Active Harmonic Mitigation

WHAT THE MANUFACTURERS DON'T TELL YOU

DESPITE THEIR HIGH COSTS, ACTIVE HARMONIC MITIgation solutions such as parallel active power filters (APFs) and active front end (AFE) drives are growing in popularity. As the newest technology, they are being touted as a better choice than the various forms of passive harmonic mitigation solutions that are presently available. Is this actually the case? Active solutions incorporate switching strategies using insulated-gate bipolar transistors (IGBTs) to make the current drawn by the adjustable-speed drive (ASD), or another nonlinear load, more sinusoidal. You will rarely hear from manufacturers that this switching introduces higher-frequency harmonics, normally above the 50th. When measurements are taken up to the 50th harmonic, the current total harmonic distortion (ITHD) is often quite low. However, when measured up to the 100th harmonic or higher, the ITHDs almost always exceed their claimed performance levels, which consider only harmonics up to the 50th. This is certainly a concern because higher-frequency harmonics are more likely to cause power system problems and issues with other connected loads than the lower-frequency harmonics that they are designed to reduce.

Although IEEE and International Electrotechnical Commission (IEC) industry standards restrict levels of harmonics in the low- and very-high-frequency ranges, there are presently no standards that address the range between 2 and 150 kHz. Therefore, manufacturers often design active harmonic mitigation equipment that generates relatively high levels of these midrange frequencies, particularly since switching IGBT frequencies typically fall precisely within this range.


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Background

APFs, or active harmonic filters as they are sometimes called, and AFE drives have emerged as new trends in harmonic mitigation technology for applications that involve ASDs. Technical publications for APFs date back to the 1980s, and AFE technology appears around the same time. Both are capable of correcting the power network harmonic distortion caused by power electronic, nonlinear loads and require state-of-the-art power electronic switches and advanced control techniques to make the nonlinear load appear almost purely resistive.

The most popular implementation of APFs is the shunt APF, which uses a pulsewidth-modulated (PWM) voltage source inverter technology as its main strategy (Figure 1). Since voltage source inverters are more popular than their alternative, current source inverters, they will be addressed here exclusively. The shunt APFs are parallel connected, reduce harmonics, and improve

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the power quality by generating a compensating current that matches the harmonic current required by the nonlinear load. This compensating current is injected either near the load or at a carefully selected point in the electrical distribution, such as the point of common coupling (PCC).

AFE drives, on the other hand, are series connected and an integral part of the ASD (Figure 2). In an AFE drive, a PWM rectifier replaces the simple diode bridge rectifier used in conventional ASDs. The PWM rectifier employs fully controlled IGBTs in essentially the same configuration as the drive's PWM output inverter. The IGBTs are controlled such that the drive draws currents in a more sinusoidal manner, with substantially fewer current harmonics, rather than the typical pulsed current waveform of the diode bridge rectifier.

While they have benefits, active harmonic mitigation systems definitely have limitations, some of which can cause serious problems.

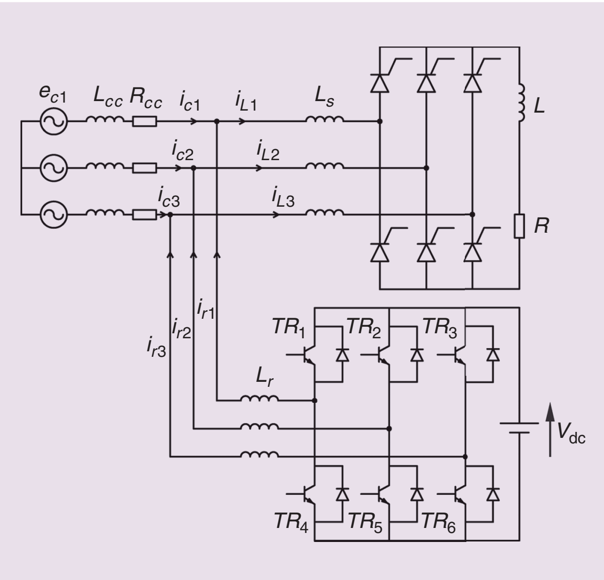


FIGURE 1. The shunt-connected APF.

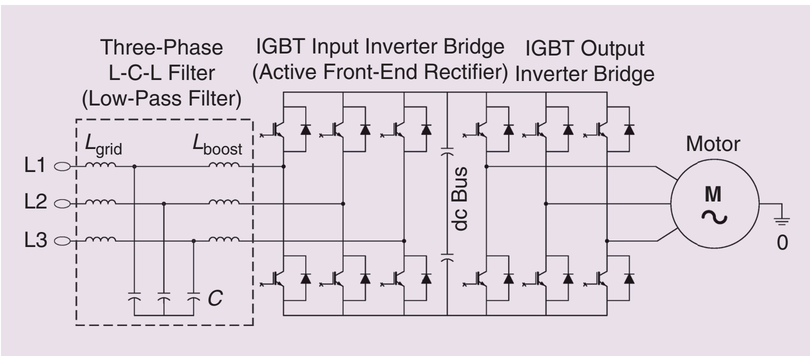


FIGURE 2. A typical AFE drive.

Although there are many benefits of active harmonic mitigation techniques, there is one principal concern that manufacturers of this technology rarely discuss: the relatively high levels of electromagnetic interference (EMI) that they introduce in the 2–150-kHz range, where no industry standard exists to limit these conducted emissions.

Problems With Active Harmonic Mitigation Systems

While they have benefits, active harmonic mitigation systems definitely have limitations, some of which can cause serious problems. APFs possess certain disadvantages, such as complex control structures, switching losses, and electromagnetic compatibility (EMC) emissions. (Switching noise is present in the line current and the line voltage.) The EMC emissions require including a low-pass passive filter (LCL) between the line and the APF. These filters are not always effective, which can lead to the injection of high-frequency switching harmonics into the power system.

