

ECONOMIC AND ELECTRICAL BENEFITS OF HARMONIC REDUCTION METHODS IN COMMERCIAL FACILITIES

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ABSTRACT

Power consumption of harmonic drawing loads is an increasing concern for cost conscious facility managers and engineers. One of the authoritative documents discussing this topic was published in the July/August 1997 IEEE Transactions on Industry Applications, by Thomas Key and Jih-Sheng Lai on “Effectiveness of Harmonic Mitigation Equipment for Commercial Office Buildings” [1]. The paper illustrated that up to 8% kW reduction could be realized by eliminating harmonic current at various points in a power distribution system, with the greatest benefits achieved with harmonic mitigation applied at the point of use. The research and results were reached through mathematical modeling of system losses and performance. In the six years since that paper was published, technology has caught up with theory and harmonic solutions now exist to quantify the results of this modeling document with empirical data.

The use of a Harmonic Suppression System (HSS) provides an opportunity to achieve similar benefits as point-of-use harmonic mitigation for large concentrations of single-phase harmonic drawing loads. HSSs are applied in series at the secondary of the distribution transformer, but are effective out to the furthest load, making conventional non-linear power supplies draw a more linear current. Data from actual field installations will illustrate the HSS features, functions and benefits. These field case studies will be confirmed and further expanded with results from controlled laboratory experiments. The collective field and laboratory results will be compared against the 1997 modeling paper. The

presentation of theory, laboratory results, and field results will provide a summary of the actual power savings expected with the application of Harmonic Suppression Systems in commercial facilities.

INTRODUCTION

In the near future, predictions concerning the “digital economy” indicate that more than 50% of all power consumed in the North America will be through power electronic devices including switch-mode power supplies, variable frequency drives, and other power electronic equipment. Harmonics drawn by these loads have significantly changed the power system requirements to protect these loads and to protect the system from these loads.

The function of the distribution system is to deliver fundamental current to the terminals of the load. Generally, fundamental current is the only component of current which performs useful work. In contrast, harmonic current is simply the “by-product” of the way non-linear loads draw current and are not necessary to perform useful work.

The “Effectiveness of Harmonic Mitigation...” [1] paper uses mathematical modeling of a 120V, 60kW, wye distribution system servicing non-linear loads to show the loss effects of harmonic currents and potential savings of removing or reducing the harmonics.

The paper segments the losses into 5 discrete segment (L4, L3, T1, L2, and L1) components starting at the 480V service entrance (Figure 1).

