

The Impact of Non-Linear Loads on D-G Power Sources

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As various distributed generation power sources become more popular in commercial and industrial environments, attention needs to be given to energy efficiency and the compatibility of the DG sources with power electronic loads. There are a couple of interesting factors involved in the marriage of DG power sources and power electronics loads. D-G power sources typically produce PWM output voltage rather than the pure sinusoidal voltage we are accustomed to receiving from our utilities. Additionally, due to the relatively high cost (dollars per KVA output) of D-G power sources, it is in the best interest of the user to maximize the total power factor of the load(s).

This paper discusses the impact of non-linear loads on D-G power sources and presents practical solutions to maximize the usable capacity of the D-G power source when feeding harmonic-producing and low power factor loads. It takes into consideration the high peak current and the rms current associated with non-linear loads and their impact on the sizing of D-G power sources. Harmonics, power factor and total power factor are discussed relative to their importance in the utilization of D-G power sources. Data and results of an actual case study will be presented.

Background

In addition to the consideration of distributed generation (D-G) power sources by utilities, there is growing interest among industrial, commercial and even residential users of electricity. The ability to supplement or replace utility power with an economical alternative is generating interest in new power sources such as fuel cells, micro-turbines, wind power, photovoltaic, geothermal

and wave/tidal power. Some of these have “green” aspects that make them even more attractive to some potential users.

Regardless of the energy conversion technology involved, it is quite typical for the D-G power source to include a DC-AC inverter at the output stage (final conversion stage). Generally speaking, this is a pulse width modulated (PWM) inverter, which creates a pseudo sine wave. As seen in Fig. 1, the output voltage waveform is similar to a sine wave, but is actually generated using numerous square wave pulses, which are caused by rapid switching output transistors.

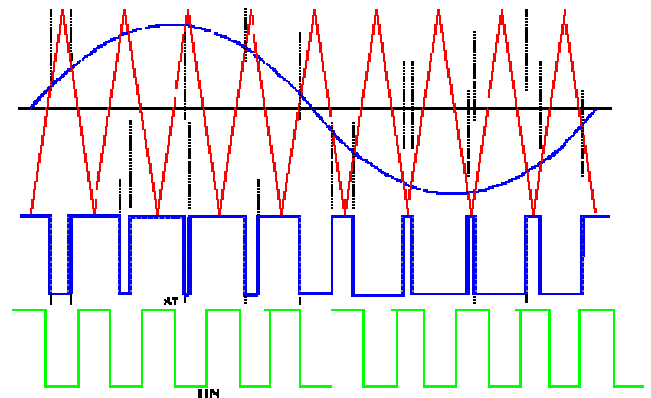


Fig. 1 Pseudo Sine-Wave Constructed from PWM Pulses (from G. Ledwich, 1998)

The modulation pulses can only be seen using a fast-response oscilloscope and therefore, to a typical slow-response oscilloscope, or power analyzer, the voltage will look sinusoidal. A fast responding scope will actually be able to decipher the square pulse construction of the voltage waveform. Regardless of which measurement device is used, the waveform will typically demonstrate ripple voltage superimposed onto the fundamental voltage

waveform. Of course, any ripple that is present on the waveform is actually distortion. This ripple typically occurs at approximate multiples of the switching frequency of the inverter. Analysis of the frequency spectrum typically shows that four sideband frequencies occur at +/- one and two times the fundamental frequency. A typical PWM inverter output frequency spectrum is illustrated in Fig. 2. Notice the sidebands of current at the various multiples of the switching frequency.

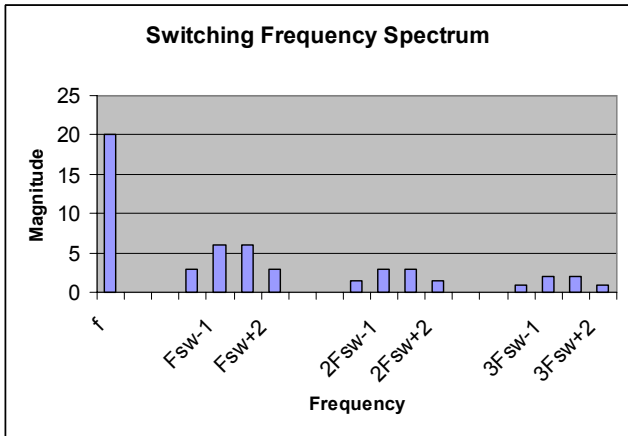


Fig. 2 Typical Frequency Spectrum for PWM Inverter

The typical method of evaluating voltage quality is to measure harmonic distortion using a harmonic analyzer. Most of the instruments available will measure voltage distortion up to about the 51st harmonic (3050 Hz for 60Hz systems and 2550 Hz for 50 Hz systems). Even careful analysis using good quality distortion analyzers will not detect the distortion associated with PWM voltage.

