A Practical Primer On Motor Drivers (Part 3): Three-Phase AC Line Voltage

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The previous installment in this series began by introducing the concepts of ac voltage, current and power as they relate to motor drives. Mainly this section was meant to familiarize readers with the basic conventions of ac power distribution as may be encountered in residential or commercial applications, where single- or three-phase power is brought from the utility pole into the customer's premises. Concepts such as RMS, peak, and peak-to-peak voltage and the relationships between them were reviewed. With this background, the basic methods of measuring ac voltages using oscilloscopes were explained and demonstrated.

In that part 2 article, the focus was on distribution and measurement of single-phase ac voltages. Now, in part 3, the discussion continues with details on the distribution and measurement of three-phase ac voltages. Most of this discussion simply reframes the concepts and techniques discussed in part 2 on single-phase waveforms as they apply to three phase. However, this part 3 article extends the discussion with a section explaining the utility voltage classes as defined by ANSI/IEEE and other organizations. Some differences in voltage classes between the U.S., Canada and Europe are noted and some related measurement implications are discussed.

Three-Phase AC Line Voltage

Three-phase ac systems are more complicated than single-phase systems when describing voltages. One may distribute three-phase voltages with a variety of different "wye" or "delta" connection configurations. It is beyond the scope of this document to describe all possible permutations, so it will describe only the most common types.

In a three-phase system, there is (by design) "balance," in that the three-phase voltage vectors have the same voltage magnitude and are separated from the other phases by 120°, or 1/3 of a full sinusoid period. Therefore, the sum of the three voltage vectors in a balanced three-phase system should be zero. Thus, practically speaking, the neutral line is always at zero voltage potential. However, if there is a fault (failure) condition or a leakage of current to ground, the neutral may have a non-zero voltage potential.

As in a single-phase system, the three different phase voltage vectors rotate at a constant rate. This rotation and separation between each phase in a three-phase system makes it possible to produce rotating magnetic fields that can perform work, such as in an electric motor.

The three-phase voltage vector system appears in Fig. 1.

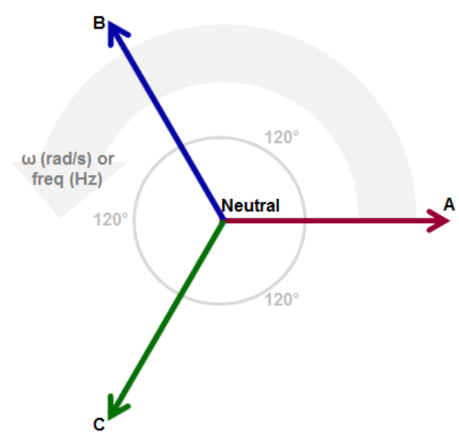

Fig. 1. Three-phase voltage vector system.

When electrically observed as three different voltage-vs-time waveforms, the "rotating" voltage vector system appears as three sinusoidal waveforms as seen in Fig. 2. The waveforms are at the same fixed frequency but out of phase with respect to each other by 120° (as described above).

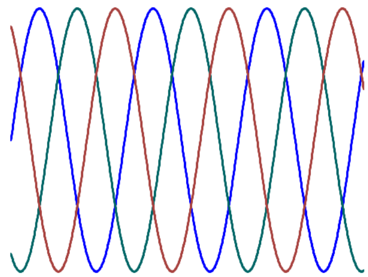

Fig. 2. When viewed in the time domain, the rotating voltage-vector system appears as three sine waves.

In a three-phase ac system, voltage can be measured either from line-to-line (phase-to-phase) or from line-to-neutral (phase-to-neutral).

Note that line-to-line may also be referred to as phase-to-phase. The convention for indicating a line-to-line measurement is to show the voltage symbol "V" followed by a subscripted "line-line" designation, with the first line shown as the "to" line and the second line shown as the "from" line. Thus, measuring from line A to line B is expressed as $V_{A\text{-}B}$ or simply V_{AB}. This is different from the vector notation for AB, which defines a vector direction from B to A.

To measure from line-to-neutral, the neutral must be present and accessible. The neutral is often present in a motor winding but is usually not available as a measurement reference point. Remember that an accessible motor case or chassis ground is ***not*** the same as winding neutral. Thus, it is more common to measure motor voltages from line-to-line than it is to measure from line-to-neutral.

