Preventing Centrifuge Failures Due to Voltage Distortion on a Drilling Rig

A. H. Hoevenaars, *Member, IEEE*, Michael McGraw, *Member, IEEE*, and Kerwin Rittammer

***Abstract*—The ac and dc drives commonly used on land and offshore drilling rigs produce extremely high levels of harmonic distortion. With voltage distortion often exceeding 20%, equipment associated with the drilling operation can experience erratic operation and equipment damage. Repeated damage to one or several ac drives is common. One land rig in Northern Alberta was experiencing failures with its centrifuge equipment on a weekly basis. During one visit to the site, a drive in the centrifuge was found to have tripped off causing the centrifuge to plug up. After cleaning out the centrifuge and restoring the drive, it tripped off again shortly after drilling operations resumed. A power quality analyzer was connected, which revealed extremely high levels of voltage distortion during drilling operations. Deep notches, which are visible in the voltage waveform, were found to be the result of silicon-controlled rectifiers in the mud pump dc drives. Total harmonic voltage distortion (v_{THD}) reached 25%. A series-connected passive filter was installed ahead of the centrifuge equipment to reduce the voltage notching and lower voltage distortion. The filter reduced the notch depth by more than half and lowered overall voltage distortion at the centrifuge panel to $<$ 9% during the most severe drilling operations. With line-side voltage distortion levels remaining in the 20% range, the filter proved to be extremely effective in eliminating all centrifuge operational and premature failure issues.**

***Index Terms*—AC drive, adjustable-speed drives (ASDs), centrifuge, commutation notches, dc drive, harmonic distortion, harmonic filter, harmonic mitigation, harmonics, notch filter, silicon–controlled rectifier (SCR), voltage ringing, wide-spectrum harmonic filter.**

I. Introduction

With their relatively weak generator-based power systems and large dc drives, drilling rigs (both land and offshore) are highly susceptible to poor power quality in the form of voltage notches and overvoltage ringing. The harmonic mitigating characteristics of series-connected wide-spectrum harmonic filters are already fairly well understood [1], but what is not recognized is the ability of these filters to mitigate source voltage harmonics to protect sensitive electrical equipment.

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 power electronic equipment.

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.

A. Centrifuge ASD Failures on a Drilling Rig

A device that incorporates ac drives for drilling applications is the centrifuge. One centrifuge rental company's control panel utilizes three adjustable-speed drives (ASDs) that run the main drive, back drive, and the pump that feeds the centrifuge. The panel includes a programmable logic controller for control.

In applications in Northern Alberta, these centrifuge units were experiencing multiple failures of ac drives believed to be caused by voltage notching associated with dc drive operation on the rig. 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 also will protect the drives by attenuating voltage notches and overvoltage ringing.

B. ASDs on Oil Rigs and Marine Applications

Applications for ASDs on oil rigs include drilling packages (either standalone or within common dc bus systems), shakers, centrifuges, compressors, and pumps. In offshore applications, the rig may also be equipped with its own propulsion systems, which are typically driven by ASDs. On ships, the trend is toward all electric systems, which require ASDs for the main propulsion and thrusters. Other applications on ships include winches, hoists, remote-operated vehicles, heating, ventilating, and air conditioning systems, etc.

Although dc drives are being replaced by ac drives in many applications, they remain fairly common in oil and gas operations. Fig. 1 provides a schematic of a typical dc drive and

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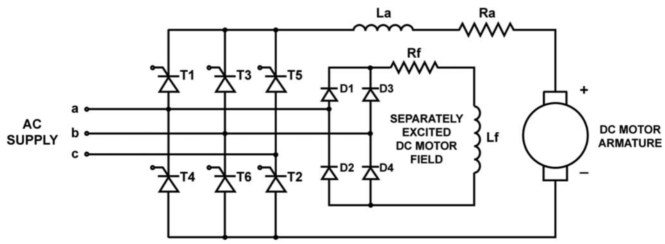

Fig. 1. Typical dc drive and motor schematic.

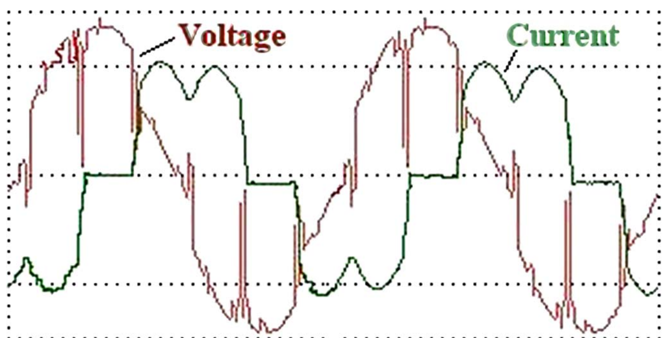

Fig. 2. Commutation notches on voltage supply due to fully controlled SCRs on dc drilling drives [3].

motor. The dc motor consists of a separately excited field circuit and an armature circuit. The field circuit draws 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. 2. These pulsed currents are high in harmonic content and can have a very fast rise time due to the delayed firing of the SCRs.

