COSTS AND BENEFITS OF HARMONIC CURRENT REDUCTION FOR SWITCH-MODE POWER SUPPLIES IN A COMMERCIAL OFFICE BUILDING

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***Abstract*—Harmonic currents generated by modern office equipment cause power system heating and add to user power bills. By looking at the harmonic-related losses in a specific electrical system—representing a commercial building—energy costs are quantified. The analysis shows that building wiring losses related to powering nonlinear electronic load equipment may be more than double the losses for linear load equipment. Current-related power losses such as I^2R, proximity of conductors, and transformer winding eddy currents ($I^2 h^2$) are considered. The cost of these losses is compared to the cost of reducing harmonics in the equipment design. Results show that an active-type harmonic-elimination circuit, built into the common electronic equipment switch-mode-power supply, is cost-effective based on energy loss considerations alone.**

I. INTRODUCTION

A common source of harmonic currents in power systems is electronic equipment that use a rectifier supplying a dc-link with storage or ripple-smoothing capacitors. This type of electronic power supply is used in everything from factory adjustable-speed drives to personal computers and home electronics. Experience has shown that the harmonic currents do not upset the end-use electronic equipment as much as they overload neutral conductors and transformers, and in general cause additional losses and reduced power factor for the electrical power system components transporting the real power along with the added harmonic components.

Overheating of building wiring has been most prominent in the commercial sector with a high usage of electronic-type equipment and a trend to even higher circuit loading in kVA per square foot. Office building electrical circuits that were designed for a relatively light plug load in the ‘60s and ‘70s may be overloaded by electronic equipment today. Increased harmonic distortion related to this equipment is common (see current waveforms in Fig 1).

There are several reasons for this trend. First, there is growing popularity of electronic equipment. Fax machines, copiers, printers, computers and other automation devices save time, reduce labor costs and can provide a significant increase in office productivity. Second, many of these electronic equipment are turned on a high percentage of the time, increasing the overall demand factor and maximum load as a percent of connected load.

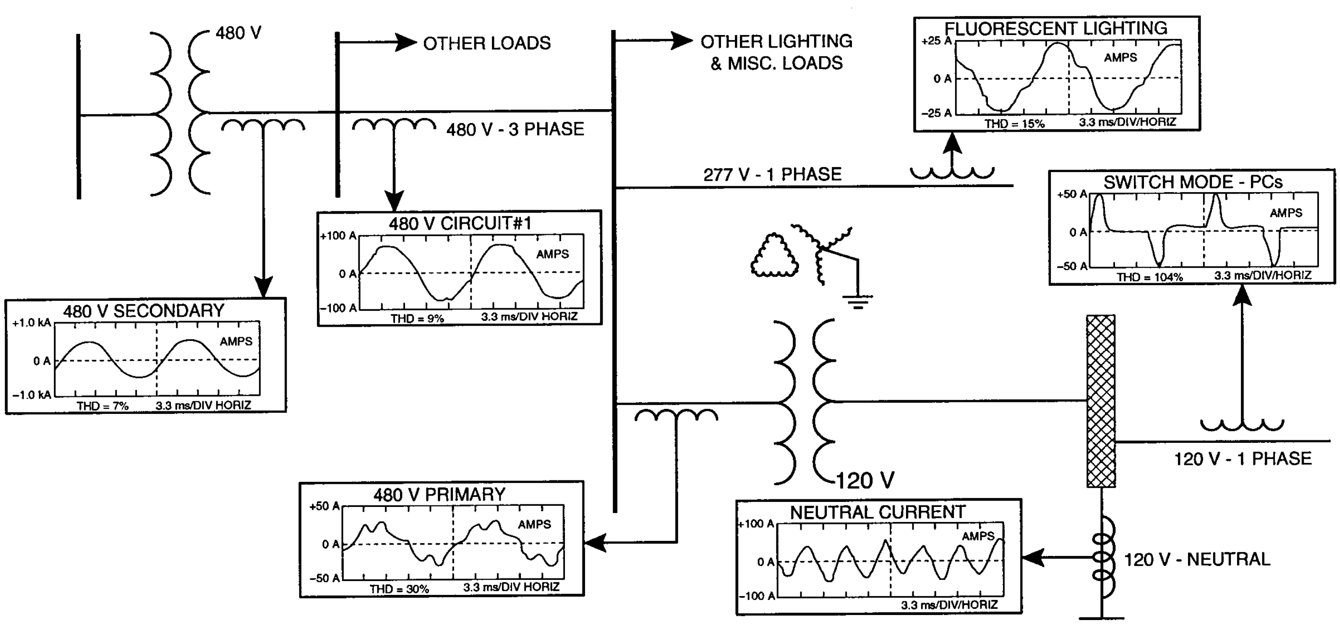


Fig. 1. Harmonic currents in a typical commercial building electrical power system (IEEE Standard 1100).

When all the harmonic currents are taken into account, these electronic appliances can have a very low power factor in terms of total watts/volt-amp. This means that there is more current flowing in the power system than is required to get the job done. The increased current contains harmonics and leads to higher wiring losses per watt of connected load. This paper calculates the cost of harmonic-related building wiring losses and compares it to the cost of a built-in harmonic elimination circuit described by the authors in [1].

