

NEW MARINE HARMONIC STANDARDS

Meeting harmonic limits using wide-spectrum passive harmonic filter

BY
TONY HOEVENAARS,
IAN C. EVANS,
& ANDY LAWSON



U.S. NAVY MILITARY SEALIF COMMAND

TO ADDRESS CONCERNS ASSOCIATED WITH ELECTRICAL POWER system harmonic distortion on ships and offshore oil rigs and platforms, marine regulating bodies have introduced strict new harmonic standards. These standards define the acceptable level of harmonic voltage distortion allowed on the vessels they certify. High-harmonic distortion levels are appearing as a result of the increased use of power-electronic drive converters for electric propulsion, drilling and pumping applications, and many other uses of variable speed-drive (VSD) systems. To meet these new standards, methods to control harmonics must be adopted. This article will discuss some of these methods and present an application where a unique wide-spectrum passive harmonic filter was used to meet harmonic limits on a cable-laying ship that previously required the use of rented generators to allow operation of VSDs.

Digital Object Identifier 10.1109/MIAS.2009.934965

1077-2618/10/\$26.00©2010 IEEE

SCIGATE
Your Automation Partner



SCIGATE AUTOMATION (S) PTE LTD

No.1 Bukit Batok Street 22 #01-01 Singapore 659592

Tel: (65) 6561 0488

Fax: (65) 6562 0588

Email: sales@scigate.com.sg

Web: www.scigate.com.sg

Business Hours: Monday - Friday 8.30am - 6.15pm

With the increasing use of ac and dc electric drives in marine vessel applications, such as electric propulsion and offshore oil-drilling operations, poor power quality due to harmonic distortion has become a critical safety issue. Electric propulsion offers significant benefits, such as greater redundancy, lower emissions, improved maneuverability, and reclaimed deck space for cargo and other important uses. Oil drilling platforms could not function without variable speed control of their motors. However, by drawing current in a nonlinear or nonsinusoidal manner, the VSDs can introduce excessive levels of both current and voltage harmonics. The nonlinear loading on marine vessels can now reach 80% of the onboard electrical generating capacity [1] and results in total harmonic voltage distortion (THDv) in excess of 20% (Figure 1).

All marine classification bodies are extremely concerned about harmonic voltage distortion and the possible consequences should some critical item of equipment malfunction or fail. Often viewed as a potential safety of life at sea (SOLAS) issue, classification bodies have imposed strict limitations on the magnitude of harmonic voltage distortion permitted on vessels classed under their rules [2]. Any vessels seeking classification are now being required to demonstrate compliance with these standards.

The harmonic standards of the various marine classification bodies all focus on voltage harmonic distortion limits. Although the increased losses associated with high levels of current harmonic distortion can be a problem in electrical distribution systems, it becomes only a serious issue when the equipment is more heavily loaded. A bigger issue with harmonic currents is that they create voltage distortion as they flow through the power distribution system. To meet voltage-distortion limits, current harmonics must be reduced. Therefore, by establishing limits for voltage distortion, the marine standards indirectly limit current distortion as well.

Voltage distortion is an accumulation of the individual voltage drops determined by Ohm's law as each harmonic current passes through the impedance of the power system. If the combination of harmonic currents and system impedance is high enough, system voltage can become severely distorted. In marine applications, the combination of heavy nonlinear loading and relatively high-source impedance of the supply generators results in excessive levels of voltage distortion as shown in Figure 1.

Harmonic Standards of Marine Classification Bodies

The Norwegian classification body, Det Norske Veritas (DNV), was one

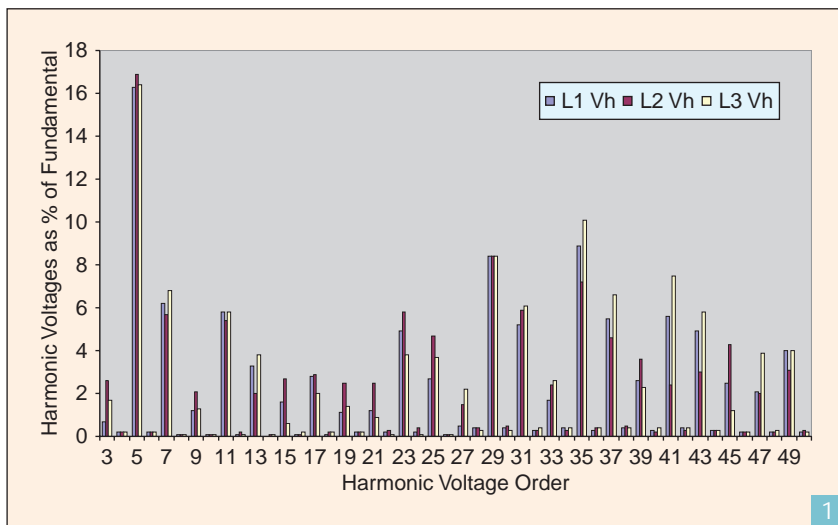
HARMONICS CAN BE A PARTICULARLY SERIOUS PROBLEM IN ZONES 1 AND 2 EXPLOSION-PROOF MOTOR INSTALLATIONS.

of the first to recognize harmonics as a problem and introduce limits. These limits fall under their Offshore Standard DNV-OS-D201—*Electrical Installations* [8].

The limits for harmonic distortion are found in Section 2, A207. THDv, in distribution systems, is not to exceed 5%, nor shall any single-order harmonic exceed 3%. These limits are allowed to be exceeded, provided that all consumers and distribution equipment subjected to the increased distortion level shall be documented to withstand the actual levels. A guidance note lists some considerations for this documentation as:

- additional heat losses in machines, transformers, and coils of switchgear and control gear
- additional heat losses in capacitors, e.g., in compensated fluorescent lighting
- resonance effects in the network
- functioning of instruments and control systems subjected to the distortion
- distortion of the accuracy of measuring instruments and protective gear (relays)
- interference of electronic equipment of all kinds, e.g., regulators, communication and control systems, position-finding systems, and radar and navigation systems.

The American Bureau of Shipping (ABS) introduced new harmonic limits in May 2006. Their publication, *Guidance Notes for the Control of Harmonics in Electrical Power Systems* [2], provides an extensive overview of harmonics, including various treatment methods. The limits are listed in Section 11. In general systems, THDv shall not exceed 5% with no individual harmonic greater than 3% of the fundamental voltage value. Measurements are to be taken at least up to the 50th harmonic.



Voltage harmonic spectrum of offshore oil production platform at 600 V. Average THDv/phase was 24.7%. Higher harmonics above 21st were due to large number of 18- and 24-pulse VFDs.

