Technical Paper

Harmonic Distortion in Data Centers

Written By:
Ian Wallace

Summary

Power quality and power reliability are critical to data center operation. As strides have been made to improve energy efficiency and Power Utilization Effectiveness (PUE) it is important to ensure harmonics and power quality are not compromised as a result. Harmonics are produced by non-linear loads such as IT equipment power supply units and variable frequency drives used to improve efficiency of cooling and air handling systems. While harmonics can negatively impact power reliability and cooling costs, solutions such as active harmonic filters and passive harmonic filters exist to maintain a low and safe level of harmonics to ensure reliable and efficient power systems in data centers.

Table of Contents

What are Harmonics?

Three phase ac voltages are supplied on the electrical power system as a smooth single frequency sinewave. Electrical equipment such as cables and transformers and end user loads are designed primarily to operate on the sinewave voltages and currents. In North America the voltage is supplied as 60Hz sinewave, which repeats at 60 times a second. Historically most loads, called linear loads, such as electric motors and incandescent light bulbs draw current at the same single frequency as the applied voltage.

Harmonics present in the voltage and current are considered to be undesirable distortion which can adversely affect power system infrastructure and loads – causing heat, lifetime degradation and equipment malfunction. Such harmonic components are integer multiples of the fundamental frequency. For example harmonics of 60Hz are 120Hz, 180Hz and so on.

An example of pure sinewave current is shown in Figure 1a and harmonic rich current is shown in Figure 1b. The current in Figure 1b has a total harmonic distortion of 40%, which is the ratio of the total harmonic current to the fundamental current. Additionally, most of the harmonic current is at 300Hz and 420 Hz respectively.