Similarly, AFE drives also have complex control structures and require the use of passive LCL filters. Some AFE drive manufacturers will claim that their technology provides the best solution for treating harmonics associated with ASDs. They are quick to note the benefits over standard six-pulse ASDs, such as reduced line current harmonics, an improved power factor, and inherent regenerative capabilities. However, they rarely mention the fact that current harmonics are much higher when measured above the 50th harmonic and that very serious problems can result from introducing these higher-frequency harmonics. Also, they will downplay a substantial loss in efficiency due to the increased switching losses of the input IGBTs.

Problems associated with applying active harmonic mitigation systems are as follows:

1) current harmonics much higher than claimed when measured above the 50th harmonic
2) high levels of voltage distortion when measured above the 50th harmonic
3) connected equipment malfunctions, including the AFE drives themselves and standard diode bridge front-end drives
4) failure of transformers and other power distribution equipment due to excessive losses at the IGBT switching frequencies (at one installation, a 2,000-kVA transformer failed as a result of switching frequency harmonics above 10 kHz introduced by APFs)

5) stability and system resonance issues, especially with capacitors in the LCL and EMI filters or installed downstream for power factor correction (PFC)
6) higher losses and lower efficiencies than similarly rated six-pulse ASDs with passive harmonic filters.

IEEE Standard 519 was established to prevent harmonics generated by nonlinear loads from negatively affecting the power system and connected loads.

The Missing Frequency Band in Electrical Standards

When today's harmonic standards were first being established, the majority of the power electronic equipment generating harmonics consisted primarily of diode, and thyristor-based rectifiers. As such, the harmonics they generated followed very predictable characteristics. For phase-to-neutral, one-phase loads, the predominant harmonics were third, fifth, seventh, and ninth. For phase-to-phase, one- or three-phase loads, the predominant harmonics were fifth, seventh, 11th, and 13th. Harmonics above the 40th or 50th were almost never at levels that would cause problems, so harmonic standards only addressed the lower frequencies. In some jurisdictions, concerns about very-high-frequency conducted and radiated harmonics (above 150th) led to standards that limited these emissions.

However, with the increasing use of high-speed switching components in devices, such as converters and inverters directly connected to the utility grid, harmonics in the range of 2–150 kHz are becoming very common and troublesome. This is because lower levels of these higher-frequency current harmonics can create high levels of voltage distortion and harmonic losses. Equipment can sometimes be sensitive to levels of distortion at these frequencies that are much lower than those at the low-frequency harmonics. Although standards in this range, which address immunity, compatibility, measurement, and emissions for some specific products, are beginning to appear, it is the opinion of the authors and others that it is now time to establish more product emission standards in this missing frequency band [9]–[11], [20], [21].

IEEE Harmonic Standards

The latest revision of IEEE Standard 519, *Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems*, was released in March 2014 [12], replacing the previous version that had been around since 1992. IEEE Standard 519 was established to prevent harmonics generated by nonlinear loads from negatively affecting the power system and connected loads. This standard was widely adopted, particularly in North America, but has recently become more commonly referenced in many other areas of the world.

IEEE Standard 519 provides recommendations and guidelines for limiting harmonic voltage and current distortion at a PCC between the electrical system owner or operator and a user. The standard recognizes the responsibility of an electricity user to not degrade the voltage of the utility by drawing heavy nonlinear or distorted currents. It also recognizes the responsibility of the utility to provide users with a near sine wave voltage. Recommended harmonic limits are found in section 5 of the standard and are also shown in Tables 1 and 2.

The definitions for THD for voltage and total demand distortion (TDD) for currents require that up to the 50th harmonic components be considered. On a 60-Hz system, that would be 3,000 Hz. However, the definitions recognize that higher frequencies may need to be controlled as well, by stipulating that, "harmonic components of order greater than 50 may be included when necessary" [12]. Of course, the problem is who determines when it is necessary: the manufacturer whose designs have not taken this into consideration or the user who does not want to experience the problems that the higher order harmonics will cause?

The following are some important differences between the 2014 and 1992 revisions of IEEE 519.
1) THD and TDD definitions now allow the inclusion of harmonics above the 50th, when necessary.
2) Voltage-distortion limits for <1-kV systems have been relaxed from 5 to 8%.
3) Lower voltage-distortion limits for special applications and higher limits for dedicated systems have been removed.
4) Current-distortion limits for >161-kV systems have been changed. The current limits for other voltage systems remain the same.
5) Very short and short time limits have been introduced.
6) An allowance for increased harmonic limits at higher frequencies can be applied when steps are taken to reduce lower-frequency harmonics.

Table 1. The voltage-distortion limits in IEEE Standard 519 (2014) [12]

Bus Voltage V at the PCC	Individual Harmonic (%)	THD (%)
$V \leq 1.0$ kV	5	8
1 kV $< V \leq$ 69 kV	3	5
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1	1.5

In the opinion of the authors, many of these changes have not been for the better, particularly relaxing the voltage-distortion limits for <1-kV systems and allowing the increase of higher-frequency harmonics when steps are taken to reduce harmonics at lower frequencies. The latter is particularly troublesome and is the focus of this article.

> **Both passive and active damping methods should be thoroughly tested since operating the converter under a resonance condition should always be avoided.**

IEC Harmonic Standards

The IEC has various standards that apply to harmonics generated by nonlinear loads. For lower-frequency harmonics (up to the 40th), IEC 61000-3-2 defines limits for harmonic current emissions for equipment with an input current <16 A/phase for single and three phases [13], while IEC 61000-3-12 defines these limits for equipment >16 and <75 A [14]. It is worrisome that there are no specific IEC standards for nonlinear loads above 75 A since large nonlinear loads inject higher levels of harmonic currents, which can cause more problems than those generated by smaller loads.

