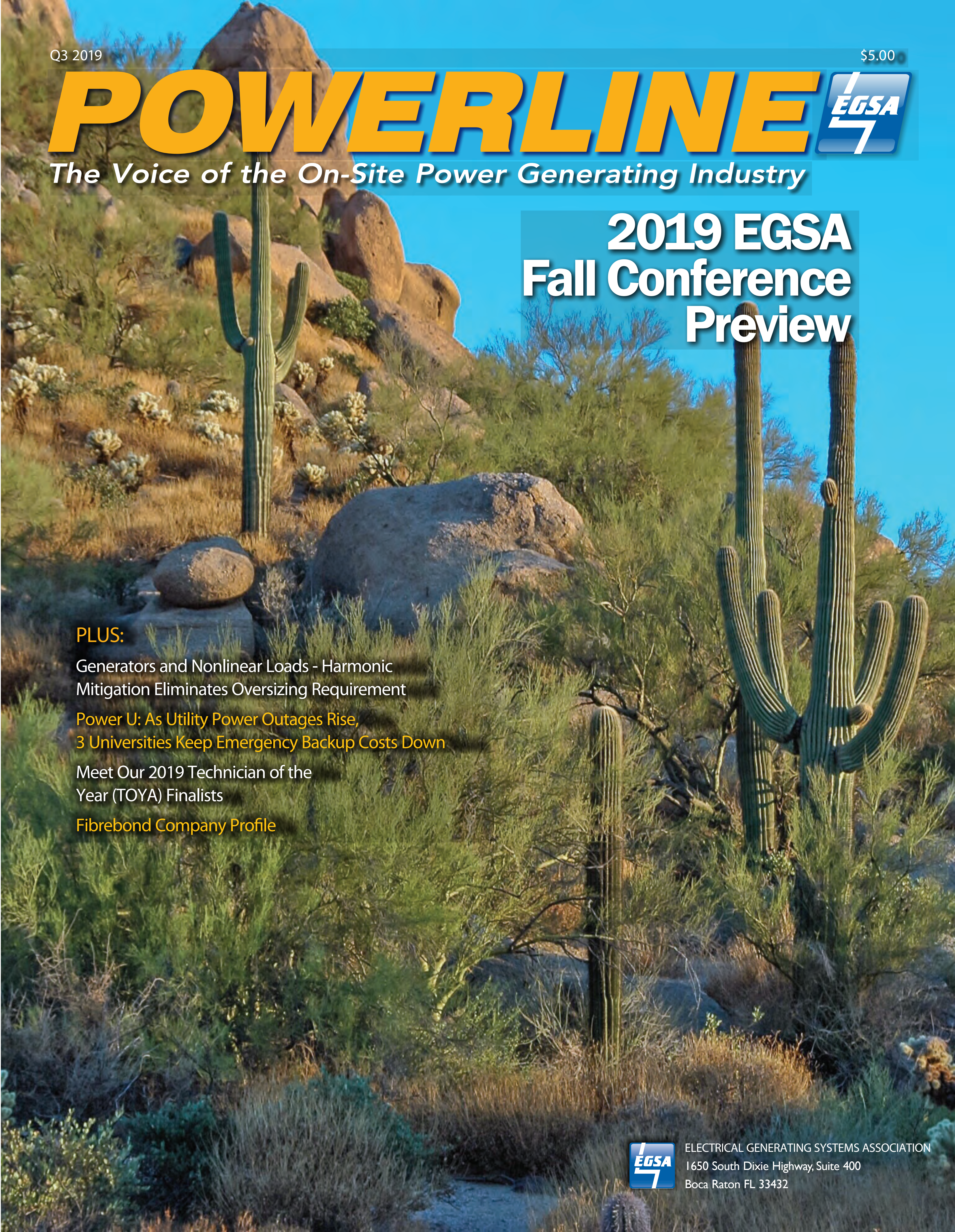

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Generators and Nonlinear Loads - Harmonic Mitigation Eliminates Oversizing Requirement

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In order to accommodate the harmonics associated with nonlinear loads, such as adjustable speed drives, UPS systems, computer equipment, lighting and other power electronic loads, generator manufacturers recommend oversizing by 2 to 2½ times rated capacity. Incorrectly calculating the effects of nonlinear load harmonics on a generator can lead to brownout conditions, overloading of the generator, nuisance tripping, misoperation of the automatic voltage regulator (AVR), generator failures and load equipment damage through elevated voltage distortion. However, oversizing the generator to accommodate the nonlinear load current harmonics will result in significantly increased installation costs and higher fuel consumption and operating costs due to poor operating efficiencies. Emissions will also be substantially higher than necessary.