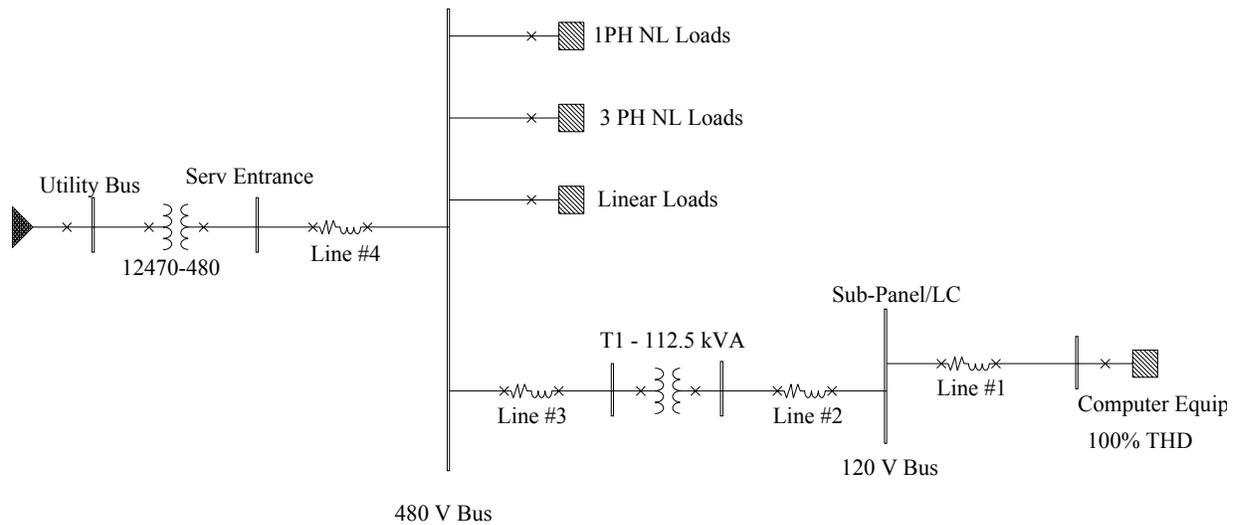


Figure 1 – Simplified Model from [1]

- L4 represents the 480V feeder from the main source transformer to the 480V main distribution panel
- L3 represents the 480V feeder from the 480V main distribution to T1
- T1 represents the 480/120-208V transformer
- L2 represents the 120V phase and neutral conductors which feed the distribution sub-panel (50 feet)
- L1 represents the 120V phase-neutral conductors feeding individual loads

Both fundamental current and harmonic current are drawn through each of the five segments while traveling to the load. As these currents are drawn through each of 5 segment resistances, the result is heat or watt losses. Heat is an undesired form of work. Both the useful work and undesired work draw kW. The intent is to reduce the kW by reducing the undesired work (heat), achieved by reducing the undesired harmonic currents.

In the model, approximately 87% of the system power is utilized by the loads to perform useful work. Five percent is lost as fundamental current heat. This is a fairly fixed loss, since reducing fundamental current would reduce useful work. Eight percent is lost as harmonic

current heat. It is important to understand the components that make up that eight percent (Figure 2).

As Figure 2 shows, L3 & L4 are insignificant and can be ignored since they have a very low impact on the total harmonic heat losses. The largest portion of harmonic heat loss is in the transformer T1. L1 and L2 are moderate components.

In summary, the original study applied a variety of technologies to mitigate the harmonics, with varying effectiveness to each portion of the distribution system and %kW savings on the primary of T1 (Table 1).

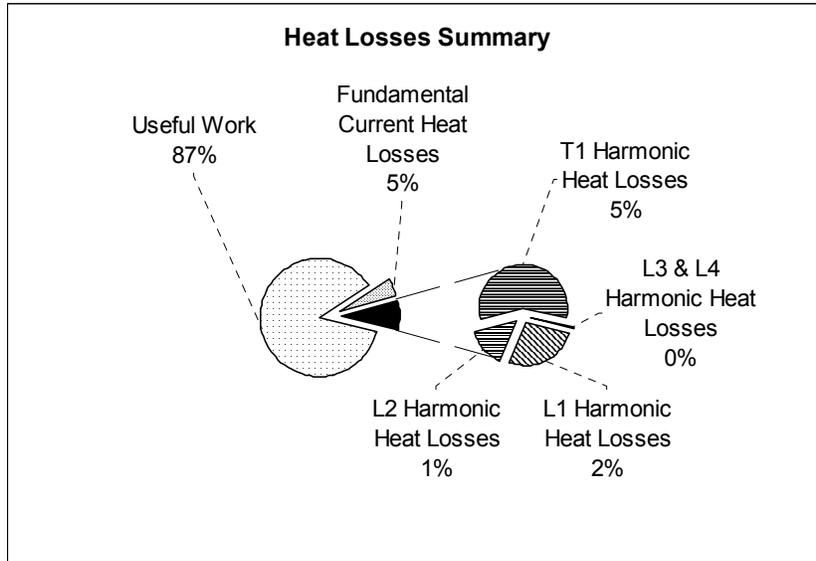


Figure 2 – Heat Losses Summary

	Load Connected		Load Center Connected		Transformer Secondary Connected
	Parallel-Connected Series Resonant Filter:	Series-Connected Parallel Resonant Filter:	Parallel Connected Active Filter	Parallel-Connected Zig-Zag Filter:	Series-Connected Neutral Current Filter
Sections Benefited	L1, L2, T1	L1, L2, T1	L2,T1	L2,T1	L1,L2,T1
% kW Savings	7.6%	7.4%	5.9%	2.5%	3.6%

Table 1 – Modeled Energy Savings by Harmonic Mitigation Methods

The Neutral Current Filter identified in the table utilizes the same technology as the Harmonic Suppression System (HSS).

