The case of the hidden harmonic filter

BY STEVE TERRY

Further adventures of the power quality detectives

I RECENTLY WROTE ABOUT NEW TOOLS for harmonic management and power quality ("New Tools Offer Power Quality and Efficiency" in the Fall 2007 issue of *Protocol*). In that article, Harmonic Blocking Filters and their incompatibility with phase-control dimming systems were explained. Coincidentally, just as the article was published, we received a call from one of our dealers, PRG, with a problematic installation of a new dimming system. The failure was quite simple in its description: when large numbers of dimmers were set to levels below full, the entire system flickered and flashed, and horrible noises came from the dimmer rack and feeders. Phase and neutral connections appeared to be torqued to specifications, and the system worked fine as long as a small number of dimmers were energized, or all dimmers were set to full. The system neutral conductor (often a culprit in this sort of flicker-and-flash failure) was sized correctly. Voltages to the dimmer rack appeared to be normal. We had a first class mystery on our hands.

In discussions with Rob Tooker, PRG Project Manager, a small but important clue emerged on an equipment label: The manufacturer of the transformer feeding the dimming system was *Harmonics Limited*. This immediately got my warning bells ringing, since standard transformer manufacturers do not generally have the word *harmonics* in their names. Could there be something hidden in this transformer that was causing the problem?

The symptoms of the failure mimicked those produced by a third harmonic blocking filter, even though there was no filter in evidence. Pulling my Sherlock Holmes hat out of the closet, I conducted a thorough search of the transformer manufacturer's website. This revealed that they make transformer enclosures with *built-in* third harmonic blocking filters connected in series with the neutral conductor (see **Figure 1**). Aha, the smoking gun revealed! Based on past experience, the presence of such a device might be the likely cause of the problem. And now, this case presented a unique and interesting opportunity: we had a system that was likely failing due to an incompatible piece of harmonic mitigation equipment (hidden from view, so far!), and we had "the suspect in the holding cell" so that we could precisely observe and analyze the reasons for the failure.

As such, I asked Rob Tooker (who was responsible for all the fieldwork in this detective story) to go back to the site armed with PRG's Dranetz 4300 power quality analysis system. This type of device is invaluable for analyzing power issues of all kinds. It typically has 4 channels of voltage measurement (A, B, C phases plus neutral-to ground) and four channels of current measurement (A, B, C phases, and neutral).It contains software to create a real-time plot of what is happening in the system, as well as Fast Fourier Transform (FFT) analysis to determine the harmonic content of voltage and current waveforms. It is useful for monitoring spurious power line events that only occur intermittently, because it can be programmed to take a

