Oil Field Retrofit of ESPs to Meet Harmonic Compliance

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***Abstract*—A large petrochemical company installed nearly 50 000 hp of electrical submersible pumps (ESPs) at an existing midwest U.S. oil field. Being equipped with adjustable-speed drives (ASDs), these ESPs introduced high levels of current harmonic distortion, which resulted in 14%–19% voltage harmonic distortion at the electrical utility supply. Initially, the utility noticed the low power factor (PF) and had the oil company pay for the installation of power factor correction (PFC) capacitors on their medium-voltage supply. Once installed, the utility began to have problems with these capacitors and continued to receive complaints from other customers adjacent to the oil field; thus, they enforced harmonic limits, as defined by IEEE Std 519, at all points of common coupling. Measurements were made with a harmonic analyzer at several locations throughout the electrical system to quantify harmonics and determine the effect the ESPs were having on the utility distribution system. Computer simulations were performed to analyze different methods of harmonic mitigation. Ultimately, passive harmonic filters were installed on all ESPs in phases. In addition, the PFC capacitors were permanently disconnected after determining that a power system resonance condition existed. Once all phases of the project were complete, the voltage distortion level decreased to below 5%, and PF improved to near unity without the PFC capacitors. This paper will describe the effect of harmonics on the electrical distribution system caused by ASDs, practical solutions to excessive voltage harmonic distortion, resonance issues with PFC capacitors, and the challenges associated with different methods of harmonic mitigation.**

***Index Terms*—Adjustable-speed drives (ASDs), capacitors, electrical submersible pumps (ESPs), harmonic distortion, harmonic filters, harmonic mitigation, harmonic quantities, harmonics, power factor correction (PFC), resonance.**

I. Introduction

ELECTRICITY generation is normally produced at a constant frequency of 50 or 60 Hz, and the source voltage can be considered practically sinusoidal. However, when a source of sinusoidal voltage is applied to a nonlinear load, the resulting current is not perfectly sinusoidal. In the presence of system impedance, this current causes a nonsinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals. In nearly all cases, harmonic distortion is produced by a customer's equipment (nonlinear) injecting electrical *noise*, in the form of harmonic currents, into the power system [i.e., adjustable-speed drives (ASDs)].

Power system harmonics are defined as sinusoidal voltage and currents at frequencies that are integer multiples of the fundamental frequency generated. They constitute the major distorting components of the utility voltage and load current waveforms.

A. General Harmonic Indices

The most common harmonic index, which relates to the voltage waveform, is total harmonic distortion (THD), which is defined as the root mean square (rms) of the harmonics expressed as a percentage of the fundamental component, i.e.,

$$\mathrm{vTHD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (V_h)^2}}{V_1} \cdot 100\% \tag{1}$$

where V_h is the single frequency rms voltage at harmonic h, $h_{\max}$ is the maximum harmonic order to be considered, and V_1 is the fundamental component of voltage rms value. For many applications, it is sufficient to consider the harmonic range from the 2nd to the 50th, as most standards specify. However, with the introduction of active front-end drives and active harmonic filters, attention is often given to higher frequency components, up to 100th, due to their high switching frequencies. Thus,

$$\mathrm{iTHD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (I_h)^2}}{I_1} \cdot 100\%. \tag{2}$$

Similarly, current distortion levels can be also characterized by a THD value, but it can be misleading when the fundamental load current, i.e., I_1, is low. A high THD value for current may not be of significant concern under light load conditions, since the magnitude (in amperes) of the harmonic current is low, although its relative distortion to the fundamental frequency is high. To avoid such ambiguity, a total demand distortion (TDD) factor is used instead, which is defined as

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (I_h)^2}}{I_L} \cdot 100\%. \tag{3}$$

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Fig. 1. Typical six-pulse rectifier current waveform.

This formula is the ratio of the root-sum-square value of harmonic content of the current to the rms value of the maximum demand load current, and it is equivalent to $\mathrm{TDD} = I_1/I_L \times \mathrm{iTHD}$.

This factor is similar to THD, except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. Since electrical power supply systems are designed to withstand the rated or the maximum load current, the impact of current distortion on the system will be more realistic if the assessment is based on the designed values, rather than on a reference that fluctuates with the load levels.

The consequences of power system harmonics are numerous and varied. Some of these include the following: 1) faulty or abnormal operation of important control and protection equipment (e.g., electronic relays and solid-state devices); 2) unexpected fuse operation; 3) thermal effect on electric rotating machines, transformers, capacitors, and cables (extra losses), including overloading of power plant; 4) pulsating torques in rotating machines; 5) lower power factor (PF) in the electrical system preventing effective utilization; 6) increased risk of faults from overvoltage conditions developed on power factor correction (PFC) capacitors; and 7) resonant conditions. Very often, the presence of harmonic distortion is only detected after an expensive failure such as destruction of PFC capacitors. Therefore, power quality can raise complicated problems that require detailed information and technical skills to find an adequate solution.

B. Harmonics and ASDs

The standard pulsewidth modulated (PWM) ASD is a voltage source converter that is characterized by a predominantly capacitive dc side and an inductive ac system. The simplest configuration is the six-pulse diode bridge rectifier with a large capacitor across the dc bus terminals. In this circuit, the capacitor is charged every half-cycle of the supply frequency by two short current pulses, as shown in Fig. 1.

For six-pulse diode bridge rectifiers

$$h = n \cdot 6 \pm 1 \tag{4}$$

where h is the harmonic number, and n is any integer (1, 2, 3, etc.).

For a six-pulse rectifier, the predominant current harmonics are $h = 5$, 7, 11, 13, 17, and 19, as shown in Fig. 2. The corresponding harmonic content can reach levels of up to 90% (fifth), 80% (seventh), 75% (11th), and 70% (13th). Triplen harmonics typically are not present. The addition of an ac line reactor or dc choke provides some reduction in the harmonic current levels and is often used with ASD applications.

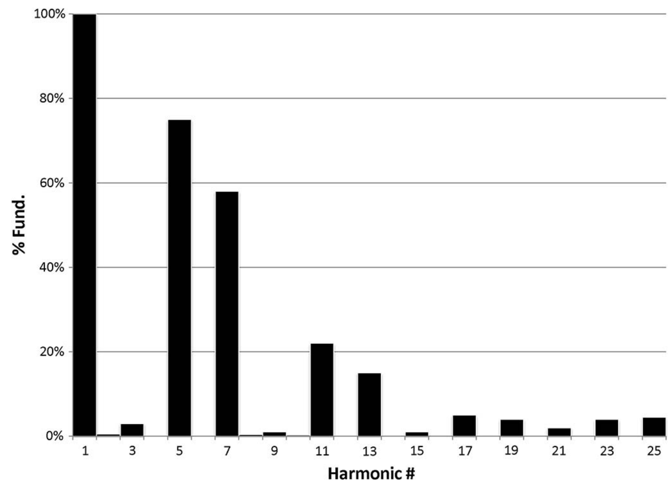

Fig. 2. Typical six-pulse rectifier current spectrum.