The convention for indicating a line-to-neutral measurement is to follow the voltage symbol "V" with a subscripted "line-neutral" designation, with the first line shown as the "from" line and the second line shown as the neutral. Thus, measuring from line A to neutral is expressed as $V_{A\text{-}N}$ or simply V_{AN}.

One may find cases in which line-to-line voltages may be too high to measure based on the rating of the available voltage measurement device, and the neutral may be inaccessible. In this case, an alternate approach to voltage measurement is on a line-reference basis by connecting the low-voltage side of the measurement devices (e.g., the "ground" of a single-ended probe or the low side of a differential probe; either must carry a sufficient voltage rating) and allowing them to "float" at a voltage other than neutral. This is not a true line-neutral voltage measurement, but it does provide a measurement to a common reference point and is suitable for many measurements.

Measurements of line-to-line RMS voltage magnitudes may be converted to line-to-neutral RMS voltage magnitudes using the simple formula, $V_{L\text{-}N} = V_{L\text{-}L} / \sqrt{3}$. The peak line-to-line voltage magnitude will lag the peak line-to-neutral magnitude by 30°. To understand these conversions, see Fig. 3, noting that the voltage vector rotation is counter-clockwise in the case shown.

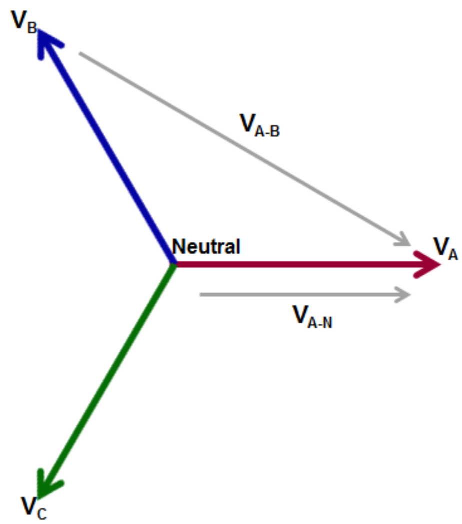

Fig. 3. This vector diagram illustrates the conversion of a line-to-neutral voltage to a line-to-line voltage.

In a three-phase system, we express the rated ac voltage in Vrms, but the rated voltage value is a line-to-line voltage value. In a single-phase system, the rated voltage value is a line-to-neutral value because there may not be a second line to reference a voltage to in a single-phase system. Therefore, if a three-phase system is rated at 480 V or 480 Vac, this means that the three-phase system is 480 Vrms *line-to-line*. Applying that knowledge allows us to calculate other voltage values, as follows:

$Vpk_{L-L} = \sqrt{2} * Vac$, or $\sqrt{2} * Vrms = 679$ V

$Vpk\text{-}pk_{L-L} = 2 * Vpk_{L-L} = 1358$ V

This is plotted in Fig. 4.

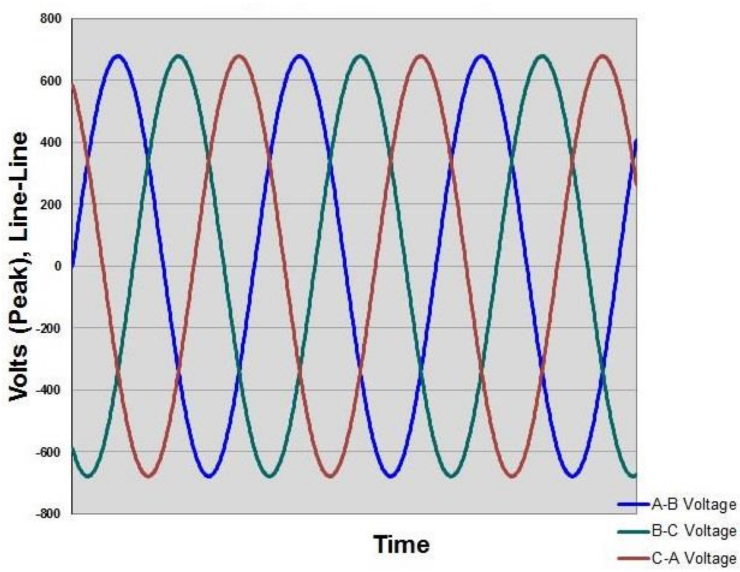

Fig. 4. AC three-phase utility voltage, 480 Vac, measured line to line.

