Rightsizing Generators Through Harmonic Mitigation Realizes Energy, Emissions, and Infrastructure Reductions

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***Abstract*—Sizing prime and backup generator packages for nonlinear loads (such as adjustable speed drives (ASDs), solid-state uninterruptible power system, dc drives, and other SCR loads and even single phase loads, such as computer systems, ballasted lighting, and other power electronic loads) is not a simple process. Including the effects of the nonlinear load harmonics is essential to properly sizing generator capacity. Incorrectly calculating the harmonic current contribution can result in significantly undersizing the generator leading to brownout conditions, overloading of the generator, nuisance tripping, misoperation of the automatic voltage regulator, generator failures, and load equipment damage through elevated voltage distortion. However, oversizing the generator to accommodate the nonlinear load current harmonics will result in increased initial installation costs, much higher fuel and operating costs due to poor operating efficiencies and higher emissions. In an oil pipeline islanded pumping application, the problems experienced with the adjustable speed drive operation on a 200 hp pump led to the generator being significantly upsized. Not until harmonic mitigation was finally considered though, did the ASD and generator operate without issues. Computer simulations were used to demonstrate how the application of a passive wide spectrum harmonic filter would reduce the ASD harmonic currents to eliminate the voltage distortion and allow the operator to retrofit the installation with a more properly sized generator that provided energy/fuel savings and emissions reduction while maintaining good power quality.**

***Index Terms*—AC drive, adjustable speed drive (ASD), dc drive, emissions reduction, energy savings, fuel savings, generators, harmonic distortion, harmonic filter, harmonic mitigation, harmonics, short-circuit ratio (SCR), silicon controlled rectifier, wide spectrum harmonic filter (WSHF).**

I. Introduction

On GENERATOR supplied systems, there have been two primary approaches used by engineers when coping with nonlinear load harmonics. The first is to ignore them and simply size the generator package and develop its specification based on traditional kW and kVA load profile analysis programs. It is easy to understand why this occurs, as engineers either do not understand the effect of harmonics on the distribution system, or have no way to model and calculate the harmonic current contribution from the nonlinear loads.

The second technique is to simply accept most generator manufacturer's recommendations to increase the generator kW rating by 2× to 2.5× in order to ensure that the system can handle the additional harmonic losses and high levels of voltage distortion resulting from the nonlinear loads. This "rule of thumb" can help but is dependent upon the harmonic profiles of the loads and the percent of the total load that they constitute.

But, is oversizing really the best approach for dealing with harmonics considering that both fuel consumption and emission levels will increase with their significant impact on operating costs and negative effect on the environment? And of course, the initial installation cost will also be significantly higher. Although the increased costs are obviously important, the environmental impact of increased emissions is arguably even more costly. Diesel generators release many hazardous air contaminants and greenhouse gases (GHG) including particulate matter (diesel soot and aerosols), carbon monoxide, carbon dioxide, and oxides of nitrogen. The consumption of one liter of diesel emits approximately 2.4–3.5 kg of CO_2 (9.08–13.2 kg/US gal) [1]. Compounding the problem is that generator operating efficiency decreases under lighter loading as fuel consumption per energy delivered (kWh) increases.

Fortunately, there is a better solution which involves rightsizing the generator systems based on a proactive harmonic mitigation strategy that can reduce initial installation cost, fuel/energy consumption, and emissions while providing increased reliability for the power system and connected equipment.

A. Generators and Harmonics

An ideal ac voltage source would have a source impedance approaching zero, voltage and frequency that are constant under any loading conditions, and a voltage waveshape that is purely sinusoidal. By these definitions, a synchronous generator is by no means an ideal power source, especially when subjected to nonlinear loading.

Due to their high source impedance, synchronous generators provide a relatively "weak" source to the connected equipment. Relative strength or weakness of an electrical supply can be described in several ways, as available short circuit current (Isc kA), fault level (MVA), source transformer kVA and impedance

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(Z%) and, in the case of generators, kVA rating and unsaturated subtransient reactance (X"d).

A generator's unsaturated subtransient reactance (X"d) is its internal impedance under normal load. The greater the X"d value, the "weaker" the system. The lower the X"d value, the "stiffer" the system. Typical X"d values range from 10% to over 20% depending upon the manufacturer, capacity, fuel source, and specified impedance levels.

Generators do not produce a perfectly sinusoidal voltage waveform even under linear loading, but when supplying nonlinear loads, the majority of the voltage distortion will be the result of voltage drop from the harmonic load currents across the generator's subtransient reactance. Understanding the strength or weakness of a source is key to understanding the relationship between the nonlinear loading and generated harmonic voltage distortion. Occasionally, engineers will specify a high subtransient reactance for a generator in order to reduce the system's fault level, but increasing the generator's impedance could have very serious consequences with respect to voltage distortion when supplying nonlinear loads unless harmonic mitigation means are adopted.

