it determines the interval at which measurements are performed. Any measured signal that corresponds to one repetitive time period can be used as the Sync (Synchronization) signal. A signal that varies around a zero crossing (e.g., line-line probed voltage signals, or line-neutral current signals) and that experiences little change in amplitude during the complete acquisition is the best choice to Sync with. In general, this would be the signal that most closely represents a sine wave, although it is not absolutely necessary to use a sine wave.

See Sync Signal (p.18) for details and recommendations on choosing the best source.

In the case of highly distorted waveforms (e.g., six-step commutated voltage or current waveforms), you will likely find that some adjustment of the Low Pass Filter (LPF) cutoff and Hysteresis (zero-crossing filter) settings is necessary. You can view the low-pass-filtered Sync signal, and in doing so, gain a better understanding of whether the software has a good periodic signal to determine zero-crossing times.

Signals with very high harmonic content (e.g., six-step commutated voltage signals) will have significant attenuation when the low pass filter is applied and may therefore be less suitable as a Sync signal. Signals that experience wide dynamic ranges, such as load current signals in acquisitions under highly dynamic loading conditions, may also be unsuitable. Thus, the choice of the Sync signal requires some thought prior to beginning motor drive set up, and perhaps a visual inspection of the filtered Sync signal, to achieve accurate power measurement results.

If in doubt as to the suitability of the chosen Sync signal, or the correctness of the settings to determine the correct zero-crossings (and therefore measurement intervals), turn on the Sync signal trace and use the Zoom+Gate controls to visually determine whether correct period determination is being made.

Avoid Non-Zero Offset Values

If possible, avoid adding channel offset when taking critical voltage, current or power measurements. By adding offset to the channel, offset error is introduced. When probing voltage signals line-reference, use of offset likely cannot be avoided. However, when probing voltage signals line-line, the peak positive voltage will be equal to the peak negative voltage, and offset can be set to zero while still maximizing the signal on the vertical grid. Best practice is to ensure that offset is set to zero, in this case, before making critical measurements.

Maximize Use of Vertical Grid

Each display grid is divided into 8 vertical divisions and 10 horizontal divisions. The 12-bit ADC resolution (4096 discrete levels) is divided equally amongst the 8 vertical divisions, with the front-end gain range (eight times the V/div setting) determining the peak-to-peak voltage represented by full scale (8 vertical divisions).

You will obtain the best accuracy for any voltage, current or power measurement by maximizing the size of the signal on the vertical grid, therefore utilizing the maximum amount of ADC counts to resolve the displayed signal. This is different than with many power analyzers that reserve a portion of the vertical grid for overshoot (based on a user-defined or factory-default crest factor assumption). Be sure to reserve an appropriate amount of the vertical grid for expected signal overshoots or dynamic range.

NOTE: Pre-processing bandwidth filters (such as ERes) are applied by the software after the hardware acquisition but before the signal is displayed. Therefore, it is recommended to first observe signals on the display grid without ERes applied so as to set the appropriate V/div (gain) for each channel. Then, apply ERes as necessary to filter the bandwidth further.

Utilize multi-grid or Q-Scope displays—or both—to view many signals when they are maximized on the vertical axis, and connect to a high-resolution external monitor to enlarge the display view. To view signal details, create a zoom of the original trace and expand the zoom trace vertically instead of changing the channel V/div.

Compensate Passive Probes

The passive probes supplied with the MDA are matched to the input impedance of the instrument but will need capacitive compensation (“trimming”) to accurately match the probe input impedance and achieve the best frequency response and step response signal fidelity. Perform a low-frequency calibration using the Cal signal available from the MDA’s front panel. Follow the directions in the probe instruction manual to compensate the frequency response of the probes.

NOTE: The top row of analog inputs (channels 1 through 4) may have small differences in input impedance (~1 pF input capacitance difference) from the bottom row of analog inputs (channels 5 through 8). For best accuracy, perform a new low-frequency calibration if the probe is moved from a top-row to a bottom-row channel.

Apply Filters to Lower Noise

You may filter analog acquisitions to reduce bandwidth (and noise) by applying an Enhanced Resolution (ERes) factor on the input channel dialog. Each channel may be filtered independent of every other channel. This may be helpful to reduce the effects of noise in the acquisition, especially given that drive input AC line frequency and drive output PWM switching frequency bandwidth tends to be much lower than the total system bandwidth.

The ERes filtered (resultant) bandwidth is displayed on the input channel dialog and is dependent on the sampling rate. If the sampling rate is changed, the filter bandwidth will change as well, for a given ERes setting.

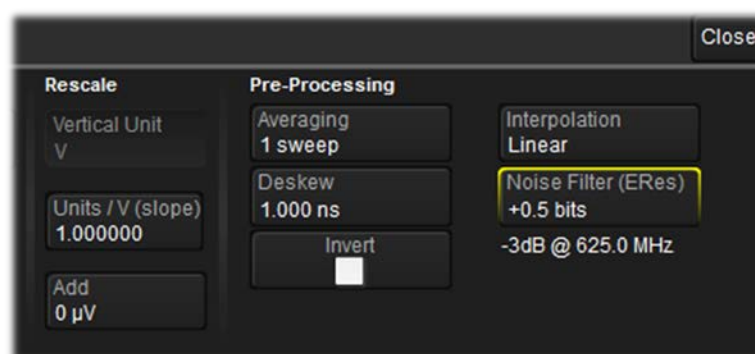


Figure 93: ERes noise filter field on channel setup (Cx) dialog.

NOTE: The ERes filter is a “software” filter applied post-acquisition to the hardware acquisition data. If the signal is suspected to have high levels of overshoot or other noise that peaks well above the top and base of the signal, then it is advisable to first acquire signals without filtering applied, ensure that no overrange conditions are occurring, and only then apply filtering to reduce the noise.

Realistically, the highest frequency signal components are not the primary contributors to power measurement accuracy for AC line, DC Bus, or PWM drive output signals. Filtering will eliminate noise from the signal, but likely not change the measurement result appreciably unless the noise levels are very high to begin with. Using the Harmonic Filter in the AC Input and Drive Output setup dialogs is more useful method to restrict the calculated Numerics to a specific set of lower frequency ranges.

Deskew Teledyne LeCroy Probes

As described in the earlier Deskew section, cables, probes and other measurement devices introduce a propagation delay from the measurement point back to the input channel of the MDA. In general, Teledyne LeCroy voltage and current probes introduce propagation delays in the range of 1 to 15 ns, and these propagation delays may essentially be ignored for purposes of measuring AC line input or PWM drive output signals and calculating power values. Furthermore, there is no meaningful inherent propagation delay between MDA input channels (either analog or digital), as this is accounted for in the MDA signal path design. You do not have to adjust for propagation delay between channels.

Deskew of Teledyne LeCroy probes would be necessary for higher speed signals, such as a high frequency drain-source voltage and drain current measurements in a MOSFET, where proper time alignment of the signals is necessary in order to achieve the highest possible accuracy for very short duration switching and conduction loss measurements.

Appendix: Power Measurement Detail

Each portion of the drive has one or more wiring configurations defined. The wiring configuration defines the user connection and setup of voltage and current probes, and the calculation methodology for the per-cycle measurement and Numeric table values.

Three Wattmeter Measurements

Three-phase, four-wire (3V3A) wiring configuration calculations are made using a three wattmeter method. In this case, line-neutral or line-reference voltages and line currents for each phase are available, and power (P , S , Q , λ , and ϕ) measurements on all three phases can be directly made with the associated voltage and current waveforms using a wattmeter for each phase.

For highly distorted waveforms, such as pulse-width modulated inverter or drive output voltage waveforms, the common-mode line-reference output voltage will be significantly greater than zero. In this case, small DC offsets in the current measurement can have large impacts in the real power (P) measurements when the Full Spectrum is used for measurements. In this case, invoking the Harmonic Filter might be justified. Furthermore, small DC offsets will cause a high calculated value of apparent power (S), which will result in high reactive power (Q) phase angle (ϕ) calculations, and subsequently a low power factor (λ) calculation. If these values are important to know with accuracy, it is recommended to use the Harmonic Filter settings to *not* include DC in the calculation.

Three-phase, three-wire (3V3A) or three-wire (2V2A) wiring configuration power calculations are also made using a three wattmeter method if a Line-Line to Line-Neutral conversion is performed in a three-phase, three-wire (3V3A or 2V2A) wiring configuration. This conversion assumes a balanced three-phase system for voltage and current to solve for one of the three-phase line currents (I_C or I_T) using the assumption that the sum of all three-phase line currents is zero, and using the assumption that the sum of all three-phase line-line voltages is zero. If the system is not balanced (e.g. due to leakage currents to ground), then the assumption is incorrect and results will differ from that of a three wattmeter method.

Two Wattmeter Measurements

Three-phase, three-wire (2V2A) wiring configuration calculations are made using a two wattmeter method. In this case, line-line voltages are available along with line currents; however, the line-line voltages do not associate directly with a line current, so while two power values are provided, the two power levels will not be balanced. They will, however, add up to the correct three-phase power.

The two wattmeter method assumes a balanced three-phase system. In this case, the I_C or I_T current in the three-phase system is ignored.

Single-phase, three-wire (2V2A) wiring configuration power calculations are also made using a two wattmeter measurement. By definition, these voltages are measured line-neutral, so there are two pairs of directly associated line voltages and currents. These two power values will add to the total single-phase power.

One Wattmeter Measurements

Single-phase, two-wire (1V1A) wiring configuration power calculations are made using a one wattmeter measurement. By definition, the voltage is line-neutral, and there is only one pair of directly associated line voltage and currents.

Zoom+Gate

When in Zoom+Gate mode, all calculations are based on the time periods defined by the Zoom+Gate Zx waveforms.

Harmonic Filtering

Unless otherwise specified, if a Harmonic Filter is applied to the AC Input or Drive Output waveforms, the methodology is the same as without the filter except that calculations are made on the voltage, current, and power waveforms computed from the sum of the harmonic components.

NOTE: The Harmonic Filter selection is not applied to calculations performed for the Harmonics Order table that is part of the Harmonics Calculation option.

Numerics Table Parameter Calculations (Full Spectrum or Fundamental)

All data acquired by the Motor Drive Analyzer is digitally sampled. These digitally sampled waveforms are analyzed over a given cycle time (period) that is based on the filtered Sync signal.

The formulas presented for the calculations are based on the following definitions:

- j = digital sample index
- i = cycle (period) index
- M = number of sample points in a cycle (period) defined by the filtered Sync signal
- M_i = number of sample points in cycle number i
- m = starting sample point index
- m_i = starting sample point index of cycle number i
- N = number of cycles, as defined by the selected Sync source signal

For a given cycle index i , the digitally sample voltage waveform is represented as having a set of sample points j in cycle index i . For a given cycle index i , there are M_i sample points beginning at m_i and continuing through $m_i + M_i - 1$. Voltage, current, power, etc. values are calculated on each cycle index i from 1 to N cycles.

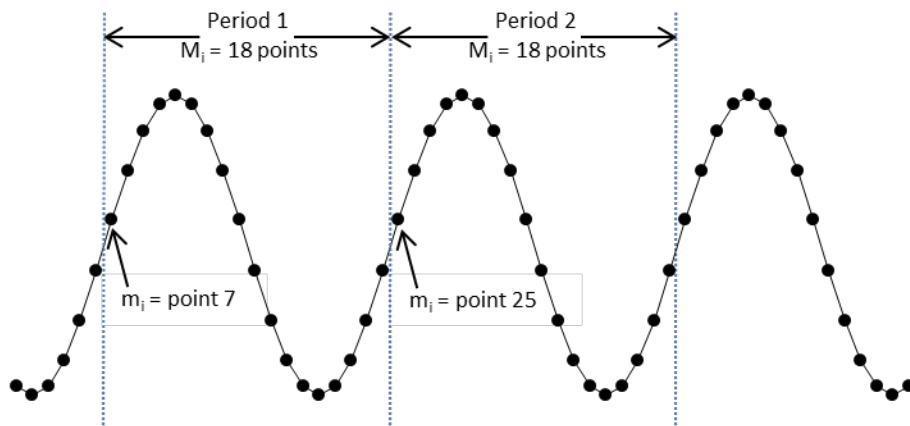


Figure 94: Measurement points used for waveform calculations

The waveform shown in Figure 94 has two cyclic periods. The first cyclic period (index $i=1$) starts at sample index $j = m_i = 7$ and has $M_i = 18$ points, and calculations are made on sample points $j = m_i$ to $m_i + M_i - 1$ (points 7 to 7+18-1, or 7 to 24). The second cyclic period (index $i=2$) starts at sample point $m_i = 25$, has $M_i = 18$ points and calculations are made on sample points 25 to 25+18-1, or 25 to 42.

