Preventing AC Drive Failures Due to Commutation Notches on a Drilling Rig

A. H. Hoevenaars, *Member, IEEE*, Ian C. Evans, and Biren Desai

***Abstract*—The operation of offshore drilling rigs and production platforms requires the extensive use of variable-speed drives. Historically, this involved dc drives almost exclusively, but more recently, ac drives have begun to find their way onto these facilities. Often, combinations of dc and ac drives are used. Silicon-controlled rectifier- or thyristor-bridge-based dc drives will distort the supply voltage by creating commutating notches. These notches can become quite deep if the source is weak, the dc drive load is heavy, and line reactors are not installed. Excessive voltage notching can cause operational problems and/or failures in other loads connected to the bus. When system resonance causes the ringing of these notches, the problem becomes even more severe. One such susceptible load is the ac drive. Wide-spectrum filters designed to reduce the harmonic currents being drawn by the ac drive can also be used to protect the drive from the harmful effects of commutation notching and other associated disturbances.**

***Index Terms*—AC drive, commutation notches, dc drive, harmonic filter, notch filter, silicon-controlled rectifier (SCR), voltage ringing, wide-spectrum harmonic filter (WSHF).**

I. Introduction

WITH THEIR relatively weak generator-based power systems and large dc drives, drilling rigs/ships and production platforms are highly susceptible to poor power quality in the form of voltage notches and overvoltage ringing. Fig. 1 shows the distortion of a typical voltage waveform when dc drives associated with drilling and pumping operations are in use. This level of distortion can cause misoperation and failures in other equipment connected to the power distribution bus.

Voltage notching and its related voltage ringing can result from diode bridge operation. They are most severe, however, with silicon-controlled rectifiers (SCRs) or thyristor bridges due to the phase back operation of these devices. SCR bridges, such as those found in dc drives, are used to convert ac voltage to the dc voltage required for dc motors. To control the level of dc voltage, the gate firing circuit of the SCRs (thyristors) can be adjusted. Voltage notching occurs when the firing circuits are delayed in order to achieve a lower dc voltage.

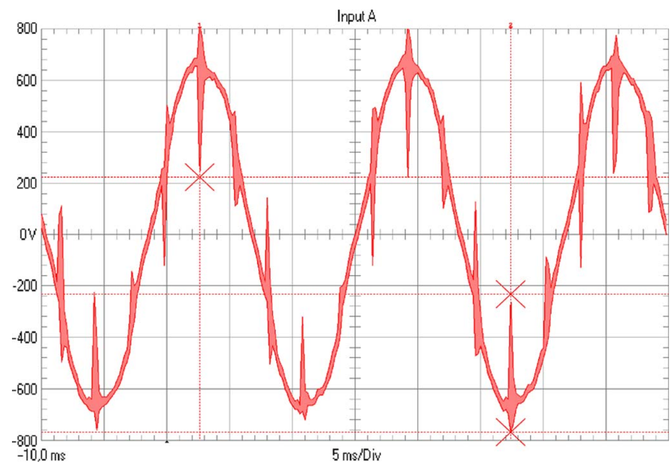

Fig. 1. Drilling-rig voltage waveform with commutation notches and voltage ringing.

One device that is susceptible to failure due to voltage notches and overvoltage ringing is the ac drive, which is now being used more frequently in oil-drilling operations. The ac drive controls the speed of ac induction motors for better process control and reduced energy consumption.

Now that ac drives have improved in reliability, they are being used in many different applications on both drilling rigs and oil production platforms. Problems being experienced include ac drive trips and component failure, such as dc bus capacitors, within the ac drives.

The failure of ac drives associated with air compressors on a drilling rig in Kazakhstan was believed to be caused by the overvoltages resulting from dc drive operation. In order to prevent these failures, special input harmonic filters were installed on the ac drives. These filters are designed to reduce the harmonics generated by the ac drives themselves but will also protect the drives by attenuating voltage notches and overvoltages.

