DATA CENTER POWER SYSTEM HARMONICS: AN OVERVIEW OF EFFECTS ON DATA CENTER EFFICIENCY AND RELIABILITY

EDITORS:

Mietek Glinkowski, ABB Inc.

Lynn Simmons, Dell

David Loucks, Eaton

Dusty Becker, Emerson Network Power

Ian Bitterlin, Emerson Network Power

Bill Campbell, Emerson Network Power

Harry Handlin, GE Energy Management

Pamela Lembke, IBM

Tom Earp, Individual Member

Darrin LeRoy, Individual Member

Andrew Lynch, Individual Member

Stephen McCluer, Schneider Electric

Jim Spitaels, Schneider Electric

Executive Summary

People familiar with the fundamental concerns of electricity in data centers may specifically be aware of the power quality issues associated with alternating current (AC) power line harmonics. Harmonic currents can distort the voltage that is being consumed by the information technology (IT) equipment, thereby disrupting the operation of the equipment. Ironically, these harmonic currents are usually caused by the power supply units (PSUs) within the IT equipment itself, but there can be other causes as well, such as variable frequency drives in cooling and ventilation equipment. Some devices meant to improve power quality, such as uninterruptible power supply (UPS) systems, can actually create harmonic currents that could interfere with equipment further upstream. Such power quality issues have been well documented and are generally understood within the technical community.

Less appreciated is the effect of harmonic currents on the overall efficiency of a data center. Harmonic currents are wasted energy that appears as heat. Not only can the heat have a detrimental effect on the performance and life expectancy of various pieces of equipment, but the harmonic currents also reduce the overall efficiency of the entire data center by increasing the amount of heat that must be removed.

It is possible to mitigate the effects of harmonic currents to some degree. Devices such as isolation transformers can trap harmonic currents and prevent their detrimental effects. But these devices themselves consume energy. Efforts to improve data center operating efficiency by removing transformers might actually be counterproductive if there are significant harmonic currents being generated by the IT equipment. A better solution is to identify the equipment that could be potential sources of harmonic currents (generally referred to as “nonlinear loads”) before such devices are put into service in a data center. This may not always be practical or even possible. An assessment may be necessary to determine the level of harmonic currents that can be tolerated within a data center, in terms of both power quality and efficiency loss, before deciding to add or remove mitigation equipment.

Instrumentation to locate harmonic currents can be fixed or portable. Instruments commonly found in data centers that measure volts and amperes, or calculate watts and watt-hours, can give false information if they are not designed for nonlinear loads. Therefore, consideration must be given to the accuracy of power and energy metering devices before calculating the power usage effectiveness (PUE™) of a data center.

Table of Contents

I. Introduction

Data center power system harmonic currents and voltages contribute to issues that often arise in the data center electrical infrastructure, such as losses to the efficiency of a system, power component overheating, negative impacts on neutral conductors (where present), and safety concerns. The causes and effects of these issues are often complex. Developed by The Green Grid Association—a non-profit, open industry consortium working to improve the resource efficiency of information technology (IT) and data centers worldwide—this white paper presents a brief overview of harmonics, including what they are, the difference between harmonic voltage and current, what causes harmonics, and what problems harmonics can cause. The paper then discusses what levels of harmonics can be tolerated and under what conditions, along with some suggested diagnostic and mitigation methods, as well as how harmonic voltages and currents can affect data center power distribution system efficiency.

This paper does not try to address the broader utility-level or campus-level causes and effects of harmonics. Instead it looks primarily at the impact of harmonics within an uninterruptible power supply (UPS) and distribution to equipment further downstream in the data center, including transformers and IT equipment PSUs.

II. Definition of Harmonics

A harmonic is a higher-order integer multiple frequency current and/or voltage distortion of fundamental waveform. If the fundamental frequency is 60 hertz (Hz), which is typical in the United States, then 120 Hz, 180 Hz, 240 Hz, and 300 Hz are the 2nd-, 3rd-, 4th-, and 5th-order harmonics, respectively. Figure 1 shows an example of a fundamental waveform and some lower-order frequencies (i.e., those that are typically of the 15th order or less). Adding those frequencies results in the distorted waveform called out in Figure 1. Even-order harmonics, such as 2nd, 4th, and so on, are less prevalent, while odd-order harmonics (3rd, 5th, etc.) more typically exist in a system.[1] Harmonics are typically integral multiples of the fundamental, but they can also be non-integral (fractional) multiples, called interharmonics.[2]

---

[1] This is due to the phase angle and the nature of wave propagation. Even-order harmonics are effectively DC components offset to the waveform.

[2] See IEC 61000-2-1 for more information or read http://www.copperinfo.co.uk/power-quality/downloads/pqug/311-interharmonics.pdf.

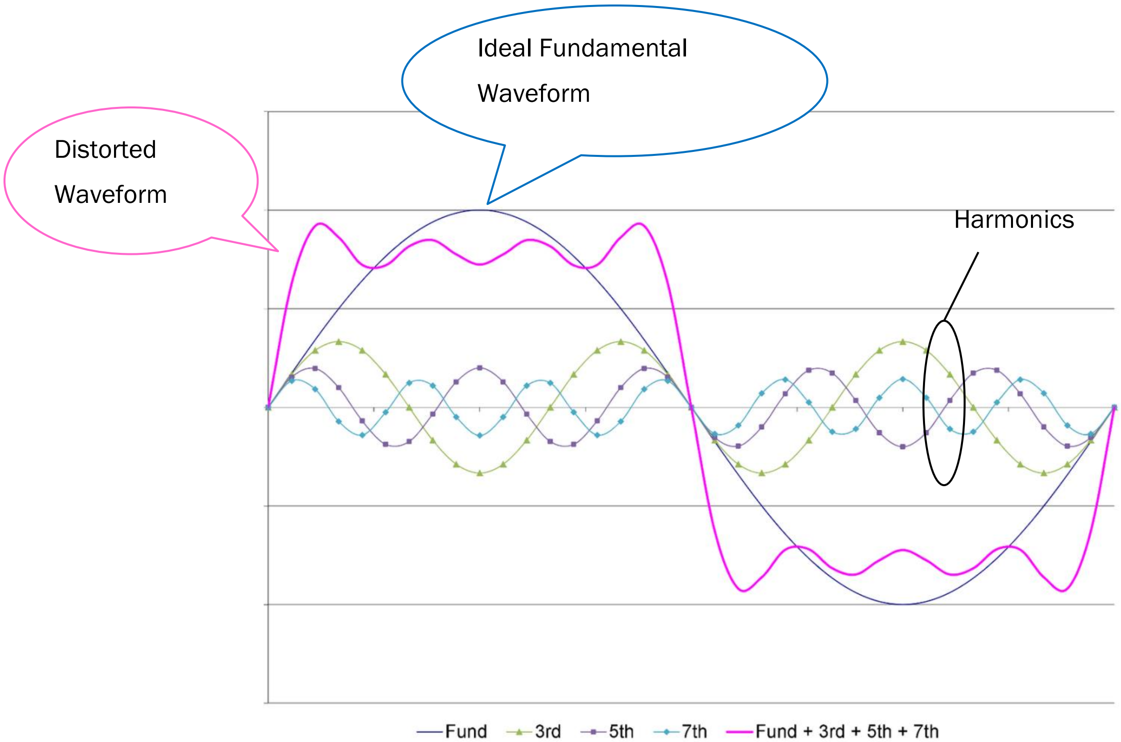

Figure 1. Example waveform with distortion

Harmonics may exist both in voltage and current. For any electrical system to be operated with good efficiency and performance, the goal is to have voltage and current waveforms primarily consist of the fundamental frequency, with minimal higher-order frequencies (i.e., frequencies that are higher than the fundamental frequency). Low-order harmonics (those that are typically of the 15th order or less) also create higher-order harmonics (those that are typically of the 25th order or higher) due to ferroelectromagnetic resonance in the power system. These higher-order harmonics may also be referred to as high-frequency noise.

