Harmonic Currents in the Data Center: A Case Study

White Paper 38

Revision 1

by Neil Rasmussen

> Executive summary

This document provides an overview of how problems related to harmonic neutral currents are solved by load diversity, with specific focus on information technology (IT) data center environments. Detailed measurements of an actual operating data center are presented. This case study illustrates the way that load diversity mitigates harmonic current levels and lowers shared neutral current in multi-wire feeders and branch circuits.

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Introduction

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Hazards of Harmonics and Neutral Overloads

Nonlinear loads cause harmonics to flow in the power lines. Harmonics are unwanted currents that are multiples of the fundamental line frequency (50 or 60 Hz). Excessive harmonic currents can overload wiring and transformers, creating heat and, in extreme cases, fire. In information technology power systems it is important to know when and how to address this issue. Recently, the problem has been mitigated by load diversity. This white paper extends the concepts related to modern IT data center loads presented in White Paper 26, *Hazards of Harmonics and Neutral Overloads*.

Nonlinear loads

Many desktop personal computers still present a nonlinear load to the AC supply. This is because they have a power supply design known as a "capacitor input switch mode power supply". Much of today's IT equipment including servers, routers, hubs, and storage systems almost universally use a different power supply design known as "Power Factor Corrected" (PFC). These devices present a very linear load to the AC supply and do not generate harmonic currents. In fact they are one of the cleanest loads on the power grid and generate less harmonic current than many other devices such as fluorescent lighting or variable speed motors. Ten years ago, these devices were nonlinear loads like personal computers, but today the majority of these loads are subject to international regulations which require them to be made with the "Power Factor Corrected" design.

Regulations

There is a significant interest on the part of society to reduce the amount of nonlinear loading on AC power systems. This loading reduces the distribution capacity of the public power system, and it can degrade the quality of the power by distorting the AC power waveform delivered to nearby customers. It can also cause a risk of fire on a customer's premises.

In the 1980s, public utilities and international regulatory authorities including the IEC (International Electrotechnical Commission) took notice of the trend that an increasing percentage of electrical power consumption was caused by electrical equipment, and that an increasing percentage of this equipment used a "capacitor input switch mode power supply". Fluorescent lighting, high performance air conditioning systems, and personal computers were key product categories driving this change. In response the IEC created in 1982 the international standard IEC 555-2 "Harmonic injection into the AC Mains". This standard specifically limited harmonic current injection of "non-professional" equipment. Switzerland, Japan, and other countries adopted the IEC 555 standard soon after release. Global suppliers of computing products first began to see a restriction on the ability to sell computers into countries that had adopted IEC 555-2 in the mid 1980's. This situation precipitated the development of PFC power supply technology.

In 1995, the IEC introduced an update of the IEC 555-2 standard, called IEC 1000-3-2. In IEC 1000-3-2 the scope of applicability was greatly expanded over IEC 555-2 to cover all equipment drawing up to 16Amps per phase. The standard added additional limitations on both the absolute and percentage values of harmonics for products with nonlinear switch mode power supplies. Many countries outside of the US and the EC adopted this standard. The EC adopted its own version of this standard later in 1995 as EN61000-3-2 and required equipment manufacturers to comply with the standard under an EC directive called "The EMC Directive". This directive gave manufacturers until 1998 to comply for existing product designs. Later, the EC further extended this deadline to Jan 1, 2001.

By 1995, almost all new computer equipment introduced for networks and communication was in compliance with IEC 1000-3-2. Even though not all countries had adopted the standard immediately, the standard represented a formidable trade barrier for companies that delayed compliance. Computer OEMs were almost universally specifying IEC 1000-3-2 compliance for OEM equipment intended for system integration. This caused virtually 100% of the IT industry to come into compliance well before the Jan 1, 2001 deadline or even the original 1998 deadline.

The USA has proposed an amendment called "amendment 14" to the standard which would weaken the standard and allow more harmonics. It is not clear which countries will adopt this amendment. Products for sale in the EC and many countries must meet the EN61000-3-2 standard. The US has not formally adopted this standard. Information technology equipment manufactured today is universally designed for worldwide application and therefore requires the CE mark and must meet the IEC standard. Therefore, IT equipment other than small PCs universally complies with the standard (non-compliant PCs are still sold in the USA). Over the past 5 years, due to the natural introduction of new equipment and change-out of equipment with newer models, harmonics have been greatly reduced in the data center environment.

Consequences of the load diversity on actual IT data center power systems

1. Load diversity as used in this paper is the natural ratio of linear (PFC) loads to nonlinear loads in the IT data center rack environment. The harmonic currents in the neutral circuit are reduced to the point where the use of oversized neutrals in multi-wire feeders and branch circuits are unnecessary.
2. This load diversity also reduces the “K" factor of the system transformer to an average value of significantly less than K-9.