II. Calculating Harmonic-Related Losses

Today's electronic equipment tends to be distributed in the building on various branch circuits and receptacles rather than centralized in one area as in a computer room where special power provisions are made. Most of the losses associated with harmonics are in the building wiring. To evaluate the energy loss impact of harmonic and reactive current flow, a wiring model was developed for a typical commercial building. Fig. 1 is the single-line diagram used for this model. It comes from in the *IEEE Emerald Book* [2], depicting actual field experience reported by Zavadil [3], and shows expected current waveforms at different points. The building contains both linear and nonlinear loads. Harmonic distortion is severe at the terminals of the nonlinear loads, but tends to be diluted when combined with linear loads at points upstream in the system.

A. *Identification of Harmonic Sources*

To power most electronic equipment in a commercial building, a switch-mode power supply uses a simple rectifier to convert ac to pulsating dc and a smoothing capacitor to reduce ripple in the dc voltage. Fig. 2 shows a circuit diagram and typical input current at the interface between the ac source and the switch-mode power supply. The output of the switch-mode dc-to-dc converter can be applied to any dc load. For computer applications, the output typically contains ±5V and ±12V to supply CPU and logic circuit power.

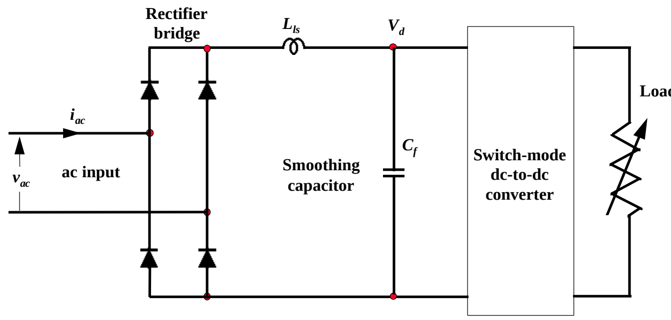
In order to maintain a constant dc voltage and to provide ride-through capability, the PC power supply requires a large capacitor C_f, typically 2 μF/W. A parasitic inductance L_{ls} is also used in this circuit. Not shown is the required π-filter at the front-end of the rectifier to reduce the electromagnetic interference (EMI). The capacitor C_f is charged from the rectifier circuit only when the peak of the ac voltage is higher than the capacitor voltage. Because the capacitor is a low-impedance device, the charging current presents high peak value over a short period. This reflects to the ac side as alternating current pulses and associated harmonics.

The total harmonic distortion, *THD*, is defined by

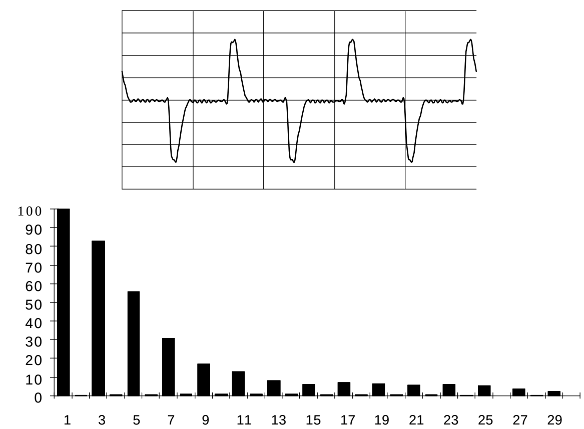
$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} {I_h}^2}}{I_1} \qquad (1)$$

where I_h is the rms current of the *h*th harmonic current, and I_1 is the rms value of the fundamental current. A typical voltage waveform doesn't exceed 5% *THD*. However, the power supply input current *THD* could easily exceed 100%.

This highly distorted waveform as shown in Fig. 2(b) indicates that the input current contains significant harmonic components as shown in the spectrum. The third harmonic is the most prominent component (>80%), and the *THD* in this case is 110%.



(a) Electronic appliance power supply circuit



(b) Input current, i_{ac}, waveform and spectrum

Fig. 2. Circuit diagram and input current of an ordinary PC switch-mode power supply.

The harmonic current generated by PC power supplies is only one of many possible harmonic producers. Other sources of harmonics in the office include 120-V equipment for communications, printing and copying, lighting with high efficiency electronic ballast, for example. At 480 V common harmonic producers include adjustable-speed drives (ASDs) for HVAC, larger computers, uninterruptible power supplies, and 277-V lighting. For electronic appliances that are retrofitted to save energy, such as lighting or ASDs, an important question raised by Celio in [4] is how much of the energy savings may be diminished by added harmonics losses in the power system.