The following conventions are used throughout in the formulas:

- Uppercase letters are used to represent lines of the three-phase systems:
 - o A, B, R, etc. is the A-phase, B-phase, R-phase
 - o AB, BC, TR is the A-B phase-phase voltage, B-C phase-phase voltage, and T-R phase-phase voltage
- Lowercase letters are used to represent a descriptive element of voltage, current or power:
 - o V_{rms} is the RMS voltage
 - o I_{pk-pk} is the peak-peak current
 - o I_{ac} is the ac value of the current
- For simplicity, formulas that may be calculated for multiple phases or lines are not shown to include the phase or line information in the formula. For example, $V_{ac_i} = V_{rms_i} - V_{dc_i}$ does not include reference to the A, B, T, etc. phase in the formula, it is assumed to apply to all.

The various per-cycle values are aggregated in the Numeric table, presented as statistical data in the Statistics table, or displayed as a per-cycle Waveform.

- Numeric table values are shown in a Numeric table cell and represent the intersection of a measurement and a source. The Numeric table value $V_{rms}(A)$ is the RMS voltage of the A phase voltage. Refer to the example below.
- Statistical table values are shown as a measurement made on a source, with statistical data (mean, min, max, standard deviation, etc.) shown. It is easy to see from the provided formulas that the mean or worst-case statistical value correlates to a Numeric table value.
- Per-cycle Waveforms show the variation of the calculated per-cycle values over time plotted as a waveform that is time-correlated to the original acquisition or Zooms (if Zoom+Gate is ON).

The following formula is for the per-cycle RMS voltage of a single measured phase voltage (measured either line-neutral, line-reference, or line-line):

$$V_{rms_i} = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$$

This indicates that the RMS voltage for a given cycle (cycle i) is calculated from the root-sum-of-squares of the digitally sample voltage waveform V_j over the sampled point range that defines the beginning and end of the cycle (period). If there is more than one cycle in the acquisition, then there will be multiple calculated values (V_{rms_1} , V_{rms_2} , V_{rms_3} , etc.). This formula does not indicate whether the calculation is done for A, B, C, R, S or T line-neutral or line-reference or AB, BC, CA, RS, ST, TR line-line phases or DC bus – it applies to all of them.

The following formula is for the Numeric table value for RMS voltage of a single measured phase voltage (measured either line-neutral, line-reference, or line-line):

$$V_{rms} = \frac{1}{N} \sum_{i=1}^N V_{rms_i}$$

This indicates that the RMS voltage reported in the Numeric table is the mean value of the N cycles calculated using the first (per-cycle) formula.

Harmonics Order Table Calculations

The Harmonics Order calculation formulas presented here are based on the same definitions as used in the Numerics table, with the following additions:

- h = harmonic order index
- H = number of harmonics
- S = number of sample points in an acquisition

Variable Frequency Mode

The following formula is for the per-order per-cycle RMS voltage of a single harmonic from a single phase (measured line-neutral or line-reference in Variable Frequency mode):

$$V_{rms_{hi}} = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_{hj}^2}$$

This indicates that the RMS voltage for a given harmonic order is calculated from the root-sum-of-squares of the digitally sample voltage waveform V_j over the sampled point range that defines the beginning and end of the cycle (period). This formula does not indicate whether the calculation is done for A, B, C, R, S or T line-neutral or line-reference – it applies to all of them. This value is calculated per-cycle for each harmonic order, but not displayed in the Harmonic Order table.

The following formula is for the Harmonics Order table value for harmonic RMS voltage of a single measured phase voltage (measured either line-neutral or line-reference):

$$V_{rms_h} = \frac{1}{N} \sum_{i=1}^N V_{rms_{hi}}$$

This indicates that the RMS voltage reported in the Harmonic table is the mean value of the N cycles calculated using the first (per-cycle) formula.

Fixed Frequency Mode

The following formula is for the RMS voltage of a single harmonic from a single phase measured over a full acquisition (measured line-neutral or line-reference in Fixed Frequency mode):

$$V_{rms_h} = \sqrt{\frac{1}{S} \sum_{j=1}^S V_{hj}^2}$$

This indicates that the RMS voltage for a given harmonic order is calculated from the root-sum-of-squares of the digitally sample voltage waveform V_j over the sampled point range that defines the beginning and end of the full acquisition. This formula does not indicate whether the calculation is done for A, B, C, R, S or T line-neutral or line-reference – it applies to all of them. This value displayed directly in the Harmonics Order table.

Speed, Direction, and Angle Calculations

Speed, direction and absolute position (angle) can be sensed using a variety of different analog or digital devices. Torque can be sensed with a variety of analog torque sensors. The calculation methodology for each type of sensor is summarized in the tables below.

Analog Tachometer

A simple analog voltage value that scales linearly to the speed can be acquired, and speed can be sensed from this signal.

- ω_H is the high speed setting in the Mechanical setup dialog.
- ω_L is the low speed setting in the Mechanical setup dialog.
- V_H is the high voltage setting in the Mechanical setup dialog.
- V_L is the low voltage setting in the Mechanical setup dialog.
- G is the gear ratio.

	Speed
Mechanical	$\omega_j = \left(\frac{\omega_H - \omega_L}{V_H - V_L} * V_j + \frac{\omega_L * V_H - \omega_H * V_L}{V_H - V_L} \right) / G$ <i>(ω_j is calculated internally and is not displayed)</i> $Speed_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \omega_j$ <i>Direction (the sign of the calculated Speed_i values) is positive for positive voltage with clockwise selection in the Mechanical setup dialog. This convention can be reversed in the Mechanical setup dialog.</i> $Speed = \frac{1}{N} \sum_{i=1}^N Speed_i$

Digital (Pulse) Tachometer

A tachometer that generates a given number of voltage pulses per revolution voltage can be acquired and speed can be sensed from this signal.

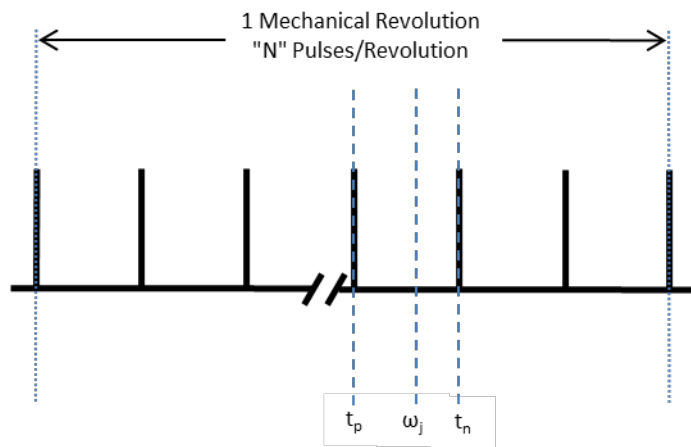


Figure 95: Digital (Pulse) Tachometer calculation points.

The elements in Figure 95 and the formulas below are defined as:

- ω_j is the instantaneous speed calculation at a given time.
- t_p is the previous measured pulse time.
- t_n is the next measured pulse time.
- PPR is the pulses per rotation.
- G is the gear ratio.

	Speed
Mechanical	$\omega_j = \left(\frac{PPR}{t_n - t_p} \right) / G$ (ω_j is calculated internally and is not displayed) $Speed_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \omega_j$ Direction calculation (the sign of the calculated Speed_i values) is positive with clockwise positive rotation convention in Mechanical setup dialog. This convention can be reversed in the Mechanical setup dialog. $Speed = \frac{1}{N} \sum_{i=1}^N Speed_i$

Hall Effect Sensors

Hall effect sensors embedded in the brushless DC motor rotor are often used to provide commutation control for the applied voltage. These sensor signals can also be acquired and speed and direction can be sensed from these signals.

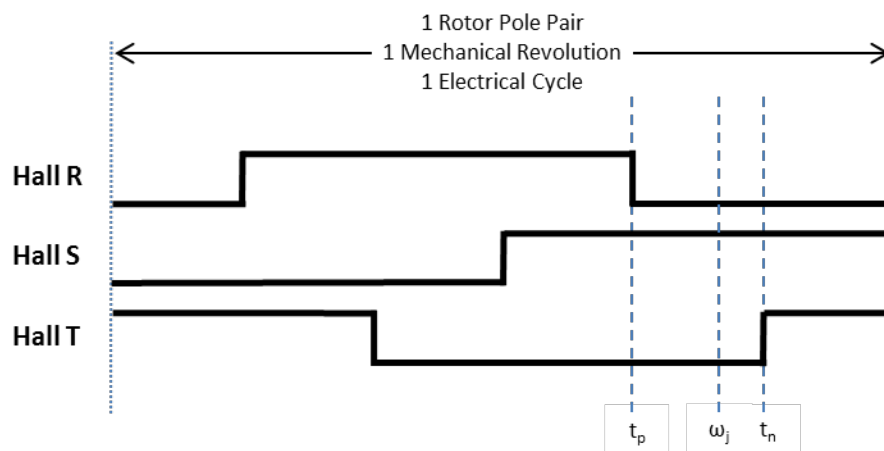


Figure 96: Hall effect sensor calculation points.

The elements in Figure 96 and the formulas below are defined as:

- ω_j is the instantaneous speed calculation over a given Hall sensor state.
- t_p is the previous Hall sensor transition.
- t_n is the next Hall sensor transition.
- RPP is the number of motor rotor pole pairs.
- G is the gear ratio.

	Speed
Mechanical	$\omega_j = \left(\frac{60^\circ / RPP}{t_n - t_p} \right) / G \quad \text{or} \quad \omega_j = \left(\frac{2\pi / 6 / RPP}{t_n - t_p} \right) / G$ (ω_j is calculated internally and is not displayed) $Speed_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \omega_j$ Direction (the sign of the calculated Speed_i values) is positive with clockwise positive rotation convention in Mechanical setup dialog for Hall sensor rising edge signal R leading S and S leading T. This convention can be reversed in the Mechanical setup dialog. $Speed = \frac{1}{N} \sum_{i=1}^N Speed_i$

Quadrature Encoder Interface

Quadrature encoder interfaces (QEI) are commonly used to provide Speed, Direction and absolute Position information. The three QEI sensor signals can be acquired and speed, direction and position can be sensed from these signals.

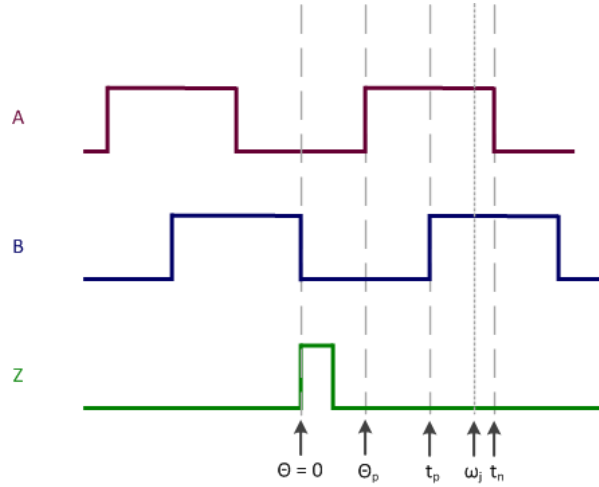


Figure 97: Quadrature Encoder Interface calculation points.

The elements in Figure 97 and the formulas below are defined as:

- θ is the rising edge location of the index pulse that defines the beginning of the QEI AB sequence, and defines the angle value as 0.
- θ_p is the previous calculated angle value.
- t_p is the previous A or B positive or negative transition.
- ω_j is the instantaneous speed calculation.
- t_n is the next A or B positive or negative transition.
- PPR is the number of pulses per rotation.
- G is the gear ratio.

