Tripped up by triplens

IF YOU SAW THE SUPER BOWL XLVII on Sunday, February 3, 2013, then you already know who won, who lost, and who sat in near darkness for half an hour. Even if you didn’t, you probably heard that less than two minutes into the third quarter, a power outage plunged the New Orleans Super Dome into half darkness and full panic after the stadium lights extinguished and the emergency backup lighting took over. What caused the power failure?

“Triplens are third-order harmonics (third, sixth, ninth, etc.), and they can cause excessive current to flow in the neutral conductor of a three-phase, four-wire plus ground system.”

According to multiple internet articles, the problem was blamed on a relay that the manufacturer, S&C Electric, says was set too low, causing it to trigger another device to interrupt the circuit. Whatever the cause, we do know that the failure was not related to Beyoncé’s halftime show, which was a spectacular affair involving pyro, more Clay Paky Sharpys than there are pickets in a picket fence, and an awesome video display. It turns out that the entire production was on generator power. Had it not been, then the blackout might have occurred about 30 minutes sooner and we would not have ever seen the best halftime production ever.

As I watched the game, I had no idea the halftime show was powered by portable generators. So when the blackout occurred, the first thought that popped into my head was that the blackout was somehow related to Beyoncé’s show. My mind went into overdrive, wondering what could have caused such a major snafu. I wondered if the lights were tripped up by triplens.

Triplens are third-order harmonics (third, sixth, ninth, etc.), and they can cause excessive current to flow in the neutral conductor of a three-phase, four-wire plus ground system. The main reason I associated the problem with triplens, wrong as it was, is because I’ve been hearing a lot from people in the industry who have had problems with nonlinear loads, including LEDs, HMIs, and switch-mode power supplies—all of which generate harmonics.

One case involves a tech at a church who noticed an issue with his electrical system. When the audio amplifiers were turned off, the voltage waveform was a beautiful sine wave, but when the amps were turned on, suddenly the voltage waveform was distorted and the peaks were flattened out. The feeder transformer was nowhere near capacity, and the distortion occurs whether or not the amplifiers are idling or at higher output.

The amplifiers in question are switching power amplifiers that use pulse-width modulation to amplify an audio signal. The amplifier electronics run on DC, which is taken from the AC mains power. The power-supply input stage has a bridge rectifier and smoothing capacitor. It only draws current when the AC supply voltage rises above the voltage of the capacitor, and it stops drawing current when the supply voltage drops below that of the capacitor. So the AC current into the power supply pulses on and off each half cycle; once at the positive half peak and once at the negative half peak. These pulses of current cause harmonics to flow in the electrical system.

When the current flows, there is voltage drop because of Ohm’s Law (voltage drop = current x resistance of the circuit). Since the voltage drop occurs only during the peaks of the voltage waveform, if the impedance of the circuit is high enough, it results in the flattening of the voltage waveform.

As the current pulses flatten the peaks
of the voltage sine wave, the waveform starts to resemble a square wave. When that happens, the amplitude of the fundamental frequency is reduced and the amplitudes of the harmonic voltages begin to rise. It’s as if there are multiple sine wave generators of various frequencies (but only whole number multiples of the fundamental frequency) with variable amplitudes. The more the current waveform deviates from the voltage waveform, the higher the amplitudes of the odd numbered multiples of the fundamental frequency (although they drop off in amplitude the higher the frequency). This voltage distortion and the resulting waveform can cause excessive heating of the transformer and shorten its life.

One of the solutions is to upgrade the feeder transformer so that it will never be loaded enough to cause it to heat up enough that it ages prematurely. According to the Computer and Business Equipment Manufacturer’s Association (CBEMA), a transformer experiencing voltage flat-topping should be de-rated according to the formula \( \frac{1.414 \times \text{RMS load current}}{(\text{peak load current})} \). This, of course, requires you to measure both the RMS current and the peak current of the distorted wave form before you can do the calculation.

Another, perhaps better, solution would be to filter out the harmonics by using a filter, either active or passive, or a harmonic mitigating transformer (HMT). Any of these would prevent the harmonic currents from flowing through the electrical system and minimize flat-topping. In the process, it also allows the electronic power supply connected to the grid to operate properly with a lower-current draw, meaning it will run cooler and have a longer life.

