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Cost-benefit Analysis of Harmonic Current Reduction in *PV System -A Review*

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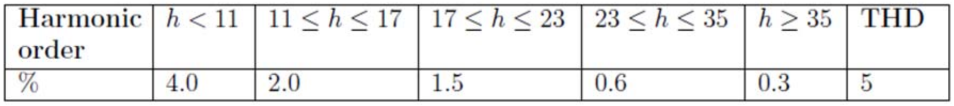
Abstract— *Harmonic currents generated by electronic equipment cause power system heating and add to consumer power bills. A common source of harmonic currents in power systems is electronic equipments and non linear loads connected with power system.. Eliminating harmonic at their source provides most effective option from a system point of view. This cost-benefit analysis compares the estimated cost of adding a harmonic-elimination circuit to the cost of harmonic related losses in the power system. The rated KW capacity of PV plant increases about 1.3% due to additional harmonic generated losses The cost of these losses is compared to the cost of reducing harmonics in the equipment design. In this paper one option of built in technology will be evaluated to determine the potential economic payback. Results show that the boost-converter circuit, 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 PV system. The best economical and technical solution often is achieved by hybrid solutions taking all factors into account. Multiple mitigation technologies can also improve overall power quality while controlling cost and reducing time to payback and 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.*

1. INTRODUCTION:

The impact on the power quality due to an introduction of PV generation is mitigated by prescribing limits in the grid codes. The standards prescribe the limits on the harmonic distortion, the unbalance and the voltage flicker to mitigate the possible adverse impact due to PV generation.

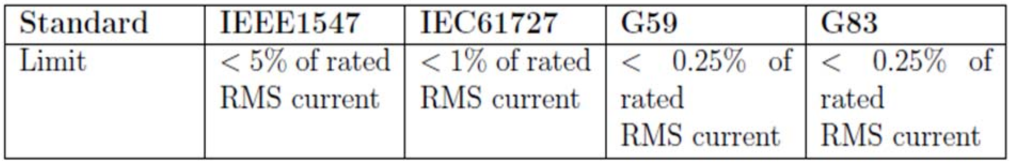
The connection of a PV generation may inject harmonics into a power system. The current harmonic limits defined in Table.1 should not be exceeded. Even harmonics limit is 25% of the odd harmonic limits [10]. The current total harmonic distortion (THD) limit is 5% and the voltage THD limit is 2.5%. In the UK, standards G83 and G59 define the harmonic distortion limits in accordance with the standard BSEN 61000-3-2 [52] [54]. In the Germany, VDEARN4105 standard defines the harmonic limit for the LV connected PV where as for the MV connected PV limits are defined in BDEW [13]. BDEW standard defines the permissible harmonic limits for each of the voltage level 10kV, 20kV and 30kV.

Table 1: IEEE1547 and IEC61727 current harmonic limits



Harmonic order	$h < 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$h \geq 35$	THD
%	4.0	2.0	1.5	0.6	0.3	5

Table 2: DC current limits:



Standard	IEEE1547	IEC61727	G59	G83
Limit	< 5% of rated RMS current	< 1% of rated RMS current	< 0.25% of rated RMS current	< 0.25% of rated RMS current

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 from factory adjustable-speed drives to personal computers and home electronics. The harmonic currents 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 Increased harmonic distortion related to this equipment is common (see current waveforms in Fig 1).