The HSS inserts a passive high impedance element into the phase or neutral conductor(s) to “block” harmonic current flow. The element is “tuned” to block a characteristic frequency but has minimal or no effect on the normal 60 Hz power flow to the loads. For the purpose of this paper and discussions concerning the effectiveness, the HSS described here is specially designed to block the 3rd harmonic current. This type of harmonic suppression system is especially appropriate for switch-mode power supply (computer) loads, the most

common harmonic drawing single-phase loads, since the primary harmonic that they draw is 3rd harmonic current. HSSs are applied in series at the secondary of the distribution transformer but are effective out to the furthest load, making conventional non-linear power supplies draw a more linear current. In addition, since the 3rd harmonic current is not allowed to flow downstream or back to the transformer, it is also not allowed to flow upstream and into the transformer thereby reducing losses in the transformer (T1 in the Figure 1).

FIELD EXPERIMENTS

[2] states that “results can be linearly extrapolated to other cases”, and this has been

done in other modeling. Any modeling, though, assumes ideal conditions. Modeling real-world applications, or creating a predictive model, requires unique application information including copper losses, eddy-current losses, transformer impedance, and current and voltage distortion profiles on the transformer primary and secondary. This information is extremely difficult to procure for real world installations since most of it not on the nameplate or in manufacturers' catalogs. In addition, the way that harmonic currents are drawn by the loads is not a linear function, meaning that if a system is loaded to 50% you cannot assume that the harmonics drawn by the loads will have the same frequency spectrum at 100% loading.

The purpose of this paper is to quantify whether or not the modeling accurately represents the potential loss savings possible with the application of an HSS in real field applications. Most corrective equipment is not easily quantifiable in field applications since it often requires disconnection or reconnection of power system components. During these changes, it is often difficult in ensure that no other subtle changes have occurred that may impact the results. In field applications and in laboratory experiments, a bypass switch provides a unique opportunity to prove the effectiveness and monitor the kW consumption with and without the HSS corrective equipment. The change can be done literally "on-line" while the loads are drawing their normal power.

To help evaluate the modeling process, the HSS has been tested ([3] and [4]) in three office

environments with a bypass switch. The resulting % kW savings are shown in Table 2. The results of the field tests are similar to the model with some variations that are discussed in the next section. The Office 3 field test is unique in that there was already a zig-zag transformer as the baseline. The zig-zag transformer has similar benefits to the zig-zag filter (parallel-connected at panel), but with the zig-zag windings built into the secondary windings of the transformer. For the zig-zag transformer, there are no harmonic current mitigation benefits at L1 or L2 but only for the primary windings of T1. Since there was already some small harmonic mitigation, the % kW savings was just slightly less on this particular field test.

LABORATORY SIMULATION – TEST BENCH

The modeling and field tests showed some level of discrepancy that deserved further investigation. Therefore, empirical methods were developed to compare the results in a more controlled environment. To facilitate this, a 15kVA test bench was devised and manufactured.

A block diagram of the test bench is shown in Figure 3. The test bench features three potential power sources. Each of the 3 transformers is 15kVA, 208V delta primary, 120/208V wye secondary, copper wound, Energy-Star compliant in the following 3 categories: a "Standard" (K1) transformer, a "K13" transformer, and a "Zig-Zag" K13 transformer.