C. Harmonic Distortion Limits

IEEE Std 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Power Systems," has become widely adopted in North America and is becoming more commonly applied globally as well. It sets limits for voltage and current distortion at a point of common coupling (PCC). It recognizes the responsibility of both user and utility in dealing with harmonic distortion. Interpretation of this standard is provided in [4].

Section 10 of IEEE Std 519 defines the limits for various harmonic indices that correlate to harmonics effects. The philosophy adopted to develop the limits for these indices was to restrict harmonic current injection from individual customers (loads) so that they would not cause unacceptable voltage distortion levels when applied to a power system. Table 10.2, "Low-Voltage System Classification and Distortion Limits," of IEEE Std 519 establishes voltage distortion limit as 5% for THD and 3% of the fundamental voltage for any individual harmonic. These limits generally will be met at the PCC provided that the current harmonic limits are met.

It should be noted that even if the voltage distortion limits are met at the PCC, they could very easily be exceeded downstream, where other connected equipment could be affected. Since voltage distortion results from harmonic currents passing through the impedance of the power system, it will always be higher downstream, where the harmonic currents are generated and where system impedance is highest. This will be further explained in the next section.

To define current distortion limits, IEEE Std 519 uses a short-circuit current ratio to establish a customer's size and potential influence on the voltage distortion of the system. The short-circuit ratio (I_{SC}/I_L) is the ratio of maximum short-circuit current (I_{SC}) at the PCC with the utility to the customer's maximum demand load current (I_L) at PCC. Lower ratios or higher impedance systems have lower current distortion limits to keep voltage distortion at reasonable levels. For power

TABLE I
CURRENT DISTORTION LIMITS FOR GENERAL DISTRIBUTION SYSTEMS (120 V THROUGH 69 000 V) [1]

Maximum Harmonic Current Distortion in Percent of maximum demand load current at PCC (I_L)						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	≥35	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
Even harmonics are limited to 25% of the odd harmonic limits above.						

systems between 120 and 69 kV, the limits can be found in Table 10.3 of IEEE Std 519 (see Table I).

The table defines TDD limits and individual harmonic current limits. For short-circuit ratio of less than 20, the limits are most severe because this lower ratio indicates a high-impedance power system or a large customer or both. Therefore, higher voltage distortion is more likely to develop from current harmonics injected at a PCC where the I_{SC}/I_L ratio is low.

D. Relationship Between System Impedance and Voltage Distortion

When a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not perfectly sinusoidal (see Fig. 3). According to Ohm's law, in the presence of system impedance, this current causes voltage drop that is also nonsinusoidal (harmonic) and, therefore, produces voltage distortion at the load terminals and other points along the distribution system.

Following Ohm's law,

$$\underline{V}_h = \underline{I}_h \times \underline{Z}_h \tag{5}$$

where

- $\underline{Z}_h$ impedance at the hth harmonic;
- $\underline{I}_h$ current of the hth harmonic;
- $\underline{V}h$ voltage of the hth harmonic.

Therefore, harmonic voltage distortion is caused by the flow of harmonic currents through the system impedance. Principal factors contributing to the system impedance are the generator, the transformer, the series line reactors or the current-limiting reactors, and the circuit conductors. While current travels only along the power path of the nonlinear load, voltage distortion affects all loads connected to that particular electrical bus or phase.

For each frequency at which harmonic current is flowing, there is corresponding impedance associated with the system and thus a voltage drop at that frequency. The circuit diagram shown in Fig. 4 demonstrates this relationship, where Z_{Sh} represents the source internal impedance, Z_{Th} represents the transformer impedance, and Z_{Ch} represents the impedance of cables. The nonlinear load is shown as the harmonic current source (I_h). The presence of any harmonic current causes distortion of the system voltage.

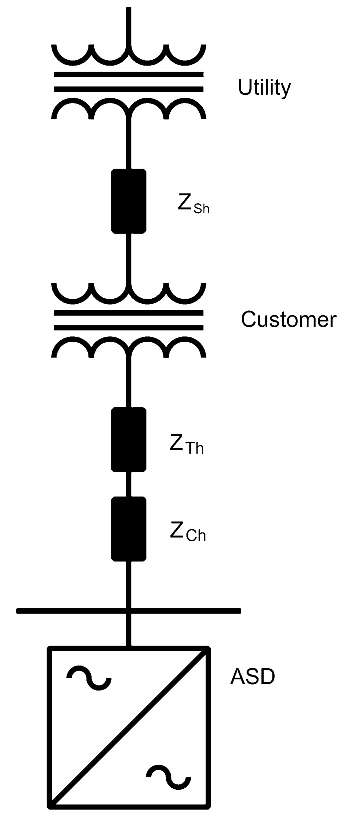

Fig. 3. Simple distribution system with nonlinear load.

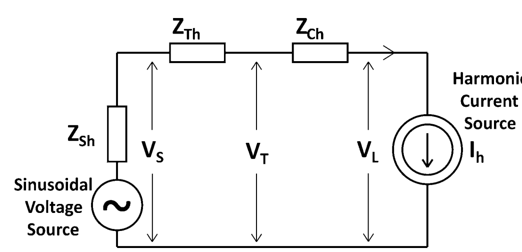

Fig. 4. Simplified harmonic current flow circuit.

The fundamental understanding is as follows. Voltage will be the least distorted nearest to the generating voltage source, where $V_S = I_h \times Z_{\mathrm{Sh}}$. Voltage distortion at the secondary of the transformer at harmonic h will be increased by the transformer impedance, i.e., $V_T = I_h \times (Z_{\mathrm{Sh}} + Z_{\mathrm{Th}})$. On the other hand, the voltage nearer the load, as the harmonic current flows through the additional cable impedance, will be the most distorted, i.e., $V_L = I_h \times (Z_{\mathrm{Sh}} + Z_{\mathrm{Th}} + Z_{\mathrm{Ch}})$.

E. PF and Harmonics

For those trained in electrical theory, the concept of PF used to be fairly simple to understand. However, with the introduction of harmonics generated by today's nonlinear loads, PF analysis has become more complex.

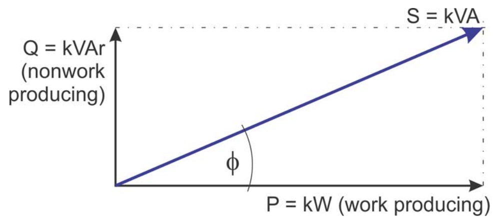

Fig. 5. Power vector configuration (linear loads).

PF is a measure of how effectively a specific load consumes electricity to do work. The higher the PF, the more work produced for a given voltage and current. PF is always measured as the ratio between real power in kilowatts and apparent power in kilovoltamperes.

