HOW2POWER TODAY
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Exclusive Technology Feature

ISSUE: March 2016

A Practical Primer On Motor Drives (Part 2): Single-Phase AC Line Voltage

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

This article series explains the basics of motor drives from the input signals (ac line inputs) through motor shaft sensing (mechanical power) and all relevant areas in between. It targets newcomers to these fields desiring a broad overview before seeking deeper technical information from other sources. Here in part 2 of this series, concepts relating to ac line voltage are explained, starting with a broad discussion on voltage, current and power, leading to a more detailed discussion on single-phase ac line voltage.

AC Line Systems (Voltage, Current, Power)

For electrical engineers familiar with printed circuit assembly (PCA) design (i.e., designs built on printed circuit boards), their knowledge of ac line power voltages and currents may end with the most basic input ratings of a switching power supply operating from a 120-V or 240-V single-phase wall socket. Unless they are working in the power or power conversion field, many electrical engineers are far more familiar with the very small dc distribution rails and digital logic family operating voltages present on PCAs than with ac line voltages and currents.

However, a basic understanding of ac line voltage and current ratings might give you valuable insight into component or product ratings. Have you ever wondered…

- Why high-voltage (HV) differential voltage probes commonly have a 1000-Vrms common-mode safety rating?
- Why something rated “120 V” could have much higher peak-to-peak voltages present?
- Why rectified ac line voltages result in the dc values that they do?
- Why a current probe with a given Arms rating may not meet your needs if you are trying to measure currents that are not rated in Arms terms?

Additionally, ac line voltages are much higher than those typically measured with oscilloscopes when probing on a low-voltage PCA. These high voltages present considerable risk to you and the equipment you are using. Thus, education is necessary so that proper cautions can be well understood and personal and equipment safety can be assured.

Background

We often refer to ac line power (and ac line voltage and current) as utility, grid, household, power line, or mains power (or voltage and current). This is the typically 50- or 60-Hz sinusoidal voltage and current transmitted through current-carrying conductors to the home or business through a service drop, and further distributed within the home or business to various other panels, “drops,” or sockets for use by the customer. While some may consider power conversion (PWM) outputs to be “ac,” we are specifically excluding their treatment in this section. Voltage, current and power for PWM signals are covered separately and the information in this section does not apply to those PWM signals.

The ac line system can contain a single “phase” or multiple “phases.” Independently invented in the late 1880s by separate inventors, three-phase systems were first extensively commercialized by a partnership between Nikola Tesla and the Westinghouse Electric Company. Three-phase systems are more efficient and cost-effective than single- or two-phase systems because, for a given level of transmitted power, three-phase systems require less material in the current-carrying conductors.

A single-phase system requires supply and return (neutral) wires both rated for the full current-carrying (power rating) of the system. A three-phase system, to deliver an equivalent amount of power, has three supply wires rated for less current-carrying capability and only requires one neutral wire. Furthermore, the neutral wire in a three-phase system need not be rated for very high current-carrying capability. That's because the neutral wire in a balanced three-phase system (the normal operating condition) conducts zero current because, by definition, the phase return currents will flow through another phase, and the three phase currents therefore sum to zero at the neutral.

Thus, for a modest 50% increase in cost (three current-carrying conductors versus two), the three-phase system supplies three times the power, which represents a 200% increase. For a variety of reasons, it is also less complicated and less expensive to build a three-phase generator and transformer. Further, three-phase power provides better control and power delivery capability for even low-power motors.

We give distinct names to each of the three phases in a three-phase system. For three-phase line systems (i.e., from the utility), they are commonly referred to as A, B, and C phases, and less commonly as L1, L2, and L3 phases. There are other even less commonly used designations as well.

An electric utility supply system always contains three phases, but a small residential service load may only have single-phase service from the three-phase transmission and distribution system. Larger commercial loads that need more power will have full three-phase service from the utility. Here are the most common combinations:

- Single-phase, two-wire
- Single-phase, three-wire
- Three-phase, four-wire
- Three-phase, three-wire.

More than three phases is uncommon, and is never present in a utility service. However, one may find four, five, or six phases in non-utility supplies or in applications that require high reliability through redundancy, such as aircraft or military applications. In such cases where there are more than three phases, they are typically generated with a motor drive and not by the utility supply. We will discuss this topic further in the upcoming section on Variable-Frequency Motor Drives.