ABS does allow a higher limit of 10% on dedicated systems. However, all connected equipment on a dedicated system must have the manufacturer's guarantee that it can operate trouble-free at this higher voltage-distortion level.

The ABS rule was relaxed somewhat for mobile offshore drilling units (MODUs) in January 2009. The harmonic information sheet for MODUs, Ref: 4-3-2/7.9, now allows THDv levels up to 8 and 5% for any individual harmonic provided the parties concerned (owners, shipyard, designer, and system integrator) have no objections.

Most of the marine classification organizations have adopted voltage-distortion limits similar to DNV and ABS. Lloyd's Register (LR), for example, uses the more relaxed level of 8%. Harmonic limits can be found in Part 6, Section 2, Item 1.7.3 of their *Rules and Regulations for the Classification of Ships* [9]. THDv is allowed to reach an 8% limit at the switchboard or sectionboard measured for harmonics up to the 50th. LR does recognize, however, that even relatively low levels of higher harmonic frequencies can cause problems and, therefore, establishes a limit of 1.5% for any individual voltage harmonic above the 25th.

VSDs and Harmonics

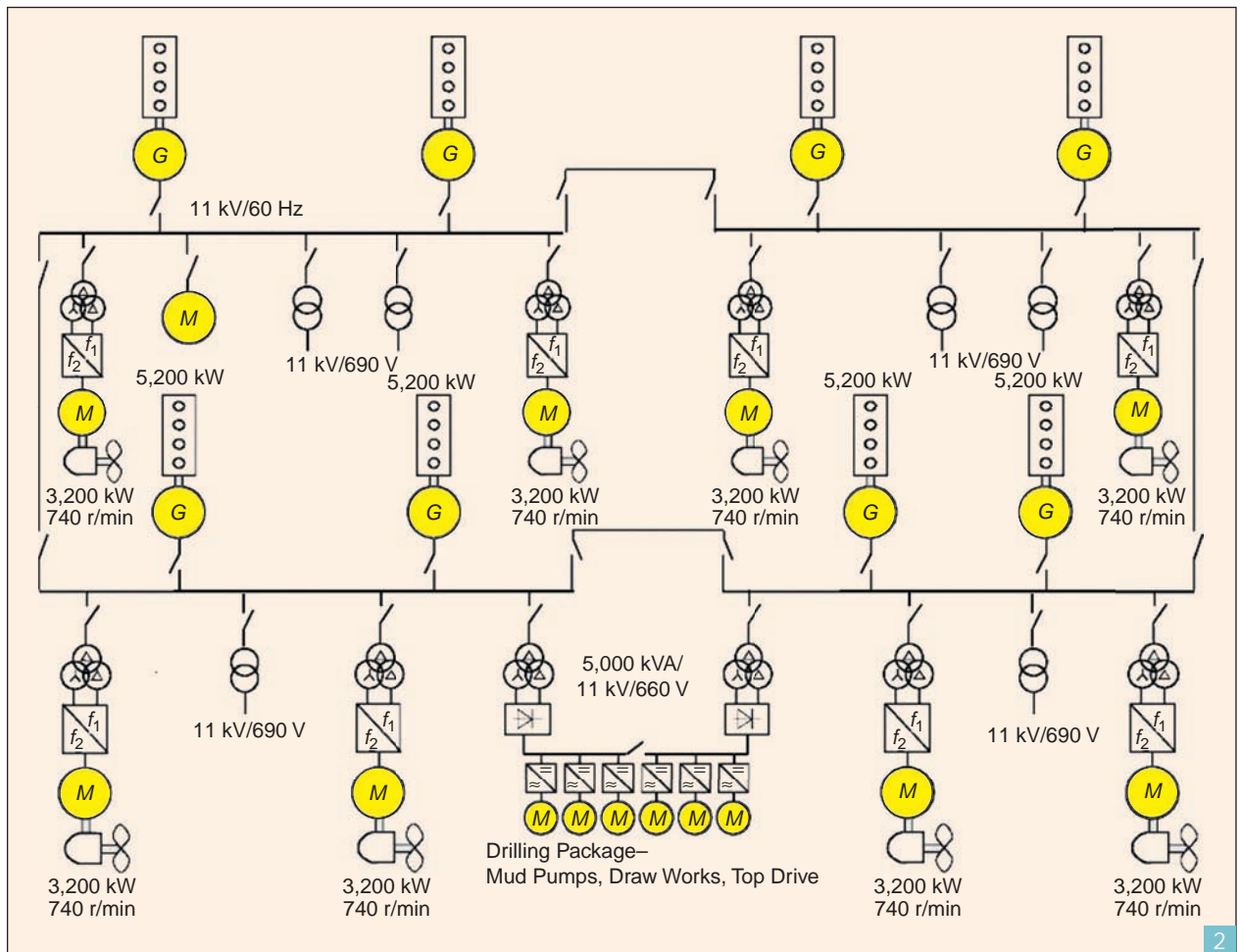
Most power systems can accommodate a certain level of harmonic current but will experience problems when the nonlinear loading becomes a significant component of the

overall load. This is certainly the case in many marine applications due to the extensive use of VSDs.

A VSD is a solid-state device that converts supply voltage to a variable voltage and frequency to control the speed of a three-phase induction motor [also referred to as a variable frequency drive (VFD)] or to dc for dc motor applications. By controlling the motor's speed, both energy savings and better motor control can be achieved. Typical VSD marine and offshore applications include main propulsion drives, thrusters, cables remotely operated trenching vehicle (ROV) drives, top-drives, draw-works, winches, mud pumps, compressors, and general purpose fan and pump drives (Figure 2).

VSDs generate harmonic currents because their front-end or input rectifiers do not draw current in a sinusoidal manner. Instead, they draw discontinuous, pulsed currents that can be broken down into harmonic components by applying Fourier analysis. For a typical three-phase rectifier bridge, the predominant harmonic currents that will be generated are fifth, seventh, 11th, and 13th. Typical current distortion levels range from 35% to more than 80%, depending on the supply impedance and whether or not an ac or dc reactor is applied to the drive.

Harmonics can be a particularly serious problem in zones 1 and 2 explosion-proof motor installations such as those encountered on oil refineries and oil production



Typical power system single-line diagram for dynamically positioned Class 3 drilling rig.

platforms. For example, an increased risk of explosion can result from the degradation of shaft seals on double-cage flameproof motors. In addition, rotors that are overheated by harmonics can degrade bearing lubrication, resulting in frictional sparking. In an attempt to protect against this, certifications on standard International Electrotechnical Commission (IEC) explosion-proof motors are now conditional upon voltage-distortion levels of 2 or 3% depending on their specific protection concept [3]–[5]. The motor will lose certification as an explosion proof type, if these limits are exceeded.