In a practical system, the harmonic currents are much lower than the theoretical values for the following reasons:

1. International IT equipment manufacturers must meet the harmonic regulations over wide ranges of voltage, manufacturing tolerances, and load, the result being that actual products are well below the compliance limits at typical operating conditions.
2. Some loads are connected phase-to-phase (particularly in the USA), and therefore do not contribute to the neutral current
3. Even with the reluctance of the USA to adopt the IEC limits, the majority of the IT data center loads have become linear (PFC). This system load diversity and its impact on harmonics and shared neutrals have been previously unknown to system designers.

Nonlinear neutral currents in 4-wire wye circuits without load diversity

$$In = 3\left(\sum_{h=3(2k-1)}^{\infty} I_{sh}^{\ 2} \right)^{1/2}$$

The formula for calculating the rms neutral currents for balanced nonlinear loads has been defined as follows.

The triplen harmonic currents are additive in the neutral and because the 3rd harmonic (180Hz) dominates, this has lead to further simplification of the formula.

The net result is the present design practice of rating the neutral conductors for three-phase Wye 4-wire feeders and branch circuits in IT data center environment at 173% of the phase current. This practice is fine, if the actual load is 100% nonlinear load. While this is correct for a high-density nonlinear distributed PC desktop or office environment, it doesn't take into account load diversity in an IT data center rack environment.

$$I_n = \cong 3\, I_{h3} \quad to \quad I_n = \sqrt{3}\, I_{line}$$

Neutral current in 4-wire wye circuits with load diversity

Where the diversity is encountered, i.e., a mixture of linear and nonlinear loads, the following formula can be used to calculate the total rms neutral current.

$$I_n(t) = I_{a0} + I_{b0} + I_{c0} + \sum_{k1}^{\infty} \Big[I_{ak}\cos(k\omega t - \theta_{ak}) + I_{bk}\cos(k(\omega t - 120°) - \theta_{bk}) + I_{ck}\cos(k(\omega t + 120°) - \theta_{ck}) \Big]$$

k = harmonic currents, i.e., triplens – 3rd (180Hz), 9th (), 15th (90540Hz 0Hz), etc.

This formula takes into account both the linear and nonlinear load effects on the neutral conductor. It also accounts for load imbalance of either linear or nonlinear loads. Generally it is sufficient to use the 3rd & 9th as these are two dominant triplen harmonic currents.

Power factor in IT data center circuits with load diversity

Where a circuit contains a diversity of loads the total circuit power factor can be calculated with the following formula.

$$PF = \frac{1}{\sqrt{1 + THD_i^2}} DPF$$

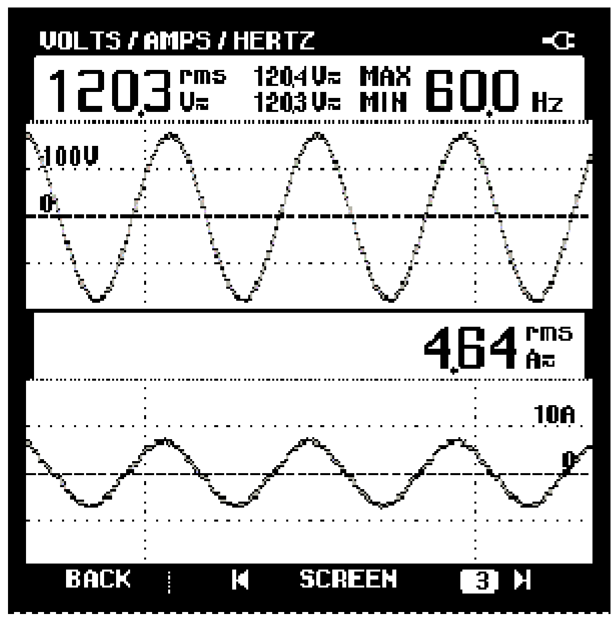
Where: DPF = Displacement Power Factor *THD_i = Circuit Current % Total Harmonic Distortion expressed as a decimal.*

Case study

The effects of load diversity are best illustrated through review of actual system data measurements. Measurements were conducted to determine the power factors, neutral current levels, and harmonics in a typical IT data center rack environment. Two installed InfraStruxure™ (ISX) Type B systems were used in this study. The InfraStruxure™ Type B architecture uses three-phase 20A multi-wire branch circuits (4-wire +ground) to efficiently feed power to high density IT rack enclosures.

