Managing Emergency Generators

with nonlinear loads

KOHLER SDMO

White paper

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In this paper we will be focusing on the harmonic distortion that occurs in an emergency power solution. The source of this harmonic distortion will be specifically from nonlinear loads.

By the end of this paper you will be able to understand the effects of nonlinear loads and its advantages, enabling you to create better specifications with nonlinear load applications and to select a better generator for your nonlinear load applications.

Introduction

Basic generator sizing is comprised of three major parts:

1. Voltage and frequency drop
2. Motor-starting capability
3. Harmonic distortion (nonlinear loads)

What are nonlinear loads?

A linear load has a linear relationship between voltage and the current drawn by the load. For a sinusoidal supply voltage, the current drawn will be sinusoidal, as shown in *Figure 1.1*. Nonlinear loads are the main cause for harmonic distortion (pollution) in an electrical power system. The current drawn *(Figure 1.2)* will be nonlinear to the supply voltage. What this means is the supply voltage will be distorted. The Total Harmonic Current Distortion (ITHD) is the total distortion in a load current drawn by the nonlinear load, as shown in *Figure 1.3.*

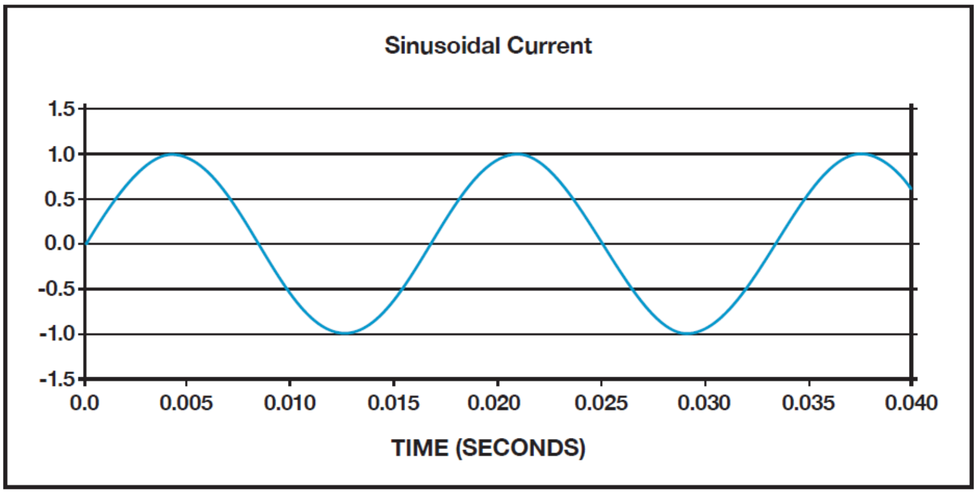

Figure 1.1

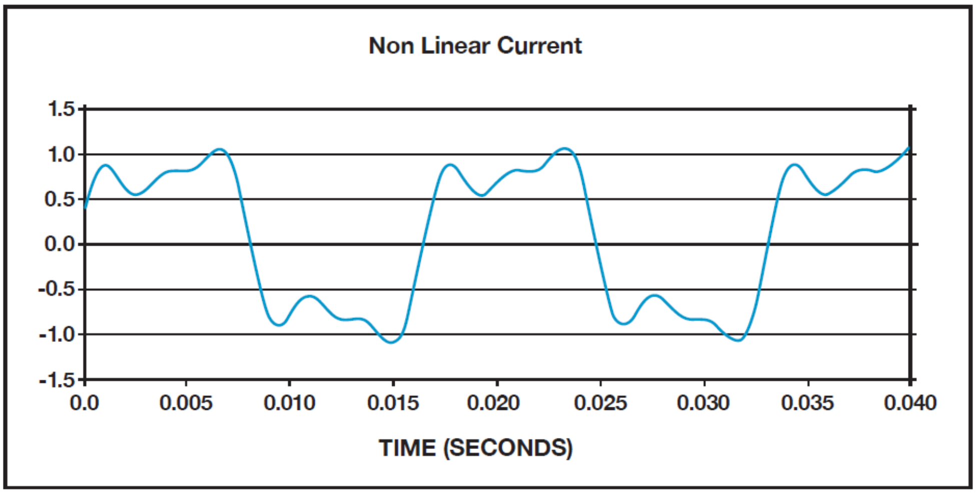

Figure 1.2

This ITHD causes a proportional Total Voltage Harmonic Distortion (VTHD) in the system circuits. We will observe a distorted supply voltage in all the electrically connected loads to the same supply, because of just one connected nonlinear load. This VTHD causes aberrant voltage drops in the supply voltage. An ITHD and VTHD are caused because of harmonics observed at a nonlinear load due to switching on and off of any solid-state electronic switching circuit. The switching circuit might have devices like thyristors, SCRs, IGBTs and ballasts which switch on and off so fast they cause multiple high frequency currents, called harmonics.