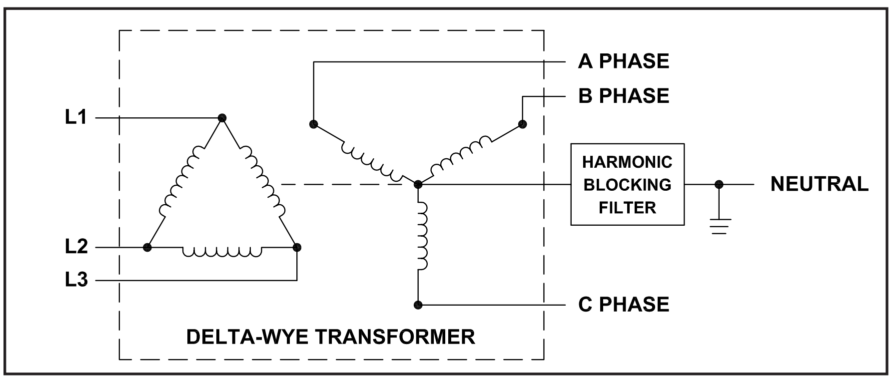

Figure 1--Typical Installation of Harmonic Blocking Filter

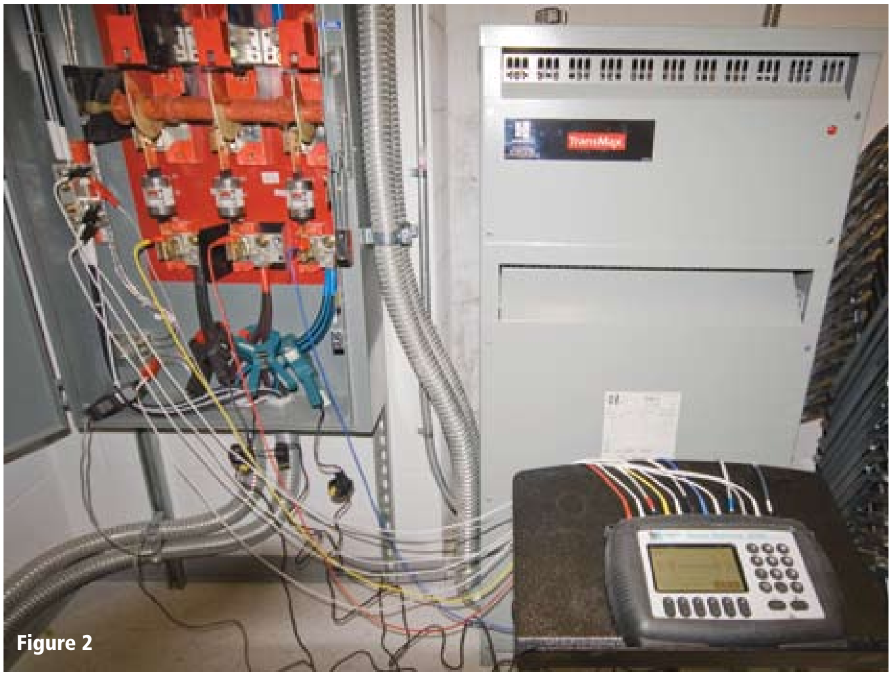
Figure 2

measurement snapshot whenever a predetermined set of thresholds is crossed. For instance, one can say: "Show me everything that happens in current and voltage when the A, B, or C phases fall below 105 volts." Or, "Give me a harmonic analysis whenever the total harmonic distortion in voltage exceeds 5% of the fundamental." It is truly a scene-of-the-crime tool that lays bare any and all power line events for careful analysis and failure mitigation. **Figure 2** shows the system connected at the problem site.

On this project, however, the advanced threshold features of the analyzer would not be needed. Rob simply got the dimming system into a failure mode by setting lots of dimmers at about 50%, and then took snapshots with the analyzer. The results are fascinating evidence of the behavior of a harmonic blocking filter that is connected to a phase-control dimming system, and present clear reasons why one should never do that. As background, let's review how a third harmonic blocking filter works.

A harmonic blocking filter (or Harmonic Suppression System) places an R-L-C (resistive-inductive-capacitive) tuned filter in series with the system neutral connection. This filter presents very high impedance to third harmonic currents of 180 Hz (three times the 60Hz fundamental frequency), and does not allow them to pass. The result, however, is very high third harmonic *voltage* distortion. These filters were originally designed to feed office equipment that uses switch-mode power supplies that do not mind high third harmonic *voltage* distortion, but they are fundamentally incompatible with phase-control dimmers.

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Figure 3--A Phase Voltage & Current--With Filter