The system studied is installed at OneBeacon in Foxboro MA. This system consists of a 60 kVA, K-1, 480 delta input, 208 Y/120 output transformer feeding an APC Symmetra™ PX (40 kW) three-phase UPS which feeds a three-phase PDU panel board supplying 16 rack cabinets via individual UL Listed individual multi-wire branch circuits. Each branch circuit is a UL Listed 20A 4-wire + ground 208 Y//120 whip utilizing a 5 conductor 12AWG SOOW cord terminated with an L21-20R Cord Cap. This in turn feeds an Schneider Electric ISX three-phase power distribution strip with 120V receptacles mounted in each rack enclosure.

Each branch circuit was tested for voltage & current waveforms, total power factor (PF), displacement power factor (DPF), percent current total harmonic distortion (% THD_I) and 3rd, 5th, 7th, 9th, 11th, 13th current harmonics percentages. Two of the 48 single-phase branch circuits were not in use and these are omitted from any calculations related to this study. Three distinct current wave form characteristics were observed on the circuits studied.

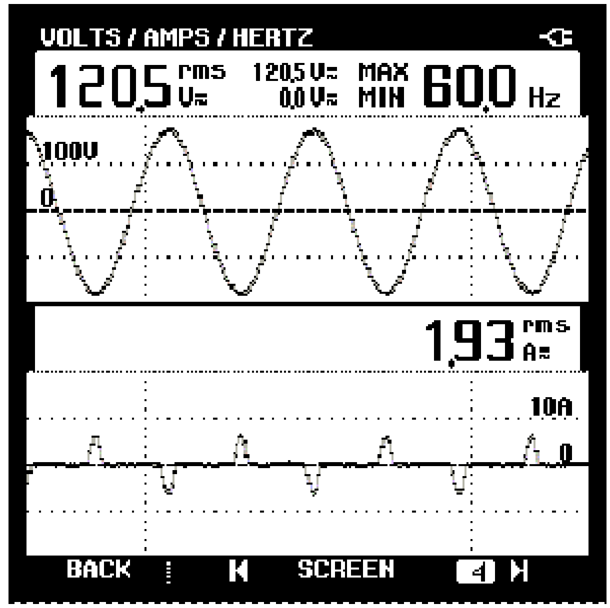


Breaker 2 Phase B

Figure 1

Wave form for breaker 2 phase B

This waveform is from circuit breaker (CB) 2 - Phase B. It is representative of linear (PFC) power supply loads such as servers, disk systems, and routers. In the typical IT data center rack environment this is the dominant load. Branch voltage is the upper trace and branch current is the lower trace.

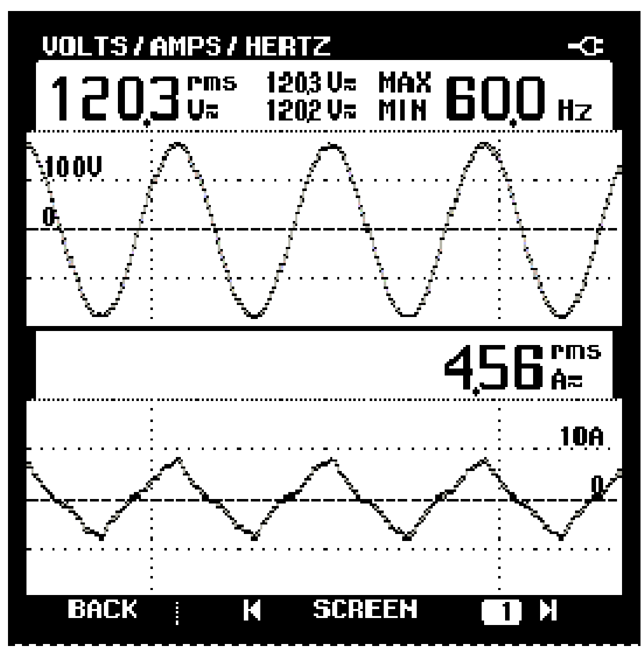


Breaker 9 Phase C

Figure 2

Wave form for breaker 9 phase C

This is the waveform from circuit breaker (CB) 9 - Phase C. It represents the nonlinear power supply loads such as monitors. In the typical IT data center rack environment this is the minority load.



