Understanding Harmonic Suppression Systems

Get a Handle on Wasted Energy and Excess Heat

By Michael Lowenstein and Jonathan Piel

A typical casino will have thousands of switched-mode power supplies on-line, twenty-four hours a day, seven days a week, 365 days a year. A typical slot machine will have at least two and likely three or more. There's the SMPS for the monitor (regardless of whether it's a CRT or an LCD), the power supply for the game's logic and often a separate power supply for the bill validator. Possibly added to the mix will be a power supply for a hopper, ticket printer and/or SMIB.

Multiply that by 2000 machines or more, add in all of the computers for the back-end system (including all of the DCUs, etc.) as well as each and every office computer and its associated monitor along with the display monitors scattered around the casino floor, in the surveillance room and, if you have a hotel, all of the television sets in the guest rooms and you begin to see that your casino has thousands of switched-mode power supplies in operation at this very moment.

"So what's the big deal about that?" you ask. "As long as the power company can provide enough current to power the machines and we have the place wired properly so the current is distributed and the loads are balanced correctly, it's all good, right?"

Well, yes and no. Sure, it all works correctly but there are hidden, insidious forces at work when you have so many switched-mode power supplies in operation at the same time. These evil forces are dropping the efficiency of your system and likely causing you to spend thousands of extra dollars each year, not only for electric power but also for the air-conditioning required to cool your casino.

These nefarious culprits are called "harmonic currents" and it's up to the White Knights of technology to eliminate them from your gaming property forever. Problems caused by harmonic currents include overheated transformers and wiring, random circuit breaker tripping and reduced useable system capacity.

Our White Knight is something called "harmonic suppression." Harmonic suppression systems can be installed to eliminate the flow of the

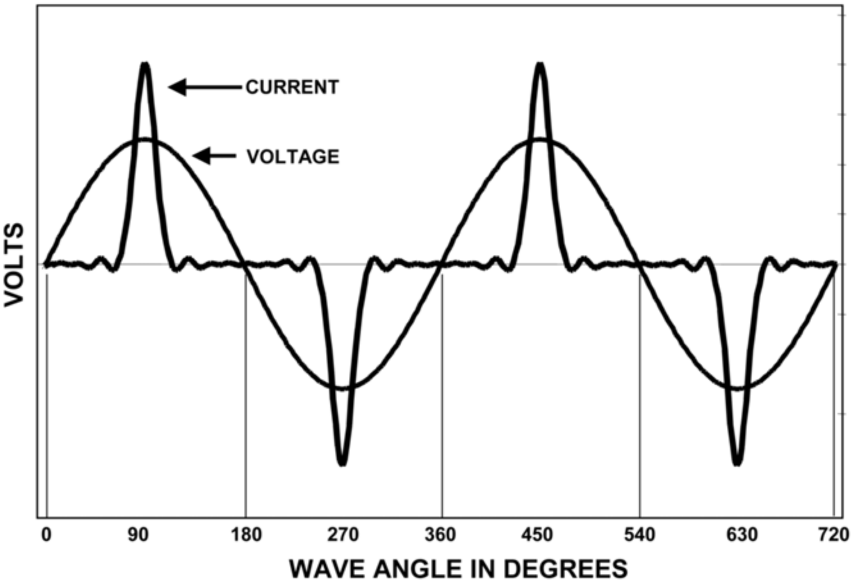
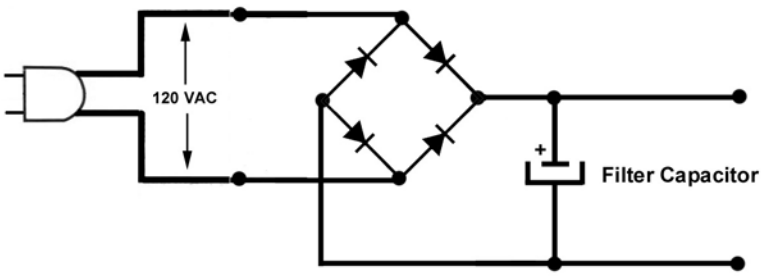


Figure 1. Here's our first problem: Although the AC voltage is a sine wave, the rectifier draws its current in spikes.



The input circuit of an SMPS is a bridge rectifier that changes the 120 volt AC input to DC. A capacitor smoothes this DC to eliminate voltage ripples and the resultant DC bus has a voltage of about 170 volts.