The problem of harmonic voltage distortion on explosion-proof motors is not without foundation. Some consideration could be given to the possibility that the world's largest offshore oil-field disaster in 1988, the Piper Alpha platform in the Scottish North Sea, may have been caused by harmonics on the power system due to large electrical submersible pumps and other VSDs. It is feasible that fixed-speed ExN motors (nonsparking for zone 2 use only) with double-cage rotors connected to a supply with high levels of voltage distortion may have caused ignition of escaping gas or vapor.

In addition, a large fire on another oil platform in the North Sea occurred in March 2006 and took more than 4 h to extinguish. The platform had high levels of voltage distortion, and the fire was attributed to the failure of an explosion-proof motor. Although no direct correlation has been made, questions still exist whether harmonics could have been a contributing factor. In 2007, two more fires occurred on North Sea platforms with causes possibly unrelated to harmonics; nevertheless, harmonics have become an issue, which authorities are starting to consider very seriously.

Phase Shifting and Multipulse Drive Systems

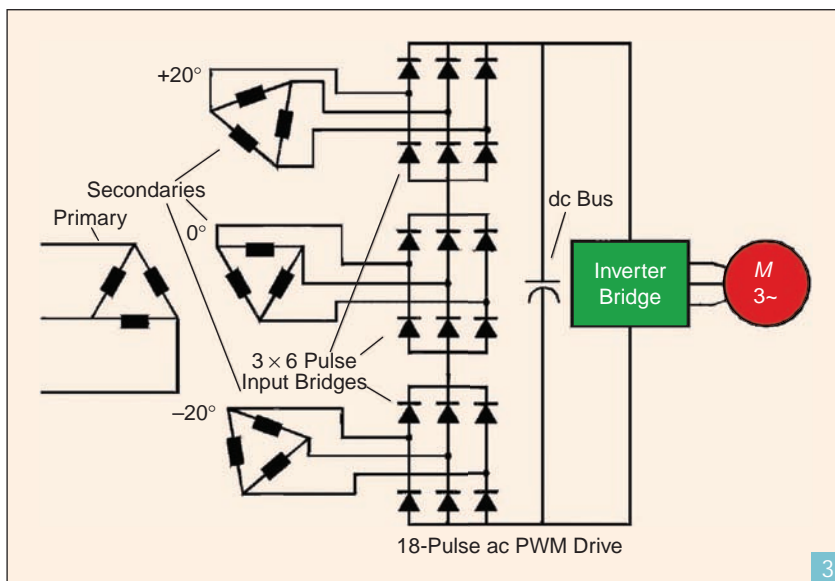
To mitigate the harmonic current and voltage distortion introduced by VSDs, a number of techniques are being used to varying degrees of effectiveness. Multipulse drive systems have been one of the most common forms of harmonic mitigation used on marine vessels to date. In this technique, transformers with multiple secondary windings are used to phase-shift multiple VSD rectifiers against each other.

A drive system's pulse number is determined by the number of discrete converters used and the phase-shift angles between these converters. The characteristic harmonics generated by the diode-bridge rectifier of a VSD will follow the relationship below:

$$b = np \pm 1,$$

where b is the harmonic number, n is any integer, and p is the pulse number of the rectifier.

Most VSDs incorporate a three-phase, six-pulse ($p = 6$) diode-bridge rectifier, which results in currents of harmonic number fifth, seventh, 11th, 13th, etc. being generated.

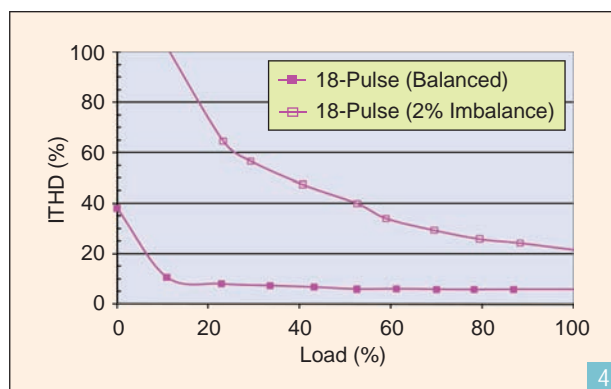


Typical 18-pulse drive system. Three six-pulse converters and three secondary windings, 20° displaced.

When dual rectifiers are used and phase shifted by 30°, a 12-pulse scheme is created. Twelve-pulse VSDs will only have residual amounts of fifth and seventh harmonics as substituting $p = 12$ in the earlier equation leaves harmonics 11th, 13th, 23rd, 25th, etc. Similarly, an 18-pulse drive consists of three input rectifiers with 20° phase shifts between them (Figure 3).

Configurations up to 48-pulse are possible for very large systems, but the effectiveness of phase shifting at high-pulse numbers becomes questionable because the phase angles of harmonic currents at higher frequencies are typically not similar enough to produce sufficient cancellation.

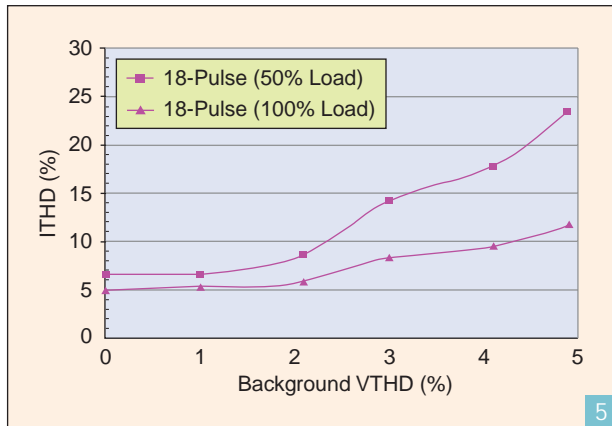
Although they are theoretically an effective means of harmonic treatment, all phase-shift drive systems can perform rather poorly under real-world conditions. Tolerances in the manufacture of the transformer windings, applied voltage imbalances, preexisting voltage distortion, and light loading levels will have a detrimental effect on the drive's ability to cancel harmonic currents at the higher frequencies. Figure 4 illustrates the effect of 2% voltage imbalance on a typical 18-pulse drive system, and Figure 5 shows the performance degradation when background voltage distortion is present.



Effect of 2% voltage imbalance on an 18-pulse drive.

It should be noted that, in addition to increasing the levels of characteristic harmonics, voltage imbalance and/or excessive levels of background voltage distortion will

also result in the appearance of uncharacteristic harmonics, including triplens and even order [1]. Background voltage distortion on ships and offshore oil platforms often reach levels above 10%, and measurements above 20% are not uncommon as illustrated in Figure 1. Therefore, when using phase-shift-based drive systems, it is important to consider if an acceptable level of mitigation will be achieved under the very likely scenario of high levels of background distortion and voltage imbalance.