C. How DC Drives Produce Commutation Notches

During the operation of a bridge rectifier, voltage discontinuities, which are 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 (see Fig. 3).

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 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

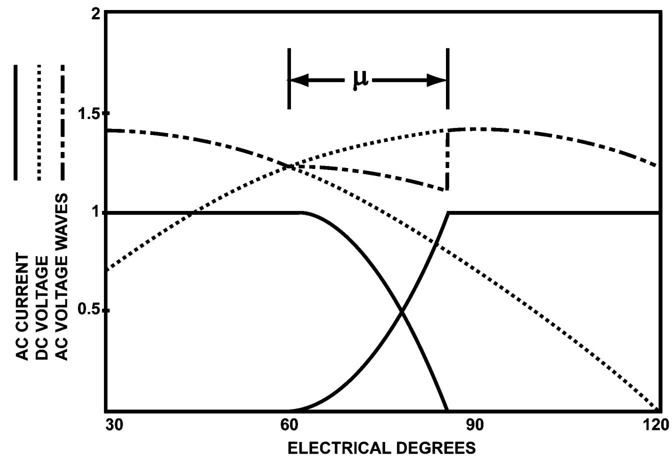

Fig. 3. Commutation overlap and notch with diode bridge operation: $\alpha = 0°$ [2].

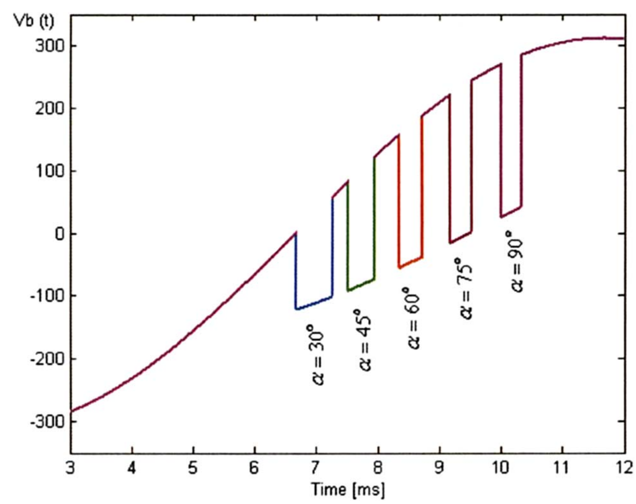

Fig. 4. Notch depth variations on firing angle changes [2].

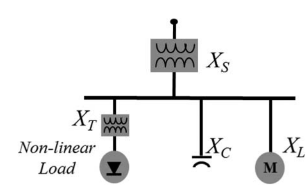

Fig. 5. Simple one-line diagram for power system.

the shorted phases, which drives more current through the short and increases the voltage drop and resulting notch. Fig. 4 shows variations in notch depths as the firing angles are varied.

D. System Resonance and Ringing

Complicating the issue further is the potential for voltage ringing to occur, resulting from power system resonance. This can occur when the capacitance of the power system matches the natural inductance of the system (see Figs. 5–7).

Fig. 5 shows a very simple one-line diagram with X_S, X_T, X_C, and X_L being the reactance of the source, drive transformer, power factor correction (PFC) capacitors, and

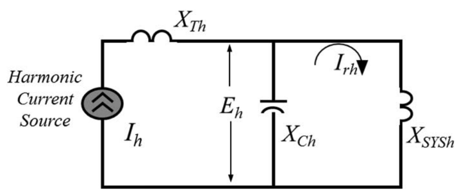

Fig. 6. Equivalent diagram.

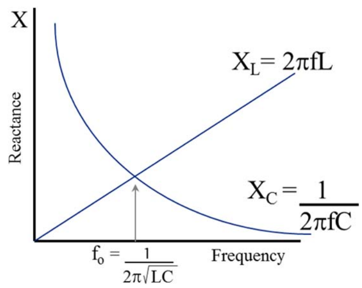

Fig. 7. Reactance curves and resonance point.