The International Electrotechnical Commission (IEC) standard IEC 61000-3-2 defines the upper limit of harmonics as the 40th harmonic of the power frequency (2.4 kilohertz [kHz] for a 60 Hz distribution system), which is the primary focus of this white paper.[3] It should be noted that there is emerging evidence that higher-frequency harmonics cause more issues than previously assumed. (For more on the effects of higher frequencies on data centers, see *Appendix A. Detailed Harmonics Overview*.)

---

[3] Frequencies above the 40th harmonic are tiny in proportion and slight in effect in data centers because of the relatively long cables involved, whose self-capacitance often acts as a good filter.

III. Causes of Harmonics

HARMONICS CAUSED BY DATA CENTER LOADS

To fully understand harmonics and their causes, the load type on the data center's electrical infrastructure needs to be understood. A linear load draws current that is instantaneously proportional to the voltage, such as in Figure 2 and Figure 3. One example of a linear load is a resistive load, such as an incandescent light bulb. A nonlinear load either draws a current waveform that is not instantaneously proportional to the voltage or is a load that causes current to distort its sinusoidal shape. The current waveform also leads or lags voltage or phase. Example components that cause nonlinear load currents include rectifiers, switch mode power supplies (SMPSs), UPSs, electronic ballasts, and variable-speed drives. Many of these components are frequently found in IT power supplies. Nonlinear loads use a switching mechanism, which generates harmonics on the current and hence the voltage. (See Figure 4.)

Examples of nonlinear load sources that can inject harmonics back into a system include variable frequency drives (VFDs), pumps (with and without motor drives), transformers, lighting (electronic and magnetic ballasts), DC-to-AC converters, and rectifiers. Even DC-to-DC converters can inject harmonics into a DC system, more commonly known as ripple and/or noise. Older, line-switched, three-phase rectifier loads (e.g., motor drives) can create higher harmonics than typical IT supplies. The behavior of current IT PSUs at light loads depends on how they are optimized around efficiency. At light loads, some more efficient supplies generate higher amounts of harmonics, although this trend is changing as the focus on low power behavior is sharpened.

Figure 1 shows a graphical representation of harmonics generated on a fundamental waveform by a nonlinear load. The pink waveform indicates the nonlinear waveform resulting from the impact of 3rd- and 5th-order harmonics on the fundamental waveform. This is a typical current waveform for a nonlinear load such as that from a VFD. For more detail on this topic and how harmonics are generated, see *Appendix A. Detailed Harmonics Overview*.)

Harmonics involve two undesirable and directly interrelated conditions: current distortion and voltage distortion. More information about current distortion, voltage distortion, total harmonic distortion, and total current demand distortion can be found in *Appendix A. Detailed Harmonics Overview*.)

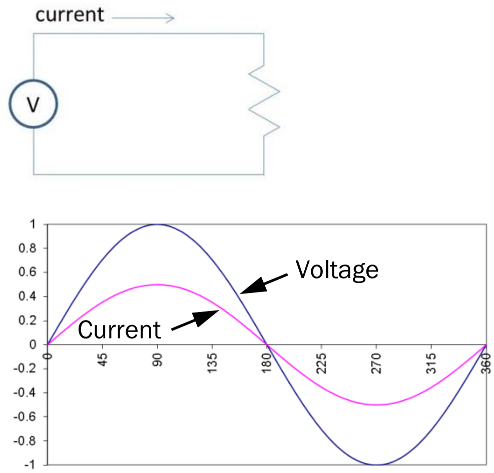

Figure 2. Linear time-aligned (unity or 100% power factor) voltage and current waveforms

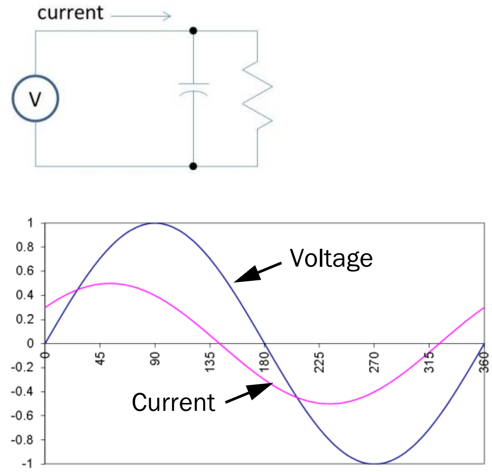

Figure 3. Linear shifted alignment (at 80% leading power factor) between voltage and current

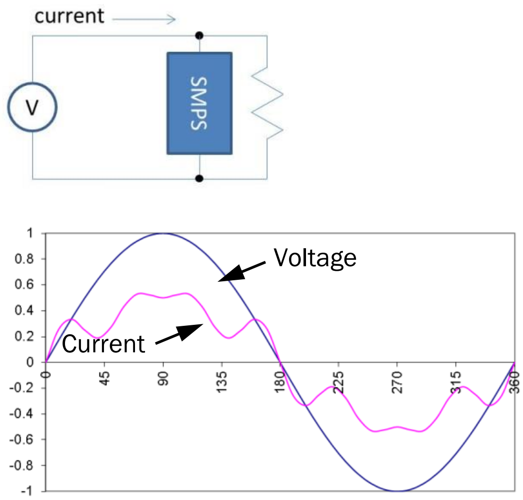

Figure 4. Nonlinear distorted current waveform contains harmonics

the green grid
get connected to efficient IT

Magnetic Devices

Devices that contain magnetic structures, such as transformers, inductors, motors, and ballasts, can exacerbate a harmonic problem, depending upon the impedance of the magnetic structure. When these magnetic structures are operated at or above their rated capacity, problems from harmonic currents can result in overheating[4] and/or a potential fire hazard.

To fix the problem, magnetic devices are typically oversized to handle the additional currents. This can decrease the efficiency of a system, because conventional wisdom says to maximize efficiency and minimize capital cost by operating devices near their rated capacities. The result is a tradeoff: for example, operating a transformer or an inverter duty motor near its rated kilovolt-ampere (kVA) capacity may lower the capital cost, but full-load operation may not be best when load-generated harmonic currents are present. Using transformers that are designed specifically to handle harmonic loads can assist in alleviating the problem. (See the *Mitigating Harmonics* section for more information.) Harmonics also cause increases in a transformer's no-load losses.

IT Power Supply Units

In a category all their own, IT PSUs, both individually and in combination, have been and continue to be a known source of harmonic currents. PSUs can interact as a group, creating high harmonic currents that cause instability at the system level. The problem is primarily found in single-phase IT equipment that incorporates switch mode power supplies (SMPSs), resulting in an abundance of triplen harmonics (the 3rd and odd multiples of the 3rd). Whereas other harmonic orders have a tendency to cancel each other out, triplen harmonics are additive, thereby creating equipment heating and high levels of voltage distortion and current on neutral conductors. In the early 1990s,triplen harmonic currents that summed in the neutral were a big problem.[5] Underrated neutral conductors provide a high impedance path that produces a higher voltage distortion. These underrated neutrals would overheat and cause fires. The solution at the time was to double the rated neutral conductor cross-sectional area or use multiple conductors to limit the individual cross-sectional area. However, modern PSUs, now connected phase-to-phase rather than phase-to-neutral, have made triplen harmonics less of a problem, as discussed below. In addition, three-phase power supplies inherently do not produce triplen harmonics.[6]

---

[4] Overheating may come from the skin effect created by nonlinear loads and the resultant harmonic components. The skin effect is a magnetic property that confines current to an increasingly thin layer in a conductor as frequency, conductivity, or permeability increase. (See *Appendix C. Skin Effect, Proximity Effect, and Eddy Currents* for more.)