Note that some other power applications such as voltage regulator modules (VRMs) in embedded computing systems also use the term "phase" in describing what are known as multi-phase buck converters. In such converters, each phase corresponds to an individual power stage (typically consisting of power MOSFETs and an inductor) where the outputs of multiple power stages are summed to generate higher levels of output current. The timing of the turn-on and turn off each power stage is adjusted according to the number of power stages or phases employed to achieve attenuation of input and output ripple. In any event, this usage of "phases" is distinctly different from the "phases" of a three-phase ac system—do not confuse the terminology in this case.

The ac frequency provided by the utility is either 50 or 60 Hz, depending on the geographic location. Synchronization of the supplied frequency occurs across the electric utility's entire s+upply grid, and is enforced for grid-stability purposes. Historically, utilities have achieved frequency synchronization and stability using generator synchronization and electromechanical volt-amperes reactive (VAr) compensation circuitry. However, power electronics systems play an increasing role in this area as semiconductor device voltages increase, power electronics systems costs decrease, and non-traditional generating sources like wind and solar become a larger component of the generated supply.

Some applications, such as shipboard or aircraft applications, may use 400-Hz ac line power supplied by separate generators, but this is not a standard electric utility frequency. In rarer cases, some other applications use different supply frequencies. These non-standard, locally-generated frequencies are not supplied by the electric utilities.

Cautions

AC systems contain a neutral conductor separate from a ground conductor. The neutral is not ground—always assume that there are voltages on the neutral wire and currents flowing through it even if the normal design case is different. In a single-phase system, the neutral conductor serves to return the current to the supply and complete the circuit. In a balanced, normally operating three-phase system, the neutral should not be carrying current, but it could carry current during a fault condition.

Ground is a safety connection from a chassis to earth potential. In a single-phase system, if the neutral connects to the ground as a result of a fault condition, the return current will flow to ground and a protective device, such as a circuit breaker or ground-fault current interrupter (GFCI), will trip and interrupt the current flow. In a three-phase system, the neutral may be connected to ground, but significant currents could flow in the neutral under various fault or other conditions.

An all-inclusive discussion of electrical codes, historically permitted connections, and all safety considerations is beyond the scope of this document. The best practice is to assume the worst and take extra precautions unless you have specific knowledge to the contrary. Furthermore, protective devices could trip in less than a cycle, or may take several cycles. So if there is voltage potential on the neutral and/or current flow present, a person who is touching the neutral could complete a current-carrying path to ground and sustain serious injury or death.

AC Line Voltage

AC line voltage values may be expressed in volts RMS (Vrms), but typically they are simply stated as V or Vac. Regardless of its expression, it is Vrms—the terms are used interchangeably in this context.

AC line voltages are always sinusoidal, with the typical utility requirement that they contain <5% total harmonic distortion (THD). Furthermore, it is required that customers not disturb the service entrance with >5% THD imposed by "noisy" equipment that generates non-linear current flows and/or results in distorted voltage waveforms on the ac lines (such as PWM motor drives or unfiltered inverters).

In either single-phase or three-phase ac systems, measurements of ac line voltage can be made from a single line (phase) to neutral (line-neutral) or from one line to another line (line-line). In addition, the rated ac voltage is referenced differently for single-phase and three-phase systems. Therefore, the understanding and calculation of the different voltages (peak, peak-peak, RMS, line-neutral or line-line, etc.) in an ac single-phase or three-phase system requires explanation.

Single-Phase AC Line Voltage

A single-phase, two-wire ac system contains a voltage wire, which is 120 V in the United States, and a neutral wire. The ground is supplied at the utility "drop" and within the building—in the United States, this is typically a physically deep-driven earth ground.

A single-phase, three-wire ac system contains two voltage wires, which are both at 120 V in the U.S., and a neutral wire. Again, the ground connection comes from within the building. A 120-V potential exists from both wires (lines) to neutral, and 240-V from line to line.

The line is "hot" and supplies the current and the current returns through the neutral line. The building contains a service panel that provides appropriate safety devices (fuses, circuit breakers, etc.) in an enclosure (commonly referred to as a panel or panel board), and the enclosure is connected to earth ground. There is also a physical bond from the utility supply to an earth ground as pictured in Fig 1.

