THE COMPREHENSIVE APPROACH TO FACILITY POWER QUALITY

by

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Abstract: *Industrial facility harmonic distortion problems can surface in many different ways. Sometimes the symptoms are overheating transformers, lost computer data, system lockup, equipment interference, equipment malfunction or failure, or audible noise. Each facility is unique and their problems are also unique to their set of circumstances - power sources, machinery, equipment, level of automation, and equipment sensitivity. Typically, there is no single textbook solution that will solve each facility's problems or even all of the problems experienced in a single facility. Nevertheless, a large and expensive piece of power quality equipment is often purchased and applied on a macro (bulk) basis in an effort to overwhelm the power quality problem. Often this results in the utility getting all of the benefit, while the facility, having spent the money, maintains a distorted and inefficient internal power system. In the application of harmonic mitigation equipment, the benefits are only realized upstream of the location where the equipment is connected. Satisfactory power quality performance and energy efficiency demand careful analysis of the facility electrical system, problems and loads. A distributed harmonic mitigation approach, with the proper solutions applied at the right locations throughout the electrical system, assures the best overall power quality and gives a multitude of benefits directly to the facility. This paper discusses the comprehensive approach to facility power quality as it relates to harmonics, with the objective to maximize power system performance, energy efficiency and facility productivity.*

The ever-increasing number of non-linear loads connected to industrial power systems is having an effect on electrical system power quality – both inside the facility as well as on utility distribution lines. Harmonics, created by power electronics equipment in the facility, can be a problem for industrial facilities as well as for the electric utilities. Every facility has unique equipment and operations and therefore deserves a comprehensive analysis of power quality with respect to the individual pieces of equipment that cause, or are susceptible to, power quality problems.

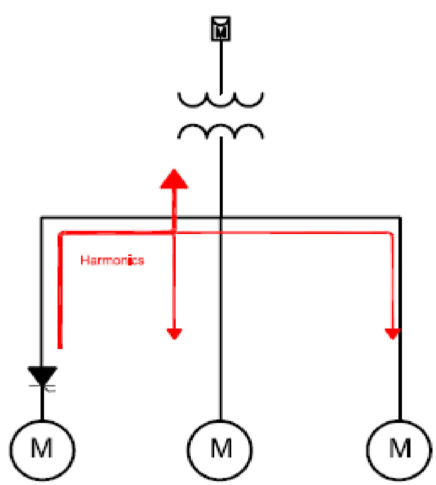

Fig. 1 Harmonic Flows (No Harmonic Mitigation)

Harmonic current, demanded by power electronic loads, flows from the power source, through the transformer and to the loads as shown in Fig. 1. Harmonic current flowing through system reactance causes harmonic voltage distortion which can affect every piece of equipment connected to the system. When there is voltage distortion on the transformer secondary (main voltage bus), then other linear loads, such as motors, will draw harmonic currents and have higher operating temperatures. A clean voltage bus enables electrical and electronic equipment to operate more effectively and efficiently, while a distorted voltage source decreases reliability and efficiency. Therefore, it is in the best interest of facility operations to minimize voltage distortion within the facility.

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Traditional Approach to Facility Power Quality
For large industrial facilities, power quality equipment such as harmonic mitigation has traditionally been applied on a bulk basis, near the electrical service entrance or at a supply transformer (Fig. 2a). The primary motivator to install equipment at these locations is to minimize initial cost. Additionally, the number of pieces of equipment is fewer, leading one to believe that equipment maintenance costs may be lower. Although bulk application may sometimes represent the lowest initial cost, the power quality benefit is actually passed on to upstream equipment (and the electrical energy provider), and is not realized throughout the facility itself. When a failure occurs in the bulk-applied power quality equipment, the facility power factor and harmonic distortion will deteriorate, and may increase energy costs.

When power factor improvement or harmonic mitigation equipment is applied in bulk at the service or at a transformer, the harmonics continue to flow between the non-linear loads and the filter, and even into other facility loads as illustrated in Fig. 2a. The power quality benefits are only experienced upstream of the filter location.