Field Results				
	Model	Office 1	Office 2	Office 3
Transformer Size (kVA)	112.5	75	75	150
Transformer Type	Standard	K13	K13	Zig-Zag
Transformer Loading	50%	25%	50%	65%
Secondary Current Distortion (no HSS)	100%	97%	80%	68%
Secondary Current Distortion (with HSS)	65%	74%	60%	32%
% kW Savings with HSS	3.60%	2.63%	2.68%	2.10%

Table 2 – HSS Application Field Results

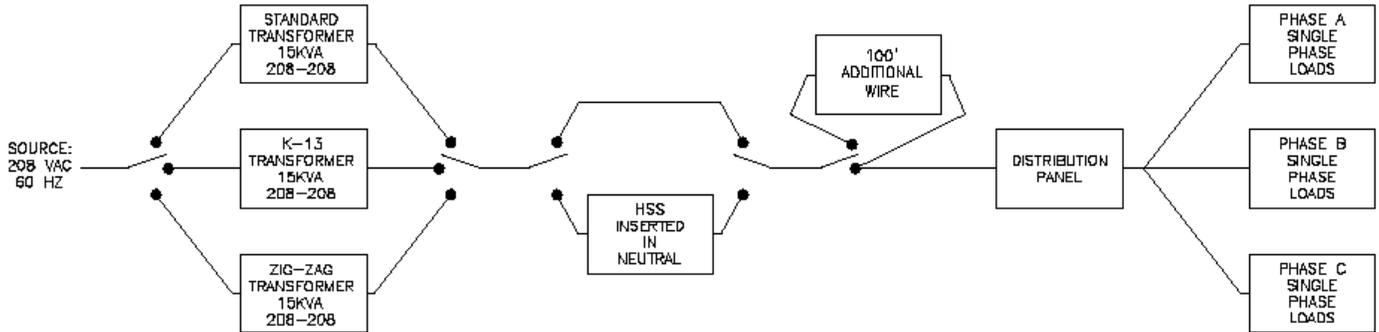


Figure 3-Test Bench Setup

The standard transformer has a typical impedance of 5.6%. K-rated transformers typically have a lower impedance than their standard transformer counterparts for equivalent kVA. On the test bench, the K-rated and the zig-zag transformers both have an impedance at or near 3.6%. In addition, the zig-zag transformer has a reduced zero-sequence impedance of 0.9%.

The loading on each phase consists of twenty 300 watt single-phase computer power supplies identical to those used in personal computers. These power supplies are each consistently loaded with resistors to about 250 watts. The test bench is configured from a central control panel. Each of the power supplies can be individually switched on or off to simulate different loading conditions. Utilizing contactors on the primary and secondary side of each transformer, the distribution system can be instantly changed to be powered by any transformer while the loads remain unchanged. Metering for the test bench is provided by two RPM model 1650 harmonic analyzers and several Fluke41B meters.

EFFECT OF IMPEDANCE ON HARMONIC CURRENTS

A discovery made while developing the test bench setup is that decreasing transformer impedance increases the percentage of current distortion. This discovery comes without evaluating harmonic mitigation methods, but just changing power sources. Utilizing the test

bench and changing only the supply transformer, while keeping all variables constant, resulted in remarkable differences in the magnitude and percent distortion of the secondary harmonic currents and primary watts consumption. Figure 4 shows each transformer providing different secondary harmonic currents for the same fixed 50% load.