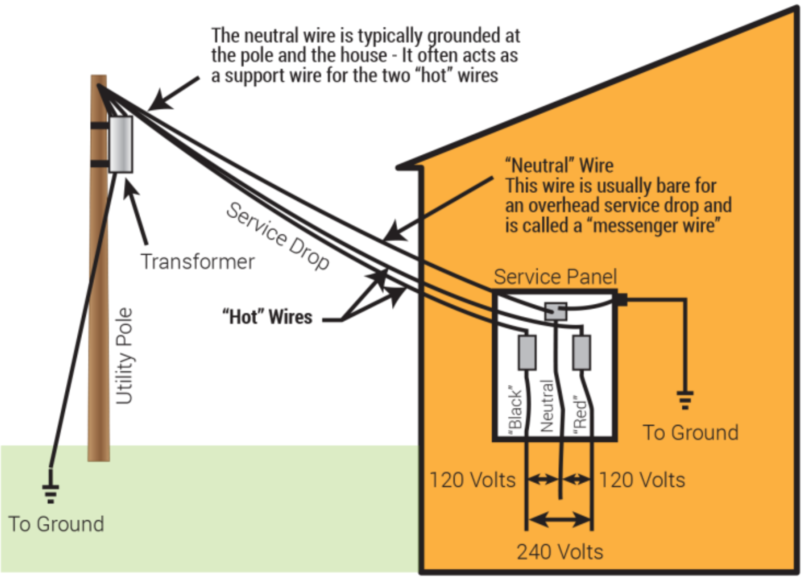


Fig. 1. Typical U.S. residential service drop for a single-phase, three-wire ac supply.

Note that the neutral wire returns current to the utility line and is connected to the utility ground at the pole and the service ground at the service panel. Earth grounds should be at identical potentials in both locations.

Although we simplify the single-phase ac voltage value to an RMS voltage value, the magnitude varies sinusoidally because the single-phase ac voltage is a rotating vector with a magnitude and an angle. The rotation period is the inverse of the supply frequency. The magnitude of this voltage vector is the instantaneous line-neutral voltage value, with a peak voltage Vpk equal to √2 * Vrms, or 169.7 V in the case of a single-phase ac system with a 120-Vrms rating.

The voltage vector completes one revolution at a rate of one period = 1/frequency (50 Hz or 60 Hz). At any given moment in time, the voltage magnitude is equal to Vpk * sin(α) where α is the angle of rotation in radians. See Fig. 2 below.

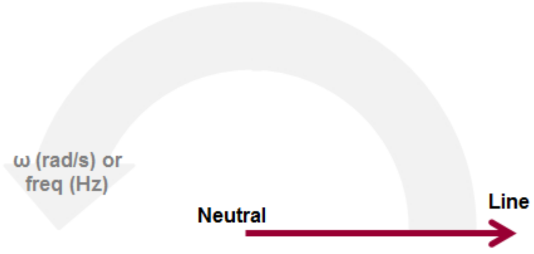


Fig. 2. Rotating voltage vector.

When electrically observed as a voltage-versus-time waveform, the "rotating" voltage vector appears as a sinusoidal waveform with a fixed period and frequency as described above (Fig. 3.)

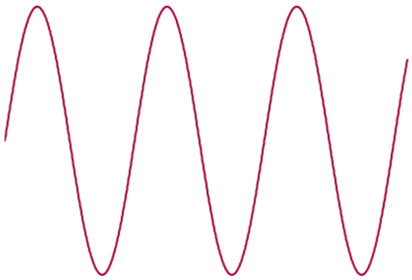


Fig. 3. When viewed as a voltage-versus-time waveform, the rotating voltage vector appears as a sine wave.

To further understand the various voltage values (peak, peak-peak, etc.) present on this waveform, let's continue with the example of a sinusoid rated at 120 V or 120 Vac. Again, what that really means is 120 Vrms. Therefore, we can calculate other voltages values, as follows:

Vpk = √2 * Vac, or √2 * Vrms = 169.7 V

Vpk-pk = 2 * Vpk = 339.4 V

Vdc = Vpk = 169.7 V (if rectified and filtered).