So 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? Diesel generators can 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 can emit approximately 2.4 to 3.5 kg of CO2 (9.08 to 13.2 kg/US gal). 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.

Generators and Harmonics

Due to their high source impedance, synchronous generators provide a relatively 'weak' source to the connected equipment. A generator's source impedance is determined by its unsaturated sub-transient reactance (X"d). The greater the X"d value, the 'weaker' the system and 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. 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. Excitation controls often get their power from the generator output which can introduce problems when this voltage is badly distorted.

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 non-linear 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 non-sinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals and throughout the power distribution system.

The standard Pulse Width Modulated (PWM) Adjustable Speed Drive (ASD) is a solid state device that converts supply voltage to a variable voltage and frequency in order to control the speed of a 3-phase motor. By controlling the motor's speed, both energy savings and better motor control can be achieved. ASD's generate harmonic currents because their front-end or input rectifiers do not draw current in a sinusoidal manner. Instead, they draw discontinuous, pulsed currents as shown in Fig. 1.

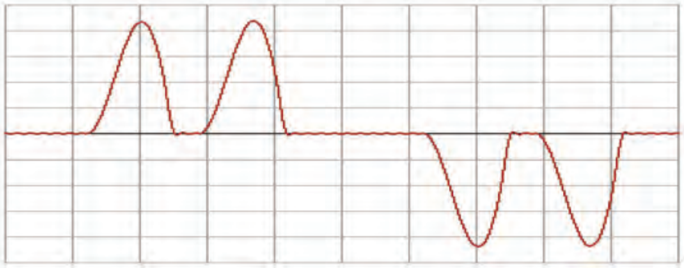


Fig. 1: Typical 6-Pulse Rectifier Current Waveform

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

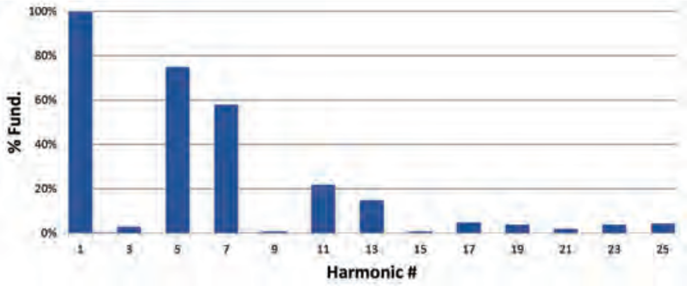


Fig. 2: Typical 6-Pulse Rectifier Current Spectrum

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. Fig. 3 and 4 show current and voltage waveforms measured at the terminals of a 15 HP, 480V 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%.

On the other hand, when the same 15 HP ASD 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% (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% (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:

- 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 automatic voltage regulator (AVR) and any sensitive connected equipment, including the ASD itself.

- 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.

- 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 greenhouse gas (GHG) emissions.

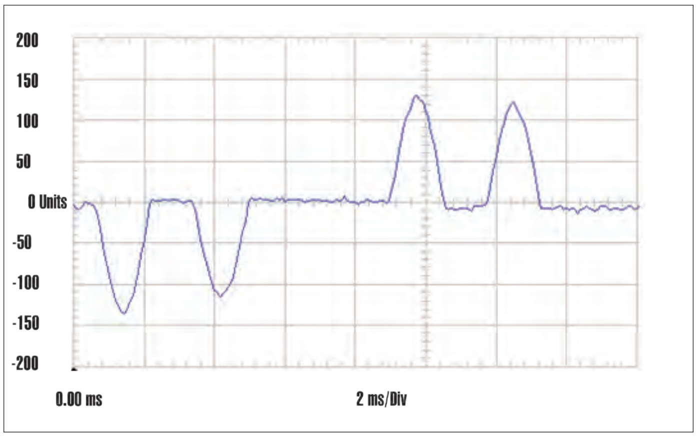


Fig. 3: Input Current of 15 HP, 6-Pulse ASD on a Stiff Utility Source (ITHD = 108%)