[5] Arthur, Robert; & Shanahan, R.A., "Neutral Currents in Three Phase Wye Systems", Square D Company, 1996. http://static.schneider-electric.us/docs/electrical%20distribution/low%20voltage%20transformers/harmonic%20mitigating/0104ed9501r896.pdf.

[6] In three-phase power supplies, 5th, 7th and 11th harmonics are present, but they do not have an effect on the neutral.

Most modern IT PSUs contain active power factor correction (PFC). This added active variable impedance can have a mitigating effect on harmonic currents.[7] However, it should be noted that PFC power supplies at partial load create a higher percentage of harmonics than PFC power supplies at full load. Therefore, simply because a power supply has PFC built in does not mean it will have a good harmonics profile. The power factor measurement is at the fundamental frequency, so it is possible to have a power factor of 1.0 (termed "unity power factor") while still having a poor harmonics profile with high 3rd- or 5th-order and higher current harmonics in the current waveform. Power factor–corrected circuits use input voltage waveforms to shape the current. If the voltage waveform is ideal, then the current waveform is also good; but, if the voltage waveform is not ideal, the current waveform will not be ideal either. When the source or line impedance is high, the IT PSU tries to correct the waveform that may have been distorted by external causes.

PSUs from two vendors with similar input and output specifications may behave very differently in the same facility due to their respective control loop characteristics. In a data center that contains thousands of IT power supplies, each experiencing different system-loading conditions, their input currents sum together. The total accumulation at the point of common coupling (e.g., at a circuit breaker panelboard) may show many random-order harmonics even though any one specific power supply may not exhibit any of them.

Power supply unit design has changed throughout the years, as evidenced by the information in Table 1, which comes from 80Plus.[8] Efficiency has increased over the past eight years; however, power factor and current harmonics (total current harmonic distortion [THDi]) have varied.

Table 1. Snapshots of PSU efficiency and total current harmonic distortion from 2005, 2010, and 2013

At Light (20-25%) Load	Typical 2005 PSU	Typical 2010 PSU	Typical New PSU
Power Factor	0.95 leading	0.9 leading	0.98 leading
THDi	7%	20%	12%
Efficiency	70%	85%	95%

[7] Many data centers today have overall power factors of around 0.98, compared with a power factor of around 0.80 only a decade or so ago. This is not necessarily true in office environments where most electronic equipment, such as personal computers, still uses switch mode power supplies without PFC. The relevant standard is IEC 61000-3 for equipment drawing less than 16 amperes at 230 volts and for "connection to the public mains." This standard addresses current harmonics (not voltage harmonics).

[8] www.plugloadsolutions.com/80PlusPowerSupplies.aspx

Static Power Converters

Static power converters, such as VFDs, rectifiers, and inverters, are nonlinear loads and thus are often sources of harmonics. VFDs are notable for their high-efficiency operation. Because of that, they are typically found, for example, on fans, chilled-water pumps, and heating, ventilation, and air-conditioning equipment in data centers; but their efficiency benefit can be offset by resulting harmonic issues. A VFD has a similar topology to a UPS, only without a backup energy source. That is, it coverts an AC voltage to a DC voltage and back to AC again. The rectified conversion is a nonlinear element, which causes upstream harmonics.

Rectifiers

In past data center installations, rectifiers caused significant harmonics when switching. These included 6-pulse, 12-pulse, 18-pulse, and 24-pulse rectifiers. Each time a device is switched, losses and harmonics are generated. Today, pulse width–modulated (PWM) rectifiers (e.g., active power semiconductor switching rectifiers such as insulated-gate bipolar transistors and metal oxide semiconductor field-effect transistors) can switch more than a thousand times per cycle, but mitigation steps implemented in the switching circuit considerably reduce the amount of harmonics generated. Figure 5, Figure 6, and Figure 7 show unfiltered current waveforms for each of the three types of rectifiers.

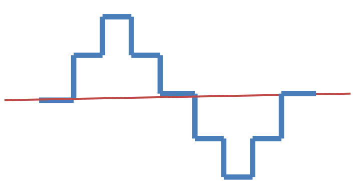

Figure 5. 6-pulse rectifier

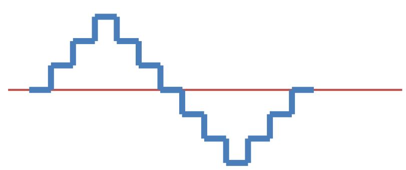

Figure 6. 12-pulse rectifier

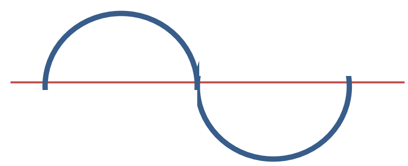

Figure 7. PWM rectifier

UPSs

Harmonics also can be caused by a UPS rectifier, as described in the Rectifiers section above. Similarly, harmonics generated while a UPS is in eco mode or bypass mode (or in any situation in which the UPS is not in line with the power path) will flow upstream to the building transformers, which could cause problems elsewhere in the data center's distribution system. The potential issue exists when the UPS is in eco or bypass mode and the power is supplied by the generator sets. This issue will likely need to be addressed in the future as eco and bypass mode UPSs become more prevalent.

Generators

The harmonic profile of a data center can change when a load transfer occurs between two power sources with different impedances, such as between a utility source and standby generator. With the change in impedance, there is a change in the voltage distortion and resonance of the system. Generator rotor/stator pitch can aggravate or mitigate various frequencies, depending upon the pitch ratio. While resonance is not typically an issue in a system (It is affected by various combinations of inductance and capacitance.), the introduction of harmonics into a system can hit a resonance point that can cause overvoltages. This can also cause problems for the facility in other ways, such as stressing insulation.

Transient Events

A phenomenon similar to harmonic currents can be caused by ongoing cumulative transient events in the data center, not just by certain types of equipment. Shutdown and turn-on events, including those for light bulbs, transformers, capacitors, and IT PSUs can be sources of harmonic frequencies. Since a harmonic is a distortion of a pure sine wave, an initial inrush is a high momentary surge that is not continuous. The individual events can last only a few microseconds to a few milliseconds, so they are not continuous. A data center's harmonics may fluctuate. If the facility has many on-going turn-on and shutdown events, it may appear to have one continuous source of varying-frequency harmonics.

ADDITIONAL CAUSES OF HARMONICS

As previously discussed, harmonics typically come from nonlinear loads, but a nonlinear source can be a cause as well. If either the source or the load is nonlinear, harmonics are generated. For example, when nonlinear currents react with the linear source impedance,[9] they distort the source voltage. What starts as a sinusoidal source voltage is distorted by the presence of the nonlinear load. Linear source impedance multiplied by load current distortion creates nonlinear voltage that adds and subtracts from the sinusoidal source voltage. The higher the source impedance, the greater the interaction effect with other loads.