In addition, harmonic currents increase losses in generators in several ways. Stray magnetic fields produced by harmonic currents in the generator will induce circulating currents in the rotor's ammortisseur or damper cage [2]. This introduces additional losses due to the electrical resistance of the cage. Stator I^2R losses will also increase due to skin effect in the stator windings. Higher frequency harmonic currents tend to flow along the outer edge of a conductor rather than through its full cross sectional area. This increases the effective resistance of the conductor and the resulting I^2R loss. Generator core losses can also increase substantially when harmonics are present.

Generator automatic voltage regulators (AVR) and excitation controls can be sensitive to the voltage distortion that is created when supplying nonlinear loads. Voltage sensing circuits of the regulator must respond quickly to either the true RMS value or the fundamental component but must not respond to harmonic distortion caused by the load [2]. Excitation controls often get their power from the generator output which can introduce problems when this voltage is badly distorted [3].

B. Nonlinear Loads and Harmonics

When a source of sinusoidal voltage is applied to a nonlinear load, the resulting current is not perfectly sinusoidal. This distorted current can be broken down into harmonic components using Fourier analysis. The most common form of distorted current drawn by a nonlinear load is a pulsed waveform and much of today's power electronic equipment draws current in that manner. In the presence of system impedance this current causes a nonsinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals and throughout the power distribution system.

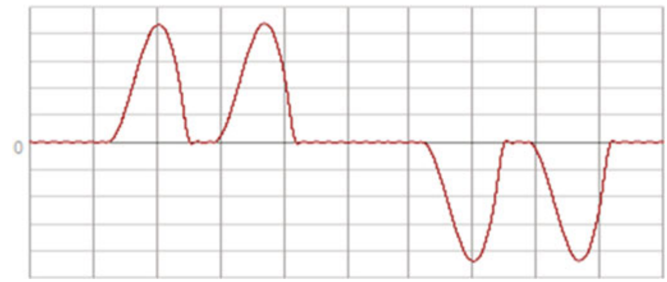


Fig. 1. Typical six-pulse rectifier current waveform.

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) increased losses in electric rotating machines (motors and generators), transformers, capacitors, cables, and generation equipment;
4) pulsating torques in rotating machines;
5) lower power factor in the electrical system preventing effective utilization;
6) increased risk of faults from overvoltage conditions developed on power factor correction capacitors, and
7) resonant conditions [4].

Very often, the presence of harmonic distortion is only detected after an expensive equipment failure, such as an adjustable speed drive (ASD) or power factor correction capacitors, has occurred.

C. ASDs and Harmonics

The standard pulse width modulated (PWM) ASD is a solid state device that converts supply voltage to a variable voltage and frequency in order to control the speed of a three-phase induction motor (also referred to as a variable frequency drive or VFD) or to dc for dc motor applications. By controlling the motor's speed, both energy savings and better motor control can be achieved.

ASDs generate harmonic currents because their front-end or input rectifiers do not draw current in a sinusoidal manner. Instead, they draw discontinuous, pulsed currents. In three-phase applications, 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 on each phase, as shown in Fig. 1.

For six-pulse diode bridge rectifiers

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

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

For a typical three-phase six-pulse rectifier bridge, the predominant harmonic currents that are generated will be the 5th, 7th, 11th, and 13th (see Fig. 2). Triplen (3rd, 9th, 15th, etc.) and even (2nd, 4th, 6th, etc.) harmonics are usually negligible in a properly operating three-phase rectifier. Typical current

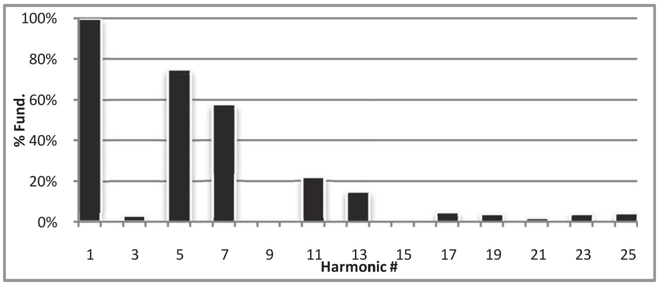


Fig. 2. Typical six-pulse rectifier current spectrum.

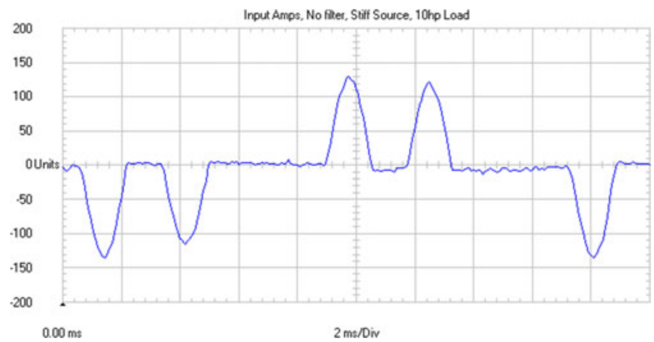


Fig. 3. Input Current of 15 hp, six-pulse ASD on a stiff utility source (ITHD = 108%).