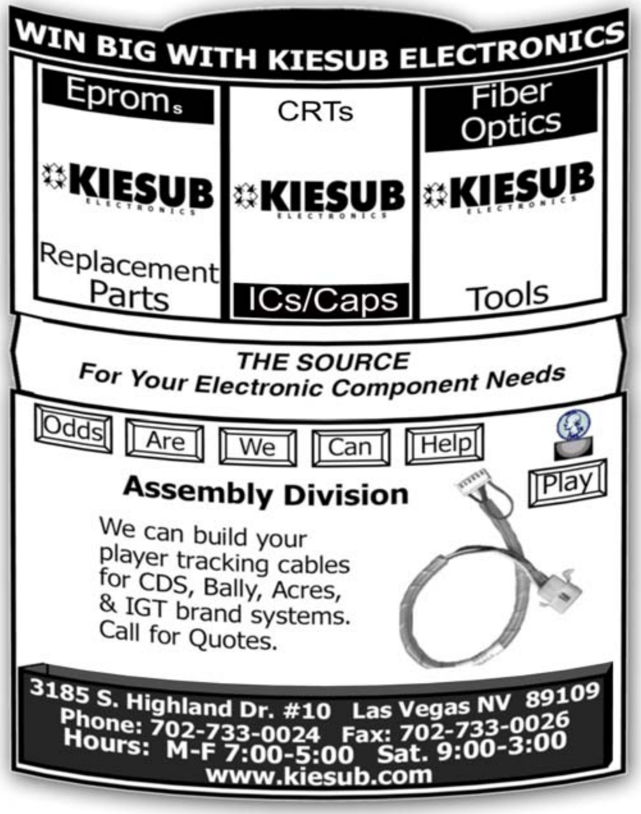
most troublesome of these bad boys, the "third harmonic" currents. Economic benefits of installing such systems include increased capacity (good if you're in California where Governor Arnold Schwarzenegger has just signed an agreement allowing unlimited slot machines) increased component lifetime and reduced down time. Later in this discussion, you'll see how it is now possible to measure the energy savings obtained when excessive harmonic current flow is eliminated in an electrical system. These savings are due to reduced I^2R losses in transformers and wiring and reduced air conditioning costs.

Harmonic Currents

Harmonic currents are a direct result of the way in which a switched-mode power supply (SMPS) draws current from the system. The input circuit of an SMPS is a bridge rectifier that changes the 120 volt AC input to DC. A capacitor smoothes this DC to eliminate voltage ripples and the resultant DC bus has a voltage of about 170 volts when the AC rms input is 120 volts. Although the AC voltage is a sine wave, the rectifier draws its current in spikes as shown in Figure 1. These spikes require that the AC supply system provide harmonic currents, primarily 3rd, 5th and 7th. These harmonic currents do not provide power to the SMPS, but they do take up distribution system capacity. The principal harmonic current is the 3rd (180 Hz) and the amplitude of this current can be equal to or even greater than that of the fundamental current.

Harmonic Current Flow in a Wye Distribution System

When SMPS loads are connected as shown in Figure 2, each phase wire carries both the 60Hz fundamental current that supplies power to the SMPS and the harmonic currents that are there because of the way the SMPS draws its current. While most