IV. Finding Harmonics Problems in your Data Center

Instrumentation is readily available that can detect and quantify harmonic currents that may be present in a data center's power distribution system. Such metering is appropriate at a point of common coupling, such as at the circuit breaker panelboard on a power distribution unit (PDU). Switchboards, panelboards, and PDUs frequently have metering capable of measuring the level of harmonic current at each frequency as well as total harmonic distortion. Such metering typically measures up to about the 40th order; other metering is available to read the higher frequencies. Where permanent metering is not built into the system, portable power-quality measurement devices can be deployed for temporary measurement. Temporary devices should remain in place for at least 30 days in order to capture a complete harmonic profile over time. Instruments are available that can measure harmonic orders into 100s.

[9] Impedance, Z: The opposition an electric circuit presents to an alternating current that causes electrical loss, typically in heat.

A word of caution: Harmonics can create inaccurate readings on devices that do not give "true RMS" readings. Voltage and current meters commonly found in rack-mounted power strips and similar devices are frequently unreliable in a harmonics-rich environment. If such meters are relied upon to calculate power usage effectiveness (PUE™), the results may be misleading. (See also *Appendix D. Data Center Measurements and Self-Cancelling Harmonics.*)

V. Acceptable Harmonics Limits

Specifications for the maximum acceptable voltage distortion emissions may vary from one IT device to another, but they are typically 5% total harmonic distortion (THD) and no single harmonic greater than 3%. Table 2 provides the harmonic limits recommended in IEC 61000-3-2.

Table 2. IEC recommendations for harmonic emission limits

Harmonic	Maximum Permissible Harmonic Current Per Watt
3	3.4
5	1.9
7	1
9	0.5
13	0.35
Other odd harmonics up to 39	3.85/n

The conversion of distributed AC power to DC power at critical loads is always accompanied by the generation of higher-frequency harmonics. A DC distribution system will minimize this issue, as will additional mitigation equipment as discussed later in this paper.

VI. Harmonics and Efficiency

CAUSES OF EFFICIENCY LOSS

Several factors contribute to reductions in data center systems' efficiency caused by harmonics. Typically, the issues are a tradeoff between efficiency, costs, and tolerable harmonic amounts that need to be reviewed by each data center and its particular business case.

Aside from ordinary resistive losses, losses in a conductor also occur because of the skin effect.[10] At higher

---

[10] Skin effect is a magnetic property that confines current to an increasingly thin outer surface layer in a conductor as frequency,

frequencies, the current in a wire flows to the outer surface of the conductor. The core is not utilized fully (i.e., the same current flows in a smaller conductor), which further increases losses and decreases efficiency.[11] In general, if the distances are short and the cables are well dimensioned, the effect of harmonics will be minimal. When transmission distances are longer and conductors are operating near their rated power levels, their efficiency may be noticeably decreased.

Second, transformer eddy currents, hysteresis, and core losses from the additional heat of the harmonics all can reduce efficiency. Triplen harmonics can also induce heating inside an enclosure, resulting in a secondary loss mechanism. In this situation, the current does not sum to zero; where there was originally no current, there now is current. This means additional losses because of the increase in circulating currents in the neutrals. These triplen harmonics are higher in frequency in the neutral, which can then induce more currents on top of that via inductive coupling (similar to a transformer). This heats the enclosure, which is both wasteful and dangerous.

Transformers that are removed for efficiency gains can also have negative effects. Removal means harmonics can now flow back to the UPS, which could be a problem if the UPS is unable to handle them. In addition, losses in other mitigation components (such as active or passive filters, power factor correction equipment, and transformers) can reduce efficiency in the overall system.

The UPS inverter may need to carry high peak currents and experience higher switching losses in semiconductors, which again translates to lower inverter efficiency. The UPS efficiency losses caused by the harmonics are more significant for low loads than for higher loads. At higher loads, the fundamental is greater and dominates the power flow. At lower loads, the fundamental is lower, so the effect on harmonics is larger. Developed by the Institute of Electrical and Electronics Engineers (IEEE), the IEEE 519[12] standard introduces the concept of total demand distortion (TDD), which allows a higher level of harmonics at lighter loads to account for this situation even though the THD percentage of harmonics increases at lower loads, the absolute harmonic levels are lower overall in the system.

---

conductivity, or permeability increase. The current density drops by 1/e for every ~1/3 inch at 60 Hz in copper. (See *Appendix C. Skin Effect, Proximity Effect, and Eddy Currents.*)

[11] Resistance is proportional to the cross-sectional area of the conductor; losses are proportional to the resistance. Please note that this skin effect is a larger issue with switch mode power supply (SMPS) transformers than distribution transformers, because switching transformers typically run at higher frequencies, causing higher-frequency harmonics. (For more detail, see *Appendix C. Skin Effect, Proximity Effect, and Eddy Currents.*)

[12] IEEE Std 519-1992 - IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, http://standards.ieee.org/findstds/standard/519-1992.html.

HOW MUCH IS TOO MUCH? THE EFFICIENCY TRADEOFF

The problems currently associated with harmonics found in data centers are much different from the harmonics issues of past decades. Today, equipment is more sensitive to input power. The main concern is the amount of voltage distortion. Active PFC is available on server power supplies and works well to mitigate effects of harmonic currents, but it can come with a cost to efficiency. It is important to find the balance of PFC, harmonics, and efficiency. When PFC is not tightly regulated, efficiency can increase. Some harmonic currents and voltage distortion might result, but they may remain within a range deemed tolerable by the data center operator. The expense of having a power factor at or near unity is incrementally higher than it would be (for example) for a power factor in the range of 0.8 to 0.9 (leading or lagging).

While low-level harmonics do have an effect on the efficiency of the data center, that effect is relatively small compared with other sources of inefficiency. In general, if a data center is looking to gain efficiency but does not have major harmonics issues (e.g., THD is <15% for current and <8% for voltage), harmonics mitigation will likely not yield much in efficiency gains.

As a general guideline, for every percentage point that THDi increases, there may be a 2% increase in losses (half from the copper and half from the transformers) in the electrical system. To determine a specific site's losses due to harmonics, the harmonics losses must be calculated per branch circuit and feeder circuit and summed up. Always conduct a harmonic study when a data center is new (i.e., acceptance testing), after the data center is fully populated and running applications, and then again following any major updates; the studies should be conducted during both standard and contingency operation modes. Particularly for high-frequency harmonics, efficiency points may be gained through line loss reduction.

VII. Mitigating Harmonics

Harmonics mitigation has a point of diminishing returns; the closer one tries to get to zero harmonics, the harder (i.e., more costly) it is to reduce them further. Harmonics can be minimized both in existing data centers and in the design of a new data center. Mitigating harmonics is an important consideration when designing a power system for a data center. Computer simulations can be conducted to predict what harmonics could arise from a system. Some specifications are available for facilities and systems that deal with harmonics. See *Appendix B. Specifications* for information on harmonics-related specifications.

UPSs

When connecting loads to the UPS, it is obvious that the UPS inverter must be able to handle the total amount of harmonic currents pulled from it by downstream equipment. One aspect often overlooked is that any upstream bypass source must also be able to handle all harmonics and nonlinear loads when the UPS is in bypass mode (for maintenance or in response to a fault), as well as any harmonic currents created by the UPS itself. For example, a generator's pole pitch can either amplify or suppress harmonics. The generator's internal impedance will also be a factor in the severity of the harmonics. Table 3 gives some examples of devices commonly found in data centers that can change the impedance within the power system.

