K-Factor can be a Misleading Power Quality Indicator

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Abstract: This paper looks at the evolution and measure of success of different harmonic treatments applied in commercial buildings. Typical levels of voltage distortion are described in light of extensive harmonic data collection at North American sites over several years at hundreds of electrical panels and transformers. The field data shows that contrary to the popular belief, doubling the neutral and derating or k-rating the transformer does not properly address the harmonic issues facing today's buildings. Voltage distortion often exceeded the 5% recommended limit set out in section 6.6 of IEEE Std 519-1992. A case study is presented that documents voltage distortion levels in a typical commercial high rise building, and the effectiveness of different transformer configurations in reducing these harmonic levels are evaluated.

Keywords: Harmonics, IEEE Std 519, IEEE Std 1100, phase angle diversity, k-factor, phase shift, low zero sequence impedance, switch-mode power supply, voltage distortion, THD.

I. HARMONIC LIMITS

One of the requirements in electrical system design is to meet the recommended levels set out in IEEE Std 519-1992 *"IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"* [1]. Much of the focus of this standard is the utility/customer interface or the point of common coupling (PCC), where limits are set for both voltage and current. Equally important but carrying a lower profile in the document is section 6.6. This section specifically identifies that electronic equipment can function erratically when subjected to voltage distortion in excess of 5% THD or to individual voltage harmonics in excess of 3%.

In light of its importance yet low profile, we will focus on this aspect of IEEE-519 in this paper. Let's begin with a direct quote from section 6.6:

> *Power electronic equipment is susceptible to misoperation caused by harmonic distortion. This equipment is often dependent upon accurate determination of voltage zero crossings or other aspects of the voltage wave shape. Harmonic distortion can result in a shifting of the voltage zero crossing or the point at which one phase-to-phase voltage becomes greater than another phase-to-phase voltage. These are both critical points for many types of electronic circuit controls, and misoperation can result from these shifts.*
>
> *Other types of electronic equipment can be affected by transmission of ac supply harmonics through the equipment power supply or by magnetic coupling of harmonics into equipment components. Computers and allied equipment such as programmable controllers frequently require ac sources that have no more than a 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonies result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences.*

Voltage distortion levels at the 120V loads have not received much attention since it has been to a great extent assumed that load diversity in conjunction with phase angle diversity results in low enough overall current distortion to keep voltage distortion low.

II. FINDINGS

The harmonic surveys analyzed in the preparation of this paper confirmed that at most building entrances voltage distortion was low, typically in the 1-2% range. Measurements in these same buildings, but at the 120 Volt electronic equipment, showed much higher voltage THD levels typically in the 4-8% range. Neutral current was typically found to be in the 80-130% range as a percentage of phase current. Where concentrations of 120V electronic equipment was high, neutral current always exceeded phase current, in some cases reaching the theoretical maximum of 173% of phase current. This finding should clear any doubt about the need to double the neutral conductor ampacity between the transformer and the panels feeding the individual single-phase circuits, and that a dedicated neutral must be run with each load circuit.

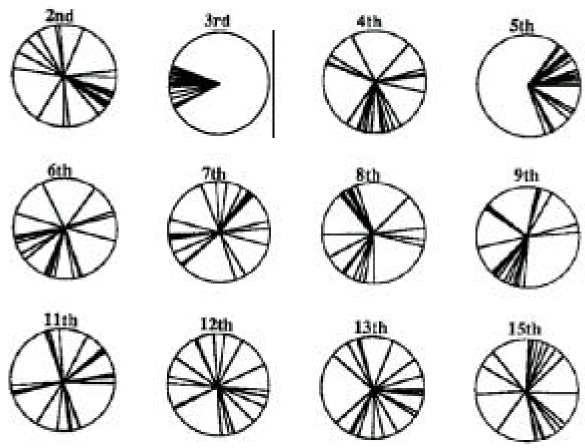


Fig. 1. Phase Angles of 120 volt Office Equipment

These findings also indicate that harmonic surveys should not be confined to the building entrance or main distribution switchboards. Data should also be collected at downstream load connection points and analyzed with respect to IEEE-519 section 6.6.

It is interesting to note that the high levels of voltage THD come despite the presence of phase angle diversity, the use of k-rated transformers and double-sized neutral conductors.