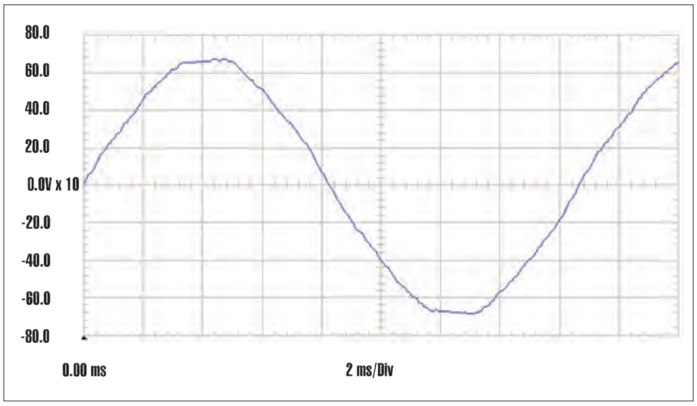


Fig. 4: Input Voltage of 15 HP, 6-Pulse ASD on a Stiff Utility Source (VTHD = 2.2%)

Application of Harmonic Mitigation for Generator Rightsizing 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

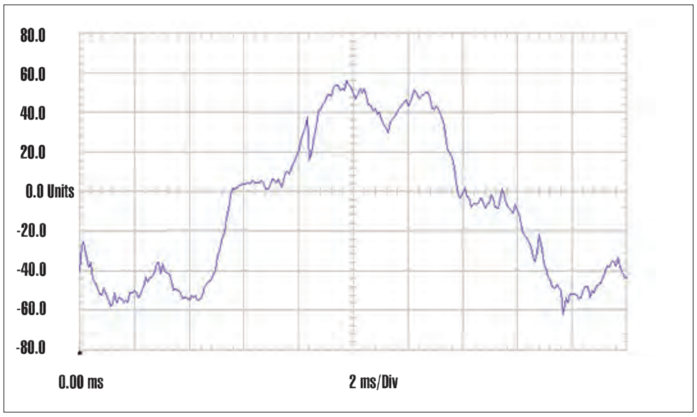


Fig. 5: Input Current of 15 HP, 6-Pulse ASD on a Weak Generator Source (ITHD = 25.8%)

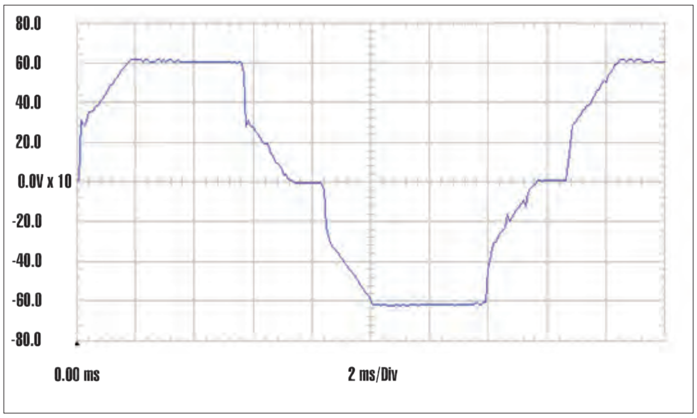


Fig. 6: Input Voltage of 15 HP, 6-Pulse ASD on a Weak Generator Source (VTHD = 13.8%)

thumb' that when ASD's represent more than 25% of the total load on the generator set, they become cause for concern. For 6-pulse ASD's, twice the running kW of the drive is a typical sizing factor used. 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 1.4x the running kW of the drive. 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 ASD's, tuned passive filters, wide spectrum harmonic filters, parallel active filters and active front-end (AFE) ASD's.

Passive Wide Spectrum Harmonic Filter (WSHF)

A very effective, reliable and economic choice for harmonic mitigation is the passive wide spectrum harmonic filter. These are not tuned to specific harmonic frequencies but rather provide harmonic reduction over a wide frequency range. A wide spectrum filter applied to a 6 Pulse ASD 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% regardless of whether the drive is equipped with a reactor (AC or DC) or not.

Mirus offers a WSHF that provides advantages such as easy integration, low capacitive reactance, excellent harmonic mitigation, high efficiency and competitive cost. It employs a combination of a blocking element and a tuned filtering element as shown in Fig. 7.