Breaker 1 Phase A

Figure 3

Wave form for breaker 1 phase A

This waveform is from circuit breaker (CB) 1 - Phase A. The current waveform represents the positive effect of the load diversity. In this case the relative high ratio of linear to nonlinear load is seen in the waveform. It also can be seen in the system power factor and THD measurements. When loads with differing characteristics are combined in a single circuit they add together to create a new harmonic current and PF profile. Because this example exhibits high power factor and relatively low current THD we can deduce that the majority load on this circuit is linear (PFC). The circuit load diversity can be defined as the ratio of linear load to nonlinear load. For example, 1200 VA linear and 300 VA nonlinear would be 1200:300 = 4:1 ratio. A diversity of greater than one indicates that the linear loads dominate and dramatically reduce the effect of the non-linear load. A diversity of zero is a pure non-linear load. Any diversity of greater than zero provides some mitigation from the theoretical problems associated poor power factor and current harmonics.

Figure 4

Results of harmonics study

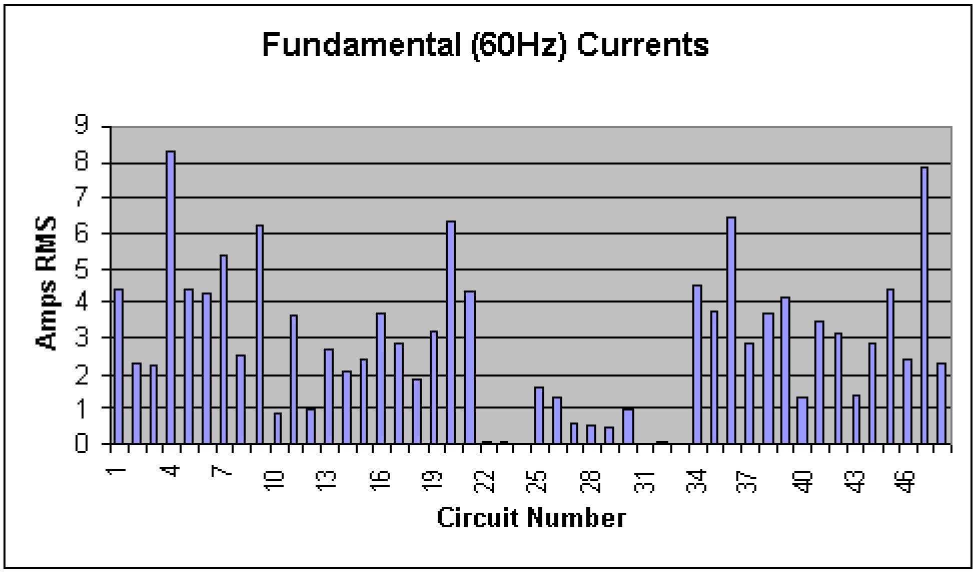
Harmonics Study at OneBeacon in Foxboro Massachussetts