Problems similar to those experienced at this rig have led marine-governing bodies, such as the American Bureau of Shipping, Det Norske Veritas, and Lloyds Register, to introduce limits for harmonic voltage distortion on ships and other marine applications. This leads engineers of drilling rigs and oil production facilities to include harmonic mitigation equipment in their designs. Harmonic filters, such as those used in the case studies in this paper, are proving to be a very effective and reliable solution for the prevention of harmonic-related power-quality problems.

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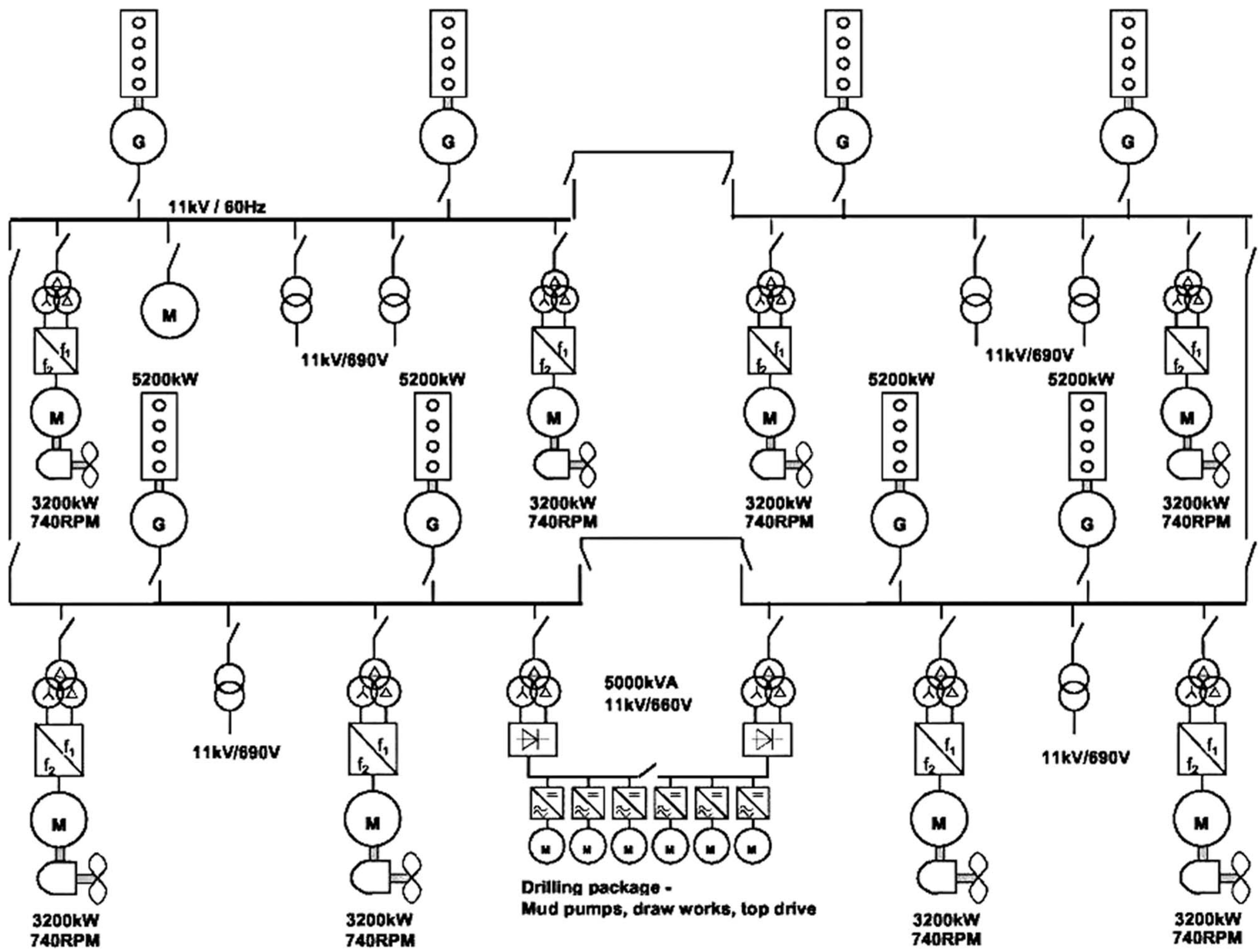

Fig. 2. Typical power system single-line diagram for dynamically positioned Class 3 drilling rig.