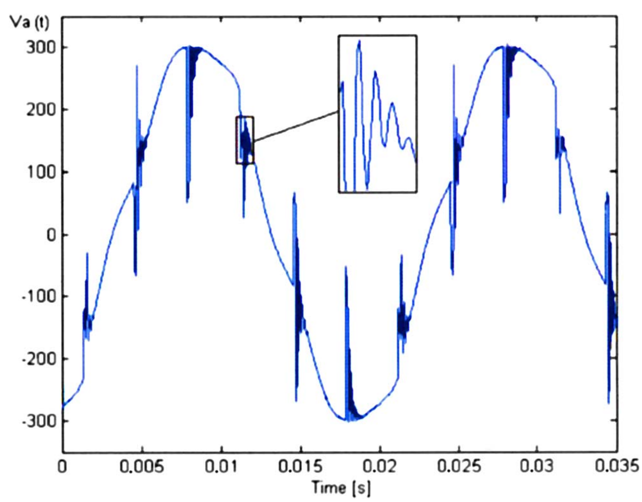

Fig. 8. Commutation notches associated with the operation of an SCR with $\alpha = 45°$ [2].

fixed speed motors, respectively. The nonlinear load represents a dc or ac drive as a current source of harmonics.

This one-line diagram can be represented as the equivalent diagram in Fig. 6, where $X_{\mathrm{SYS}h}$ is the equivalent parallel reactance of the source and motor loads at harmonic "h." Parallel resonance will occur at the frequency where the capacitive reactance and inductive reactance are essentially equal. This resonance can result in both excessive current and high levels of voltage distortion at that harmonic frequency.

Since the notch introduced by an SCR has a relatively high frequency compared to 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 (see Fig. 8). Often, it can be the electromagnetic interference (EMI) filters on ac drives that contribute to these resonance conditions.

II. Analysis

A. Computer Simulation of Drilling Rig With AC and DC Drives

A typical one-line diagram for a land-based drilling rig is shown in Fig. 9. The predominant load consists of both dc and ac drives, which can dramatically distort the voltage waveform when in operation. The major components in the one-line diagram are the following:

- 3 × 1500-kW 600-V generators;
- 2 × 1500-HP dc drives for mud pumps;
- 1 × 1500-HP dc drive for draw works;
- 1 × 1200-HP ac drive for top drive;
- 300-kW linear load.

This one-line diagram was entered into computer simulation software to analyze the effect of the drives on the power system. The computer program uses nodal analysis by formulating the nodal matrix and solving the set of numerical ordinary differential equations using the backward Euler (second- and third-order) method. At each point in time, nonlinear devices are replaced by equivalent linear circuit models, which often require many iterations before calculations converge to a solution. The program dynamically adjusts the time step to improve accuracy and reduce long simulation times. Transient analysis is achieved by solving the set of ordinary differential equations on each time point for the set time interval.

Fig. 10 shows the computer simulation results for the voltage waveform and harmonic spectrum at the centrifuge input. The operating conditions chosen were those expected during "back reaming" operation (also known as "tripping the hole"), which is known to produce the highest levels of voltage distortion. The deep voltage notch and high-frequency ringing are very typical phenomena observed on drilling rigs. When severe, these distortions often cause misoperation or failure of connected equipment.

B. Wide-Spectrum Passive Harmonic Filter

The use of passive filters to treat harmonics generated by nonlinear load circuits is fairly common but not that well understood. Passive filters are harmonic mitigating devices usually applied to six-pulse ASDs to reduce the harmonics they generate. There are many types of passive filters on the market, with some being much better than others. Depending on its configuration, the passive filter might be tuned to mitigate harmonic currents at targeted harmonic frequencies. The best passive filter technology, however, is not tuned to specific harmonic frequencies but rather provides harmonic reduction over a wide frequency range. For example, a wide-spectrum filter applied to a six-pulse drive will reduce all of the characteristic harmonics, but particularly the 5th, 7th, 11th, and 13th.

The goal is to mitigate the current harmonic generated by the load device, thereby mitigating the current harmonic effect on the system impedance and reducing the resulting voltage distortion created by that particular load. The advantages of using wide-spectrum passive filters versus other forms of harmonic