This is plotted mathematically in Fig. 4.

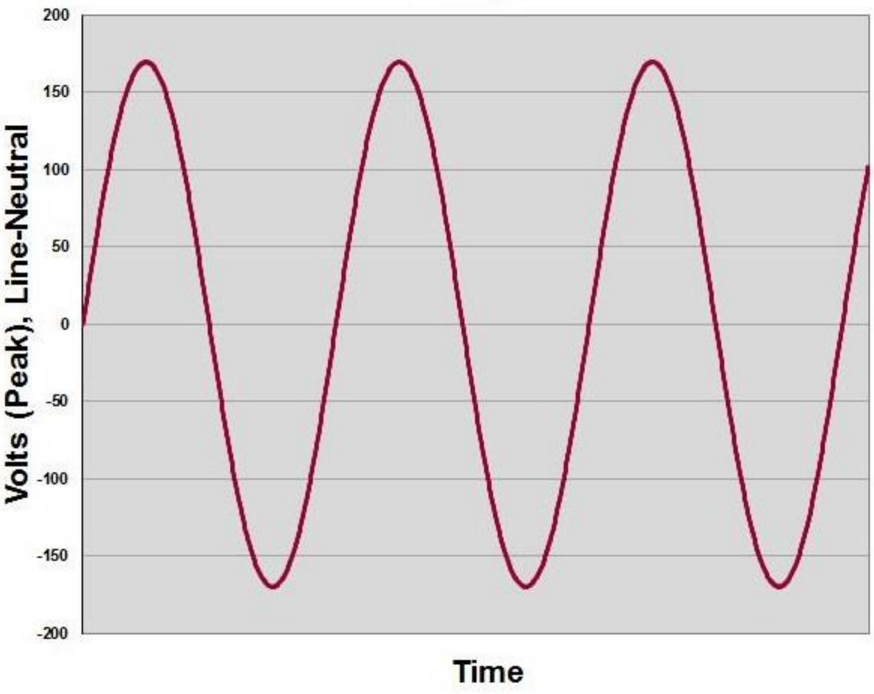
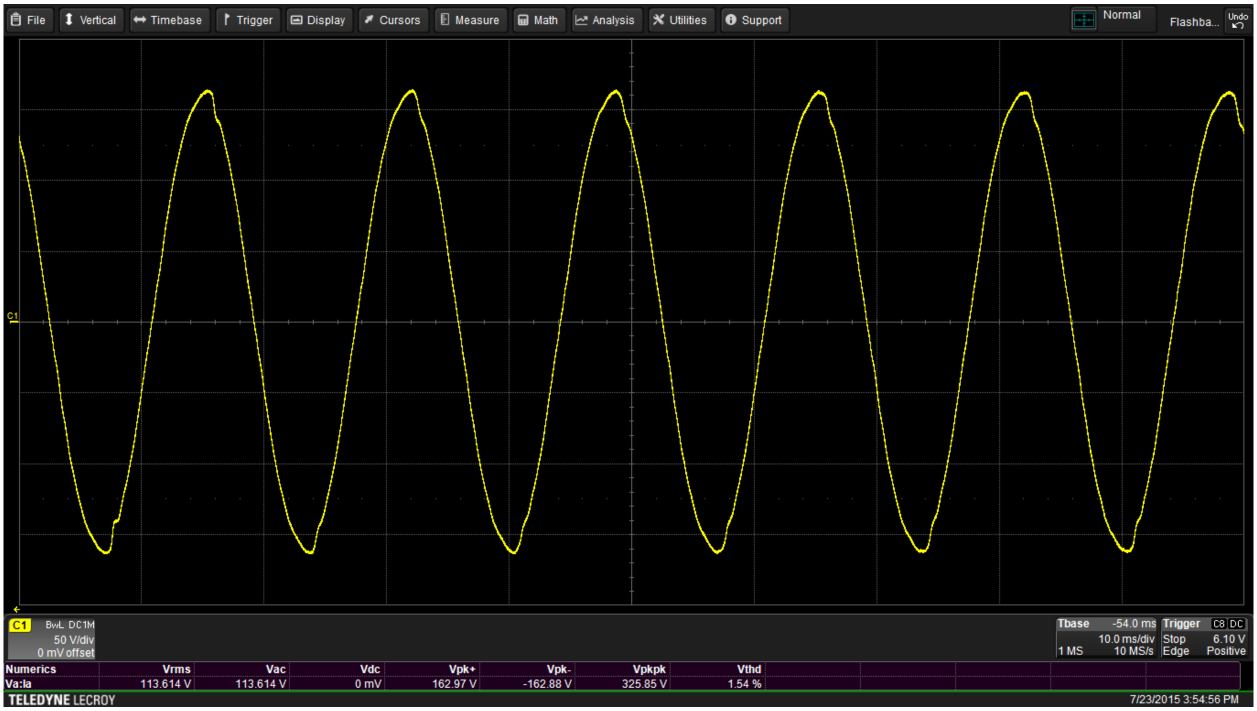