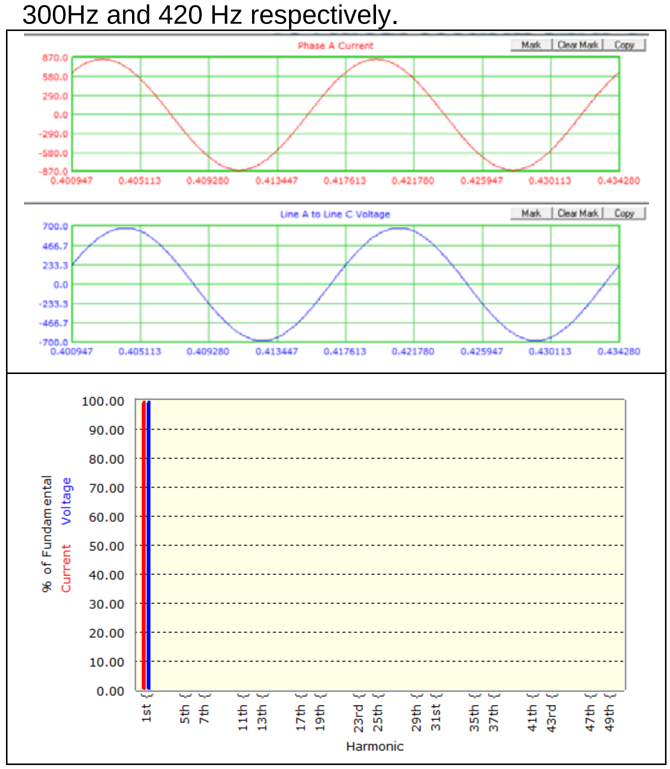


Figure 1a: Current waveform with no harmonics

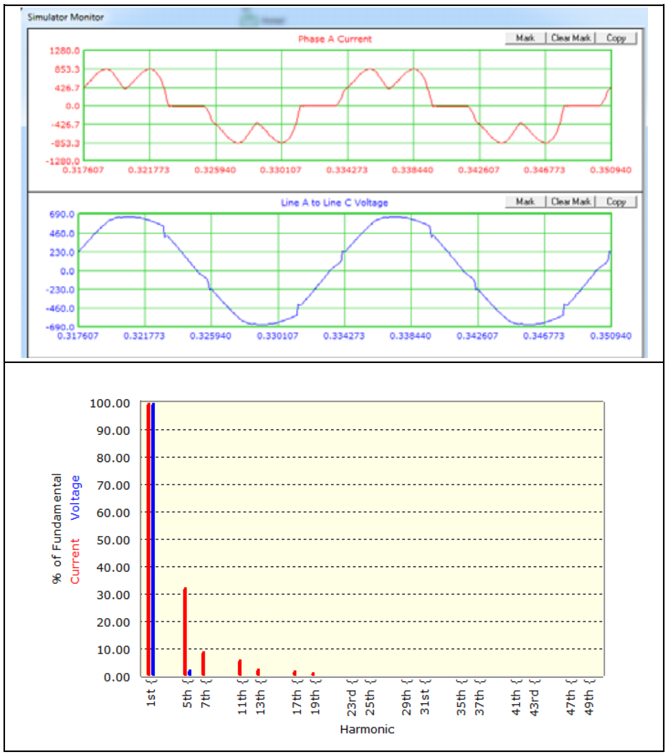


Figure 1b: Current waveform with 40% harmonics

Effects of Harmonics

Typically, non-linear loads draw harmonic currents to operate correctly, causing current distortion. Voltage distortion is then produced as a result of the harmonic current flowing through inductive impedance in upstream transformers, generators and cables. Harmonics can negatively impact equipment reliability, uptime and energy costs in data centers. While small amounts of voltage or current distortion may be tolerated by power distribution equipment and loads, it is critical to understand the impacts of higher harmonic levels in order to specify acceptable levels.

- Power reliability due to distortion: Harmonic currents can cause false circuit breaker tripping due to thermal or electronic trips. Harmonic voltages can cause motor damage, equipment malfunctions and synchronization errors of UPSs and generators during transfers. Generators can be susceptible to high harmonics due to overheating and voltage regulator malfunction.
- Higher energy costs due to increased heating: High frequency harmonic currents drive up eddy current and proximity losses in distribution transformers and cables. Additionally, high voltage distortion drives up transformer core losses. Higher losses show up as higher energy and cooling costs and increased PUE.
  PUE is Power Usage Effectively = Total facility Energy / IT equipment energy
- Reduced Equipment Lifetime due to thermal stress: Higher losses lead to higher operational temperatures which are known to reduce the lifetime of transformers and generators.
- Higher Equipment Costs due to oversizing: A commonly used approach that addresses the negative effects of harmonics is oversizing which increases the initial acquisition cost. Oversized equipment also operates at partial load leading to lower efficiencies and increased operating costs.

Causes of Harmonics in Data Centers

The most common and prolific causes of harmonic currents in data centers are non-linear loads such as variable speed motor drives and the power supply units in IT equipment. These loads account for the vast majority of power usage in data centers. Other loads that generate smaller amounts of harmonics are transformers, generators and line connected pump or fan motors and lighting.