When using a Motor Drive Analyzer with a suitably rated voltage probe (e.g., a Teledyne LeCroy HVD3106 HV differential probe) to perform line-to-line probing of a 480-V electric utility ac supply, we may verify these signal levels through use of the cursors and measurement parameters. Note that in this case, a differential voltage probe is required with sufficient isolation to ground (a safe value is the calculated Vdc value) and a differential voltage measurement capability equal to the maximum peak-to-peak voltage expected (in this case 1358 V) plus a sufficient margin (determined by the user).

The HVD series of probes is rated for 1000 Vrms isolation to ground and up to 2000 Vpk-pk, making it a suitable choice. See the screen image in Fig. 5 for an example of (nominal) 480-Vac three-phase voltage signals acquired and displayed.

Fig. 5. Waveforms for a 480-Vac three-phase line as measured by a Motor Drive Analyzer and suitably rated voltage probes.

Fig. 6 offers a zoomed version of the Numerics table at the bottom of the display. This table provides measurement parameters.

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Vthd
Vab:Ia	473.24 V	473.24 V	0 mV	677.3 V	-677.9 V	1.3545 kV	934 m%
Vbc:Ib	483.34 V	483.34 V	0 mV	693.5 V	-692.9 V	1.3865 kV	956 m%
Vca:Ic	478.16 V	478.17 V	0 mV	686.1 V	-685.5 V	1.3716 kV	955 m%
Σabc	478.25 V	478.25 V	0 mV	693.5 V	-692.9 V	1.3865 kV	948 m%

Fig. 6. The voltage readings associated with the 480-Vac waveforms displayed in Fig. 5.

Note that the Vrms and Vac values are the same for a given line-to-line voltage, but differ slightly among the phases (this is normal). Vdc is 0 V, and the Vpk+ and Vpk- values are roughly equal. These various voltage values differ only slightly from the nominal values described earlier, most likely because these various voltage values were measured under a no-load condition.

Under load, the voltage may be reduced (as with the 120-V example described earlier) and this is why 480 Vac is also commonly referred to as 440 Vac or 460 Vac. Note also that the THD is a small percentage (<1%) but is not zero. If a load were present, there would likely be more distortion on this signal.

The setup dialog for the measurements above appears in Fig. 7. Note that calculations are made with a harmonic filter applied (harmonic orders included through the 50^{th} harmonic) and excluding dc measurement offsets ("include DC" checkbox is unchecked) to eliminate the slight (<0.25%) dc offset introduced by the measurement system.

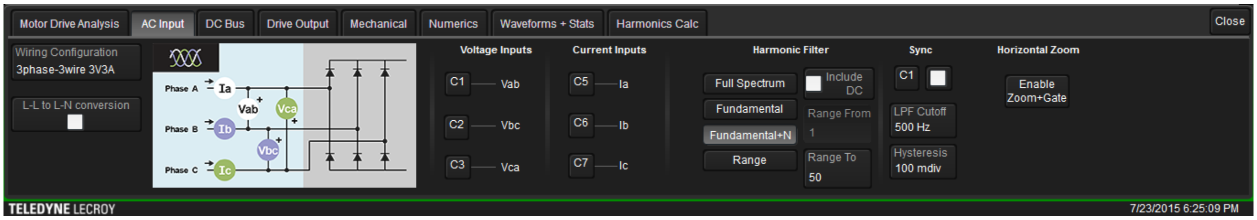

Fig. 7. Setup dialog for 480-Vac three-phase voltage measurements.

If a neutral wire is present, then the three-phase voltages may be measured line-to-neutral. Applying our earlier description allows us to calculate the following:

$Vrms_{L\text{-}N} = Vrms_{L\text{-}L} / \sqrt{3} = 277$ V (in this case)

$Vpk_{L\text{-}N} = \sqrt{2} * Vac_{L\text{-}N}$, or $\sqrt{2} * Vrms_{L\text{-}N} = 392$ V

$Vpk\text{-}pk_{L\text{-}N} = 2 * Vpk_{L\text{-}N} = 792$ V

$Vdc = \sqrt{2} * Vac_{L\text{-}N} * \sqrt{3} = 392 \text{ V} * \sqrt{3} = 679$ Vdc (if rectified and filtered).