Harmonics often Treated as an Afterthought
In many cases, harmonic mitigation has been undertaken only as an afterthought when PF (power factor) improvement equipment is being installed. To satisfy utility PF requirements, industrial facilities have often located PF improvement equipment at the service entrance to improve the facility PF at the utility metering point. This popular technique requires little analysis and simply applies a bulk solution without the consideration of internal facility power quality. It neglects the impact of various loads on each other as well as on the electrical infrastructure. While this method of connection may satisfy the utility requirements and thus reduce the financial penalty associated with low PF, it neglects the potential internal benefits to the facility.

Problems with Bulk-Applied Power Factor Improvement and Harmonic Filtering Equipment
Due to the nature of capacitors to attract harmonics, because they offer low impedance to harmonic frequencies, one must consider the impact of harmonics on all PF improvement equipment and incorporate either harmonic blocking or filtering technology into the design of the capacitor bank. To protect power factor improvement capacitors from harmful harmonic currents and voltages, a capacitor protection reactor (CPR) may be used to detune the capacitor bank and block harmonics from entering the capacitor. Alternatively, the capacitor bank may be converted to a harmonic filter, thus tuning the capacitor in such a way as to remove a specific harmonic from the upstream electrical system.

In either case, harmonics will continue to flow, unmitigated, throughout the industrial facility. If the capacitor bank is converted to a harmonic filter and located near the service entrance, then harmonic currents will continue to flow between all non-linear loads and the location of the harmonic filter. The tuned filter does not eliminate all of the harmonics, because it is typically only tuned for one to three harmonic frequencies. Therefore, harmonics will still flow to the utility system as illustrated in Fig. 2a and Fig. 2b. If the capacitor bank includes a capacitor protection reactor, then harmonic currents continue to flow between all non-linear loads and the utility supply. This bulk application of PF improvement or harmonic mitigation equipment may represent the lowest initial cost, but this method foregoes all of the potential internal benefits for the facility – many of which can improve the bottom line. Only by distributing harmonic mitigation (and power factor improvement) equipment close to the actual loads, can the maximum benefit be realized.

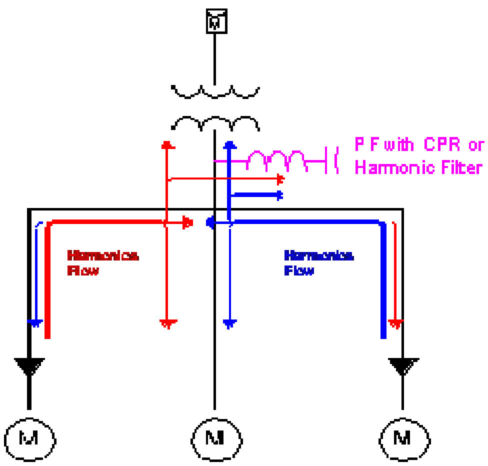

Fig. 2a
Harmonic Flows with Bulk-Applied Harmonic Filter

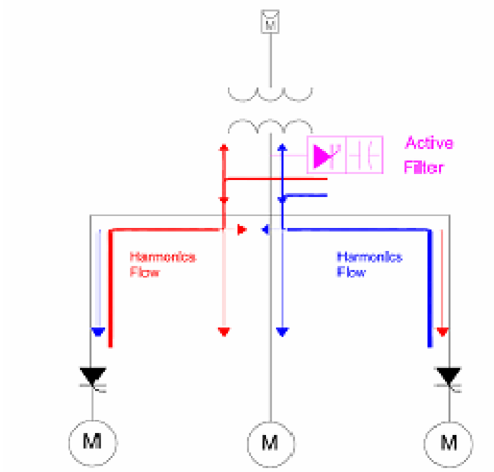

Fig. 2b
Harmonic Flows with Bulk-Applied Active Filter

Whether the harmonic mitigation solutions involve either passive or active filters, if they are installed in bulk at a centralized point, the internal facility power quality results are the same – and the facility foregoes any internal benefit (Fig. 2a and 2b). In this case, a payback analysis relies primarily upon the reduction of power factor premiums compared to initial cost. When harmonics are mitigated locally at the individual non-linear loads, then there can be many contributions toward payback in addition to the elimination of power factor premiums.