Effect of background voltage distortion on an 18-pulse drive.

Active Filters

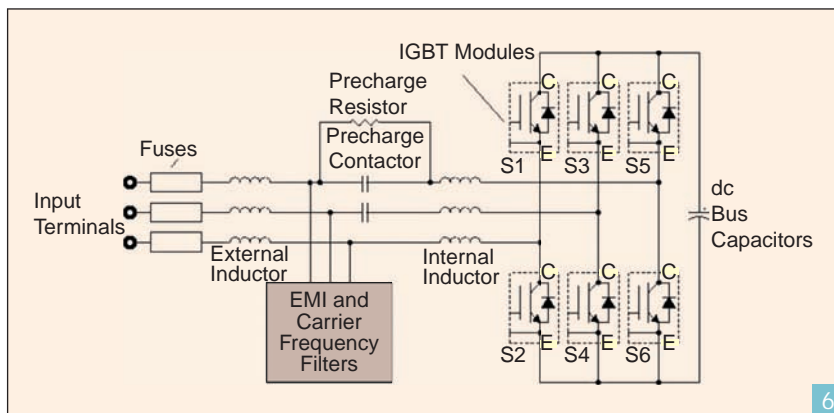
Active filters are current injection devices and are categorized into two distinct types: selective fast Fourier transform (FFT) and broadband. Selective FFTs allow for the selection of the harmonic orders being mitigated up to a maximum number, usually 15 or 25 harmonic orders. Broadband systems, on the other hand, can treat all the nonfundamental currents not just integer harmonics. This includes noncharacteristic harmonics, interharmonics, and load-generated disturbances. In addition,

the selective FFTs respond rather slowly (40–50 ms), whereas broadband systems respond at 40–100 μs and are therefore more suited to dynamic loads. In this article, only the broadband type of active filter is considered (Figure 6).

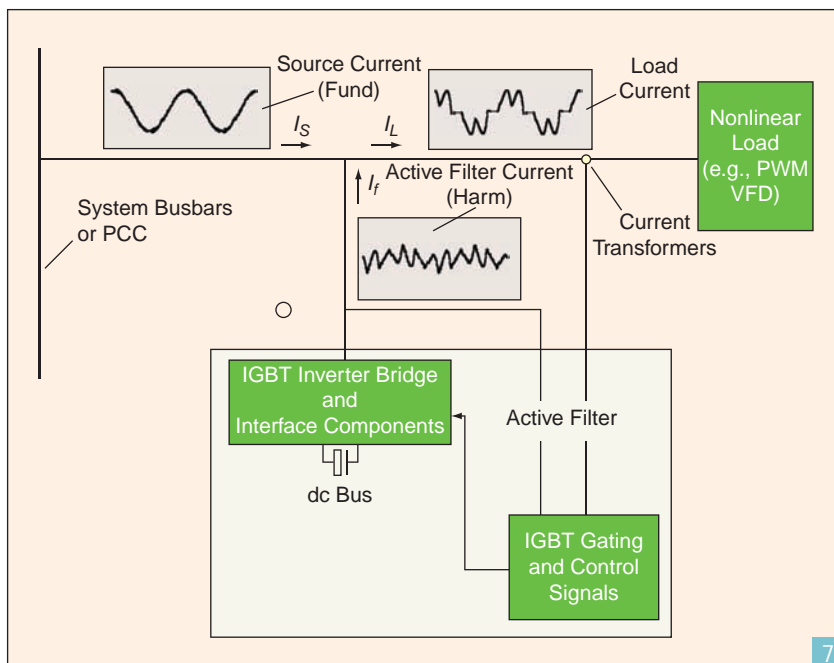
An active filter is connected in parallel with the loads (nonlinear and any linear loads) and monitors the load current through two current transformers (CTs) located on the load side of the active filter connection (Figure 7). Measurements from the CTs, which include the current waveshapes, are fed into a notch filter (i.e., band-stop filter), which removes the fundamental component of current (i.e., 50 or 60 Hz component). The remaining signal is then classed as distortion current (i.e., all nonfundamental currents). The signal is processed and used to construct a current waveform, which when added in real time to the load current waveform, results in a near sinusoidal current upstream of the filter.

If the filter's cancellation current rating is properly sized, it will produce the harmonic currents, which the load requires to function, and the source will only be asked to provide the fundamental current. An active filter cannot be overloaded. At 100% cancellation rating, the device will current limit, and any additional harmonic currents will spill over into the source as distortion current, increasing the total harmonic current distortion (THDi) and associated THDv on the source side.

If applied correctly, active filters can offer very high levels of performance (i.e., <5% THDi), but their high cost



Simplified power circuit of broadband active filter.



Block diagram of typical shunt connected broadband active filter with associated current waveforms.

(purchase, spares, commissioning, and maintenance) and complexity often limits their use. Other concerns include the possibility of system resonance at the carrier frequency of the filter's insulated-gate bipolar transistors (IGBTs) and the filter's own susceptibility to background voltage distortion.

Case Study 1: Active Filter Application on an Offshore Production Platform

An offshore oil production platform operating 6×800 hp, six-pulse dc drives produced current distortion in excess of 30% (Figure 8) and voltage-distortion levels greater than 10%. To prevent operational problems that could arise from these high levels of THDv, 2×300 A broadband active filters were installed on each side of the main switchboard.

Current distortion was reduced from 34 to 3.6% (Figure 9). By removing the current harmonics, the active

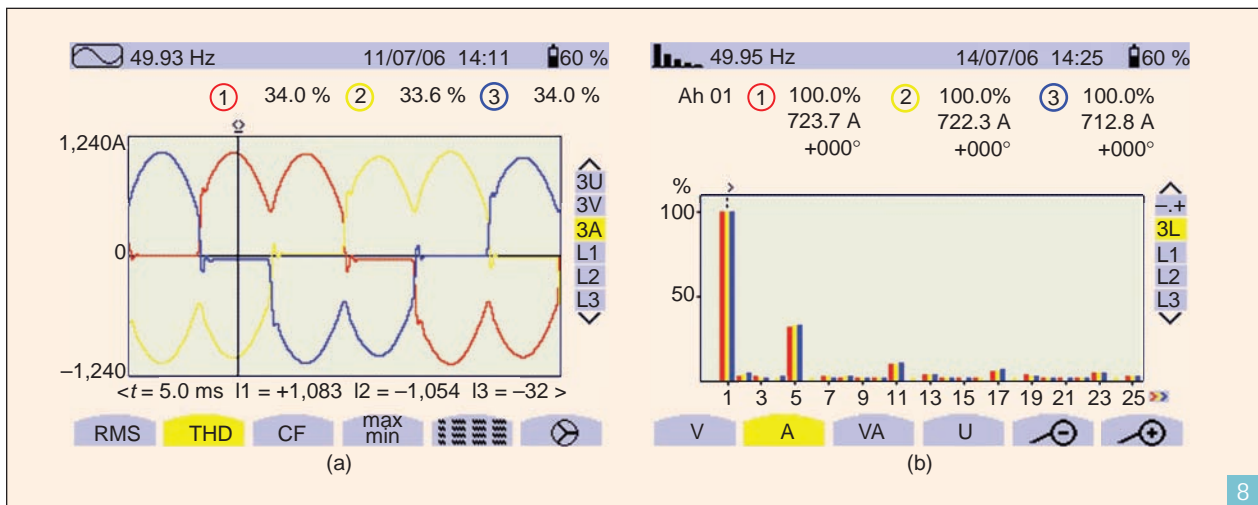
MOST OF THE
MARINE
CLASSIFICATION
ORGANIZATIONS
HAVE ADOPTED
VOLTAGE-
DISTORTION
LIMITS SIMILAR TO
DNV AND ABS.