Examples of Nonlinear loads:

1. Computers–switching power supplies
2. Electronic and magnetic ballasts
3. Uninterruptible power supplies (UPS)
4. Printers, fax machines, copiers
5. HID Lighting/fluorescent lights
6. Variable-frequency drives (VFD) and DC motor drives
7. Battery chargers
8. Silicon-controlled rectifier controllers (SCRs)
9. Welders

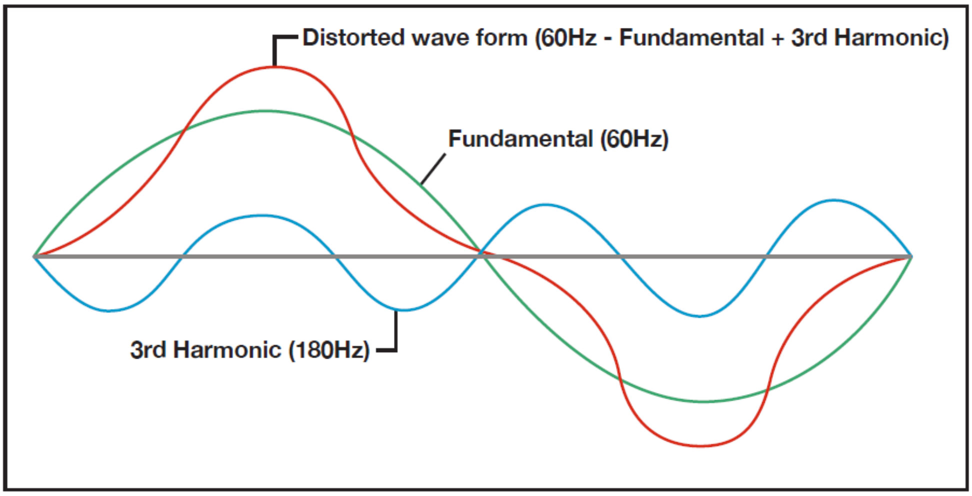

Figure 1.3

ITHD is the cumulative effect of individual current harmonics. *Figure 1.4* shows the supply voltage distortion that occurred in the system based on a six-pulse VFD load current draw. The distorted current waveform in *Figure 1.3* can be described as the addition of different frequency sinusoids like 3rd, 5th, 7th, etc., harmonics. Harmonics such as the 5th, 7th, 11th are harmonics that create a negative torque working against the fundamental torque. The harmonics are 5, 7, 11 times the frequency of the fundamental. For example, the 3rd harmonic will be 180 Hz, as shown in *Figure 1.3*. The figure shows how the harmonics and the sinusoidal supply voltage create the distorted red output wave.

Now, this distorted red wave (with multiple voltage drops) will be the supply voltage for the electrically connected devices to the generator, causing multiple functionality issues to harmonic sensitive devices. Most hospital generator specifications, for example, are driven by the fact that MRI scanners will be affected by voltage drops in the supply, which could cause inaccurate scans. Similarly, every application would have specific requirements which might be affected by a nonlinear load. The circle in *Figure 1.4* (load current and resultant voltage have different scales) shows when a switching circuit in a nonlinear load pulls current, it will result in a voltage drop. Depending on the number of these switching devices, the wave form for each individual nonlinear load will vary.