Breaker Number	Phase	Current	Voltage	PF	DPF	VA	Watts	%THD(I)	Harmonics % (current)					
									3rd	5th	7th	9th	11th	13th
1	A	4.48	120.5	0.97	0.98	540	524	20	19	2.6	3.3	2.5	2.2	0.7
	B	2.49	121.6	0.93	0.99	303	282	34.2	32.1	4	7.1	7.4	5.4	2.9
	C	2.45	120.6	0.93	0.98	295	275	31.5	27.1	10.6	10	4.8	2.3	1
	N	3.04												
2	A	8.64	121.8	0.96	0.96	1052	1010	6.1	5.2	2.4	1	1.2	0.4	0.3
	B	4.6	121.4	0.95	0.95	558	531	5.9	5	2.3	0.9	1.3	0.2	0.6
	C	4.45	121.9	0.96	0.95	542	521	7	6.2	2.3	0.9	1.5	0.3	0.1
	N	4.01												
3	A	5.56	120.5	0.97	0.98	670	650	12.7	12.5	1.2	1.3	1.4	0.8	1.6
	B	2.54	121.6	0.97	0.98	309	300	18.4	18.1	2.2	1	1.6	1.2	1.6
	C	6.28	121.9	0.98	0.98	766	750	10.3	10.1	0.9	0.8	0.7	0.3	0.7
	N	1.96												
4	A	0.89	121.8	0.98	0.98	108	106	11.8	10.9	1.1	1.6	0.2	2.5	2.2
	B	3.73	121.7	0.97	0.97	454	440	8	7.5	1.5	1.3	0.9	1.1	0.7
	C	0.97	122	0.98	0.97	118	116	11.6	10.1	1.6	1.6	2.6	2.9	1.9
	N	2.82												
5	A	2.77	121.7	0.98	0.98	337	330	7.3	6.8	1.7	1.1	0.9	0.8	0.4
	B	2.09	121.6	0.97	0.99	254	247	23.7	17.7	11.1	8.5	5	3.2	0.9
	C	2.47	120.7	0.98	0.98	298	292	7.3	6.9	1.4	0.4	1	0.3	0.4
	N	1.12												
6	A	3.74	121.8	0.99	0.96	456	451	6.7	6.3	1.7	0.5	0.9	0.2	0.4
	B	3.05	121.7	0.95	0.95	371	353	7.8	1	7.2	1.7	0.6	1.2	0.7
	C	1.95	121.9	0.97	0.98	238	231	6.5	6.1	1.5	0.6	1.6	0.4	0.7
	N	1.8												
7	A	3.24	121.7	0.97	0.99	394	382	20.6	18.8	6.4	4.1	2.5	1.1	1.8
	B	6.4	121.6	0.98	0.99	778	763	16.1	14.8	4.7	3.3	1	0.8	1.1
	C	4.44	120.6	0.97	0.98	535	519	17.2	15.9	5.1	3.3	1	1.1	1.4
	N	3.55												
8	A	0.12	121.8	0.65	0.68	15	10	23	17.5	2.3	2.2	4.1	2.2	2
	B	0.1	121.7	0.91	0.94	12	11	83	65.1	21.1	18.3	25.2	19.1	16.9
	C	0	121.9	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N	0.1												
9	A	1.67	121.8	0.94	0.99	203	191	31.6	22.2	13.6	14.4	7.6	6.3	3.5
	B	1.31	120.5	0.99	0.99	158	156	12.7	7.2	1.1	4.6	3.1	3.3	2.9
	C	1.07	121.9	0.57	0.98	130	74	81.5	48.1	42	35	27.2	19.4	12.5
	N	1.69												
10	A	0.8	121.8	0.65	0.99	97	63	75.4	50.4	38.2	29.7	20.7	12.6	0.04
	B	0.75	121.7	0.6	0.99	91	55	79.5	56.4	46.3	29.7	21.9	12.1	4.2
	C	1.45	121.9	0.67	0.99	177	118	73.9	57.4	37.3	27.5	13.3	6	1.9
	N	1.76												
11	A	0	121.8	N/A	N/A	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	B	0.11	121.7	0.62	0.78	13	8	56.7	12.3	26.7	19.3	16.4	17.4	14.3
	C	0.11	120.6	0.17	0.25	13	2	73.7	69.3	8.3	7	8.3	1.4	2.7
	N	0.13												
12	A	4.66	121.8	0.97	0.98	568	551	11.2	10.5	2.8	1.2	0.4	0.9	0.8
	B	3.95	121.7	0.96	0.98	481	461	17.5	16.5	4	3.1	0.7	1.9	1.7
	C	6.72	120.8	0.96	0.97	812	779	12	11.2	3.3	1.7	0.6	0.9	0.7
	N	2.97												
13	A	2.99	121.7	0.96	0.99	364	349	7.3	6.9	1.7	1	0.7	0.3	0.5
	B	3.78	120.5	0.97	0.95	455	442	29.3	6.9	9.3	5.1	2.9	2.4	0.8
	C	4.27	121.8	0.97	0.99	520	504	13.7	12.9	2.7	1.3	2.4	1.6	0.8
	N	2.13												
14	A	1.34	121.7	0.96	0.98	163	157	17.8	17.6	1.9	1.3	0.3	2.6	0.9
	B	3.54	121.7	0.97	0.98	431	418	15.7	15.1	1.5	2.1	1.6	1.8	0.6
	C	3.2	120.6	0.97	0.98	386	374	13.9	13.3	0.9	2.5	0.1	1.3	1.2
	N	2.25												

Using the raw branch circuit data from the chart above, analysis was done and bar charts were created to provide better visualization of the circuit conditions.