filter lowered voltage-distortion levels to less than 4%. To demonstrate this, Figure 10 shows a trend line of THDv while switching the filter on and then off again.

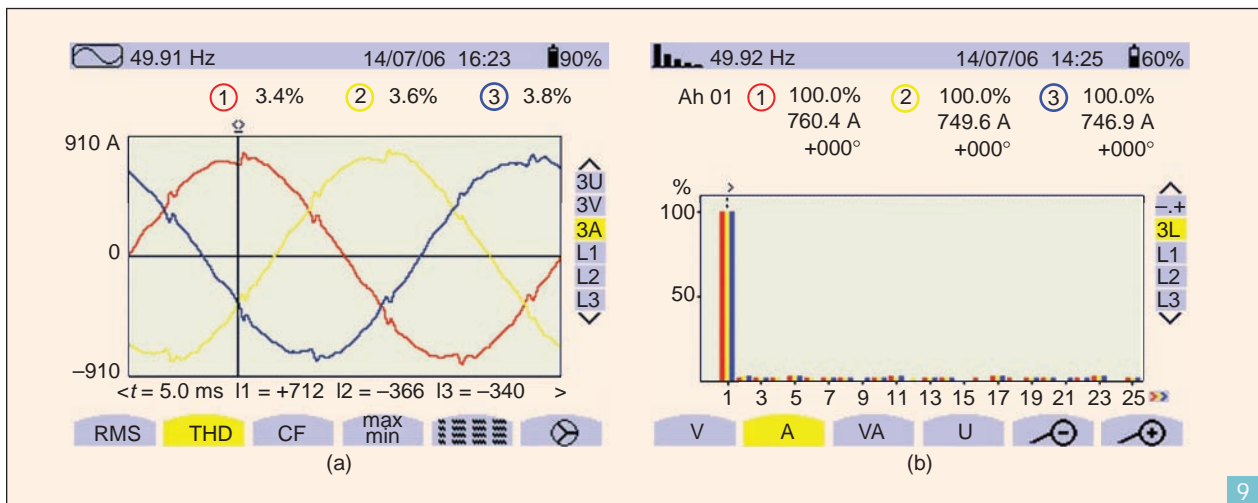
Active Front-End Drives

An active front end (AFE) drive consists of an ac pulsewidth modulation (PWM) VFD in which the standard six-pulse, diode-input rectifier is replaced by a bidirectional IGBT rectifier (Figure 11). The input rectifier draws current that is closer to sinusoidal but usually contains fairly high levels of higher frequency harmonics. To reduce these, a passive L-C-L filter tuned near the switching or carrier frequency of the IGBTs (usually between 2 and 3.5 kHz) must be used.

AFE drives are often promoted as the best technical solution for marine drive applications because of their low-harmonic current-distortion profile (typically $<5\%$ THDi).



(a) Current waveform and (b) spectrum without active filter. THDi = 34%.



(a) Current waveform and (b) spectrum with active filter. THDi = 3.6%.

Although harmonic performance below the 50th harmonic is far superior to that produced by a standard six-pulse VFD, there are growing concerns regarding the harmonic performance of AFE drives above the 50th harmonic, which are directly attributed to the carrier switching frequency of the input IGBT rectifier. Figure 12 provides a high-speed oscilloscope trace of a typical current waveform at the input terminals of an AFE drive with the high-frequency components clearly visible [6].

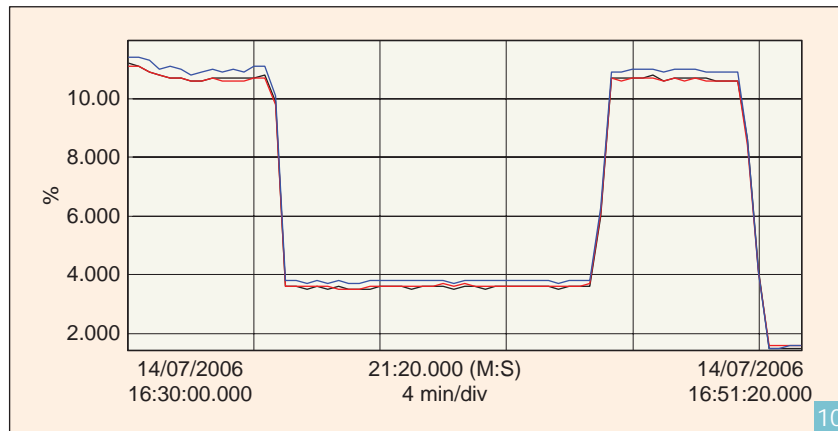
Recent measurements taken by the Polish Register of Shipping (PRS) on a research vessel with 2×90 kW and 2×315 kW AFE drives used for propulsion also show that current distortion can be $>5\%$ even with harmonics

up to the 50th only being measured [7]. Voltage spectrum measurements above the 50th harmonic taken on the same ship show a significant increase in voltage distortion occurring near the 67th harmonic (Figure 13).