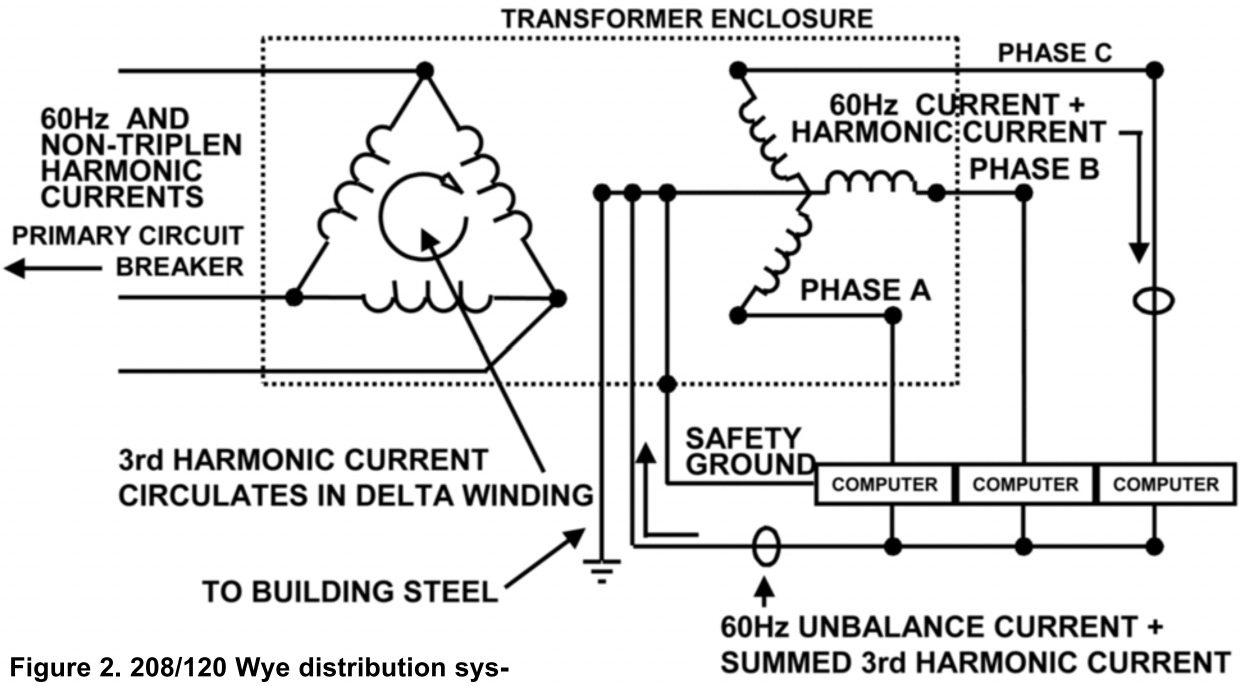


Figure 2. 208/120 Wye distribution system with phase-neutral computer loads

of the harmonic currents cancel in the neutral wire, just as the 60Hz currents do, the 3rd harmonic current and other currents divisible by three are additive in the neutral wire. Thus, if the 3rd harmonic current were 100 amps in each phase, the 3rd harmonic current returned to the X0 transformer connection by the common neutral wire would be 300 amps.

This fact has implications for system design, since the entire electrical system must meet the national electrical code specifications for wire and conduit size. If it is expected that SMPS loads will cause high neutral currents, wires must be sized for the anticipated load. Instead of downsizing neutral wires, once common practice for a system supporting only linear loads, now neutral wires must be oversized or doubled. Larger conduit must be installed to handle more or larger wires. (Although the code permits downsized neutrals if the system is not powering non-linear loads, language in NEC 310.15(B)(4)(b, c) (2002) requires neutral conductors to be considered current-carrying conductors when nonlinear (SMPS) loads are present. It should be noted that there is no code requirement for double neutrals, only that the neutrals be properly sized for the expected current.)

System Problems Caused by 3rd Harmonic Currents

The effect of current distortion on distribution systems can be serious, primarily due to the increased current flowing throughout the system. Following are some of the problems that must be considered.

1. All distribution systems are rms current limited. For instance, a 150 kVA 208/120 wye transformer is rated for 416 rms amps per phase. The more harmonic current flowing, the less fundamental current can be supplied. Since the harmonic current does not deliver any power, its presence uses up system capacity and reduces the number of loads that can be powered. Either the system must be de-rated or a larger system, that can only be partially utilized, must be installed.

2. Harmonic currents flowing through the system wiring cause increased I^2R heat losses. This heating can increase the temperature of wires and switchgear to the point that erratic operation or even fires can occur. One study found that 33% of telecommunication fires were

caused by failures of power systems or components.

3. Balanced 3rd harmonic currents cannot flow out of a delta primary. Therefore, they circulate in the primary of the transformer where they are dissipated as heat, Fig. 2. The current circulating in the transformer delta primary winding contributes to the load on the winding, but does not flow through the primary circuit breaker protection. Thus the transformer primary winding can be overloaded and the breaker that is expected to protect the transformer will not do so.

4. Heat dissipated by transformers, switchgear, and wiring represents wasted energy. Energy losses, brought about by harmonic current flow, can result in significant increases in operating costs.

Alternatives for Harmonic Mitigation

Accommodation Methods

Traditional methods used to mitigate the effects of harmonic currents involve "accommodation" of the currents after they are in the system.

1. Overbuild the system to handle the extra current. Double-sized neutral wires, oversized switchgear, and transformers de-rated to less than their full capacity are examples of system overbuilding.

2. Install a k-rated transformer. To reduce the chance of transformer failure due to overheating, special transformers, known as "k-rated," have been designed to handle high harmonic loading, including 3rd harmonic currents circulating in the delta primary. The k-rated transformer will survive overheating when subjected to high harmonic loading, but the harmonic currents are still present in the system.