II. VSDs on Drilling Rigs

Applications for variable-speed drives (VSDs) on offshore oil rigs include drilling packages (either stand-alone or within common dc bus systems), shakers, centrifuges, compressors, and pumps. Included in the pumping category are electrical submersible pumps or ESPs which are beginning to see widespread use.

When an offshore rig is equipped with its own propulsion systems, often, these are also driven by VSDs (see Fig. 2). On ships, the trend is toward all electric systems which require VSDs for main propulsion and thrusters. Other applications on ships include winches; hoists; remote-operated vehicles; heating, ventilation, and air-conditioning systems; etc.

Although dc drives are being replaced by ac drives in many applications, they remain fairly common in marine projects. Fig. 3 provides a schematic of a typical dc drive and motor. The dc motor consists of a separately excited field circuit and an armature circuit. The field circuit draws a relatively small current through a diode bridge rectifier to develop a magnetic field around the armature. The speed of the motor rotation induced by this magnetic field varies with the level of voltage applied to the armature. To adjust the speed of the motor, the armature voltage is varied by a fully controlled SCR or thyristor bridge circuit.

The operation of the SCR bridge results in pulsed current waveforms being drawn by the armature similar to those shown in Fig. 4. These pulsed currents are high in harmonic content and can have a very fast rise time due to the delayed firing of the SCRs.

III. How DC Drives Produce Commutation Notches and Ringing

During the operation of a bridge rectifier, voltage discontinuities, referred to as "commutation notches," may occur. Commutation is defined as the moment when current switches from one conducting pair of diodes to another pair. In an ideal diode rectifier, this occurs instantaneously but, in reality, inductance in the circuit results in a momentary period when both diode pairs are conducting. During this overlap period, a short circuit is created between two phases of the three-phase supply voltage. This short circuit causes a brief drop in voltage which appears as a "notch" in the voltage waveform (Fig. 5).

With a simple diode bridge rectifier, the notch depth is typically quite small because the voltage difference between the phases that are short circuited during commutation is near zero. However, with a fully controlled SCR or thyristor bridge, the commutation notch becomes more severe. When the dc

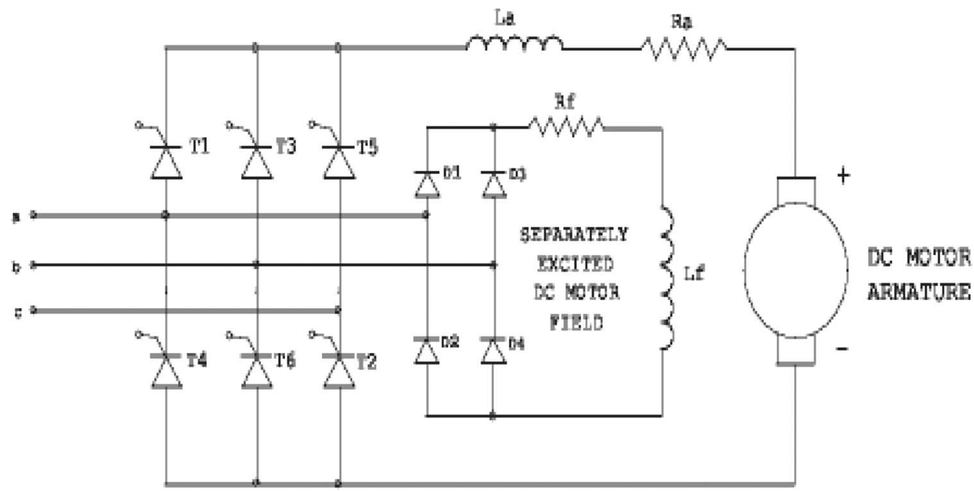

Fig. 3. Typical dc drive and motor schematic.