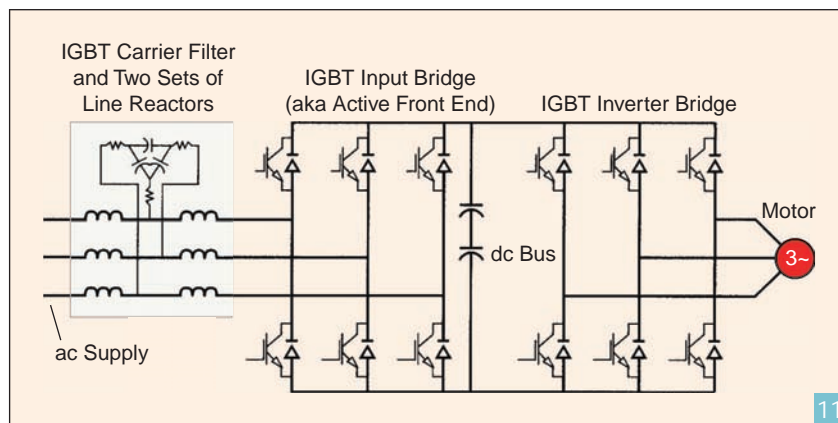
This would be the result of excessive current harmonics drawn by the AFE drives near their carrier frequency. The THDv at harmonics below the 50th was 3.32% and above the 50th was 3.25%. The total THDv (<100 th harmonic) was 4.65%. It is not surprising that some marine classification bodies, including the ABS and the PRS, now stipulate in their respective rules that “On vessels with AFE drives, the harmonics up to the 100th shall be measured” [2].

There are other issues associated with AFE drives, which must be addressed to ensure a problem-free installation:

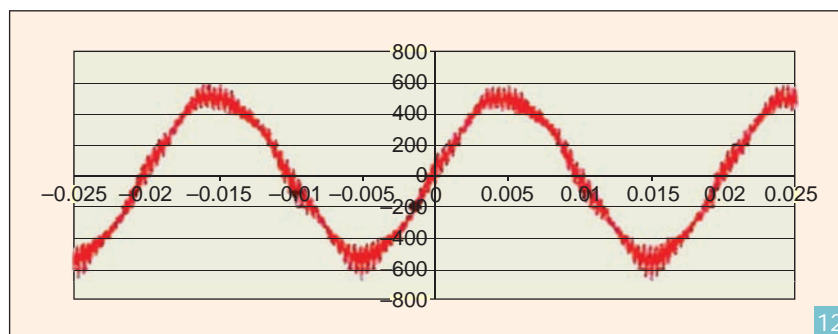
- 1) The electromagnetic interference (EMI) emissions, both conducted and radiated, emanating from AFE drives are almost double that from a standard six-pulse VFD with diode bridge rectifier. A vessel's power distribution system is usually based on IT networks (i.e., isolated neutral) where the vessel's cabling provides a high-frequency conducted emissions path to ground. These high-frequency emissions, which circulate throughout the power system, can seriously disrupt sensitive equipment. Standard EMC filters cannot be applied in IT networks because of high-leakage current through their capacitors to ground and the likely occurrence of damage to the filter in the event of a ground fault.
- 2) The capacitors in the L-C-L filter used to attenuate the ripple associated with the switching of the AFE IGBT rectifier may cause resonance with the network. This may require adjustment of the filter's capacitors to resolve, likely reducing its filtering effectiveness.
- 3) One advantage of an AFE drive is its ability to regenerate power (i.e., they are full four-quadrant drives). While this may be applicable to cranes, hoists, etc., it is of no benefit to pumps, fans, and other single-quadrant applications. For main propulsion applications, the regenerative capability may be of limited value



THDv on 3×800 hp dc SCR drives without-with-without broadband active filters. THDv is reduced from 11.2 to 3.7%.



The ac PWM drive with IGBT AFE.



AFE drive typical input current waveform [6].

depending on the ability of the generators to accept the regenerated power without tripping. The British Royal Navy recently decided against AFE drives for their new Type 45 destroyers, which have 2×20 MW, 4.16 kV, 15-phase, multilevel PWM drives with six-pulse SCR rectifiers and dynamic braking, after considering the damage to the gas turbine generators that could result from excessive regeneration from the AFE drives during crash stop and other violent maneuvers.

- 4) On systems where AFE drives and standard six-pulse VFDs have been applied to the same bus, there may be problems due to the AFE rectifier's high-frequency currents being impressed on the dc bus of the standard six-pulse VFDs [5]. Recent studies have suggested that the six-pulse dc bus voltage can rise by up to 15%. If the six-pulse converter is running at light loads, it may run the risk of tripping out on over-voltage dc bus.
- 5) On marine applications, reliability is paramount, especially on equipment for propulsion where the ability to get me home is crucial. As a much more complex device, an AFE drive is arguably less reliable than a standard six-pulse drive. In addition, if the IGBT rectifier being used to reduce harmonics were to fail, the entire drive would be out of service. A failure of the phase-shift transformers on multipulse drive systems would also cause these drives to shutdown. However, with input filters, such as the wide-spectrum filter presented next, the device may simply be bypassed in the event of failure, allowing the drive to operate. Harmonics would be generated, but the drive would likely be capable of operating at a reduced output without problems.

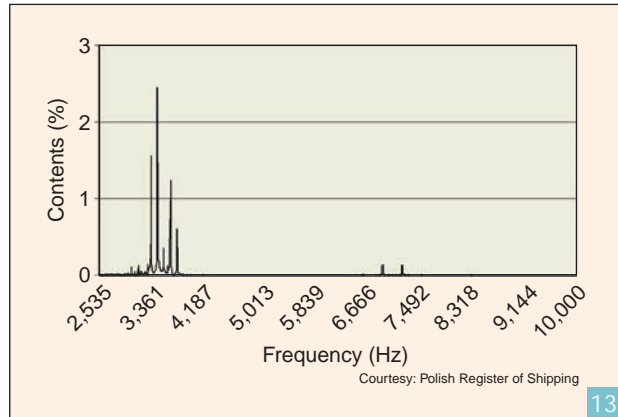
Wide-Spectrum Passive Filter

The wide-spectrum filter consists of a reactor with multiple windings on a common core and a relatively small capacitor bank. This design exploits the mutual coupling between the windings to improve performance. Figure 14 shows a configuration of this filter. A high-impedance winding, L1, is used as the main blocking inductance and is sized to prevent the importation of upstream harmonics. A filtering winding, L3, combines with the capacitor bank to provide a low-impedance path to filter out the harmonic currents generated by the downstream load. To decrease through impedance and reduce voltage drop across the filter, a compensating winding, L2, can be used and is wound in opposite polarity to the blocking winding.