The data reflects the fact that while phase angle diversity exists and results in lower harmonic current content, it is not the only reason for reduced current distortion levels. More importantly, whatever factors lower the harmonic current content, they are not enough to provide an acceptable level of voltage distortion as set out in IEEE-519, section 6.6 [2, 3, 4].

Figure 1 illustrates phase angle diversity of individual loads taken at a particular site where there was a high density of 120 volt office equipment. Our field data, which documents phase angle diversity despite the close similarity of the loads, supports published data [5, 6, 7, 8].

There is a close correlation between the phase angles at the 3rd and to a lesser extent the 5th harmonic, but that even with the 7th there is a notable difference among some equipment. Higher harmonics display even more phase angle randomness. Notably the largest harmonic currents (3rd and 5th) add almost arithmetically from the individual loads, with very little attenuation and as a result cause substantial voltage distortion.

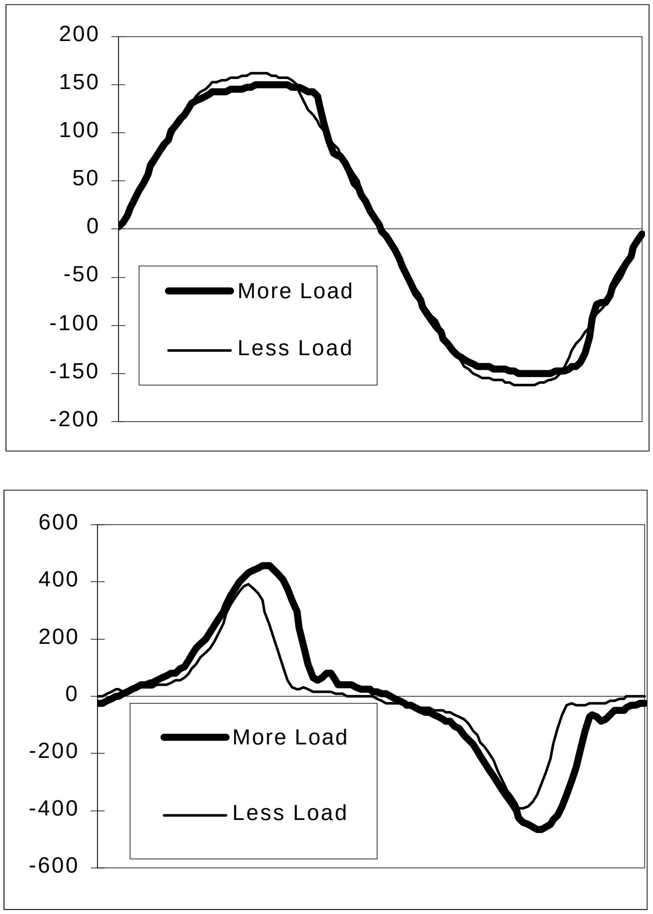
A typical panel of 120 Volt electronic loads will have a harmonic current spectrum of predominately 3rd and 5th harmonics, with substantial attenuation at the higher order harmonics. This "natural" narrowing of the harmonic profile is certainly beneficial as the higher harmonics won't require treatment, but the resulting presence of excessive levels of 3rd and 5th harmonic voltage needs to be acknowledged and addressed.

The phase angle diversity shown in figure 1 also shows that there is little value in trying to apply theoretically derived phase shift cancellation for higher order harmonic currents, since they already tend to cancel. As a result, the implementation of a phase shift for higher harmonics could actually result in **higher** harmonic levels.

III. EFFECT OF VOLTAGE FLAT-TOPPING ON CURRENT DISTORTION

As switch-mode power supply (SMPS) loads are added to a system, the common observation is that overall current distortion levels go down. Most attribute this exclusively to phase angle diversity among the loads. Analysis of the data collected indicates that it is only partially responsible.

A look at the voltage waveform would typically reveal that as the load increases, so does voltage THD as evidenced by the flat-topping of the waveform (fig. 2). The reason is simply Ohm's Law, where increased harmonic current through the same impedance results in an associated increase in harmonic voltage.