For linear loads, which are defined as resistive, inductive, or capacitive, the apparent power in kilovoltamperes (S) is the vector sum of the reactive power in kilovoltamperes (Q) and the real power in kilowatts (P). The PF is $\mathrm{P/S} = \mathrm{Cos}\phi$, where ϕ is the angle between S and P (see Fig. 5). This angle is the same as the displacement angle between the voltage and the current for linear loads and is therefore often referred to as displacement PF (dPF).

Purely resistive loads draw their current in phase with the voltage and have a PF of 1. When the load is reactive, it stores energy, releasing it during a different part of the cycle. Inductive loads, such as electric motors, cause their current to lag the voltage, whereas capacitors cause their current to lead the voltage. Therefore, lagging versus leading describes whether the net reactance is either inductive or capacitive. For circuits with strictly linear loads, simple capacitor banks may be added to the system to improve a lagging PF due to induction motors or other lagging loads.

Nonlinear loads, such as rectifier circuits, do not typically shift the current waveform, they simply distort it. These distorted waveforms can be broken down into harmonic components using Fourier analysis. The harmonic currents produce no useful work and therefore are reactive in nature. Nonlinear loads are extremely prevalent on today's power systems and are often the result of the rectifiers used to convert ac power to dc in power electronic equipment. Examples include variable-speed drives, computers, broadcasting equipment, compact fluorescent, and light-emitting diode lighting, electrical chargers, induction furnaces, and many other devices.

For nonlinear loads, the power vector relationship becomes three dimensional with distortion reactive power H combining with both Q and P to produce the apparent power which the power system must deliver (see Fig. 6). PF remains the ratio of kilowatts to kilovoltamperes, but the kilovoltamperes now has a harmonic component as well. True PF (TPF) becomes the combination of dPF and distortion PF. dPF is still equal to $\mathrm{Cos}\Phi$, with Φ being the angle between the fundamental current and voltage. dPF can be either leading or lagging. Distortion PF is then TPF (kW/kVA) divided by dPF. Distortion PF is neither leading nor lagging. For typical nonlinear loads, the dPF will be near unity. TPF, however, is normally very low because of the distortion component. For example, the dPF of a variable-speed

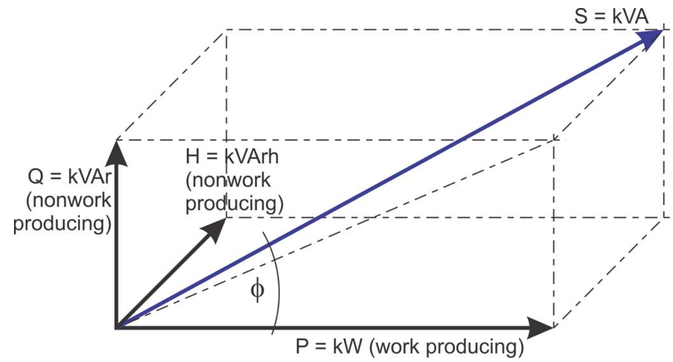

Fig. 6. Power vector configuration (nonlinear loads).

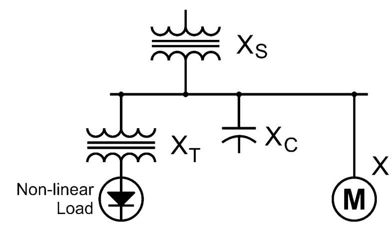

Fig. 7. Simple power system one-line diagram.

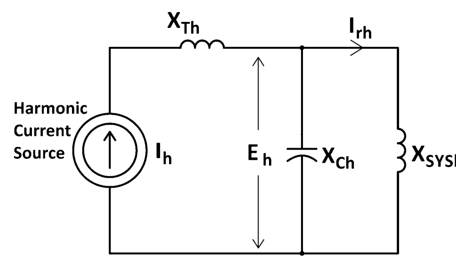

Fig. 8. Equivalent diagram.

drive will be near unity, but its TPF is often in the 0.7–0.75 range, unless harmonic mitigation equipment is applied.

With the heavy proliferation of nonlinear loads, low PF on a power system is often the result of a high distortion reactive power component and not inductive reactive power. Therefore, one can no longer assume that low PF is caused by electric motors and other inductive loads. In addition, since the best way to improve a poor PF caused by nonlinear loads is to remove the harmonic currents, the traditional means of adding PFC capacitors is, quite often, no longer suitable. In fact, simply adding capacitors may often make the problem worse as they can resonate with the power system inductance.

II. Analysis

A. *Power System Resonance With PFC Capacitors*

Adding capacitors in an attempt to improve PF will cause the power system to be tuned to a certain frequency. Parallel resonance occurs when the natural power system inductive reactance matches the capacitive reactance of the capacitors (see Figs. 7–9). When this occurs near the frequency of a

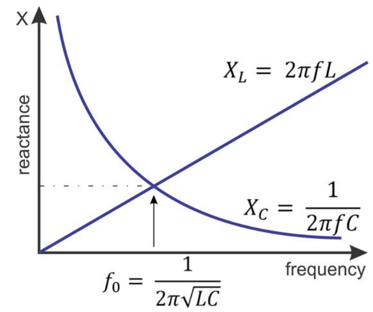

Fig. 9. Reactance curves and resonance point.

predominant harmonic, for example, the 5th, 7th, or 11th, serious consequences can result, similar to those defined earlier.

Fig. 7 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, PFC capacitors, and fixed-speed motors, respectively. The nonlinear load represents an ASD as a current source of harmonics.

This one-line diagram can be represented as the equivalent diagram in Fig. 8, where X_{SYSh} 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 the inductive reactance are essentially equal. This resonance can result in both excessive current and high levels of voltage distortion at that harmonic frequency.

B. Harmonic Mitigation

When planning installation of large nonlinear devices or large quantities of smaller nonlinear loads, a decision has to be made on the type of mitigation to be used. One method commonly used incorporates phase-shifting transformers for multipulse control of rectifier bridges. In this technique, transformers with multiple secondary windings are used to phase shift multiple ASD 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 (i.e., 18-pulse drive consists of three input rectifiers with 20° phase shifts between them). Configurations up to 48-pulse are possible for larger 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 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, particularly at higher frequencies [6].

There are various forms of passive harmonic filters being employed by ASD manufacturers, but the most effective consists of a combination of a blocking element and a tuned filtering element. One such configuration is shown in Fig. 10.

Crucial in the design of an effective filter is the prevention of harmonic importation from the line side of the filter. Without

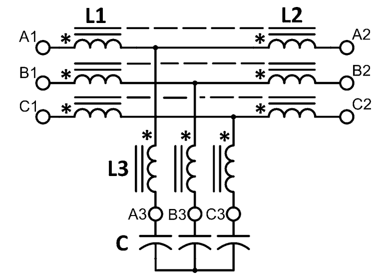

Fig. 10. Wide-spectrum harmonic filter schematic.