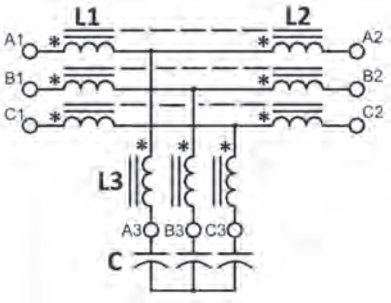


Fig. 7: Wide Spectrum Harmonic Filter Schematic

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, non-linear 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, 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.

Generator Rightsizing Analysis

For the rightsizing analysis, let's consider the actual application of a 200 HP (150 kW), 480V unmanned pump in a remote area of the USA that required an islanded generator supply and was equipped with a 6-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 before the many advantages of a low capacitive reactance, series connected wide spectrum harmonic filter (WSHF) made it a logical selection. 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.

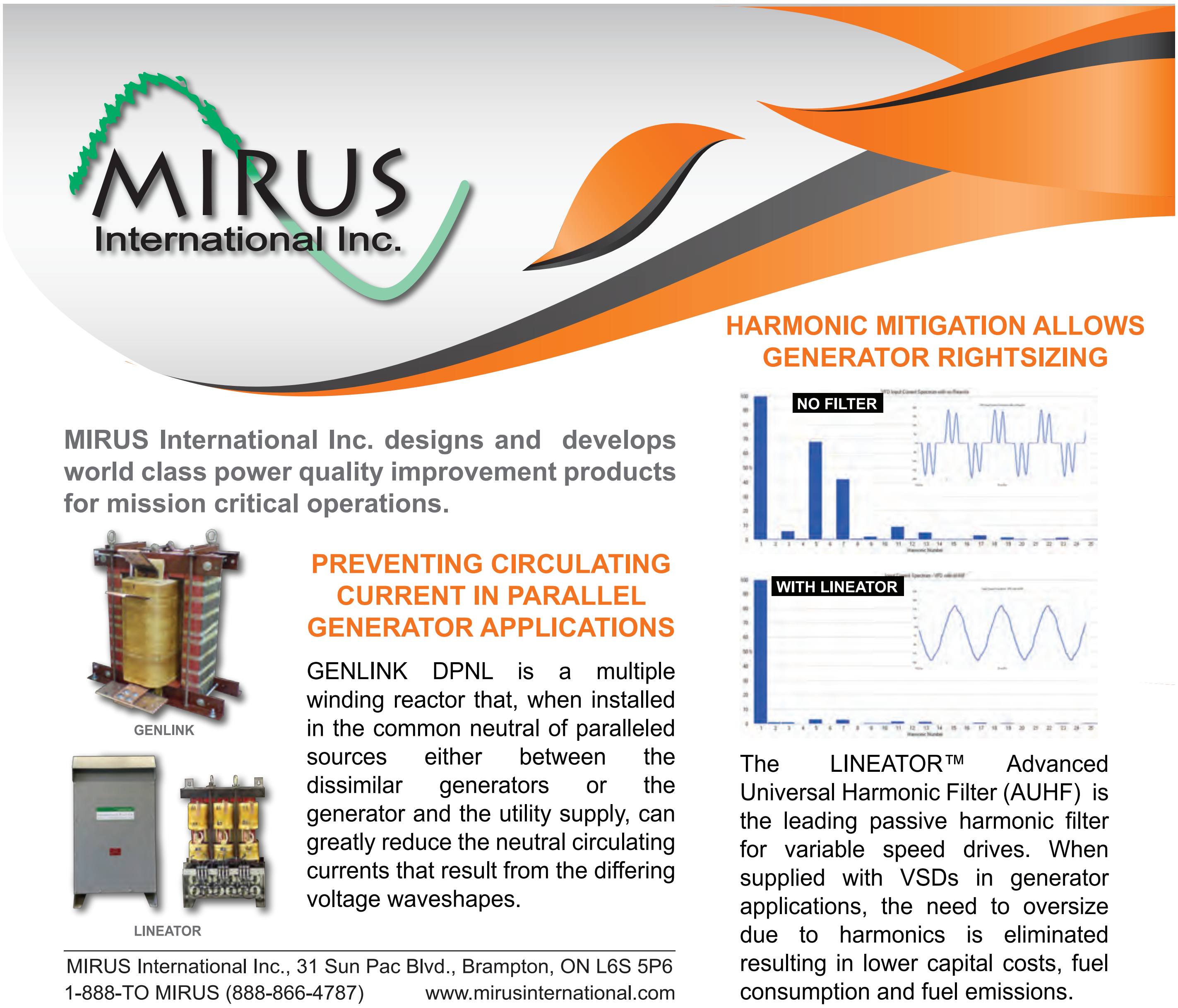
Remote Pump Site in Midwest USA

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.