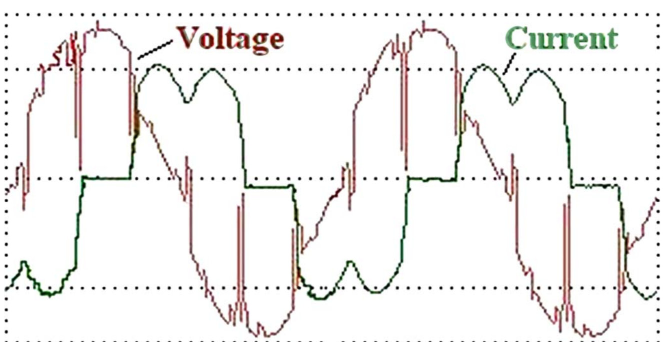

Fig. 4. Commutation notches on voltage supply due to fully controlled SCRs on dc drilling drives [3].

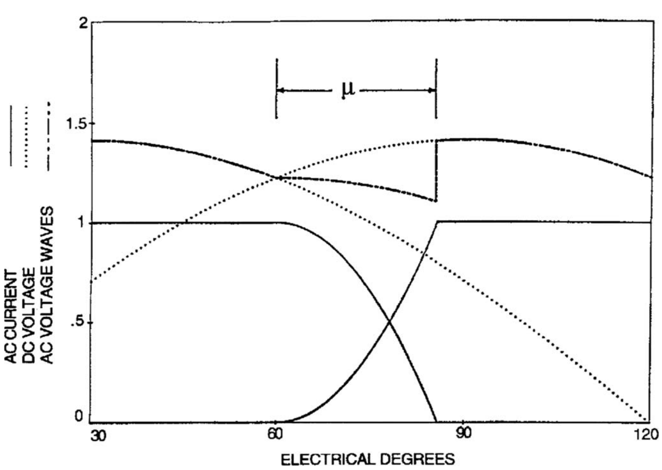

Fig. 5. Commutation overlap and notch with diode bridge operation, $\alpha = 0°$ [2].

bus voltage is lowered by delaying the thyristor firing (i.e., extending the firing angle α), commutation is also delayed until after the phase voltages have diverged. After firing, when commutation does occur, there is a potential difference between the shorted phases which drives more current through the short and increases the voltage drop and resulting notch. Fig. 6 shows variations in notch depths as the firing angles are varied.

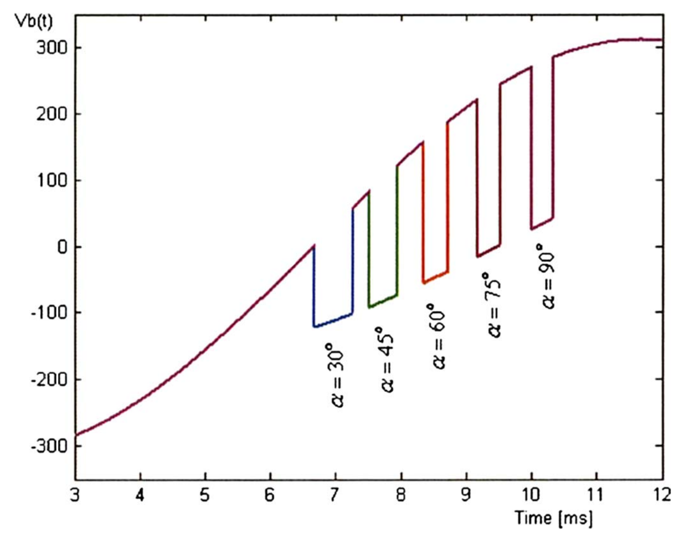

Fig. 6. Notch-depth variations on firing-angle changes [4].

Complicating the issue further is the potential for voltage ringing to occur. Since the notch has a relatively high frequency compared with the fundamental, it can be excited by system resonance. If the system impedance happens to create a resonance point near the notch frequency, voltage oscillations can result (Fig. 7). Often, it can be the electromagnetic-interference (EMI) filters on ac drives that create these resonance conditions.