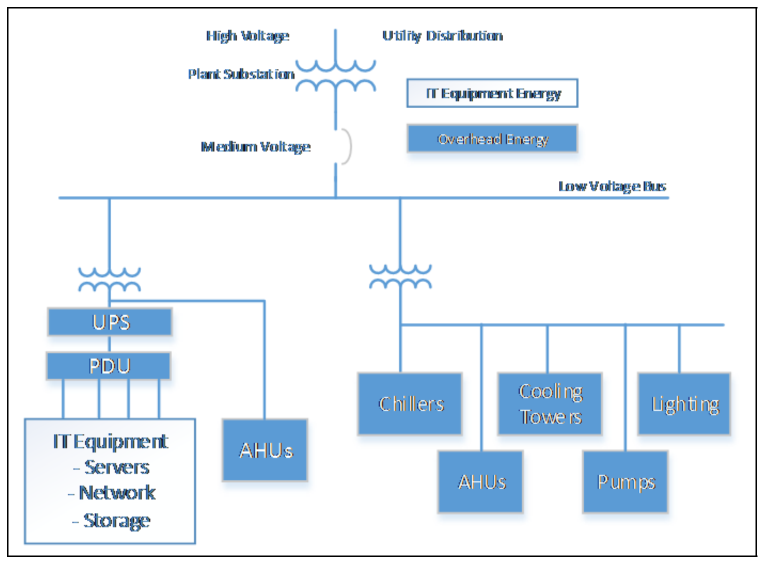


Figure 2: Harmonic generating equipment in a data center

Variable Speed Motor Drives

Variable speed motor drives are used throughout the cooling system including chillers, CRAC units, air handlers, water pumps and cooling towers. These drives deliver energy savings through variable speed control of air and fluid flow and help achieve a lower PUE. However, the front end rectifiers in the motor drives are usually six pulse diode rectifiers which typically draw 30-50% total harmonic distortion.
For example a typical 500HP VFD on a 480V 60 Hz supply draws 544 Amps at 35% current THD. If the drive is fed by a 2000 kVA transformer with 5.75% impedance it could produce up to 4% voltage distortion across the transformer. The resulting VFD input current and 480V power system voltage waveforms are shown in Figure 3.

	Units	Standalone VFD Performance Data
VFD Power Rating	**HP**	500
Input Current	**Amps**	544
Input Current Distortion	**% iTHD**	35.2%
Input Voltage Distortion	**% vTHD**	4.03%

Table 1: Summary of standalone 500HP VFD performance data

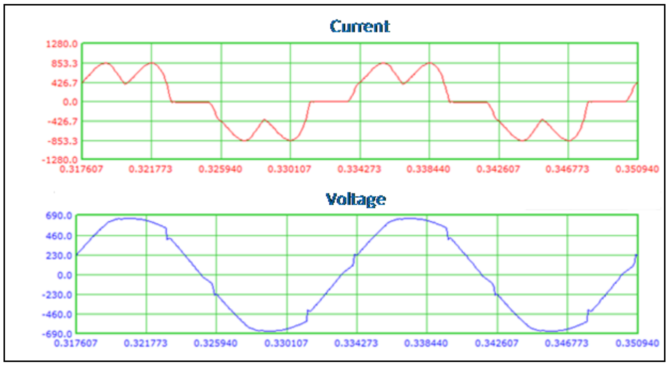


Figure 3: VFD Input current (35% iTHD) and voltage (4% vTHD) time domain waveforms for a standalone VFD fed by a 2000kVA Transformer

IT Equipment Power Supply Units (PSUs)

All AC fed IT equipment contain power supply units that draw some harmonic currents from the AC supply. The PSUs contain input rectifiers and/or switch mode power supplies that convert the relatively high ac input voltage to lower dc levels useable by the direct IT equipment loads.
Typically the PSUs have active power factor correction front end rectifiers which draw near-sinusoidal current. Depending on the technology and power supply design, the input current harmonic distortion can be 12% [1]. This can be due to distortion in the supply voltage or due to discontinuous operation at light load, a known phenomenon in switch mode power supplies [2].
Table 2 shows how power supply units have changed over recent years; energy efficiency has improved, but displacement power factor and harmonic current distortion have varied. One drawback of the PSU low harmonic input is a leading power factor due to filter capacitors on the PSU input. Leading power factor must be limited to ensure generator compatibility.

	Typical 2005	Typical 2010	Typical 2013
Power Factor	0.95 leading	0.90 leading	0.98 leading
Harmonic Current Distortion (% THD)	7%	20%	12%
Efficiency	70%	85%	95%

Table 2: Typical PSU Performance at light load (25% - 50% load) [1]

Solutions for Data Center Harmonic Issues:

A variety of solutions exist for reducing or eliminating harmonic currents and the resulting harmonic voltages. These include active filters, passive filters and harmonic mitigating transformers, among others. Active filters are typically applied to the low voltage bus where they can both filter all of the harmonic generating loads (IT equipment and VFDs) as well as compensate for any leading power factor from IT equipment. Passive filters are effective as one-to-one filters for each VFD load in the CRAC units and air handlers. Taking this approach enables the highest THD loads to be filtered. However harmonics and the leading power factor from the IT equipment cannot be compensated, potentially making the power system incompatible with back-up generators. Harmonic mitigating transformers may be used to cancel the 5th and 7th harmonics in VFD loads from reaching the source but require balancing of the loads on their secondary windings to be effective.
A comparison of the performance of a 1000kVA data center's electrical power system without any filters, with an active filter and with passive filters on VFD loads is made in the following section to demonstrate the effectiveness of these different filtering technologies.

Harmonic Mitigation with Active Filters

The active filter works by measuring the power system current and injecting the necessary harmonic and reactive current to cancel the load harmonics. As the filter is an active device it can quickly respond to changes in loading and power system voltage, frequency, unbalance and background voltage distortion conditions. This concept of applying an active filter is illustrated in Figure 4. Here the active filter is applied to the low voltage bus and filters the harmonics from all the IT and cooling loads and also corrects for power factor.

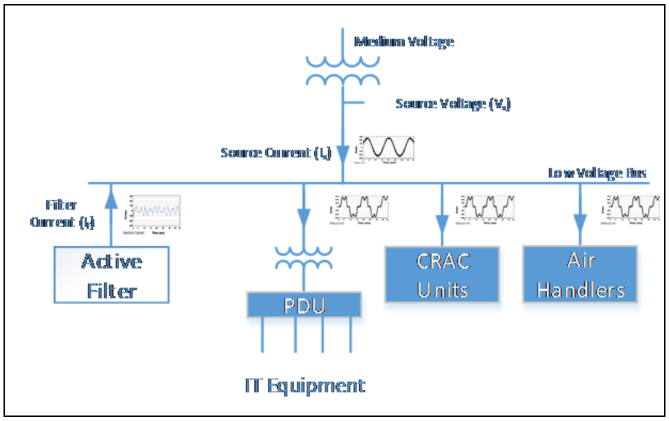
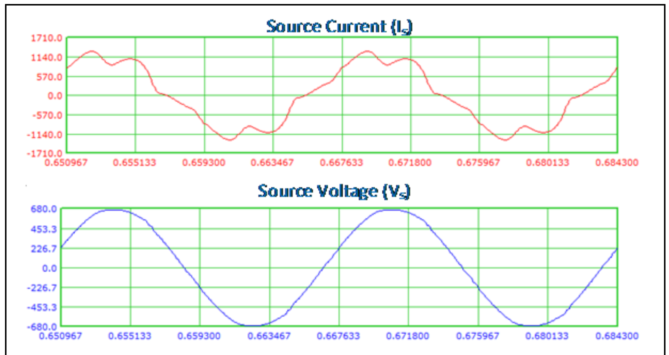


Figure 4: Data Center Power System Example #1 with an Active Filter applied to filter the low voltage bus and harmonics from IT equipment and VFD loads.

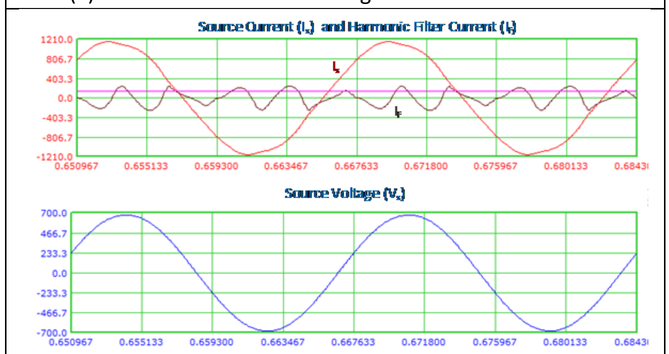
The benefits of applying active filters to the low voltage bus are as follows:

- Modular and flexible filtering – they can be deployed at the power service entrance, individual branch circuits, or modular data center pods.
- Parallel filters for redundancy or capacity – depending on the critical power needs, the filters can be paralleled to ensure redundancy requirements are met, or paralleled to meet the full harmonic current demand.
- Can achieve harmonic reduction to <5% iTHD
- Provides Power Factor Correction to correct for leading VARS from PSU SMPSs. Ensures generator compatibility.
- Because it is installed as a separate element on the power system, the active filter is suitable for green field or retrofit applications.
- Simple and straight forward filter sizing based on harmonic amp correction needed.
- Ability to operate with severe background voltage distortion (8%).