Another drawback to bulk-applied harmonic filters is the difficulty in matching both harmonic mitigation capacity and reactive VARs to actual needs that may change frequently based on facility operations. Since typical harmonic filtering techniques involve various amounts of capacitance, then adding bulk filters at a single location also adds bulk reactive KVARs to the system. This may solve harmonics problems but over-correct power factor which results in low power factor and over-voltage that can potentially damage electrical and electronic equipment. It may be difficult to achieve the desired harmonic distortion level if the harmonic filter KVAR's are selected based on the reactive power required to improve the power factor to the target level. Bulk-applied filters have the potential problem of either over-correcting the power factor, or under-filtering harmonics.

Many industrial facilities have a wide variety of loads and the loads may change throughout the day due to cyclical operation of equipment, production demands or environmental conditions. When loads change, the reactive power demand and harmonic conditions can also change – requiring varying amounts of reactive compensation and of harmonic filtering. If power factor improvement or harmonic mitigation equipment is applied in bulk and connected at a single location, it is very difficult to optimize the overall power quality, unless expensive monitoring and switching systems are employed to insert and remove varying degrees of reactive KVARs or harmonic filtering.

There are several disadvantages to applying bulk harmonic mitigation equipment at a single point in the electrical system. They include:

- Harmonics continue to flow on the electrical system between each load and the mitigation equipment,
- Benefits go upstream only, so the utility gets cleaner power while facility power quality does not improve,
- Equipment upgrades are required whenever additional loads are installed in facility,
- Difficult to achieve desired performance as loads change,
- Over-correction during light loads can increase voltage,
- Complexity and cost increase for automatic systems,
- Equipment failures may impact entire facility.

Minimize Voltage Distortion for Best Performance and Efficiency

If harmonic current flows through a transformer to multiple loads, including one or more non-linear loads, as in Fig. 3, the common voltage bus will be distorted. The magnitude of voltage distortion will be a function of both current and reactance at each harmonic frequency. Therefore, the common voltage source is distorted and each load will draw additional harmonic current proportional to the magnitude of harmonic voltage present on this system. Normally, pure linear loads do not draw harmonic current unless they are supplied from a distorted voltage source. When linear loads draw harmonic currents, their operating temperature can increase, efficiency, thereby decreasing reliability and life expectancy. Additionally, sensitive electronic loads that depend on a source of quality electrical power may malfunction or fail when they are supplied from a distorted voltage source.