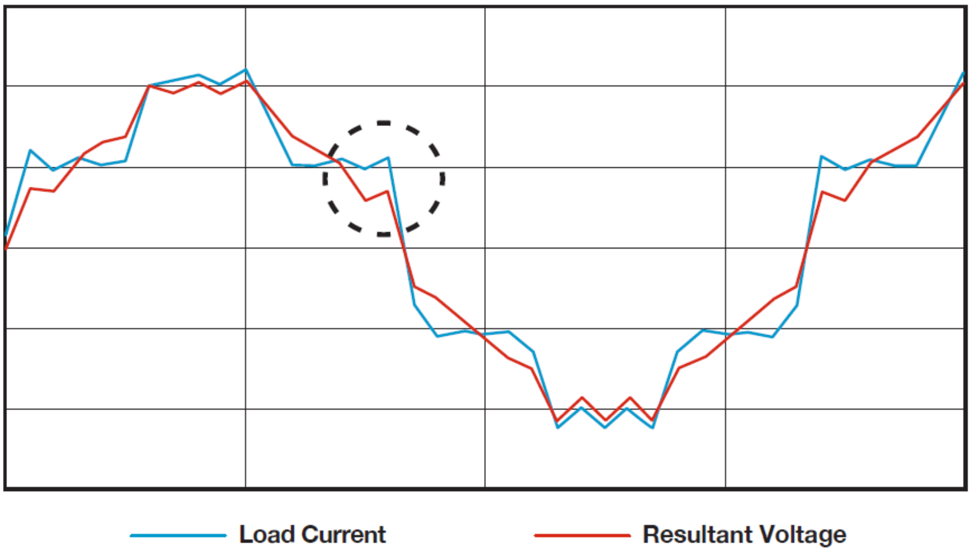

Figure 1.3

What are the effects of nonlinear loads on the generator?

VTHD is the combined effect of ITHD and alternator's Xd". ITHD is usually observed as the percentage of the harmonic content to the total amplitude of the current of the load. Many typical (linear and nonlinear) loads might face control issues because of the distorted voltage supply. This is an important reason why more and more applications such as wastewater treatment plants, data centers, and medical centers require low subtransient reactance alternators, which is the most common way to avoid problems with system harmonics. VTHD is emphasized more for generator sizing due to the sizable impact of voltage distortion on electrically connected loads and the generator. The ITHD from the load might not have a huge impact on the VTHD in the system if the nonlinear load is very small compared to the rated alternator kVA.

For example, an unfiltered ballast used for LED lighting might have VTHD of 3.1% even if the ITHD is 167%. But a six-pulse UPS with ITHD 28.9% can have VTHD of 15.4% even if the load is 50% of the total alternator capacity.

- The harmonic effects are listed below in rising harmonic order.
- Communication errors and improper operation of sensitive electronics.
- Overheating in the generator, motors, transformers and electrically connected loads. Due to higher harmonics, the total power is equivalent to the fundamental (real power), while the higher-level distortion causes reduced power. The reverse current harmonics 5th, 7th, 11th are essentially the cause of overheating. Due to this distortion, higher current is drawn by the nonlinear load to compensate, causing overheating.
- Alternator life is shortened because of the thermal aging of the insulation.
- Breakers can observe odd tripping because of the large voltage harmonic distortions.
- Over frequency situations are observed in the voltage regulator (auxiliary excited alternator) presence of higher harmonics.

How to mitigate harmful effects from nonlinear loads?

Table 4.1 shows the generator state and the dependent mathematical quantity responsible for that state. The Xd, Xd', Xd", etc., are mathematical quantities for evaluating the performance of a synchronous machine. As the Xd" value decreases, the generator will be able to handle more harmonic distortion caused by a harmonic load. Many generator specifications in the industry specify 12% Xd" as a standard limit for harmonic distortion but harmonic distortion from the nonlinear load should also be considered before generator sizing.
Table 4.2 shows the typical example current distortion in a six-pulse UPS.

Time After Load Change	State	Mathematical Quantity
5 sec & above	Steady State	Synchronous Reactance (Xd)
3 cycles - 5 sec	Transient (motor-starting capability)	Transient Reactance (Xd')
Up to 3 cycles	Harmonic Distortion	Subtransient Reactance (Xd")

Table 4.1. (Note: 1 cycle is 0.0167 second)

ITHD	28.9%
3rd	0.0%
5th	20.0%
7th	14.0%
9th	0.0%
11th	9.0%
13th	8.0%
15th	0.0%
17th	6.0%
19th	5.0%
21st	0.0%
23rd	4.0%
25th	4.0%

Table 4.2

Understanding important factors in sizing case study 1: (subtransient reactance cost impetus)

UPS system 150 kVA (nonlinear load) + 150 kVA (linear load) = 300 kVA

If no VTHD (voltage distortion) limit is mentioned in the specification, you can follow the rule of thumb 10%. The ITHD (current distortion) from the nonlinear load for the UPS industry standard which is 30% (can be quite lower with new UPS)

System Xd" required = (VTHD %/ITHD %) x (pulses for the UPS/6) x 10

So for Case 1 the Xd"= 3.33%

For Class-F insulated 300 kVA 480 V alternator with 12% Xd", the Xd" with the UPS will be 150/300 x 12% = 6% which is way higher than 3.33%, so the alternator is unacceptable.

For a 600 kVA 480 V alternator with Class-F insulation and 10% Xd", the Xd" for the UPS system will be 150/600 x 12% = 3% which is within the acceptable limit of 3.33%, so the alternator is acceptable.

From the above case we can see that the alternator size and cost can go up immensely based on a nonlinear load requirement.