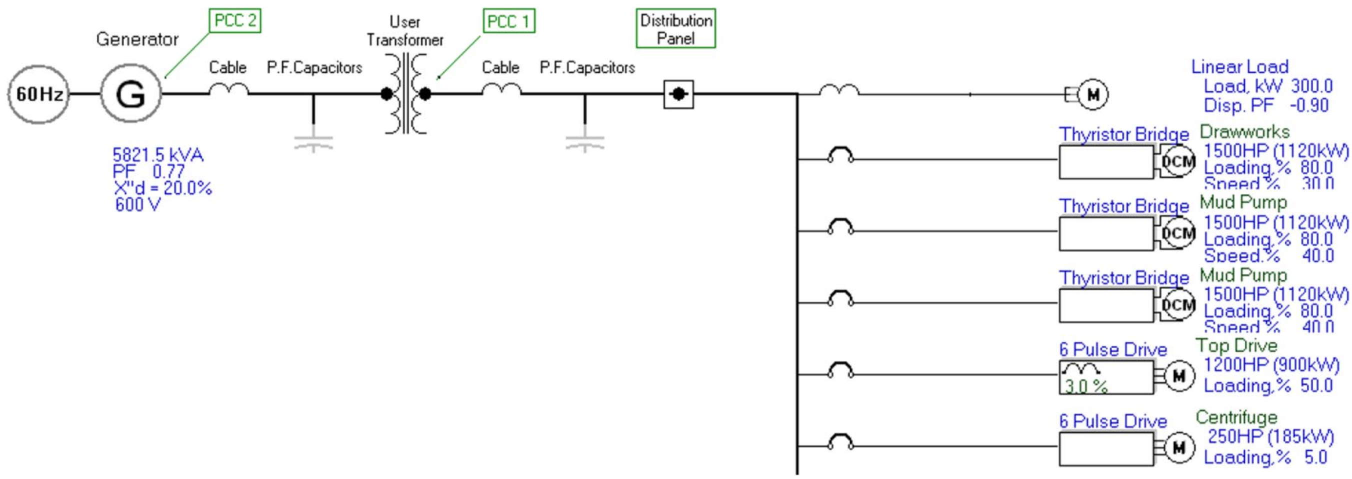

Fig. 9. One-line diagram for drilling rig used in computer simulation.

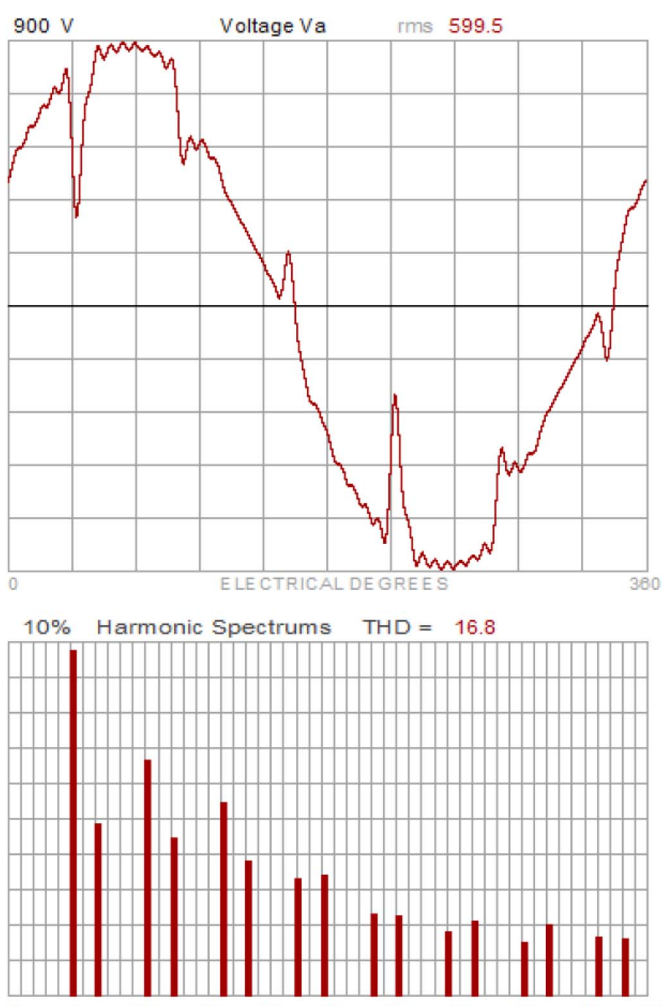

Fig. 10. Computer-simulated voltage waveforms and harmonic spectrum at the centrifuge.

mitigation are i) cost, ii) simplicity of integration and operation, iii) broad speed/load operating range, and iv) much better efficiency.

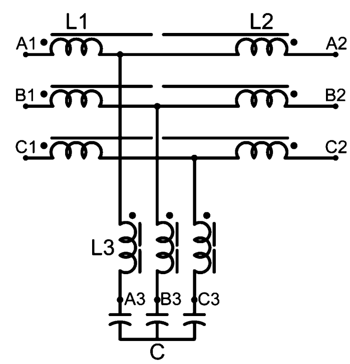

Fig. 11. Wide-spectrum harmonic filter schematic.

There are various forms of passive harmonic filters being used by ASD manufacturers, but most employ a combination of a blocking element and a tuned filtering element. One such configuration is shown in Fig. 11.