The trouble is that the inverter-switching frequency is often 3.6 kHz or higher. This means that the waveform distortion, caused by transistor switching, and occurring at the inverter switching frequency (and higher), is at frequencies above the 51st harmonic. Therefore, although it is present in the waveform, the distortion may go unrecognized by harmonic distortion measurement equipment.

When loads are supplied from distorted voltage sources, such as PWM voltage created by various D-G equipment and on-line uninterruptible power supplies, they will draw current at each of those frequencies. Some possible effects of PWM frequencies include

increased heating in motors and EMI/RFI interference.

Effects of PWM on Motors

It is a well-known fact that motors experience higher operating temperatures when fed from a distorted source, rather than from a pure sinusoidal voltage source. Nema-std-MG-1, part 30, shown in Fig. 3, provides a recommendation for de-rating motors that are fed from distorted voltage sources.

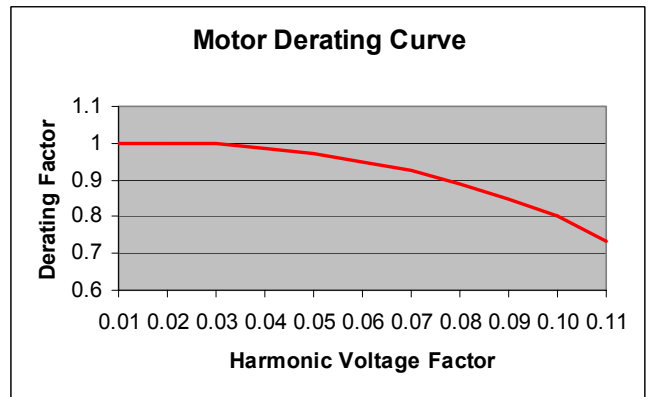


Fig. 3 Nema MG-1, part 30, Motor De-rating Curve

Motors fed from a PWM voltage source have demonstrated greater heating than those supplied from a sine wave power source. One motor user reported thermal performance as follows for a 200 HP TEFC (totally-enclosed, fan-cooled) motor:

Operating Conditions

<u>Voltage Source</u>	<u>Speed</u>	<u>Temperature</u>
Sine Wave	Full	61C
PWM	Full	67C
PWM	1/2	98C

Since this was a totally enclosed motor, operating at reduced speed also reduced the cooling effect of the internal fan. Even at full speed though, the motor operating temperature increased by 6 degrees. Considering that an increase of 10° C will decrease motor life by 50%, six degrees can have a major effect on motor life.

Characteristics of Non-Linear Loads

In determining the size of a D-G power source, one must consider not only the size of the loads to be connected, but also the type of loads. Linear loads utilize sine wave voltage and current, however, non-linear loads draw current in gulps or pulses as shown in Fig. 4.

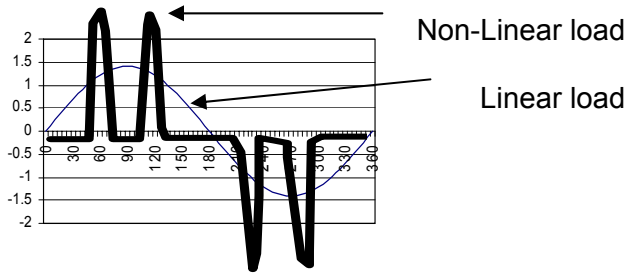


Fig. 4 Current Waveforms for Linear vs. Non-Linear Loads

For linear loads, and all sinusoidal waveforms, the crest factor of the current waveform (peak divided by RMS) is 1.414. For non-linear loads, however, the crest factor may be as high as 3.0. This means that the peak current demanded by non-linear loads is higher than for linear loads and can actually be two to three times as high.