The $Vpk\text{-}pk_{L\text{-}N}$ and Vdc terms are plotted in Fig. 8.

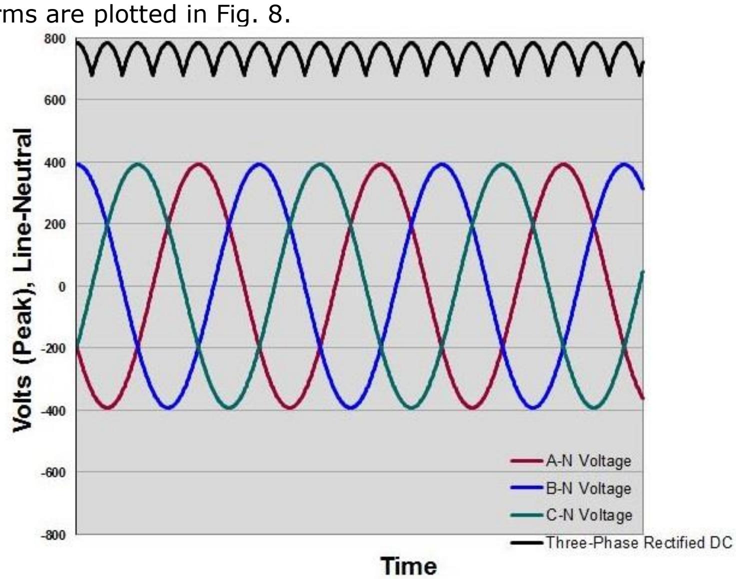

Fig. 8. AC three-phase "utility" voltage 480 Vac, measured line-to-neutral.

When using a Motor Drive Analyzer with a suitably rated voltage probe (e.g., a Teledyne LeCroy HVD3106 HV differential probe) to perform line-to-neutral probing of a 480-V electric utility ac supply, we may verify these signal levels through use of the cursors and measurement parameters. The screen image in Fig. 9 shows an example of a (nominal) 480-Vac signal acquisition with a complete set of voltage measurements.