Crucial in the design of an effective filter is the prevention of harmonic importation from the line side of the filter. Without this ability, a filter could easily be overloaded when installed on a power system where other harmonic-generating nonlinear loads exist on the same bus. A wide-spectrum harmonic filter consisting of a reactor with multiple windings on a common core and a relatively small capacitor bank can be a very effective solution since this design exploits the mutual coupling between the windings to improve performance. To prevent importation of upstream harmonics, the resonant frequency, as seen from the input terminals, is near the 4th harmonic, which is comfortably below the predominant harmonics of three-phase rectifiers.

The unique reactor design 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. The filter is connected in series between the main supply and the drive. Current total harmonic distortion (I_{THD}) is typically reduced to $< 6\%$, when applied to a six-pulse ac pulsewidth modulation (PWM) drive, regardless of whether the drive is equipped with an ac or dc reactor or not.

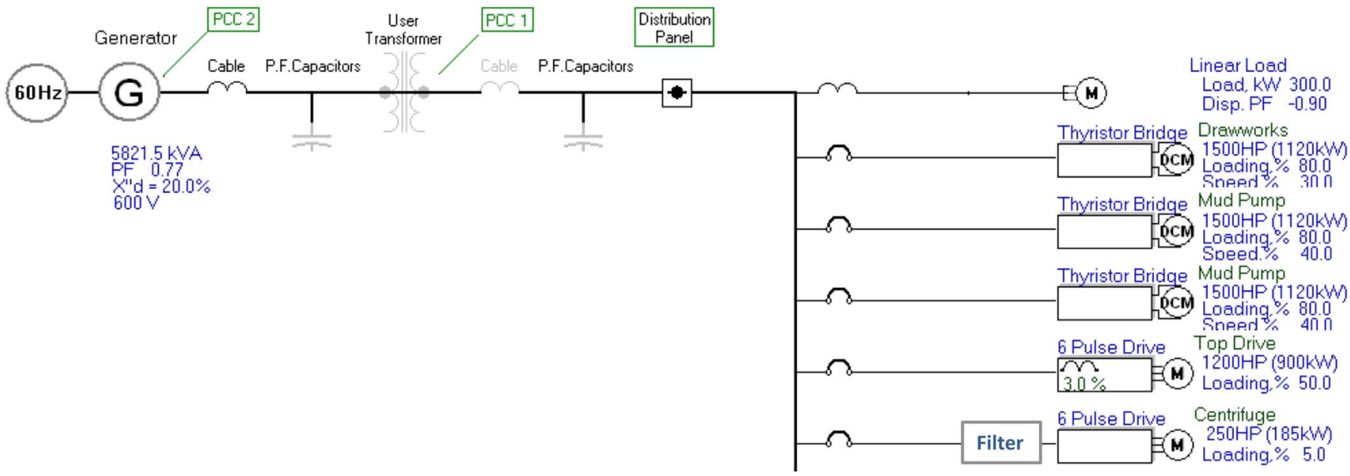

Fig. 12. Computer simulation with filter used to protect the centrifuge.

Another use for the wide-spectrum harmonic filter that is not commonly known is suppression of voltage distortion to protect sensitive loads from the harmful effects of these distortions. This was not the original intent for the filter but was an observed byproduct of the application of the passive filter to real-world conditions.

Most commercially available passive filters feature high capacitance values in relation to their base kilowatt rating, i.e., 30% or greater. These passive filter designs can create voltage source issues for their connected loads, such as voltage boost and leading power factors. In addition, their deployment on islanded systems, such as remote generator-fed oil and gas production facilities or land-based and offshore drilling and production facilities, created regulation issues for the site generation since, at low loads, leading power factors can interfere with generator regulation systems. To address this, many filter suppliers incorporate a capacitive switching contactor into the assembly to switch out the capacitors at low load levels. This impacts on their harmonic mitigation capability and eliminates the protective characteristics of the device. Only after the design of a much lower capacitive reactance filter, which avoided the need for capacitive switching, was the full capability and advantages of the wide-spectrum passive filter able to be explored.

The wide-spectrum harmonic filter provides several protection characteristics.

1) In extreme cases, such as drilling applications that utilize thyristor drives (dc drives), voltage commutations can approach the zero voltage crossing triggering the misfiring of connected devices. The capacitive element of the passive filter helps support the voltage to substantially reduce the notch depth, thereby avoiding zero voltage crossing and triggering of power supply and firing circuit misoperation.
2) In these same thyristor drive applications, a common phenomenon is a transient recovery voltage and resonance after recovery. The series inductance of the passive filter changes the resonance frequency to help suppress the ringing.
3) The wide-spectrum harmonic filter will help balance voltages.
4. Low-level voltage sags or surges, as may be witnessed from upstream capacitor bank switching and sudden load changes, will be reduced.

