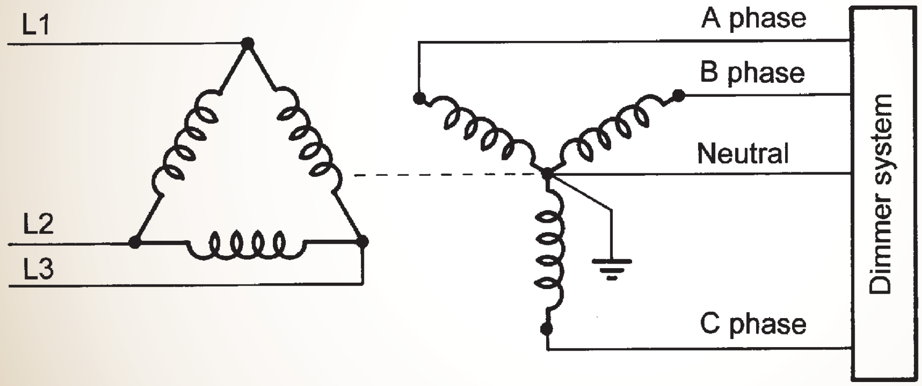


Typical Delta-wye transformer

New power tools provide quality **and** efficiency

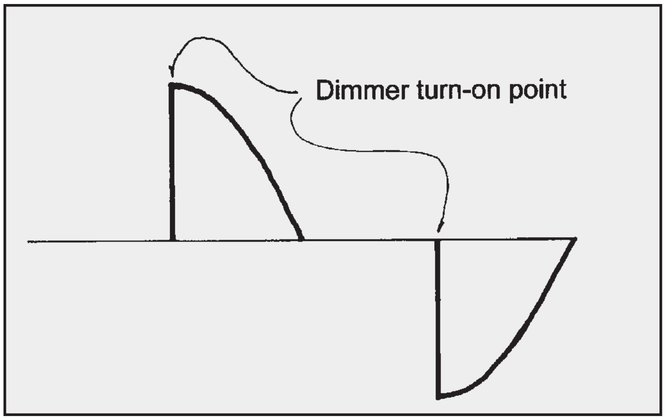
BY **STEVE TERRY**

FOR QUITE SOME TIME, it has been well understood that phase-control SCR dimming systems used in the entertainment industry are producers of harmonic currents that require consideration in the design of the electrical system. Phase-control dimming systems are non-linear loads—they do not draw current in a pure sine wave, but in a chopped version of a sine wave, depending on the aggregate level settings of all the dimmers in the system. These non-linear currents produce triplen harmonics (3rd, 9th, 15th, et cetera) of the fundamental 60 Hz or 50 Hz line frequency. Also known as zero-sequence harmonics, triplens on three phases add rather than cancel in the system neutral conductor. They can cause excessive heating of conductors, neutral overcurrents, nuisance tripping of circuit breakers, excessive heating of transformers, and excessive distortion of the voltage supplied to other equipment in a facility.

The basic design of phase-control SCR dimmers dictates that they (and the loads connected to them) are harmonic-producing non-linear loads. There is no practical design change to an SCR dimmer that can change this fact. The trick in using phase-control dimmers effectively and efficiently is to insure that those harmonic **currents** do not create harmonic **voltage** distortion on the power line that supplies other equipment in a facility. To accomplish this, a number of tools have been used in the last 20 years. These tools have been effective in managing the harmonic problem, but now new developments in harmonic mitigation have increased system efficiency and decreased operating costs. In this article, we will explore the old, standard techniques and examine some of the new ones.

K-Rated transformers—the good and the bad

One of the primary tools used to manage harmonics produced by phase-control dimming systems has been the delta-wye, K-rated transformer designed for non-linear loads. These transformers are constructed to withstand the additional heating produced by harmonic currents, accomplished through the use of more copper, different winding geometries, cooling ducts, more iron in the core, and an oversized neutral terminal. The delta-wye transformer configuration has always been an effective barrier to triplen harmonic currents, keeping them away from other parts of the electrical system, since they recirculate in the transformer's delta primary. This means increased power dissipation in the transformer, but it insures that the triplen harmonic currents do not propagate onto the rest of the electrical distribution system.

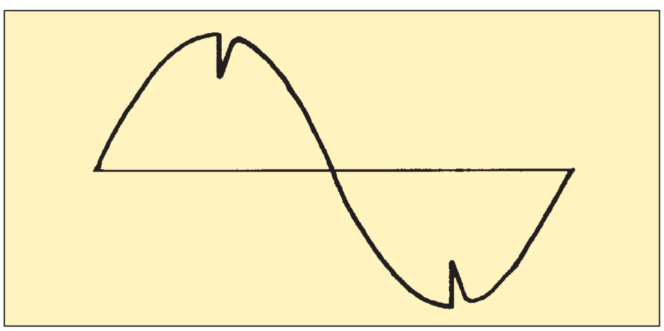


Non-linear current waveform of a phase-control dimming system.