B. *Harmonic-Related Loss Mechanisms in Power Wiring*

1) Cables: The only cable power loss component is I^2R, where *I* could be augmented by the harmonic distortion, and the *R* value is determined by its dc value plus ac skin and proximity effects. The rms value including harmonic current,

I, can be obtained from individual harmonic contents, as expressed in (2).

$$I = \sqrt{\sum_{h=1}^{\infty} I_h^{\,2}} = \sqrt{I_1^{\,2} + I_2^{\,2} + I_3^{\,2} + \cdots} \tag{2}$$

Manipulating (1) and (2) yields the total rms current in

$$I = I_1\sqrt{1 + THD^2} \tag{3}$$

Equation (3) indicates that without harmonics, the total rms current is simply the value of the fundamental component. For the above switching power supply example, with 110 percent *THD*, the total rms current is nearly 50 percent higher than the fundamental current.

Taking into account the frequency-related effects, a ratio of ac to dc resistance, k_C, can be defined as

$$k_c = \frac{R_{ac}}{R_{dc}} = 1 + k_{SE} + k_{PE} \tag{4}$$

where k_{SE} is the resistance gain due to skin effect, and k_{PE} is the resistance gain due to proximity effect, from Rice in [5]. Equation (5) defines a skin effect parameter, x, as a function of frequency and dc resistance.

$$x = 0.027678\sqrt{\frac{f\,u}{R_{dc}}} \tag{5}$$

Here f is the frequency in Hz, u is the magnetic permeability of conductor (equal to one for non-magnetic material), and R_{dc} is the dc resistance in Ω/1000 ft. The resistance gain due to skin effect, k_{SE}, is a nonlinear function of x and can be obtained from a cable handbook [6]. For computational purposes, k_{SE} was approximated by curve-fitting, and the following fifth-order equation was derived by the authors.

$$k_{SE}(x) = \begin{cases} 10^{-3}(-1.04x^5 + 8.24x^4 - 3.24x^3 + 1.447x^2 \\ -0.2764x + 0.0166) \quad \text{for } x \le 2 \\ 10^{-3}(-0.2x^5 + 6.616x^4 - 83.345x^3 + 500x^2 \\ -1061.9x + 769.63) \quad \text{for } 2 < x \le 10 \end{cases} \tag{6}$$

The resistance gain due to proximity effects is expressed by

$$k_{PE} = k_{SE}\, s^2 \left(\frac{1.18}{k_{SE} + 0.27} + 0.312 s^2 \right) \tag{7}$$

where σ is the ratio of the conductor diameter and the axial spacing between conductors.

Consider four different sized cables: 500 kcmil, 4/0 AWG, 1/0 AWG, and 12 AWG, typically used in a building power distribution system. The conductor spacing is based on *National Electric Code* insulation type THHN, which is a relatively thin heat-resistant thermoplastic rated at 90ºC and often used in building wiring systems. The insulated conductors are adjacent and separated only by insulation thickness. This spacing is used to obtain the σ values for the four types of cables. Their ac/dc resistance ratios at different frequencies can then be plotted in Fig. 3.

Fig. 4(a) illustrates the differences between proximity and skin effects at different frequencies for 12 AWG cable. For such small-sized cables, the proximity effect is more dominant than the skin effect at all frequencies. In these formulas, a non-metallic (nm) sheathed cable is assumed. Differences in R_{ac}/R_{dc} for conductors at a different spacing or in metal conduit or raceway are difficult to predict and should not result in a worse case. Fig. 4(b) shows the comparison of proximity and skin effects for the 4/0 AWG cable. For this size and larger-sized cable, the proximity effect may be more dominant in low frequencies but not at higher frequencies. However, in practical power systems the level of harmonic currents at these higher frequencies is quite small. Therefore, proximity effects tend to be the most significant.

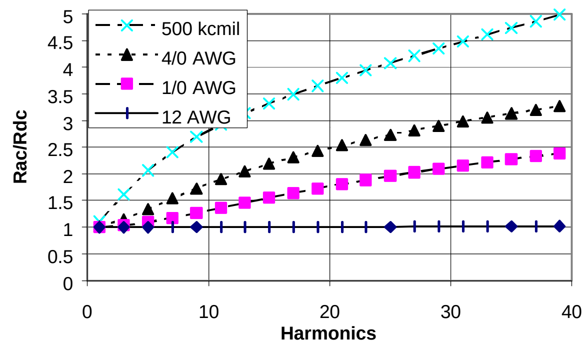
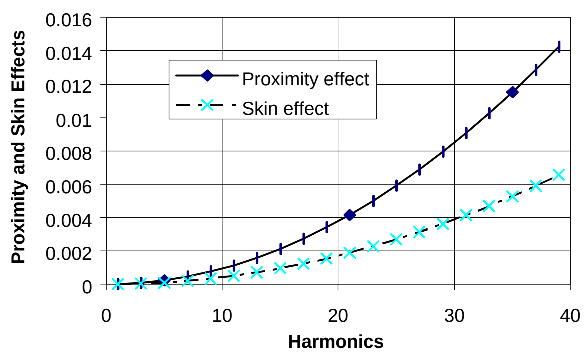
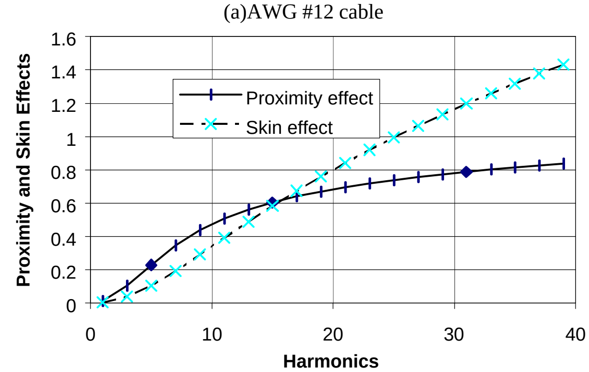


Fig. 3. Cable ac/dc resistance ratios as a function of harmonic frequencies.