Fig. 4. AC single-phase utility voltage, 120 Vac.

Note that the commonly used phrase "true RMS" is a "marketing definition" to describe a mathematically correct RMS calculation as compared to a measurement shortcut taken using inexpensive instruments whereby RMS voltages (or currents) are calculated from Vpk-pk/2. This measurement shortcut is true only for a pure, single-frequency sinewave, which is rarely present.

With an oscilloscope such as Teledyne LeCroy's 12-bit HDO8000 series (or the MDA800 series Motor Drive Analyzers built on the HDO8000 platform) and a suitably rated voltage probe (such as a Teledyne LeCroy HVD3106 HV differential probe) the electric utility's 120-Vac line can be probed. Then, the built-in oscilloscope measurement functions can be used to measure the various voltage levels.

The screen image in Fig. 5 shows an example of a nominal 120-Vac signal captured with a Teledyne LeCroy 8-channel, 12-bit Motor Drive Analyzer with three-phase power analysis measurement capabilities. This particular instrument is model MDA810.



Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Vthd
Va:Ia	113.614 V	113.614 V	0 mV	162.97 V	-162.88 V	325.85 V	1.54 %

Fig. 5. 120-V ac signal captured with a Teledyne LeCroy 8-channel, 12-bit Motor Drive Analyzer.

The Numerics table at the bottom of the display provides the built-in oscilloscope measurements:

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Vthd
Va:Ia	113.614 V	113.614 V	0 mV	162.97 V	-162.88 V	325.85 V	1.54 %

Fig. 6. The Numerics table lists key measurement values from the waveform in Fig. 5.

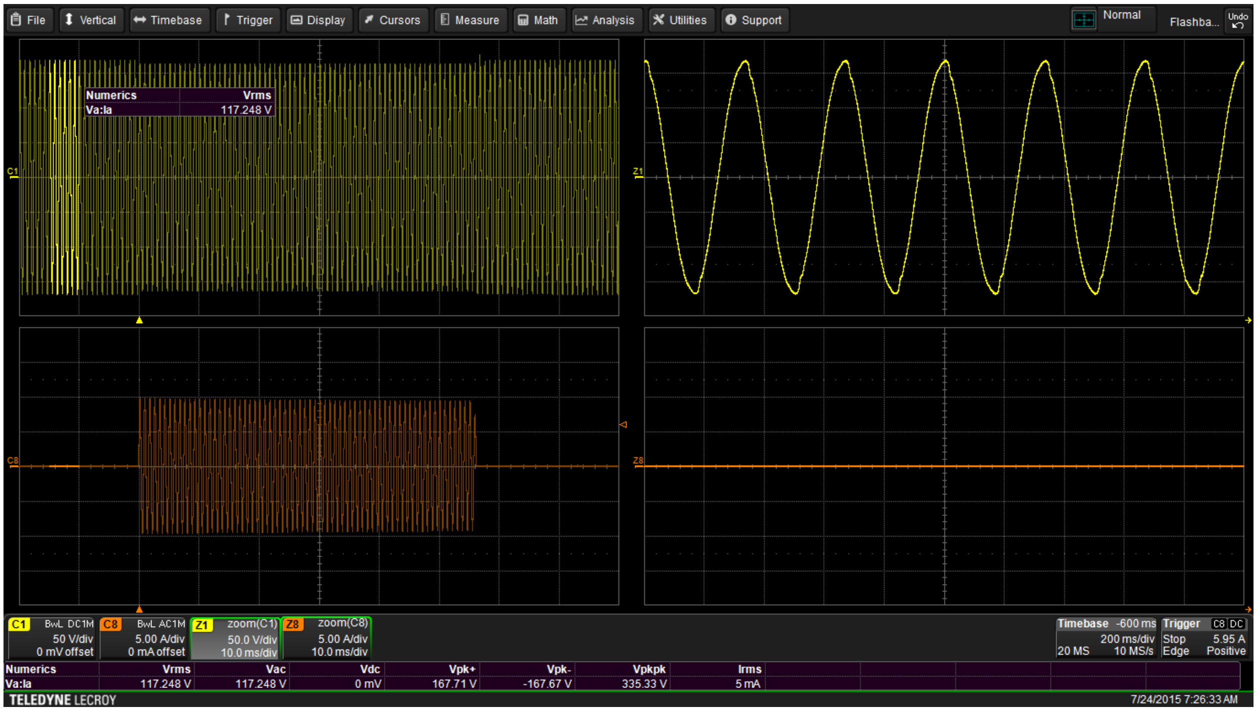
Note that the Vrms and Vac values are the same, Vdc is 0 V, and the Vpk+ and Vpk- values are roughly equal. While these values differ from the nominal values described earlier, keep in mind that this voltage is measured at the end of a long cable run far from the service drop entrance and is a "load" voltage taken coincident with an ~10-A current draw.