However, the K-rating of a transformer is only a survivability rating that guarantees the transformer will not overheat or be damaged in the presence of harmonic currents. It turns out that K-rated transformers suffer in two other areas of performance:

- Excessive voltage distortion under non-linear loads
- Low efficiency with low loads or no load

The wye secondary of a K-rated transformer presents a relatively high impedance to triplen harmonic currents. This means that in the presence of these harmonic currents, the transformer responds by delivering a distorted voltage waveform to the load. High quality professional dimmers go to great lengths to maintain voltage regulation in the face of this voltage distortion, but it is far from ideal. Above certain distortion levels, the line barely resembles a sine wave, and even the best phase-control dimmers have trouble with stability and regulation. In electrical system design, engineers strive to achieve compliance with IEEE Standard 519-1992 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*. This standard recommends maintaining the voltage quality in the system to not more than 5% total harmonic distortion (THD_V)—a relatively pure sine wave. With a large phase-control dimming system and a K-rated transformer, it is often difficult or impossible to meet this standard. The best one can hope for is a dimming system that can tolerate the voltage distortion (often called *self-pollution* by dimmer designers) and a transformer that blocks the harmonic currents and resulting voltage distortion from the rest of the facility.



Resulting distortion in the voltage waveform feeding the dimming system caused by the non-linear current waveform.

An entertainment dimming system spends most of its life in an OFF or lightly loaded condition. In Europe, it is normal to de-energize the dimming system and any associated local transformer when the system is not being used. However, in North America the dimming system and its local transformer are likely to stay energized all the time. Even with no load, the transformer is consuming power and dissipating heat. A typical 500 kVA, K-13 transformer can consume as much as 5 kW, 24 hours per day, 7 days per week, even where there is absolutely no load from the dimming system it is feeding. That is a big carbon footprint and big cost for power that is doing absolutely no work. And there is a further paradox: it is possible to improve the power quality (voltage distortion) of a K-rated transformer by over-sizing it. However, it then operates in a more lightly-loaded mode, which produces lower efficiency.

Harmonic-Mitigating Transformers to the rescue

A new tool has emerged in the last five years: the Harmonic-Mitigating Transformer (HMT). These devices are also known as zig-zag transformers due to the topology of their windings. This type of transformer was pioneered by companies such as PowerSmiths and Mirus, but is now available from virtually all major transformer manufacturers. HMTs minimize the voltage distortion in the presence of harmonic currents by reducing the impedance seen by the harmonic currents. This is accomplished through techniques such as "zero sequence flux cancellation" to kill triplen harmonics, and through phase shifting, which allows cancellation of the 5th, 7th, and 11th harmonics often seen in variable frequency drives, but not present in a typical phase-control dimming system. As such, this article will not delve into phase-shifting techniques.

The secondary winding configuration of the HMT cancels the zero sequence fluxes (those produced by the 3rd, 9th, 15th triplen harmonics) without coupling them to the primary windings. The coil of wire used for each phase in the secondary winding is split between three poles of the iron transformer core. This flux cancellation also results in much lower impedance to the zero sequence currents and hence lower voltage distortion in the presence of these harmonic currents. In addition, the reduced primary winding circulating current will increase efficiency and allow the transformer to run cooler.

An HMT has a cost premium over a K-rated or conventional transformer. However, the increase in efficiency and reduced no-load losses appear to generate relatively short payback periods for the higher capital cost. In addition, if you are looking for a green solution (see related article on page 42) to power consumption, this is it.

The net results of using a Harmonic Mitigating Transformer:

- Better power quality at input to dimmer system—lower THD_V
- Big operating cost savings due to increased transformer efficiency and reduced no-load losses
- Lower transformer heating
- Reduced facility carbon footprint

Finally, compatibility between entertainment phase-control dimmer systems and HMTs has been proven in a number of high-profile, mission-critical installations such as NBC Studios in New York and the Wynn Hotel in Las Vegas.

Harmonic blocking filters—not for dimming systems

Another solution that has been put forward is the harmonic blocking filter, or harmonic suppression system (HSS). This device is a resistive/inductive/capacitive (RLC) filter tuned to the third harmonic frequency of 180 Hz for a 60 Hz line. It is connected in series between the system neutral conductor and the neutral connection point of the secondary of the delta-wye transformer (and there is a whole other argument way beyond the scope of this article about whether that connection method is NEC-compliant or safe). The device presents a very high impedance to third harmonic currents and a very low impedance to 60 Hz fundamental currents. This prevents harmonic currents from flowing in the neutral and thus the phase conductors as well.