(a)AWG #12 cable



(b) AWG 4/0 cable

Fig. 4. Skin effect (k_{SE}) and proximity effect (k_{PE}) for two different cables.

2) Transformers: Transformer loss components include no-load loss, P_{NL}, and load-related loss, P_{LL}, as shown in (8). The load loss, as a function of load current, can be divided by I^2R loss (P_R), stray losses. The stray load losses are caused by eddy-currents that produce stray electromagnetic flux in the windings, core, core clamps, magnetic shields, tank walls, and other structural parts. For harmonic-rich current, the eddy-current loss in the windings may be the most dominant loss component in the transformer. This component is singled out and identified as P_{EC}. The other stray losses in the structural parts are defined as P_{ST}. as shown in (9).

$$P_{Loss}=P_{NL}+P_{LL} \quad (8)$$

where $$P_{LL}=P_R+P_{EC}+P_{ST} \quad (9)$$

For nonsinusoidal load currents, the total rms current can be obtained by (2), or the power loss can be obtained by the sum of the squares of the fundamental and harmonic currents, as shown in (10).

$$P_R = \sum_{h=1}^{h_{\max}} I_h^2 R_h \quad (10)$$

The winding eddy current loss in transformers increases proportional to the square of the product of harmonic current and its corresponding frequency. Given the winding eddy current loss at the fundamental frequency, P_{EC-1}, the total eddy current losses including harmonic frequency components can be calculated by

$$P_{EC} = P_{EC-1}\sum_{h=1}^{h_{\max}} I_h^2 h^2 \quad (11)$$

This relationship has been found to be more accurate for lower harmonics (3rd, 5th, 7th), and an over-estimation of losses for higher harmonics (9th, 11th, 13th, and so on), particularly for large-diameter windings and large-capacity transformers.

3) *Other equipment in the building:* Other equipment that may be affected by harmonics include motors, capacitors, reactors, relays, instrumentation and standby or emergency generators. The major harmonic effects to other equipment include performance degradation, increased losses and heating, reduced life, and potential resonance. For motors or relays, the primary loss mechanism is the harmonic voltage that is present at the terminals of the equipment. For power system equipment such as standby generators or series reactors, the harmonic current is the predominant factor.

III. Case Study of Office Building Harmonic Losses

Fig. 5 is from the same single-line diagram for a commercial building described in Fig. 1. The voltage levels, cable sizes and transformer capacities are based on an actual system selected to be a typical case. Note that cable segment lengths and related losses will vary significantly with the shape of the buildings. For example, a skyscraper is likely to have longer cable lengths than a school.

The example office building model contains 60 kW of personal computers, 240 computers on 120 branch circuits, and other related electronic office equipment. Lighting loads are conventional magnetic-ballasted fluorescence at 277V. The office area is fed by a conventional 480V to 120/208V, 112.5-kVA step-down transformer. Loads in this area are assumed to operate 12 hours per day and 365 days per year.

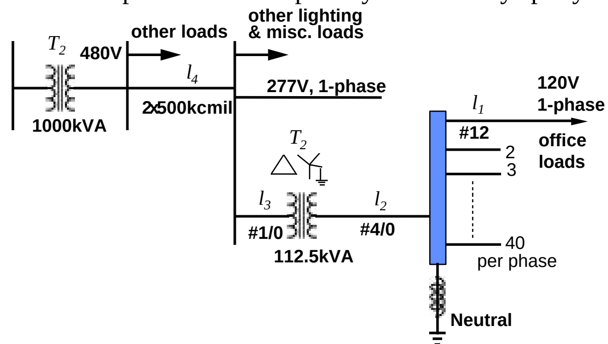


Fig. 5. Single-line diagram of a commercial building ac distribution system.

A. Cable Losses

Four segments of the cables are considered, l_1, l_2, l_3, and l_4. The lengths will vary depending on the site. Segment lengths used in this analysis are believed to be reasonable. Albeit arbitrary, the results can be linearly extrapolated to other cases. Harmonic levels for each line segment follow Fig. 1. For example, cables l_1 and l_2 directly serve offices, which contain mainly PC-related loads with highly distorted currents exceeding 100% *THD*. Cables l_3 and l_4 currents are expected to be significantly less distorted. Voltage is assumed to contain a 1~5% level of distortion. For each segment the harmonic current losses at different *THD*s are compared with the losses at an ideal 5% *THD*. From this difference in losses, the cost differences are calculated.