Unlike IEEE Standard 519, these IEC standards apply limits on the loads themselves. Voltage-distortion levels are not defined since they are addressed in IEC 61000-2-2 as "compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems" and IEC 61000-3-6 as "assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems" [15], [16].

For high-frequency harmonic limits, IEC 61800-3 is often used. Table 3 shows the limits in the frequency band from 150 kHz to 30 MHz from this standard. It is interesting to note that the standard does not provide limits for the frequency band 9–150 kHz but does mention that they are under consideration [17].

Table 2. The current-distortion limits in IEEE Standard 519 for systems rated 120 V–69 kV [12]

	Maximum Harmonic Current Distortion in a Percent of I_L					
	Individual Harmonic Order (Odd Harmonics)					
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
<20	4	2	1.5	0.6	0.3	5
$20 < 50$	7	3.5	2.5	1	0.5	8
$50 < 100$	10	4.5	4	1.5	0.7	12
$100 < 1000$	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

Table 3. The IEC 61800-3 values of limits for main terminal disturbance voltage in the 150-kHz–30-MHz frequency band [17]

Size of Power Drive System	Frequency Band (MHz)	Unrestricted Distribution: Quasi-Peak dB (μV)	Unrestricted Distribution: Average dB (μV)	Restricted Distribution: Quasi-Peak dB (μV)	Restricted Distribution: Average dB (μV)
Low-power drive system ($I < 25$ A)	$0,15 \le f < 0,5$	66, decreases with log of frequency down to 56	56, decreases with log of frequency down to 46	79	66
	$0,5 \le f \le 5,0$	56	46	73	60
	$5,0 < f < 30,0$	60	50	73	60
Medium-power drive system ($I \ge 25$ A)	$0,15 \le f < 0,5$	79	66	79	66
	$0,5 \le f \le 5,0$	73	60	73	60
	$5,0 < f < 30,0$	73	60	73	60

Equipment Trend Toward Higher-Frequency Harmonics

With the lower harmonic limits these standards impose for power electronic equipment, current harmonics are being reduced, at least at the lower frequencies. Figure 3 shows this trend from measurements taken from large groups of computer users from 2002 to 2009 [20]. As can be seen, there has been a dramatic drop in emissions at the third, fifth, and seventh harmonics.

To further demonstrate this trend but also to highlight the introduction of higher-frequency harmonics, Figure 4 shows the current waveform and spectrums of a modern television [20]. Although the lower-frequency harmonics are reduced (third is the highest at around 30%), relatively high levels of high frequencies appear close to 5 kHz and 50–70 kHz. These higher-frequency emissions did not appear in older technology using simple rectifiers on their front ends.

Most power-quality analyzers that measure up to only the 50th harmonic would not have highlighted these high distortion levels.

Supraharmonics: 2–150 kHz

Figure 5 shows the range of frequencies that each harmonic standard addresses. As can be seen, the frequency band between 2 and 3 kHz to 150 kHz is not covered by any standard. This frequency range is beginning to be referred to as *supraharmonics* [20]. It is curious that this frequency band is not covered but even more so when we consider that most power electronic switching devices, such as IGBTs, switch precisely within this band (2–8 kHz or higher).

Also of concern in this band is that most instruments used to measure power-quality indices measure up to only the 50th harmonics, which is 2.5 kHz on a 50-Hz system and 3 kHz on a 60-Hz system. Therefore, they will not detect high levels of harmonics in this frequency band because they are above the 50th.

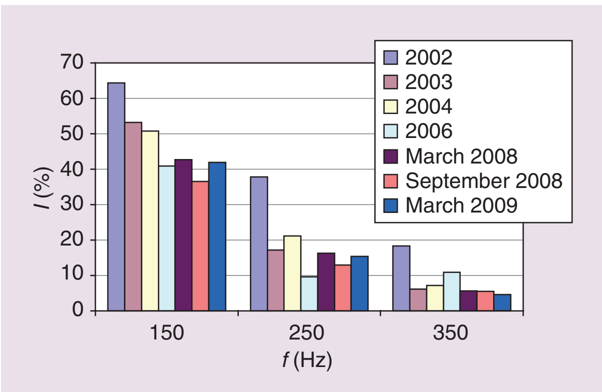


FIGURE 3. The emissions from a large group of state-of-the-art computers, 2002 through 2009 [20]. (Used with permission from [44].)

Passive Filters Required for Active Harmonic Mitigation Equipment

Since the IGBT switching frequencies, or carrier frequencies as they are often called, appear in the input current of active devices, they must be controlled with passive filters. At the switching frequencies themselves, these filters typically consist of an LCL network. At much higher, reflected frequencies, EMI/RFI filters are required.

This article focuses on the switching frequencies, so design requirements for the LCL filter will be discussed. One key consideration is the potential for power system resonance. If not suitably addressed, an LCL filter can resonate with the natural inductance of the source impedance, resulting in high levels of both current and voltage harmonics.

