Alternative Designs to Support Electronic Loads in Extensive UPS Distribution Systems

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HARMONIC LIMITS

IEEE-519, rev.1992 "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems" sets out harmonic limits for both voltage and current. Harmonic current limits apply at the point of connection to the utility. Voltage distortion limits for electronic equipment (like PCs), on the other hand, apply where the equipment is connected - at the end of the line. This is also where voltage distortion is highest because it is the equipment itself that is the source of harmonic currents that flow back through the system impedance creating voltage distortion. Ironically, this same equipment is itself sensitive to voltage distortion - to which it contributes. This sensitivity is so important that IEEE-519 devotes Section 6.6 to describing the many problems that can result if total harmonic voltage distortion (THD) exceeds 5%, or if any individual harmonic exceeds 3% of the fundamental. These are the key reference numbers to compare against during any harmonic analysis. Harmonic measurements must be made at the loads, since this is where the voltage distortion limits apply.

Harmonic Analysis of UPS Distribution System

The following estimates are based on the distance estimates provided from the UPS to the main 480V distribution panels as noted, 250-350' from main DP to the transformers, 100' from snorkels to 100A panels, and 50' from there to the loads. For loading, the UPS load at 200kVA and 300kVA was taken to be divided evenly among the feeders. The load profile used was a single-phase 120V power supply typical across all PC manufacturers.

THE STATUS QUO

Transformers: 75kVA, K13

Module	Distance	Estimated Vthd				Neutral-GND
	UPS to main DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	5.5-8.0%	7-10%	8.5-11.5%	10.5-13.5%	4.5 - 6.0 V
B	410'	4.5-7.5%	6-9%	7.5-10.5%	9.5-12.5%	4.5 - 6.0 V
C	300'	4-7%	5.5-8.5%	7-10%	9-12%	4.5 - 6.0 V
D	530'	5-8%	6.5-9.5%	8-11%	10-13%	4.5 - 6.0 V
E	700'	6-9%	7.5-10.5%	9-12%	11-14%	4.5 - 6.0 V
F	825'	6.5-9.5%	8-11%	9.5-12.5%	11.5-14.5%	4.5 - 6.0 V

NOTE: EXPECTED PF AT UPS OUTPUT: 0.65 to 0.75

As shown in the table, the analysis estimates voltage distortion (THD) at the loads will vary between 9% best case and 14.5% worst case depending on the length of feeder and load. Predicted levels are therefore between double and triple the maximum IEEE-519-1992 recommended limit of 5%. As described in IEEE-519, equipment malfunctions and premature failures can be expected where voltage distortion is excessive. The amount of downtime increases as voltage THD goes up. Although sometimes difficult to quantify in an office setting, associated costs can be substantial.

In one case where hard numbers were available, a bank trading floor with 160 PC workstations (120V), voltage THD at the loads was found to be 15%. Three full-time technicians supported the floor maintaining and replacing equipment. An annual cost was estimated at $400,000 not including financial consequences of the downtime. With harmonic treatment in place, voltage THD was reduced to 4.3%, the problems ceased, and the technicians and equipment replacement were no longer required.

While it can be difficult to quantify the hard costs of excessive harmonic distortion, higher maintenance costs along with lost productivity will no doubt exist.

A note on Power Factor

The power factor of the load on the UPS will likely be in the .65-.75 range. This low range is due almost entirely to the harmonic content, since displacement factor of the switch-mode power supply is almost unity (0.97-1.0). This low PF substantially reduces the effective capacity of the UPS.

OPTION #1

PROPOSED HARMONIC TREATMENT

Replace the K-13 transformers with PowerStar™ T1000 Harmonic Cancellation Transformers

Whereas a K-rated transformer survives harmonic current, the ***PowerStar™ T1000*** cancels it, establishing electromagnetic compatibility between the electrical system and sensitive electronic equipment connected to the system. This is an important difference because while the K-rated transformer will not overheat due to the harmonic currents it does nothing for compatibility - a very important deficiency.