1) *Cable l_1 losses:* The average consumption of each computer system along with its associated office machines is assumed to be 250-W input with every two computer systems fed by a single 12 AWG branch circuit. We assume that there are 240 offices on 120 individual branch circuits. This results in 40 branch circuits per phase served from one or more subpanels. In this segment there are individual neutral wires for each single-phase circuit. The cable loss needs to be doubled for round trip. Table I shows the calculated cable losses and energy costs (@10¢ per kWH) for a 200-ft length.

TABLE I
Cable l_1 Harmonic-Related Power Loss and Cost Penalty per Year

Load = 20kW/phase, 120V, 40 branches of #12 cable at 200 feet			
THD (%)	5	50	100
Current (pu)	1.00	1.12	1.41
Current (amps)	166.9	186.3	235.7
Line loss per phase = I^2R (W)	442.2	551.4	882.3
Cost for 3-phase/year	$581.09	$724.55	$1,059.29
Penalty w.r.t. 5% THD	$0.00	$143.46	$578.19

2) *Cable l_2 losses:* The load currents are combined in this single line segment. For a 4/0 AWG cable at 166.7 A (assumes a unity power factor load, which is not the case), this segment is about 50% loaded. The neutral along this path is shared and carries only the imbalance portion of the 3-phase currents plus the total of all triplen harmonic currents. The harmonic loss and its cost penalty can be

significant when the cable is long. According to Fig. 4, the skin and proximity effects need to be considered in a 4/0 cable. Equation (12) is used to calculate line loss, P_l, and incorporates effects of harmonics on current and line resistance harmonic levels. This equation may be applied to any cable size. However it was not used for cable l_1 because the losses were insignificant for the 12 AWG cable.

$$P_l = \sum_{h=1}^{h_{\max}} I_h{}^2 R_h \tag{12}$$

The magnitude of R_h at h frequencies can be obtained from Fig. 4. The magnitude of I_h varies with the power supply design, load condition, and supply voltage. In this analysis the harmonic components listed in Table II represent the percentage of the harmonic current at h frequencies for typical 100% *THD* single-phase loads.

TABLE II
TYPICAL SINGLE-PHASE HARMONIC CONTENT AT 100% *THD*

Harmonic h	1	3	5	7	9	11	13	15	17	19	21	23	25
Current I_h	100	77	46	27	20	18.2	15.1	11.4	8.5	6.0	4.2	5.1	3.2

Assume the three-phase currents are balanced. The triplen harmonics of each phase add in the neutral line. We can calculate three-phase line losses and neutral line loss separately by considering the harmonic current components. Table III lists the cable losses and cost estimates at different *THD*s. The row "Line loss" indicates the single line power loss, and the "Neutral loss" row assumes a balanced condition and considers only triplen harmonics.

TABLE III
CABLE l_2 HARMONIC-RELATED POWER LOSS AND COST PER YEAR

Load = 60 kW 3-phase, 208V, on #4/0 cable at 50 feet			
THD (%)	5	50	100
Current (pu)	1.00	1.12	1.41
Current (amps)	166.9	186.4	235.7
Line loss per phase = I^2R (W)	69.65	90.99	151.82
Neutral loss = I^2R (W)*	0.01	116.28	465.11
Cost for 4-line/year	$93.06	$170.49	$403.21
Penalty w.r.t. 5% THD	$0.00	$77.43	$310.15

* includes high triplens from all 3 phases, mostly 180 Hz

3) Cable l_3 losses: As compared to the previous line segments, the current in cable l_3 is much less distorted because of triplen-harmonic current cancellation in the delta-wye transformer connection A level of 30% *THD* is observed in Fig. 1 on the high side and 100% *THD* on the low side of the step-down transformer. To calculate the skin- and proximity-related line losses for the different frequency components, the harmonic components listed in Table IV for a 30% *THD* was used. Table V shows the calculated losses for this 150-ft, 1/0 AWG cable segment.

4) Cable l_4 losses: The current in this segment is further smoothed by other linear loads. Field experience backed by studies such as by Mansoor in [7] show that several factors including attenuation, diversity and system impedance act to reduce harmonic currents as they travel farther from their source. Typical *THD* in this section may be less than 10 percent. The exception would be where harmonic resonances occur and amplify the distortion.

TABLE IV
TYPICAL THREE-PHASE HARMONIC COMPONENTS AT 30% *THD*

Harmonic h	1	3	5	7	9	11	13	15	17	19	21	23	25
Current I_h	100	1.4	25	15	1	6	4	.3	2	1.5	.1	1.2	1.1

TABLE V
CABLE l_3 HARMONIC-RELATED POWER LOSS AND COST PER YEAR

Load = 60kW 3-phase, 480V, on #1/0 cable at 150 ft			
THD (%)	0.05	0.20	0.30
Current (pu)	1.00	1.02	1.04
Current (amps)	72.33	73.67	75.42
Line loss per phase = I^2R (W)	78.47	81.84	86.28
Cost for 3-phase/year	$103.11	$107.53	$113.38
Penalty w.r.t 5%THD	$0.00	$4.42	$10.27

B. Transformer T_1 losses

The transformer core or no-load losses depend on voltage, which is this case is assumed to be constant with distortion less than 5%. These no-load losses are neglected for a conservative estimate. In contrast, load-related losses are variable with loading and are highly affected by the harmonic distortion of the load current. In this case the transformer T_1 is loaded to approximately 55 percent of its 112 kVA rating. Assuming balanced three-phase conditions, each phase is loaded at 20 kW and the I_{rms} is 166.7 A, when the load is fully compensated, (that is, unity power factor and no harmonics). These conditions define the base case. The objective here is to calculate the additional losses caused by harmonics in the load current.