	Speed	Angle & Position
Mechanical	$\omega_j = \left(\frac{360^\circ / (4 * PPR)}{t_n - t_p} \right) / G \quad \text{or} \quad \omega_j = \left(\frac{2\pi / (4 * PPR)}{t_n - t_p} \right) / G$ <i>(ω_j is calculated internally and is not displayed)</i> $Speed_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \omega_j$ <i>Direction calculation (the sign of the calculated Speed_i values) is positive with clockwise positive rotation convention in Mechanical setup dialog for A rising edge leading B rising edge after the index pulse. This convention can be reversed in the Mechanical setup dialog.</i> $Speed = \frac{1}{N} \sum_{i=1}^N Speed_i$	$\theta_j = \left(\frac{360^\circ}{4 * PPR} \right) / G + \theta_p \quad \text{or} \quad \theta_j = \left(\frac{2\pi}{4 * PPR} \right) / G + \theta_p$ <i>(θ_j is calculated internally and is not displayed)</i> $Angle_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \theta_j$ <i>Angle value resets to zero after one full shaft rotation.</i> $Angle = \frac{1}{N} \sum_{i=1}^N Angle_i$

Resolver

Resolvers are commonly used to provide Speed, Direction and absolute Position information for more complex control systems in environments where high reliability is required. The three resolver signals can be acquired and speed, direction and position can be sensed from these signals.

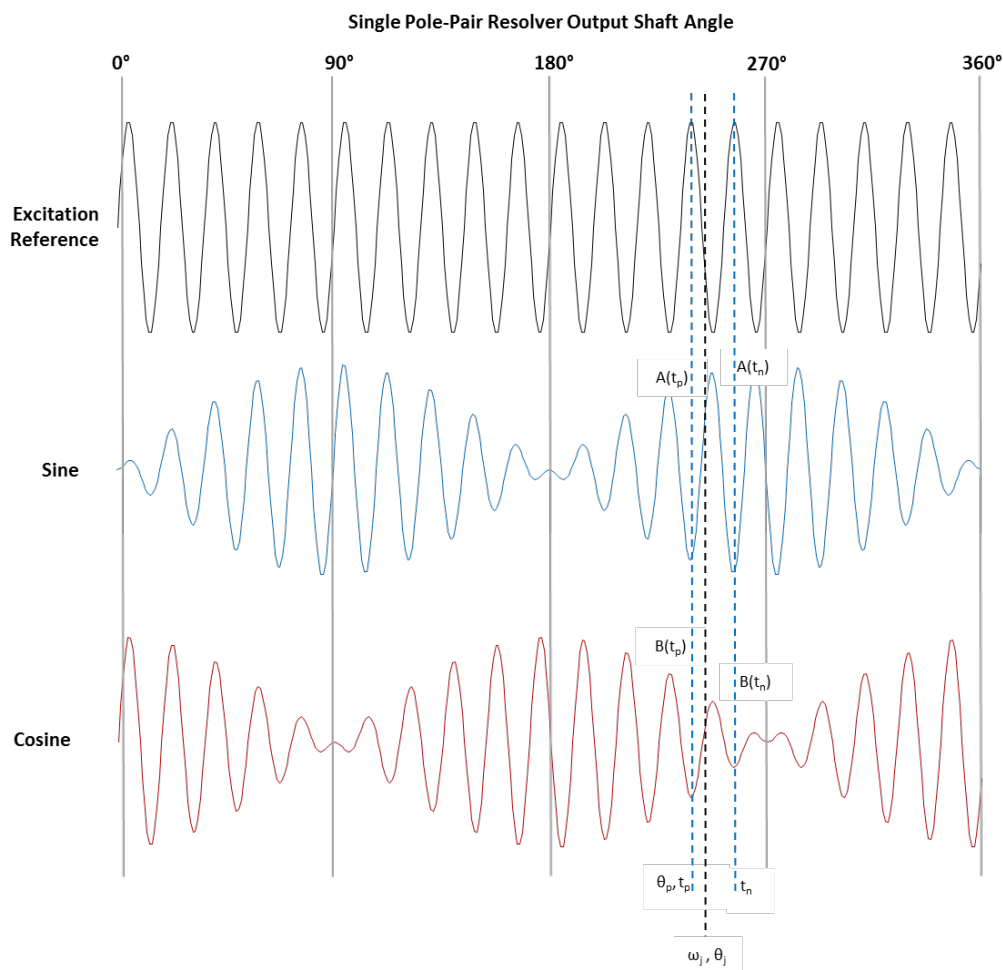


Figure 98: Resolver calculation points.

The elements in Figure 98 and the formulas below are defined as:

- A is the measured amplitude value of the waveform defined by the sine signal.
- B is the measured amplitude value of the waveform defined by the cosine signal.
- θ_p is the previous calculated angle value.
- θ_j is the instantaneous angle calculation.
- t_p is the previous peak of excitation.
- ω_j is the instantaneous speed calculation.
- t_n is the next peak of excitation.
- RPP is the number of resolver pole pairs.
- G is the gear ratio.

	Speed	Angle & Position
Mechanical	$\omega_j = \left(\frac{\theta_j(t) - \theta_p(t)}{t_n - t_p} \right) / G$ <i>(ω_j is calculated internally and is not displayed)</i> $Speed_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \omega_j$ <i>Direction calculation (the sign of the calculated Speed_i values) is positive with clockwise positive rotation convention in Mechanical setup dialog if the difference between two angle values θ_{n+1} and θ_n is positive. This convention can be reversed in the Mechanical setup dialog.</i> $Speed = \frac{1}{N} \sum_{i=1}^N Speed_i$	$\left(\theta_j = \tan^{-1} \frac{A(t_n)}{B(t_n)} \right) / (RPP * G)$ <i>(θ_j is calculated internally and is not displayed)</i> $Angle_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \theta_j$ <i>$\tan^{-1}$ is always within 360° or 2π, so angle value inherently stays within this bounded range.</i> $Angle = \frac{1}{N} \sum_{i=1}^N Angle_i$

Torque Calculations

Torque can be sensed using analog voltage signals proportional to torque. The calculation methodology is summarized in the table below:

Analog 0-Vdc Method

- T_H is the high torque setting in the Mechanical setup dialog.
- T_L is the low torque setting in the Mechanical setup dialog.
- V_H is the high voltage setting in the Mechanical setup dialog.
- V_L is the low voltage setting in the Mechanical setup dialog.

	Torque
Mechanical	$T_j = \left(\frac{T_H - T_L}{V_H - V_L} * V_j + \frac{T_L * V_H - T_H * V_L}{V_H - V_L} \right) / G$ <i>(Tj is calculated internally and is not displayed)</i> $Torque_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} T_j$ $Torque = \frac{1}{N} \sum_{i=1}^N Torque_i$

Analog mV/V Method

- T_H is the high torque setting in the Mechanical setup dialog.
- T_L is the low torque setting in the Mechanical setup dialog.
- V_{mVpV} is the mV/V setting in the Mechanical setup dialog.
- V_S is the supply voltage in the Mechanical setup dialog.

	Torque
Mechanical	$T_j = \frac{(T_H - T_L)/2}{V_S * V_{mVpV} * 0.001} * V_j$ <i>(Tj is calculated internally and is not displayed)</i> $Torque_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} T_j$ $Torque = \frac{1}{N} \sum_{i=1}^N Torque_i$

3-phase/4-wire (3 voltage and 3 current) Calculations

In this case, a Neutral is present, voltage is probed Line-Neutral and Line currents are sensed. The calculation methodology for Voltage, Current, and Power is summarized in the tables below. The line-neutral voltage values and line current values are shown as A, B, C, R, S, and T.

	VRMS (Line-Neutral)	IRMS (Line-Neutral)
A, B, C, R, S, T	$Vrms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$ $Vrms = \frac{1}{N} \sum_{i=1}^N Vrms_i$	$Irms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j^2}$ $Irms = \frac{1}{N} \sum_{i=1}^N Irms_i$
ΣABC	$Vrms_{\Sigma ABC_i} = \frac{1}{3}(Vrms_{Ai} + Vrms_{Bi} + Vrms_{Ci})$ $Vrms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma ABC_i}$	$Irms_{\Sigma ABC_i} = \frac{1}{3}(Irms_{Ai} + Irms_{Bi} + Irms_{Ci})$ $Irms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma ABC_i}$
ΣRST	$Vrms_{\Sigma RST_i} = \frac{1}{3}(Vrms_{Ri} + Vrms_{Si} + Vrms_{Ti})$ $Vrms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma RST_i}$	$Irms_{\Sigma RST_i} = \frac{1}{3}(Irms_{Ri} + Irms_{Si} + Irms_{Ti})$ $Irms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma RST_i}$

	VDC (Line-Neutral)	IDC (Line-Neutral)
A, B, C, R, S, T	$Vdc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j$ $Vdc = \frac{1}{N} \sum_{i=1}^N Vdc_i$	$Idc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j$ $Idc = \frac{1}{N} \sum_{i=1}^N Idc_i$
ΣABC	$Vdc_{\Sigma ABC_i} = \frac{1}{3}(Vdc_{Ai} + Vdc_{Bi} + Vdc_{Ci})$ $Vdc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma ABC_i}$	$Idc_{\Sigma ABC_i} = \frac{1}{3}(Idc_{Ai} + Idc_{Bi} + Idc_{Ci})$ $Idc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma ABC_i}$
ΣRST	$Vdc_{\Sigma RST_i} = \frac{1}{3}(Vdc_{Ri} + Vdc_{Si} + Vdc_{Ti})$ $Vdc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma RST_i}$	$Idc_{\Sigma RST_i} = \frac{1}{3}(Idc_{Ri} + Idc_{Si} + Idc_{Ti})$ $Idc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma RST_i}$

	VAC (Line-Neutral)	IAC (Line-Neutral)
A, B, C, R, S, T	$Vac_i = V_{rms_i} - V_{dc_i}$ $Vac = \frac{1}{N} \sum_{i=1}^N Vac_i$	$Iac_i = I_{rms_i} - I_{dc_i}$ $Iac = \frac{1}{N} \sum_{i=1}^N Iac_i$
ΣABC	$Vac_{\Sigma ABC_i} = \frac{1}{3}(Vac_{Ai} + Vac_{Bi} + Vac_{Ci})$ $Vac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma ABC_i}$	$Iac_{\Sigma ABC_i} = \frac{1}{3}(Iac_{Ai} + Iac_{Bi} + Iac_{Ci})$ $Iac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma ABC_i}$
ΣRST	$Vac_{\Sigma RST_i} = \frac{1}{3}(Vac_{Ri} + Vac_{Si} + Vac_{Ti})$ $Vac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma RST_i}$	$Iac_{\Sigma RST_i} = \frac{1}{3}(Iac_{Ri} + Iac_{Si} + Iac_{Ti})$ $Iac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma RST_i}$

	$V_{PK}^+, V_{PK}^-, V_{PK-PK}$ (Line-Neutral)	$I_{PK}^+, I_{PK}^-, I_{PK-PK}$ (Line-Neutral)
A, B, C, R, S, T	$Vpk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk-pk_i = Vpk^+_i - Vpk^-_i$ $Vpk^+ = \max_{i=1 \text{ to } N} Vpk^+_i$ $Vpk^- = \min_{i=1 \text{ to } N} Vpk^-_i$ $Vpk-pk = \max_{i=1 \text{ to } N} Vpk-pk_i$	$Ipk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk-pk_i = Ipk^+_i - Ipk^-_i$ $Ipk^+ = \max_{i=1 \text{ to } N} Ipk^+_i$ $Ipk^- = \min_{i=1 \text{ to } N} Ipk^-_i$ $Ipk-pk = \max_{i=1 \text{ to } N} Ipk-pk_i$
ΣABC	$Vpk^+_{\Sigma ABC_i} = \max(Vpk^+_{Ai}, Vpk^+_{Bi}, Vpk^+_{Ci})$ $Vpk^-_{\Sigma ABC_i} = \min(Vpk^-_{Ai}, Vpk^-_{Bi}, Vpk^-_{Ci})$ $Vpk-pk_{\Sigma ABC_i} = \max(Vpk-pk_{Ai}, Vpk-pk_{Bi}, Vpk-pk_{Ci})$ $Vpk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma ABC_i}$ $Vpk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma ABC_i}$ $Vpk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma ABC_i}$	$Ipk^+_{\Sigma ABC_i} = \max(Ipk^+_{Ai}, Ipk^+_{Bi}, Ipk^+_{Ci})$ $Ipk^-_{\Sigma ABC_i} = \min(Ipk^-_{Ai}, Ipk^-_{Bi}, Ipk^-_{Ci})$ $Ipk-pk_{\Sigma ABC_i} = \max(Ipk-pk_{Ai}, Ipk-pk_{Bi}, Ipk-pk_{Ci})$ $Ipk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma ABC_i}$ $Ipk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma ABC_i}$ $Ipk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma ABC_i}$
ΣRST	$Vpk^+_{\Sigma RST_i} = \max(Vpk^+_{Ri}, Vpk^+_{Si}, Vpk^+_{Ti})$ $Vpk^-_{\Sigma RST_i} = \min(Vpk^-_{Ri}, Vpk^-_{Si}, Vpk^-_{Ti})$ $Vpk-pk_{\Sigma RST_i} = \max(Vpk-pk_{Ri}, Vpk-pk_{Si}, Vpk-pk_{Ti})$ $Vpk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma RST_i}$ $Vpk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma RST_i}$ $Vpk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma RST_i}$	$Ipk^+_{\Sigma RST_i} = \max(Ipk^+_{Ri}, Ipk^+_{Si}, Ipk^+_{Ti})$ $Ipk^-_{\Sigma RST_i} = \min(Ipk^-_{Ri}, Ipk^-_{Si}, Ipk^-_{Ti})$ $Ipk-pk_{\Sigma RST_i} = \max(Ipk-pk_{Ri}, Ipk-pk_{Si}, Ipk-pk_{Ti})$ $Ipk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma RST_i}$ $Ipk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma RST_i}$ $Ipk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma RST_i}$