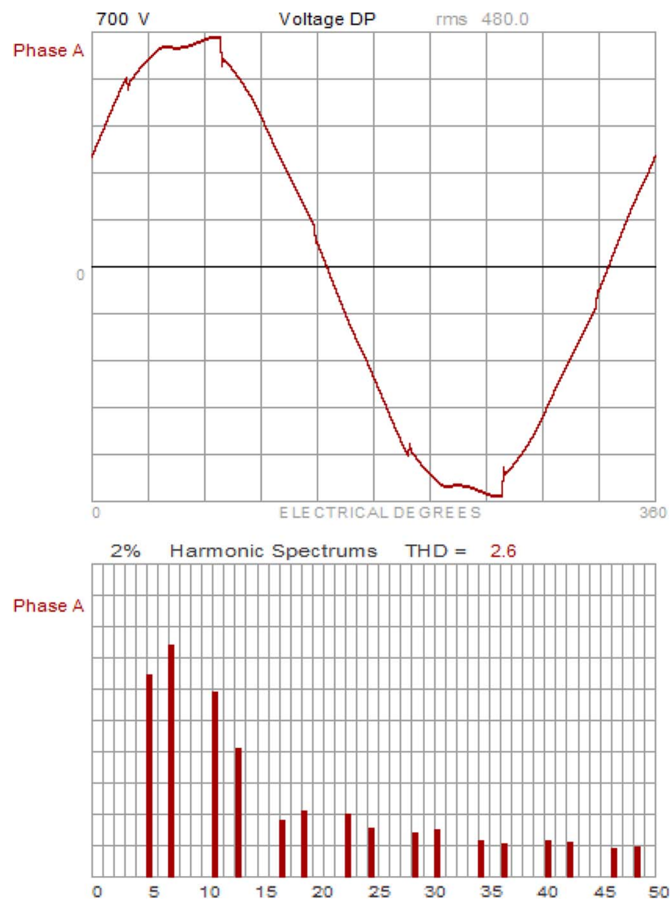

Fig. 11. Voltage at 400-hp ASD with low source impedance, vTHD = 2%.

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 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 fourth harmonic, 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

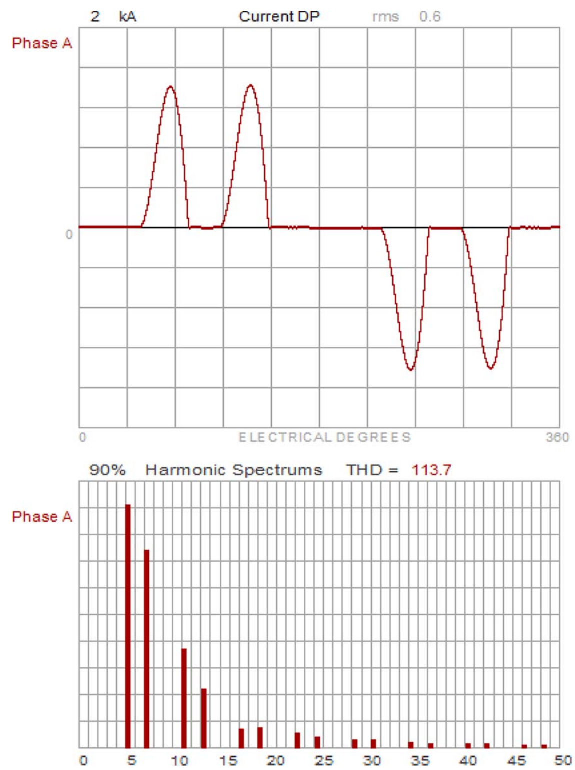

Fig. 12. Current at 400-hp ASD with low source impedance, iTHD $= 127\%$.

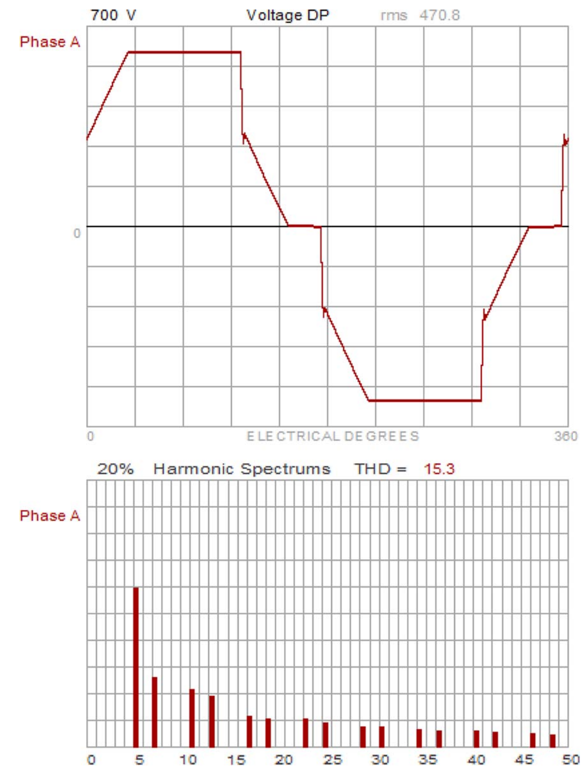

Fig. 13. Voltage at 400-hp ASD with weak source, vTHD $= 16\%$.

and the drive. Current THD (ITHD) is typically reduced to $< 6\%$ when applied to a six-pulse ac PWM drive regardless of whether the drive is equipped with an AC or a dc reactor or not.

Wide-spectrum filters can be applied to ac drives with diode or silicon-controlled rectifier precharge input rectifiers and can be applied to single or multiple drives. The filter can be usually retrofitted to existing drives without the requirement for drive modifications, whether for single- or for multiple-drive applications. This method has been described in [6].

Other methods include application of converters with active harmonic elimination capability such as active front-end drives and active harmonic filters. These alternatives have been discussed in [5]. All of these topologies will lower harmonic current content of the ASD to some extent. The current and voltage distortion performance for each topology under ideal laboratory-type conditions with the utility supply is provided in [6]. Due to its technical and economical advantages, including 2%–3% power efficiency improvement over other methods, the wide-spectrum passive harmonic filter was chosen as the most appropriate and practical solution to address the harmonic distortion concerns in the oil field where high numbers of electrical submersible pumps were in use.

C. *Computer Simulation*

Computer simulation software can be used to demonstrate how source impedance affects the level of harmonic distortion both with respect to current and voltage. A 400-hp ASD without a line reactor or dc link choke and supplied from a stiff system will draw current with very sharp pulses and iTHD $>$ 100% (see Figs. 11 and 12). However, due to the very low source impedance, there is very little voltage distortion. With the same ASD, however, fed from a weak generator supply, the ASD draws a more broadened pulse with iTHD $< 30\%$ (see Figs. 13 and 14). The extra impedance of the supply results in severe flat-topping of the voltage waveform with vTHD $> 15\%$.

To analyze ASD applications, many models have been created for power system components and ASD topologies according to information provided. This allowed simulation of real-world conditions by adjusting system parameters such as voltage imbalance and background voltage distortion. Since these conditions can have dramatic effects on certain topologies, making them a less desirable option for the application, computer analysis was performed prior to field installation.

Table II presents computer simulation results for a selected water station as before and after harmonic mitigation has been implemented.

