BY DON LANCASTER

Modern power-factor correction and Internet addressing

THE INTENT AND MEANING OF THE TERM *POWER FACTOR CORRECTION* SURE HAS CHANGED A LOT LATELY. THIS APPEARS TO BE CAUSING A LOT OF CONFUSTION ON MY HELP-LINE. TO STRAIGHTEN SOME OF THIS out, lets get back to the basics...

Power factor: then and now

An electronic *component* is *passive* when there's zero net energy input from anywhere other than its input leads. A component is *linear* if it does not change in any manner with time. Also, in any linear component, the stimulus must be proportional to the response. Kick it twice as hard and it should "ouch" twice as loud.

There are only three possible *ideal* passive linear electronic components. All real components are made up of lumped or distributed combinations of these three.

The first component is the *resistor*. A resistor converts current into heat or light energy, following a *power = volts (amps* equation. Since there is zero energy storage, there is no way your current can get behind or ahead of the voltage. Current and voltage are said to be *in phase*.

When a fixed-frequency sinewave voltage is applied, a sinewave current will result. This current follows the voltage per Ohm's law.

The second component is known as the *inductor*. An inductor is a coiled conductor with or without a field-intensifying core. An inductor *temporarily* will convert current into energy storage in a *magnetic field*.

The voltage-current rule for any inductor states that...

$$e = L\Delta i/\Delta t$$

This tells us that the voltage across an inductor is proportional to its size times the *rate of change* of a current through it. As the current increases, the magnetic field energy will go up and vice versa.

A pure inductor does *not* "waste" energy. It simply *stores* energy in its internal magnetic field.When a voltage gets applied to an inductor, its current will slowly build up. Thus, current will be "behind" the voltage in an inductor. If you apply a voltage sinewave, you should see a current *cosine* wave which is precisely one quarter cycle behind. Since there are 360 degrees of phase in one full cycle, we say that the inductor current *lags* in phase by exactly 90 degrees.

The third ideal component is called the *capacitor*. A capacitor is a pair of conducting plates separated by air or other insulating material. A capacitor *temporarily* converts voltage into energy storage in some *electric field*.

The current-voltage rule for a capacitor states that...

$$i = C\Delta V/\Delta t$$

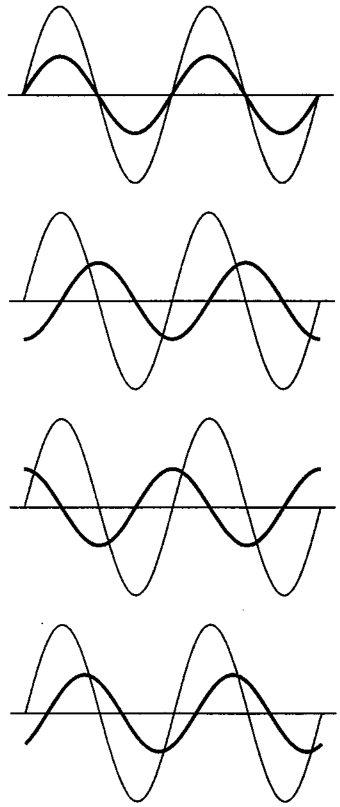
...telling us that the current into a capacitor is proportional to its size times the *rate of change* of voltage across it. As the voltage goes up, the electric field energy goes up and vice versa. Reversing the voltage also reverses the sense of the field energy.

As with the inductor, an ideal capacitor does *not* waste any energy. It stores that energy in its electric field. If a current is sent to a capacitor, its voltage will slowly build up. The current will usually be ahead of the voltage in a capacitor. Which has to mean that the voltage will usually be behind the current. If you apply a voltage sinewave, you'll get a current *negative cosine* that is precisely one quarter cycle *ahead*. Since there are 360 degrees of phase in one full cycle, we can say that the current *leads* by 90 degrees.

There's an easy and ancient way to remember all this: Good old *ELI the ICE* man. The *E* (voltage) is ahead of the *I* (current) in the *L* (inductor). The *I* is ahead of the *E* in the *C* (capacitor).

Ideal components do not occur in the real world. Because an insulator, conductor, or semiconductor above absolute zero *will* have resistance and unavoidable conversion of current into heat. Any conductor that routes between two separate points in space *will* have inductance and unavoidable magnetic field energy storage. And any two con-

ELI THE ICE MAN



In an ideal **RESISTOR**, all incoming energy is converted to heat without any field storage. Voltage and current are in phase. The power factor is 1.0.

In an ideal **INDUCTOR**, all incoming energy is converted to energy storage in a magnetic field. Current **lags** voltage by 90 degrees. The power factor is 0.