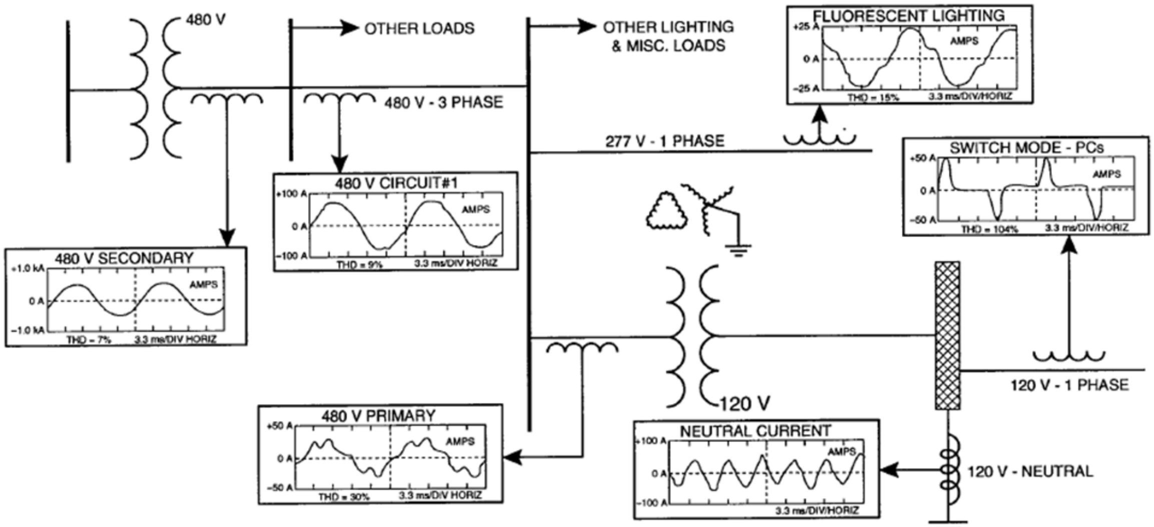


Fig. 1. Harmonic currents in a typical commercial building electrical power system

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 presents filtering options cost-effective ways to reduce harmonics inside electronic equipment, possibilities of limiting harmonics to comply slandered codes and compares it to the cost of a built-in harmonic elimination circuit described by the authors in [1].

2. EVELUATING HARMONIC-RELATED LOSSES :

Today's electronic equipment tends to be distributed in the building on various branch circuits. 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

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.

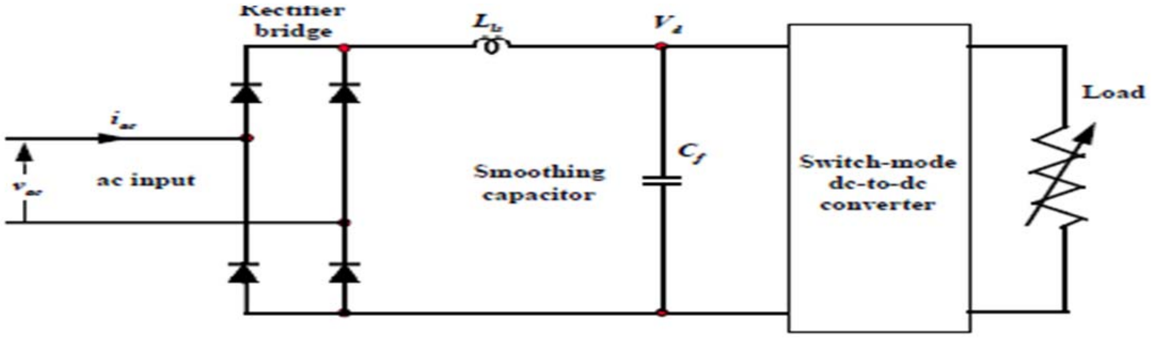
In order to maintain a constant dc voltage, the PC power supply requires a large capacitor *Cf*, typically 2 mF/W. An inductance *LIs* is also used in this circuit. The capacitor *Cf* is charged from the rectifier circuit only when the peak of the ac voltage is higher than the capacitor voltage. Since 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.

Total Harmonic Distortion:

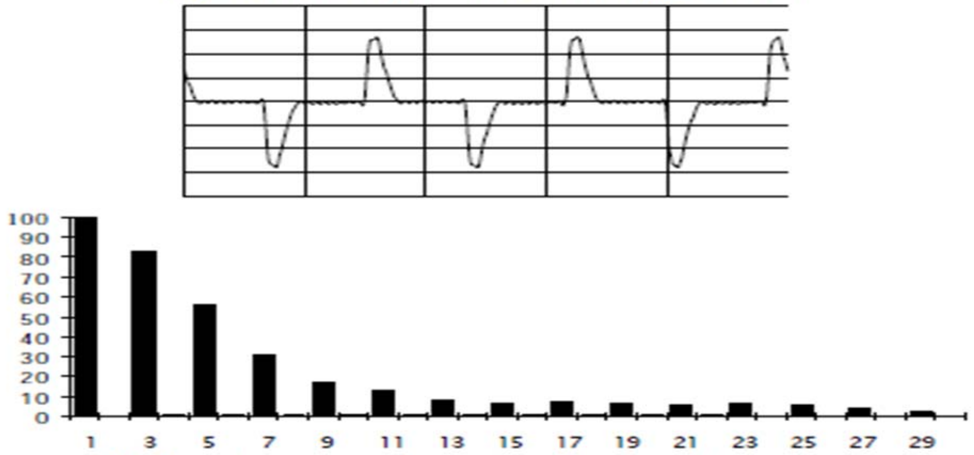
The total harmonic distortion, *THD*, is defined by

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\,2}}}{I_1}$$

where *Ih* 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 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) , larger computers, uninterruptible and power supplies

3. LOCATION FOR ELIMINATING HARMONIC-RELATED LOSSES :

The study shows 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. There are a numbers of filtering options for harmonic mitigation are commercially available and can be evaluated on a cost/benefit basis. It is clear that selecting the right location will be critical to effectiveness. Fig. 3. 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.

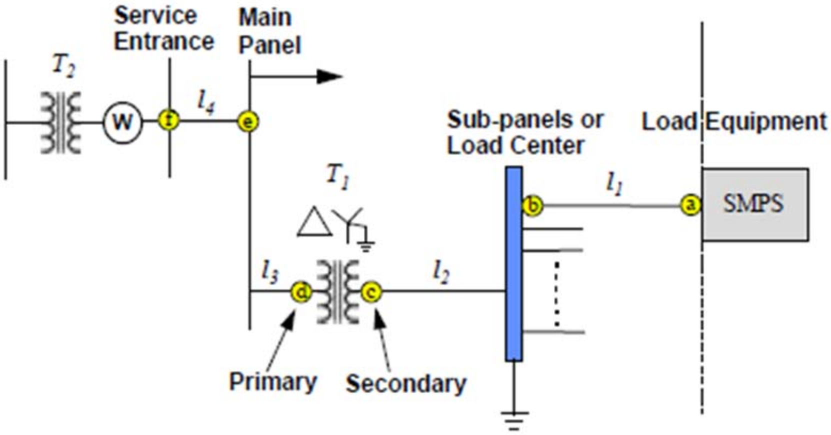


Fig. 3: Possible locations for harmonic mitigation in office power system

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.

4. COMPENSATION BUILT- INTO LOAD EQUIPMENT :

As it is clear that that eliminating harmonics at their source provides the most effective option from a system point of view. The deciding factor is viability and cost. Many manufacturers are looking for cost-effective ways to reduce harmonics inside electronic equipment. Considering, possibilities of limiting harmonics to comply with IEC have been analyzed Results are reported in [1] and [9]. Four methods are considered:

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

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. Active filter is the latest technology into the rectifier stage of a drive, UPS or other power electronics equipment.

(a) 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].

(b) 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.4. 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 *Ls*, 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 *Cs*. 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. 5. 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 (60 kHz) switching ripples. The size of the boost converter is less than any passive filters, but the performance is much better. It is difficult to sell power supplies with active power factor correction because of expected higher cost and lower reliability related to additional components.