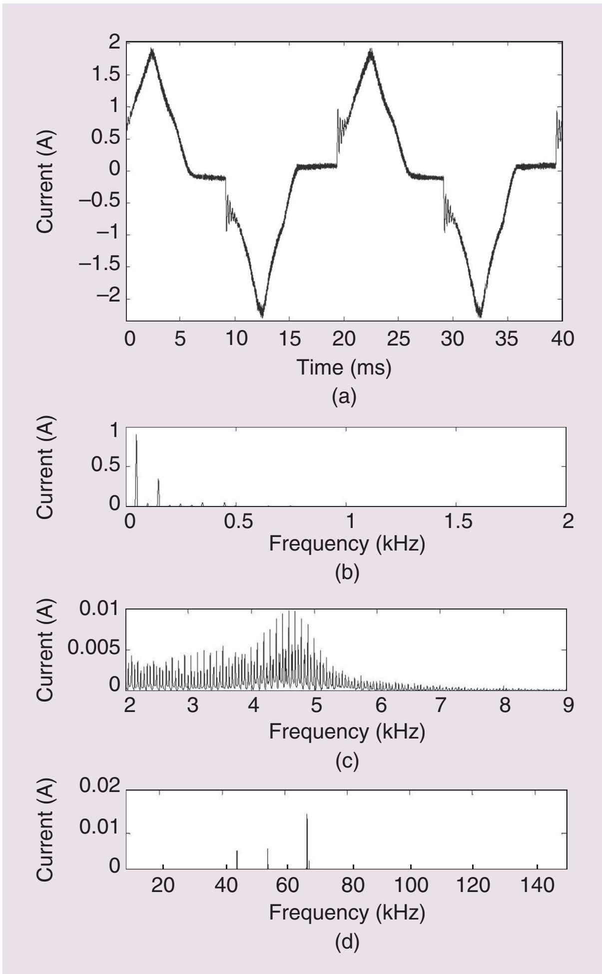


FIGURE 4. Modern television: (a) current waveform and current spectrum, (b) 0–2 kHz, (c) 2–9 kHz, and (d) 9–150 kHz [20]. (Used with permission from [45].)

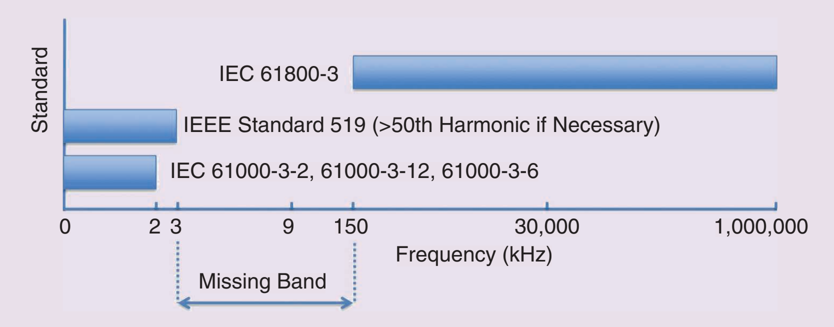


FIGURE 5. The frequencies covered by IEEE and IEC harmonic standards.

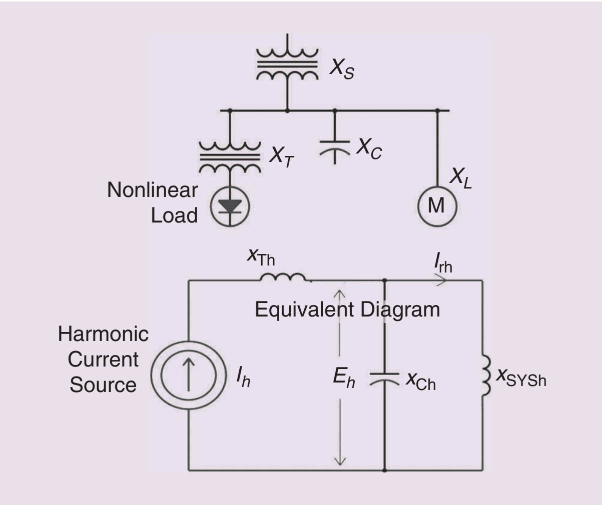


FIGURE 6. A one-line and equivalent circuit of a simple power system with an ASD nonlinear load.

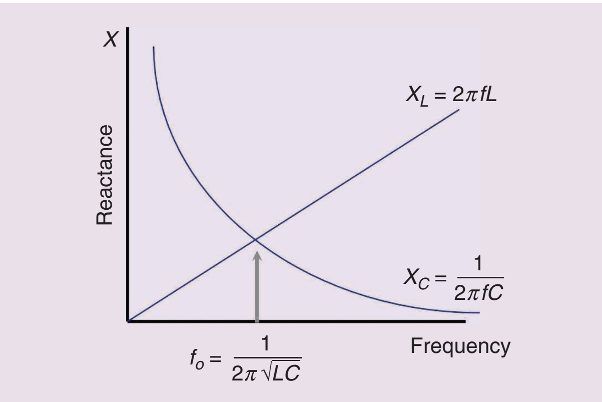


FIGURE 7. The resonant frequency occurs at the point where the inductive reactance and capacitive reactance curves cross.

LCL Filter's Susceptibility to Resonance With the Power System

Whenever capacitors are used in an electrical power system, they introduce the possibility of resonance. This is true for passive filters used to control the harmonics generated by six-pulse rectifier ASDs as well as the LCL filters used to control switching frequencies in active harmonic mitigation devices. Resonance with characteristic power system harmonics can be averted in six-pulse filters if the tuned frequency at the input is below the fifth harmonic, but exposure to system resonance is very difficult to prevent for LCL filters due to their higher tuned frequency values.

To control the IGBT switching frequency, an LCL filter is typically designed as a low-pass filter with its "knee" or cutoff frequency tuned comfortably below the switching frequency. For example, an AFE ASD that has an IGBT switching range of 2–8 kHz will require an LCL filter tuned comfortably below 2 kHz, often at 1 kHz. On a 60-Hz system, 1 kHz is close to the 17th harmonic, which typically allows the LCL filter to be smaller than a standard six-pulse rectifier filter.

However, this exposes the filter to resonance with the power system at a predominant harmonic, such as the 11th, 13th, or lower, because the power system is almost always inductive, which lowers the tuned frequency. A capacitive power system typically only occurs when it is overcompensated for by PFC capacitors, which should always be avoided because it can introduce many other issues.