Table 3. Comparison of impedance characteristics of various power equipment types

Device	Typical Impedance
Transformerless static UPS	Zero up to current limit
Utility transformer	5-7%
UPS with transformer	4-10%
Generator set	12-20%

Some static UPSs and rectifiers—especially 6- and 12-pulse rectifiers using silicon-controlled rectifiers (SCRs)—can create enough harmonic currents to interfere with the regulation of upstream generators. A lower impedance generally means a higher potential fault current, which in turn can mean that all circuit breakers downstream may have to be rated with a higher current interrupting capacity (kAIC).

TRANSFORMERS

Making modifications to an existing system, such as replacing a transformer-based PDU with a transformerless PDU to improve efficiency, can have a measureable impact on harmonics. Removing the transformer reduces the impedance of the circuit, which can increase current harmonics while simultaneously decreasing voltage harmonics. The consequences of this change should be reviewed prior to the removal of the PDU transformer.

De-rating the power capacity (i.e., the kVA rating) of a standard transformer may be necessary when nonlinear loads are introduced into a data center. De-rating means a transformer is overrated in order to deal with the harmonic currents. De-rating may not be the most desirable approach because a de-rated transformer takes up more space and is physically heavier than other transformers, can cost more money, and puts out more heat.

A European-type distribution system (i.e., distributed neutral, four-wire system) does not use the three-wire, wye isolation transformer that is found in North America. In the absence of a transformer, currents will sum in the neutral. However, the neutral then takes the harmonic currents back to the service entrance (or the first separately derived source).

When designing new systems, be sure to consider transformers that are designed for use with any anticipated nonlinear loads. Such transformers are type-rated by "k-factor."[13] A higher k-factor indicates a higher compatibility with nonlinear loads. Changing the k-factor rating to match the anticipated loads is important when dealing with loads that create harmonics. However, higher k-factor transformers are more expensive and typically physically larger, and they can be less efficient than non-k-factor-rated transformers. To mitigate the skin effect at high frequencies, nonlinear transformer design should optimize the surface area of the conductors in the windings. Greater surface area minimizes the skin effect;[14] the more surface area there is, the less skin effect there is. Rectangular conductors have greater surface area compared with round conductors. In the end, a smaller, more efficient transformer that is sized appropriately and contains a better steel core (i.e., lower loss) may be the best solution, even though it is more expensive.

Zigzag transformers can be obtained with varying phase shifts, and when applied properly, paralleled zigzag transformers can cancel higher-order harmonics.

OTHER MITIGATION TECHNIQUES

Other harmonics mitigation techniques are available for new data centers in the design phase. These include selecting PWM rectifiers over 12-pulse rectifiers, 12-pulse rectifiers over 6-pulse rectifiers, and high-frequency PWM inverters over lower-frequency PWM inverters. Avoid equipment that has high surge start-up characteristics. Reduce source impedances, and check for harmonic characteristics at lighter loads as well as at heavier loads. Harmonics generation is a characteristic that needs to be considered during system design, similar to other considerations. Higher-order frequency harmonics can be mitigated using waveform correction technology.

As with all engineering design challenges, there are compromises with each harmonic mitigation technique. The Green Grid recommends contacting a qualified power engineer for assistance with designing any new data center.

FIXING HARMONICS WITH ADDITIONAL HARDWARE

Fixes for harmonics issues are available in many form factors and price ranges. Harmonic filters can be fitted on site-wide UPSs. Zigzag transformers can act as a higher-order harmonics filter and be used when triplen

---

[13] See ANSI/IEEE C57.110, http://standards.ieee.org/findstds/standard/C57.110-2008.html, and IEEE 1100 Emerald Book, http://standards.ieee.org/findstds/standard/1100-2005.html.

[14] The current density drops by 1/e for every ~1/3 inch at 60 Hz in copper. (See *Appendix C. Skin Effect, Proximity Effect, and Eddy Currents*.)

harmonics are present for non-PFC loads, such as motor drives. Simply adding a zigzag transformer can trigger side effects, however. For example, zigzag transformers add impedance for the source in addition to their effect of cancelling or minimizing harmonics, and they are a passive filter that needs to be tuned and reviewed carefully at installation. At the other end of the cost spectrum, active harmonic filters have higher costs but can cover a broad spectrum with minimal tuning. It should be noted that adding any equipment detracts from the reliability of the system, increases the need for maintenance, and usually reduces availability.

It is impossible to completely remove low-order harmonics from the electrical system. The amplitude of low-order harmonics is large compared with higher-order harmonics, especially the 3rd and 5th harmonics. It is preferable to select equipment that minimizes the generation of low order harmonics in the first place. To mitigate low-order harmonic amplitudes, large chokes (harmonics filters) can be installed in series. These chokes shunt the low order harmonic currents back to their source. It is a typical but not a preferred practice to shunt higher-order harmonics to ground. However, injecting higher-order harmonics into ground conductors can cause problems elsewhere. In addition, for personnel safety reasons, there are limitations imposed on total ground current levels.

In view of the negative consequences of higher-order harmonic noise in a data center's electrical system, The Green Grid strongly recommends using a waveform-correcting technology that also has low pass filtering capability to remove higher-order harmonics. Such waveform correctors should not shunt energy to the ground and should be installed in parallel. (Series filters are relatively large in size and also consume more energy for their no-load operation.) The most reliable solution is to design a system to handle expected harmonics without overheating or producing too much voltage distortion.

VIII. Conclusion

Harmonic currents can be a major factor in power quality and efficiency issues within a data center and can be a complex subject to understand. Causes of harmonic currents can come from any number of nonlinear loads in the data center, including older IT server PSUs, non-server IT equipment, external power supplies for laptop computers, electronic ballasts, variable frequency drives, UPSs in eco or bypass mode, and electronic and magnetic ballasted lighting. The expectation is that without careful study and planning, harmonics in the data center will continue to increase as the number and types of devices that generate harmonics are more widely adopted. Mitigation techniques for harmonics are available, but without proper analysis and planning, they may come at a cost to efficiency. Similarly, harmonics may increase as data centers strive to make improvements in efficiency; careful study and analysis must be made to find the optimal balance of harmonic currents and efficiency in the data center.

IX. About The Green Grid

The Green Grid Association is a non-profit, open industry consortium of end users, policy makers, technology providers, facility architects, and utility companies that works to improve the resource efficiency of information technology and data centers throughout the world. With its member organizations around the world, The Green Grid seeks to unite global industry efforts, create a common set of metrics, and develop technical resources and educational tools to further its goals. Additional information is available at www.thegreengrid.org.

Appendix A. Detailed Harmonics Overview

CURRENT DISTORTION

When nonlinear loads draw nonlinear current in short pulses instead of a smooth, sinusoidal manner, they cause a distortion on the fundamental current waveform. The frequencies in the distorted waveform occur in multiples of the fundamental frequency. For example, for a fundamental frequency of 60 Hz, the 2nd harmonic would be 120 Hz (2 x 60 Hz), the 3rd would be 180 Hz (3 x 60 Hz), and so on. All harmonics, especially high-frequency harmonics (i.e., in general, those above 3 kHz), can cause losses in the electrical system. However, high-frequency harmonics typically come in lower magnitudes overall and diminish very quickly across both the spectrum and the distribution system.