Figure 5

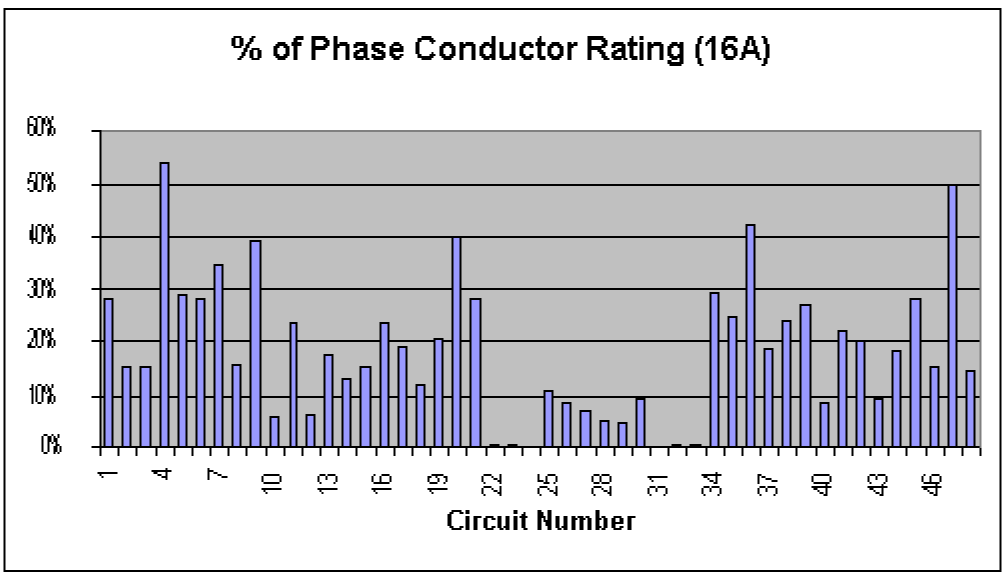
Fundamental (60Hz) currents



The circuit numbers 1-48 correspond to the individual breaker poles in the main PDU panel board as shown in the previous data chart. Therefore, "1, 2, 3 are multi-wire branch circuit #1 in the above analysis chart, i.e., A, B, and C phases respectively. This data shows that none of the 16 three-phase multi-wire branch circuits are carrying balanced load.

Figure 6

% of phase conductor rating (16A)



This chart shows the branch circuit loads relative to the 16A conductor rating for each branch. Once again there is no balance indicated for any of the three-phase multi-wire circuits and the highest % load is ~ 55% on branch # 4 (CB #2- A Phase). The majority circuit loading is under 30% of the conductor rating.

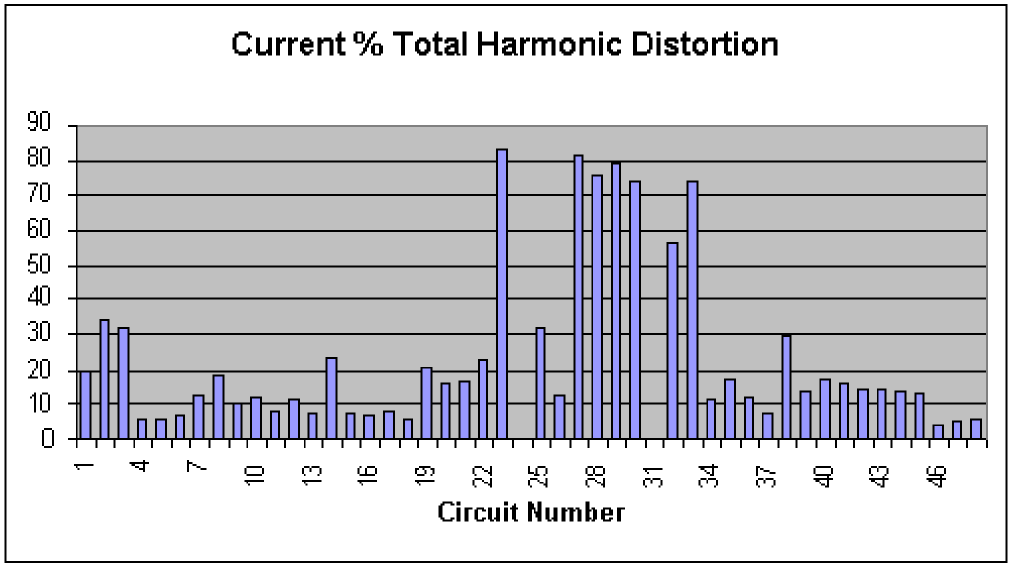


Figure 7

Current % total harmonic distortion

This chart is the analysis of the percent total harmonic distortion for the currents (% THDi) on each branch circuit. This shows us that the majority of branch circuits are loaded with less than 20% THDi. If we compare this to the previous charts we can see a pattern developing, i.e., the loads with the highest THDi (circuits 21-33) have some of the lowest branch circuit loading, i.e., ~ 10% or less of the circuit rating.