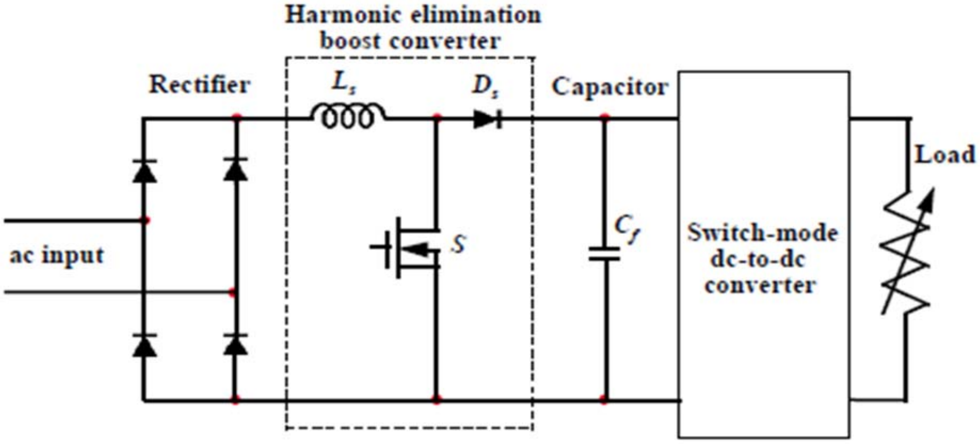
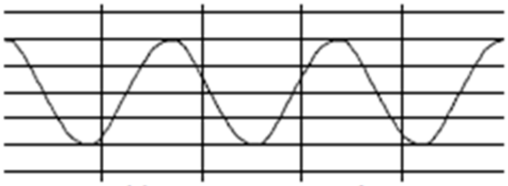
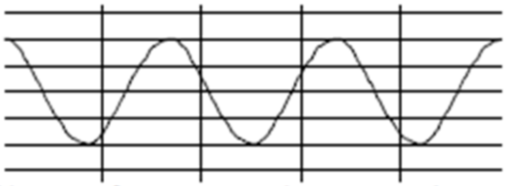


Fig. 4. Boost converter current and switch-mode dc-to-dc converter circuits.



(a) power system voltage



(b) power factor corrected power supply current

Fig. 5. Experimental input voltage and current waveforms.

(c) Active filters :

The latest technology available for mitigation of harmonics is the active filter. Active filtering techniques can be applied either as a standalone harmonic filter or by incorporating the technology into the rectifier stage of a drive, UPS or other power electronics equipment. The application of an active filter is illustrated in Fig 6.

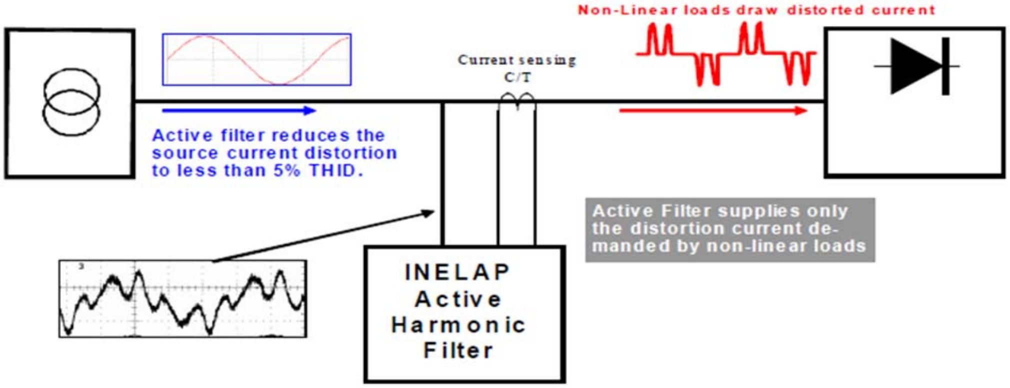


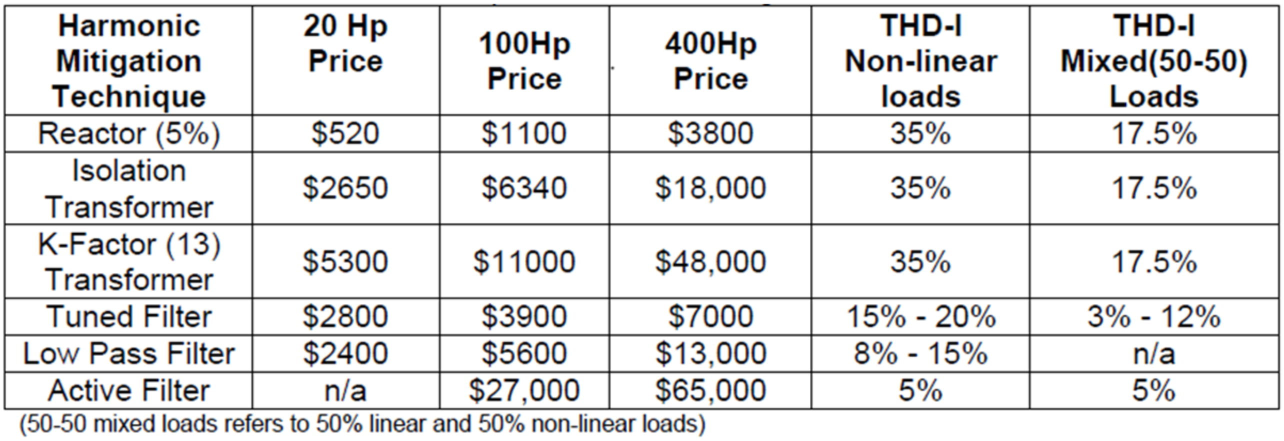
Fig. 6 Typical connection and performance of active filters.