VOLTAGE DISTORTION

Voltage distortion is generated as a result of harmonic currents or current distortion. This can be explained best when looking at a power supply. First, PSUs have a power factor, which means the measured current is split between real and reactive current. Real power does the work. Although necessary, reactive power does not do any useful work, rather it appears in forms such as heating in wires and conductors. This type of example can be conceptually extended to harmonics; fundamental power divided by harmonic power is analogous to real and reactive power.

TOTAL HARMONIC DISTORTION

Harmonics can be generated by the load or the source. Total harmonic distortion (THD) is a measured percentage of the total distortion compared to the fundamental. THD can describe either voltage distortion (THDv) or current distortion (THDi), for the two types of harmonics mentioned above. The Green Grid recommends using the THDv and THDi notations to clarify between the two data points. The lower the THD percentage, the closer the current waveform is to the true fundamental waveform.

By definition, current or voltage THD is equal to the effective value of all the harmonics divided by the effective value of the fundamental. Equation 1 describes THD in the case of distorted current.

Equation 1[15]

Total harmonic distortion for current = $THD_i = \frac{\sqrt{\sum_{h=2}^{h=H} I_h^2}}{I_1}$ or $THD_i = \sqrt{\left(\frac{Irms}{I_1}\right)^2 - 1}$

[15] www.electrical-installation.org/enwiki/Total_harmonic_distortion_%28THD%29

Equation 2 shows THD in the case of a distorted voltage.

Equation 2[16]

Total harmonic distortion for voltage = $THD_u = \frac{\sqrt{\sum_{h=2}^{h=H} U_h^2}}{U_1}$

Where U = voltage)

Table 4. Example calculations

Where $I_{rms} = \frac{I_1 * (1 + 2(I_{thd}))}{2}$

THDi	I_{rms}	= $I_{rms}{}^2R$
0.0%	1.00000	1.0000
5.0%	1.00125	1.0025
10.0%	1.00499	1.0100
25.0%	1.03078	1.0625
50.0%	1.11803	1.2500
75.0%	1.25000	1.5625
100.0%	1.41421	2.0000

These equations demonstrate that sinusoidal voltages and currents have a THD of zero, whereas non-sinusoidal waveforms will have considerable THD levels. Table 4 illustrates the increase in I^2R losses (where R = a relative 1) that can occur in a distorted current waveform. If, for example, THDi = 25%, then the additional heating losses (from the $I_{rms}{}^2R$ column) due to the 25% distortion = (1.0625 – 1.000) = +6.25%.

A similar but different number can also be calculated. Total current demand distortion (TDD) is a calculated harmonic current distortion based on the full load of the system and typically addressed at the building level (per IEEE 519). This is important when comparing individual unit harmonics with the harmonic distortion of the data center as a whole (at the point of common coupling, per IEEE519). A single piece of equipment that has a high harmonic distortion may not have a big effect on the overall data center. High harmonics at one component could be effectively mitigated at the point of common coupling, but they could still have serious consequences for other pieces of equipment nearby in the power distribution line, including localized

[16] www.electrical-installation.org/enwiki/Total_harmonic_distortion_%28THD%29

inefficiencies and heat problems.

The absolute harmonics do not change much as some loads decrease, such as power supplies and UPSs. However, the ratio (THD, see Equation 1 and Equation 2 above) increases at lower loads, not because harmonic current is increasing, but because the fundamental current (the denominator I_1), is getting smaller. There are no additional harmonics in the system and transformers are not any hotter, but there is a different ratio.

TRIPLEN HARMONICS

Triplen harmonics is the name given to odd multiples of the 3rd harmonic, including the 3rd, 9th, 15th, etc. High triplen harmonics can lead to overheating in transformers and increased current in the neutral conductor (which is normally meant to be a non-current-carrying conductor). Excessive neutral current can cause overheating of the neutral conductor, which in turn can result in possible fire hazards in the neutral. Triplen harmonics are not normally present in three-phase, delta-connected loads with no neutral. (To learn more about triplens and their effect on transformers, review information on k-rated transformers.[17]) For example, due to single-phase, phase-to-neutral connected loads on a three-phase distribution system, an analysis of data center load distribution could reveal unbalanced transformers with heavy currents of 60 to 70 amperes (A) on the neutral, with all other portions of the electrical system also excessively hot. To mitigate, the data center should first balance its load and then install a waveform correction product to help reduce the harmonics.

In general, the magnitude of the harmonic decreases as the harmonic order increases.

POSITIVE, NEGATIVE, AND ZERO SEQUENCE HARMONICS

Harmonics can be further classified into three groups, because each harmonic has a zero-sequence, positive, and negative relationship. Triplen harmonics are zero-sequence currents, the fundamental is positive sequence, and the second harmonic is negative sequence. Positive harmonics produce magnetic fields and currents in the same direction as the fundamental frequency. Negative harmonics fields and currents rotate in the direction opposite to the fundamental. Zero-sequence harmonics do not rotate in either direction.

These harmonic groupings play a part in motors. Negative sequence current and harmonics are particularly problematic for rotating machines such as motors and generators. Zero-sequence harmonics sum in the

[17] See ANSI/IEEE C57.110, http://standards.ieee.org/findstds/standard/C57.110-2008.html, and IEEE 1100 Emerald Book, http://standards.ieee.org/findstds/standard/1100-2005.html.

neutral, whereas positive and negative sum to cancel each other out. If there are zero-sequence harmonics, the neutral conductor must be sized to carry the additional current. For motors or generators, the heat produced by 1 A of negative sequence current is 5 to 7 times higher than for 1 A of positive-sequence current.

GENERATION OF HIGH-ORDER HARMONICS

Electrical power is distributed by wires (conductors) that have inductance, capacitance, and resistance distributed over their length. For a straight wire that is feeding a resistive (linear) load, the wire has only resistance, and the current or voltage flowing through this wire is sinusoidal. Due to nonlinear loads (in switched loads or non-ideal/real-world resistors, inductors, and capacitors) the wire no longer has a purely resistive load, and the current and voltages through this wire are not sinusoidal.

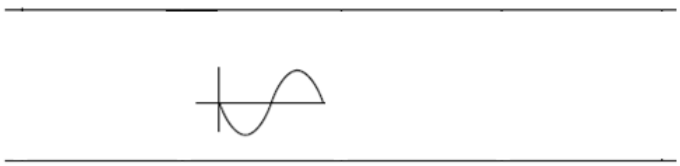

Figure 8. Sinusoidal waveform in resistive wire

Figure 8 shows a waveform in a resistive wire without inductance or capacitance. The waveform is sinusoidal. However, after adding the wire's inductive and capacitive reactance, the current or voltage waveform resonates back and forth between the capacitive and inductive elements, and the harmonics are amplified, as shown in Figure 9. (This is known as resonance). This is an evolving area of research and concern. Often harmonics problems can be solved using methods addressed previously in this paper, but sometimes more detailed analyses such as those discussed in this appendix are required.

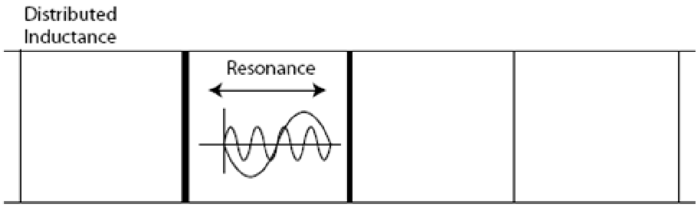

Figure 9. Harmonics on the waveform

Resonance creates amplification of the signal, and amplification of the signal at regular intervals is called harmonics. Due to the presence of nonlinear loads generating low-order harmonic currents and voltages, the waveform in the wire may no longer be sinusoidal. Distributed inductance and capacitance in the wire and electrical system creates electromagnetic resonance on this low-order harmonic waveform and can amplify harmonics.