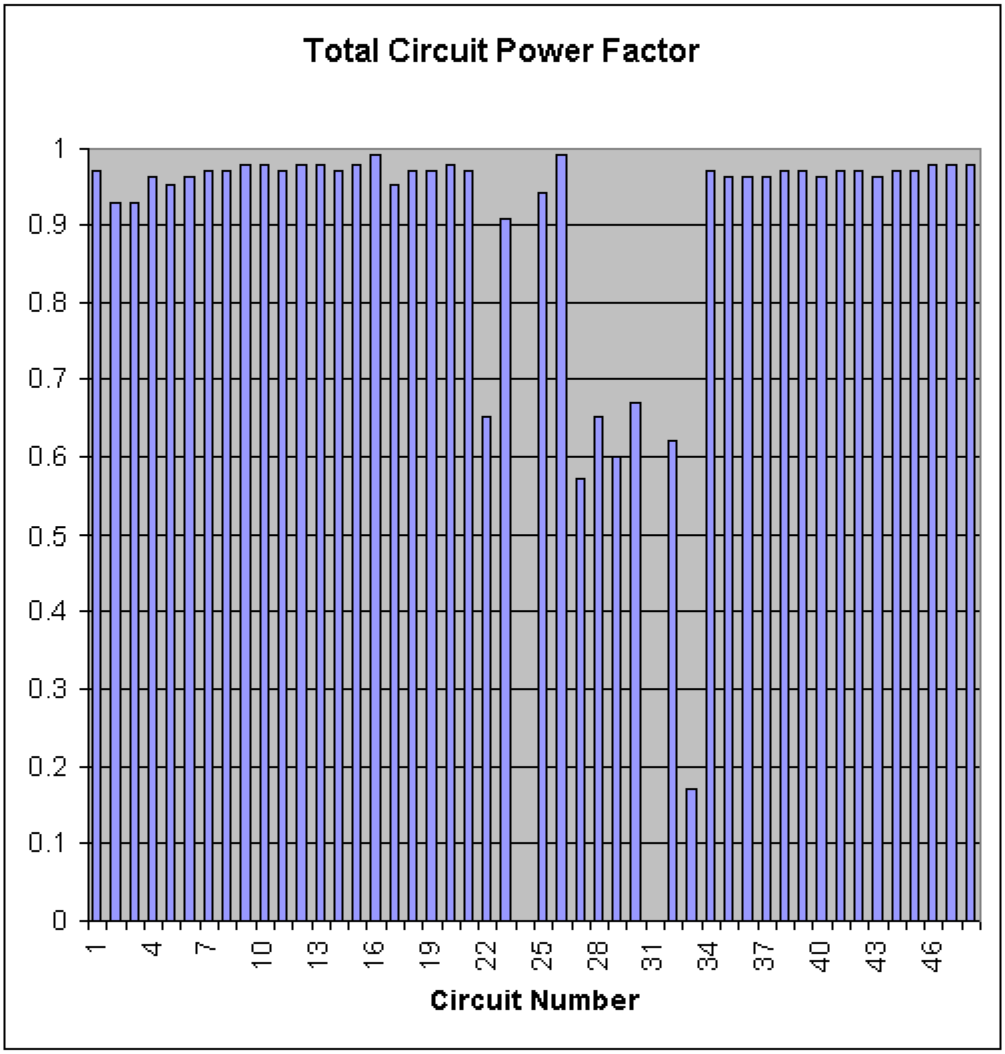


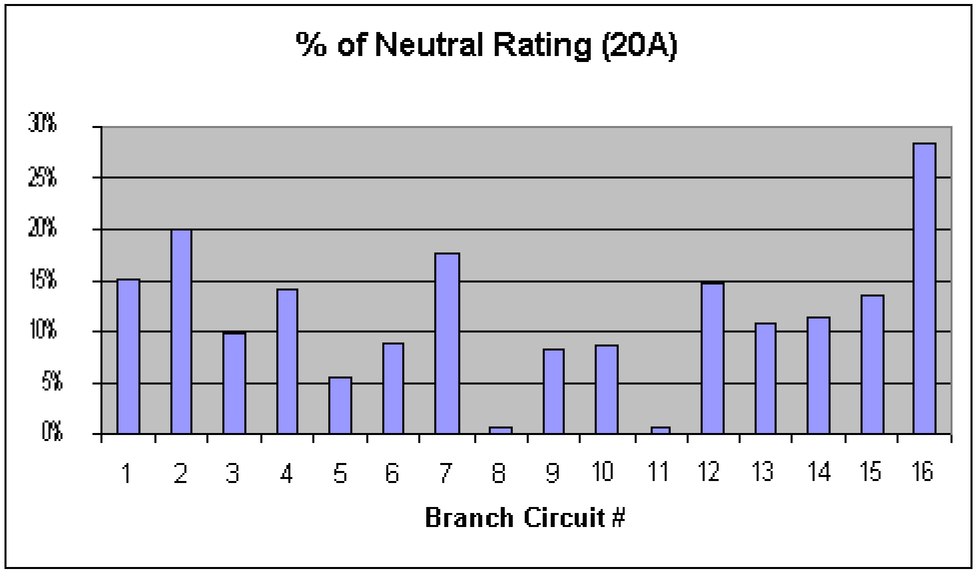
Figure 8

Total circuit power factor

This chart shows the total power factor of all branches. We can see that the majority load is .95 or better and also has same pattern as the previous charts, i.e., lowest power factor is the lightest loaded circuits. The overall power factor of the system will be higher than the average of these power factors, because the data shows that the circuits with low power factor also have low current, and therefore the circuits with low power factor make a low contribution to the total reactive power.