Understanding important factors in sizing case study 2: (nonlinear load tradeoffs)

The methods for connecting a motor across the generator used in the example below for comparison are I) Across the Line (no specific starter), II) VFD

Assumptions for this study:

• Voltage drop limit is 30%

• Frequency drop limit is 10%

• VTHD limit is 10%

• Genset load 25%-90%

• Voltage distortion is only associated with VFD application since distortion is zero for across the line application.

Comparison: VFD vs Across the Line start

• VFD provides better torque control and is therefore excellent for applications like hoists and elevators, providing smooth control.

• Modern software programming provides better functionality and remote control over the load.

• The inrush caused during across the line starting is avoided.

• Energy savings is another advantage for the VFD since a big motor running a pump in a HVAC system does not need to run at 100% capacity all the time, thus the VFD modifies the curve for the pumps. Based on the affinity laws of speed and pressure, the approximate power required to run a pump at 80% or rated speed is 51.2 % which is almost half of the total capacity. Based on available data for every 10% drop in speed, the energy savings is 27%.

		Alternator selected		
Total Mixed Load (kW)	Nonlinear Portion of Load (kW)	Across the Line (kW)	VFD (kW)	Voltage Distortion %
300	81.11	350	350	4.55
300	222.22	700	500	9.23
303.33	303.33	800	700	7.74

Table 4.3

This case study emphasizes the application details needed to judge what kind of emergency power source it would require. For example, if voltage drop is a main concern, a soft starter or VFD might be a good solution, but if harmonic distortion injected in the Electrical supply needs to be curtailed, then a direct start (across the line) would be a wise choice. Oversizing the alternator is another way to carry out harmonic mitigation, where the total starting KVA required for a nonlinear load is low. The major guideline in the industry is that total nonlinear voltage harmonic distortion should be less than 25%. The ratio of the nonlinear load to the full load drives the total harmonic distortion. The smaller this ratio, the better the THD of the generator set. If we look at *Table 4.3*, we can see how the voltage distortion goes up with the increase in nonlinear load. We need to keep in mind that for across the line application of the motor, there is no voltage distortion, so it is considered 0% (from the load). There is an advantage in starting the big 222.22 kW motor. VFD's are more efficient, so the genset size required (500 kw) goes down compared to the across the line start (700 kW).

How industry standards govern nonlinear loads?

IEEE 5-19-2014 provides guidelines on allowable limits for harmonic distortion. IEEE recommends point of common coupling (PCC) to measure the harmonic content. However, PCC is relative to utility and not emergency generator set, so the PCC would be anything that ties the generator to the loads, e.g., automatic transfer switch (ATS). Also, IEEE suggests that nonlinear load-based harmonics should be a shared responsibility between the genset manufacturer and the specifying engineer.

The bigger the alternator compared to the nonlinear load, the better its harmonic mitigating capability. Hence, a VFD-driven motor will have less voltage drop and less voltage distortion when connected to utility, compared to an emergency generator set. The harmonic content might be different based on the point of measurement.

Filters and better nonlinear loads

Different filters can be applied to the system to nullify the individual harmonics. The methods are as follows:

• Passive filter: This is basically a capacitor/ inductor circuit which filters specific harmonics but doesn't eliminate all of them. Also, make sure that the passive filter is not just capacitive, because that will produce leading power factor which can lead to self-excitation and loss of voltage control.

• Active filter: Active filtering is a more expensive way to filter the harmonics and add a lot of overhead cost to the project. Current draw is controlled to correct the power factor in which case the harmonic distortion is almost zero.

• Lower ITHD loads: Use higher pulse nonlinear loads such as 12-& 18-pulse VFDs instead of six-pulse VFD. The 12-& 18-pulse VFDs consists of multiple rectifiers which provide faster switching so the lower level harmonics get eliminated.

Conclusion

This paper recommends best practices for identifying and mitigating nonlinear loading effects seen in a modern power system. At the start of this paper, we talked about harmonic effects on emergency generator sizing. Case studies suggest that selection of a generator set to power the application depends upon the selection of the loads and application. The end result drives the specification, and sizing examples in this paper prove that pertinent information on application is essential before a specification is released.

Nonlinear loads have many risks and can create tricky situations such as identifying main concerns (voltage drops or distortion handling capacity, etc.), but they are essential to critical applications such as data centers, medical centers and wastewater treatment plants. Therefore, consulting Kohler during specifications stage is vital to select an effective and efficient emergency solution.

Not all the scenarios of specific load effects are discussed in this paper, so using the KOHLER-SDMO Sizing Program, which takes into account specific application details, is suggested.

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Figure 1.3 is Courtesy of lecture on Power Quality by M.Jagadeesan ASP/EEE KLN, College of Engineering Pottapalayam

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