IV. WSHF

The wide-spectrum harmonic filter (WSHF) is a passive device designed to mitigate the harmonics generated by rectifier systems, both diode and thyristor bridges. It is a series-connected device designed for application on any power system. It is comprised of inductive and capacitive elements that are tuned to filter all of the characteristic rectifier harmonic currents from the downstream nonlinear load without attracting these harmonics from other nonlinear loads connected to the upstream bus.

The WSHF consists of a reactor with multiple windings on a common core and a relatively small capacitor bank. This

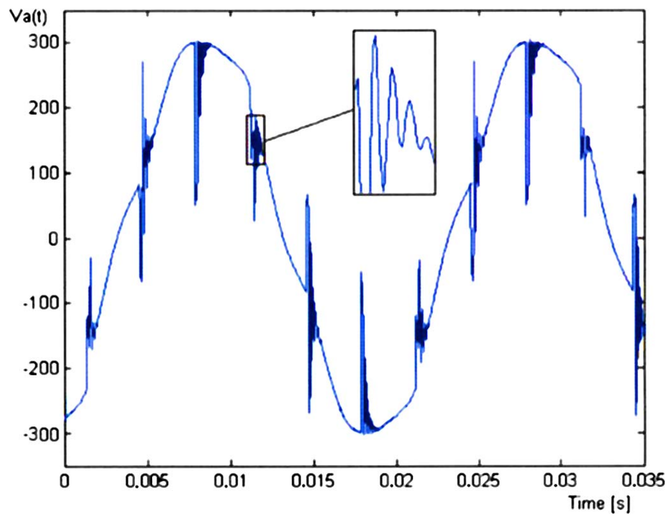

Fig. 7. Commutation notches associated with the operation of an SCR with $\alpha = 45°$ [4].

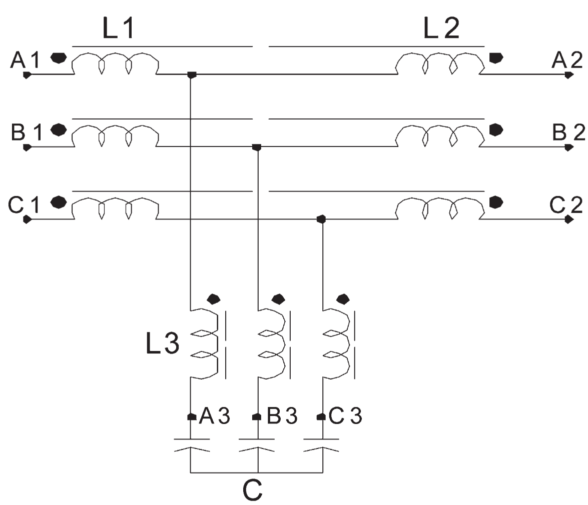

Fig. 8. WSHF schematic [5].

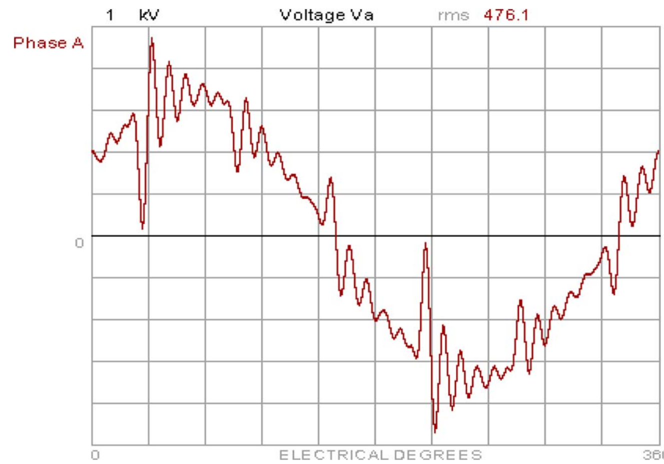

Fig. 9. Computer-simulated voltage at the distribution panel supplying a large dc drive fed from a generator.