3. Install a zig-zag reactor. The zig-zag reactor contains special windings connected so as to present a low impedance to 3rd harmonic currents and a high impedance to 60 Hz currents. When a zig-zag reactor is connected between the phases and neutral of a wye system, the 3rd harmonic currents are diverted through the device. These currents no longer flow, from the point where the zig-zag is connected in the system, upstream to the transformer. However, the phase and neutral wires from the zig-zag toward the loads still carry all the harmonic currents including the 3rd, and double neutral wires are recommended.

4. Install a zig-zag transformer. A "zig-zag" transformer can be used to replace the standard transformer in a system. This device has the special windings of the zig-zag reactor built into the transformer secondary so that the 3rd harmonic currents are cancelled in the secondary and do not circulate in the primary winding. Again, the phase and neutral wires from the transformer to the loads still carry all the harmonic currents and double neutral wires are recommended.

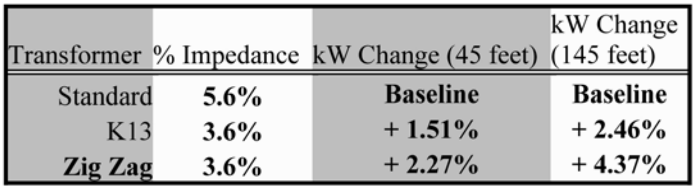
Problems with Accommodation Methods

While accommodation methods enable the electrical system to survive harmonic currents, they have a number of shortcomings.

1. Useful system capacity is not changed. Harmonic currents still flow throughout the system wiring and rms current is not decreased.

2. Heating of wires and switchgear is not reduced. Although the temperature of transformers may be reduced, harmonic currents still flow throughout the system wiring.

3. Energy losses due to I^2R heating are not reduced. Since the harmonic currents still flow throughout the system wiring, energy is still wasted. In fact, studies have shown that the installation of certain accommodation methods may actually increase energy losses. The typical impedance of zig-zag transformers and k-rated transformers is lower than that of a standard transformer. Likewise, an oversized transformer typically shows a lower impedance than a smaller transformer. Since transformer impedance is lower, harmonic current flow throughout the system is actually increased. A recent study shows that a signifi-



Transformer	% Impedance	kW Change (45 feet)	kW Change (145 feet)
Standard	**5.6%**	**Baseline**	**Baseline**
K13	**3.6%**	**+ 1.51%**	**+ 2.46%**
Zig Zag	**3.6%**	**+ 2.27%**	**+ 4.37%**

Table 1. Increase in kW useage due to decrease in transformer impedance

cant increase in kW usage results from installing a lower impedance transformer. Data from this study are shown in Table 1.

Harmonic Suppression

Harmonic suppression systems (referred to as HSS) use a different approach to mitigate harmonic currents in the distribution system. Their application is based on the same concept that is used in modern medicine, “preventative action. “Instead of treating the symptoms of a disease, it is far better to keep the disease from occurring. The HSS is designed to prevent the flow of harmonic currents in the distribution system, rather than treating or accommodating the currents after they are there.

The HSS consists of a parallel resistive/inductive/capacitive (RLC) network tuned to the 3rd harmonic, or 180 Hz for a 60 Hz fundamental frequency. The electrical characteristics of this type of circuit are such that it has a very high resistance to the flow of 3rd harmonic current and a very low resistance to the flow of the fundamental 60Hz current. Application of the HSS is shown in Figure 3.

The HSS is connected between the neutral wire and the transformer X0. All current that flows through the phase wires to the load must return through the neutral. If 3rd harmonic current cannot flow in the neutral, due to the high impedance of the HSS, then no 3rd harmonic current can flow in the phase wires. The damaging 3rd harmonic current is blocked throughout the entire distribution system from the transformer out to the furthest load. There is no 3rd harmonic current circulating in the delta transformer primary because there is no 3rd harmonic current available to circulate. The transformer is now fully protected by the primary circuit breaker against overloading. Phase