C. Computer Simulation Demonstrating How a Wide-Spectrum Harmonic Filter Can Be Used to Protect AC Drives

To analyze the protective capabilities of the wide-spectrum harmonic filter, additional computer simulations were performed with the filter inserted, as shown in Fig. 12.

Although the simulation did not show the filter eliminating the voltage notch completely, it did reduce it substantially. In addition, the high-frequency ringing was also reduced. Voltage distortion v_{THD} was reduced by more than 50% (from 20% to 9%). The largest improvement was in the reduction of 5th harmonic, but all harmonic values were lowered. It should be noted that the scale on the harmonic spectrum graphs is different for the input results (10%) versus the output results (4%), as shown in Figs. 13 and 14.

III. Findings and Field Measurements

A. Centrifuge Application on a Northern Alberta Land Rig

After multiple failures of the ASDs on the centrifuge system of a land rig in Northern Alberta, a means of preventing these failures was sought after. Service technicians were being called to the location to investigate nuisance tripping, odd behavior, and buzzing noises in the control panel of the centrifuge system.

Upon arriving at the site on one occasion, the technician was told that there had been a blackout of the rig as it was being fired up. A prior issue on a different hole was described as the main drive tripping and fluid spewing out the feed tube, which indicated brownout-type behavior. Further discussions confirmed that this was likely the case as only one generator was running at the time. A second generator on the rig was fired up, which temporarily alleviated startup problems with the centrifuge equipment.

The following day, the technician was once again called to the site to investigate an incident overnight when the back

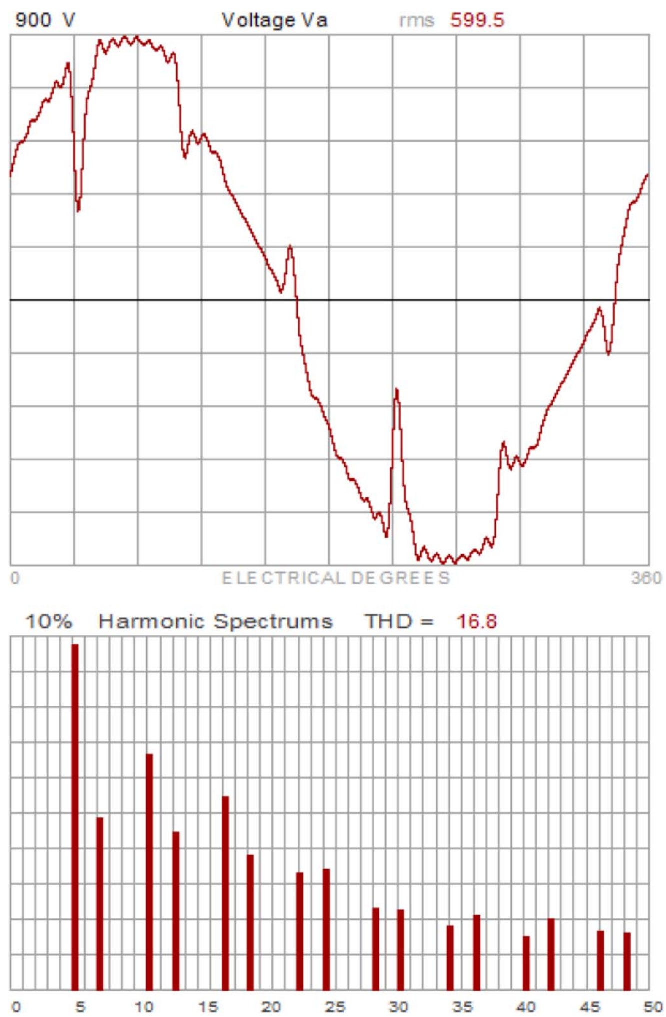

Fig. 13. Computer-simulated voltage waveforms and harmonic spectrum at input to filter.