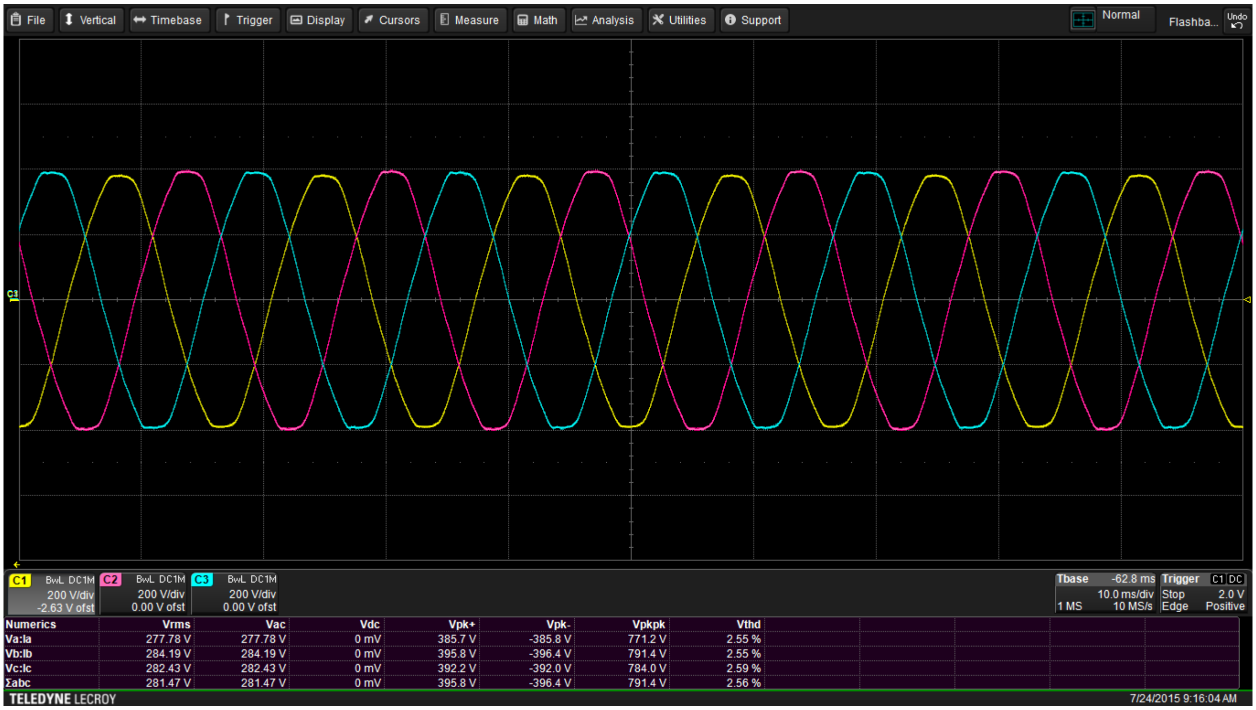

Fig. 9. 480-Vac three-phase line waveforms measured line to neutral.

The Numerics table at bottom of the display provides the following measurement parameters (Fig. 10.)

Numerics	Vrms	Vac	Vdc	Vpk+	Vpk-	Vpkpk	Vthd
Va:Ia	277.78 V	277.78 V	0 mV	385.7 V	-385.8 V	771.2 V	2.55 %
Vb:Ib	284.19 V	284.19 V	0 mV	395.8 V	-396.4 V	791.4 V	2.55 %
Vc:Ic	282.43 V	282.43 V	0 mV	392.2 V	-392.0 V	784.0 V	2.59 %
Σabc	281.47 V	281.47 V	0 mV	395.8 V	-396.4 V	791.4 V	2.56 %

Fig. 10. The voltage readings associated with the 480-Vac waveforms displayed in Fig. 9.

Note that the Vrms and Vac values are the same, Vdc is 0 V, and the Vpk+ and Vpk- values are roughly equal. The Vrms values are slightly higher than the nominal calculated values described earlier, most likely because these voltages were measured early in the morning before most nearby commercial customers were drawing significant load current from the utility service.

If the three line-to-neutral waveforms are "six-pulse rectified" (using an absolute value math function in the Motor Drive Analyzer, shown as F1, F2, and F3 in the right half of the display) and summed (shown as F4, also in the right half of the display), we see that the rectified voltage value varies from ~700 V to ~790 V (Fig. 11.)