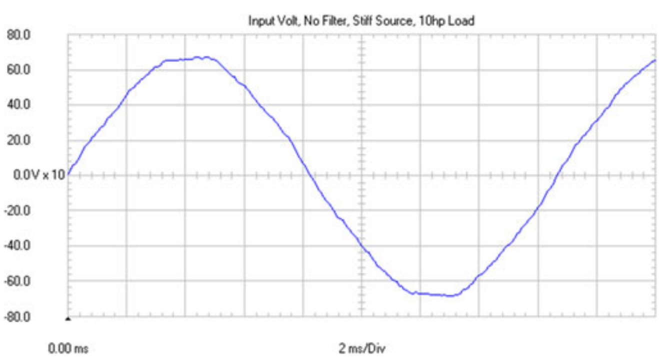


Fig. 4. Input voltage of 15 hp, six-pulse ASD on a stiff utility source (VTHD = 2.2%).

total harmonic distortion (ITHD) levels range from 35% to over 100% depending upon the supply impedance and whether or not an ac or dc reactor is applied to the drive.

D. How Source Impedance Effects Current and Voltage Distortion

A power system's source impedance will have a significant impact on the current harmonics drawn by an ASD or other nonlinear load and on the voltage harmonics these nonlinear loads create on the power system. Figs. 3 and 4 show current and voltage waveforms measured at the terminals of a 15 hp, 480 V ASD fed from a relatively "stiff" ac supply. Although the ITHD of this pulsed current waveform was over 100%, the low source impedance resulted in very low voltage distortion on the distribution system as the measured voltage total harmonic distortion (VTHD) at the drive terminals was only 2.2%.

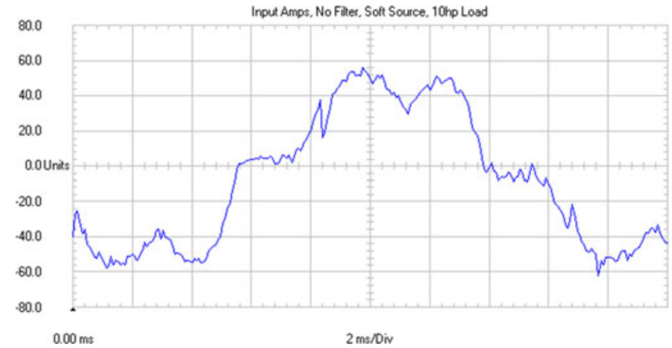


Fig. 5. Input current of 15 hp, six-pulse ASD on a weak generator source (ITHD = 25.8%).

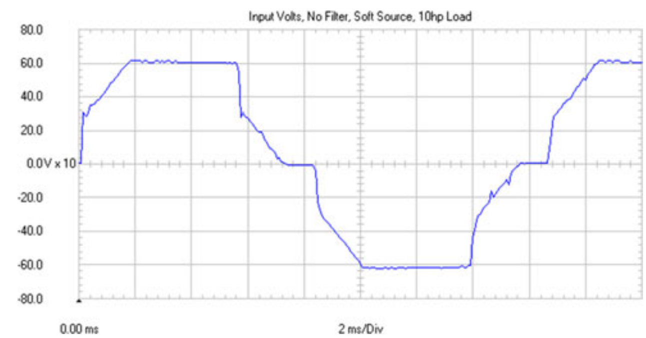


Fig. 6. Input voltage of 15 hp, six-pulse ASD on a weak generator source (VTHD = 13.8%).

On the other hand, when the same 15 hp ASD (without a line reactor) operating at the same load level was fed from a relatively "weak" generator source, the high source impedance smoothed out the current pulses reducing the ITHD to 25.8% (see Fig. 5). But even at this much lower current distortion level, the high source impedance produced severe voltage flat-topping and very high levels of VTHD at nearly 14% (see Fig. 6). At these high levels of voltage distortion, connected equipment can certainly have operational problems and premature failure due to overheating of components. By considering the effect of source impedance on current and voltage distortion and understanding that harmonic losses can substantially reduce energy efficiency, the following observations can be made when operating on a generator supply.

1) High levels of nonlinear load, such as ASDs, on a generator supply without harmonic mitigation strategies in place will create significant voltage distortion on the distribution bus, which can lead to problems with the generator's AVR and any sensitive connected equipment, including the ASD itself.
2) The additional losses introduced by excessive current harmonics will increase the operating temperature of the source generator and all current carrying components within the distribution system, compromising the operating life expectancy of this equipment.
3) The introduction of nonlinear load devices can have a substantial impact on the operating efficiency of the generator system by increasing fuel consumption and emissions. This can substantially increase operating costs,

maintenance, and equipment repair over the entire life of the installation and increase GHG emissions.

E. Concept for Rightsizing a Generator Under Nonlinear Loading

As described earlier, harmonic currents drawn by a nonlinear load will significantly reduce the ability of a generator to supply that load due to both an increase in losses and voltage distortion. To address this, generator manufacturers offer a "rule of thumb" that when ASDs represent more than 25% of the total load on the generator set, they become cause for concern. For six-pulse ASDs, twice the running kW of the drive is a typical sizing factor used [5]. When the amount of ASD loading is higher, even greater oversizing is required.