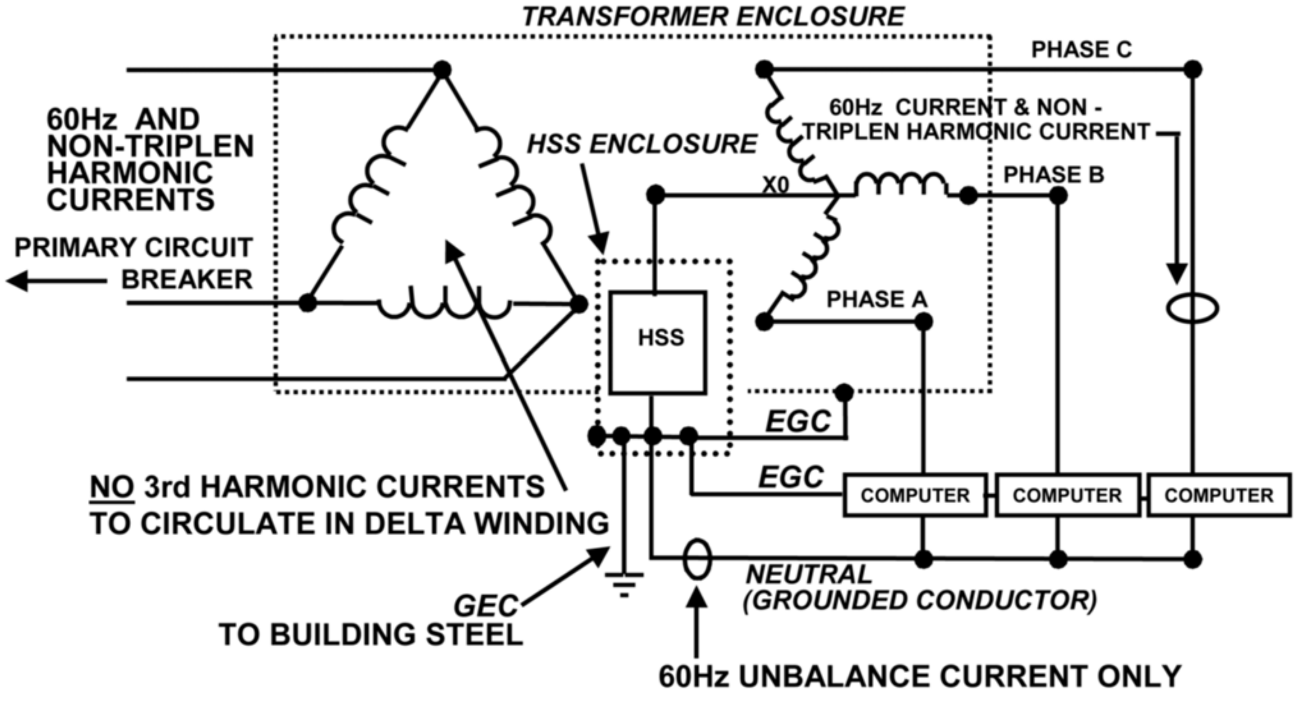