The first analysis performed was with the 500 kW (625 kVA) generator supplying the 200 HP pump with (i) no mitigation, (ii) a 3% AC reactor and (iii) WSHF. 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 480V ratings. A 200 HP (150 kW) PWM AC ASD was selected as the load, running at 90% capacity.

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 1.

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 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 2 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.

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%.

	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 1 - Computer Simulation of 500 kW Generator Supplying 200 HP Pump with ASD and Various Forms of Harmonic Mitigation

	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

Table 2 - Measured Values of 200 HP Pump with ASD Supplied by 500 kW Generator and Operating at 240 BPH

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 I2R 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 experienced previously. A 350 kW (437.5 kVA) unit was chosen instead.

Fed from a 350 kW generator, computer simulations predicted current distortion 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 would both be comfortably within the requirements of harmonic standards such as IEEE Std 519.

Actual Performance on a 350 kW Generator

Rather than replace 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 (Table 3).

	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 3 - Comparison of Computer Simulation and Field Measurements for a 200 HP Pump with WSHF fed from a 350 kW Generator

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.

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.

Table 4 shows the measured power requirement for a flow rate of 240 BPH in three operating scenarios: 500 kW generator with AC reactor, 500 kW generator with WSHF and 300 kW

	500 kW (with AC Reactor)	500 kW (with WSHF)	300 kW (with WSHF)
Load (kW)	137.5	111.5	117.2
Load %	27.4	22.2	39.2
Fuel Consumption Rate at % Load (gal/hr)	11.8	10.1	7.3
Fuel Consumption at 24 hrs/day, 30 days/mo (gal/mo)	8,496	7,272	5,256
Fuel Cost (USD/mo)	$32,285	$27,634	$19,973
Fuel Savings (USD/mo)			
% Savings	N/A	14.4%	38.1%
Emissions ($kgCO_2/hr$)	120	103	74
Monthly Emissions ($kgCO_2/mo$)	86,400	74,160	53,280
Monthly Emissions Reduction ($kgCO_2/mo$)	N/A	12,240	33,120

Table 4 - Comparison of 500 kW and 300 kW Generator Supplying 200 HP Pump with ASD Operating at 240 BPH

generator with WSHF. The cost of diesel delivered to the site was $3.80 USD/gal. CO2 emissions were calculated based on 10.2 kg/gal. Operation was taken to be steady at 240 BPH, 24 hrs/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 $4,651 which provided a 1 ½ month payback on the WSHF. Emissions reduction was 12,240 kgCO2/mo which is the equivalent of operating approximately 30 automobiles in the USA.

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 CO2 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.

Conclusions

For generator applications, whether prime or backup power, consideration must be given to the amount of non-linear 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 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 adjustable speed drive. 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. ■

About the Authors

Anthony (Tony) Hoevenaars (BESc'79) is President and CEO of Mirus International, Brampton, ON, Canada, a company specializing in the treatment of power system harmonics. With over 35 years of direct experience in resolving electrical power system problems, beginning in the 1980s as Chief Facilities Electrical Engineer at an IBM manufacturing facility in Toronto, Tony has earned an international reputation as a power quality and harmonics expert. As a Professional Engineer, Tony has published various papers on power quality. He is an active member of the IEEE having presented papers at PCIC conferences in 2003, 2008, 2009, 2010, 2014, 2015, 2016 and 2018.

Michael McGraw is Region Manager for Mirus International. Prior to joining Mirus in 2018, Mike was President of NSOEM Inc. a company he founded in 1996 that specializes in transformer and filter harmonic mitigation applications for land and offshore Oil & Gas systems and MV Solid State starting for large motors. Previously Mike was the OEM Sales Manager for MV Switchgear manufactured by Powercon Corp. Mike is a member of the IEEE and has published previous papers presented at the PCIC in 2010, 2014, 2015, 2016 and 2018 conferences.