To calculate these harmonic-related losses transformer T_1 characteristics must be known. For this case we assume that the 60-Hz I^2R loss is 2.5% of the kVA loading, and the eddy current loss factor (P_{EC-1}) is 5%. Based on the eddy current loss as a percent of the I^2R loss under sinusoidal 60-Hz loading conditions, this percentage usually must be obtained from the manufacturer. Using (10) and (11), the additional load loss caused by the current harmonics can be obtained. Table II shows the secondary harmonic current contents, and Table IV shows the primary harmonic current contents. Note the filtering action of the delta-wye transformer. Using the per-unit copper loss ($\Sigma I^2 R_h$), and the eddy current loss ($\Sigma I^2 h^2$), the calculated transformer load losses due to harmonics and their associated cost per year are listed in Table VI. Energy cost is again based on the assumption that the load runs 12 hours per day, 365 days per year.

TABLE VI
TRANSFORMER T_1 HARMONIC-RELATED LOSES AND COST PER YEAR

Load = 60 kW 3-phase, on 112 kVA	P_{loss} (W)	Cost/Year
Copper loss = $\Sigma I_h^2 R$	2986	$1,308
Eddy current loss $P_{EC} = \Sigma\, I_h^2 h^2$	1336	$585
Total load loss $P_{LL} = \Sigma I_h^2 R + P_{EC}$	4322	$1,893
Base load loss = $1.05 \times I^2 R$	1575	$690

Penalty = P_{LL}–1.05×I^2R	2747	$1203

The total load loss for T_1 is more than double the predicted 60-Hz loss because of high harmonic currents. At 100 percent *THD*, the copper loss doubled, and the eddy current loss increased by more than 17 times. Consequently, the 112-kVA transformer is overloaded by only 60 kW of computers.

C. Cost Penalty of Harmonic-Related Losses

The total cost penalty depends on the loading condition, time of operation, and the cable lengths. In the above case, most system components are over-sized. Even so the losses are not trivial, particularly in transformer T_1. Table VII summarizes expected harmonic-related losses and costs per year for this case. Note that harmonic-related losses on cable l_4 and transformer T_2 are negligible for office the PC scenario.

TABLE VII
SUMMARY OF HARMONIC-RELATED LOSSES AND COSTS PER YEAR

	Current THD	Cable Length	Harmonic Loss (W)	Harmonic Cost/ year
Cable l_1:	100%	200 ft	1320	$578
Cable l_2:	100%	50 ft	712	$310
Xformer T_1:	*THD*: 100% primary, 30% secondary		2747	$1,203
Cable l_3:	30%	150 ft	23	$10
Total			**4802**	**$2,101**

D. Options for Eliminating Harmonic-Related Losses

The case study illustrates that harmonic losses due to office equipment are expected to be distributed in the building wiring serving that equipment. About 50% was in the cables and 50% in the 480/120-208V step-down transformer. A number of filtering options for harmonic mitigation are commercially available and can be evaluated on a cost/benefit basis. It should be clear that selecting the right location will be critical to effectiveness.

Fig. 6 shows possible locations, '*a* through *f*,' for harmonic elimination or reactive compensation. **Elimination at the source of harmonics generation, location '*a*', before any additional current flows in the power system, will always be the most complete approach.** However, this leads to many small rather than a few large filtering devices. The expected economy of a larger scale filter suggests that the best location is where several distorted currents are combined, such as a load center. The number and size of the of harmonic filters will also affect internal losses of the filter and operating cost. Special wiring-related conditions such as neutral conductor overload and cancellation should also be considered.

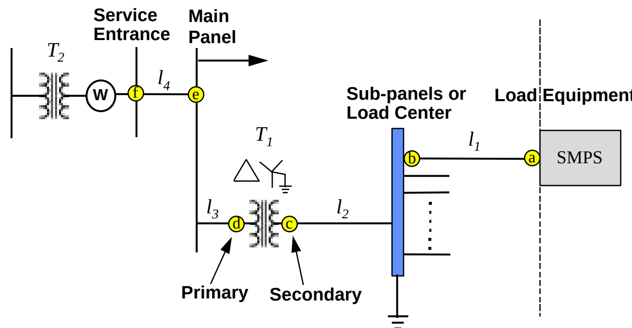


Fig. 6: Possible locations for harmonic mitigation in office power system

Given the interesting varieties and trade-offs in harmonic mitigation methods, more evaluation is need to compare cost- effectiveness of different options and locations. However, in this paper only one option of the build-in circuits will be evaluated to determine the potential economic payback.