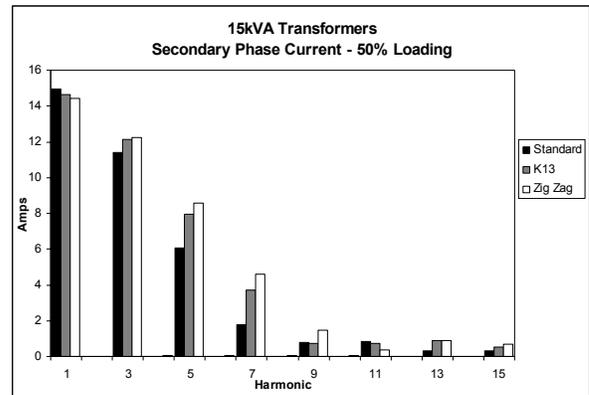


Figure 4 – Secondary Harmonic Current Spectra

The reason for these differences is directly related to the differences in transformer impedances. The effect is similar to industrial applications where 3% or 5% impedance line reactors are added in front of 3-phase drives to reduce harmonic currents drawn by the drives. The higher the impedance, the lower the current harmonics. IEEE P519A/D7 [6] illustrates this point with the example shown in Figure 5 comparing the difference in line current based on a 1% reactor and a 3% reactor (%Z).

Similarly, the test bench shows that using lower impedance transformers increases harmonic currents drawn by non-linear power supplies (Figure 6).

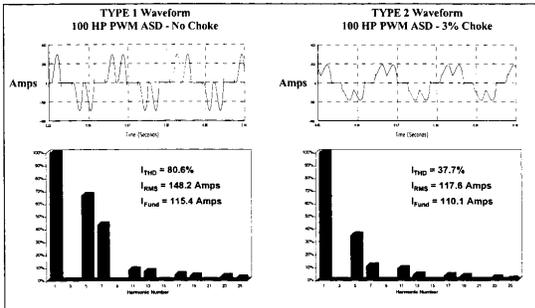


Figure 5 – IEEE 519A Benefit of Line Reactors

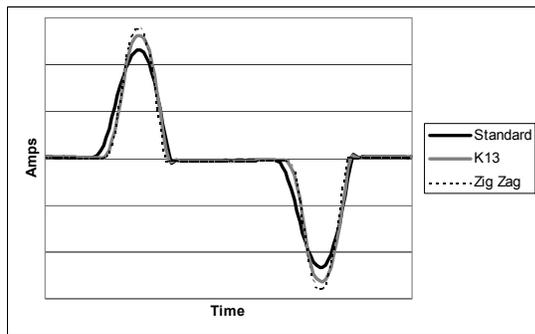


Figure 6 – Test Bench Load Current Difference By Source

For the K-rated transformer and the zig-zag transformer, the source impedance is reduced from the load standpoint, resulting in higher harmonics. This effect is even more significant for the zig-zag transformer with special windings for low zero-sequence impedance. Figure 6 shows the difference in one cycle of total load current. Notice that the higher the impedance, the lower the total current distortion. In drive applications, this phenomena yields diminishing returns and substantial voltage drop once the impedance exceeds about 6% of the load size.

EFFECT OF % LOADING ON HARMONIC CURRENTS

A second and closely-related discovery is that decreasing transformer loading increases the percentage of current distortion. This is also related to the actual impedance versus the load size. Very lightly loaded transformers allow to

flow very steep current waveforms which are very rich in harmonics.

The percent impedance (%Z) mentioned here is defined as an impedance compared to a specific load size, similar to the percent impedance that is defined for application of a line reactor for a drive or the impedance of a transformer (5.5% on a 15 kVA basis). IEEE and other sources define the percent impedance for a load based on the full load of the drive or other load. In this case, a bank of dc power supplies equal to the transformer nameplate of 15 kVA is considered to be full load or 100% loaded. This is an important distinction because a 5% reactance offers 5% impedance to a 100% load; but at 50% load, the equivalent impedance is 50% of 5%, or 2.5%, allowing more harmonic current to flow compared to full load. For this reason, harmonic currents for a loading of less than 100% tend to have higher %THD resulting from smaller per-unit line reactance. This point is illustrated in Table 3.