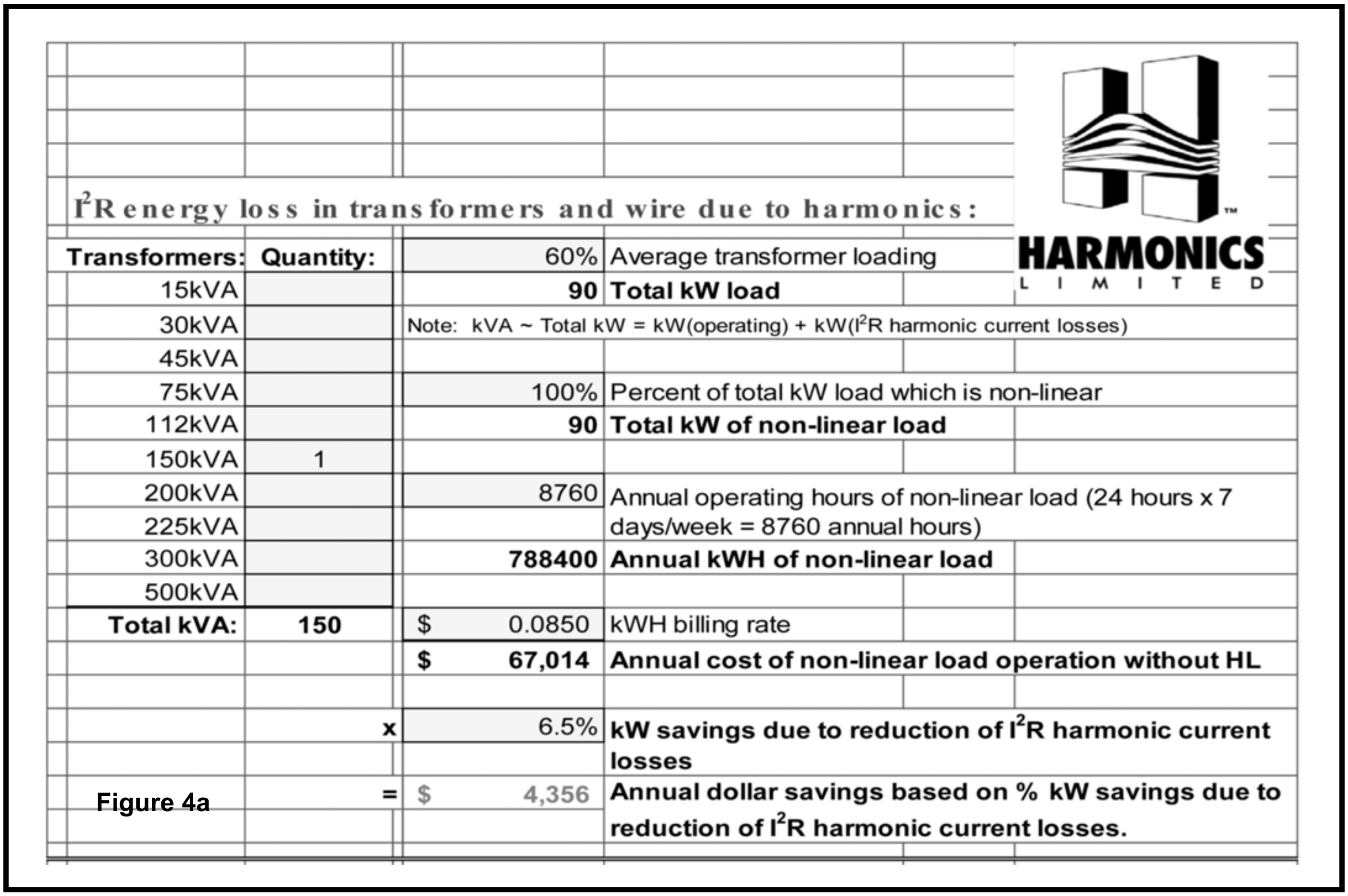