Waveforms and spectrums of this simulation are presented in Figs. 15–18, and the single-line diagram is shown in Fig. 19. Simulations upstream at the substation level were also performed and are shown in Fig. 20 and Table III.

III. FINDINGS AND FIELD MEASUREMENTS

A. *Location and Background Information*

Sites under investigation were located in Montana and North Dakota surrounding the town of Baker. From a total of 145 well sites, a number of different sites with ASDs installed were investigated and designated as Miller, 11C5, Harr, Clark, and Canter.

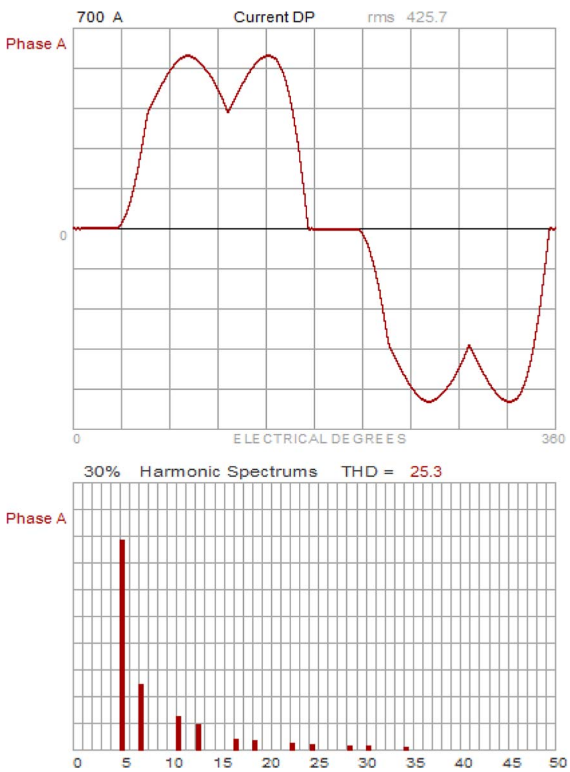

Fig. 14. Current 400-hp ASD with weak source, iTHD $= 25\%$.

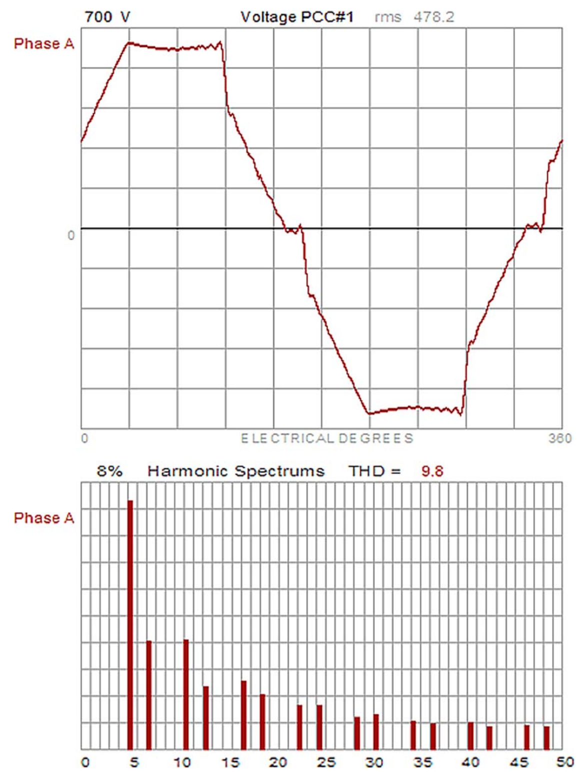

Fig. 15. Computer simulation results for selected water station with no harmonic treatment, voltage at PCC 1.

TABLE II
COMPUTER SIMULATION RESULTS FOR SELECTED WATER STATION

PCC #1	before	after
VTHD, % =	9.8	2.7
ITHD, % =	36.9	6.5
Irms, A =	1608.1	1508.4
Isc/Iload =	23.2	23.3
disp. PF =	-0.97	-0.99
True PF =	0.92	0.99

After interviewing the relevant personnel within the utility company and the client, it was apparent that the field electrical loading had been precipitously increased over the previous few years. Moreover, the majority of the loading in the field was nonlinear in the form of ASDs. Multiple ASD vendors were represented. According to field reports, the operational history was characterized by unexplained periodic ASD shutdowns.

The following contains data and observations from the investigation for fields in Baker, Montana.

B. PFC Capacitors

The initial issue raised by the utility at the site was a low PF that was limiting the system capacity. The original rating of the distribution system was 9.6 MW at 0.8 PF. To allow for expansion of the field, shunt connection of PFC capacitors was proposed to improve PF to near unity in the hopes of increasing capacity to 12 MW.

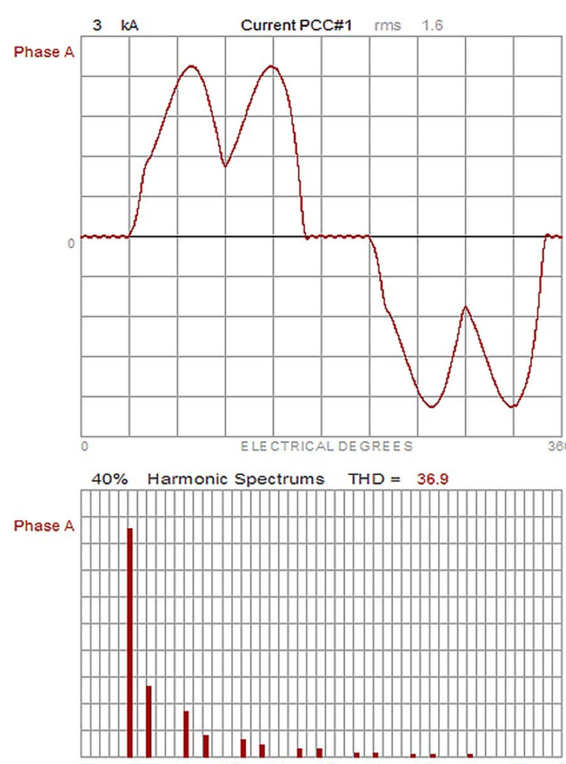

Fig. 16. Computer simulation results for selected water station with no harmonic treatment, current at PCC 1.