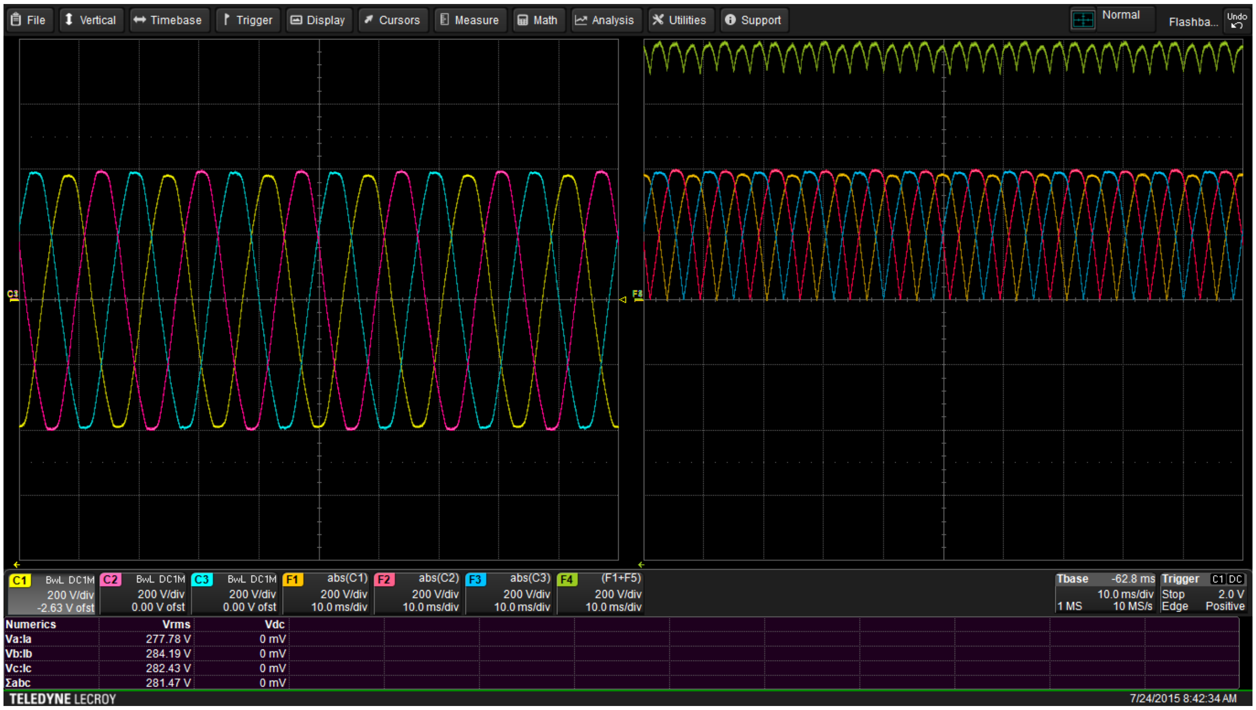

Fig. 11.Probed L-N voltages (left side) and rectified math traces (right side).

If we actually measure the dc bus voltage using a high-precision (1% accuracy), high-voltage differential probe, we can compare the predicted (math) result above to the actual 480-Vac drive dc bus voltage that is both six-pulse rectified and filtered to obtain a near-constant dc value. The dc bus voltage appears as channel 8 (orange trace), and the actual as-measured value is 693 V after rectification and filtering (Fig. 12.) This is consistent with a math calculation ($\sqrt{2} * 281.47 * \sqrt{3} = 689.5$ V) and within the 1% accuracy rating of the high-voltage differential probe.

Fig. 12. Applying actual rectification and filtering to the 480-Vac waveforms produces the dc bus voltage measured on channel 8 (orange trace). Its value is 693 V, which is close to the value calculated previously by the Motor Drive Analyzer.

The setup dialog for all of these three-phase voltage measurements appears in Fig. 13. Note that calculations are made with a harmonic filter applied (harmonic orders included through the 50th harmonic) and excluding dc measurement offsets ("include DC" checkbox is unchecked) to eliminate the slight (<0.25%) dc offset introduced by the measurement system.

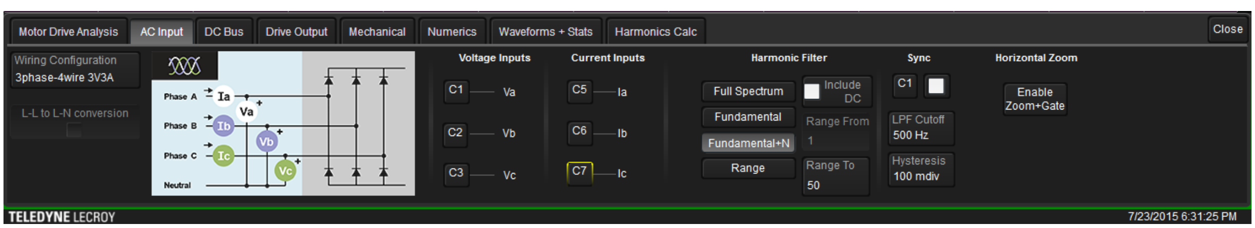

Fig. 13. Setup dialog for 480-Vac three-phase voltage measurements.

Utility Voltage Classes

Various standards bodies, including the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC) and many others, define equipment and testing standards with representatives from the electric utility industry. These standards apply to the various products used to generate, transmit and distribute electricity through an electric utility power system. Standards help to simplify the power system design, equipment purchase, and manufacture of products within a country or region following the same standards.

A voltage "class" is a grouping of similar voltages or voltage ranges, and it is one of the items that is standardized by ANSI, IEEE, IEC, and others. Below is a listing of the ANSI C84.1-1989 standard describing voltage classes. ANSI is a United States organization but organizations in other countries standardize similarly, and many of the standards cross-reference each other.