	V_{CF} (Line-Neutral)	I_{CF} (Line-Neutral)
A, B, C, R, S, T	$Vcf_i = \frac{[\max(Vpk^+_i , Vpk^-_i) - Vdc_i]}{Vac_i}$ $Vcf = \max_{i=1 \text{ to } N} Vcf_i$	$Icf_i = \frac{[\max(Ipk^+_i , Ipk^-_i) - Idc_i]}{Iac_i}$ $Icf = \max_{i=1 \text{ to } N} Icf_i$
ΣABC	No calculation is made for this measurement and source	No calculation is made for this measurement and source
ΣRST	No calculation is made for this measurement and source	No calculation is made for this measurement and source

	P	S	Q
A, B, C, R, S, T	$P_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j * I_j$ $P = \frac{1}{N} \sum_{i=1}^N P_i$	$S_i = Vrms_i * Irms_i$ $S = \frac{1}{N} \sum_{i=1}^N S_i$	magnitude $Q_i = \sqrt{S_i^2 - P_i^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q = \frac{1}{N} \sum_{i=1}^N Q_i$
ΣABC	$P_{\Sigma ABC_i} = P_{Ai} + P_{Bi} + P_{Ci}$ $P_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABC_i}$	$S_{\Sigma ABC_i} = S_{Ai} + S_{Bi} + S_{Ci}$ $S_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma ABC_i}$	$Q_{\Sigma ABC_i} = Q_{Ai} + Q_{Bi} + Q_{Ci}$ $Q_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma ABC_i}$
ΣRST	$P_{\Sigma RST_i} = P_{Ri} + P_{Si} + P_{Ti}$ $P_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma RST_i}$	$S_{\Sigma RST_i} = S_{Ri} + S_{Si} + S_{Ti}$ $S_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma RST_i}$	$Q_{\Sigma RST_i} = Q_{Ri} + Q_{Si} + Q_{Ti}$ $Q_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma RST_i}$
Mechanical	$P_{MECHANICAL_i} = T_i * \omega_i$ $P_{MECHANICAL} = \frac{1}{N} \sum_{i=1}^N P_{MECHANICAL_i}$		

	P_{PK+}, P_{PK-}	λ (Power Factor)	ϕ (Phase Angle)
A, B, C, R, S, T	$Ppk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $Ppk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $Ppk^+ = \max_{i=1 \text{ to } N} Ppk^+_i$ $Ppk^- = \min_{i=1 \text{ to } N} Ppk^-_i$	$\lambda_i = \frac{P_i}{S_i}$ $\lambda = \frac{1}{N} \sum_{i=1}^N \lambda_i$	magnitude $\phi_i = \cos^{-1} \lambda_i$ sign of ϕ_i is positive if the fundamental voltage vector leads the fundamental current vector $\phi = \frac{1}{N} \sum_{i=1}^N \phi_i$
ΣABC	$Ppk^+_{\Sigma ABC_i} = \max(V_{Aj} * I_{Aj} + V_{Bj} * I_{Bj} + V_{Cj} * I_{Cj})$ $Ppk^-_{\Sigma ABC_i} = \min(V_{Aj} * I_{Aj} + V_{Bj} * I_{Bj} + V_{Cj} * I_{Cj})$ $Ppk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma ABC_i}$ $Ppk^-_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ppk^-_{\Sigma ABC_i}$	$\lambda_{\Sigma ABC_i} = \frac{1}{3}(\lambda_{Ai} + \lambda_{Bi} + \lambda_{Ci})$ $\lambda_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N \lambda_{\Sigma ABC_i}$	$\phi_{\Sigma ABC_i} = \frac{1}{3}(\phi_{Ai} + \phi_{Bi} + \phi_{Ci})$ $\phi_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N \phi_{\Sigma ABC_i}$
ΣRST	$Ppk^+_{\Sigma RST_i} = \max(V_{Rj} * I_{Rj} + V_{Sj} * I_{Sj} + V_{Tj} * I_{Tj})$ $Ppk^-_{\Sigma RST_i} = \min(V_{Rj} * I_{Rj} + V_{Sj} * I_{Sj} + V_{Tj} * I_{Tj})$ $Ppk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma RST_i}$ $Ppk^-_{\Sigma RST} = \max_{i=1 \text{ to } N} Ppk^-_{\Sigma RST_i}$	$\lambda_{\Sigma RST_i} = \frac{1}{3}(\lambda_{Ri} + \lambda_{Si} + \lambda_{Ti})$ $\lambda_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N \lambda_{\Sigma RST_i}$	$\phi_{\Sigma RST_i} = \frac{1}{3}(\phi_{Ri} + \phi_{Si} + \phi_{Ti})$ $\phi_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N \phi_{\Sigma RST_i}$
Mechanical	$Ppk^+_{MECHANICAL_i} = \max_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^-_{MECHANICAL_i} = \min_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^+_{MECHANICAL} = \max_{i=1 \text{ to } N} Ppk^+_i$ $Ppk^-_{MECHANICAL} = \min_{i=1 \text{ to } N} Ppk^-_i$		

	Slip	Stage-Stage Efficiency (η_1)	Cumulative Efficiency (η_2)
ΣABC DC Bus ΣRST Mechanical	$Slip_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \left(\frac{\omega_{Sj} - \omega_j}{\omega_j} \right)$ ω_{Sj} is the instantaneous speed calculation of the stator magnetic field. ω_{Sj} and ω_j are calculated internally and are not displayed. $Slip = \frac{1}{N} \sum_{i=1}^N Slip_i$	$\eta_{1i} = \left(\frac{P_{STAGE2i}}{P_{STAGE1i}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{1i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.	$\eta_{2i} = \left(\frac{P_{LASTi}}{P_{FIRSTi}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{2i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.

3-phase/3-wire (3 voltage and 3 current) Calculations

In this case, a no neutral is present, voltage is probed Line-Line and Line currents are sensed. The calculation methodology for Voltage, Current, and Power is summarized in the tables below. The line-line voltage values are shown as V_{AB} , V_{BC} , V_{CA} , V_{RS} , V_{ST} , and V_{TR} , and line current values are shown as I_A , I_B , I_C , I_R , I_S , and I_T .

	VRMS (Line-Line)	IRMS (Line-Neutral)
Voltage: AB, BC, CA, RS, ST, TR Current: A, B, C R, S, T	$Vrms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$ $Vrms = \frac{1}{N} \sum_{i=1}^N Vrms_i$	$Irms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j^2}$ $Irms = \frac{1}{N} \sum_{i=1}^N Irms_i$
ΣABC	$Vrms_{\Sigma ABC_i} = \frac{1}{3}(Vrms_{AB_i} + Vrms_{BC_i} + Vrms_{CA_i})$ $Vrms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma ABC_i}$	$Irms_{\Sigma ABC_i} = \frac{1}{3}(Irms_{A_i} + Irms_{B_i} + Irms_{C_i})$ $Irms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma ABC_i}$
ΣRST	$Vrms_{\Sigma RST_i} = \frac{1}{3}(Vrms_{RS_i} + Vrms_{ST_i} + Vrms_{TR_i})$ $Vrms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma RST_i}$	$Irms_{\Sigma RST_i} = \frac{1}{3}(Irms_{R_i} + Irms_{S_i} + Irms_{T_i})$ $Irms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma RST_i}$

	V _{DC} (Line-Line)	I _{DC} (Line-Neutral)
Voltage: AB, BC, CA, RS, ST, TR Current: A, B, C R, S, T	$Vdc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j$ $Vdc = \frac{1}{N} \sum_{i=1}^N Vdc_i$	$Idc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j$ $Idc = \frac{1}{N} \sum_{i=1}^N Idc_i$
ΣABC	$Vdc_{\Sigma ABC_i} = \frac{1}{3}(Vdc_{AB_i} + Vdc_{BC_i} + Vdc_{CA_i})$ $Vdc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma ABC_i}$	$Idc_{\Sigma ABC_i} = \frac{1}{3}(Idc_{A_i} + Idc_{B_i} + Idc_{C_i})$ $Idc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma ABC_i}$
ΣRST	$Vdc_{\Sigma RST_i} = \frac{1}{3}(Vdc_{RS_i} + Vdc_{ST_i} + Vdc_{TR_i})$ $Vdc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma RST_i}$	$Idc_{\Sigma RST_i} = \frac{1}{3}(Idc_{R_i} + Idc_{S_i} + Idc_{T_i})$ $Idc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma RST_i}$

	VAC (Line-Line)	IAC (Line-Neutral)
Voltage: AB, BC, CA, RS, ST, TR Current: A, B, C R, S, T	$Vac_i = V_{rms_i} - Vdc_i$ $Vac = \frac{1}{N} \sum_{i=1}^N Vac_i$	$Iac_i = I_{rms_i} - Idc_i$ $Iac = \frac{1}{N} \sum_{i=1}^N Iac_i$
ΣABC	$Vac_{\Sigma ABC_i} = \frac{1}{3}(Vac_{ABi} + Vac_{BCi} + Vac_{CAi})$ $Vac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma ABC_i}$	$Iac_{\Sigma ABC_i} = \frac{1}{3}(Iac_{Ai} + Iac_{Bi} + Iac_{Ci})$ $Iac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma ABC_i}$
ΣRST	$Vac_{\Sigma RST_i} = \frac{1}{3}(Vac_{RSi} + Vac_{STi} + Vac_{TRi})$ $Vac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma RST_i}$	$Iac_{\Sigma RST_i} = \frac{1}{3}(Iac_{Ri} + Iac_{Si} + Iac_{Ti})$ $Iac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma RST_i}$

	V _{PK+} , V _{PK-} , V _{PK-PK} (Line-Line)	I _{PK+} , I _{PK-} , I _{PK-PK} (Line-Neutral)
Voltage: AB, BC, CA, RS, ST, TR Current: A, B, C R, S, T	$Vpk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk-pk_i = Vpk^+_i - Vpk^-_i$ $Vpk^+ = \max_{i=1 \text{ to } N} Vpk^+_i$ $Vpk^- = \min_{i=1 \text{ to } N} Vpk^-_i$ $Vpk-pk = \max_{i=1 \text{ to } N} Vpk-pk_i$	$Ipk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk-pk_i = Ipk^+_i - Ipk^-_i$ $Ipk^+ = \max_{i=1 \text{ to } N} Ipk^+_i$ $Ipk^- = \min_{i=1 \text{ to } N} Ipk^-_i$ $Ipk-pk = \max_{i=1 \text{ to } N} Ipk-pk_i$
ΣABC	$Vpk^+_{\Sigma ABC_i} = \max(Vpk^+_{ABi}, Vpk^+_{BCi}, Vpk^+_{CAi})$ $Vpk^-_{\Sigma ABC_i} = \min(Vpk^-_{ABi}, Vpk^-_{BCi}, Vpk^-_{CAi})$ $Vpk-pk_{\Sigma ABC_i} = \max(Vpk-pk_{ABi}, Vpk-pk_{BCi}, Vpk-pk_{CAi})$ $Vpk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma ABC_i}$ $Vpk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma ABC_i}$ $Vpk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma ABC_i}$	$Ipk^+_{\Sigma ABC_i} = \max(Ipk^+_{Ai}, Ipk^+_{Bi}, Ipk^+_{Ci})$ $Ipk^-_{\Sigma ABC_i} = \min(Ipk^-_{Ai}, Ipk^-_{Bi}, Ipk^-_{Ci})$ $Ipk-pk_{\Sigma ABC_i} = \max(Ipk-pk_{Ai}, Ipk-pk_{Bi}, Ipk-pk_{Ci})$ $Ipk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma ABC_i}$ $Ipk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma ABC_i}$ $Ipk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma ABC_i}$
ΣRST	$Vpk^+_{\Sigma RST_i} = \max(Vpk^+_{RSi}, Vpk^+_{STi}, Vpk^+_{TRi})$ $Vpk^-_{\Sigma RST_i} = \min(Vpk^-_{RSi}, Vpk^-_{STi}, Vpk^-_{TRi})$ $Vpk-pk_{\Sigma RST_i} = \max(Vpk-pk_{RSi}, Vpk-pk_{STi}, Vpk-pk_{TRi})$ $Vpk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma RST_i}$ $Vpk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma RST_i}$ $Vpk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma RST_i}$	$Ipk^+_{\Sigma RST_i} = \max(Ipk^+_{Ri}, Ipk^+_{Si}, Ipk^+_{Ti})$ $Ipk^-_{\Sigma RST_i} = \min(Ipk^-_{Ri}, Ipk^-_{Si}, Ipk^-_{Ti})$ $Ipk-pk_{\Sigma RST_i} = \max(Ipk-pk_{Ri}, Ipk-pk_{Si}, Ipk-pk_{Ti})$ $Ipk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma RST_i}$ $Ipk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma RST_i}$ $Ipk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma RST_i}$