Figure 6 shows a simplified power system one line and its equivalent circuit. In this example, the nonlinear load, the ASD, is represented as a current source of harmonics. Each current harmonic is injected into the power system and passes through the transformer reactance X_{Th} and then encounters the combined capacitive reactance X_{Ch} and system inductive reactance X_{SYSh}, which is the paralleled combined inductance of the source and the other connected loads.

The parallel combination of the PFC capacitors and the system inductive reactance has a natural tuned frequency, as shown in Figure 7. If the tuned frequency happens to be at a harmonic frequency that is prevalent in the power system, resonance will result in high levels of that harmonic in both the current and voltage.

Why is it a problem when a passive filter is tuned to a frequency that is above the predominant power system harmonics but not when tuned below these frequencies? It stems from the fact that the power system is naturally inductive and, as such, shifts the resonant frequency down toward the predominant harmonics. Figure 8 shows how this occurs.

Therefore, any passive filter that is tuned above the predominant power system harmonics (i.e., fifth, seventh, 11th, or 13th) will be susceptible to resonance with these frequencies when connected to the power system. This is particularly true when the power systems are weak (i.e., high impedance), such as a relatively small utility transformer or high-impedance generator source.

However, this is not a concern for a passive filter tuned below the predominant harmonics because the natural inductance of the power system will shift the resonance frequency lower and further away from the predominant harmonics.

To address this tendency, various methods of damping oscillations at the LCL filter input have been proposed [37]–[43], including both passive and active methods. The passive approach uses a damping resistor that is connected in a series or parallel with the filter inductor or capacitor. Although this method can stabilize the system, it causes undesirable excessive conduction losses resulting in a severe reduction in system efficiency.

One active method incorporates a virtual resistor [39], which is an additional control algorithm that causes the LCL filter to behave as if a real resistor was connected. Since there is no real resistor in the circuit, the transient oscillations can be suppressed without sacrificing efficiency. However, this method requires an additional current or voltage sensor and a differentiator.

Both passive and active damping methods should be thoroughly tested since operating the converter under a resonance condition should always be avoided. In high source impedance environments such as generators, it has been reported [43] that the AFE units with active damping may not even start the converter, so a hybrid method was proposed to overcome this problem. A 1% passive damping resistor is used in a series with the LCL filter capacitor and virtual resistor for an additional active damping algorithm. Using only 1% passive damping resistor is enough to stabilize the system, but it is not enough to eliminate the resonance. The active damping method must be enabled for complete elimination of the resonance [43].

Case Study 1: APF Switching Harmonics Causing Failure of the DC Power Supply

At a photovoltaic (PV) panel and solar inverter manufacturing plant in Toronto, Canada, a 450-A APF was installed on the inverter test line to reduce the low-frequency harmonics generated by the diode bridge rectifier used to generate dc power. Technicians on the PV panel test line located on a floor below, who were unaware of the APF installation, began to experience failure of a dc power supply in their PV tester each time it was powered on.

When power-quality measurements were taken at the PV tester, it was discovered that the voltage waveform had a high-frequency ripple (Figure 9). Measured voltage total harmonic distortion (VTHD) was <1%, which was well within the requirements of any harmonic standard, yet the dc power supply was failing. Measuring the

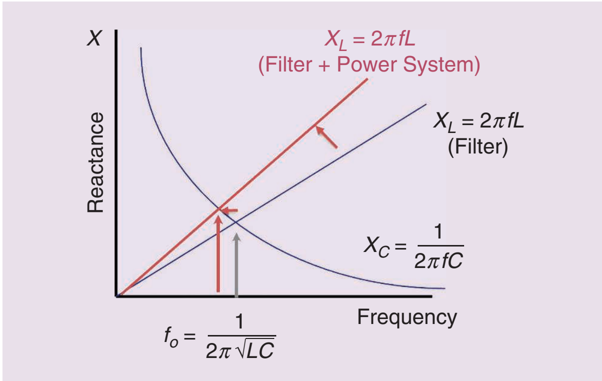


FIGURE 8. The power system inductive reactance increases the inductance reactance curve, lowering the resonant frequency.

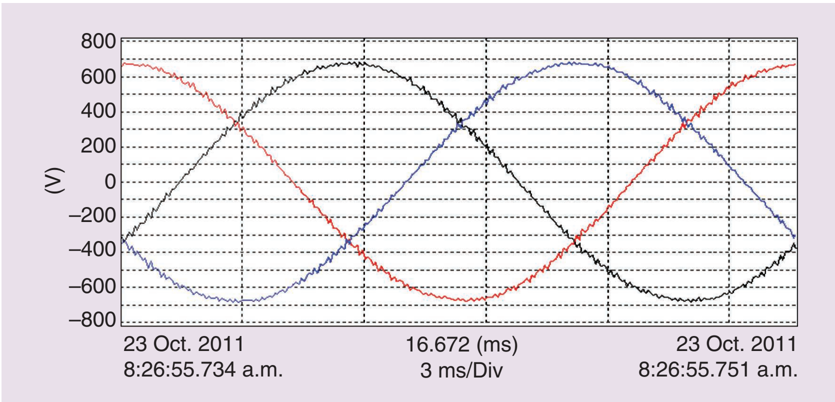


FIGURE 9. The voltage waveform at the PV tester with a high-frequency ripple caused by APF VTHD < 1%]. Div: time divisions along the *x*-axis.