Such a voltage drop is typical for near full-load conditions in a typical commercial or industrial building. Thus, 120 Vac is also commonly referred to as 115 Vac. Note also that while THD is small (1.54%), it is not zero. Pure sinusoids are rare in the real world.

To test the hypothesis that a high-current load causes a voltage drop from a nominal 120-Vac line, we can acquire a waveform spanning a longer period of time using the Motor Drive Analyzer and evaluate the performance before, during, and after the application of a load. In this case, the load is a toaster, so applying the load is as simple as "making toast."

The screen image in Fig. 7 shows a two-second capture beginning with no load, then application of a load for approximately 1 s and then no load again. The full 2-s line-voltage capture appears in the upper left quadrant of the display, the full 2-s line-current capture is in the lower left quadrant of the display, and the corresponding zoomed areas are to the right.

Because the three-phase power calculation software is operating in "Zoom+Gate" mode, the calculations are gated to the zoomed portion of the waveforms (shown to the right of the 2-s acquisitions). With a volts RMS value of 117.2 V, it is clear in this case that there is negligible current draw.



Numerics	Vrms
Va:Ia	117.248 V

C1 BwL DC1M 50 V/div 0 mV offset
C8 BwL AC1M 5.00 A/div 0 mA offset
Z1 zoom(C1) 50.0 V/div 10.0 ms/div
Z8 zoom(C8) 5.00 A/div 10.0 ms/div
Timebase -600 ms 200 ms/div 20 MS 10 MS/s
Trigger C8 DC Stop 5.95 A Edge Positive

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Irms
Va:Ia	117.248 V	117.248 V	0 mV	167.71 V	-167.67 V	335.33 V	5 mA