Fortunately, these problems with harmonics can be avoided by applying effective harmonic mitigation equipment. For example, if an input filter is used to limit current distortion to <10%, the sizing factor can be reduced to 1.4× the running kW of the drive [5]. Therefore, for large nonlinear loads or large quantities of smaller nonlinear loads, harmonic mitigation measures should be considered. The most common types are ac or dc reactors, multipulse ASDs, tuned passive filters, wide spectrum harmonic filters (WSHFs), parallel active filters, and active front-end (AFE) ASDs.

There are many parameters that need to be taken into consideration when analyzing the most suitable harmonic mitigation for a particular application, some of which are as follows.

1) ac or dc reactors: Reactors are relatively easy to apply and will typically lower the current distortion drawn by the ASD or other nonlinear device by approximately 50%. But this is very often not enough to meet acceptable voltage distortion limits. Typical values of reactance used are 3%–5%. Simply increasing the impedance of the reactor further will have minimal effect on lowering current harmonics and can lead to excessive voltage drops, which will reduce the output power rating of the ASD. [6]
2) Multipulse ASDs: 12, 18, 24 or higher pulse level ASDs are available with harmonic current reduction increasing with the pulse number. Phase shifting transformers or autotransformers are either built into the ASD or supplied separately. These transformers will add losses reducing the efficiency of the ASD. Also, the effectiveness of the phase shifting in cancelling harmonics can be susceptible to background voltage distortion and voltage imbalance. As little as 2% imbalance can drop the performance to levels no better than a six-pulse ASD equipped with an ac or dc reactor. [6]
3) Tuned passive filters: Each parallel connected tuned passive filter will target a single harmonic. Therefore, to address the most predominant harmonics, multiple level filters are required. As a parallel connection, these devices must be reviewed for suitability whenever new loads are added or the power system is modified. Under lightly loaded conditions, capacitive reactive power can be quite high so consideration must be given to the generator's excitation controls and AVR's ability to handle this capacitive reactance. In addition, under light loading, the large capacitor banks can boost the line voltage causing nuisance over voltage tripping of ASDs.
4) Passive WSHF: These series connected low pass filters are designed to reduce the full spectrum of characteristic harmonics drawn by six-pulse ASDs. Some filters are capable of reducing current distortion levels to <5% at full load. Consideration must be given to the fact that some designs, but not all, introduce high levels of capacitive reactance under lightly loaded conditions which could lead to generator operational issues [6]. It is important to either select a filter with low capacitive reactive power or include capacitor switching contactors.
5) Parallel active harmonic filter (AHF): Parallel connected AHF's are designed to provide the harmonic currents required by the connected nonlinear load. If sized properly, reduction in current harmonic distortion can be quite significant at the targeted harmonics below the 50th, but this requires that all six-pulse ASDs are equipped with at least a 3% ac reactor or a dc choke. The AHF accomplishes this by the use of IGBTs, which can inject higher frequency harmonics above the 50th. At these higher frequencies, equipment problems can result at much lower distortion levels than for lower frequency harmonics.
6) AFE ASD (AFE): AFE drives reduce input current harmonics with the use of IGBT's to regulate the current drawn by the rectifier. Input current distortion can be substantially reduced at harmonic levels below the 50th. However, much like the AHF, AFE drives also inject higher frequency harmonics above the 50th, which will usually raise the current total harmonic distortion levels above 5% when harmonics up to the 100th are taken into consideration. As with the AHF, these higher frequency harmonics can cause problems at much lower distortion levels than the lower frequency harmonics [7].

II. Analysis

For the rightsizing analysis, we will consider the actual application of a 200 hp (150 kW), 480 V unmanned pump in a remote area of USA that required an islanded generator supply and was equipped with a six-pulse ASD. Not realizing the effects that a nonlinear load would have on the generator, it was initially sized without consideration of the ASD harmonic currents. With an original generator sized at 176 kW, the application had numerous problems, including generator instability and multiple ASD failures. At the recommendation of the generator manufacturer, a replacement generator was installed sized at 500 kW. Although this did improve the operation, it did not eliminate the ASD problems altogether so a better solution was needed.

Various forms of harmonic mitigation were considered. A multipulse ASD option was ruled out due to the fact that it required replacement of the existing ASD and its higher losses would increase the energy/fuel consumption and emissions. Also, the pipeline company had other installations with 18-pulse ASDs that were having operational problems when fed from generators. Replacing the existing ASD with an AFE model

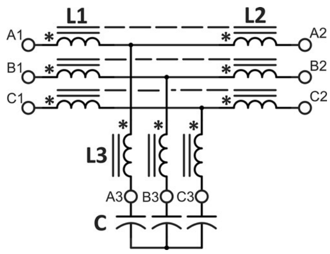


Fig. 7. WSHF schematic.

was not chosen because of the high cost, higher losses, and potential for introducing high frequency harmonics. For the same reasons, a parallel AHF was also not chosen.

When considering a passive filter solution, the many advantages of a low capacitive reactance, series connected WSHF made it an easy decision over paralleled tuned passive filters. These included better performance, simpler configuration, little concern for resonance with the power system, and especially the low capacitive reactance, which made it compatible with the generator.