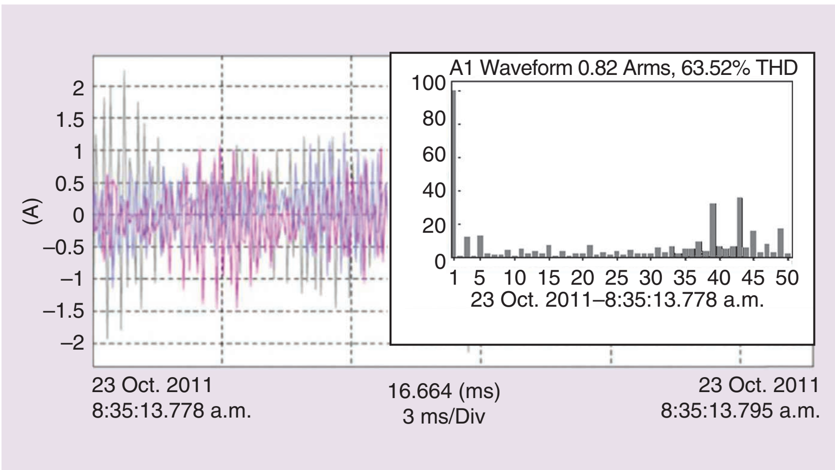


FIGURE 10. The waveform and spectrum (inset) of the no-load current drawn by a dc power supply with high-frequency components.

power supply current while operating at no load offered clues to the reason (Figure 10). Harmonics in the voltage waveform between the 39th and 43rd levels were resonating with the dc power supply, resulting in excessive currents at these frequencies being drawn by the power supply.

To test this theory, the APF was turned off, and repeat measurements were taken at the PV tester. With the APF off, the ripple in the voltage waveform disappeared (Figure 11), and the no-load current of the dc power supply no longer contained the high-frequency components (Figure 12). When informed of the problem, the APF manufacturer tried replacing the reactor in its LCL filter, but to no avail. Ultimately, the only solution was permanently disabling the APF, which became a very expensive and useless piece of equipment.

Today's active harmonic mitigation equipment introduces switching frequency harmonics that fall into a band of frequencies that are not presently covered by any standards.

Case Study 2: AFE Drive Not Meeting ITHD Requirements When Measured to the 150th Harmonic

In an application in which a relatively new AFE technology was being employed, measurements taken up to the 150th harmonic showed that the expected level of <5% ITHD was not being met. In much the same way that the high-speed switching of the IGBTs in the APF of case study 1 introduced a ripple on the voltage waveform, the devices in the AFE converter also created a ripple in the voltage waveform (Figure 13). This undulation resulted from the harmonic voltage drops that were created when the high-frequency currents drawn by the AFE passed through the impedance of the power system.

A view of the harmonic spectrum of the AFE drive's input current shows that although current distortion was below 8% when measured up to the 50th harmonic, it exceeded this when harmonics up to the 150th were considered (Figure 14). The actual total harmonic current distortion approached 10% while the expected level was to be <5% ITHD.

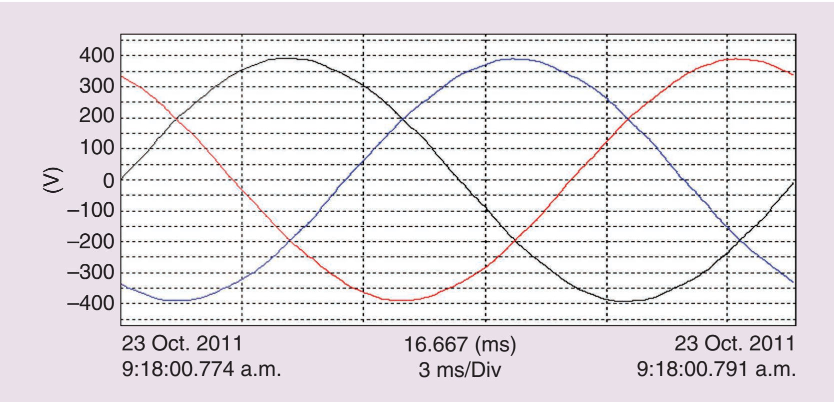


FIGURE 11. The voltage waveform at the PV tester with APF off.

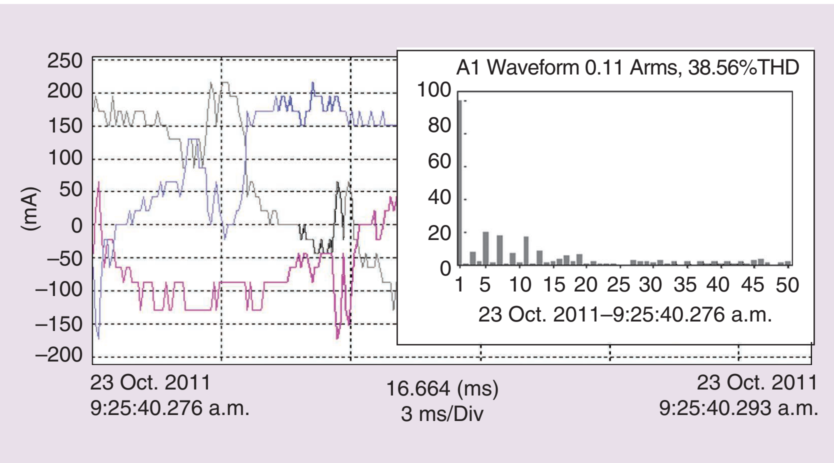


FIGURE 12. The waveform and spectrum (inset) of no-load current drawn by the dc power supply with APF off.