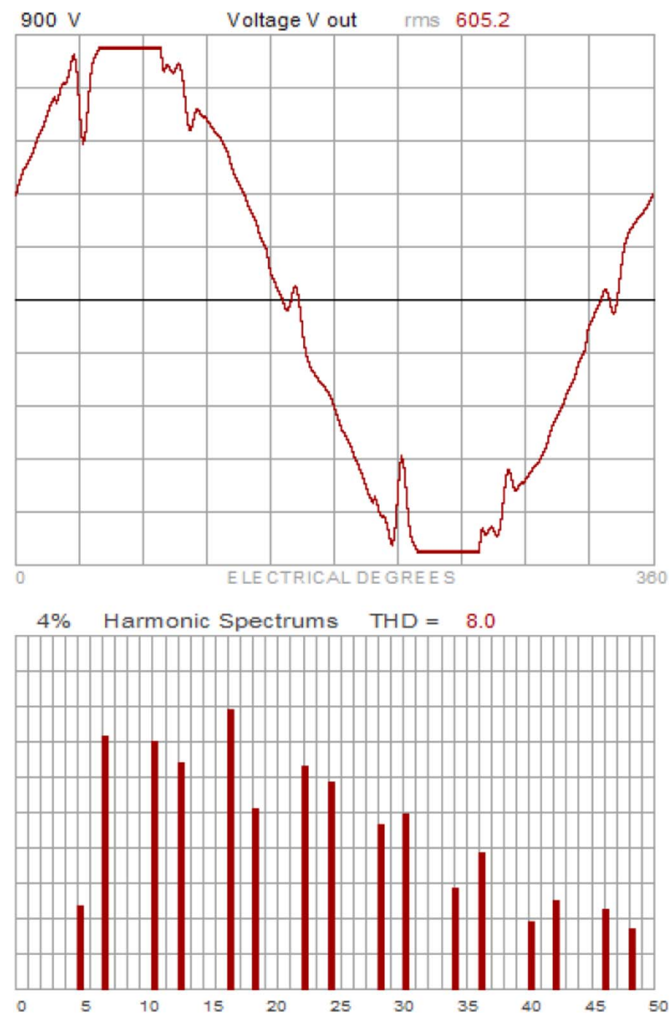

Fig. 14. Computer-simulated voltage waveforms and harmonic spectrum at output of filter.

drive tripped off and then the centrifuge plugged up. While investigating, the back drive tripped again. Parameters on the drive were adjusted in an attempt to limit these nuisance trips.

A power analyzer was then used to check power to the centrifuge panel, while the rig was "tripping" out of the hole (withdrawing the drill from the hole). This operation proved to be most insightful as power quality was observed to fall dramatically. As the measured voltage distortion exceeded a certain level, a loud audible buzzing was heard from the drives in the centrifuge panel. This sound would typically be associated with potential damage to the panel electronics. The buzzing would stop as the tripping stopped, and the power returned to a relatively "clean" sine wave again (see Figs. 15 and 16).

It was noted that the voltage was not overshooting, but rather dropping due to the commutating notches. This explained why there was no outright damage to the panel, just the ASDs tripping offline. The notches in voltage were expected to have a damaging effect over time however.

The following day, measurements were taken during the drilling operation (see Figs. 17 and 18). While drilling, dc drives operating the mud pumps were in use, leading to much higher voltage distortion levels.

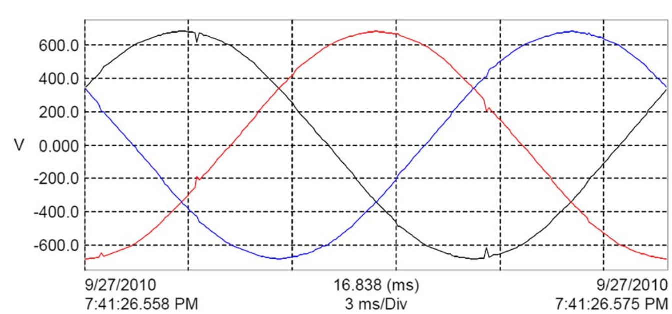

Fig. 15. Voltage waveform when not "tripping" the hole ($v_{\mathrm{THD}} = 1.2\%$).

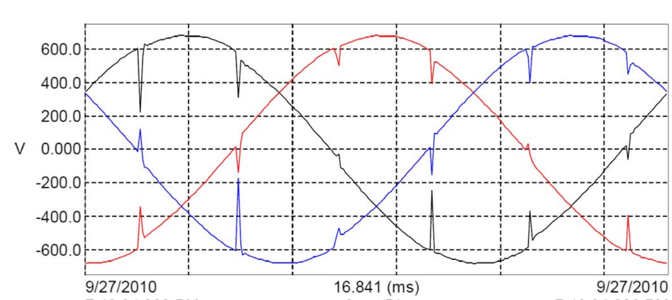

Fig. 16. Voltage waveform when "tripping" the hole ($v_{\mathrm{THD}} = 5.8\%$).

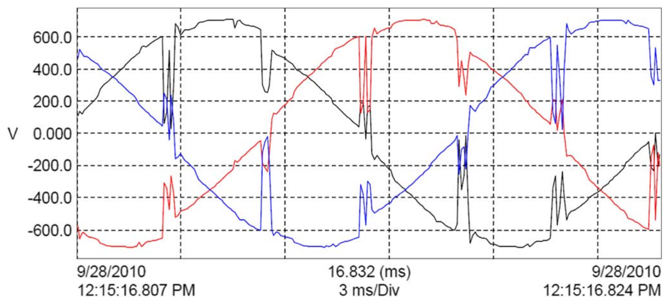

Fig. 17. Voltage distortion during full drilling operation ($v_{\mathrm{THD}} = 20\%$).