A. Passive WSHF

The use of passive filters to treat harmonics generated by nonlinear load circuits is fairly common but not that well understood. The best passive filter technology is not tuned to specific harmonic frequencies but rather provides harmonic reduction over a wide frequency range. A wide spectrum filter applied to a six-pulse drive will reduce all of the characteristic harmonics, but especially the 5th, 7th, 11th, and 13th. The filter is connected in series between the main supply and the drive. ITHD at full load can be reduced to as low as 5% when applied to a six-pulse ac PWM drive regardless of whether the drive is equipped with a reactor (ac or dc) or not.

The goal is to reduce the current harmonic generated by the load device, thereby mitigating the effect of the system impedance on the resulting voltage distortion created by that particular load. The advantages of using WSHFs versus other forms of harmonic mitigation are:

1) cost;
2) simplicity of integration and operation;
3) broad speed/load operating range;
4) much better efficiency.

There are various forms of WSHF's 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. 7.

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 WSHF 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, 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. Many WSHF's feature high capacitance values in relation to their base kW rating—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 pipeline pumping facilities, can create regulation issues for the site generation since at low loads, high capacitive reactive power can interfere with generator regulation systems. To address this, many filter suppliers incorporate a 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 under light loading.

B. Computer Simulation of 200 hp (150 kW) Pumping Application

After increasing the generator size and adding a 3% ac line reactor, the ASD of the 200 hp pump still occasionally experienced operational problems. Harmonic analysis was performed to determine if a better solution was possible. A computer simulation software package, that incorporates nodal analysis by formulating a nodal matrix and solving the set of numerical differential equations by the backward Euler (second order and third order) method, was used. At each point in time, nonlinear devices are replaced by equivalent linear circuit models which require many iterations before calculations converge to a solution. The program therefore, dynamically adjusts the time step to improve accuracy and reduce long simulation times.

The first analysis performed was with the 500 kW (625 kVA) generator supplying the 200 hp pump with: 1) no mitigation; 2) a 3% ac reactor; and 3) WSHF [see Fig. 8(a)–(c)]. From the generator's nameplate, the subtransient reactance of 11.8% and power factor of 0.8 were entered into the software in addition to its 500 kW and 480 V ratings. A 200 hp (150 kW) PWM ac ASD was selected as the load, running at 90% capacity. The software is capable of including cables in the analysis but since the distance between the load and generator was very short, cables could be neglected.

With no harmonic mitigation applied to the ASD, the computer simulation predicted ITHD of over 40% and VTHD at the generator of nearly 8%. With a 3% ac line reactor added, ITHD dropped to just over 30% and VTHD to above 5%. By adding a WSHF instead of the line reactor, current distortion dropped to $<7\%$ and voltage distortion lowered to $<2\%$. A summary of these simulation results is provided in Table I.

It is important to note that although the computer simulation program does calculate both fundamental and harmonic losses in power system components such as cables and transformers, it does not calculate these losses in the generator. Therefore, the predicted power does not reflect the lower generator losses that