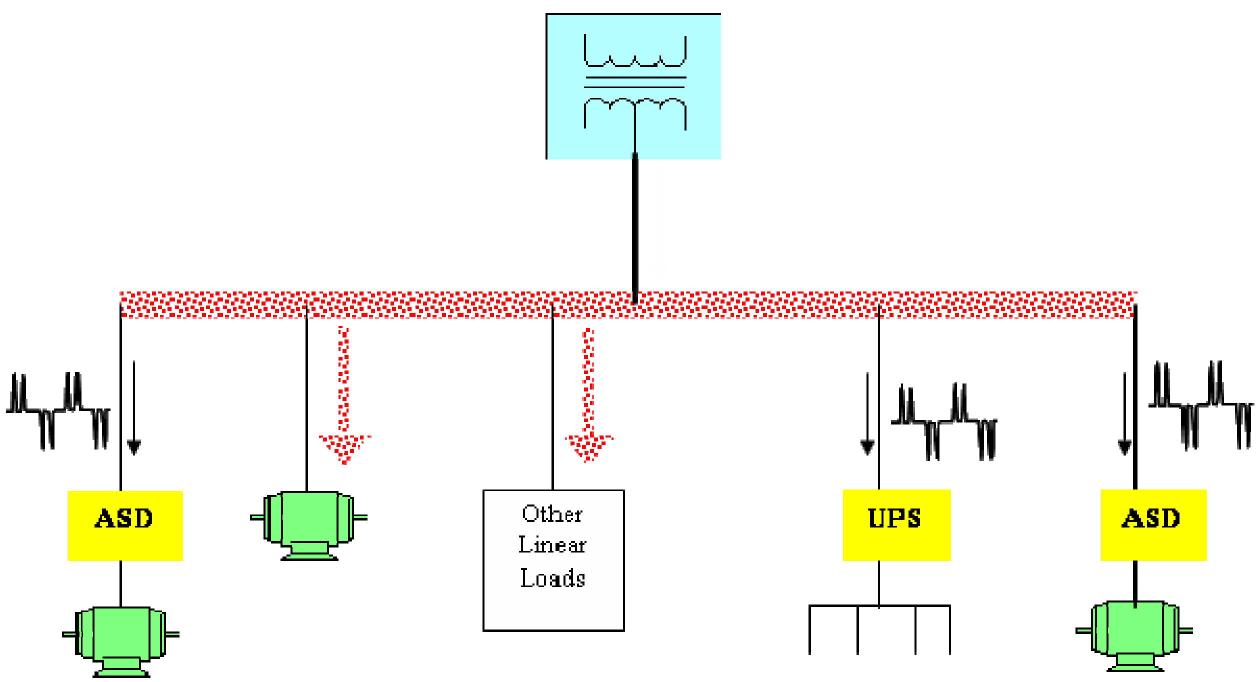

Fig. 3 Voltage Bus Distorted by Harmonic Currents Flowing to Non-Linear Loads

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Although the connection of bulk harmonic mitigation equipment at a single point in the electrical system can improve the facility power quality from the perspective of the electric utility, it leaves the internal facility electrical system susceptible to adverse effects of harmonic distortion.

Distribute Harmonic Mitigation Equipment Close to Non-Linear Loads

Whether applying harmonic filters or power factor improvement equipment, the benefits are realized in the direction that is upstream from their point of connection on the electrical system. Therefore, to gain the greatest internal benefit, power quality equipment such as harmonic filters and power factor correction must be applied as close as possible to the appropriate loads as illustrated in Fig. 4.

By connecting harmonic filters electrically close to the individual non-linear loads, harmonics are reduced right at their source and the entire power system upstream from this point is cleansed. By reducing harmonics at the load, the true rms (trms) and peak current demand upon power sources is reduced as well as the thermal current flow through upstream conductors and feeders, switches, fuses, transformers, etc. By reducing harmonic current distortion right at the non-linear load (its source), harmonic voltage distortion throughout the facility is also reduced. Electrical and electronic equipment can operate more efficiently and effectively when source voltage distortion is reduced and when trms current is reduced.

The electrical losses in conductors and feeders will be reduced when harmonics are mitigated, not only due to the lower trms (thermal) current, but also because the skin effect losses will be lower when harmonics are mitigated. Losses in equipment such as transformers and motors (those comprised of both iron and copper) reduce more appreciably because both copper and iron losses increase for higher harmonic levels. Reduced conductor and equipment losses equates to improved energy efficiency as well as extended equipment life. (Typically, 10° C temperature reduction equates to 50% more life.)