To demonstrate the straight forward filter sizing and performance in a data center application consider the system Example #1 in Figure 4. Here, a 2000kVA transformer feeds a combined IT equipment and mechanical systems loading of 821 Amps at 17% current THD. The VFD loads operate at 40% current THD and the IT equipment operate at 8% current THD with a slightly leading power factor. Time domain waveform is shown in Figure 5a showing the current distortion and resulting voltage distortion on the low voltage bus. Using the Harmonic Guard Solution Center sizing tool, found online at www.transcoil.com, and entering a target of reducing the current distortion below 5%, we find that a 150 Amp active filter frame is needed to meet stated power quality requirements. Figure 5b shows the filtered current and voltage after the active filter is installed.



(a) Source Current and voltage without active filter



(b) Source current, filter current and voltage with 100Amp active filter

Figure 5: Power System Example #1 - Current waveform with and without active filter

The effectiveness of the active filter can be seen from the results shown in Table 3. The active filter reduced the total RMS currents in the source from 17% to 2.3% and as a result, the voltage distortion was reduced to under 0.5%.

	Units	Baseline	With 150 Amp Active Filter
IT and VFD Load Current	**Amps**	833	822
IT and VFD 60Hz Current	**Amps**	821	821
IT and VFD Harmonic Current	**Amps**	140	19
Input Current Distortion	**% iTHD**	17%	2.3%
Input Voltage Distortion	**% vTHD**	1.5%	0.2%
On a 480V, 60Hz power system with 2000kVA transformer with 5.75% impedance			

Table 3: Summary of power system Example #1 - without and with a 150 Amp Active Filter

Harmonic Mitigation with Passive Filters

Passive harmonic filters are comprised of inductive and capacitive filter networks in series with the input of a standard VFD to filter the input harmonic current. Today's passive filter technology can achieve 5% current THD and is an integral part of a system designed to meet IEEE-519 harmonic standards. To demonstrate the filter performance in a data center application consider Example #2 in Figure 6. Here, a 2000kVA transformer feeds a combined IT equipment and mechanical systems loading of 821 Amps at 17% current THD. The VFD loads operate at 40% input current THD and the IT equipment loads operate at 8% current THD with a leading power factor. The time domain waveform showing the current distortion and resulting voltage distortion on the low voltage bus is shown in Figure 7a.