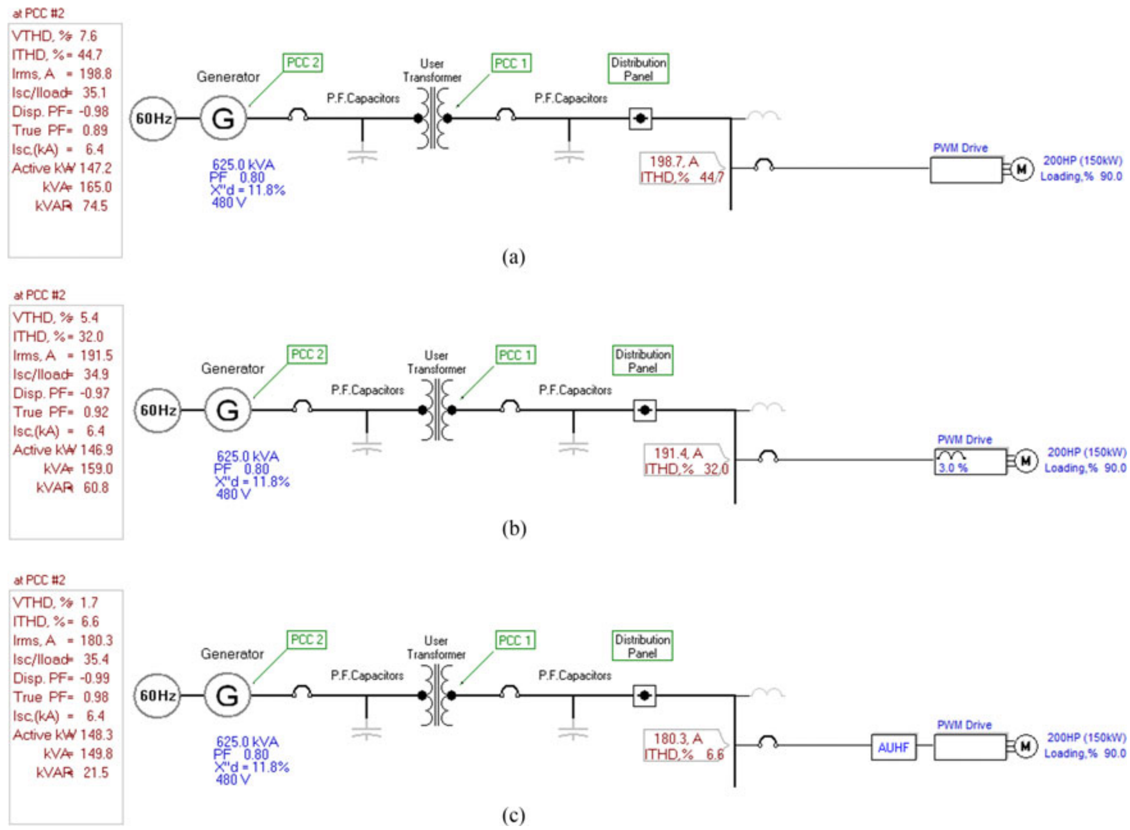


Fig. 8. (a) Computer simulation of 500 kW generator feeding 200 hp pump with no harmonic mitigation. (b) Computer simulation of 500 kW generator feeding 200 hp pump with 3% ac reactor. (c) Computer simulation of 500 kW generator feeding 200 hp pump with WSHF.

TABLE I
COMPUTER SIMULATION OF 500 KW GENERATOR SUPPLYING 200 HP PUMP WITH ASD AND VARIOUS FORMS OF HARMONIC MITIGATION

	No Harmonic Mitigation	With 3% ac Reactor	With WSHF
VTHD	7.6%	5.4%	1.7%
ITHD	44.7%	32.0%	6.6%
Current (Amp)	198.8	191.5	180.3
Real power (kW)	147.2	146.9	148.3

TABLE II
MEASURED VALUES OF 200 HP PUMP WITH ASD SUPPLIED BY 500 KW GENERATOR AND OPERATING AT 240 BPH

	With 3% ac Reactor	With WSHF
VTHD	6.0%	2.3%
ITHD	23.7%	5.7%
Current (Amp)	181	137
Real power (kW)	137.5	111.5

are expected with the reduction in harmonic current drawn by the load after the WSHF is applied.

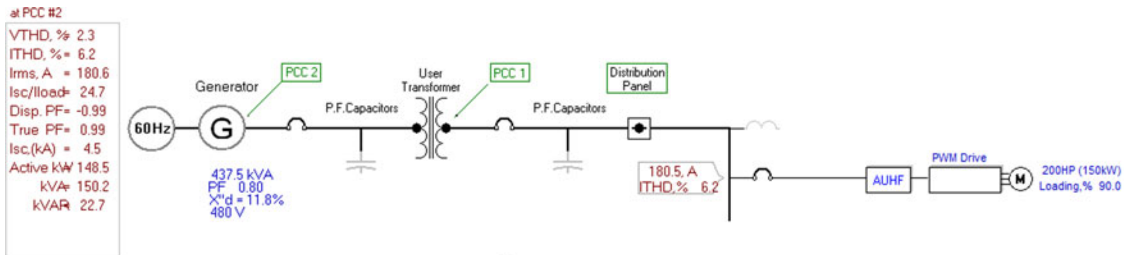
Based on the predicted improvement in both current distortion and voltage distortion, the pipeline operator decided to replace the ac line reactor with a WSHF sized to the 200 hp load.

Table II provides field measurements of the pumping operation with the ac reactor and with the WSHF. For both measurements, the pump was operating at a set flow rate of 240 BPH, which was maintained by a separate control system. There was a very small linear load component of approximately 1 kW.

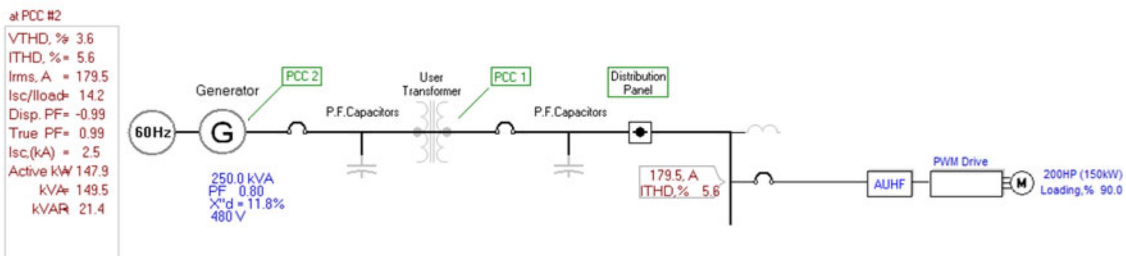
As predicted by the computer simulation, both current and voltage distortion decreased substantially with the installation of the WSHF. ITHD dropped from about 24% to <6%, which subsequently reduced VTHD from 6% to just over 2%.