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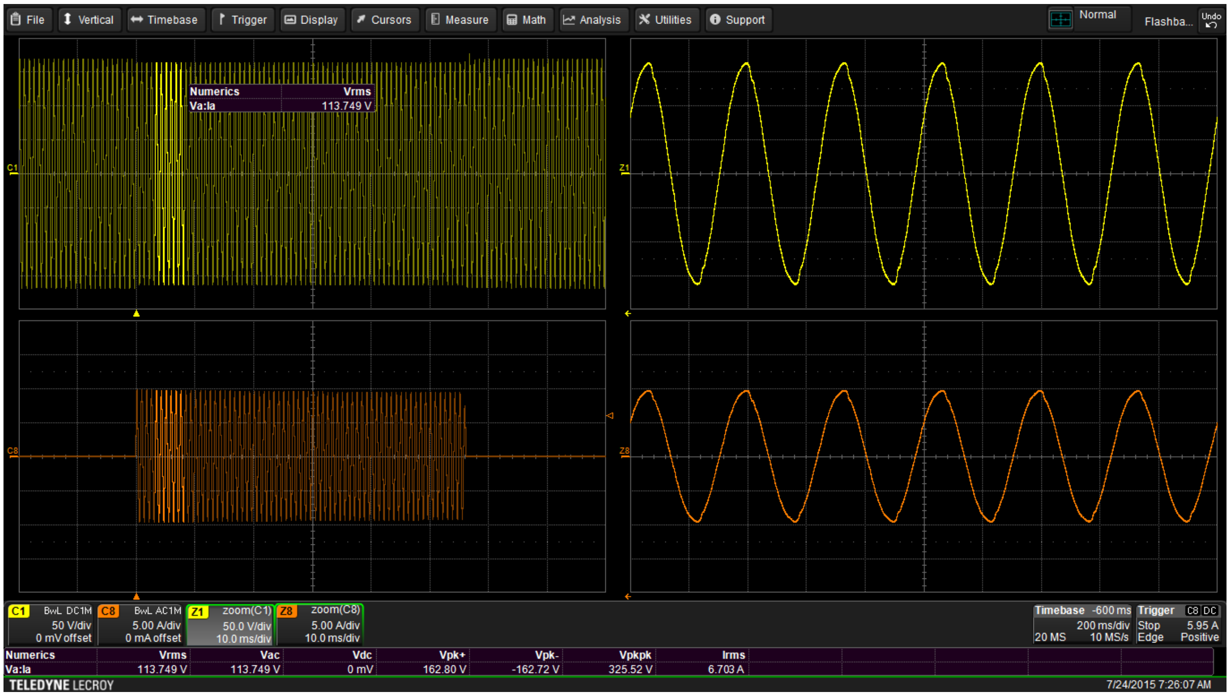
Fig. 7. AC line measurement in the upper left shows a 2-s capture of the line voltage with no load, followed by a toaster load and then no load again. A 2-s capture of the line current is shown in the lower left. Zoomed versions of the voltage and current waveforms are shown on the right.

However, when the toaster is "toasting" (drawing current), the line voltage dips to 113.7 V as shown in Fig. 8. The voltage drop appears in the amplitude of the long voltage capture and its calculated value appears in the Numerics table at bottom.



Numerics	Vrms
Va:Ia	113.749 V

C1 BwL DC1M 50 V/div 0 mV offset
C8 BwL AC1M 5.00 A/div 0 mA offset
Z1 zoom(C1) 50.0 V/div 10.0 ms/div
Z8 zoom(C8) 5.00 A/div 10.0 ms/div
Timebase -600 ms 200 ms/div 20 MS 10 MS/s
Trigger C8 DC Stop 5.95 A Edge Positive

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Irms
Va:Ia	113.749 V	113.749 V	0 mV	162.80 V	-162.72 V	325.52 V	6.703 A

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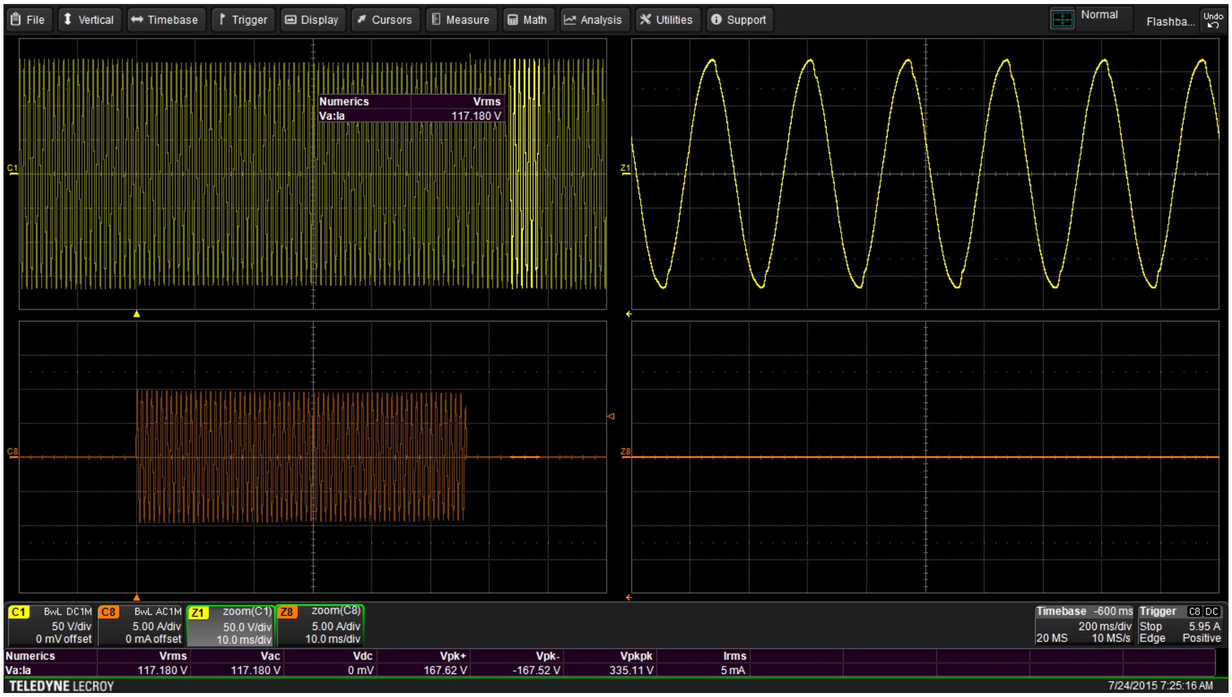
Fig. 8. AC line measurement reveals the voltage drop (117.2 V - 113.7 V) that occurs when the toaster is toasting and drawing current.