- Low-voltage, 600-V class (distribution), <1000 Vrms
    - Single-phase (residential and small commercial)
        - 120 V
        - 208 V
        - 240 V
    - Three-phase
        - 400 V
        - 480 V
        - 600 V
- Medium-voltage (generation, distribution, subtransmission)
    - 5 kV (includes 2.4 kV, 3.3 kV, 4.16 kV, etc.)
    - 15 kV (includes 6.6 kV, 6.9 kV, 7.2 kV, 13.8 kV, 14.4 kV, etc.)
    - 25 kV
    - 35 kV
    - 69 kV
- High-voltage and extra-high-voltage transmission are >69 kV

Note that the definition of "low voltage" is very different from what is present on a typical circuit board.

The voltage class ratings are "nominal." The voltage "classes" may also be known by a slightly lower voltage (e.g., 110 V or 115 V instead of 120 V, 380 V instead of 400 V, 440 V or 460 V instead of 480 V, or 575 V instead of 600 V). The lower voltage simply represents a possible or expected supply voltage reduction through the distribution lines in a home or commercial location. Additionally, standards define, and equipment manufacturers often assume, that the nominal voltage will be 15% higher and test accordingly.

Companies may also produce equipment for export at a higher voltage rating than would be used in the home market. To wit, Europe is predominantly 400 V, the United States is predominantly 480 V, and Canada is predominantly 600 V. Companies that produce devices likely design, test, and certify them to operate at all of these voltages. Thus, a European company will need to test 600 V-rated products, and likely will want to test them at 600 V + 15% (690 Vrms) voltage ratings. If we apply this to earlier calculations of voltage values,

$Vpk_{L-L} = \sqrt{2} * Vac$, or $\sqrt{2} * Vrms = 976$ V

$Vpk\text{-}pk_{L-L} = 2 * Vpk_{L-L} = 1952$ V.

The line-to-neutral measurement case is as follows:

$Vrms_{L-N} = Vrms_{L-L} / \sqrt{3} = 398$ V (in this case)

$Vpk_{L-N} = \sqrt{2} * Vac_{L-N}$, or $\sqrt{2} * Vrms_{L-N} = 563$ V

$Vpk\text{-}pk_{L-N} = 2 * Vpk_{L-N} = 1127$ V

$Vdc = \sqrt{2} * Vac_{L-N} * \sqrt{3} = 392 \text{ V} * \sqrt{3} = 976$ Vdc (if rectified and filtered).

Many HV differential probes are rated to 1000 Vrms and the above calculations indicate why this is the case. A voltage of 1000 Vrms is just above the maximum common-mode voltage that could be present in a 600-V class system in the field or under test conditions, as defined by the standards bodies.

If we perform the same calculations on a 4,160 V system (a typical 5-kV class voltage), the results would be:

$Vpk_{L-L} = \sqrt{2} * Vac$, or $\sqrt{2} * Vrms = 5883$ V

$Vpk\text{-}pk_{L-L} = 2 * Vpk_{L-L} = 11.766$ kV.

The line-neutral measurement case is as follows:

$Vrms_{L-N} = Vrms_{L-L} / \sqrt{3} = 2402$ V

$Vpk_{L-N} = \sqrt{2} * Vac_{L-N}$, or $\sqrt{2} * Vrms_{L-N} = 3397$ V

$Vpk\text{-}pk_{L-N} = 2 * Vpk_{L-N} = 6793$ V

$Vdc = \sqrt{2} * Vac_{L-N} * \sqrt{3} = 392 \text{ V} * \sqrt{3} = 5879$ Vdc (if rectified and filtered).

Another widely used, yet unofficial voltage "class," known as low-voltage 50-V safety, rests on the assumption that contact with 50 V presents little danger to people. Many low-voltage motors driven from batteries, such as power tools, or motors in automobiles, operate at <50 V. Additionally, some power conversion systems that drive motors step down the 120-V or 240-V inputs to a lower voltage to drive a motor at <50 V line-to-line or line-to-neutral.

Conclusion

In this part, concepts relating to three-phase ac line voltage were explained. In the next installment in this series (part 4), the discussion shifts to ac line current concepts and measurement techniques. 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.