D-G power sources must be selected and sized based on their ability to supply the peak current demanded by the connected loads. It becomes apparent then that for non-linear loads, the KVA rating of the power source will need to be greater than for the linear load, due to the high peak current. This can result in additional initial cost for a D-G source larger than demanded by the rms current, but suitable for the peak current, and will also decrease the operating efficiency of the D-G equipment. An alternative is to convert the non-linear load into a pseudo linear load by applying a harmonic filter to significant non-linear loads.

Consider an application involving a micro-turbine power source and a UPS. During battery charge mode, the voltage (Fig. 5) and current waveforms (Fig. 7) are distorted and one also notices that the harmonic spectrum (Fig. 6 and Fig. 8) contains virtually every harmonic, odd and even, up to the limit of the data collection equipment. This is much different than for the same load operating on utility power, where only the odd harmonics are experienced.

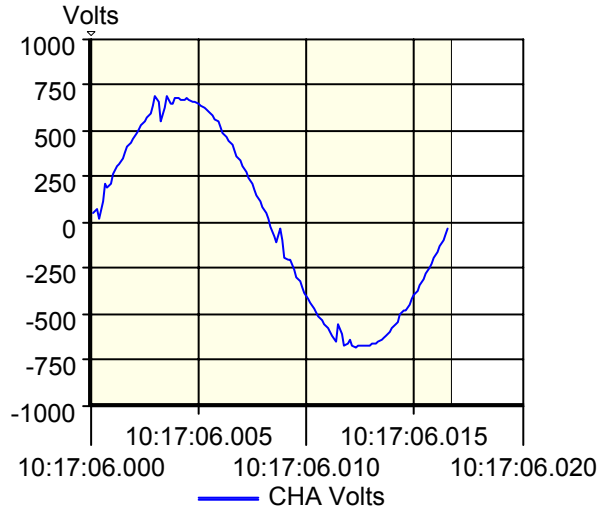


Fig. 5 UPS Input Voltage Waveform (microturbine source)

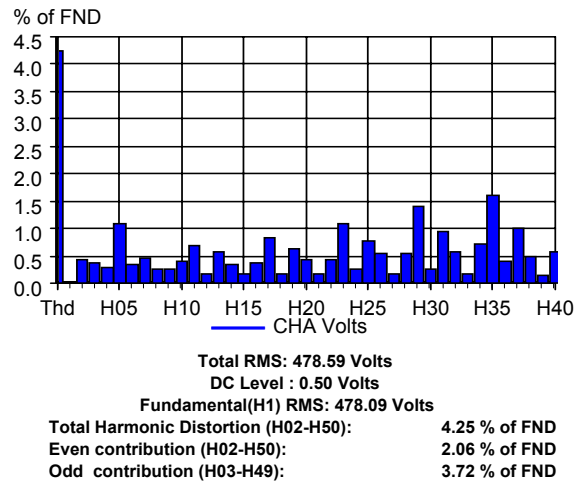


Fig. 6 Input Voltage Spectrum (UPS on microturbine source)

Not only does the peak current associated with nonlinear loads affect the size and efficiency of the D-G power source, the harmonics can also increase the rms current demand and reduce system efficiency. Figs. 7 and 8 illustrate the input current waveform and spectrum for a 30 KVA UPS operating on a microturbine power source.

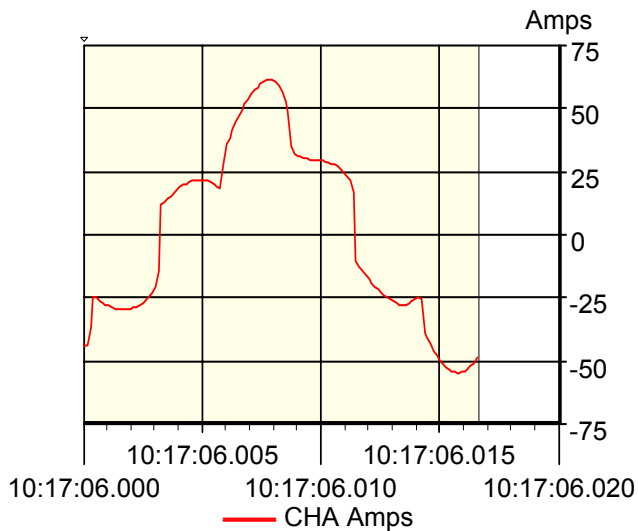


Fig. 7 Input Current (UPS on microturbine power source)