	V_{CF} (Line-Line)	I_{CF} (Line-Neutral)
Voltage: AB, BC, CA, RS, ST, TR Current: A, B, C R, S, T	$V_{cf_i} = \frac{[\max(V_{pk^+}_i , V_{pk^-}_i) - V_{dc_i}]}{V_{ac_i}}$ $V_{cf} = \max_{i=1 \text{ to } N} V_{cf_i}$	$I_{cf_i} = \frac{[\max(I_{pk^+}_i , I_{pk^-}_i) - I_{dc_i}]}{I_{ac_i}}$ $I_{cf} = \max_{i=1 \text{ to } N} I_{cf_i}$
ΣABC	No calculation is made for this measurement and source	No calculation is made for this measurement and source
ΣRST	No calculation is made for this measurement and source	No calculation is made for this measurement and source

	P	S	Q
A, B, C, R, S, T	Not calculated – the line-line voltage and line currents are not directly related in phase. If a Line-Line to Line-Neutral voltage conversion is applied, then the formula is as detailed in 3-phase 4-wire (3V3A) method.		
ΣABC	$P_{\Sigma ABC_i} = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $P_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABC_i}$	$S_{\Sigma ABC_i} = V_{rms_{ACi}} * I_{rms_{Ai}} + V_{rms_{BCi}} * I_{rms_{Bi}}$ $S_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma ABC_i}$	$\text{magnitude } Q_{\Sigma ABC_i} = \sqrt{S_{\Sigma ABC_i}^2 - P_{\Sigma ABC_i}^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma ABC_i}$
	If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
ΣRST	$P_{\Sigma RST_i} = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $P_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma RST_i}$	$S_{\Sigma RST_i} = V_{rms_{RTi}} * I_{rms_{Ri}} + V_{rms_{STi}} * I_{rms_{Si}}$ $S_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma RST_i}$	$\text{magnitude } Q_{\Sigma RST_i} = \sqrt{S_{\Sigma RST_i}^2 - P_{\Sigma RST_i}^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma RST_i}$
	If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
Mechanical	$P_{MECHANICAL_i} = T_i * \omega_i$ $P_{MECHANICAL} = \frac{1}{N} \sum_{i=1}^N P_{MECHANICAL_i}$		

	P_{PK+}, P_{PK-}	λ (Power Factor)	ϕ (Phase Angle)
A, B, C, R, S, T	Not calculated – the line-line voltage and line currents are not directly related in phase. If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
ΣABC	$Ppk^+_{\Sigma ABCi} = \max_{j=m_i \text{ to } m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $Ppk^-_{\Sigma ABCi} = \min_{j=m_i \text{ to } m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $Ppk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma ABCi}$ $Ppk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Ppk^-_{\Sigma ABCi}$	$\lambda_{\Sigma ABCi} = P_{\Sigma ABCi} / S_{\Sigma ABCi}$ $\lambda_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABCi} / S_{\Sigma ABCi}$	magnitude $\phi_{\Sigma ABCi} = \cos^{-1} \lambda_{\Sigma ABCi}$ sign of ϕ_i is positive if the fundamental voltage vector leads the fundamental current vector $\phi_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N \cos^{-1} \lambda_{\Sigma ABCi}$
If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.			
ΣRST	$Ppk^+_{\Sigma RSTi} = \max_{j=m_i \text{ to } m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $Ppk^-_{\Sigma RSTi} = \min_{j=m_i \text{ to } m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $Ppk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma RSTi}$ $Ppk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Ppk^-_{\Sigma RSTi}$	$\lambda_{\Sigma RSTi} = P_{\Sigma RSTi} / S_{\Sigma RSTi}$ $\lambda_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma RSTi} / S_{\Sigma RSTi}$	magnitude $\phi_{\Sigma RSTi} = \cos^{-1} \lambda_{\Sigma RSTi}$ sign of ϕ_i is positive if the fundamental voltage vector leads the fundamental current vector $\phi_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N \cos^{-1} \lambda_{\Sigma RSTi}$
If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.			
Mechanical	$Ppk^+_{MECHANICALi} = \max_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^-_{MECHANICALi} = \min_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^+_{MECHANICAL} = \max_{i=1 \text{ to } N} Ppk^+_i$ $Ppk^-_{MECHANICAL} = \min_{i=1 \text{ to } N} Ppk^-_i$		

	Slip	Stage-Stage Efficiency (η_1)	Cumulative Efficiency (η_2)
ΣABC DC Bus ΣRST Mechanical	$Slip_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \left(\frac{\omega_{Sj} - \omega_j}{\omega_j} \right)$ ω_{Sj} is the instantaneous speed calculation of the stator magnetic field. ω_{Sj} and ω_j are calculated internally and are not displayed. $Slip = \frac{1}{N} \sum_{i=1}^N Slip_i$	$\eta_{1i} = \left(\frac{P_{STAGE2i}}{P_{STAGE1i}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{1i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.	$\eta_{2i} = \left(\frac{P_{LASTi}}{P_{FIRSTi}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{2i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.

3-phase/3-wire (2 voltage and 2 current) Calculations

In this case, no neutral is present, voltage is probed Line-Line and Line currents are sensed. The calculation methodology for Voltage, Current, and Power is summarized in the tables below. Since the two wattmeter method is implicitly selected, only two voltage readouts and two current readouts are provided. The line-line voltage values are shown as V_{AC} , V_{BC} , V_{RT} , and V_{ST} , and line current values are shown as I_A , I_B , I_R , and I_S .

	VRMS (Line-Line)	IRMS (Line-Neutral)
Voltage: AC, BC, RT, ST Current: A, B, R, S	$Vrms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$ $Vrms = \frac{1}{N} \sum_{i=1}^N Vrms_i$	$Irms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j^2}$ $Irms = \frac{1}{N} \sum_{i=1}^N Irms_i$
ΣABC	$Vrms_{\Sigma ABC_i} = \frac{1}{2}(Vrms_{ACi} + Vrms_{BCi})$ $Vrms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma ABC_i}$	$Irms_{\Sigma ABC_i} = \frac{1}{2}(Irms_{Ai} + Irms_{Bi})$ $Irms_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma ABC_i}$
ΣRST	$Vrms_{\Sigma RST_i} = \frac{1}{2}(Vrms_{RTi} + Vrms_{STi})$ $Vrms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma RST_i}$	$Irms_{\Sigma RST_i} = \frac{1}{2}(Irms_{Ri} + Irms_{Si})$ $Irms_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma RST_i}$

	VDC (Line-Line)	IDC (Line-Neutral)
Voltage: AC, BC, RT, ST Current: A, B, R, S	$Vdc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j$ $Vdc = \frac{1}{N} \sum_{i=1}^N Vdc_i$	$Idc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j$ $Idc = \frac{1}{N} \sum_{i=1}^N Idc_i$
ΣABC	$Vdc_{\Sigma ABC_i} = \frac{1}{2}(Vdc_{ACi} + Vdc_{BCi})$ $Vdc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma ABC_i}$	$Idc_{\Sigma ABC_i} = \frac{1}{2}(Idc_{Ai} + Idc_{Bi})$ $Idc_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma ABC_i}$
ΣRST	$Vdc_{\Sigma RST_i} = \frac{1}{2}(Vdc_{RTi} + Vdc_{STi})$ $Vdc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma RST_i}$	$Idc_{\Sigma RST_i} = \frac{1}{2}(Idc_{Ri} + Idc_{Si})$ $Idc_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma RST_i}$

	VAC (Line-Line)	IAC (Line-Neutral)
Voltage: AC, BC, RT, ST Current: A, B, R, S	$Vac_i = Vrms_i - Vdc_i$ $Vac = \frac{1}{N} \sum_{i=1}^N Vac_i$	$Iac_i = Irms_i - Idc_i$ $Iac = \frac{1}{N} \sum_{i=1}^N Iac_i$
ΣABC	$Vac_{\Sigma ABC_i} = \frac{1}{2} (Vac_{ACi} + Vac_{BCi})$ $Vac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma ABC_i}$	$Iac_{\Sigma ABC_i} = \frac{1}{2} (Iac_{Ai} + Iac_{Bi})$ $Iac_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma ABC_i}$
ΣRST	$Vac_{\Sigma RST_i} = \frac{1}{2} (Vac_{RTi} + Vac_{STi})$ $Vac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma RST_i}$	$Iac_{\Sigma RST_i} = \frac{1}{2} (Iac_{Ri} + Iac_{Si})$ $Iac_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma RST_i}$

	V _{PK+} , V _{PK-} , V _{PK-PK} (Line-Line)	I _{PK+} , I _{PK-} , I _{PK-PK} (Line-Neutral)
Voltage: AC, BC, RT, ST Current: A, B, R, S	$Vpk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk-pk_i = Vpk^+_i - Vpk^-_i$ $Vpk^+ = \max_{i=1 \text{ to } N} Vpk^+_i$ $Vpk^- = \min_{i=1 \text{ to } N} Vpk^-_i$ $Vpk-pk = \max_{i=1 \text{ to } N} Vpk-pk_i$	$Ipk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk-pk_i = Ipk^+_i - Ipk^-_i$ $Ipk^+ = \max_{i=1 \text{ to } N} Ipk^+_i$ $Ipk^- = \min_{i=1 \text{ to } N} Ipk^-_i$ $Ipk-pk = \max_{i=1 \text{ to } N} Ipk-pk_i$
ΣABC	$Vpk^+_{\Sigma ABC_i} = \max(Vpk^+_{ACi}, Vpk^+_{BCi})$ $Vpk^-_{\Sigma ABC_i} = \max(Vpk^-_{ACi}, Vpk^-_{BCi})$ $Vpk-pk_{\Sigma ABC_i} = \max(Vpk-pk_{ACi}, Vpk-pk_{BCi})$ $Vpk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma ABC_i}$ $Vpk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma ABC_i}$ $Vpk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma ABC_i}$	$Ipk^+_{\Sigma ABC_i} = \max(Ipk^+_{Ai}, Ipk^+_{Bi})$ $Ipk^-_{\Sigma ABC_i} = \max(Ipk^-_{Ai}, Ipk^-_{Bi})$ $Ipk-pk_{\Sigma ABC_i} = \max(Ipk-pk_{Ai}, Ipk-pk_{Bi})$ $Ipk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma ABC_i}$ $Ipk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma ABC_i}$ $Ipk-pk_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma ABC_i}$
ΣRST	$Vpk^+_{\Sigma RST_i} = \max(Vpk^+_{RTi}, Vpk^+_{STi})$ $Vpk^-_{\Sigma RST_i} = \max(Vpk^-_{RTi}, Vpk^-_{STi})$ $Vpk-pk_{\Sigma RST_i} = \max(Vpk-pk_{RTi}, Vpk-pk_{STi})$ $Vpk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma RST_i}$ $Vpk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma RST_i}$ $Vpk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma RST_i}$	$Ipk^+_{\Sigma RST_i} = \max(Ipk^+_{Ri}, Ipk^+_{Si})$ $Ipk^-_{\Sigma RST_i} = \max(Ipk^-_{Ri}, Ipk^-_{Si})$ $Ipk-pk_{\Sigma RST_i} = \max(Ipk-pk_{Ri}, Ipk-pk_{Si})$ $Ipk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma RST_i}$ $Ipk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma RST_i}$ $Ipk-pk_{\Sigma RST} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma RST_i}$