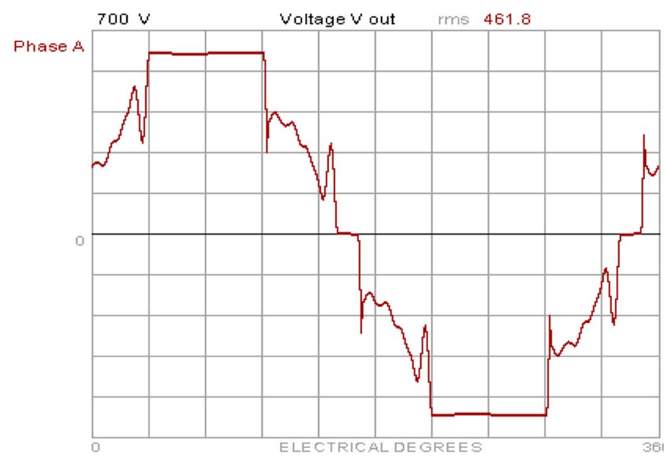

Fig. 10. Computer-simulated voltage at the input to the ac drive with input voltage to the WSHF as in Fig. 9.

design exploits the mutual coupling between the windings to improve performance. Fig. 8 shows a configuration of this filter. A "high-impedance winding," L1, is used as the main blocking inductance and 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, is occasionally included and wound in opposite polarity to the blocking winding [5].

Although its typical use in marine applications is to reduce the harmonic currents generated by ac and dc drives in order to prevent harmonic problems and meet the harmonic standards of marine certifying bodies, it can also be used to protect these devices from damage caused by commutation notches.

The capacitors used to filter VSD harmonics are also capable of supporting the voltage during notch dips. Computer simulations can be used to demonstrate this. The one line in the computer simulation is set up as a 2000 kVA generator with Xd$''$ of 16%, supplying an 800-hp dc drive operating at reduced speed (i.e., delayed firing angle) and a 100-hp ac drive equipped with a WSHF. A small capacitor bank was also included to create voltage ringing by exciting resonance. Fig. 9 shows the voltage waveform with commutation ringing as found at the distribution bus from which the dc drive is supplied.

Fig. 10 shows the output voltage waveform of the WSHF supplying the 100-hp ac drive with the input voltage as per Fig. 9. As can be seen, the voltage notching has been substantially reduced and the ringing essentially eliminated. The somewhat trapezoidal voltage wave shape may seem different but it is as expected at the output of the filter. Since the ideal voltage wave shape for a diode bridge rectifier would be a square wave, the trapezoidal wave shape of the WSHF actually helps reduce the dc bus ripple in the ac drive.

V. Case Study 1—Application of WSHFs to Protect AC Drives on a Kazakhstan Drilling Rig

The failure of ac drives associated with air compressors on a drilling rig in Kazakhstan was believed to be caused by the overvoltages resulting from dc drive operation. In order to prevent these failures, input harmonic filters were installed on the ac drives. These filters are designed to reduce the harmonics

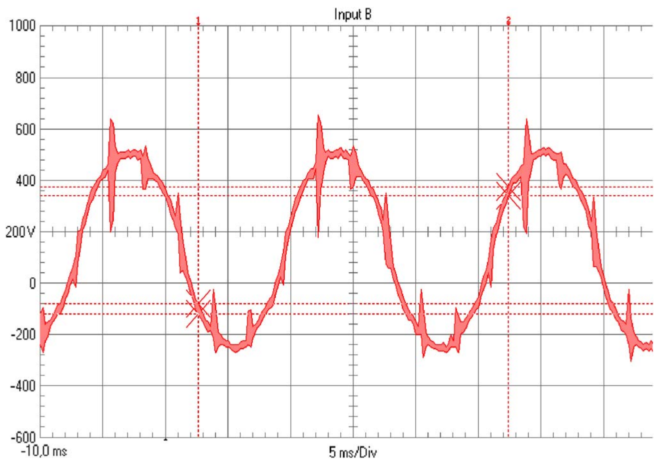

Fig. 11. Voltage waveform at input to harmonic filter.