Although a reduction in losses was expected in the generator due to the removal of the harmonic current, a real power reduction in kW downstream of the generator was not predicted. But while running at the same throughput of 240 BPH, the pump consumed only 111 kW with the WSHF supplying the ASD instead of 137 kW with the ac reactor and no WSHF. This was a reduction of 19% with no sacrifice in production. One possible explanation that could have contributed to this is that the WSHF had less of a voltage drop across it than did the ac reactor. This would lower the current demand of the ASD/Pump package, reducing I^2R losses and resulting in more efficient operation. Also, the WSHF is very efficient so it would introduce less losses than the ac reactor.

Now that the harmonic distortion was substantially reduced, the ASD and generator operated without issue allowing the pump operator to consider a smaller generator to further reduce energy/fuel consumption and environmental emissions. The pump now delivered the required 240 BPH while consuming only 111 kW real power. This seemed to justify a reduction in generator size to at least 200 kW (250 kVA) but the operator was too nervous to go that small due to the many problems



(a)



(b)

Fig. 9. (a) Computer simulation of 350 kW generator feeding 200 hp pump with WSHF. (b) Computer simulation of 200 kW generator feeding 200 hp pump with WSHF.

experienced previously. A 350 kW (437.5 kVA) unit was chosen instead. Computer simulations were done for both scenarios and are shown in Fig. 9(a) and (b).

Fed from a 350 kW generator, current distortion was predicted to be 6.2% and voltage distortion 2.3% while on the smaller 200 kW generator they were 5.6% and 3.6%, respectively. These both would be comfortably within the requirements of harmonic standards such as IEEE Std 519 [12].

Figs. 10 and 11 show the voltage waveforms and spectrums as determined by the computer simulation for the 500 kW generator [see Fig. 8(a)] without harmonic mitigation and the 200 kW generator with WSHF [see Fig. 9(b)]. Note that the scales for the spectrum chart are different—6% full scale for the 500 kW example and 3% for the 200 kW. These demonstrate how much improvement proper harmonic mitigation can achieve even on a much smaller generator supply.

C. Actual Performance on a 350 kW Generator

Rather than replacing the 500 kW generator with a smaller diesel generator, the operator decided to take the opportunity to use available flare gas and installed a 350 kW natural gas generator instead. Field measurements were taken and compared with the computer simulation (see Table III).

Current and voltage distortion levels matched the simulation results very well but, once again, the actual power consumption was significantly lower than simulated even though the 240 BPH flow rate was maintained. As mentioned earlier, this is likely due to improved operation of the ASD/pump package when supplied from the WSHF.

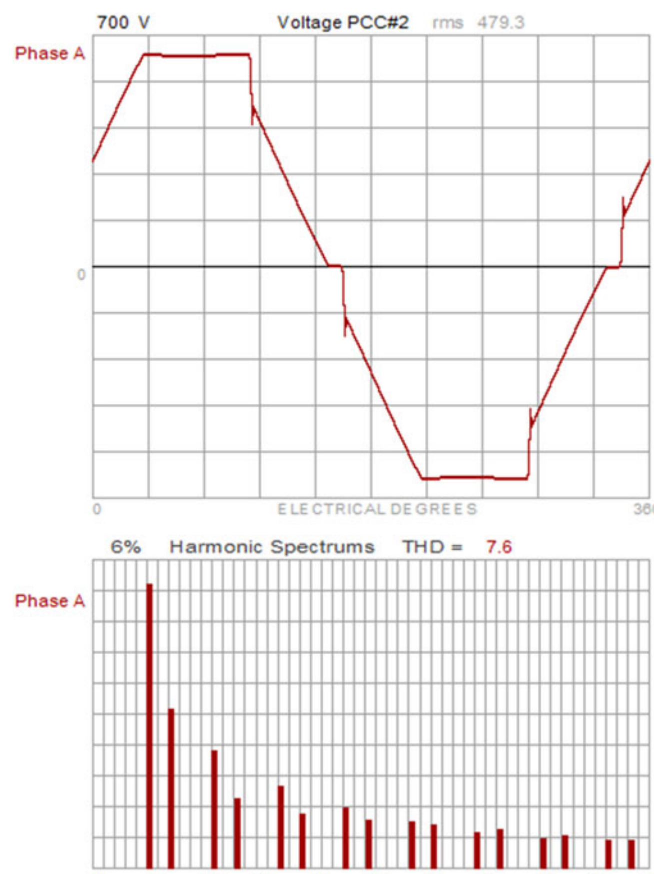


Fig. 10. Simulated voltage waveform and spectrum on 500 kW GEN without mitigation.

D. Fuel and Emission Reductions

In order to determine the fuel and emissions savings that the harmonic mitigation equipment provided, calculations were done based on generator loading and fuel consumption data from the generator technical data sheets. For the smaller generator, a 300 kW unit was selected as that was the size that the operator would have chosen if a diesel generator was used.