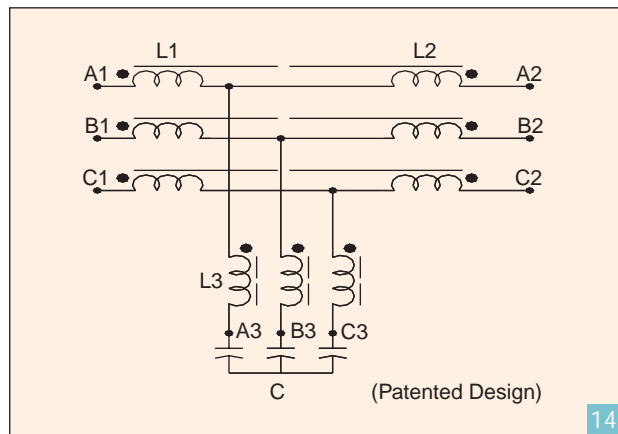
One key advantage of the unique reactor design of the wide-spectrum filter is that it allows for the use of a significantly smaller capacitor bank (typically <15% reactive power as a percent of full-load rating). This will reduce voltage boost and reactive power at no load to ensure compatibility with generators. Capacitors introduce a source of reactive current (i.e., leading power factor) to the generator(s), which will tend to boost the generator voltage. Generators are designed to adjust for voltage drop as their load increases and typically have minimal ability to lower voltage when raised by a leading power-factor load. It is therefore important that any filtering device that incorporates

capacitors is designed to ensure that the filter's maximum capacitive reactive current (which occurs under no-load conditions) is comfortably below the maximum allowed by the generator.

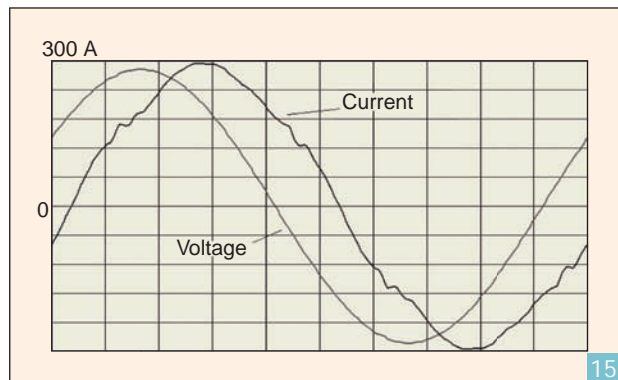
The filter is connected in series between the main supply and drive. THDi is typically reduced to <6% when applied to a six-pulse ac PWM drive (Figure 15), regardless of whether the drive is equipped with an ac or dc reactor or not.



Voltage frequency spectrum on vessel with AFE propulsion drives. THDv attributed to voltage harmonics above 50th (i.e., 3 kHz) was 3.26%. Below the 50th harmonic, the THDv was 3.23%, and the total THDv was 4.65% [7].



Wide-spectrum harmonic filter schematic.

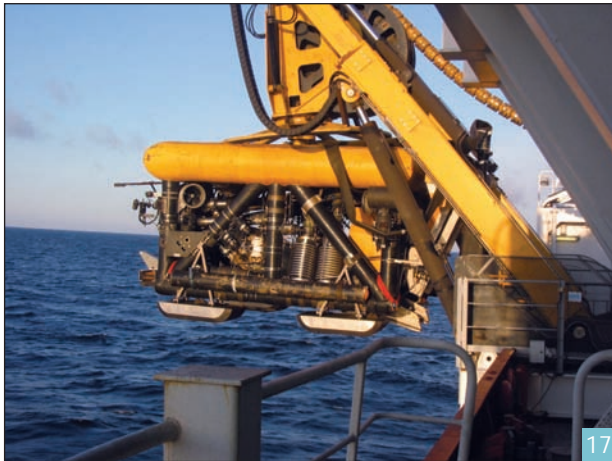


Input waveforms with wide-spectrum filter. THDi = 4.8%.



16

Ocean Challenger cableship.



17

Remotely operated trenching vehicle with 10×30 kW thrusters and 4×300 kW pumps onboard.

The wide-spectrum filters can be applied to ac drives with diode or SCR precharge input rectifiers ranging in size from 5 hp/4 kW to 3,500 hp/2,600 kW at present. They can be applied to single or multiple drives, but only drive loads should be connected as the filter is designed specifically for rectifier operation. The filter can usually be retrofitted to the existing drives without the requirement for drive modifications, whether for single- or multiple-drive applications. The filter can also operate on fully controlled SCR bridges as used in dc drives but with a slight reduction in performance.

Case Study 2: Cableship Application of the Wide-Spectrum Filter

Harmonic distortion resulting from the operation of numerous ac VFDs on a Norwegian cable laying vessel known as the Ocean Challenger (Figure 16) was preventing the ship from sailing without the use of rented generators. When connected to the ship's

main electrical distribution, voltage distortion significantly exceeded the 5% level permitted by the classification body, DNV. By supplying all harmonic generating VSDs from the rented generators, the voltage distortion created was isolated from the rest of the equipment on the ship. The ship's operators wanted to reduce costs and reclaim deck space by finding a cost-effective solution for treating the VSD harmonics, so that the drives could be returned to the ship's main distribution supply and the rented generators could be eliminated.

The Ocean Challenger's trenching operation is performed by a remotely operated pipe-line trenching vehicle or ROV (Figure 17). The ROV is equipped with ten 30-kW electric thrusters for maneuvering and four 300-kW high-volume, flow-rate electric pumps.

The electric thrusters and pumps are independently speed controlled via ac PWM VSDs mounted in the surface module. Each VSD was equipped with a 3% ac line reactor to partially attenuate the harmonic currents they generate. When connected to the ship's normal power supply, however, the 1.5 MW of ac drives produced high-harmonic voltage distortion on the two 2,800 kVA shaft generators, preventing operation in this mode.

The ship's operator, CTC Marine Projects, installed 2×750 kW wide-spectrum filters—one for each of two groups of 5×30 kW thrusters and 2×300 kW pump drives. Each 750-kW filter (Figure 18) was connected to one of the 2,880 kVA main power-shaft generators.

In sea trials, the THDi measured at the terminals of the filter under the ROV's maximum loading of about 85% was 6.1 and 6.4% for the port and starboard filters, respectively (Figure 19). It should be noted that if the VSDs could have been run up to their full-rated load, the THDi would have approached levels of <5%.

The THDv at the filter terminals was measured at 2.2 and 2.7% (Figure 20) at the 85% loading. Ship staff monitored both the operation of the two shaft generators and the THDv on the main switchboards. The ship's electrical engineer reported that the generators operated flawlessly and at no time did the THDv rise above 1.4 and 1.6% on their respective switchboards. Figure 20 shows the display from a Fluke 43 measured at the switchboard connected to the port filter.

The installation of the two 750-kW filters allowed the vessel to meet the 5% voltage-distortion limit of the DNV without the need for the rented generators and additional deck space. Two years after installation, CTC Marine Projects were able to report that the filters had worked fully to specification without any incident, cost effectively resolving the high-voltage distortion issue.