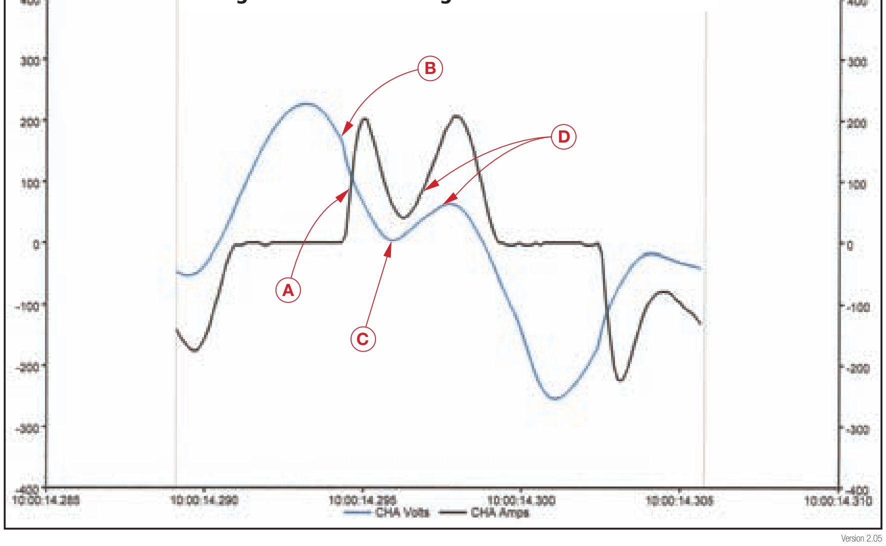


Figure 4--A Phase Voltage Distortion--With Filter

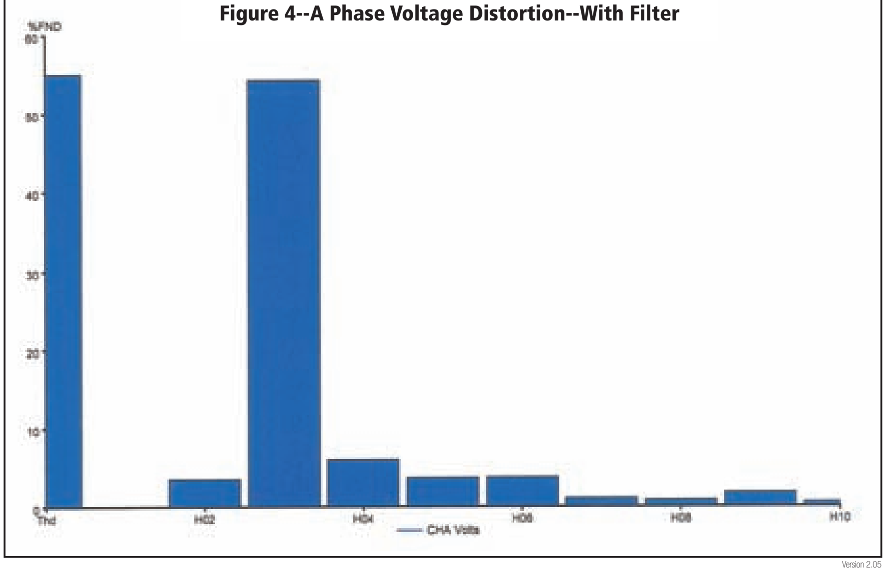
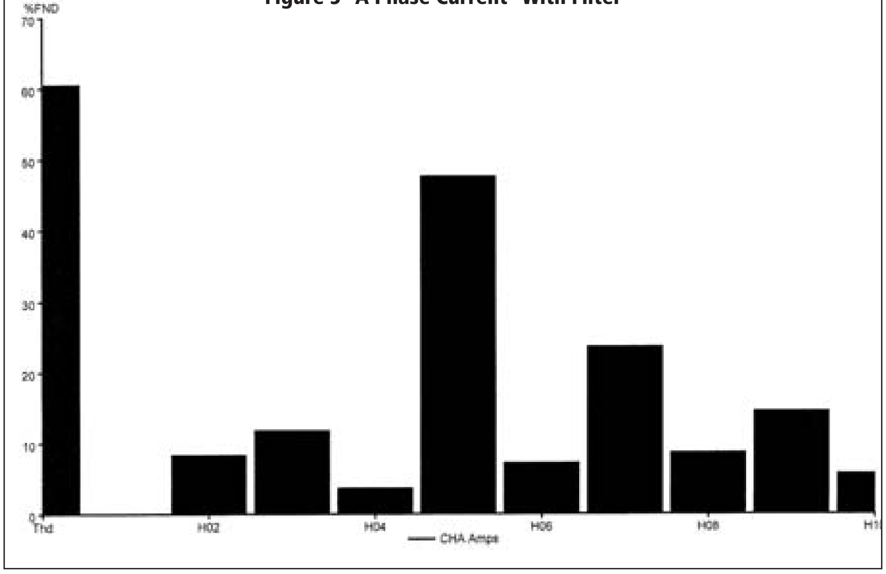