	VCF (Line-Line)	ICF (Line-Neutral)
Voltage: AC, BC, RT, ST Current: A, B, R, S	$Vcf_i = \frac{[\max(Vpk^+_i , Vpk^-_i) - Vdc_i]}{Vac_i}$ $Vcf = \max_{i=1 \text{ to } N} Vcf_i$	$Icf_i = \frac{[\max(Ip k^+_i , Ip k^-_i) - Idc_i]}{Iac_i}$ $Icf = \max_{i=1 \text{ to } N} Icf_i$
ΣABC	No calculation is made for this measurement and source	No calculation is made for this measurement and source
ΣRST	No calculation is made for this measurement and source	No calculation is made for this measurement and source

	P	S	Q
A, B, C, R, S, T	Not calculated – the line-line voltage and line currents are not directly related in phase. If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
ΣABC	$P_{\Sigma ABC_i} = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $P_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABC_i}$	$S_{\Sigma ABC_i} = Vrms_{ACi} * Irms_{Ai} + Vrms_{BCi} * Irms_{Bi}$ $S_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma ABC_i}$	$\text{magnitude } Q_{\Sigma ABC_i} = \sqrt{S_{\Sigma ABC_i}^2 - P_{\Sigma ABC_i}^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma ABC_i}$
	If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
ΣRST	$P_{\Sigma RST_i} = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $P_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma RST_i}$	$S_{\Sigma RST_i} = Vrms_{RTi} * Irms_{Ri} + Vrms_{STi} * Irms_{Si}$ $S_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma RST_i}$	$\text{magnitude } Q_{\Sigma RST_i} = \sqrt{S_{\Sigma RST_i}^2 - P_{\Sigma RST_i}^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma RST_i}$
	If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.		
Mechanical	$P_{MECHANICAL_i} = T_i * \omega_i$ $P_{MECHANICAL} = \frac{1}{N} \sum_{i=1}^N P_{MECHANICAL_i}$		

	P_{PK+}, P_{PK-}	λ (Power Factor)	ϕ (Phase Angle)
A, B, C, R, S, T	<i>Not calculated – the line-line voltage and line currents are not directly related in phase. If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.</i>		
ΣABC	$Ppk^+_{\Sigma ABCi} = \max_{j=m_i \text{ to } m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $Ppk^-_{\Sigma ABCi} = \min_{j=m_i \text{ to } m_i+M_i-1} (V_{ACj} * I_{Aj} + V_{BCj} * I_{Bj})$ $Ppk^+_{\Sigma ABC} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma ABCi}$ $Ppk^-_{\Sigma ABC} = \min_{i=1 \text{ to } N} Ppk^-_{\Sigma ABCi}$	$\lambda_{\Sigma ABCi} = P_{\Sigma ABCi} / S_{\Sigma ABCi}$ $\lambda_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABCi} / S_{\Sigma ABCi}$	$\phi_{\Sigma ABCi} = \cos^{-1} \lambda_{\Sigma ABCi}$ $\phi_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N \cos^{-1} \lambda_{\Sigma ABCi}$
<i>If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.</i>			
ΣRST	$Ppk^+_{\Sigma RSTi} = \max_{j=m_i \text{ to } m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $Ppk^-_{\Sigma RSTi} = \min_{j=m_i \text{ to } m_i+M_i-1} (V_{RTj} * I_{Rj} + V_{STj} * I_{Sj})$ $Ppk^+_{\Sigma RST} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma RSTi}$ $Ppk^-_{\Sigma RST} = \min_{i=1 \text{ to } N} Ppk^-_{\Sigma RSTi}$	$\lambda_{\Sigma RSTi} = P_{\Sigma RSTi} / S_{\Sigma RSTi}$ $\lambda_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma RSTi} / S_{\Sigma RSTi}$	$\phi_{\Sigma RSTi} = \cos^{-1} \lambda_{\Sigma RSTi}$ $\phi_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N \cos^{-1} \lambda_{\Sigma RSTi}$
<i>If a Line-Line to Line-Neutral voltage conversion is applied, the formula is as detailed in 3-phase 4-wire (3V3A) method.</i>			
Mechanical	$Ppk^+_{MECHANICALi} = \max_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^-_{MECHANICALi} = \min_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^+_{MECHANICAL} = \max_{i=1 \text{ to } N} Ppk^+_{i}$ $Ppk^-_{MECHANICAL} = \min_{i=1 \text{ to } N} Ppk^-_{i}$		

	Slip	Stage-Stage Efficiency (η_1)	Cumulative Efficiency (η_2)
ΣABC DC Bus ΣRST Mechanical	$Slip_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \left(\frac{\omega_{Sj} - \omega_j}{\omega_j} \right)$ ω_{Sj} is the instantaneous speed calculation of the stator magnetic field. ω_{Sj} and ω_j are calculated internally and are not displayed. $Slip = \frac{1}{N} \sum_{i=1}^N Slip_i$	$\eta_{1i} = \left(\frac{P_{STAGE2i}}{P_{STAGE1i}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{1i}$ <i>In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.</i>	$\eta_{2i} = \left(\frac{P_{LASTi}}{P_{FIRSTi}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{2i}$ <i>In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.</i>

1-phase/3-wire (2 voltage and 2 current) Calculations

In this case, a neutral is present, voltage and currents are probed Line-Neutral. This selection is available only for AC Input. The line-neutral voltage values are shown as V_A and V_B and line current values are shown as I_A and I_B . The calculation methodology for Voltage, Current, and Power is summarized in the tables below.

	VRMS (Line-Neutral)	IRMS (Line-Neutral)
A, B,	$Vrms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$ $Vrms = \frac{1}{N} \sum_{i=1}^N Vrms_i$	$Irms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j^2}$ $Irms = \frac{1}{N} \sum_{i=1}^N Irms_i$
ΣAB	$Vrms_{\Sigma AB_i} = \frac{1}{2} (Vrms_{Ai} + Vrms_{Bi})$ $Vrms_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Vrms_{\Sigma AB_i}$	$Irms_{\Sigma AB_i} = \frac{1}{2} (Irms_{Ai} + Irms_{Bi})$ $Irms_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Irms_{\Sigma AB_i}$

	V _{DC} (Line-Neutral)	I _{DC} (Line-Neutral)
A, B	$Vdc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j$ $Vdc = \frac{1}{N} \sum_{i=1}^N Vdc_i$	$Idc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j$ $Idc = \frac{1}{N} \sum_{i=1}^N Idc_i$
ΣAB	$Vdc_{\Sigma AB_i} = \frac{1}{2} (Vdc_{Ai} + Vdc_{Bi})$ $Vdc_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Vdc_{\Sigma AB_i}$	$Idc_{\Sigma AB_i} = \frac{1}{2} (Idc_{Ai} + Idc_{Bi})$ $Idc_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Idc_{\Sigma AB_i}$

	V _{AC} (Line-Neutral)	I _{AC} (Line-Neutral)
A, B	$Vac_i = Vrms_i - Vdc_i$ $Vac = \frac{1}{N} \sum_{i=1}^N Vac_i$	$Iac_i = Irms_i - Idc_i$ $Iac = \frac{1}{N} \sum_{i=1}^N Iac_i$
ΣAB	$Vac_{\Sigma AB_i} = \frac{1}{2} (Vac_{Ai} + Vac_{Bi})$ $Vac_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Vac_{\Sigma AB_i}$	$Iac_{\Sigma AB_i} = \frac{1}{2} (Iac_{Ai} + Iac_{Bi})$ $Iac_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N Iac_{\Sigma AB_i}$

	V_{PK+}, V_{PK-}, V_{PK-PK} (Line-Neutral)	I_{PK+}, I_{PK-}, I_{PK-PK} (Line-Neutral)
A, B	$Vpk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk-pk_i = Vpk^+_i - Vpk^-_i$ $Vpk^+ = \max_{i=1 \text{ to } N} Vpk^+_i$ $Vpk^- = \min_{i=1 \text{ to } N} Vpk^-_i$ $Vpk-pk = \max_{i=1 \text{ to } N} Vpk-pk_i$	$Ipk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk-pk_i = Ipk^+_i - Ipk^-_i$ $Ipk^+ = \max_{i=1 \text{ to } N} Ipk^+_i$ $Ipk^- = \min_{i=1 \text{ to } N} Ipk^-_i$ $Ipk-pk = \max_{i=1 \text{ to } N} Ipk-pk_i$
ΣAB	$Vpk^+_{\Sigma AB_i} = \max(Vpk^+_{Ai}, Vpk^+_{Bi})$ $Vpk^-_{\Sigma AB_i} = \min(Vpk^-_{Ai}, Vpk^-_{Bi})$ $Vpk-pk_{\Sigma AB_i} = \max(Vpk-pk_{Ai}, Vpk-pk_{Bi})$ $Vpk^+_{\Sigma AB} = \max_{i=1 \text{ to } N} Vpk^+_{\Sigma AB_i}$ $Vpk^-_{\Sigma AB} = \min_{i=1 \text{ to } N} Vpk^-_{\Sigma AB_i}$ $Vpk-pk_{\Sigma AB} = \max_{i=1 \text{ to } N} Vpk-pk_{\Sigma AB_i}$	$Ipk^+_{\Sigma AB_i} = \max(Ipk^+_{Ai}, Ipk^+_{Bi})$ $Ipk^-_{\Sigma AB_i} = \min(Ipk^-_{Ai}, Ipk^-_{Bi})$ $Ipk-pk_{\Sigma AB_i} = \max(Ipk-pk_{Ai}, Ipk-pk_{Bi})$ $Ipk^+_{\Sigma AB} = \max_{i=1 \text{ to } N} Ipk^+_{\Sigma AB_i}$ $Ipk^-_{\Sigma AB} = \min_{i=1 \text{ to } N} Ipk^-_{\Sigma AB_i}$ $Ipk-pk_{\Sigma AB} = \max_{i=1 \text{ to } N} Ipk-pk_{\Sigma AB_i}$

	V_{CF} (Line-Neutral)	I_{CF} (Line-Neutral)
A, B	$Vcf_i = \frac{[\max(Vpk^+_i , Vpk^-_i) - Vdc_i]}{Vac_i}$ $Vcf = \max_{i=1 \text{ to } N} Vcf_i$	$Icf_i = \frac{[\max(Ipk^+_i , Ipk^-_i) - Idc_i]}{Iac_i}$ $Icf = \max_{i=1 \text{ to } N} Icf_i$
ΣAB	No calculation is made for this measurement and source	No calculation is made for this measurement and source

	P	S	Q
A, B	$P_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j * I_j$ $P = \frac{1}{N} \sum_{i=1}^N P_i$	$S_i = V_{rms_i} * I_{rms_i}$ $S = \frac{1}{N} \sum_{i=1}^N S_i$	$Q_i = \sqrt{S_i^2 - P_i^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q = \frac{1}{N} \sum_{i=1}^N Q_i$
ΣAB	$P_{\Sigma ABC_i} = P_{Ai} + P_{Bi}$ $P_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N P_{\Sigma ABC_i}$	$S_{\Sigma ABC_i} = S_{Ai} + S_{Bi}$ $S_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N S_{\Sigma ABC_i}$	$Q_{\Sigma ABC_i} = Q_{Ai} + Q_{Bi}$ $Q_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Q_{\Sigma ABC_i}$
Mechanical	$P_{MECHANICAL_i} = T_i * \omega_i$ $P_{MECHANICAL} = \frac{1}{N} \sum_{i=1}^N P_{MECHANICAL_i}$		