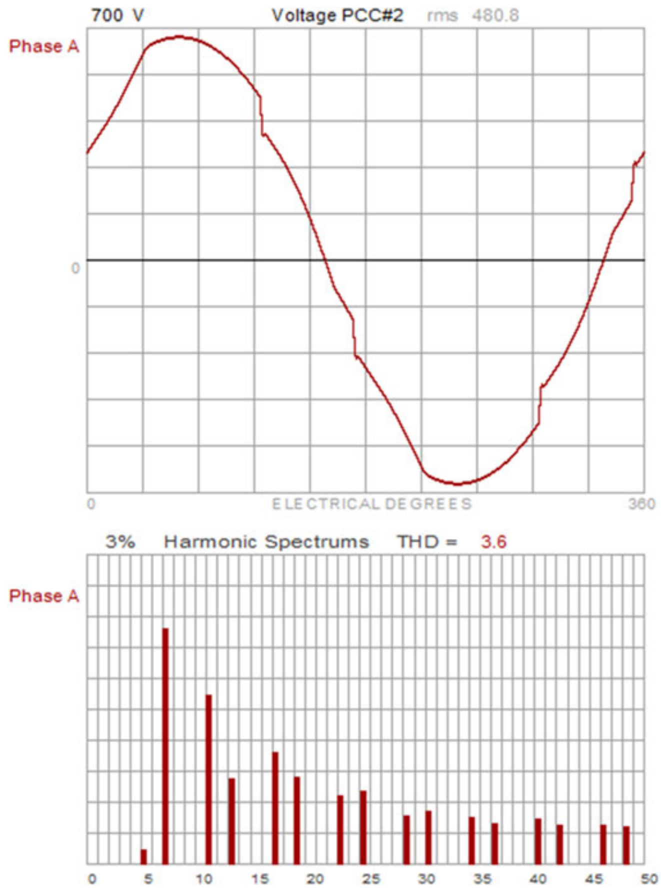


Fig. 11. Simulated voltage waveform and spectrum on 200 kW GEN with WSHF.

TABLE III
COMPARISON OF COMPUTER SIMULATION AND FIELD MEASUREMENTS FOR A 200 HP PUMP WITH WSHF FED FROM A 350 KW GENERATOR

	Computer Simulation	Field Measurements
VTHD	2.3%	2.5%
ITHD	6.2%	5.8%
Current (Amp)	180.6	144
Real power (kW)	148.5	117.6
Apparent power (kVA)	150.2	118.9
Reactive power (kVAR)	22.7	17.4
True PF	0.99	0.99

Table IV shows the measured power requirement for a flow rate of 240 BPH in three operating scenarios: 1) 500 kW generator with ac reactor; 2) 500 kW generator with WSHF; and 3) 300 kW generator with WSHF. The cost of diesel delivered to the site was $3.80 USD/gal. CO_2 emissions were calculated based on 10.2 kg/gal [1]. Operation was taken to be steady at 240 BPH, 24 h/day, 7 days/week, which was very typical for this location.

While operating on the same 500 kW generator, application of the harmonic mitigation equipment significantly reduced fuel consumption and emissions. From the table, it can be seen that one month's savings in fuel totaled $4651, which provided a 1.5 mo payback on the WSHF. Emissions reduction was

TABLE IV
COMPARISON OF 500 KW AND 300 KW GENERATOR SUPPLYING 200 HP PUMP WITH ASD OPERATING AT 240 BPH

	500 kW (with AC Reactor)	500 kW (with WSHF)	300 kW (with WSHF)
Load (kW)	137.5	111.5	117.6
Load %	27.4	22.2	39.2
Fuel consumption rate at % load (gal/h)	11.8	10.1	7.3
Fuel consumption at 24 h/day, 30 days/mo (gal/mo)	8496	7272	5256
Fuel cost (USD/mo)	$32 285	$27 634	$19 973
Fuel savings (USD/mo)	N/A	$4651	$12 312
% Savings	N/A	14.4%	38.1%
Emissions ($kgCO_2$/h)	120	103	74
Monthly emissions ($kgCO_2$/mo)	86 400	74 160	53 280
Monthly emissions reduction ($kgCO_2$/mo)	N/A	12 240	33 120

12 240 $kgCO_2$/mo, which is the equivalent of operating approximately 30 automobiles in USA [10].

While operating on the smaller 300 kW generator with harmonic mitigation, fuel consumption reduction was projected to be over 38% when compared with the previous operating mode of a 500 kW generator with only an ac line reactor. This would result in monthly CO_2 emission reductions of 33 120 kg (84 less automobiles) and fuel savings of over $12 000 USD, easily justifying the installation of the smaller generator.

III. CONCLUSION

For generator applications, whether prime or backup power, consideration must be given to the amount of nonlinear loading and the harmonic distortion that these loads will introduce. "Rule of thumb" sizing practices of, at least, doubling the generator rating has led to an inefficient operation, much higher installation and operating costs, and excessive emissions. Also, in many applications, simply doubling the generator rating may not be enough to reduce voltage distortion to levels that will not affect the operation of connected equipment, such as an ASD. A much better approach is to perform a harmonic analysis and apply proactive harmonic mitigation and rightsizing practices for the generator selection. This will reduce initial equipment costs and provide energy/fuel cost savings and lower emissions for the entire operating life of the installation.

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