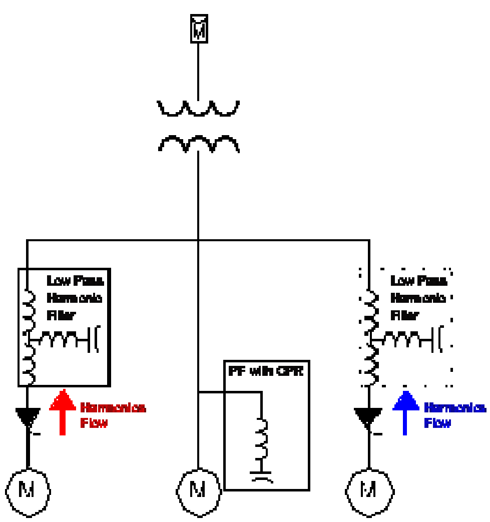

Fig. 4 Single-line Diagram illustrating Distributed Mitigation Techniques

The situation for power factor improvement is similar in that for maximum benefit, reactive compensation should be distributed close to the inductive loads. All upstream conductors and equipment will experience reduced current flow resulting in lower power loss and even released system capacity, which may be used to supply new (additional) loads. By applying the power quality equipment close to the loads, more equipment (loads) may be supplied from the existing facility electrical infrastructure. This saves money and prevents unnecessary shutdowns otherwise necessary to upgrade switchgear, transformers and feeders for example. In the traditional application of power factor improvement and harmonic mitigation equipment, all loads are downstream of the connection point and therefore the potential internal benefits cannot be realized.

By distributing the power quality equipment near the facility loads, the entire distribution system experiences greater power quality. System voltage distortion is reduced, voltage support is improved and distribution losses are reduced. The benefits of this are realized by utility customers, whose equipment performs better and more efficiently, as well as by the electrical distribution companies, whose power losses are significantly reduced.

The concept of distributing power quality equipment near to the loads also works for electric utility distribution systems. Traditionally, power factor equipment has been installed at the electrical substation to improve power factor for the electrical transmission system and upstream to the generator. The distribution lines, in this case, must still carry all of the reactive power and harmonics demanded by the loads in all of the connected facilities. The combined power losses, due to reactive power and harmonic current flow through the distribution system can be significant. By distributing power factor improvement and harmonic mitigation equipment near the loads (service drop or pole), distribution system losses can be reduced while power factor and voltage can be improved.

Benefits of Distributing Harmonic Mitigation Equipment throughout system

When harmonic mitigation and power factor improvement equipment is distributed throughout the system and connected near the loads, several internal facility benefits can be realized. A distributed mitigation system can:

- reduce current through all upstream conductors, feeders and equipment,
- improve facility voltage quality and electrical efficiency,
- release electrical system capacity (add more loads to existing system),
- reduce equipment operating temperature and facility cooling requirements,
- extend equipment life and reduce equipment downtime,
- increase system reliability,
- minimize the impact of mitigation equipment failure, and
- allow additional loads (machinery, equipment) without upgrade to mitigation system.

All of these potential benefits can add up to electrical energy savings, increased productivity and a healthier bottom line for the industrial facility. When power factor improvement and harmonic mitigation equipment is connected at the service entrance, the focus is on power factor premium reduction, rather than on an internal benefit to the facility electrical systems.

Distributed Harmonic Mitigation Improves Electrical System Reliability

When the distributed approach to harmonic mitigation is used, the overall reliability of the electrical system improves because the failure of one system or component will not shut down the facility. The loss of the one and only, bulk-connected harmonic filter (or power factor solution) can cause a dramatic effect on the overall facility power quality.

Example

Consider the following example as represented in Fig. 5. This system consists of two panelboards (PB-1 and PB-2), each supplied by their own transformer, and each supplying power to both variable frequency motor drives (VFDs) and across- the-line started motors. Without the use of any harmonic mitigation equipment, the total harmonic current distortion (THD-I) at each panelboard is 14.8% (PB-1) and 47.9% (PB-2), and at the main switchboard the distortion is 42.2% THD-I. The actual harmonic current at the main switchboard is about 335 amps. Each of the 100 HP motors have power factor correction capacitors. Due to the presence of harmonics on the system, capacitor protection reactors (CPR) are used to prevent harmonics from being absorbed by the capacitors (which can cause rapid deterioration of the capacitors). The primary objective for this case was to meet 5% current distortion at the MSB.