	Voltage THD	Current THD
More load	7.7%	65%
Less load	3.2%	81%

Fig. 2. Effect of increased loading on voltage and current waveforms

Flat-topping of the voltage waveform is the way voltage THD manifests itself in commercial environments due to the pulsed nature of the SMPS load profile, with the pulses of current being drawn at the peaks of the voltage waveform. However, a flat-topped voltage has a reduced peak voltage, and as the peak voltage comes down, so does the energy stored in the SMPS reservoir capacitor, and as a result the pulse of current widens in order to provide the same total energy required by the dc side electronics. When translated into harmonic terms, a wider pulse has a lower harmonic content. There are several negative associated consequences that reduce the operational reliability of the electronic equipment. These include reduced ride-though capability of the power supply and increased duty cycle on power supply components.

This relationship between peak voltage and current THD is typically overlooked as the reason for reduced current distortion, yet in most commercial applications it plays a more significant role in the reduction of current than does phase angle diversity.

IV. REDUCED LOAD K-FACTOR vs. INCREASED VOLTAGE THD

K-factor is another way of looking at the harmonic content of a load. In IEEE Std 1100-1992 [9], the “Emerald Book”, k-factor is defined as:

$$K = \sum_{h=1}^{h=h_{\max}} I_h^2 \cdot h^2 \qquad (1)$$

where I_h= rms current at harmonic *h*, in per unit of rated rms load current

It is essentially a transformer survival rating. As long as the load k-factor is lower than the ‘k’rating of the transformer, the full kVA rating of the transformer can be used. The transformer survives the harmonic losses without overheating but voltage distortion remains essentially unaffected.

In the context of the discussion on reduced harmonic distortion due to voltage waveform flat-topping and phase angle diversity, the k-factor is also reduced.

Unfortunately, some have taken this reduction in k-factor as justification for the use of transformers with lower k-ratings such as k-4 rather than k-13. At first glance this might seem to make sense, however it overlooks the IEEE-519 section 6.6 requirement to deliver less than 5% voltage THD to the electronic equipment fed from the transformer. The reduced k-factor comes at the price of subjecting the loads to excessive voltage distortion – not an acceptable result.

To be considered a harmonic treatment, a transformer must be able to perform all of the following functions (The k-factor transformer cannot predictively deliver these functions.):

1. carry the heating effects of the load harmonic currents

2. minimize associated losses
3. maintain voltage distortion at a level acceptable to the connected load.

V. EXCESSIVE VOLTAGE THD

Whatever the method, reduction of harmonic current cannot be at the expense of exposing equipment to excessive levels of voltage distortion. Unfortunately, this is exactly what happens in many commercial and high tech installations.

Despite the observed relationship of decreasing current distortion with increasing load, the reality is that at some load level, the voltage distortion rises above the acceptable 5% limit, reducing the operational reliability of the connected electronic equipment.

VI. CASE STUDY

The following is a typical example of a four-story commercial office building. There is a main 600V distribution panel in the basement, feeding among other loads, a 600V riser. The riser feeds a standard delta-wye 112.5kVA 600-208/120V step-down distribution transformer on each floor feeding typical office automation equipment such as personal computers and laser printers. Voltage THD is above 5% on all floors. The transformers are near half of their nameplate rating and the panels feeding the individual load circuits are in the same electrical room as the riser tap box and the transformer.

Location	Voltage THD
600V riser	2.8%
1st floor panel	5.1%
2nd floor panel	5.4%
3rd floor panel	5.9%
4th floor panel	7.7%

Fig. 3. Voltage distortion in 4-story commercial office building

As the data in fig. 3 illustrates, voltage distortion level on the riser is below 3% but at the electronic equipment it exceeds the 5% recommended limit. On the fourth floor, both 3rd and 5th harmonic voltages were above the 3% individual limit. This end result is in spite of a reduction in harmonic current distortion that has occurred as a result of phase angle diversity, flat-topped voltage waveform, and trapped 3rd harmonic current in the primary winding of the delta-wye step-down transformers.

None of the transformers were overloaded even when derated for the harmonic content of the load. The example used here is representative of dozens of similar sites with distribution at 480V (USA) and 600V (Canada).

VII. TREATMENT

Analysis of the harmonic profiles both at the panels and on the riser indicated that the replacement of a single transformer, the one on the fourth floor, could deliver the required system-wide reduction in harmonic voltage distortion if it addressed both 3rd and 5th harmonic currents.