	PPK+, PPK-	λ (Power Factor)	ϕ (Phase Angle)
A, B	$Ppk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $Ppk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $Ppk^+ = \max_{i=1 \text{ to } N} Ppk^+_i$ $Ppk^- = \max_{i=1 \text{ to } N} Ppk^-_i$	$\lambda_i = \frac{P_i}{S_i}$ $\lambda = \frac{1}{N} \sum_{i=1}^N \lambda_i$	$\phi_i = \cos^{-1} \lambda_i$ <i>sign of ϕ_i is positive if the fundamental voltage vector leads the fundamental current vector</i> $\phi = \frac{1}{N} \sum_{i=1}^N \phi_i$
ΣAB	$Ppk^+_{\Sigma AB_i} = \max(Ppk^+_{Ai}, Ppk^+_{Bi})$ $Ppk^-_{\Sigma AB_i} = \max(Ppk^-_{Ai}, Ppk^-_{Bi})$ $Ppk^+_{\Sigma AB} = \max_{i=1 \text{ to } N} Ppk^+_{\Sigma AB_i}$ $Ppk^-_{\Sigma AB} = \max_{i=1 \text{ to } N} Ppk^-_{\Sigma AB_i}$	$\lambda_{\Sigma AB_i} = \frac{1}{2}(\lambda_{Ai} + \lambda_{Bi})$ $\lambda_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N \lambda_{\Sigma AB_i}$	$\phi_{\Sigma AB_i} = \frac{1}{2}(\phi_{Ai} + \phi_{Bi})$ $\phi_{\Sigma AB} = \frac{1}{N} \sum_{i=1}^N \phi_{\Sigma AB_i}$
Mechanical	$Ppk^+_{MECHANICAL_i} = \max_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^-_{MECHANICAL_i} = \min_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $Ppk^+_{MECHANICAL} = \max_{i=1 \text{ to } N} Ppk^+_i$ $Ppk^-_{MECHANICAL} = \min_{i=1 \text{ to } N} Ppk^-_i$		

	Slip	Stage-Stage Efficiency (η_1)	Cumulative Efficiency (η_2)
ΣAB DC Bus Mechanical	$Slip_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \left(\frac{\omega_{Sj} - \omega_j}{\omega_j} \right)$ ω_{Sj} is the instantaneous speed calculation of the stator magnetic field. ω_{Sj} and ω_j are calculated internally and are not displayed. $Slip = \frac{1}{N} \sum_{i=1}^N Slip_i$	$\eta_{1i} = \left(\frac{P_{STAGE2i}}{P_{STAGE1i}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{1i}$ <i>In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.</i>	$\eta_{2i} = \left(\frac{P_{LASTi}}{P_{FIRSTi}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{2i}$ <i>In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.</i>

1-phase/2-wire Wiring Configuration Calculations

1-phase/2-wire (1 voltage and 1 current) AC Input or DC Bus Calculations

1-phase/Half-Bridge (1 voltage and 1 current) Drive Output Calculations

1-phase/Full-Bridge (1 voltage and 1 current) Drive Output Calculations

In this case, a neutral is present, voltage and currents are probed Line-Neutral. These selections are available in AC Input, DC Bus, or Drive Output. The line-neutral voltage values are shown as V_A and V_R and line current values are shown as I_A and I_R . The calculation methodology for Voltage, Current, and Power is summarized in the tables below.

	VRMS	IRMS
A R DC Bus	$Vrms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j^2}$ $Vrms = \frac{1}{N} \sum_{i=1}^N Vrms_i$	$Irms_i = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j^2}$ $Irms = \frac{1}{N} \sum_{i=1}^N Irms_i$

	VDC	IDC
A R DC Bus	$Vdc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j$ $Vdc = \frac{1}{N} \sum_{i=1}^N Vdc_i$	$Idc_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_j$ $Idc = \frac{1}{N} \sum_{i=1}^N Idc_i$

	VAC	IAC
A R DC Bus	$Vac_i = Vrms_i - Vdc_i$ $Vac = \frac{1}{N} \sum_{i=1}^N Vac_i$	$Iac_i = Irms_i - Idc_i$ $Iac = \frac{1}{N} \sum_{i=1}^N Iac_i$

	V_{PK+} , V_{PK-} , V_{PK-PK}	I_{PK+} , I_{PK-} , I_{PK-PK}
A R DC Bus	$Vpk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j$ $Vpk-pk_i = Vpk^+_i - Vpk^-_i$ $Vpk^+ = \max_{i=1 \text{ to } N} Vpk^+_i$ $Vpk^- = \min_{i=1 \text{ to } N} Vpk^-_i$ $Vpk-pk = \max_{i=1 \text{ to } N} Vpk-pk_i$	$Ipk^+_i = \max_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk^-_i = \min_{j=m_i \text{ to } m_i+M_i-1} I_j$ $Ipk-pk_i = Ipk^+_i - Ipk^-_i$ $Ipk^+ = \max_{i=1 \text{ to } N} Ipk^+_i$ $Ipk^- = \min_{i=1 \text{ to } N} Ipk^-_i$ $Ipk-pk = \max_{i=1 \text{ to } N} Ipk-pk_i$

	V_{CF}	I_{CF}
A R DC Bus	$V_{cf_i} = \frac{[\max(V_{pk^+}_i , V_{pk^-}_i) - V_{dc_i}]}{V_{ac_i}}$ $V_{cf} = \max_{i=1 \text{ to } N} V_{cf_i}$	$I_{cf_i} = \frac{[\max(I_{pk^+}_i , I_{pk^-}_i) - I_{dc_i}]}{I_{ac_i}}$ $I_{cf} = \max_{i=1 \text{ to } N} I_{cf_i}$

	P	S	Q
A R DC Bus	$P_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_j * I_j$ $P = \frac{1}{N} \sum_{i=1}^N P_i$	$S_i = V_{rms_i} * I_{rms_i}$ $S = \frac{1}{N} \sum_{i=1}^N S_i$	magnitude $Q_i = \sqrt{S_i^2 - P_i^2}$ sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector $Q = \frac{1}{N} \sum_{i=1}^N Q_i$
Mechanical	$P_{MECHANICAL_i} = T_i * \omega_i$ $P_{MECHANICAL} = \frac{1}{N} \sum_{i=1}^N P_{MECHANICAL_i}$		

	P_{PK+}, P_{PK-}	λ (Power Factor)	ϕ (Phase Angle)
A R DC Bus	$P_{pk^+}_i = \max_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $P_{pk^-}_i = \min_{j=m_i \text{ to } m_i+M_i-1} V_j * I_j$ $P_{pk^+} = \max_{i=1 \text{ to } N} P_{pk^+}_i$ $P_{pk^-} = \min_{i=1 \text{ to } N} P_{pk^-}_i$	$\lambda_i = \frac{P_i}{S_i}$ $\lambda = \frac{1}{N} \sum_{i=1}^N \lambda_i$	magnitude $\phi_i = \cos^{-1} \lambda_i$ sign of ϕ_i is positive if the fundamental voltage vector leads the fundamental current vector $\phi = \frac{1}{N} \sum_{i=1}^N \phi_i$
Mechanical	$P_{pk^+_{MECHANICAL_i}} = \max_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $P_{pk^-_{MECHANICAL_i}} = \min_{j=m_i \text{ to } m_i+M_i-1} T_j * \omega_j$ $P_{pk^+_{MECHANICAL}} = \max_{i=1 \text{ to } N} P_{pk^+}_i$ $P_{pk^-_{MECHANICAL}} = \min_{i=1 \text{ to } N} P_{pk^-}_i$		

	Slip	Stage-Stage Efficiency (η_1)	Cumulative Efficiency (η_2)
A R DC Bus Mechanical	$Slip_i = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} \left(\frac{\omega_{Sj} - \omega_j}{\omega_j} \right)$ ω_{Sj} is the instantaneous speed calculation of the stator magnetic field. ω_{Sj} and ω_j are calculated internally and are not displayed. $Slip = \frac{1}{N} \sum_{i=1}^N Slip_i$	$\eta_{1i} = \left(\frac{P_{STAGE2i}}{P_{STAGE1i}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{1i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.	$\eta_{2i} = \left(\frac{P_{LASTi}}{P_{FIRSTi}} \right) * 100\%$ Numeric table values $\frac{1}{N} \sum_{i=1}^N \eta_{2i}$ In the event of unequal sync cycle periods, a new efficiency value will be calculated on each cyclic positive transition.

Harmonics Calculations

The MDA Harmonics Calculation option adds the capability to measure and display harmonic values for current, voltage, and power on the AC Line Input or Drive Output. These values are displayed in a separate Harmonics Order table along with the Total Harmonic Distortion (THD) for each phase being measured. When probing line-to-line, the line-to-neutral conversion is automatically performed to calculate the harmonics values in the Harmonics Order table. The Numerics table does not automatically perform this conversion unless the L-L conversion checkbox is selected.

Harmonics Order Table

The table below shows the format of the Harmonics Order table. It can be used as a cross reference to show where the values for voltage, power, and current calculated from the formulas are placed within the table. The example table assumes the limits are set to A/V/W and the number of harmonics is set to 5. The Freq[Hz], Limit[mA], and Pass/Fail columns are only shown while in Fixed Frequency mode; they are omitted in Variable Frequency mode.

Order (RST)	Freq[Hz]	Vr[V]	Pr[mW]	Ir[mA]	Limit[mA]	Pass/Fail
1	Order ₁	Vrms _{h(1)}	P _{h(1)}	Irms _{h(1)}		
2	Order ₂	Vrms _{h(2)}	P _{h(2)}	Irms _{h(2)}	2 nd order limit	Pass or Fail
3	Order ₃	Vrms _{h(3)}	P _{h(3)}	Irms _{h(3)}	3 rd order limit	Pass or Fail
4	Order ₄	Vrms _{h(4)}	P _{h(4)}	Irms _{h(4)}	4 th order limit	Pass or Fail
5	Order ₅	Vrms _{h(5)}	P _{h(5)}	Irms _{h(5)}	5 th order limit	Pass or Fail
Total: 2-5		V _{THD(rms)}	P _{THD(W)}	I _{THJD(rms)}		

Harmonics Order table cross reference key:

- Order_n = frequency of the nth order
- Vrms_{h(n)} = RMS voltage measurement of the nth order
- P_{h(n)} = power measurement of the nth order
- Irms_{h(n)} = RMS current measurement of the nth order
- V_{THD(rms)} = total harmonic distortion for voltage
- P_{THD(W)} = total harmonic distortion for power
- I_{THD(rms)} = total harmonic distortion for current

Harmonics Order Table Calculation Formulas

The following tables describe the calculations for the Harmonics Order table. These calculations apply to all available wiring diagrams. In cases where the wiring diagram is a Line-Line configuration, the Line-Line to Line-Neutral conversion is automatically applied for these Harmonic Order table calculations.

VARYING FREQUENCY MODE CALCULATIONS

	$V_{THD}(V_{rms})$	$V_{THD}(dB\mu V)$	$V_{THD}(\%)$
A, B, C R, S, T	$V_{rms_{hi}} = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_{hj}^2}$ $V_{rms_{hi}}$ is calculated internally and is not displayed $V_{rms_h} = \frac{1}{N} \sum_{i=1}^N V_{rms_{hi}}$ $V_{THD}(V_{rms}) = \sqrt{\sum_{h=2}^H V_{rms_h}^2}$	See calculation for V_{rms_h}, first column $V_{dB\mu V_h} = 20 * \log(V_{rms_h} * 10^6)$ $V_{THD}(dB\mu V) = \sqrt{\sum_{h=2}^H V_{dB\mu V_h}^2}$	See calculation for V_{rms_h}, first column $V_{\%h} = \frac{V_{rms_h}}{V_{rms_{h(1)}}} * 100$ $V_{THD(\%)} = \sqrt{\sum_{h=2}^H V_{\%h}^2}$

	$I_{THD}(A)$	$I_{THD}(dB\mu A)$	$I_{THD}(\%)$
A, B, C R, S, T	$I_{rms_{hi}} = \sqrt{\frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} I_{hj}^2}$ $I_{rms_{hi}}$ is calculated internally and is not displayed $I_{rms_h} = \frac{1}{N} \sum_{i=1}^N I_{rms_{hi}}$ $I_{THD}(rms) = \sqrt{\sum_{h=2}^H I_{rms_h}^2}$	See calculation for I_{rms_h}, first column $I_{dB\mu A_h} = 20 * \log(I_{rms_h} * 10^6)$ $I_{THD}(dB\mu A) = \sqrt{\sum_{h=2}^H I_{dB\mu A_h}^2}$	See calculation for I_{rms_h}, first column $I_{\%} = \frac{I_{rms_h}}{I_{rms_{h(1)}}} * 100$ $I_{THD(\%)} = \sqrt{\sum_{h=2}^H I_{\%h}^2}$