Comparison of Principles of operation of the *PowerStar*^{TM} *T1000* and a Delta-Wye Transformer Item	Delta-Wye (same if K-rated)	*PowerStar*^{TM} *T1000*
3rd harmonic current (& other zero sequence currents)	• flows through the secondary winding and into its primary delta winding where it re-circulates. • significant 3rd harmonic voltage distortion at output. • lost capacity (not for K) higher losses.	• **canceled within its secondary winding.** • **extremely low 3rd harmonic voltage distortion at output.** • **full capacity available.** • **very low losses.** • **improved load balancing.**
5th & 7th harmonic current	• flows through the transformer and into the primary system (30 degree phase-shift primary/secondary at 60Hz.). • typically substantial voltage drop through transformer at 5th & 7th harmonic. • 5th & 7th harmonic currents add together in primary system at the common feed point (main 480V panels) for a high harmonic current flow back to UPS. • substantial voltage THD at main 480V panel due to long feeder run. • lost capacity. • decreased PF.	• ***PowerStar*^{TM} *T1000's* are installed in pairs, one model is configured to phase-shift 5th & 7th as they pass through, the other does not phase-shift.** • **Small voltage drop at 5th & 7th through *PowerStar*^{TM} *T1000.*** • **5th & 7th currents subtract from each other at common point feeding multiple.** • ***PowerStar*^{TM} *T1000* units (main 480V panels) dramatically reducing the harmonic current flowing back to the UPS.** • **very little voltage THD at main 480V panel.** • **freed up system capacity.** • **increased PF.**

Predicted Harmonic Levels with POWERSMITHS *PowerStar*™ *T1000* transformers

The harmonic analysis yielded the following estimated Voltage THD levels, based on the same system configuration except replacing the 75kVA K-13 transformers with ***POWERSMITHS PowerStar*™ *T1000*** transformers.

Transformers: 75kVA, POWERSMITHS *PowerStar*™ *T1000*

Module	**Distance**	**Estimated Vthd**				**Neutral-GND**
	UPS to main 480V DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	2.5-3.0%	3-3.5%	3.5-4%	5.5-6%	4.5 - 6.0 V
B	410'	2-2.5%	2.5-3%	3-3.5%	5-5.5%	4.5 - 6.0 V
C	300'	2-2.5%	2.5-3%	3-3.5%	5-5.5%	4.5 - 6.0 V
D	530'	2.5-3.%	3-3.5%	3.5-4%	5.5-6%	4.5 - 6.0 V
E	700'	2.5-3%	3-3.5%	3.5-4%	5.5-6%	4.5 - 6.0 V
F	825'	2.5-3%	3-3.5%	3.5-4%	5.5-6%	4.5 - 6.0 V

NOTE: EXPECTED PF AT UPS OUTPUT: 0.87-0.95

Note that the range of voltage distortion is reduced because of the harmonic cancellation. Note that the voltage THD is still above slightly above the recommended 5% level at the load, this is due to the fact that harmonic currents still flow downstream of the point of treatment, and this run is over 100 feet long.

Neutral-Ground Voltage

Note that in both cases of transformer-based treatment alone, the neutral-ground voltage level is the same high level. The reason is that the neutral is bonded to ground at the transformer per electrical code requirements. Flow of current along the neutral conductor back to the transformer results in a build-up of neutral-ground voltage downstream of any transformer be it a K-rated or POWERSMITHS transformer. The neutral-ground voltage level is determined Ohm's law (Voltage = Current x Impedance), and therefore is a function of neutral current amps as well as neutral cable size and feeder length to the panel. The level can be expected to be high where high densities of single-phase electronic equipment like PCs are located far from the transformer. Many manufacturers of electronic equipment recommend maintaining neutral- ground voltage at a minimum (less than 3 volts, and sometimes less) insure reliable equipment operation.

Achieving full compliance with IEEE-519 recommendations

To bring the system fully within IEEE recommended levels, treatment closer to the loads is required. By far, the most effective price/performance point is at the 3-phase panel feeding the circuits to the loads. While this maybe difficult to achieve in the case at hand, it should be considered since it is the only way to be fully compliant.