E. Compensation Built into Load Equipment

Eliminating harmonics at their source provides the most effective option from a system point of view. The question is viability and cost. With incentives like IEC Standard 1000-3-2 (previously 555-2 [8]), which will require some mitigation of harmonics at equipment terminals, many manufacturers are looking for cost-effective ways to reduce harmonics inside electronic equipment. Considering the PC power supply as an example, possibilities of limiting harmonics to comply with IEC have been analyzed and tested by the authors. Results are reported in [1] and [9]. Four methods were considered:

1. Filtering by a series inductor added at the input circuit
2. Building in the active boost converter current shaping to replace the front-end rectifier-capacitor smoothing circuit
3. Filtering by a parallel-connected, series LC-resonant (PCRF)
4. Filtering by a series-connected, parallel LC-resonant (SCRF)

Of these methods a simple inductor and the electronic active boost converter are the most practical for build-in harmonic mitigation—where space and real estate are very expensive. The tuned-filter methods, PCRF and SCRF, are more practical for cord connection, which is a subject for future analysis.

1) Series inductor filter: A series inductor at the input to a power supply prevents sudden current changes (di/dt) and acts as a simple filter component. The rectifier circuit operates in the same way except the harmonic content and the peak current are reduced. It is possible to manipulate the inductor value to suit IEC, but the cost and size increment could be excessive. For example, a 200-W power supply requires a 10-mH series inductor to meet IEC 1000-3-2 [8].

2) Boost converter with power factor correction: The boost converter is also called "step-up converter" which converts low dc voltage to high dc voltage. Fig. 7 shows a power supply containing a front-end boost converter. The switch *S* controls energy flow. When *S* turns on, a current builds up on the inductor L_s, meanwhile the diode *D* remains in the reverse blocking mode because the on-state of *S* means a zero voltage across. When *S* turns off, the energy stored in the inductor charges through the diode *D* to the capacitor C_s. The inductor current can be controlled to follow a desired wave shape. In power factor correction circuit, the inductor current is normally controlled to follow the rectified voltage, and the ac-side current will be in phase with the ac voltage.

Fig. 8 shows experimental input voltage and current of a PC power supply with a boost converter circuit from [9]. The current is nearly sinusoidal with almost invisible high-frequency (70 kHz) switching ripples. The size of the boost converter is significantly less than any passive filters, but the performance is much better. It is expected that the active power factor correction will meet any future strict power quality regulation, such as IEC 1000-3-2. Unfortunately, it is difficult to sell power supplies with active power factor correction because of expected higher cost and lower reliability related to additional components.

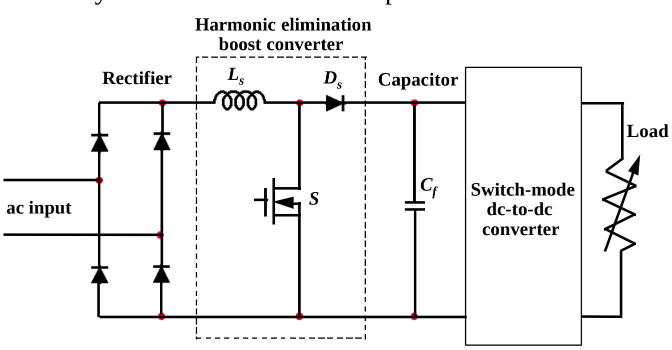
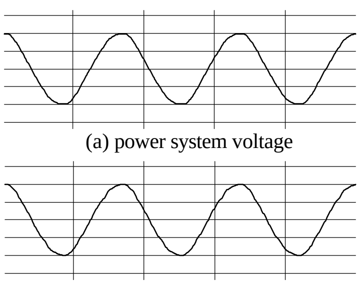


Fig. 7. Boost converter current shaping circuit inserted between the rectifier and switch-mode dc-to-dc converter circuits.



(a) power system voltage

(b) power factor corrected power supply current

Fig. 8. Experimental input voltage and current waveforms.

IV. Analysis of Harmonic Elimination Cost-Benefit

This cost-benefit analysis compares the estimated cost of adding a harmonic-elimination circuit to the electronic power supply to the potential avoided cost of harmonic-related losses in the power system. The avoided cost is based on the previous determination of harmonic-related losses in commercial building model. This analysis assumes 60 kW of office electronic load. The cost of energy is $.10/kWH. The load includes 240 distributed personal computers on 120 branch circuits, and other related electronic office equipment, which operate 12 hours per day, 365 days per year.

A. The Benefit of Harmonic Elimination

From the previous analysis it is clear that location of the harmonic elimination equipment is critical. Fig. 6 shows six possible locations in a typical commercial building. Of these the greatest potential for energy savings derived from harmonic reduction is near the source of the harmonic current, as illustrated in Table VIII, which shows the maximum potential energy saving at different locations in the building wiring based on the case study. The loss reductions will vary depending on load harmonic content as well as the power and the location of the compensating equipment. In this case losses are based on the 60 kW computer load.