	$P_{THD}(W)$	$P_{THD}(dB\mu W)$	$P_{THD}(\%)$
A, B, C R, S, T	$P_{hi} = \frac{1}{M_i} \sum_{j=m_i}^{m_i+M_i-1} V_{hj} * I_{hj}$ P_{hi} is calculated internally and is not displayed $P_h = \frac{1}{N} \sum_{i=1}^N P_{hi}$ $P_{THD}(W) = \sum_{h=2}^H P_h$	See calculation for P_h, first column $P_{dB_h} = 20 * \log(P_h * 10^6)$ $P_{THD}(dB\mu W) = \sum_{h=2}^H P_{dB\mu W_h}$	See calculation for P_h, first column $P_{\%} = \frac{P_h}{P_{h(1)}} * 100$ $P_{THD(\%)} = \sum_{h=2}^H P_{\%h}$

FIXED FREQUENCY MODE CALCULATIONS

	$V_{THD(V)}$	$V_{THD(dB\mu V)}$	$V_{THD(\%)}$
A, B, C R, S, T	$V_{rms_h} = \sqrt{\frac{1}{S} \sum_{j=1}^S V_{hj}^2}$ $V_{THD(rms)} = \sqrt{\sum_{h=2}^H V_{rms_h}^2}$	See calculation for V_{rms_h}, first column $V_{dB\mu V_h} = 20 * \log(V_{rms_h} * 10^6)$ $V_{THD(dB\mu V)} = \sqrt{\sum_{h=2}^H V_{dB\mu V_h}^2}$	See calculation for V_{rms_h}, first column $V_{\%} = \frac{V_{rms_h}}{V_{rms_{h(1)}}} * 100$ $V_{THD(\%)} = \sqrt{\sum_{h=2}^H V_{\%h}^2}$

	$I_{THD(A)}$	$I_{THD(dB\mu A)}$	$I_{THD(\%)}$
A, B, C R, S, T	$I_{rms_h} = \sqrt{\frac{1}{S} \sum_{j=1}^S I_{hj}^2}$ $I_{THD(rms)} = \sqrt{\sum_{h=2}^H I_{rms_h}^2}$	See calculation for I_{rms_h}, first column $I_{dB\mu A_h} = 20 * \log(I_{rms_h} * 10^6)$ $I_{THD(dB\mu A)} = \sqrt{\sum_{h=2}^H I_{dB\mu A_h}^2}$	See calculation for I_{rms_h}, first column $I_{\%} = \frac{I_{rms_h}}{I_{rms_{h(1)}}} * 100$ $I_{THD(\%)} = \sqrt{\sum_{h=2}^H I_{\%h}^2}$

	$P_{THD(W)}$	$P_{THD(dB\mu W)}$	$P_{THD(\%)}$
A, B, C R, S, T	$P_h = \frac{1}{S} \sum_{j=1}^S V_{hj} * I_{hj}$ $P_{THD(W)} = \sum_{h=2}^H P_h$	See calculation for P_h, first column $P_{dB\mu W_h} = 20 * \log(P_h * 10^6)$ $P_{THD(dB\mu W)} = \sum_{h=2}^H P_{dB\mu W_h}$	See calculation for P_h, first column $P_{\%} = \frac{P_h}{P_{h(1)}} * 100$ $P_{THD(\%)} = \sum_{h=2}^H P_{\%h}$

THD Measurement Calculations (Numerics Table)

THD measurement parameters calculations may yield marginally different results in the Numerics and Harmonics Order tables due to slightly different calculation methods used in each table. The different calculation methods are shown below. While they are different, in both cases the methods meet the standard for calculating THD.

3-PHASE/4-WIRE (3 VOLTAGE AND 3 CURRENT) CALCULATIONS

	Vthd	Ithd
A,B,C R,S,T	$Vthd_i = \frac{\sqrt{\sum_{h=2}^H Vrms_{hi}^2}}{Vrms_{h(1)i}} * 100$ $Vthd = \frac{1}{N} \sum_{i=1}^N Vthd_i$	$Ithd_i = \frac{\sqrt{\sum_{h=2}^H Irms_{hi}^2}}{Irms_{h(1)i}} * 100$ $Ithd = \frac{1}{N} \sum_{i=1}^N Ithd_i$
ΣABC	$Vthd_{\Sigma ABC_i} = \frac{1}{3}(Vthd_{Ai} + Vthd_{Bi} + Vthd_{Ci})$ $Vthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma ABC_i}$	$Ithd_{\Sigma ABC_i} = \frac{1}{3}(Ithd_{Ai} + Ithd_{Bi} + Ithd_{Ci})$ $Ithd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma ABC_i}$
ΣRST	$Vthd_{\Sigma RST_i} = \frac{1}{3}(Vthd_{Ri} + Vthd_{Si} + Vthd_{Ti})$ $Vthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma RST_i}$	$Ithd_{\Sigma RST_i} = \frac{1}{3}(Ithd_{Ri} + Ithd_{Si} + Ithd_{Ti})$ $Ithd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma RST_i}$

	Pthd
A,B,C R,S,T	$Pthd_i = \frac{\sum_{h=2}^H P_h}{Prms_{h(1)i}} * 100$ $Pthd = \frac{1}{N} \sum_{i=1}^N Pthd_i$
ΣABC	$Pthd_{\Sigma ABC_i} = \frac{1}{3}(Pthd_{Ai} + Pthd_{Bi} + Pthd_{Ci})$ $Pthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma ABC_i}$
ΣRST	$Pthd_{\Sigma RST_i} = \frac{1}{3}(Pthd_{Ri} + Pthd_{Si} + Pthd_{Ti})$ $Pthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma RST_i}$

3-PHASE/3-WIRE (3 VOLTAGE AND 3 CURRENT) CALCULATIONS

	Vthd	Ithd
Voltage: AB,BC,CA RS,ST,TR Current: A, B, C R, S, T	$Vthd_i = \frac{\sqrt{\sum_{h=2}^H Vrms_{hi}^2}}{Vrms_{h(1)i}} * 100$ $Vthd = \frac{1}{N} \sum_{i=1}^N Vthd_i$	$Ithd_i = \frac{\sqrt{\sum_{h=2}^H Irms_{hi}^2}}{Irms_{h(1)i}} * 100$ $Ithd = \frac{1}{N} \sum_{i=1}^N Ithd_i$
ΣABC	$Vthd_{\Sigma ABC_i} = \frac{1}{3}(Vthd_{ABi} + Vthd_{BCi} + Vthd_{CAi})$ $Vthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma ABC_i}$	$Ithd_{\Sigma ABC_i} = \frac{1}{3}(Ithd_{ABi} + Ithd_{BCi} + Ithd_{CAi})$ $Ithd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma ABC_i}$
ΣRST	$Vthd_{\Sigma RST_i} = \frac{1}{3}(Vthd_{RSi} + Vthd_{STi} + Vthd_{TRi})$ $Vthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma RST_i}$	$Ithd_{\Sigma RST_i} = \frac{1}{3}(Ithd_{Ri} + Ithd_{Si} + Ithd_{Ti})$ $Ithd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma RST_i}$

	Pthd
Voltage: AB,BC,CA RS,ST,TR Current: A, B, C R, S, T	$Pthd_i = \frac{\sum_{h=2}^H P_h}{Prms_{h(1)i}} * 100$ $Pthd = \frac{1}{N} \sum_{i=1}^N Pthd_i$
ΣABC	$Pthd_{\Sigma ABC_i} = \frac{1}{3}(Pthd_{ABi} + Pthd_{BCi} + Pthd_{CAi})$ $Pthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma ABC_i}$
ΣRST	$Pthd_{\Sigma RST_i} = \frac{1}{3}(Pthd_{RSi} + Pthd_{STi} + Pthd_{TRi})$ $Pthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma RST_i}$

3-PHASE/3-WIRE (2 VOLTAGE AND 2 CURRENT) CALCULATIONS

	Vthd	Ithd
Voltage: AB,BC,CA RS,ST,TR Current: A, B, C R, S, T	$Vthd_i = \frac{\sqrt{\sum_{h=2}^H Vrms_{hi}^2}}{Vrms_{h(1)i}} * 100$ $Vthd = \frac{1}{N} \sum_{i=1}^N Vthd_i$	$Ithd_i = \frac{\sqrt{\sum_{h=2}^H Irms_{hi}^2}}{Irms_{h(1)i}} * 100$ $Ithd = \frac{1}{N} \sum_{i=1}^N Ithd_i$
ΣABC	$Vthd_{\Sigma ABC_i} = \frac{1}{2}(Vthd_{ABi} + Vthd_{BCi})$ $Vthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma ABC_i}$	$Ithd_{\Sigma ABC_i} = \frac{1}{2}(Ithd_{ABi} + Ithd_{BCi})$ $Ithd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma ABC_i}$
ΣRST	$Vthd_{\Sigma RST_i} = \frac{1}{2}(Vthd_{RSi} + Vthd_{STi})$ $Vthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma RST_i}$	$Ithd_{\Sigma RST_i} = \frac{1}{2}(Ithd_{Ri} + Ithd_{Si})$ $Ithd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma RST_i}$

	Pthd
Voltage: AB,BC,CA RS,ST,TR Current: A, B, C R, S, T	$Pthd_i = \frac{\sum_{h=2}^H P_h}{Prms_{h(1)i}} * 100$ $Pthd = \frac{1}{N} \sum_{i=1}^N Pthd_i$
ΣABC	$Pthd_{\Sigma ABC_i} = \frac{1}{2}(Pthd_{ABi} + Pthd_{BCi})$ $Pthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma ABC_i}$
ΣRST	$Pthd_{\Sigma RST_i} = \frac{1}{2}(Pthd_{RSi} + Pthd_{STi})$ $Pthd_{\Sigma RST} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma RST_i}$

1-PHASE/3-WIRE (2 VOLTAGE AND 2 CURRENT) CALCULATIONS

	Vthd	Ithd
A, B	$Vthd_i = \frac{\sqrt{\sum_{h=2}^H Vrms_{hi}^2}}{Vrms_{h(1)i}} * 100$ $Vthd = \frac{1}{N} \sum_{i=1}^N Vthd_i$	$Ithd_i = \frac{\sqrt{\sum_{h=2}^H Irms_{hi}^2}}{Irms_{h(1)i}} * 100$ $Ithd = \frac{1}{N} \sum_{i=1}^N Ithd_i$
ΣAB	$Vthd_{\Sigma ABC_i} = \frac{1}{2} (Vthd_{Ai} + Vthd_{Bi})$ $Vthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Vthd_{\Sigma ABC_i}$	$Ithd_{\Sigma ABC_i} = \frac{1}{2} (Ithd_{Ai} + Ithd_{Bi})$ $Ithd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Ithd_{\Sigma ABC_i}$

	Pthd
Voltage: AB,BC,CA RS,ST,TR Current: A, B, C R, S, T	$Pthd_i = \frac{\sum_{h=2}^H P_h}{Prms_{h(1)i}} * 100$ $Pthd = \frac{1}{N} \sum_{i=1}^N Pthd_i$
ΣABC	$Pthd_{\Sigma ABC_i} = \frac{1}{2} (Pthd_{Ai} + Pthd_{Bi})$ $Pthd_{\Sigma ABC} = \frac{1}{N} \sum_{i=1}^N Pthd_{\Sigma ABC_i}$

1-PHASE/2-WIRE WIRING CONFIGURATION CALCULATIONS

1-phase/2-wire (1 voltage and 1 current) AC Input or DC Bus Calculations

1-phase/Half-Bridge (1 voltage and 1 current) Drive Output Calculations

1-phase/Full-Bridge (1 voltage and 1 current) Drive Output Calculations

	Vthd	Ithd
A R DC Bus	$Vthd_i = \frac{\sqrt{\sum_{h=2}^H Vrms_{hi}^2}}{Vrms_{h(1)i}} * 100$ $Vthd = \frac{1}{N} \sum_{i=1}^N Vthd_i$	$Ithd_i = \frac{\sqrt{\sum_{h=2}^H Irms_{hi}^2}}{Irms_{h(1)i}} * 100$ $Ithd = \frac{1}{N} \sum_{i=1}^N Ithd_i$

	Pthd
A R DC Bus	$Pthd_i = \frac{\sum_{h=2}^H P_h}{Prms_{h(1)i}} * 100$ $Pthd = \frac{1}{N} \sum_{i=1}^N Pthd_i$

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