HIGHER-ORDER/HIGH-FREQUENCY HARMONICS

Higher-order harmonics (high-frequency noise) can cause severe power quality problems, including:

- An increase in the skin effect and thus the heat in the system/load (by increasing effective conductor resistance)
- An increase in eddy current and hysteresis losses in the transformers and motors
- Mis-programming in digital equipment (by non-integral multiples of the fundamental frequency)
- Data loss and/or data corruption in metallic communication channels (by non-integral multiples of the fundamental frequency)
- A decrease in the efficiency of the electrical system (overall contribution of harmonics on the system)

HARMONICS AND POWER FACTOR

In a PSU that is not power factor–corrected, the rectifier only switches on when the voltage is slightly greater than the capacitor voltage (called forward biased). Switching on to charge the capacitor causes the current to spike. This means the current is no longer time-aligned, resulting in a lagging power factor. When power factor correction (PFC) is added, a leading power factor can result. Harmonics mimic power factor: fundamental power divided by harmonic power.

Power factor is the ratio of real power (watts) to apparent power (volts times amps). The measurement of apparent power depends upon the average of sinusoids (random points on the sinusoidal envelope of the waveform); any spikes or harmonics cause distortion in sinusoids. (Spikes and harmonics will have higher-frequency sinusoids.) This distortion in the measurement of real and apparent power causes a decrease in the power factor. Apparent power depends upon the reactive power. Therefore, distortion in reactive power causing harmonics will also decrease the power factor.

Appendix B. Specifications

SPECIFICATIONS

Many data centers request that equipment meet the IEEE 519-1992 "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems." The IEEE website[18] summarizes the standard as follows:

> "This guide applies to all types of static power converters used in industrial and commercial power systems. The problems involved in the harmonic control and reactive power compensation of such

[18] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?&arnumber=210894

converters are addressed, and an application guide is provided. Limits of disturbances to the AC power distribution system that affect other equipment and communications are recommended."

Although IEEE 519 specifies voltage harmonic content, it does not apply to IT PSUs—IEEE 519 is meant for the point of coupling between the facility and the utility grid.

The Green Grid believes the discussion for data centers and vendors needs to move from IEEE 519 and total voltage harmonic distortion to current harmonic distortion. Current harmonics can be controlled; voltage harmonic distortion depends on the current harmonics and the source impedance. Voltage harmonic distortion cannot be controlled directly; it can only be controlled through the management of current harmonics and source impedances.

The standard that applies to individual products is IEC 61000-3-2, "Electromagnetic compatibility (EMC) Part 3-2: Limits – Limits for harmonic current emissions,"[19] specifically those products that draw less than or equal to 16 A per phase. The IEC website summarizes the IEC 61000-3-2 standard as follows:

> "IEC 61000-3-2:2005+A1:2008+A2:2009 deals with the limitation of harmonic currents injected into the public supply system. Specifies limits of harmonic components of the input current which may be produced by equipment tested under specified conditions. Harmonic components are measured according to Annexes A and B. This part of IEC 61000 is applicable to electrical and electronic equipment having an input current up to and including 16 A per phase, and intended to be connected to public low voltage distribution systems. Arc welding equipment which is not professional equipment, with input current up to and including 16 A per phase, is included in this standard. Arc welding equipment intended for professional use, as specified in IEC 60974-1, is excluded from this standard and may be subject to installation restrictions as indicated in IEC 61000-3-4 or IEC 61000-3-12. The tests according to this standard are type tests. Test conditions for particular equipment are given in Annex C."

Within a range of 16 A to 75 A per phase, IEC61000-3-12 is the applicable standard.

Appendix C. Skin Effect, Proximity Effect, and Eddy Currents

Skin depth (ρ in Figure 10) is the measurement of the distance between the AC path and the surface of the wire. Skin depth should be equal to the radius of the conductor for maximum efficiency of the wire. Skin depth

[19] http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/42835

in a material is that depth where the current density has fallen to 1/e of the initial value; e is the base of natural logarithms, about 2.7. Lower skin depth means that the flow of charge or current is pushed more toward the skin of the wire and heats up the insulator of the wire.

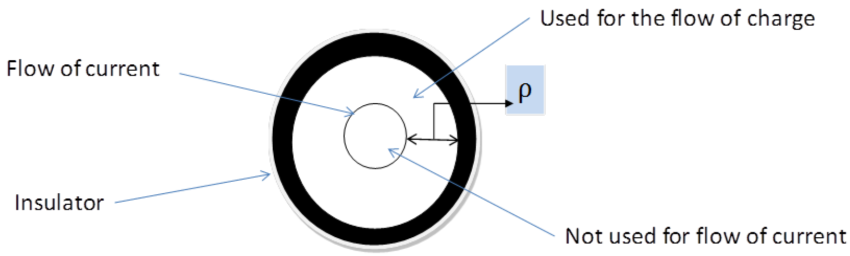

Figure 10. Skin depth

Skin effect is a magnetic property of systems using alternating current that confines current to an increasingly thin layer in a conductor as frequency, conductivity, or permeability increase. As the frequency of the current in the wire increases, the inductive reactance increases. It pushes the current to the skin of the wire. (See Figure 11.) At 60 Hz, the skin depth in copper is about 0.34 inches (8.5 millimeters [mm]). At 2.4 kHz, the skin depth drops to about 0.02 inches (0.508 mm). So at 60 Hz, the current density drops significantly less quickly than at 2.4 kHz (40th harmonic), and more of the conductor is “available” for carrying current. Thus, the higher the frequency, the less cross-sectional area is available for a given current frequency component, raising the resistance for that circuit and increasing power losses. This can be partially offset by reducing the magnitude of the higher-order harmonic currents, but enough additional heating can occur to still create problems. In addition, the higher-voltage drop in the conductors at the harmonic frequencies distorts the voltage waveform. In Figure 11, the black-shaded region indicates the available space for the current. As the frequency increases, the available space decreases, causing the current to flow on the skin of the wire.

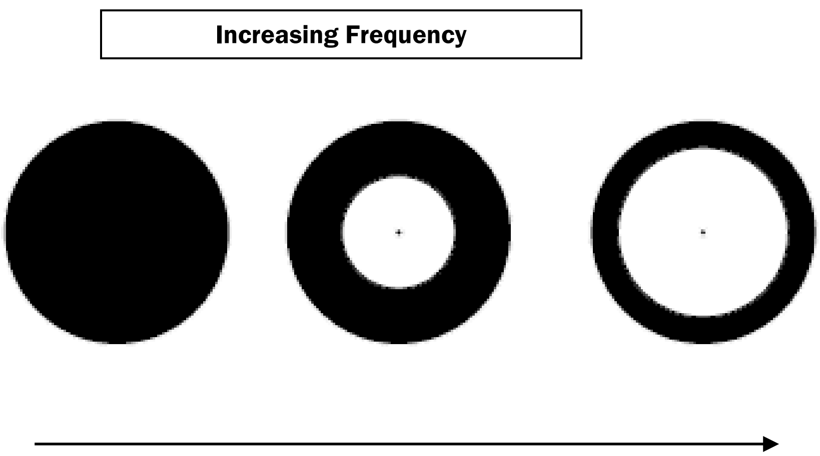

Figure 11. General skin effect diagram showing the results from left to right as frequency increases

Figure 12 shows the relative wire losses at any frequency for various cable sizes, where Rac = relative AC resistance and Rdc = relative DC resistance. As the wire diameter decreases, the losses increase at higher harmonics.