OPTION #2

PROPOSED Fully Compliant HARMONIC TREATMENT

POWERSMITHS PowerStar^{TM} T1000 transformers with N1000 neutral current reducers at each local panel (4 per transformer)

To fully address the neutral-ground voltage issue, removal of the neutral current is needed at the 3-phase panel closest to the loads - in this case at each 100A panel downstream of the distribution transformer. The ***POWERSMITHS PowerStar^{TM} N1000*** will accomplish this. It is connected in parallel at the panel, where it has provides several benefits: significant drop in 3rd harmonic current, neutral current and neutral-ground voltage, improved load balancing, improved power factor, reduced peak and average current, voltage support in case of single-phase outage, reduced current and voltage distortion. The required size for the N1000 is a 120 Amp neutral current rating.

While many N1000's are required for this UPS system configuration, they are relatively small in size and cost, and provide many tangible benefits.

The following table summarizes the anticipated performance:

Transformers: 75kVA, POWERSMITHS T1000, with 120A N1000 at each 100A panel (4 per transformer)

Module	Distance	Estimated Vthd				Neutral-GND
	UPS to main DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	2.5-3.0%	3-3.5%	3-4%	3.5-4.5%	0.5-1.0 V
B	410'	2-2.5%	2.5-3%	2.5-3.5%	3.5-4.5%	0.5-1.0 V
C	300'	2-2.5%	2.5-3%	2.5-3.5%	3.5-4.5%	0.5-1.0 V
D	530'	2.5-3.%	3-3.5%	2.5-4%	3.5-4.5%	0.5-1.0 V
E	700'	2.5-3%	3-3.5%	2.5-4%	3.5-4.5%	0.5-1.0 V
F	825'	2.5-3%	3-3.5%	2.5-4%	3.5-4.5%	0.5-1.0 V

As shown in the table, lower levels of voltage THD and neutral-ground voltage are evident. The combination of T1000 transformers and local N1000 is a total solution that will be in full compliance with IEEE-519.

OPTION #3

PROPOSED Fully Compliant HARMONIC TREATMENT

Standard transformers with alternating PowerStar^{TM} N1000 and PowerStar^{TM} N1000 PLUS at local panels (2 of each per transformer)

To fully address the neutral-ground voltage issue, removal of the neutral current is needed at the 3-phase panel closest to the loads - in this case at each 100A panel downstream of the distribution transformer. This means the 3rd harmonic at the local panel. Remember that the loads are also generating 5th & 7th harmonic current that require treatment. Instead of dealing with 5th & 7th back at the transformers, this can also be accomplished closer to the loads (which is better) by using a combination of N1000 PLUS and N1000 . The N1000 PLUS is an in-line device compared to the N1000 which is connected in parallel. The advantage of the N1000 PLUS is that in addition to removing the 3rd harmonic it phase-shifts the 5th & 7th harmonic currents as they flow through it. Therefore, if half of the panels have N1000 PLUS and the other half have N1000, the 3rd is always removed at the panel. The 5th & 7th flow unchanged from the panels with N1000, and they cancel with the phase-shifted 5th & 7th that flow back from the panels that have N1000 PLUS . This combination means that 3rd, 5th, 7th, neutral current and neutral-ground voltage are all treated downstream of the transformer. Treatment close to the loads means excellent harmonic reduction, and an added benefit is that since the harmonics have been removed there is no longer a need for a special transformer. The net result is a significant drop in 3rd harmonic current, neutral current and neutral-ground voltage, improved load balancing, improved power factor, reduced peak and average current, voltage support in case of single-phase outage, reduced current and voltage distortion. Therequired size for the N1000 is a 120 Amp neutral current rating. The N1000 PLUS should be sized for the feeder protection. For a 100A feed, a 30kVA N1000 PLUS is appropriate, a 150A feed needs a 45kVA unit, and a 200A or 250A feed needs a 75kVA N1000 PLUS.