Transformer Loading:	25%	50%	75%	100%
I-THD(F):	101%	88%	76%	67%

Table 3 – %THD Based on Percent Loading (for Fixed Impedance Transformer)

EFFECT OF IMPEDANCE ON LOSSES AND KW CONSUMPTION

As these harmonic currents are drawn through each portion of the distribution system, the result is harmonic heat. Power loss due to harmonic heat is an undesired form of work and directly impacts the kW consumption as measured on the primary side of the transformer. Table 4 shows each transformer primary drawing different absolute 3-phase kW for the same fixed 50% load. Note that all of the transformers used in this investigation are labeled Energy-Star transformers. Decreasing the transformer impedance actually increases the watt losses as a percentage. Normally, increasing the impedance and thus, the resistance, would theoretically increase the I^2R losses. However, the reduction in current is more predominant in the equation since it is a squared term. Therefore, the net

benefit of reducing current and increasing resistance, in this case, yields a reduction in total losses.

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%, 0.9%	+2.27%	+4.37%

Table 4 – Comparison of Losses (50% Load) without Corrective Equipment Installed

Differences in kW consumption can become even greater as distribution impedance becomes greater, as with longer distribution runs. The secondary distribution distance on the base case test bench is fairly short (45 feet). Increasing the secondary distribution distance to 145 feet and re-testing each transformer source results in kW consumption differences in excess of 4%. All of this empirical testing shows that impedance of the transformer is one of the greatest influences on kW losses resulting from harmonics. Increasing other downstream impedances only magnifies this existing influence.

COMPARISON OF MODELING RESULTS TO FIELD RESULTS

While it may seem logical to extend the model linearly to different applications, it has been discovered that there are significant variables outside direct harmonic mitigation which may influence energy usage. The most influential variables not related to the mitigation method include:

Transformer loading – centering loads on a single relatively heavily loaded transformer rather than several lightly loaded transformers;
Impedance of the transformer – utilizing a standard transformer, where possible, to utilize the preferred higher impedance level.

HARMONIC MITIGATION SOLUTION EQUIPMENT SELECTION

The dichotomy of the aforementioned recommendations is that the standard transformer is not suitable for heavy non-linear loads. Utilizing a standard transformer may require harmonic mitigation solutions, which make the current consumption more linear.

	Load Connected		Load Center Connected		Transformer Secondary Connection	
	Parallel-Connected Series Resonant Filter:	Series-Connected Parallel Resonant Filter:	Parallel Connected Active Filter	Parallel-Connected Zig-Zag Filter:	Integral Zig-Zag Transformer: (Secondary Winding)	Series-Connected Neutral Current Filter
Passive Operation	X	X		X	X	X
Line-Side Harmonic Current Mitigation	X	X	X	X	X	X
Load-Side Harmonic Current Mitigation	N/A	N/A				X
Eliminates Oversized Neutrals	X	X				X
Sized per Transformer or Load	Load	Load	Load	Load	Transformer	Transformer

Table 5 – Comparison of Harmonic Mitigation Techniques

[1] and [2] identify that harmonic mitigation solutions applied at/in the load have maximum effectiveness, since they can reduce I-THD to 5% or less upstream throughout the distribution system (Table 5). Unfortunately, it is well recognized that this is a very expensive method, and utilizing a central mitigation technique may provide a better cost/benefit ratio. Of the non-load connected solutions, the HSS (aka: series-connected Neutral Current Filter) provides the most benefits without requiring resizing the device for changing loads or oversizing neutrals.

The 3rd harmonic (180Hz for 60Hz distribution system) is the most dominant harmonic for single-phase non-linear loads. As a triplen harmonic, it is also the most damaging since it combines in the shared neutral conductors and circulates in the delta windings of the transformer. To address this dominant harmonic, the HSS is tuned to have its maximum impedance at the 3rd harmonic (180Hz for 60Hz distribution systems). By addressing the worst of the harmonics, K-rating of the transformer is no longer necessary. Figure 7 shows the significant reduction of the normal non-linear load current with the application of the HSS. Note that it approaches the waveshape of the fundamental current, thus showing that by reducing the harmonics, the system becomes more efficient and provides the load only what it needs for real work.