It should be noted that replacement of any of the transformers with a k-rated transformer whether k-4 or k-13 would not have substantially dropped the voltage distortion level. Levels would have remained unchanged at the lower floors since the 5th & 7th harmonic currents would still flow through to the riser, the same as with the conventional delta-wye transformer, and the 3rd harmonic current, while trapped in the primary delta winding is flows through a substantial zero sequence impedance.

By swapping out the delta-wye transformer on the fourth floor with a Powersmiths International Corp. PowerStar™ T1000 harmonic cancellation transformer, model '0' degree phase-shift, we could guarantee to our customer that we would reduce voltage distortion to acceptable levels throughout the system.

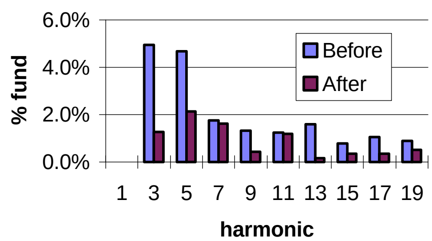
The less than 0.25% zero sequence reactance on the output side of the PowerStar™ T1000 allows the 3rd harmonic current to flow through a reduced impedance, delivering the required reduction in 3rd harmonic voltage.

The '0' degree primary-secondary phase shift of the PowerStar™ T1000 puts in place a relative phase shift of 30 degrees when compared to the other three transformers, since they are all delta-wye configurations with the associated 30 degree primary-secondary phase shift. This creates a phase angle inversion of 5th, 7th, 17th, and 19th harmonic currents. Referring back to the phase angle diversity chart in figure 1, we see that the result will be that the 5th harmonic current from the fourth floor will tend to subtract from those of the other three floors when they meet on the riser. For the 7th and other inverted harmonics, the pre-existing phase angle diversity will mean that on average we can't expect big drops in these harmonic currents, but of course where there is phase angle diversity, harmonic current levels and hence associated voltage harmonics are already low.

The drop in harmonic current on the riser results in a corresponding drop in voltage distortion again by Ohm's Law – less harmonic current flowing through the same impedance, equals less harmonic voltage drop.

The importance of the drop in voltage THD on the riser is that the voltage waveform at the riser is supplied to all four floors. So any reduction in voltage THD on the riser is directly passed on to all loads downstream.

VIII. RESULTS



Location	Voltage THD BEFORE	Voltage THD AFTER
600V riser	2.8%	1.7%
1st floor panel	5.1%	4.0%
2nd floor panel	5.4%	4.3%
3rd floor panel	5.9%	4.8%
4th floor panel	7.7%	3.2%

Fig. 4. Comparison of Voltage distortion levels in a 4-story commercial office building before and after replacement of 4th floor transformer

As the spectrum in figure 4 shows, there has been a substantial drop in voltage THD at the 4th floor panel with the drop in 3rd and 5th that were targeted by the transformer treatment being mostly responsible. Voltage THD dropped from an excessive 7.7% as found, to 3.2% after the transformer replacement.

Looking at the rest of the system, voltage THD dropped on the 600V riser as well as at the panels on the three floors that were not touched. The drop of 1.1% at the riser level, from 2.8% to 1.7%, was observed, as expected, at each of the floors. The result was that voltage distortion at all four floors was improved to less than 5%.

IX. CONCLUSIONS

The data collected clearly indicates that both voltage flat-topping and phase angle diversity result in lower harmonic current distortion. Of the two, voltage flat-topping plays a more significant role in this reduction. Despite the drop in current distortion, voltage distortion at the electronic equipment still commonly exceeded the 5% recommended limit as set out in IEEE-519 section 6.6. This finding leads to the conclusion that harmonic treatment is often required at the 208/120V level in order to maintain levels of voltage THD within acceptable limits for the electronic equipment connected, and that derating or k-rating the transformer does not deliver this required reduction. Doubling the size of the neutral conductor downstream of the transformer is recommended when feeding 120V electronic equipment.

A case study involving the replacement of a delta-wye transformer with a transformer combining phase-shifting and low zero sequence impedance illustrated that harmonic treatment with the Powersmiths International Corp. PowerStar™ harmonic cancellation transformer was able to provide the necessary reduction in voltage distortion.

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