The minimum fault level at the point of connection was 158 MVA, which is equivalent to a per-unit maximum system impedance of $X_S = 7.6\%$ [0.076 per unit (p.u.)] at a 12-MW

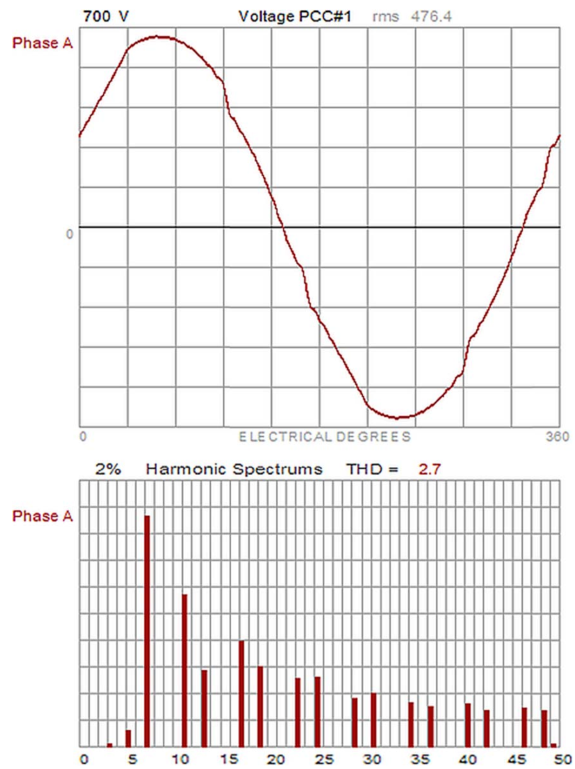

Fig. 17. Computer simulation results for selected water station with wide-spectrum filter, voltage at PCC 1.

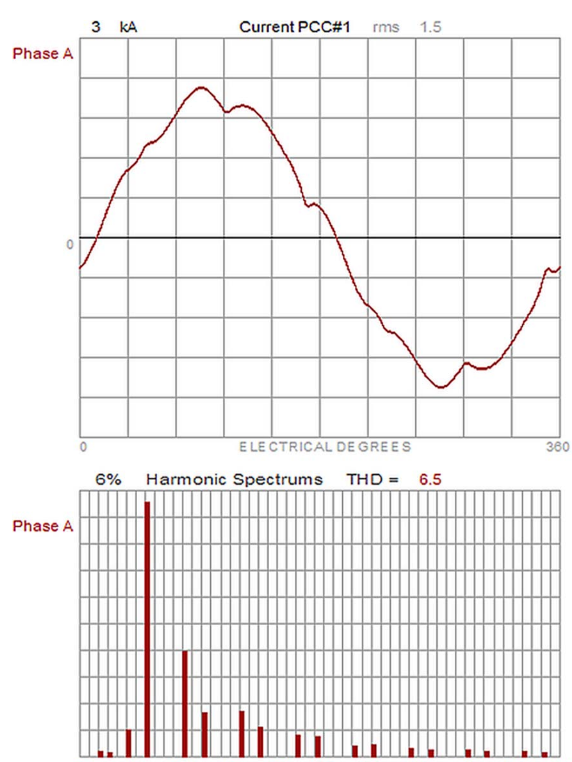

Fig. 18. Computer simulation results for selected water station with wide-spectrum filter, current at PCC 1.

base. The conversion from 9.6 to 12 MW required 7.2 MVAr (60% or 0.6 p.u. on the 12-MVA base). The corresponding capacitance being $X_c = \mathrm{V}^2/\mathrm{MVAr} = 1/(0.6) = 1.667$ p.u., and this capacitance was divided into two independently switched banks.

The converter harmonic currents were now injected into the ac system impedance in parallel with the PFC capacitors; the corresponding parallel resonant frequency can be calculated from

$$n \cdot X_s = \frac{1}{n} \cdot X_c \tag{6}$$

where $n = \omega_n/\omega$; therefore, $n^2 = X_c/X_s = 1.667/0.076 = 1250/57 = 21.93$, and $n = 4.683$ when all the capacitance is connected, and $n = 3.3$ with one of the two banks disconnected.

C. Power System Resonance

However, due to power system resonance, installation of the PFC capacitors actually made the problem worse, not better. As problems persisted, harmonic distortion levels were measured and found to be excessive. Still unaware of the resonance condition, the utility required that the oil company apply harmonic mitigation equipment to meet IEEE Std 519 requirements. A review of the harmonic measurements found that the voltage distortion levels were as high as 14%. This was unusually high even for the large quantity of electrical submersible pumps (ESPs) connected, which seemed to point to a resonance condition. A request was made for the utility to take measurements with the capacitor banks disconnected. The results of those measurements are found in Table IV.

There were two sets of capacitor banks, and as each set was removed from service, both voltage distortion and current distortion levels lowered. Voltage distortion dropped from over 14% to under 9%, which demonstrated that the capacitors were resonating with the power system. This provided evidence that capacitors are not always the best solution for improving a low PF. The utility agreed to keep the capacitor banks disconnected so that wide-spectrum passive harmonic filters could be added to address the harmonic distortion.

D. Harmonic Distortion on the Power Distribution System

The utility through a contract engineering firm carried out additional evaluation of the sources and magnitudes of the harmonic distortion in the oil field. The data collected from two substations are provided in Table V. Substation 1, which is named Cedar Hill, has a transformer of 10 000 kVA, 115 kV-25/14.4 kV with an impedance of $Z = 8.15\%$. Substation 2, which is named Sunset Butte, has a transformer of 12 000 kVA, 115 kV-25/14.4 kV with an impedance of $Z = 7.6\%$. The harmonic distortion levels recorded were prior to the addition of any harmonic treatment.

Measured levels of harmonic distortion at the Sunset Butte Substation were high: voltage THD in the range of 14%–15% and current TDD in range of 31%–32%.

This has implications not only for the level of harmonic distortion present in the field but also for the utility power system and its relative "stiffness." It was reported by the engineering representative that I_{SC}/I_L ratio for the Sunset Butte Substation

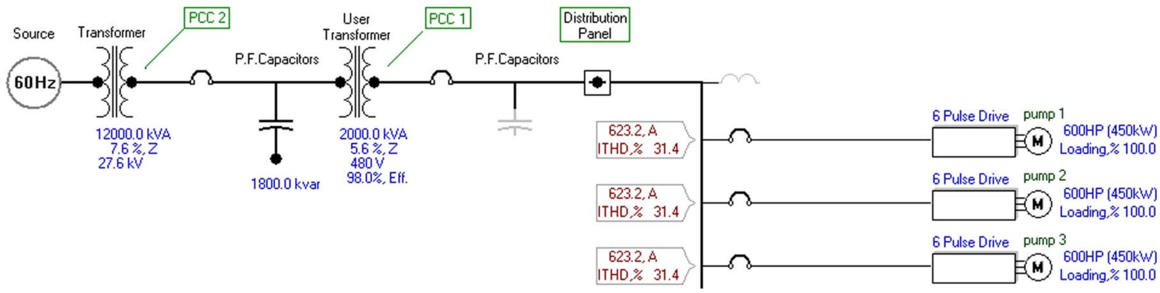

Fig. 19. Computer simulation for selected water station with three 600-hp pumps and 2000 kVA, $Z = 5.6\%$, supply transformer at the service entrance.