Figure 3. 208/120 Wye distribution system with phase-neutral loads and HSS



I^2R energy loss in transformers and wire due to harmonics:

Transformers:	Quantity:			
15kVA			60%	Average transformer loading
			90	**Total kW load**
30kVA			Note: kVA ~ Total kW = kW(operating) + kW(I^2R harmonic current losses)	
45kVA				
75kVA			100%	Percent of total kW load which is non-linear
112kVA			**90**	**Total kW of non-linear load**
150kVA	1			
200kVA			8760	Annual operating hours of non-linear load (24 hours x 7 days/week = 8760 annual hours)
225kVA				
300kVA			**788400**	**Annual kWH of non-linear load**
500kVA				
Total kVA:	**150**		\$ 0.0850	kWH billing rate
			\$ 67,014	**Annual cost of non-linear load operation without HL**
		x	6.5%	**kW savings due to reduction of I^2R harmonic current losses**
		=	\$ 4,356	**Annual dollar savings based on % kW savings due to reduction of I^2R harmonic current losses.**

Figure 4a

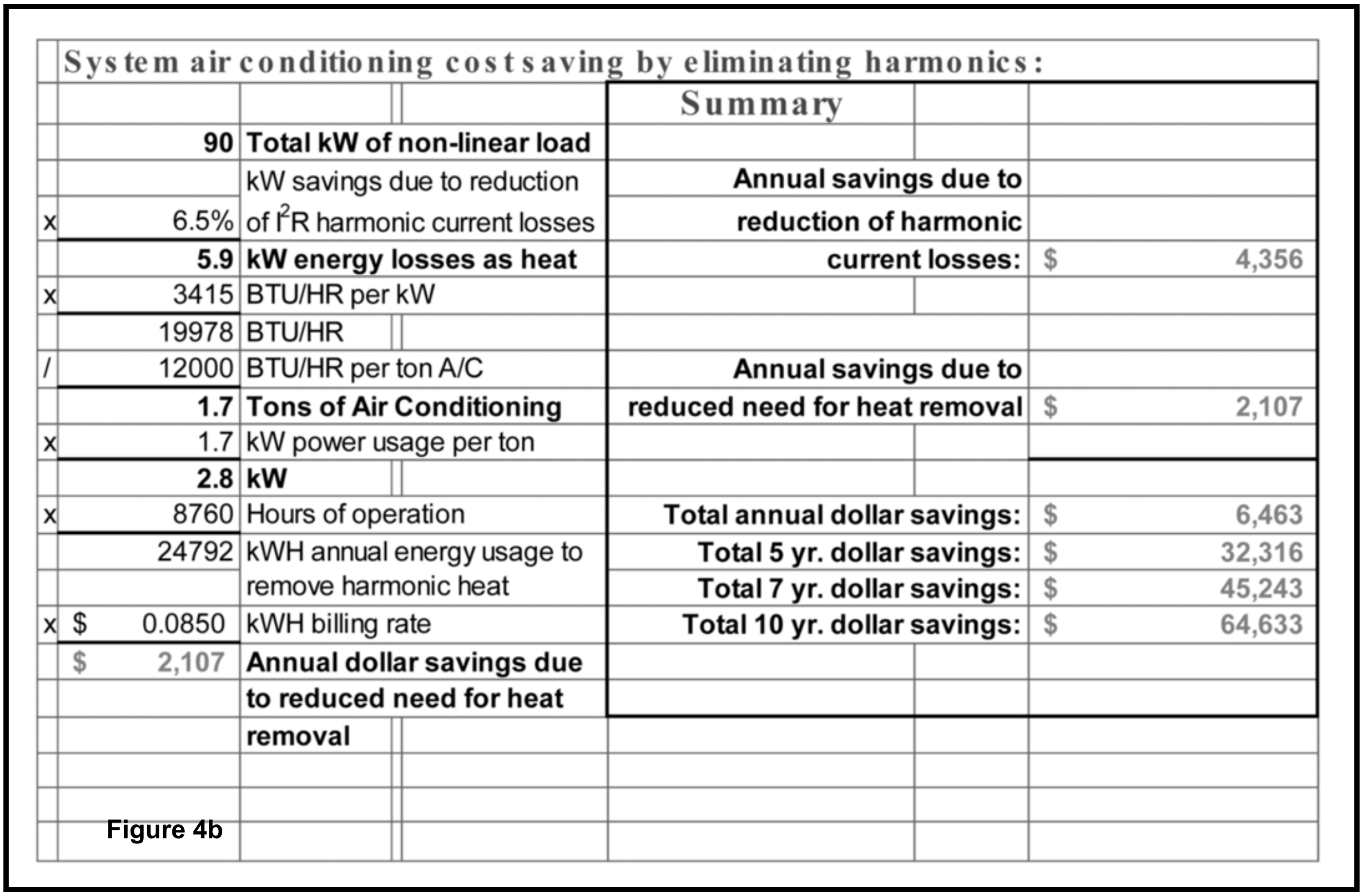
wires have more capacity available to carry useful load and double neutrals are not necessary. The neutral, for code purposes, need no longer be considered a current carrying conductor. Overheating of transformers, switchgear, and wiring is eliminated, increasing the lifetime of all system components.

Benefits of the HSS

Four areas will be discussed: 1) enhanced life safety; 2) increased system capacity; 3) greater reliability; 4) energy and operating cost savings.

1) Enhanced Life Safety.
3rd harmonic currents flowing in the system can overload transformers, switchgear, and wiring. With neutral currents greater than the phase currents, facilities, and particularly older facilities, are at risk from overheated wiring leading to fires. Transformers with high 3rd

A typical installation



	System air conditioning cost saving by eliminating harmonics:			
			Summary	
	90	**Total kW of non-linear load**		
		kW savings due to reduction	**Annual savings due to**	
x	6.5%	of I^2R harmonic current losses	**reduction of harmonic**	
	5.9	**kW energy losses as heat**	**current losses:**	$ 4,356
x	3415	BTU/HR per kW		
	19978	BTU/HR		
/	12000	BTU/HR per ton A/C	**Annual savings due to**	
	1.7	**Tons of Air Conditioning**	**reduced need for heat removal**	$ 2,107
x	1.7	kW power usage per ton		
	2.8	**kW**		
x	8760	Hours of operation	**Total annual dollar savings:**	$ 6,463
	24792	kWH annual energy usage to	**Total 5 yr. dollar savings:**	$ 32,316
		remove harmonic heat	**Total 7 yr. dollar savings:**	$ 45,243
x	$ 0.0850	kWH billing rate	**Total 10 yr. dollar savings:**	$ 64,633
	$ 2,107	**Annual dollar savings due**		
		to reduced need for heat		
		removal		

Figure 4b

harmonic currents circulating in the primary, and unprotected against overloading, can fail or catch fire. By eliminating 3rd harmonic currents from the transformer to the furthest outlet, the HSS eliminates the risk of overcurrent caused fires.