Figure 5--A Phase Current--With Filter



That incompatibility is precisely what happened at our site, as the analysis data shows. Refer to **Figure 3**, which shows the voltage and current waveforms for the A phase when the dimming system is set with all dimmers at 50%. The black trace is current and blue is voltage. At callout A, you can see all the A-phase dimmers turn on and current begin to flow. At this point, the majority of the current is in the third harmonic (normal for a phase-control dimmer), which is where the tuned-filter presents a high impedance. Almost immediately, at callout B, you can see the blue voltage waveform collapse as the third harmonic current is choked off by the filter. The voltage collapse is so severe that the voltage waveform experiences a false zero-crossing at callout C. At callout D, the filter recovers and both the voltage and current begin to rise. Of course, that does not matter much, since our phase-control dimming system is failing miserably due to the extra zero crossing and voltage fluctuations that are far outside its ability to regulate.

Now take a look at **Figure 4**, which is a FFT (Fast Fourier Transform) analysis of the voltage waveform in **Figure 3**. There is tremendous third harmonic voltage distortion, about 55% of the fundamental. And this has exactly the effect that the filter manufacturer wants, as shown in **Figure 5**, a FFT analysis of the *current* in **Figure 3**. You can see that the third harmonic current has been reduced to just over 10% of the fundamental current (see typical third harmonic current in **Figure 9** for what we would expect in a normally operating phase control dimming system). But wait, what's happening here in **Figure 5**? The *fifth* and *seventh* harmonic currents are now nearly 50% and 25% of the fundamental, respectively! Interesting, since phase-control dimmers do not generate fifth and seventh harmonics! Oh yes they do, when presented with a voltage waveform that is so grossly distorted and rich in third harmonic as the one in **Figure 3**. But this presence of fifth and seventh harmonic current is only academically interesting, since the dimming system is failing miserably under these conditions.

Since our harmonic blocking filter is a high impedance in series with the *neutral* (look back at **Figure 1**), which is common to all three phases, it also causes interaction artifacts between the three phases. For a good view of this, take a look at **Figure 6**, a picture of the voltage waveforms on all three phases. These waveforms bear little resemblance to sine waves.

Having conclusively determined that the harmonic blocking filter hidden in our transformer enclosure was the culprit, we asked the owner to determine if the filter could be removed without removing the transformer itself. It could indeed be removed, and when it was, the system magically began functioning normally! Triumph of the Power Quality Detectives!

Rob then went back to the site to gather before and after data. Take a look at **Figure 7** for the A Phase voltage and current waveforms under approximately the same conditions as those of **Figure 3**, but *without* the culprit filter in line. At callout E, the dimmers turn on at about 50% and the current begins to flow. But instead of causing the complete collapse of the voltage waveform that we saw in **Figure 3**, the result of this dimmer turn-on is merely a small notch in the voltage waveform at callout F.