Then, when the "toast is done," the current draw ends and the voltage level returns to its no-load value as shown in Fig. 9.



Numerics	Vrms
Va:Ia	117.180 V

C1 BwL DC1M 50 V/div 0 mV offset
C8 BwL AC1M 5.00 A/div 0 mA offset
Z1 zoom(C1) 50.0 V/div 10.0 ms/div
Z8 zoom(C8) 5.00 A/div 10.0 ms/div
Timebase -600 ms 200 ms/div 20 MS 10 MS/s
Trigger C8 DC Stop 5.95 A Edge Positive

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Irms
Va:Ia	117.180 V	117.180 V	0 mV	167.62 V	-167.52 V	335.11 V	5 mA

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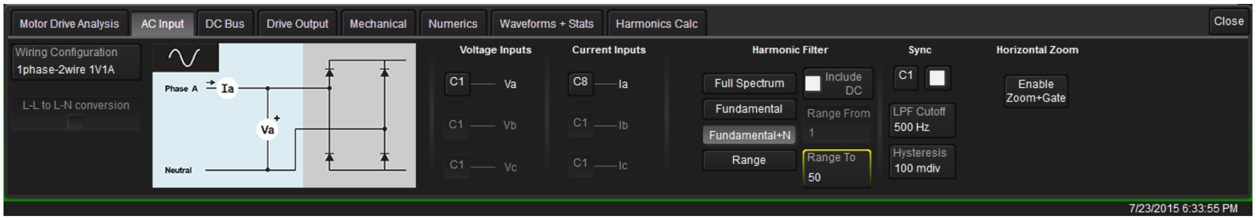
Fig. 9. AC line measurements with toaster load off.

The setup dialog for the single-phase line voltage and current measurements in this example is displayed in Fig 10. Note that calculations are made including a harmonic filter (with harmonic orders included through the 50th harmonic) and excluding dc measurement offsets (the "include DC" checkbox is unchecked) to eliminate the slight (<0.25%) dc offset introduced by the measurement system.



Wiring Configuration: 1phase-2wire 1V1A

Voltage Inputs: C1 — Va; C1 — Vb; C1 — Vc

Current Inputs: C8 — Ia; C1 — Ib; C1 — Ic

☐ Include DC

Range From: 1

Range To: 50

Sync: C1 ☐

LPF Cutoff: 500 Hz

Hysteresis: 100 mdiv

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Fig. 10. Set-up dialog for single-phase ac line measurements in the toaster load example.

Conclusion

In this part, concepts relating to ac line voltage in motor drives have been explained with a focus on single-phase ac voltages. In the next installment in this series (part 3), the discussion continues with explanations of concepts relating to three-phase ac voltages and utility voltage classes. For a full list of topics that will be addressed in this series, see part 1.

About The Author

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

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