	(%)		(%)		(%)
H01	100.0	H19	5.4	H37	2.0
H02	0.5	H20	0.3	H38	0.3
H03	0.2	H21	0.2	H39	0.6
H04	0.4	H22	0.9	H40	1.1
H05	8.2	H23	1.6	H41	2.2
H06	0.4	H24	0.7	H42	0.9
H07	2.4	H25	2.4	H43	3.1
H08	0.2	H26	0.8	H44	1.1
H09	0.3	H27	0.4	H45	0.3
H10	0.5	H28	0.8	H46	0.8
H11	6.3	H29	5.6	H47	2.9
H12	0.5	H30	1.1	H48	0.9
H13	5.4	H31	5.6	H49	2.9
H14	0.6	H32	0.9	H50	0.9
H15	0.2	H33	0.1		
H16	0.8	H34	1.2		
H17	7.7	H35	3.2		
H18	0.9	H36	0.9		

Fig. 18. Harmonic spectrum of voltage during full drilling operation.

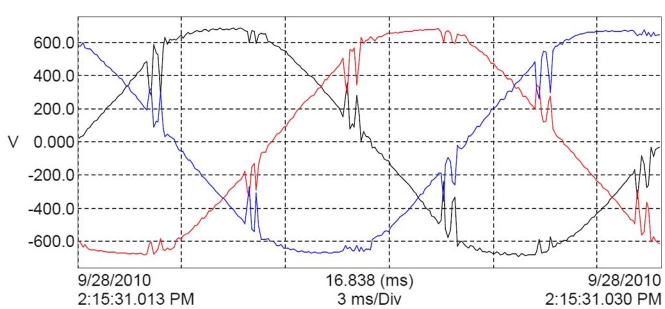

Fig. 19. Reduced voltage distortion during drilling operation with wide-spectrum harmonic filter ($v_{\mathrm{THD}} = 5.9\%$).

B. Application of the Wide-Spectrum Harmonic Filter on a Centrifuge

After application of the wide-spectrum harmonic filter, voltage distortion during drilling operation was substantially reduced (see Fig. 19). The 5th harmonic, in particular, was reduced from over 8% to virtually 0 (see Figs. 18 and 20).

The filter unit was run on a problem rig for an entire hole without having any service callout for the centrifuge (see Fig. 21). Prior to this, there would have been two to three nuisance callouts over the same period.

After the success of this installation, the filters have been applied on several other drilling rigs. Some of which previously were having multiple blown ac drives, resulting in extremely costly downtime and repairs. On rare occasions, all three ac drives on the centrifuge system catastrophically failed simultaneously. Now that the reason for failure is better understood, the finger pointing directed at the centrifuge rental company that typically occurs after drive failure can be more easily defended.

	(%)		(%)		(%)
H01	100.0	H19	1.4	H37	1.2
H02	0.1	H20	0.3	H38	0.2
H03	1.3	H21	0.2	H39	0.3
H04	0.2	H22	0.5	H40	0.3
H05	0.2	H23	0.5	H41	1.3
H06	0.2	H24	0.4	H42	0.6
H07	1.9	H25	0.6	H43	1.8
H08	0.4	H26	0.2	H44	0.3
H09	0.4	H27	0.2	H45	0.3
H10	0.3	H28	0.5	H46	0.4
H11	1.6	H29	0.1	H47	1.8
H12	0.3	H30	0.2	H48	0.8
H13	1.9	H31	0.3	H49	2.4
H14	0.3	H32	0.1	H50	0.5
H15	0.4	H33	0.3		
H16	0.3	H34	0.3		
H17	1.2	H35	0.8		
H18	0.3	H36	0.4		

Fig. 20. Harmonic spectrum of voltage during full drilling operation with wide-spectrum harmonic filter.

Fig. 21. Wide-spectrum harmonic filter fit for drilling rig application.

IV. Conclusion

The use of thyristor-controlled dc drives on drilling rigs can lead to very severe voltage notching on the supply bus, which can cause connected equipment misoperation and failure. Particularly sensitive to this voltage distortion is the ac drive, which is now being used much more frequently in these applications. The application of a wide-spectrum harmonic filter ahead of an ac drive can reduce the notching affect and thereby protect the ac drive. Centrifuges are one such application where this approach has been successfully implemented.

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