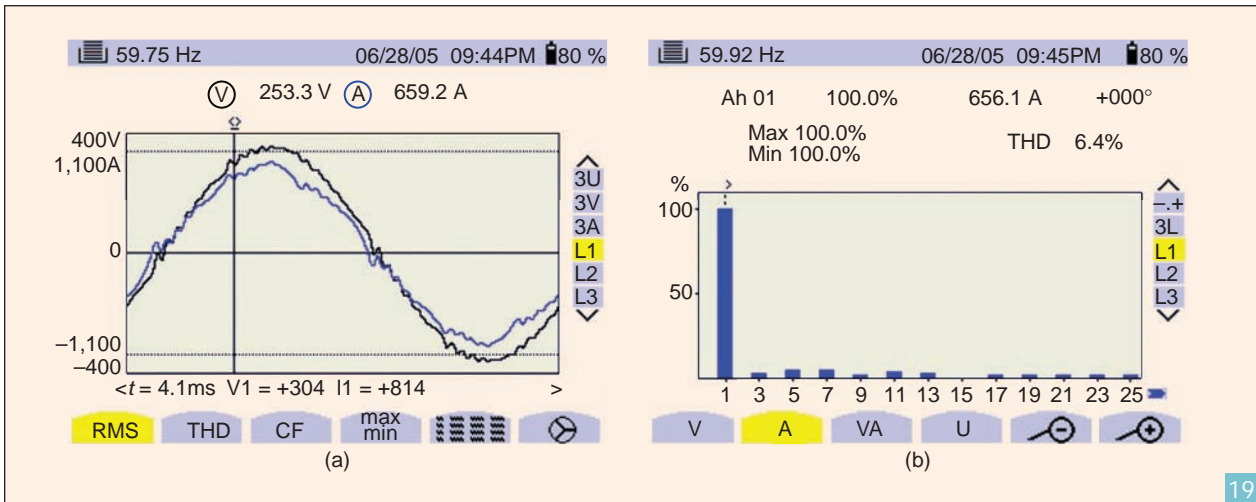
Conclusion

As the marine industry has moved toward electric propulsion and other uses for VSDs, harmonics have become a major power-quality concern. This



18

One of two 750-kW wide-spectrum harmonic filters installed on each group of combined thruster and pump load.



(a) Starboard filter current and voltage waveforms and (b) current spectrum, THDi = 6.4%.

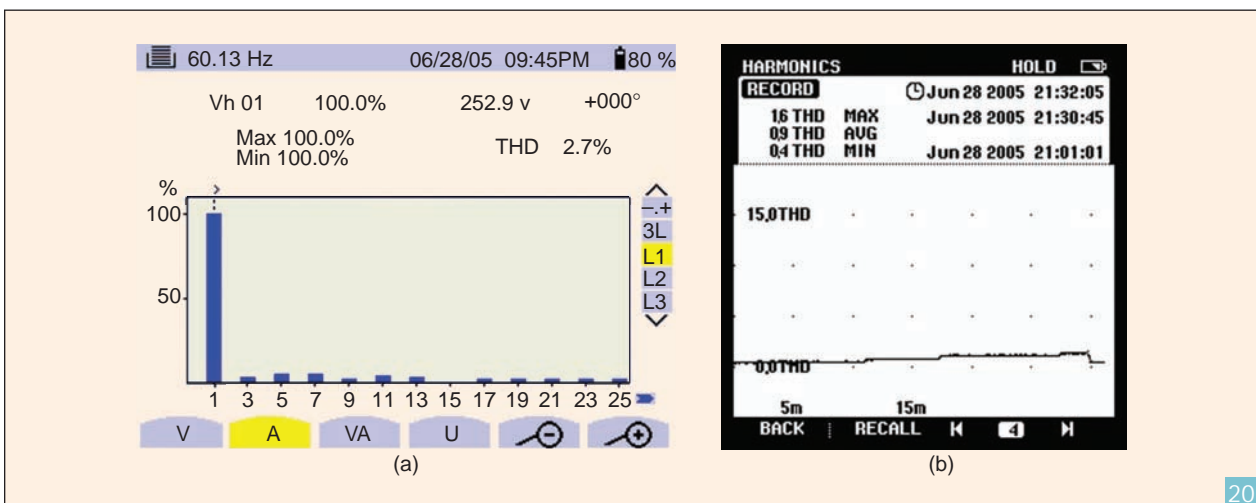
has led classification bodies to demand that voltage distortion remain below acceptable levels. A few of the technologies being adopted to mitigate the effects of harmonics have been reviewed, and a case study was presented where a unique passive, wide-spectrum filter was successfully installed on a cable laying ship to meet the limits required by one of these classification bodies, DNV.

References

- [1] S. Bourguet, P. Guerin, and R. Le Doeuff, *Non-Characteristic Harmonics Generated by Frequency Converter*, GE44, Laboratory, Saint-Nazaire, France, All Electric Ship 2003, Edinburgh.
- [2] *ABS Guidance Notes on Control of Harmonics in Electrical Power Systems*, American Bureau of Shipping, May 2006.
- [3] *Rotating Electrical Machines—Part 1: Rating and Performance*, IEC 60034-1, 2004.
- [4] *Rotating Electrical Machines—Part 12: Starting Performance of Single-Speed Three-Phase Cage Induction Motors*, IEC 60034-12, 2002–2004.
- [5] I. C. Evans, "Are we playing with fire," *Elect. Rev.*, (U.K.), vol. 221, no. 3, p. 32, Feb. 1988.

- [6] L. Moran, J. Espinoza, M. Ortiz, J. Rodrique, and J. Dixon, "Practical problems associated with the operation of ASDs based on active front end converters in power distribution systems," in *Proc. Industrial Applications Conf.*, 2004, vol. 4, pp. 2568–2572.
- [7] J. Mindykowski, T. Tarasiuk, M. Szveda, and I. C. Evans, "Electric power quality measurements on an all electric ship with active front end propulsion drives," Polish Register of Shipping, Gdynia Maritime Univ., May–June 2007.
- [8] *Electrical Installations*, Offshore Standards DNV-OS-D201, Jan. 2005.
- [9] *Rules and Regulations for the Classification of Ships*, Lloyd's Register, July 2001.

Tony Hoevenaars (hoevenaars@mirusinternational.com) is with Mirus International Inc. in Mississauga, Ontario, Canada. Ian C. Evans is with Harmonic Solutions Co., Scotland. Andy Lawson is with Parkburn Precision Handling Systems Inc. in Hamilton, Scotland. Hoevenaars is a Member of the IEEE. This article first appeared as "Meeting New Marine Harmonic Standards" at the 2008 Petroleum and Chemical Industry Conference.



(a) Voltage spectrum at starboard filter where THDv = 2.7% and (b) port-side generator voltage distortion that reached a maximum of 1.6%.