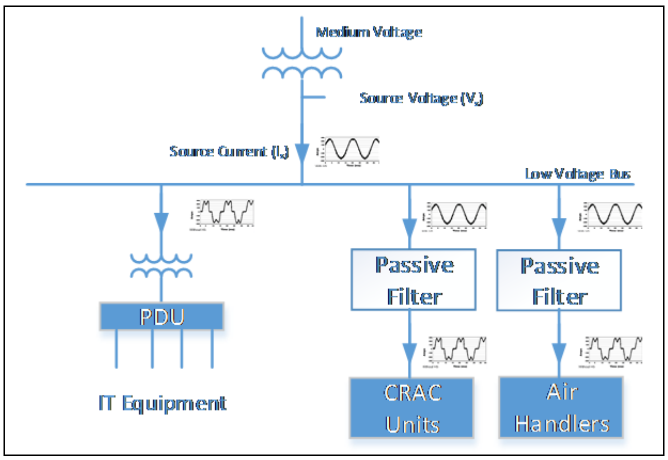
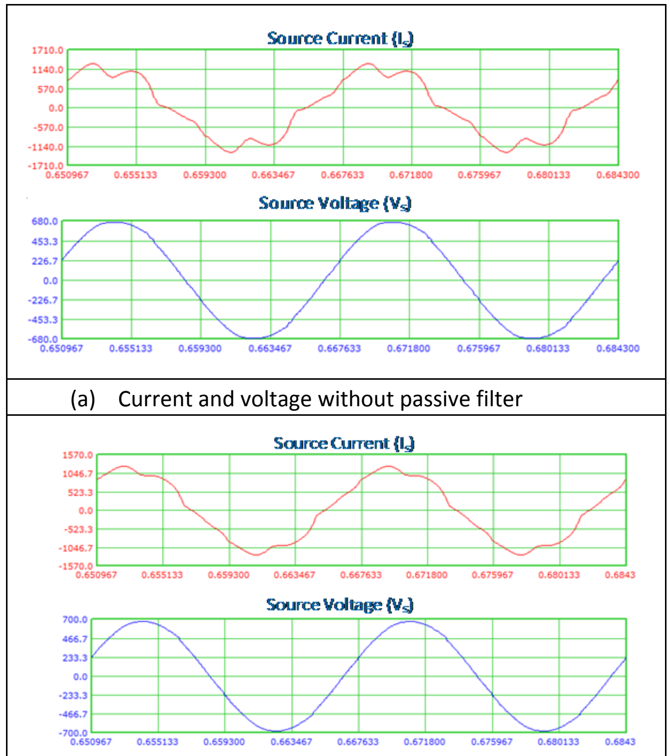


Figure 6: Data Center Power System Example #2 - Passive filters on VFD loads in CRAC units and air handlers

Passive filters can be installed on the CRAC and air handler VFDs resulting in lower distortion in the source current. Every VFD, whether primary or redundant, has to be supplied with a passive filter. However, since the IT equipment is unfiltered the current THD is only reduced to 8% and remains at 0.98 leading power factor. This could cause a generator compatibility issue. Time domain waveform of the source current with the VFD applied passive filters is shown in Figure 7b.



(a) Current and voltage without passive filter

(b) current and voltage with passive filter

Figure 7: Power System Example #2 - Current waveform with and without passive filters on VFDs

	Units	Baseline	With Passive Filter on VFDs
IT and VFD Load Current	**Amps**	833	824
IT and VFD 60Hz Current	**Amps**	821	821
IT and VFD Harmonic Current	**Amps**	140	68
Input Current Distortion	**% iTHD**	17%	8.3%
Input Voltage Distortion	**% vTHD**	1.5%	0.9%
On a 480V, 60Hz power system with 2000kVA transformer with 5.75% impedance			

Table 4: Summary of power system Example #2 - performance of a 1000kVA data center with and without passive filters on the VFD loads.

Conclusion

Control of harmonics distortion is critical to maintaining reliability in data centers. Variable frequency drives and front end power supply units in IT equipment draw harmonic currents, which must be filtered to maintain harmonic current distortion and voltage distortion to safe levels.

An active filter is an effective way to eliminate both harmonic and reactive currents from the AC source, and reduce the harmonic voltage in the plant. Active filters can be applied to the entire plant power system, specific branch circuits or individual modular data centers. Passive filters and harmonic mitigating transformers are other options that can be effective but attention should be paid to load balancing and power factor.

References

[1] The Green Grid White Paper publication, "Data Center Power System Harmonics: An Overview of Effects on Data Center Efficiency and Reliability", www.thegreengrid.org.

[2] Sunit Kumar Saxena, Deepak Bhimrao Mahajan, "A Novel Hybrid Low Cost Controller for Maintaining Low Input Current Harmonic on a Wide Range of Load Conditions for Power Factor Corrected Boost AC to DC Converter, 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), March 17-21 2013, pp. 1508-1513

transfab TMS

175 rue Jules-Léger
Boucherville, QC J4B 7K8
T: (866) 540-0412

transfabtms.com