Figure 8 shows us the FFT analysis of the voltage with the filter removed. Note that there is some third harmonic distortion caused by the notching, but the Total Harmonic Distortion in voltage is *less than 5%* of the fundamental, well within the limits set by IEEE 519-2 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*. Now take a look at **Figure 9**, the FFT analysis of the current being drawn by the dimming system with the filter removed. You can see large amounts of third harmonic, and the Total Harmonic Distortion in current is 43% of the fundamental. This sounds like a large number, but because the electrical system is now properly designed to handle

Figure 6--A, B, C Phase Voltage--With Filter

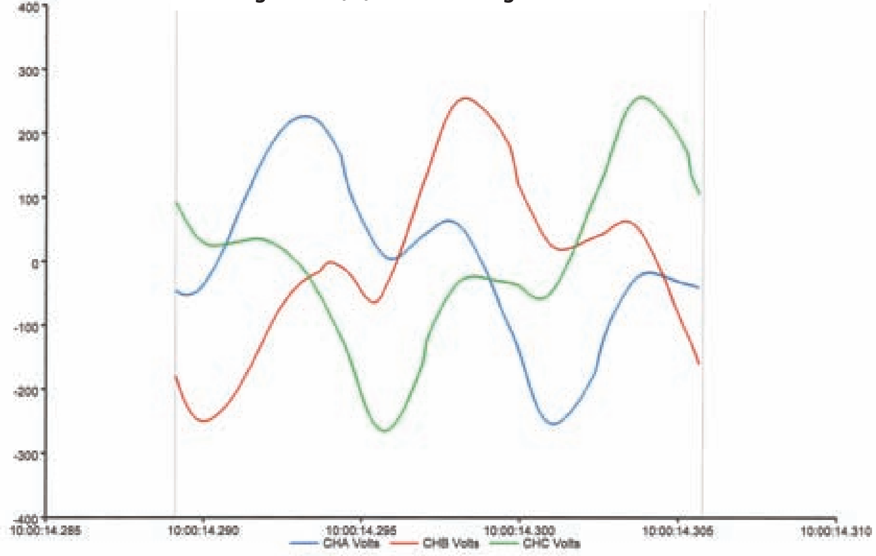


Figure 7--A Phase Voltage & Current--Filter removed

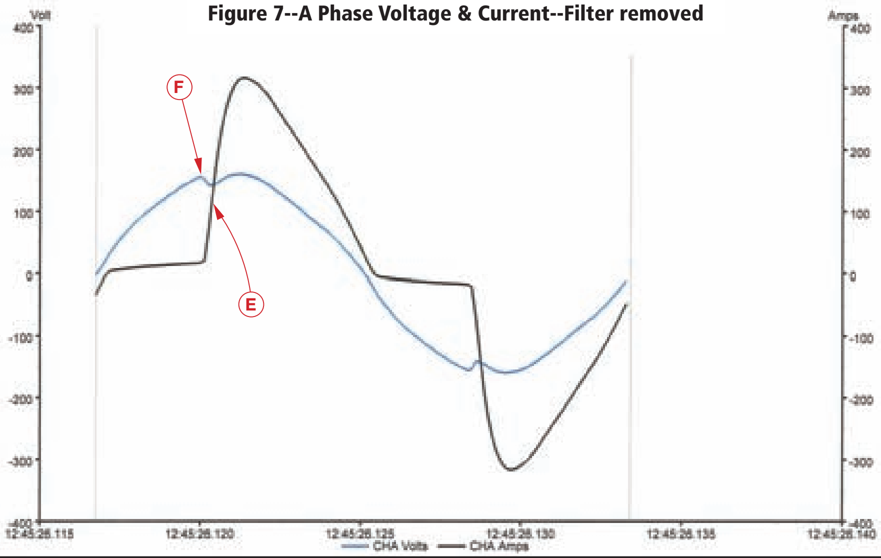


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Figure 8--A Phase Voltage Distortion--Filter removed