Another case involves a movie shoot where there was a mix of HMs and tungsten lights on a portable power generator. The main problem was that the HMs would drop out unless they were on a different generator than the tungsten lights. In this case, the cable runs were very long and they were also close to their maximum ampacity, so in addition to harmonics, excessive voltage drop was probably a significant contributing factor. According to the electrician’s calculations and measurements, the voltage drop alone should not have caused the HMs to drop out, so it was likely the addition of harmonics that pushed the system into the trouble zone.

But how do harmonics contribute to voltage drop?

In a balanced three-phase four-wire plus ground system with no harmonics, the current in the neutral cancels because all three phases are all 120° out of phase with each other. Harmonics cause current to flow in the neutral, even if the system is completely balanced. That’s because every third harmonic—the triplens—reinforce instead of cancel, resulting in current flowing through the neutral conductor.

What does additional current flowing in the neutral conductor have to do with voltage drop? It’s simple. If you understand Ohm’s Law, then you know that the voltage drop is a function of the current times the resistance of the cable. Third-order harmonics can cause more current to flow in the neutral conductor than the amount of current flowing in any one of the three phase conductors—up to 1.732 times as much—so the voltage drop could be almost tripled since the circuit includes the outgoing current in the phase conductor plus the return current in the neutral conductor.

To complicate matters, the phase angle between the voltage and current also influences the current flowing through the entire circuit. The lower the power factor, the greater the phase angle, and the more current will flow through the entire circuit.

The solution in many of these types of cases is to de-rate the equipment to account for the problems caused by harmonics, which can include excessive current flow in the neutral conductor, increased heating in transformers, generators that can lead to shortened life, nuisance tripping of fuses and circuit breakers, damage to power factor correction capacitors, and overheating of cables. Most of these problems can be avoided by making sure the power distribution equipment is not operating close to its full capacity. As with the previous audio problem, there are other solutions, including filtering, both passive and active, and the use of harmonic mitigating transformers.

And if matters weren’t complicated enough already, let’s throw in our metering...
devices as well. If you try to measure the current flow using an average reading meter instead of a true RMS meter, then you won’t read the harmonic currents, only the current contributed by the fundamental frequency. So you might think you are not approaching the ampacity of the cables when you might be doing just that.

It used to be that the only nonlinear loads we used in live event production were dimmers; so we didn’t worry too much about harmonics with the typical lighting system. But that’s all changing. Now, almost everything we plug in is a nonlinear load, usually either pulse-width modulated power supplies (like LEDs and digital amplifiers) or switch-mode power supplies (like digital consoles, video projectors, or anything with a computer chip in it). Our systems are getting bigger and more power hungry, and the nature of our loads is changing, so we should be more aware of how harmonics can affect an electrical system.

Even though the halftime show had nothing whatsoever to do with the Blackout Bowl, it did spark a discussion that might one day prevent another blackout from happening. If you’ve read this far, the show you save might be your own.

“Now, almost everything we plug in is a nonlinear load…”

**What are harmonics?**

In an electrical system, harmonics are sine waves (either voltage or current) with frequencies that are whole number multiples of the power supply frequency—in North America it’s 60 Hz, and in Europe and Australia it’s 50 Hz. The second harmonic in North America, for example, is 120 Hz, the third is 180 Hz, etc.; and in Europe and Australia, the harmonics occur at 100 Hz, 150 Hz, etc. Harmonic currents are created in an electrical circuit any time the connected load draws current in a way that causes the waveform to be different than the voltage waveform feeding it.

It can be challenging to wrap your head around the concept of harmonics at first. Audio engineers sometimes grasp it easier because of the nature of timbre or sonic shapes. A sine wave is a very pure sounding tone, like that used for an emergency broadcast signal. They aren’t very interesting from a timbre standpoint. But if you add some distortion, then the tone begins to have some character. The more a waveform deviates from a sine wave, the more distortion it has, the more character it has, and the more harmonic content it has.

Any waveform that is not a pure sine wave is a complex waveform. You can build complex wave forms using pure sine waves. You start with a sine wave of the fundamental frequency and add harmonics of smaller and smaller amplitudes; the higher the frequency, the lower the amplitude. Any wave shape can be created this way. By the same token, any complex waveform can be deconstructed into a series of sine waves with different frequencies and amplitudes.

When a voltage or current waveform is distorted, it can be thought of as having multiple components, each of which is a harmonic with a different frequency and amplitude.