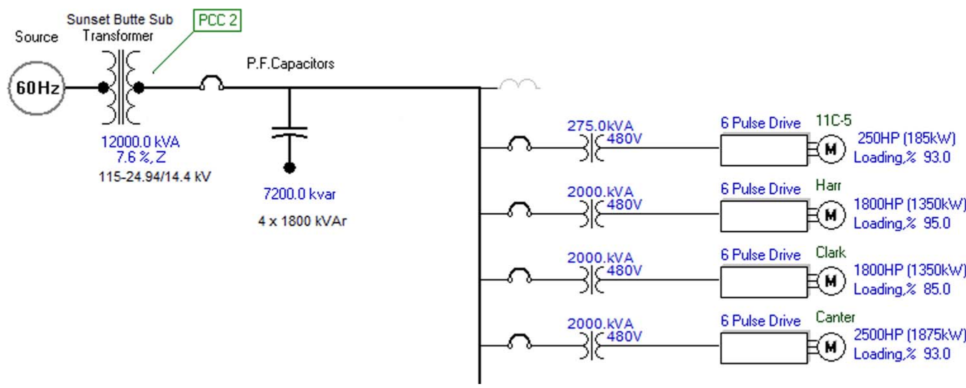

Fig. 20. Computer simulation for Sunset Butte Substation with four nonlinear loads at various sites.

TABLE III
COMPUTER SIMULATION RESULTS FOR SUNSET BUTTE SUBSTATION

PCC #2	before	after
VTHD, % =	5.2	1.5
ITHD, % =	18.2	5.4
Irms, A =	167.9	101.2
Isc/Iload =	20	32.7
disp. PF =	0.99	-0.98
True PF =	0.58	0.97

TABLE IV
HARMONIC DISTORTION MEASUREMENTS SHOWING RESONANCE WITH PFC CAPACITORS

Cap Banks	MW	%VTHD			%iTHD		
		A	B	C	A	B	C
2 on	12.0	14.2	14.0	14.4	33.6	31.3	32.1
1 on	11.9	11.2	12.2	11.7	18.4	20.9	20.7
None on	12.1	8.0	8.9	8.7	11.4	12.3	12.4

was in the range of 20 to 50. According to IEEE Std 519, for a substation of this category, current TDD should be kept under 8%.

Table VI shows field measurements at the selected sites being fed by Sunset Butte Substation and confirm the general findings for the field. Voltage distortion levels were in the range of 14%–19%, and current TDD was reaching 24%. This was not surprising, given the relative "softness" of the power system, coupled with a large number of six-pulse ASDs—all of

TABLE V
VOLTAGE THD (% OF FUNDAMENTAL) AND CURRENT TDD FROM THE SUNSET BUTTE SUBSTATION

	VTHD (%) [% volts]			TDD (%) [% Amps]		
Sunset Butte	14.78	14.89	14.70	31.06	31.4	31.81
Cedar Hill	7.88	8.12	8.27	21.79	22.11	23.77

TABLE VI
HARMONIC DISTORTION LEVELS AT PCC WITH NO HARMONIC MITIGATION

Substation Name	Site Name	THDv	THDi
"Cedar Hills"	Miller WSW	8.8%	39.5%
"Sunset Butte"	CHSU 11C-5 NH05	15.9%	23.7%
"Sunset Butte"	Harr Water Plant	17.3%	15.4%
"Sunset Butte"	Clark Water Plant	16.7%	18.8%
"Sunset Butte"	Canter Water Station	18.9%	16.5%

Voltage and current THD values are three phase average values.

which, regardless of manufacturer, produce harmonic current distortion in the range of 30%–40%.

At the various PCC locations, harmonic distortion is cumulative, and there are many harmonic producing loads in the field which are all contributing to the combined distortion levels. While the customer was working toward a prudent course of action in installing harmonic filters on all the largest loads, there was no guarantee that it would cure the problem from the power company standpoint.

In order to fully evaluate the effectiveness of various harmonic mitigation approaches, it was recommended that the

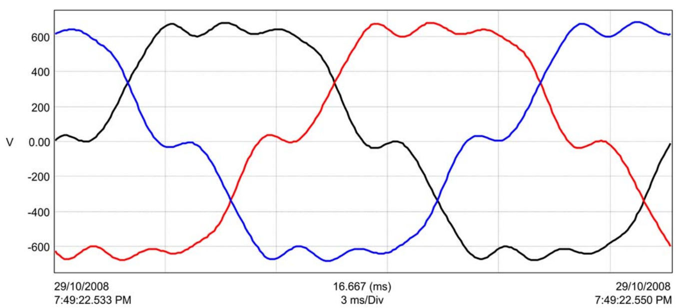

Fig. 21. Voltage waveforms, all pumps and filters turned off (background voltage measured on the output of the main transformer).

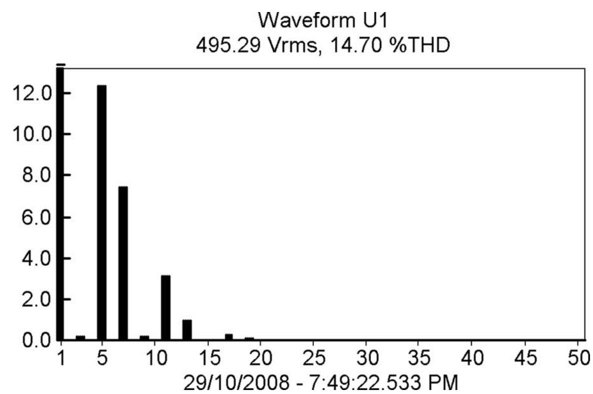

Fig. 22. Harmonic spectrum, background voltage measured on the output of the main transformer, fundamental component removed for clarity.

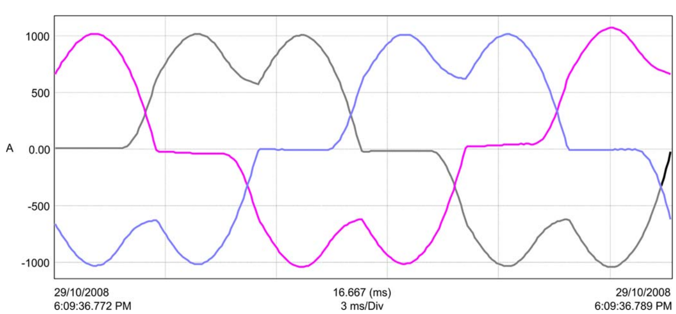

Fig. 23. Current waveforms measured at the input of the ASD (single pump).

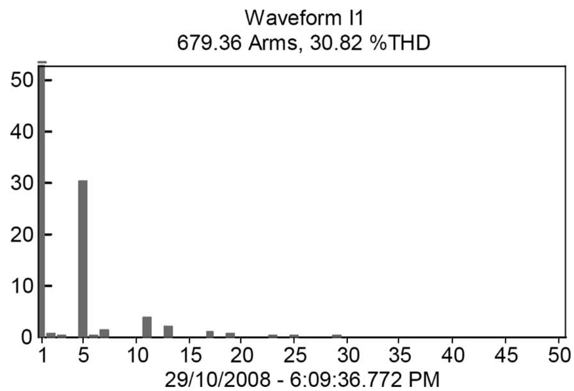

Fig. 24. Current spectrum measured at the input of the ASD (single pump).