The following table summarizes the anticipated performance:

Transformers: 75kVA, standard, not K-rated, with alternating 120A N1000 and 30kVA N1000 PLUS at the local 100A panels (2 of each per transformer)

Module	**Distance**	**Estimated Vthd**				**Neutral-GND**
	UPS to main DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	2.5-3.0%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V
B	410'	2-2.5%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V
C	300'	2-2.5%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V
D	530'	2.5-3.%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V
E	700'	2.5-3%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V
F	825'	2.5-3%	2.5-3%	2.5-3%	3-4%	0.5-1.0 V

As shown in the table, the combination of N1000 and N1000 PLUS at the local panels is a total solution that will be in full compliance with IEEE-519.

OPTION #4

PROPOSED Fully Compliant HARMONIC TREATMENT

POWERSMITHS PowerStar^{TM} T2000 transformers feeding pairs of local panels.

Since the build-up of neutral-ground voltage and 3rd harmonic voltage is due to the long feeders downstream of the transformers in the snorkel, local panel treatment would address these items. The option of adding N1000's at each panel is one way, but there is another way that is perhaps more ideal from an electrical point of view. However, this would involve the modification of the distribution system to accommodate T2000 transformers that would each feed pairs of 100A panels. This would mean the elimination of the need for transformers since 480V would now be supplied directly to the T2000 units. Only 2 feeds would now be required from each main 480V panel.

Assuming that 2 of the local 100A panels could be placed within 10-20 feet or so of the T2000 , there would be little neutral-ground voltage at the loads, the 3rd harmonic would be canceled within the secondary windings, and the 5th & 7th from each panel would subtract from each other also within the secondary windings, resulting in essentially complete harmonic current cancellation at the T2000.

Typical Distribution system layout downstream of the main 480V panel

The following table summarizes the anticipated performance:

Transformers: 45kVA, POWERSMITHS *PowerStar^{TM} T2000*

Module	**Distance**	**Estimated Vthd**				**Neutral-GND**
	UPS to main DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	2.5-3.0%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V
B	410'	2-2.5%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V
C	300'	2-2.5%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V
D	530'	2.5-3.%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V
E	700'	2.5-3%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V
F	825'	2.5-3%	2.5-3%	2.5-3%	3-3.5%	0.3-0.8V

As shown in the table, use of the T2000 means full compliance with IEEE-519 is easily achieved.

The following analysis shows why it is not acceptable to address the 5th & 7th but not treat 3rd harmonic on the secondary side.

For example, let's look at transformers that have dual secondary phase-shifted windings but trap 3rd harmonic in the primary delta winding.

While this approach does treat 5th & 7th effectively, it does not treat 3rd harmonic current, but simply traps it and other zero sequence currents in the primary Delta winding of the transformer - like any Delta-wye transformer (see previous comparison table).

By phase shifting between two secondary windings, 5th and 7th harmonics can be canceled, but in these transformers the zero sequence impedance is high, therefore, voltage distortion is high at the 3rd harmonic since it is by far the largest harmonic current generated by single-phase electronic equipment. Therefore the only suitable use for these transformers is when the loads are exclusively line-line or 3-phase.

The following table summarizes the anticipated performance:

Module	**Distance**	**Estimated Vthd**				**Neutral-GND**
	UPS to main DP	Main DP	Transformer Primary	Transformer Secondary	At Load	Voltage @ Load
A	600'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V
B	410'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V
C	300'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V
D	530'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V
E	700'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V
F	825'	2.5-3.0%	2.5-3%	6-7.5%	6.5-8%	0.3-0.8V

The unacceptable performance of these transformers highlights the importance of using the POWERSMITHS approach which provides a true and complete harmonic treatment.

Conclusion

This article has looked at a power distribution system that is quite common where a large central UPS feeds distributed loads. Our analysis shows that without the right harmonic treatment voltage distortion will definitely be excessive at the loads. It also shows that while K-rated transformers will survive harmonic currents they do nothing for voltage distortion, which is a key issue for the reliable operation of equipment that is considered critical enough to be fed from a UPS.

The POWERSMITHS product family provides several alternatives that will ensure that the system is fully compliant with IEEE-519.