Case Study 3: Catamaran Equipped With Main and Auxiliary Propulsion AFE Drives

Figure 15 shows frequency spectrums of the voltage at the bridge distribution panel of a catamaran equipped with main and propulsion AFE drives [10]. Measurements were taken over three frequency bands: up to the 50th harmonic [Figure 15(a)], 50th to 10 kHz [Figure 15(b)], and 10–50 kHz [Figure 15(c)]. A summary of the measurements is shown in Figure 15(d). Although the voltage harmonics were quite low in the lower-frequency range (VTHD = 1.68%), they were very high in the frequency range above the 50th (VTHD = 8.14%) with a band around 3,500 Hz (70th harmonic) produced by the AFE drives operating at a 3.6-kHz switching frequency. Most power-quality analyzers that measure up to only the 50th harmonic would not have

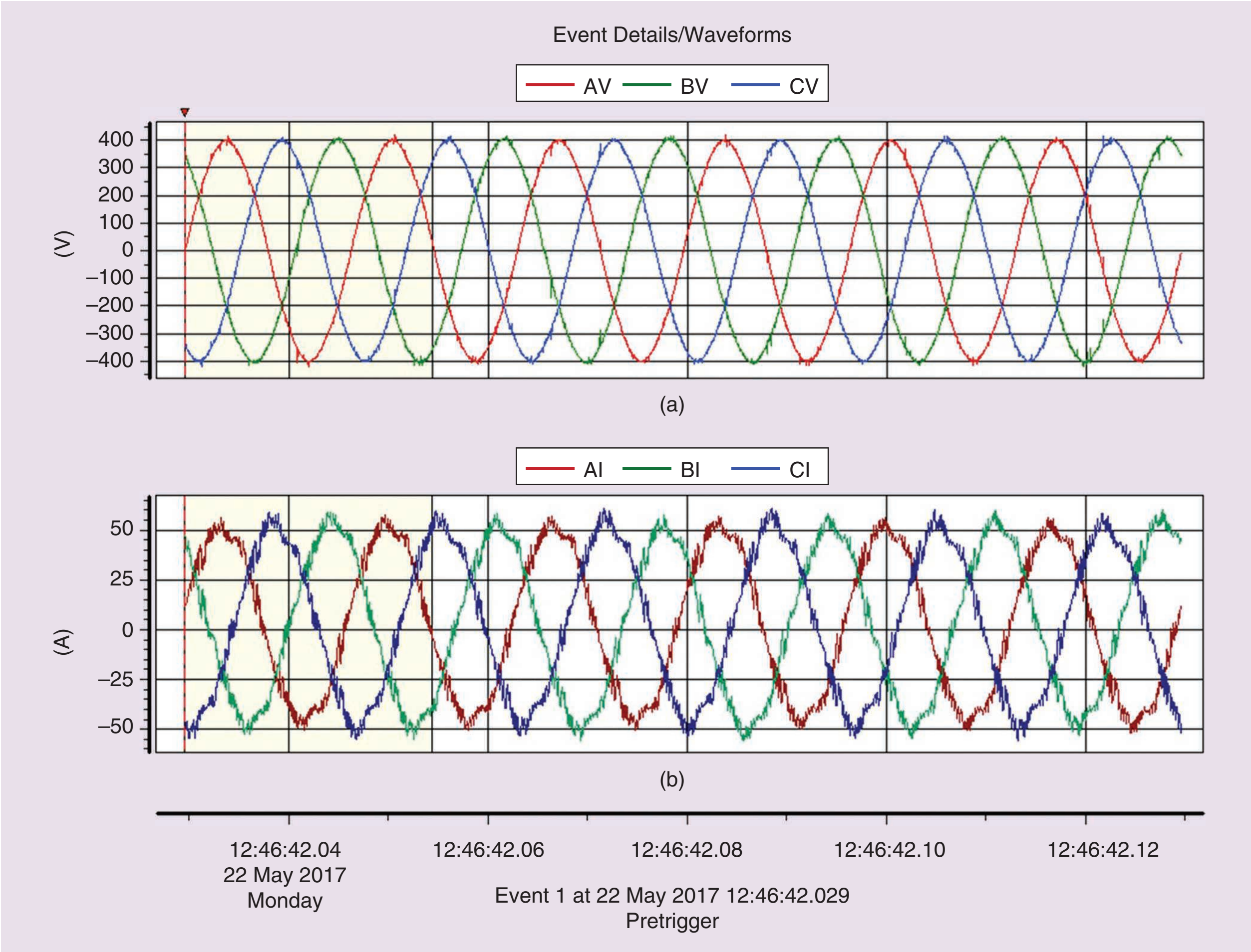


FIGURE 13. The (a) voltage and (b) current waveforms at the input of 40 HP (30 kW) AFE drive.