Figure 9

% of neutral rating (20 A)



This is the key chart that summarizes the implications regarding the sizing of neutral wires. The chart shows the neutral load current versus 20A branch rating for all 16 multi-wire branch circuits. Legacy design guidelines would predict that these neutral currents would be as much as 170% of rating, whereas the data shows actual currents in a real installation are on the order of 20%. Furthermore, the dominant source of the observed neutral currents is actually load imbalance between phases, and not harmonic currents. These results are expected when an understanding of modern computer power supplies is applied to the analysis, and they clearly show that the legacy approach of oversizing neutrals in this application is unwarranted.

System phase loading in all branch circuits is under 60% and is under 20% for the majority of the 48 branch circuits studied. The circuits with highest ITHD percentage exhibit the lowest circuit loading. These same circuits also exhibit the lowest neutral currents and poorest power factor. The reason for this is that they represent a very small fraction of the modern IT data center load.

OneBeacon feeder circuit data analysis

In the chart below we see the effects of load diversity on the feeder circuit from the UPS to PDU panel board. We also see there is harmonic current flowing on the neutral conductor. But the neutral current is also ~41.7% of the lowest phase current (19.9/47.7 = .41719). The feeder neutral in this case is a 1/0AWG conductor rated at 150 amperes. Therefore the % load on the neutral is ~ 13.3% of its 150A rating (19.9/150 = .13266.). At the same time the load power factor is very high, at .97-.98PF. Once again we see the positive load diversity effects in the feeder, i.e., same as those seen in the branch circuit waveform of CB 1- A Phase shown previously.

Figure 10

Feeder circuit data analysis

Feeder Harmonics Study at OneBeacon in Foxboro Massachussetts

UPS Output	Phase	Current	Voltage	PF	DPF	VA	Watts	Harmonics % (current)						
								%THD(I)	3rd	5th	7th	9th	11th	13th
Q2	A	47.7	120.4	0.98	0.99	5743	5628	11.7	11.2	1.4	2.5	16	18	0.8
	B	52	120.5	0.98	0.98	6266	6141	13.6	13.1	1.3	2.7	0.8	1.2	0.7
	C	49.2	120.6	0.97	0.98	5934	5756	14.4	13.5	2.5	3.5	1.3	1.2	0.7
	N	19.9												

IT data center rack environment loads and K-Factor

The K-factor requirement for the system can be determined from the data measured at the example site. The calculated K-factor for the feeder load at OneBeacon is K-1.25, i.e., using the C Phase harmonic current values.

Legacy design guidelines would predict that the K-factor requirement would be as much as 21, whereas the data shows the actual K-factor requirement is approximately 1. These results are expected when an understanding of modern computer power supplies is applied to the analysis, and they clearly show that the legacy approach of specifying high K-factors of 15 or 21 in this application is unwarranted.

Conclusion

The power characteristics of the modern IT data center rack environment are very different from the computer room of the early 1980's. Dramatic improvements in IT equipment power factor and harmonics have lead to corresponding improvements in the overall system power factor along with a large harmonic current reduction. Actual measurements of real systems demonstrate these improvements. K-factor specifications of 15 or 21 drive unnecessary cost when the actual K-factor of real installation is approximately 1. Neutral oversizing of 170% to 200% drives unnecessary costs when the actual neutral current is only 20% of circuit rating. Legacy design practices and specifications for data center power systems should be updated to reflect the actual requirements of modern data centers.

About the author

Neil Rasmussen is a Senior VP of Innovation for Schneider Electric. He establishes the technology direction for the world's largest R&D budget devoted to power, cooling, and rack infrastructure for critical networks.

Neil holds 19 patents related to high-efficiency and high-density data center power and cooling infrastructure, and has published over 50 white papers related to power and cooling systems, many published in more than 10 languages, most recently with a focus on the improvement of energy efficiency. He is an internationally recognized keynote speaker on the subject of high-efficiency data centers. Neil is currently working to advance the science of high-efficiency, high-density, scalable data center infrastructure solutions and is a principal architect of the APC InfraStruXure system.

Prior to founding APC in 1981, Neil received his bachelors and masters degrees from MIT in electrical engineering, where he did his thesis on the analysis of a 200MW power supply for a tokamak fusion reactor. From 1979 to 1981 he worked at MIT Lincoln Laboratories on flywheel energy storage systems and solar electric power systems.

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