But, remember our discussion of K-rated transformers above? They *also* present a high impedance to third harmonic currents, and the result is voltage distortion or poor power quality. It turns out that with harmonic blocking filters, just as Robert Heinlein said, "*Tanstaafl*" applies. "There ain't no such thing as a free lunch." Blocking filters suppress the third harmonic **current** in the neutral and thus the phase conductors, but at the expense of tremendous third-harmonic **voltage** distortion. Proponents of harmonic blocking filters argue that the devices connected to the line that created the harmonics to begin with are likely to be personal computers or office equipment with switch-mode power supplies. They go on to prove that such devices do not mind excessive voltage distortion. In fact, their argument suggests that switch-mode power supplies actually operate *more* efficiently with excessive voltage distortion caused by triplen harmonics. That may be true, and it is probably just fine if the *only* thing connected to the filter is this type of device.

Remember our phase-control dimming system that might be connected to the filter? It simply cannot perform well when presented with a flat-topped, almost trapezoidal waveform that bears little resemblance to a sine wave. And that is what the harmonic blocking filter produces. The result may be flickering dimmers, poor output regulation, or other failure modes. The bottom line: *Stay away from any tuned Harmonic Blocking Filter in the feed to a phase-control dimming system.*

What about sine wave dimmers?

No discussion of dimming systems and power quality or efficiency would be complete without mentioning sine wave dimmers, a new technology that has come to market in the last five years. Sine wave dimmers produce a nearly pure, sine wave output (generally as good as the sine wave on the line they are fed from). Their primary benefit is reduction of lamp filament noise and the ability to dim many types of loads. A strong secondary benefit is the fact that a sine wave dimmer draws current in a sinusoidal waveform, and is therefore considered a linear load. To acknowledge this, the upcoming *2008 National Electrical Code* has two new definitions added to Article 520, covering *Theaters [sic], Audience Areas of Motion Picture and Television Studios, and Similar Locations*:

> **Solid-State Phase-Control Dimmer.** A solid-state dimmer where the wave shape of the steady-state current does not follow the wave shape of the applied voltage, such that the wave shape is non-linear.
>
> **Solid-State Sine-Wave Dimmer.** A solid-state dimmer where the wave shape of the steady-state current follows the wave shape of the applied voltage, such that the wave shape is linear.

In addition, Sections of Article 520 and 518 (*Assembly Occupancies*) that previously required the neutral feeding solid-state dimming systems to be considered a current-carrying conductor (for wire and conduit fill de-rating to deal with harmonic-produced neutral currents) have been modified. Now, dimming systems that use **only** sine wave dimmers no longer need to consider the neutral a current carrying conductor. However, systems that use a **mix** of sine wave and phase-control dimmers, or that **can** have phase-control dimmers interchangeably field installed with sine wave dimmers, must continue to consider the neutral a current-carrying conductor.

So, this sounds like an indication that sine wave dimmers are the answer to all our efficiency, harmonic mitigation, and power quality problems, right? Yes, but for one consideration: cost. Where sine wave dimmers are needed for absolute quiet in a facility, or to dim a wide variety of load types, their high cost is easily justified. They bring along the added icing on the cake benefit of lower installation costs because they are linear loads. Standard transformers can be used, and neutral overcurrents are a thing of the past. However, sine wave dimmers are still generally thought to be too costly to be justified only as a harmonic mitigating tool.

Legislated power quality?

For some years, there has been a threat that government in Europe and eventually North America might legislate regulations that would obsolete high power phase-control dimmers used in entertainment systems due to their harmonic current waveforms. This has not happened yet, for a number of reasons, not least of which is the very small number of these systems in the world compared to other harmonic producers (arc furnaces, variable-frequency motor drives, and others), as well as the very low duty cycle of entertainment dimming systems. Such proposed legislation was thought to be driven by power utilities who wanted to avoid power quality pollution on their systems and the generation of reactive power that cannot be billed to customers and does no real work. Every discussion of harmonic mitigation (engineered or legislated) has focused on the "point of common coupling" or PCC. This is the point at which customer A's and customer B's electrical systems meet. In North America, this is usually the primary side of a facility's transformer. The goal of any proposed legislation is to prevent power line pollution from one customer from reaching the facility of another customer or the utility's distribution infrastructure. The proposed regulations care little about self-induced power pollution on sections of the electrical system within a facility.

The PCC discussion relates to harmonic currents of entertainment dimming systems, since a local Harmonic Mitigating Transformer is a very effective, efficient, and economical means of stopping the propagation of harmonic currents beyond the transformer-to-dimmer system connection. Should the threatened legislation ever occur, the HMT could be a valuable tool to make phase control dimmer systems compliant with new regulations. ■

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