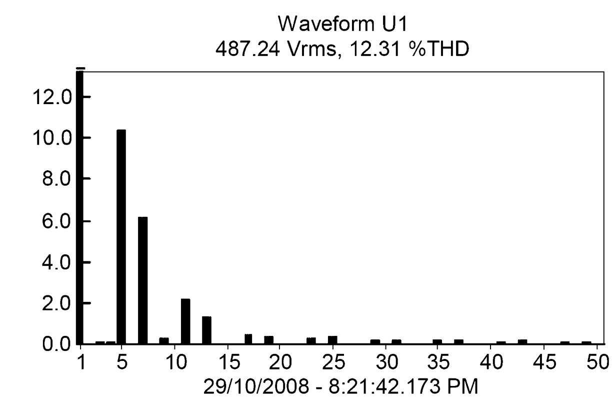

Fig. 25. Water station voltage THD with all pumps at full speed and all filters turned on.

customer carry out a full power survey of the field, taking into account all nonlinear loads and plans for future expansion.

Harmonic distortion levels were recorded at PCCs after some harmonic mitigation was implemented. To determine background voltage distortion at the output of the main transformer at 480-V level, measurements were taken at the water station with all pumps turned off and no harmonic mitigation (see Fig. 21). The harmonic spectrum for these voltages is shown in Fig. 22.

Predominantly fifth and seventh harmonic components present in the voltage waveform, as well as 11th and 13th, are the typical signature of ASDs with six-pulse rectifier front end (see Figs. 23 and 24). This led to a conclusion that harmonic mitigation was necessary to lower the voltage distortion to acceptable levels. As a result, the utility forced the client to apply harmonic mitigation and comply with IEEE Std 519.

Various methods of harmonic mitigation were considered, followed by computer simulations, to analyze the different options. The customer also approached various manufacturers for solutions and tested installations for their true performance in the field. The passive harmonic filter solution with the best performance was selected for application at all sites.

As initial studies had been already conducted for the Miller, 11C-5, Harr, Clark, and Canter stations, and they were considered to be the most troublesome sites, harmonic mitigation was begun there. Passive harmonic filters were applied to each individual ASD at each of these water stations.

The three water plants are very similar, and tests were performed for all. One set of representative results is provided for the selected station (Clark), as shown in Figs. 25 and 26. The voltage distortion was lowered by about 20% and current distortion by almost 50%, but still did not reach the required 5% VTHD and 8% TDD levels to comply with IEEE Std 519.

It should be noted that there were also 24-pulse drive applications implemented on a number of sites. However, due to high voltage THD as seen upstream, their performance was rather poor, if not disappointing.

The final step was to ask the utility to disconnect the PFC capacitors completely. In the meantime, more passive harmonic filters were added in three phases to address more nonlinear loads that were polluting the utility voltage. Once all PFC capacitors at the substations were disconnected and several

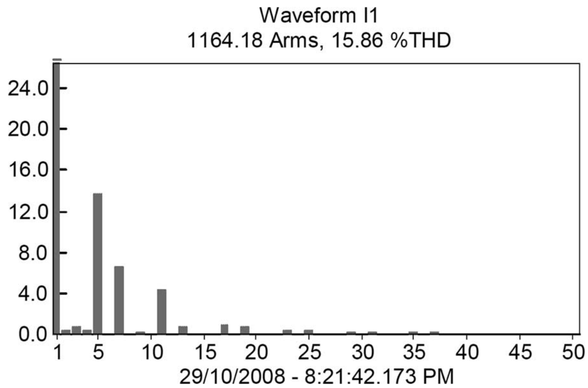

Fig. 26. Clark current THD with all pumps at full speed and all filters turned on.

TABLE VII
VOLTAGE THD (% OF FUNDAMENTAL) AND CURRENT TDD FROM THE SUNSET BUTTE SUBSTATION

	VTHD (%) [% volts]			TDD (%) [% Amps]		
Sunset Butte	< 5%	< 5	< 5	< 8	< 8	< 8
Cedar Hill	2.39	2.43	2.36	3.55	3.23	3.31

filters were installed, the bus voltages and load demand current limits as recommended by IEEE Std 519 were met. Results are provided in Table VII.

IV. CONCLUSION

As the oil and gas industry uses more and more ASDs in their applications, harmonics and power quality have become a major concern. ESPs now being employed in many oil fields, such as the ones cited in this paper and in [8]–[10], are particularly troublesome due to their high concentrations. Several different technologies commonly being adopted to mitigate the effects of harmonics have been reviewed, and a case study was presented, where unique passive wide-spectrum filters were successfully implemented on various electrical submersible pumps and water plants to meet the limits required by the utility company. Resonance issues associated with PFC capacitors and nonlinear loads were discussed.

REFERENCES

[1] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Std 518-1992, Jun. 15, 2004.

[2] J. Arrillaga and N. R. Watson, *Power System Harmonics*. Hoboken, NJ, USA: Wiley, 2003.

[3] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics—Converters, Applications, and Design*. Hoboken, NJ, USA: Wiley, 2002.

[4] A. H. Hoevenaars, K. LeDoux, and M. Colosino, "Interpreting IEEE Std 519 and meeting its harmonic limits in VFD applications," in *Proc. IEEE PCIC*, 2003, pp. 145–150, Paper PCIC-2003-15.

[5] A. H. Hoevenaars, I. C. Evans, and A. Lawson, "New marine harmonic standards," *IEEE Ind. Appl. Mag.*, vol. 16, no. 1, pp. 16–25, Jan./Feb. 2010.

[6] A. H. Hoevenaars, M. Fahrney, M. James, and M. McGraw, "Design considerations when applying various LV ASD topologies to meet harmonic compliance," *IEEE Trans. Ind. Appl.*, vol. 47, no. 4, pp. 1578–1585, Jul./Aug. 2011.

[7] A. H. Hoevenaars and I. C. Evans, "Meeting harmonic limits on marine vessels," in *Proc. IEEE ESTS*, Arlington, VA, USA, May 21–23, 2007, pp. 115–121.

[8] P. Buddingh, D. Valentina, and H. Groten, "Oil field harmonic concerns resulting from high impedance sources, multiple power converters and long cables," presented at the IEEE Petroleum Chemical Ind. Conf., Cincinnati, OH, USA, 2008, Paper PCIC-08-121.

[9] R. Pragale and D. D. Shipp, "Investigation of premature ESP failures and oil field harmonic analysis," presented at the IEEE Petroleum Chemical Ind. Conf., New Orleans, LA, USA, 2012, Paper PCIC-2012-65.

[10] M. H. Shwehdi, A. H. Mantawy, and H. H. Al-Bekhit, "Solving the harmonic problems produced from the use of adjustable speed drives in industrial oil pumping field," in *Proc. Int. Conf. Power Syst. Technol.*, 2002, pp. 86–92.

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