Typically, active filters will monitor the load currents, filter out the fundamental frequency currents, analyze the frequency and magnitude content of the remainder, and then inject the appropriate inverse currents to cancel the individual harmonics. Active filters will normally cancel harmonics up to about the 50th harmonic and can achieve harmonic distortion levels as low as 5% THD-I or less Active filters utilize power electronics circuitry and therefore maintenance requirements can be higher than for passive solutions drive. The losses associated with active filters also tend to be higher than for passive solutions. In terms of harmonic cancellation current, the prices of active filters can range from about $30,000 to $100,000

5. COMPARISON OF HARMONIC MITIGATION ALTERNATIVES :

Table III shows the approximate costs and typical performance of various *aftermarket* solutions for three phase harmonic mitigation techniques..

Table III – Comparison of aftermarket mitigation alternatives



Harmonic Mitigation Technique	20 Hp Price	100Hp Price	400Hp Price	THD-I Non-linear loads	THD-I Mixed(50-50) Loads
Reactor (5%)	$520	$1100	$3800	35%	17.5%
Isolation Transformer	$2650	$6340	$18,000	35%	17.5%
K-Factor (13) Transformer	$5300	$11000	$48,000	35%	17.5%
Tuned Filter	$2800	$3900	$7000	15% - 20%	3% - 12%
Low Pass Filter	$2400	$5600	$13,000	8% - 15%	n/a
Active Filter	n/a	$27,000	$65,000	5%	5%

(50-50 mixed loads refers to 50% linear and 50% non-linear loads)

Hybrid Solutions:

In most cases, there is no single product that is always the best solution for harmonics. Each facility has its own set of circumstances, from harmonic generating loads to load sensitivity to harmonics. Some facilities may face premium costs for harmonics in the form of utility charges, reduced equipment life, or equipment downtime. The best economical and technical solution often is achieved by hybrid solutions that take all factors into account. By combining multiple mitigation technologies, one can improve the overall power quality while controlling costs and reducing the time to payback.. Some hybrid technologies with cost and distortion limit are listed below.

ALT 1 - Tuned Harmonic Filters:

The proposed unit would have two (5th and 7th) tuned filter sections. The total capacity of the system would be about 750kVAr.

DISTORTION = 7.85 % THD-I, ESTIMATED COST = $46,000.

ALT 2 - Hybrid Tuned Filter + Line Reactors:

Install 5% line reactors at each VFD with a lower capacity tuned filter. At the input to the harmonics will be about 33% THD-I, The capacity of the automatic tuned harmonic filter can be reduced to 525kVA .The value of line reactors is about $5000.

DISTORTION = 6.02% THD-I, ESTIMATED COST = $26,000.

Hybrid Filter (Tuned Harmonic filters and line reactors) saves $20,000. (43%).

ALT 3 - Active Filter:

This requires that we use a 600 amp active filter at the transformer secondary. The active filter will also provide power factor correcting VArs to the motor loads.

DISTORTION = less than 5% THD-I , ESTIMATED COST = $150,000.

1.4 ALT 4 – Hybrid Active Filter:

5% line reactors at each VFD, and a smaller capacity active filter at the transformer. At the input harmonics will be about 33% THD-I, and there will only be 291 amps of harmonics flowing on the transformer secondary. Now, the amount of harmonics to be removed is 291 – 118 = 173 amps. The value of line reactors is about $5000.