In an ideal **CAPACITOR**, all incoming energy is converted to energy storage in an electic field. Current **leads** voltage by 90 degrees. The power factor is 0.

A real **MOTOR** has both inductive and resistive components. Current lags voltage by the ratio of real to reactive power. The power factor shown here is 0.8 lagging.

FIG. 1—THE POWER FACTOR of a circuit is the ratio of the real to reactive input power. Power factor is expressed as the cosine of the phase angle between the voltage and current. A classic power factor correction involves getting the input fundamental frequency voltage and current in phase.

ductors separated by an insulator *will* have capacitance and unavoidable electric field storage. I have summarized these lead-lag rules in Fig. 1.

Enter the power company– stage left

The power company only charges you for the energy you actually *use*. Generating light, burning it as heat, converting it to a mechanical motion (which ultimately becomes heat), or by otherwise never returning it. On the other hand, the energy you store in an inductor gets returned early on in the next cycle. As does any energy you might store in any capacitor.

We can define *real* power as the energy you actually use. The *reactive* power is energy that swaps back and forth between you and your utility company, temporarily getting stored in electric or magnetic fields.

The *power factor* is defined as the ratio of the real energy to reactive energy. Specifically, it is the *cosine* of the *phase angle* of the current waveform compared with the voltage.

A purely resistive load would have a power factor of 1.0 or unity. Any load which stores as much magnetic energy in an inductor as gets actually used would lag by 45 degrees or have a power factor of 0.707 *lagging*. A load which retains as much electric energy in a capacitor as gets actually used would lead by 45 degrees or have a power factor of 0.707 *leading*.

The power factor of any ideal inductor or capacitor is zero. Why? Because the cosine of +90 or (90 degrees is precisely zero. Why should the power utility care how much reactive power you use? After all, you're going to give it right back a few milliseconds later. The problem is that line *current* is required *both* for real and reactive power. The *extra* current consumed by all your reactive loads still causes utility losses in the resistance of their lines. It also demands higher currents in all the generators and transformers and such. The utility's costs go up, yet they have sold no more electricity.

Most of your home loads are resistive (light bulbs, for example) or partially inductive (motors and compressors). Capacitive loads (such as an electroluminescent night light) are quite rare in normal home or industrial use. Thus, you are likely to have a lagging power factor.

The power company applies *power factor compensation* to clean up their own act. They might compensate their reactive power by hanging capacitors on poles every now and then, or by purposely overdriving a synchronous generator to intentionally produce a *leading* power factor.

But note that hanging capacitors on one line end to compensate for inductors on the other does not fix much, because the reactive current *between* the two still contributes to huge transformer and line losses. Thus, *a utility cannot "fix" a customer's power factor*. Utilities do punish large industrial electricity users if their power factor is too low. Their bill goes up when their power factor goes down. This encourages the industrial user to do its own power factor correction with capacitors or overdriven generators.

So, the classic definition of *power factor correction* was taking steps to reduce longer distance fundamental frequency reactive energy transfers. Getting the fundamental frequency voltage and current waveforms back in phase with each other.

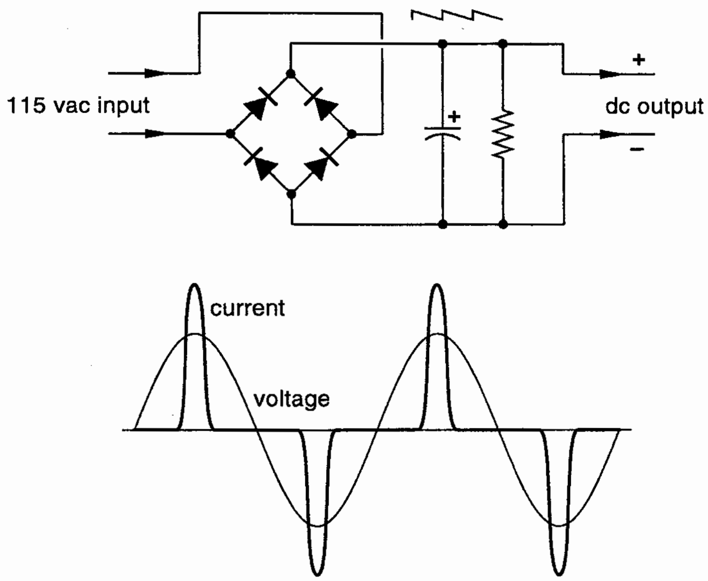


FIG 2—A TYPICAL LINE-OPERATED POWER SUPPLY draws its current in very large, very narrow, and high harmonic mid-cycle pulses. Modern power-factor correction involves both minimizing these harmonics and getting the input fundamental frequeny voltage and current in phase.