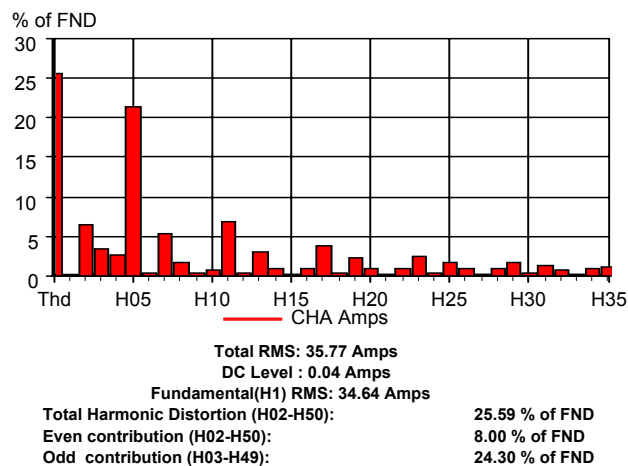


Fig. 8 Input Current Spectrum (UPS on microturbine)

Again, we see that the input current contains non-characteristic harmonics: odds, evens and even triplen harmonics.

Non-linear loads increase the burden on any power source whether it is utility power, standby generator or other D-G power source. The combined effects of high peak current along with the additional I^2R losses and skin effect losses contribute to this increased demand. D-G power sources must be sized to support the entire load for all operating conditions.

Low power factor loads increase the KVA requirement for the power sources. Improving the displacement power factor of the loads will help to reduce the size and initial cost of the D-G

equipment. Since a capacitor will appear as a short circuit to high frequency pulses produced by the inverter, capacitors should only be applied as detuned capacitors or tuned capacitors (harmonic filters).

Since D-G power sources have a relatively high dollar per KVA cost, it may be more advantageous to apply the appropriate measures to convert the loads to pseudo linear loads. This can be accomplished by using special filters. Depending on the circuit topology, different styles of filters may be required. In all cases, where the source voltage is derived from a PWM inverter, care must be taken in applying capacitors, which can look like a short circuit to the high frequency inverter output transistors. One must also consider the PWM heating effects on filter magnetic components.

PWM to Sine Wave Conversion Filters

In cases where the PWM voltage is unfiltered, it may be necessary to apply a sine wave filter that will convert the PWM pulsed square waveform to a sinusoidal waveform. This filter combines a series reactor and shunt capacitor in a low-pass configuration, as illustrated in Fig. 9. The fundamental frequency is able to pass easily to the load, while switching frequency components are attenuated. The use of a capacitor in this configuration increases the burden on the reactor and can cause severe heating of an unsuitable reactor. Care must be taken to use a reactor that is specially designed for the high frequency content of this application.

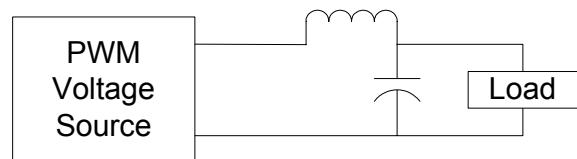


Fig. 9 PWM to Sinewave Filter

This filter technique can also help to attenuate the characteristic and non-characteristic harmonics associated with the PWM voltage. Once the PWM waveform is converted to a near sine wave, it is a much friendlier voltage source for all types of loads (both linear and non-linear). Nevertheless, nonlinear loads still need to be

addressed to minimize the peak current demand and distortion levels.

Harmonics

Since we have seen that the output current and voltage waveforms from the PWM power source may contain virtually all orders of harmonics, including both even and odd, it is best to avoid filters with the potential to create parallel resonance. Therefore, the easiest technique to apply may typically be a low pass filter. While there are several methods of constructing a low pass filter, the general concept is to allow fundamental frequency current to flow easily while all harmonic frequencies are attenuated.

The objective here is to reduce the demand on the D-G power source, enabling a smaller unit to be used, at lower initial cost and with higher efficiency. Solving the load harmonics and peak current associated with non-linear type loads, also enables an existing D-G power source to supply additional new loads. The harmonic filter can improve total power factor by increasing displacement power factor and be reducing harmonic distortion. While the PWM-to-sine-wave filter improves the voltage for the loads, the harmonic filter only improves harmonics between the power source and the filter.