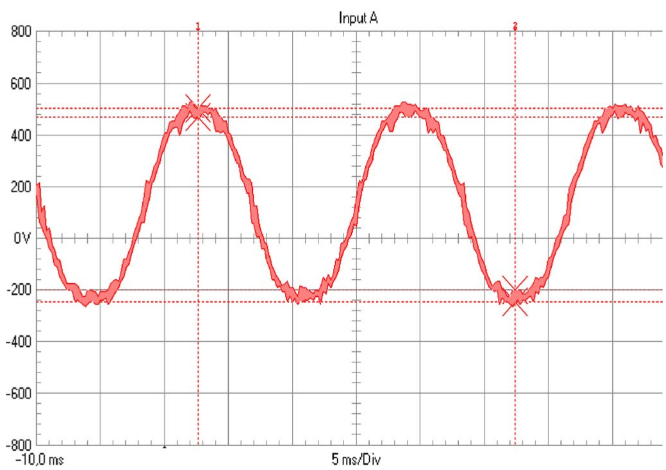

Fig. 12. Voltage waveform at output of harmonic filter supplying ac drive.

generated by the ac drives themselves but also will protect the drives by attenuating voltage notches and overvoltages.

It is worthy to note that the ac drives were equipped with input ac line reactors. Although the input line reactors were providing some protection against overvoltages, they were not capable of preventing the dc bus trips in this particular application.

Figs. 11 and 12 show the input and output voltage waveforms measured at the ac drives. As can be seen, the notches and overvoltages have been essentially eliminated. The ac drives were restored to service and have been operating trouble-free ever since the installation of the harmonic filters.

VI. Case Study 2—Application of Wide-Spectrum Filter on DC Drive in Automobile Assembly Plant

Harmonic problems associated with DC drives are not confined to marine and offshore applications. Fig. 13 provides the voltage waveform at the input to a 700-hp dc four-quadrant press drive at a major U.K. automotive manufacturer (Fig. 14). The waveform exhibits severe line notching with total harmonic voltage distortion measured at $> 12\%$. This distortion resulted in considerable failures of ac drives, ac servo drives, and other equipment in the facility.

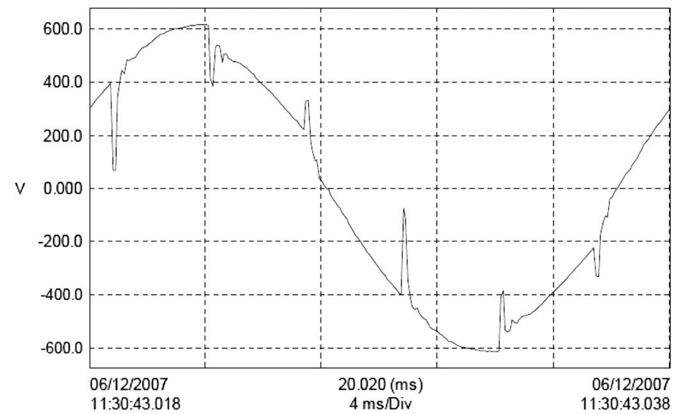

Fig. 13. Voltage notching on supply bus before applying harmonic treatment on 700-hp dc drive. Vthd $> 12\%$.

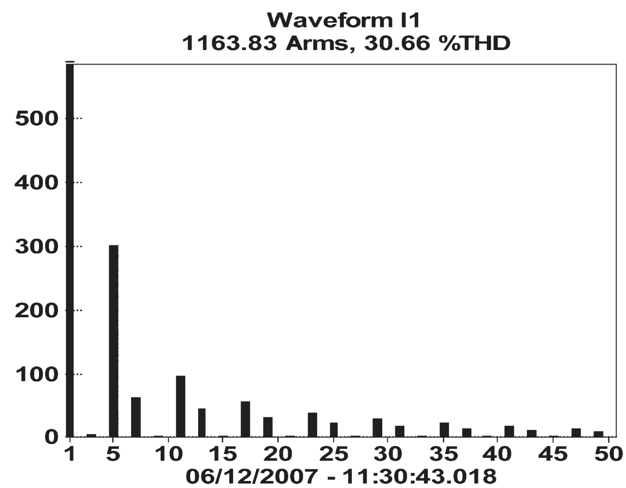

Fig. 14. Harmonic current spectrum of 700-hp dc press drive before treatment. Ithd $= 30\%$.