DISTORTION = less than 5% THD-I ,ESTIMATED COST = $85,000.

Hybrid Filter (Active Harmonic filters and line reactors) saves $65,000. (43%).

6. 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 30 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.

The Benefit of Harmonic Elimination:

Fig.3. shows six possible locations in a typical commercial building. Of these the greatest potential for energy savings is near the source of the harmonic current. The maximum potential energy saving at different locations in the building wiring is 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 30 kW computer load.

TABLE III: Energy saving potential at different potential:

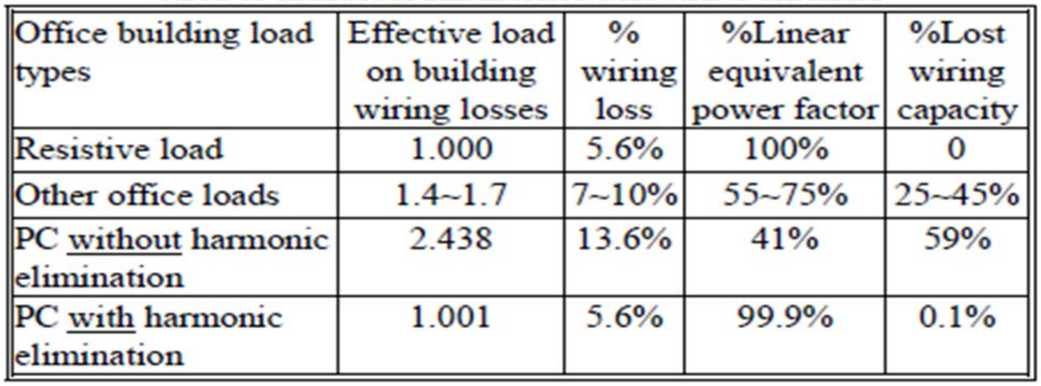
Location option for harmonic mitigation	Above X former primary	At X former primary	At load center at sub panel	At load Equipment or built in
Total loss **without** compensation	4074	4074	4074	4074
Total loss **with** compensation	4061	2700	2334	1872
% total losses with compensation/30 KVA	13.60%	9.00%	7.80%	6.6%
Saving at L1 at 200 ft (W)	0	0	0	660
Saving at L2 at 50 ft (W)	0	0	356	356
Saving at T1 at 112KVA (W)	0	1372	1373	1373
Saving at L3 at 150 (W)	13	13	13	13
Total saving for 30KVA load (W)	13	1385	1742	2402
% Saving / 30KVA	0.04%	4.20%	5.80%	8.00%
$ Saving per year	$5	$607	$762	$1050

From table III, It is clear that additional losses due to the harmonic loading are more than 4 kW, so that more than 34 kW will be required at the service entrance to serve a 30 kW office computer load. The harmonic-related losses increase the total expected losses in the building wiring by 250%, from 1872 to 4074 watts. Compensation of harmonics near the service entrance has very little value, perhaps $ 5 per year, while compensation near the electronic load has a significant potential effect, saving $ 1050 per year. This is the key benefit of a harmonic-free power supply.

Another benefit of reducing harmonics at their source is the release of capacity in the building electrical power system.. Upgrading existing transformers and wiring is often more costly than the original installation. Table IV compares different load types with respect to their burden on building wiring and their kW consumption.

TABLE IV

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 perform like the pure resistive load.

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, $720 per 30 kW. This cost is based on prior investigations in [1]. A life of 6 years has been taken for this investment, which is based on the expected life of the computer system. 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 $1870 at 30 kW, and the total life-cycle cost for harmonic elimination is $2590 (720+1870). The present value of energy savings in reduced building wiring losses is $5,017 over the 6-year period. From this a pay-back period is calculated to be 3.1 years.

7. CONCLUSION

Harmonic-related losses 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 increasing capacity of the power system. Reducing harmonics will save electrical 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 nonlinear load equipment such as a PC. This boost-converter circuit, 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.

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