You may notice a difference in the performance of harmonic mitigation techniques on D-G applications due to the presence of non-characteristic harmonics and PWM voltage. For the best overall results, the PWM-to-sine-wave filter can be used in conjunction with a low pass filter as shown in Fig. 10. This provides the best attenuation of all unwanted frequencies. Both the PWM-to-sine-wave conversion filter and the low-pass filter should be sized large enough to handle the total capacity of the D-G power source.

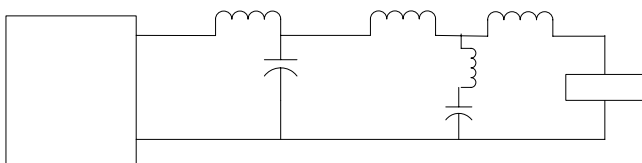


Fig. 10 Multi-Stage Filter for PWM Voltage Source and Non-Linear Loads

The total filter solution, involving multiple stages to accomplish both PWM filtering as well as complete wide band harmonic filtering, is appropriate when all loads are non-linear. When complete filtering is performed, it is possible to achieve sinusoidal voltage waveforms for the load, and nearly sinusoidal current demand on the D-G power source. Fig. 11 illustrates the voltage and current available when both the PWM to sinewave and low pass harmonic filters are used. This achieves the highest level of efficiency while minimizing the size of the D-G source.

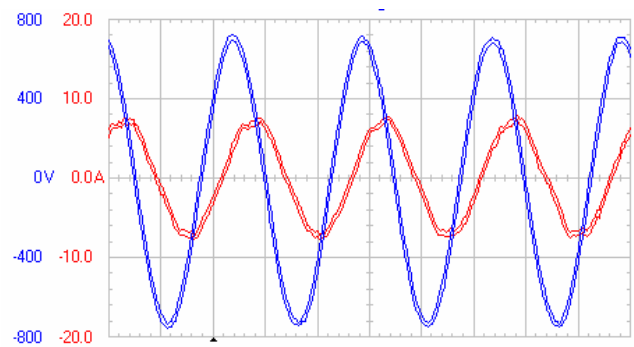


Fig. 11 Fully Filtered D-G Power Source Output

Since the low pass filter technology typically incorporates series reactance, there will be distorted voltage at the filter output terminals. This is also experienced any time a line reactor is installed in series with the input to an adjustable speed drive. Of course the non-linear load does not object to this distortion because it is immediately rectified to DC.

When the total load involves a mixture of linear and non-linear loads, then the PWM filter should be sized for the rated capacity of the inverter output. The individual non-linear loads should be filtered individually or as load groups. Any linear loads should be powered directly from the output of the sine wave filter, not from the low pass filter. For best performance, size the low pass filter as close as possible to the size of the non-linear load.

Conclusion

Attention should be given to the types of loads that are to be connected to commercial and industrial D-G power sources. Overall system

efficiency may be impacted by the load's reaction to a PWM voltage source, as well as the harmonics associated with any non-linear loads. The required size of the D-G power source (KVA) will be minimized when non-linear load peak current and harmonics are controlled through effective harmonic mitigation techniques. The initial cost of the D-G source as well as its operating costs and life expectancy can depend upon adequate filtering of the PWM voltage and load harmonics.

About the Authors

Cesar Chavez is Manager of Electrical Engineering (Low Voltage products) at Inelap, a leading North American manufacturer of electrical power quality systems and a Beckwith Electric Solutions Partner. Chavez earned his Master's degree in Electrical Engineering from the Instituto Politecnico Nacional of Mexico. Chavez's career has involved managerial responsibilities in MCC production, field engineering and design engineering. He has held positions responsible for the production, design, and commissioning of electrical power quality equipment. Chavez has extensive experience in the design, application and commissioning of reactive compensation and harmonic mitigation equipment. His expertise encompasses both passive and active solutions.

John Houdek is an electrical engineer (Milwaukee School of Engineering, MSOE) and has a MBA (Keller Graduate School of Management). Houdek has over twenty years experience in the application engineering of sine wave correction techniques for the power electronics industry. He has delivered seminars and technical papers in Europe, Asia, Mexico, Canada and the U.S.A. As an employee of Allied Industrial Marketing, a technical marketing support firm, he provides application engineering support for Beckwith Electric, Inelap's exclusive North American distribution partner. Houdek also teaches a course in electrical power quality at MSOE.

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