The modern problem

All of that is ancient electrical engineering. But lately, things went nonlinear. Electronic circuits started needing lots of rectifiers for internal DC power. The loads were no longer time-invariant. Figure 2 shows the current waveform of a typical capacitor-input full-wave rectifier. For most of each half cycle, *zero* power is drawn. It is only very near the *peak* of each half cycle that the diodes switch on and draw a humongous and very narrow slug of current.

The utility has to provide this peak current. In spite of the fact that they are doing *absolutely nothing useful* for the rest of the cycle.

Well, the *fundamental frequency* voltage and current are still in phase with each other. At first glance, there appears to be no need for any classic power-factor correction.

But my oh my, the harmonics. As we have seen before, narrow pulses consist of a fundamental frequency and lots of harmonics. Mostly odd, some even. *Fourier* series and all. Besides having to provide ten or twenty times the peak fundamental current capability, there's bunches of harmonics overloading the utility's transformers and such.

Ordinary home electronics is bad enough. But we've now got lighting ballasts and industrial motor controls adding to the mess. Something has to be done to minimize these harmonics and outrageous current slugs.

The trick is to do what you have to so that your drawn current gets back to looking at least roughly like an in-phase fundamental frequency sinewave. And that is what modern power factor correction is really all about—harmonic stomping.

So, the definition for "new" power factor correction is making all of the current drawn to be in phase with the fundamental voltage *while* having as little harmonic energy as possible.

One way to handle this waveform improvement is with a *preregulator*. You still use a full wave rectifier, but you only *lightly* filter it with a small capacitor. The diodes now conduct over nearly the full cycle. You next take this changing full wave rectified waveshape and then *step it up* to a fixed and higher DC voltage. Say 200 volts. You can do this with a special regulator that involves a *power factor correction* integrated circuit.

Now for the tricky part: Not only do you have to step your voltage up differently in different parts of *each* half cycle, but you also want to draw *less* current with *large* stepups. And *more* current with *small* stepups!

The reason for all this is that you will want the *average* of your drawn current to look pretty much like a fundamental and in-phase sinewave. Thus, early in your half cycle, you'll want low currents but high voltage

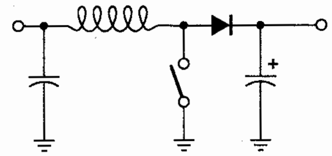


FIG. 3—A BOOST SWITCHING REGULATOR CIRCUIT is normally used for stepping up DC voltages. Repeatedly closing the switch ramps up the current. Opening it transfers the stepped-up voltage to the load. The same idea can be used for power-factor correction if you input a full-wave rectified waveform and if you use very fancy switch duty cycles and repetition rates. The tricky part involves drawing more average current mid-cycle and less near the edges.

stepups. A quarter way into the half cycle, you should want to be drawing more current but providing for less voltage stepup. And midway at the half cycle peak, you'll want lots of current but only a minimal stepup.

Figure 3 shows a switching circuit known as a *boost regulator*. You briefly close your switch. The current in the inductor starts at zero and begins ramping up. Open the switch. Because of good old ($\Delta i/\Delta t$), you can not immediately change the current through an inductor.

The current through the inductor will be the same immediately before and immediately after you open the switch.

The diode now conducts and the inductor delivers its current into the output capacitor and load.

The inductor's current should now start dropping, caused by the draw of any resistive load. Close the switch again to ramp up your current. Open the switch to transfer energy to the load. The inductor's current will be roughly constant but has a slight high frequency triangular ripple.

Your typical switching frequencies these days go from 20 kHz on upwards. As you vary the *duty cycle*, or the percentage of time the switch is on, you'll vary the output voltage. Feedback can hold the output voltage to any voltage you like.

Well, any voltage *above* the input supply that is. If you never close the switch, your input voltage appears at the output. Thus, a boost converter is just that–a method for controllably *increasing* an input voltage. To convert a boost regulator into a power factor corrector, we have to get sneaky with our switch timing. At mid waveform, we will want a *short* on-time for a limited step up. However, we will also want a *high frequency* for maximum current.

Near the waveform zeros, we will want a *long* on time for a *large* step up. But we'll also need a much *lower frequency* to do the stepups not as often for lower current. Thus, some really fancy footwork is required to continuously change *both* the step up ratio and the drawn current. All the while adjusting for a changing load current or a drifting supply voltage. But all you are doing is continuously changing the repetition rate and the pulse width in a magic way.

Note that the small input filter capacitor provides an averaging energy storage for these high frequency variations. All that the utility has to give us is a clean fundamental frequency current sinewave at unity power factor. Three primary sources for power factor correction chips include *Micro Linear*, *SGS* and *Unitrode*. Free applications notes are available. The trade magazines here include *Power Quality* and the *EPRI Journal*.