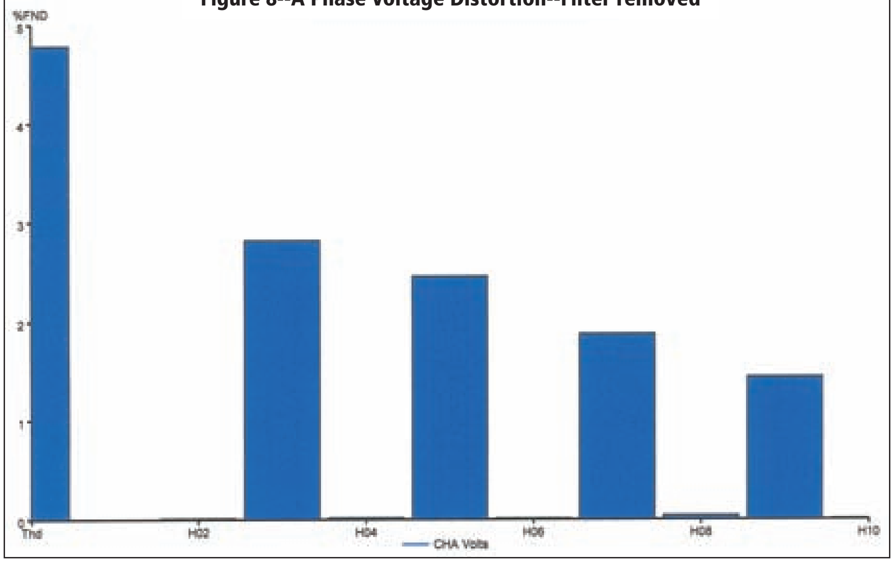
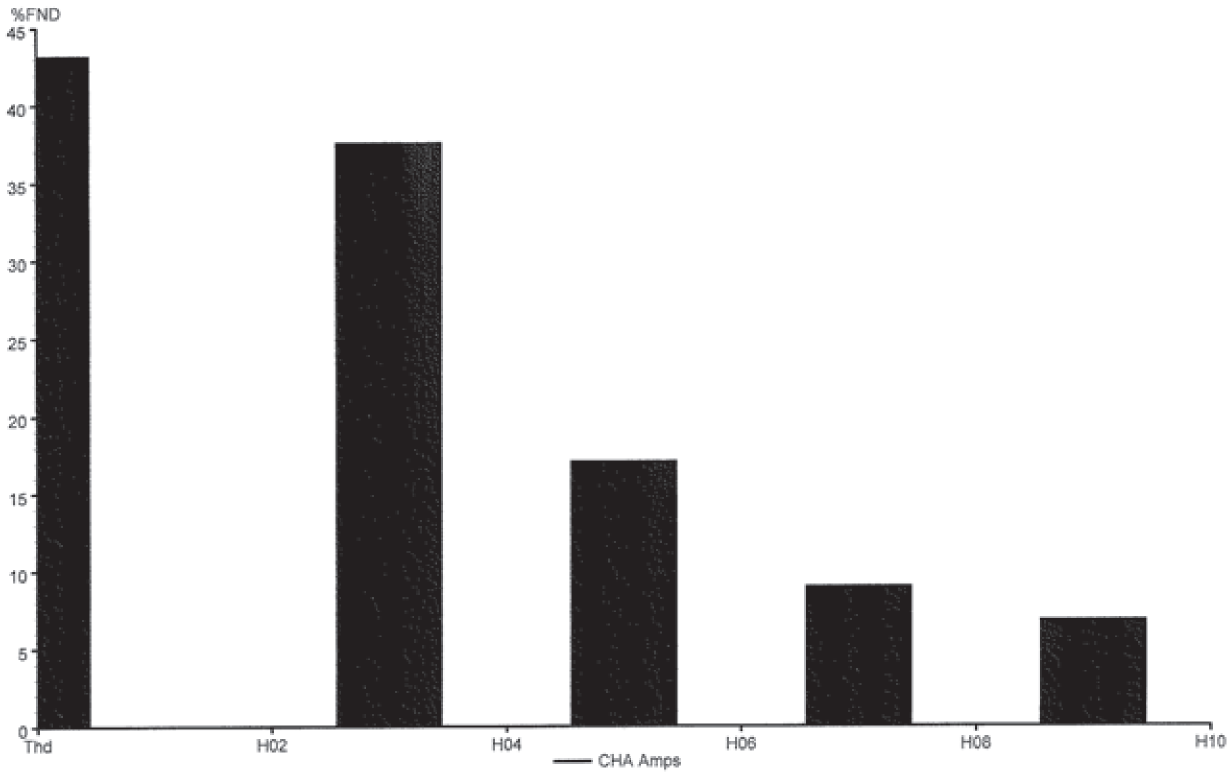