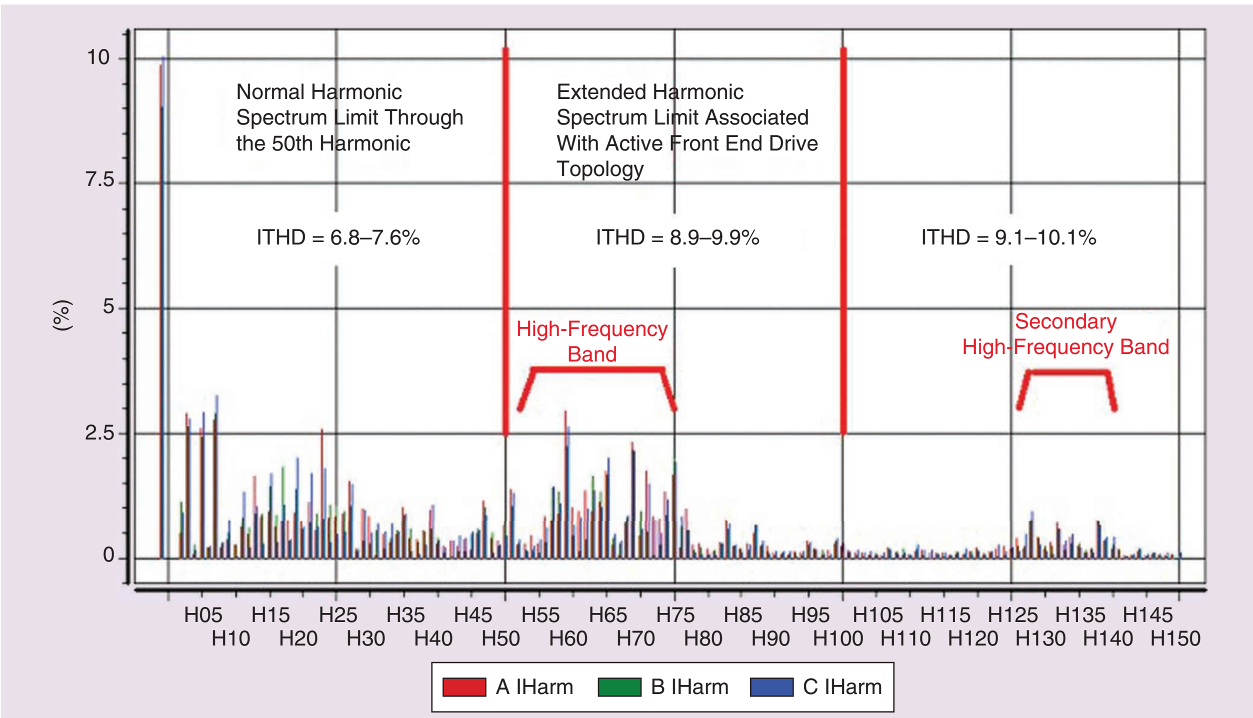
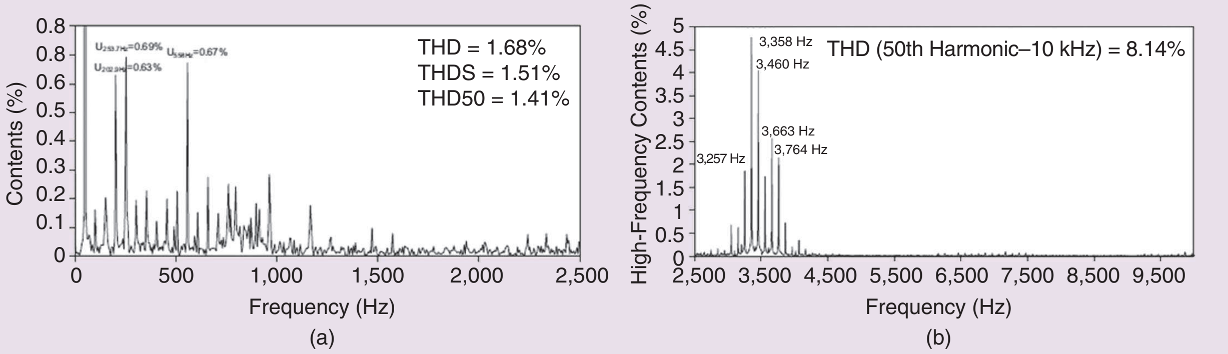
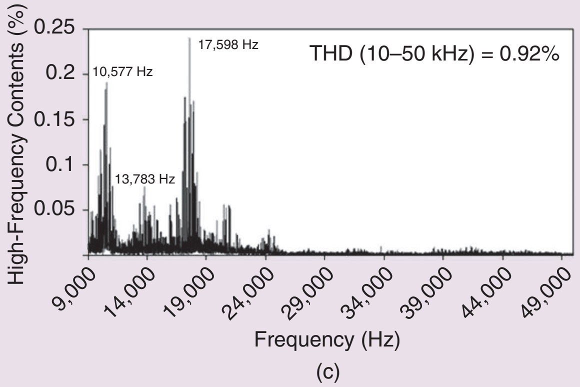


FIGURE 14. The AFE current harmonic spectrum measured up to the 150th harmonic.





Frequency Bands	THD (%)
0–50 kHz	8.38
0–50th Harmonic	1.68
50th Harmonic–10 kHz	8.14
10–50 kHz	0.92

(d)

FIGURE 15. The voltage harmonic spectrum of a catamaran with main and auxiliary propulsion AFE drives. (a) Up to the 50th harmonic (VTHD = 1.68%). (b) The 50th harmonic to 10 kHz (VTHD = 8.14%). (c) 10–50 kHz (VTHD = 0.92%). (d) A summary of VTHD at various frequency bands. (Used with permission from [10].)

highlighted these high distortion levels. These measurements were taken with a spectrum analyzer and highlight how one can be deceived into thinking harmonic distortion is low if only the low frequencies are considered.

Conclusions

In an effort to reduce harmonic distortions in our power systems, standards limiting harmonic current emissions have been established by both IEEE and IEC. Unfortunately, these standards presently only target low frequencies (up to 50th harmonic) and very high frequencies (above 150 kHz). Today's active harmonic mitigation equipment, which includes APFs and AFE drives, introduces switching frequency harmonics that fall into a band of frequencies that are not presently covered by any standards (i.e., 2–150 kHz), allowing manufacturers to use relatively ineffective and inexpensive LCL passive filters.

By not filtering effectively, these active devices introduce high levels of distortion that can cause severe consequences, including those highlighted in the case studies. The more that these devices are used, the more connected equipment problems arise due to these high distortion levels. Even relatively low levels can cause issues when the distortion is primarily at higher frequencies. Therefore, the use of AFE and APF technologies for harmonic mitigation, especially when connected to the public grid, requires thorough engineering of the application and a network analysis to understand potential resonance issues. Attention should also be given to how well these devices attenuate the switching frequency harmonics they generate. In many cases, when low harmonics are the goal, a properly designed passive harmonic filter applied to a conventional six-pulse ASD still is a better option. Since there are no standards to refer to at the switching frequencies, it is recommended that harmonic limits should be applied at least up to the 100th harmonic when active harmonic mitigation solutions are used.

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