Power-Line Characteristics

by Dennis L. Feucht

Design of off-line power supplies requires some knowledge of power-line characteristics. This article recounts a few basic design facts.

Power-Line Voltages and Frequencies

The typical US wall outlet supplies 120 V ac rms at 60 Hz. The range of these parameters is contrasting indeed. While line voltage varies significantly line frequency is locked to the NIST frequency standard, transmitted by such stations as WWV in Fort Collins, Colorado at 10 MHz (exactly.) Power companies, such as PGE in Portland, OR, tune in and synchronize their hydro turbines to more significant figures than I could readily count while visiting their control facility years ago.

For design purposes, I use a line voltage range from the nominal value of 117 V rms that has a high value of 135 V (or +15%) and a low value of 100 V (or –15%.) By using 120 V as a nominal design value, the peak voltage is then $120\text{ V} \times \sqrt{2} \cong 170$ V, the nominal, rectified, dc value. The maximum rectified dc value is 190 V, allowing storage capacitor ratings of 200 V. Because the line rarely goes as high as it does low, sometimes a +10%, –15% range from 117 V is used, whereby the maximum voltage is about 130 V rms, or about 185 V peak.

There is no precise design-range value for line voltage because equipment is run on lines distributed under widely varying conditions. An outlet in a building at the end of a long feeder line that is supplied by a near-brownout-loaded grid may be lower than this - especially if the building is wired with aluminum wire, a short-lived fad a while back.

In many parts of the world, such as Western Europe and South America, the power-line frequency is the more calculable 50 Hz instead. And beyond this are Air Force power systems that run at 440 Hz for the benefit of mobile vehicles such as aircraft. The space station uses 10 kHz.

Nominal power-line voltages vary too. Besides 120 V, there is differential 120 V, or ±120 V, which is 240 V end-to-end. Transformers on the distribution lines are center-tapped to allow the two ends to be sources for building wiring. The center-tap is earth grounded.

For three-phase power, the line of each phase has a nominal 120 V to the neutral line. In a symmetric system, each line conducts equal current and the vector sum, which flows in the neutral line, is zero. The phases are separated by 360°/3 or 120°. Across two lines, a and b, is a voltage which is the vector difference of their phase voltages, or $a - b$. Suppose that in the phasing sequence, b leads a by 120°. Then when b is inverted (for subtraction), it lags a by 60°. The phase-to-phase (line-to-line) voltage is the vector difference between two 120 V vectors separated by 120°. The resulting vector magnitude is $120\text{ V} * \sqrt{3}$, or nominally 208 V, with a resulting phase lag of 30° behind the a phase.

To accommodate the world's different line voltages, power supplies are now designed for a *universal line input* range of 85 V rms to 265 V rms. The corresponding peak (rectified dc) values are 120 V to 375 V. For universal-input design, it is convenient to keep the following chart available.

Universal Line Voltage	**Minimum**	**Midrange**	**Maximum**
rms	85 V	175 V	265 V
avg	108 V	223 V	338 V
peak	120 V	248 V	375 V
design peak	100 V	250 V	400 V

The "design peak" row entries are rounded values with some margin, for use in worst-case design. The two extreme values are separated from the midrange value by 150 V. Switching supply simulations or other calculations can use these three voltages as parameters when evaluating the effects of input voltage on converter performance.

Power-Line Impedance

If power-line voltage range is hard to specify, its source impedance is even harder. Power lines are long enough to be regarded as transmission lines, though at 60 Hz, the wavelength is 5 Mm, half way from the equator to either pole. Transmission-line effects result from higher frequencies conducted onto the line from switching loads. Above 1 MHz, the typical power-line has a characteristic impedance of $Z_n = 50\ \Omega$, though it can be as high as 300 Ω and as low as 10 Ω. Below 1 MHz, Z_n rolls off at 20 dB/decade until it reaches its dc resistance value.

In the development of line-operated products some semblance of a typical power line is needed. A Line Insertion Standardization Network (LISN) is a power-line buffer that presents to the load a controlled impedance for test purposes. It usually consists of a power filter that presents a controlled impedance to the device under test. Alternatively, a high-quality UPS not only provides a controlled impedance but also regulates the input voltage to a nominal value. Because UPSs are in high-volume production they are lower in cost than the specialized LISNs and can be a cost-effective alternative. Another line-power source for development are instrument-grade inverters, sold as ac power sources of one or three phases.

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