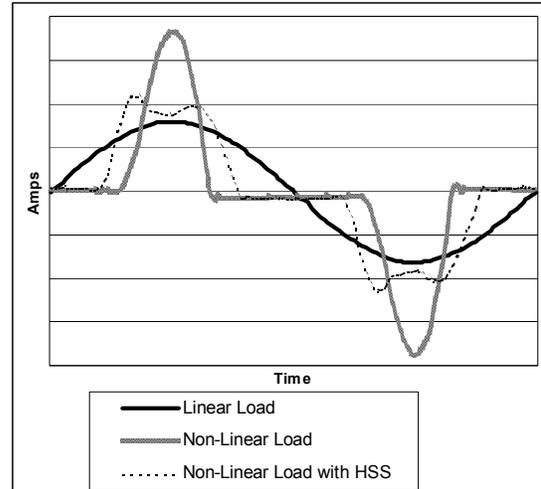


Figure 7 – Typical Current Waveshapes – Fixed Fundamental Baseline

By tracking energy changes when applying the HSS to the standard transformer on the test bench [5], similar results can be obtained relative to the model and the field data (Table 6). Under most loading conditions, the measured savings with the test bench are still slightly lower than predicted by the model, but this is mostly accounted for in the shorter secondary distribution distance on the test bench and transformer variables. When the distribution distance is increased an additional 100’ on the test bench, the energy savings become significantly more pronounced. This is mostly due to significant losses in the long, shared neutral conductor.

Laboratory Results						
	Model	Test Bench				
Transformer Size (kVA)	112.5	15	15	15	15	15
Transformer Type	Standard	Standard	Standard	Standard	Standard	Standard
Transformer Loading	50%	25%	50%	75%	100%	25%
Secondary Distribution Distance	200'	44'	44'	44'	44'	144'
Secondary Current Distortion (no HSS)	100%	101%	88%	76%	67%	70%
Secondary Current Distortion (with HSS)	65%	64%	53%	44%	36%	50%
Measured Energy Savings	3.60%	2.68%	2.35%	2.97%	3.66%	6.15%

Table 6 – Comparison of Laboratory Results

SUMMARY

With the use of Harmonic Suppression System technology, the 1997 [1] model predicts 3.6% kW savings, and the field results show an average 2.5% kW savings from harmonic reduction alone. These values are close, and differences reflect other variables not addressed in the modeling. The 15kVA test bench can be used to accurately simulate field results and show energy savings from 2.35% to 3.66% depending on changes to these variables; energy savings exceeding 6% is demonstrated with additional cable lengths. Results using the test bench show that there are significant impacts on %kW savings from variables not directly related to the HSS harmonic mitigation, including:

Variable	Measured kW Consumption Difference
Transformer Impedance	2.27%
Transformer Loading	1.31%

Table 7 – kW Impact of Other Variables

For switch-mode power supply loads, of the configurations tested, the best mix of variables to minimize non-linear load kW consumption include:

- loading the transformer close to its rating,
- minimizing wiring distances,
- designing with a standard transformer to utilize the preferred higher impedance,
- applying an HSS to reduce harmonics resulting in current being drawn much more linearly.

Use of the Harmonic Suppression System on a 120/208V distribution system heavily loaded with switch-mode power supplies will follow the modeling predictions and can vary from 2% to 6% kW savings depending on other variables.

The economic benefit and the potential savings identified in this paper can be illustrated in the following example for a data center operation. For a 150 kVA transformer loaded at 80%, the annual savings (at \$0.085/kWh) would range from \$1,800 to \$5,300 per year.

AUTHORS' BIOGRAPHIES

Jonathan 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. He has developed and presents weekly power quality lectures utilizing a versatile 15kVA distribution system. Jonathan is active in the IEEE Power Engineering Society.

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