Figure 9-A Phase Current--Filter Removed



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it, the large harmonic currents, which are a fact of life with phase-control dimming systems, are having almost no effect on the quality of the voltage supplied to the system.

There are many methods of dealing with harmonics (see The Harmonic Mitigation Toolbox on page 25). This mystery shows in great detail why the third option, "Accept harmonic currents" method is the weapon of choice when dealing with phase-control dimming systems. Equally important is that not all harmonic mitigation methods work well for all types of equipment, a point that was graphically proved with our culprit harmonic blocking filter. ■

Steve Terry is the VP of Research & Development at ETC, and a sometime Power Quality Detective. He is the alternate USITT representative on National Electrical Code Panel 15, and a member of the ESTA Board of Directors.

The Harmonic Mitigation Toolbox

There are many, many paths to harmonic mitigation in power systems, but the common ones fall into three basic categories:

1. Suppress the objectionable harmonic current. This is the approach of the *passive harmonic blocking filter*.

Pros

- Inexpensive harmonic mitigation solution
- Useful for local harmonic mitigation of specific type of loads such as PC's and office equipment

Cons

- Produces large voltage distortion as a byproduct of suppressing harmonic currents. This voltage distortion may adversely affect equipment other than PC's and office equipment that use switch-mode power supplies. Such voltage distortion may not comply with IEEE 519-2 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.*
- Incompatible with some types of equipment like phase-control dimmers, the mainstay of the entertainment industry. This requires policing of connected loads to maintain compatibility.
- As an artifact, may produce *different* harmonic currents than the mitigation target of the filter. These may require yet another, additional mitigation approach.

2. Inject current into the system using an *intelligent adaptive filter* or *active filter.* These devices contain analysis hardware and software that characterizes the non-sinusoidal current waveform of the harmonic-producing equipment, and then injects current into the feeder in a complementary waveform to make the final current waveform into a pure sine wave.

Pros

- A properly designed and specified adaptive filter will eliminate objectionable harmonic currents without negative byproducts.

Cons

- Breathtakingly expensive—especially at the high power levels typical of entertainment dimming systems
- Physically large and complex—subject to a shorter mean time between failures than passive devices
- Major components such as capacitors (the items that store the current injected into the feeder) have a finite life and require regular replacement.
- May be incompatible with certain types of equipment—there is no industry experience with phase-controlled dimmers

3. Accept the harmonic currents from certain types of electrical equipment (like phase-control dimmers) and **design** the rest of the electrical system to prevent propagation of damaging voltage distortion. This approach relies on proper transformer selection (Harmonic Mitigating or K-rated) and upsizing of neutral conductors where required.

Pros

- Relatively inexpensive
- Completely compatible with phase-control dimming systems—this makes it the choice of the entertainment industry
- Especially applicable to the triplen harmonics produced by phase-control dimming systems, since these are blocked at the delta-wye transformer—the primary tool of this approach.
- Does not require policing of connected loads to insure compatibility with mitigation method
- New, efficient solutions like Harmonic Mitigating Transformers (HMT's) can now do a greener job on this approach than popular K-rated transformers previously used
- Very simple and reliable
- Insures compliance with IEEE 519-2

Cons

- Requires delta-wye HMT's or K-rated transformers between the harmonic producing device (a phase-control dimming system, for example) and the rest of the facility.

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