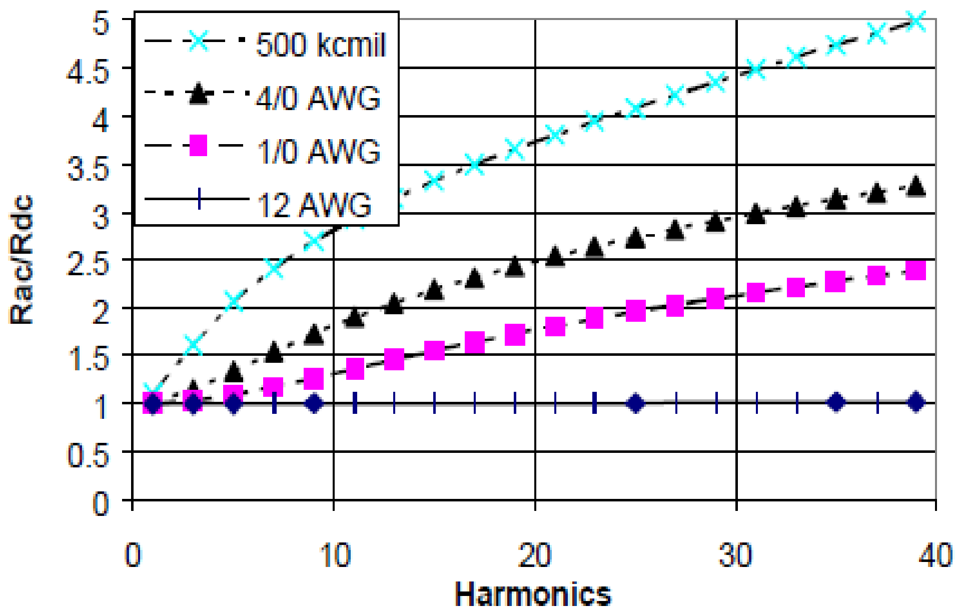

Figure 12. Relative cable losses at any given frequency for various cable sizes[20]

For direct current, the current density is basically constant throughout the conductor.
Increases in high-frequency noise decreases skin depth, which means the total available volume of the wire is not utilized for carrying current. A decrease in skin depth due to the skin effect increases the AC resistance of the wire and hence increases the ohmic losses (I^2R losses). Also, the skin effect results in the reduction of the permittivity of the material (i.e., reduction in the electric field in the material). The skin depth for Cu at 20 kHz is 0.47 mm, and for one meter of wire, half of the resistance is contributed by the skin effect. The more magnetic a material is, the more pronounced the skin effect.

The migration of the current to the wire's outer surface requires energy. More current is being pushed through smaller volume; consequently, the resistivity increases, creating losses. Outdoor power transmission line (steel core for strength, surrounded by aluminum conductors) and rectangular bus bars are examples of solutions to the skin effect problem. Although the higher-order harmonics' magnitude is small compared with lower-order

[20] "Cost and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building;" Thomas Key & Jih-sheng Lai; IEEE IAS, October 1995.

harmonics, the impact of higher-order harmonics on the skin effect is significant, due to the fact that the skin effect increases at higher frequencies. (The skin effect is directly proportional to frequency.)

THE PROXIMITY EFFECT

The proximity effect is defined as the coupling of a magnetic field from one conductor to another conductor. Equation 3 shows the AC losses associated with proximity effect.

Equation 3

$$P = \frac{GB^2}{\mu^2 \rho}$$

Where P = losses due to proximity effect

G = proximity factor

ρ = skin depth of the wire (see explanation above)

μ = permeability of the material (permeability is the magnetic property of wire that tells about the quality of wire)

Proximity factor depends on the wire's shape (round, symmetrical, bent at angles, etc.) and its position relative to other conductors in the system. The more bends in the wire and the greater the asymmetry of its shape, the greater the value of G and the greater the electrical losses.

Lower material permeability means the quality of the wire is degraded, such as from rust or repeated arc-overs on the conductors. When the quality of the wire degrades, its ability to carry current decreases and losses will increase.

EDDY CURRENTS AND HYSTERESIS

Fundamental and higher-order harmonics also influence eddy currents and hysteresis losses in the system. Eddy currents and hysteresis losses increase as the frequency increases. For example, at 10 A with the 3rd harmonic at 70% of the fundamental, the neutral ends up carrying about 1.7 times the phase current. This causes overheating in the neutral wire, possibly causing fires.

Appendix D. Data Center Measurements and Self-Cancelling Harmonics

Harmonic spectrum and magnitude measurements should be taken on each conductor, starting with the load and working back to the incoming substation. Harmonics can be both additive and self cancelling. When a measurement for THD is taken at the panelboard, the measurement may not reflect the higher levels of distortion that are measured directly at the load. The difference could be great—the THD at the load could be 25% whereas the panel only shows 2% of the total load capacity. In such a scenario, the impact of harmonic loss can be significant for the operation of the data center, despite the low level measured at the point of common coupling.

Figure 13 shows an example of the data center locations where measurements were taken.[21]

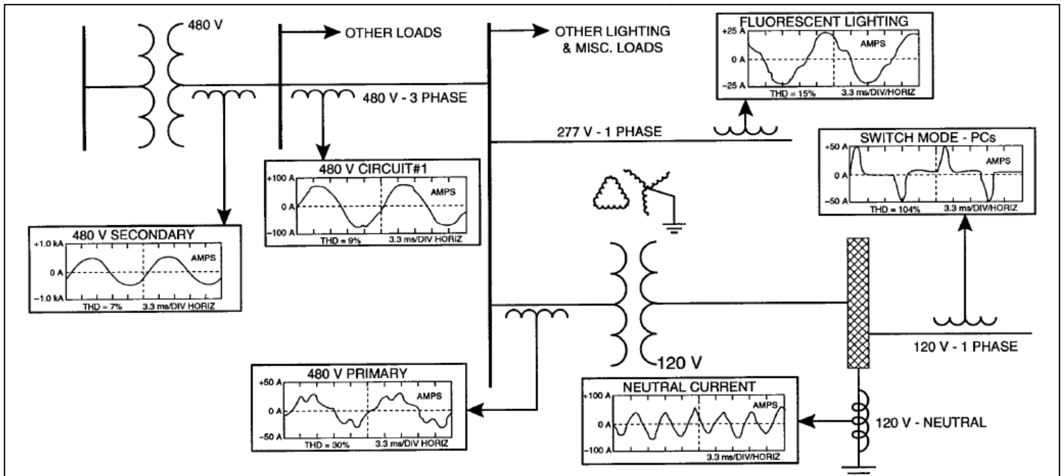

Fig. 1. Harmonic currents in a typical commercial building electrical power system (IEEE Standard 1100).

Figure 13. Example measurement locations in a data center building

An example of a problematic measurement of harmonics occurred at one data center that decided to measure THD as it individually turned on each piece of equipment. Everything was shut down and then, one by one, equipment was turned on and measured. The biggest harmonics culprit for start-up was the copy machine. However, when all the equipment was on, the THD at the point of common coupling canceled the majority of the copy machine's effects, so ultimately they were not an issue.

[21] "Cost and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building;" Thomas Key & Jih-sheng Lai; IEEE IAS, October 1995.