TABLE VIII
ENERGY SAVING POTENTIAL AT DIFFERENT LOCATIONS

Location Options for Harmonic Mitigation Equipment	Above Xformer Primary	At Xformer Secondary	At Load Center or Sub Panel	At Load Equipment or Built-in
Total losses without compensation (W)	8148	8148	8148	8148
Total losses with compensation (W)	8125	5378	4666	3346
% total losses with compensation / 60 kVA	13.54%	8.96%	7.78%	5.58%
Saving l_1 at 200 ft. (W)	0	0	0	1320
Saving l_2 at 50 ft. (W)	0	0	712	712
Saving T_1 at 112 kVA (W)	0	2747	2747	2747
Saving l_3 at 150 ft.(W)	23	23	23	23
Total saving for 60 kVA load (W)	23	2770	3482	4802
% saving / 60 kVA	0.04%	4.62%	5.80%	8.00%
$ Saving per year	$10	$1213	$1523	$2101

Table VIII also shows that additional losses due to the harmonic loading are more than 8kW, so that more than 68kW will be required at the service entrance to serve a 60kW office computer load. The harmonic-related losses increase the total expected losses in the building wiring by 250%, from 3346 to 8148 watts. Compensation of harmonics near the service entrance has very little value, perhaps $10/year, while compensation near the electronic load has a significant potential effect, saving $2101 per year. This is the key benefit of a harmonic-free power supply.

Another, perhaps less obvious, benefit of reducing harmonics at their source is the release of capacity in the building electrical power system. Insufficient capacity can be a significant problem in existing building wiring that has become overloaded due to new office equipment. Upgrading existing transformers and wiring is often more costly than the original installation. Table IX compares different load types with respect to their burden on building wiring and their kW consumption. In this table the term "linear equivalent power factor" is a fictitious power factor for nonlinear loads that identifies the linear load power factor that would have an equivalent effect on wiring loss. This concept is getting important as the number of nonlinear loads are rapidly increasing.

TABLE IX
VALUE OF HARMONIC ELIMINATION FOR WIRING CAPACITY

Office building load types	Effective load on building wiring losses	% wiring loss	%Linear equivalent power factor	%Lost wiring capacity
Resistive load	1.000	5.6%	100%	0
Other office loads	1.4~1.7	7~10%	55~75%	25~45%
PC without harmonic elimination	2.438	13.6%	41%	59%
PC with harmonic elimination	1.001	5.6%	99.9%	0.1%

Without harmonic elimination, the wiring loss by the PC power supply load is 2.4 times that by the pure resistive load. In other words, the system wiring is 20% overloaded even with 50% load. With harmonic elimination (5% *THD*), the wiring loss by PC loads is significantly reduced and performs like the pure resistive load. Wiring system losses due to “other office loads,” such as magnetic lamp ballasts, vary among different types. The varying range indicated in Table IX is taken from the calculated results which have a medium point at 15% *THD* and 0.9 displacement power factor.

B. The Cost of Harmonic Elimination

The added cost to install a boost converter-type harmonic elimination circuit in a switch-mode power supply is estimated at $6 per 250-W PC system, $1440 per 60 kW. This cost is based on prior investigations in [1], and recent quotes from power supply manufacturers located in Taiwan. A life of 6 years was chosen for this investment, which is based on the expected life of the computer system before reaching obsolescence. Another cost for this investment is the energy lost in the operation of the boost converter. Efficiency of the converter elimination circuit is expected to be 97%, therefore 3% is lost.

Using these added costs and a discount rate of 8%, the present value of the harmonic losses is $3739 at 60 kW, and the total life-cycle cost for harmonic elimination is $5179 (1440+3739). The present value of energy savings in reduced building wiring losses is $10,034 over the 6-year period. From this a pay-back period is calculated to be 3.1 years.

V. CONCLUSION

Harmonic-related losses in building wiring can be calculated using a typical model of building power system components and harmonic generating load equipment. These losses may be significant, overheating wiring, increasing power bills and tying up capacity of the power system. Reducing harmonics will save energy and release additional capacity to serve other loads.

There is a variety of methods available for reducing harmonics in building wiring. Results for an office building show that the location of harmonic reduction equipment within the building wiring is crucial to effectiveness. The greatest potential for loss reduction and released power system capacity is near the harmonic generating loads, while installation near the service entrance may be of little value.

A specific harmonic elimination method that maximizes these values is a harmonic elimination circuit built into non-linear load equipment such as a PC. This boost-converter circuit, previously investigated by the authors, was shown to be cost-effective, yielding a 3-year pay back, based on energy savings alone. The approach holds great promise for achieving economy at the small scale required to eliminate harmonics in individual equipment.

VI. FUTURE WORK

Active or tuned passive filters may be required to solve existing harmonic problems. Application data on these filters, particularly their use in both harmonic reduction and reactive compensation, is not adequate in the literature or in standards. Further analysis comparing the cost and effectiveness of the variety of different harmonic mitigation options is needed. The value of released capacity and the concept of linear equivalent power factor are significant issues and need further documentation and development. This is indeed a good research topic for follow-up investigations.

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