2)Increased System Capacity.
All electrical distribution systems are rms current limited. Harmonic currents carried by transformers, switchgear, and wiring use up system capacity that could be used to carry 60Hz currents that do work. By eliminating 3rd harmonic currents throughout the entire distribution system, the HSS provides the facility with more useful capacity without requiring that the electrical system be upsized.

3) Greater Reliability.
The major cause of failure for transformers and switchgear is overheating. Random breaker tripping due to harmonic heating is well known. The elimination of 3rd harmonic currents reduces heat in all parts of the distribution system, thereby reducing the likelihood that system components will fail or trip off due to excessive temperatures. The elimination of high neutral currents lowers neutral-ground voltages and reduces the likelihood that data errors will occur.

4) Reduced Energy and Operating Costs.
Excessive heat in electrical distribution systems means wasted energy. The heat is due to I^2R losses in all system components, and appears directly in energy bills as increased kW hour charges. Installation of the HSS eliminates this wasted energy and leads to a direct reduction in energy costs. One recent study showed that, depending on transformer loading and the distribution distance from the transformer, the energy saved by eliminating 3rd harmonic currents ranged from a minimum of 2. 5% to a maximum of 8% of the energy used to power computers. [3]Another study, conducted for the California Energy Commission, measured realized energy savings, due to the HSS, of from 4 to 6%. [4]

Energy Estimator

An energy savings estimator is available as a Microsoft

Excel spreadsheet as illustrated in Figures 4a and 4b on the next page. This estimator allows the user to input electrical system parameters for any system. The dollar savings expected for the system when an HSS is installed are quickly calculated.

In addition to the direct waste of energy caused by harmonic currents, there is a secondary effect. Air conditioners must be powered to remove this excess heat. Reducing extra operation of air conditioners, necessary because of harmonic generated heat, can add another 1-3% to the energy saved by an HSS.

Case Studies

Three case studies are outlined below. In each study, neutral 3rd harmonic currents were almost totally eliminated and useful load capacity was increased. It was estimated that energy savings due to the HSS would result in complete payback of the purchase cost in 14. 5 to 26 months.

Case study 1. A major TV broadcast studio

The following data were obtained for this facility:
1. 3-500 kVA UPSs
2. Neutral current reduced by 81% from 1513 to 283 amps
3. 3rd harmonic current reduced by 96% from 1508 to 56 amps
4. rms phase current reduced by 8%
5. Using energy savings estimator, ROI = 18 months

Case study 2. A major computer manufacturer

The following data were obtained for this facility:
1. 3-story office building
2. 225 kVA transformer 53% loaded
3. Neutral current reduced by78% from 301 to 67 amps
4. 3rd harmonic current reduced by 98% from 290 to 6 amps
5. rms phase current reduced by 12%
6. Using energy savings estimator, ROI = 26 months

Case study 3. An internet hosting facility

The following data were obtained for this facility:
1. 8-150 kVA k-13 transformers
2. Combined neutral current reduced by 76% from 1940 to 451 amps (average 56 amps)
3. 3rd harmonic current reduced by 98% from 1890 to 44 amps (average 5 amps)
4. rms phase current reduced by 21%
5. Using energy savings estimator, ROI = 14. 5 months

Conclusions

The harmonic suppression system is a well-established technology. As the case studies show, it has been embraced by a wide variety of users, including major computer manufacturers, banks, stock exchanges, educational institutions, insurance companies and broadcast facilities. In short, any group that uses multiple computers (such as a casino) can benefit from this technology. The capacity and energy savings are well documented and life safety and reliability issues also are addressed. The bottom line is that the installation of an HSS can pay for itself, by energy savings, in one to three years.

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Michael Z. Lowenstein holds an A. B. in chemistry from Oberlin College, and an MS and Ph. D. in physical and analytical chemistry and physics from Arizona State University. He spent 13 years as a College Chemistry Professor and 8 years as a National Program Manager for the Solar Energy Research Institute. His experience with harmonics includes 15 years designing filters for 3-phase industrial drives. In 1989 he founded Harmonics Limited, a company devoted to solving harmonic problems caused by multiple computer loads. He is currently President and Chief Technology Officer of the company.

Jonnathan K. Piel received a BSEE degree from Michigan Technological University. He is currently the Engineering Manager at Harmonics Limited, Milwaukee, Wisconsin, where he is responsible for power quality-related research, training, and product development. His main area of research has been single-phase non-linear harmonic phenomena and solution applications.