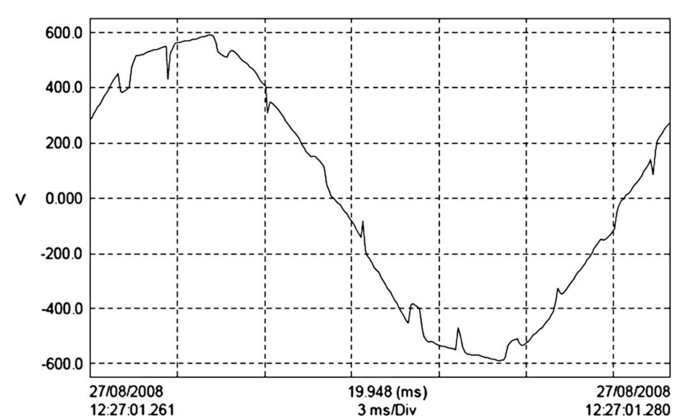

Fig. 15. Voltage notching on supply bus with filter installed.

Fig. 15 shows the much reduced voltage notching on the supply bus after treatment of the 700-hp dc drive with a WSHF. Much of the remaining waveform notch can be attributed to a 400-hp and two 350-hp dc drives that are fed from the same supply but have not been fitted with any mitigation for harmonics or line notching. The total harmonic current distortion produced by the 700-hp dc drive was reduced to 5.8% (Fig. 16).

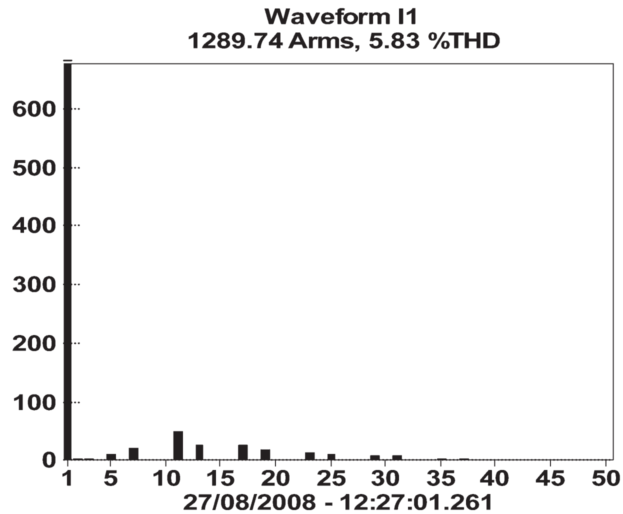

Fig. 16. Harmonic current spectrum of 700-hp dc press drive after treatment with WSHF. Ithd $= 5.8\%$.

VII. Conclusion

The failure of ac variable-frequency drives due to line voltage notches introduced during dc drive operation has become a serious problem in offshore production platforms and drilling rigs. When system resonance causes the ringing of the voltage notch, overvoltages can result in the dc bus of the ac drive. If severe enough, these overvoltages can lead to ac drive trips and/or dc bus capacitor failures.

By applying a WSHF at the input to the ac drive, the notch and associated ringing as seen by the ac drive can be substantially reduced. The notch and ringing will remain upstream but the ac drive will be protected. To reduce the notch throughout the power system, the WSHF can be applied at the source of the notch, the dc drive, or other SCR load.

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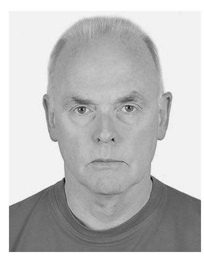

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