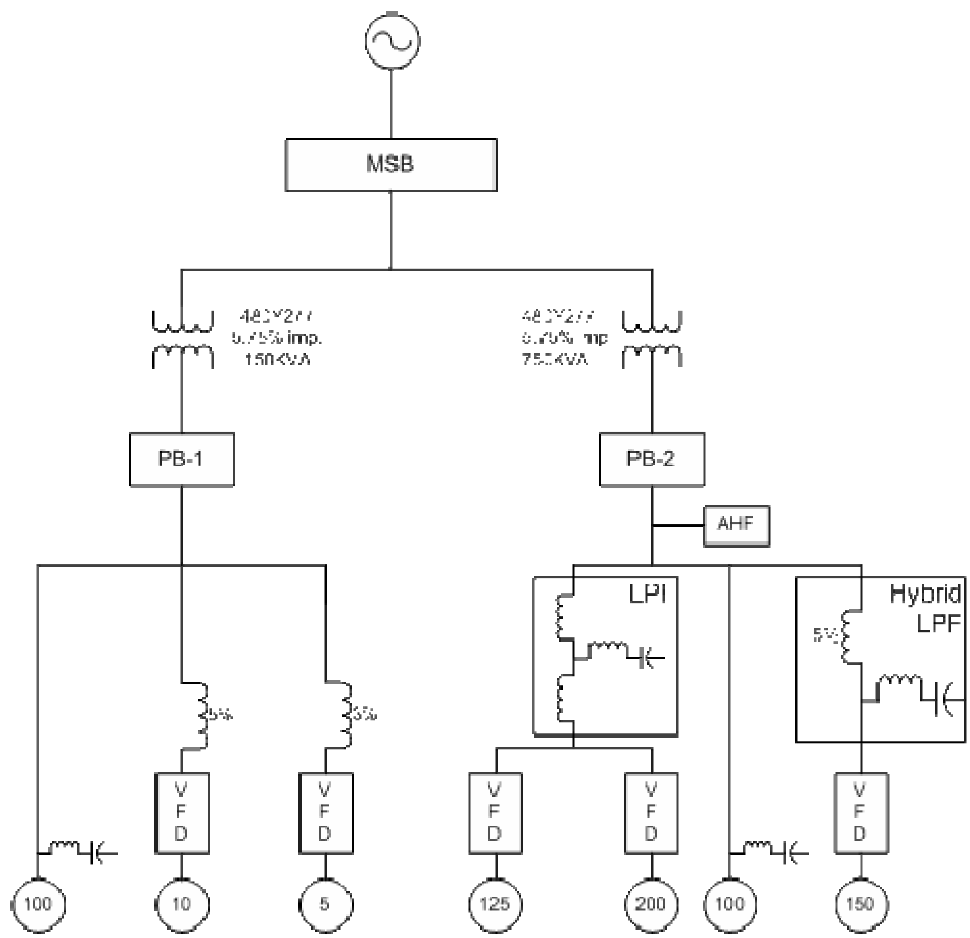

Fig. 5 Industrial Facility with Harmonic Mitigation Equipment Installed

In the traditional, bulk-mitigation approach, a multi-frequency (5th and 7th harmonic) harmonic filter could be applied at MSB. Its capacity would have to be adequate to reduce the harmonic distortion down to an acceptable level (that is, 5% THD-I) or from about 335 amps down to about 42 amps of harmonic current. This 87.5% reduction in harmonic current can be difficult to achieve with a bulk-applied solution. The bulk solution would require a significant amount of reactive KVARs at the MSB and may cause the power factor to become leading (and lower).

Distributed Mitigation Approach

The distributed mitigation approach can use a variety of relatively low-cost solutions such as line reactors, low-pass harmonic filters and a hybrid filter. Power factor improvement is applied at each motor, for greatest internal benefit, along with capacitor protection reactors to protect the capacitors from harmonics. Table 1 tabulates the harmonic current distortion, both with and without any harmonic mitigation equipment, for each load and for each panel board (PB-1 and PB-2). With this distributed mitigation solution, harmonics are reduced to extremely low levels (within the facility) and contained between loads and each respective filter.

Table 1 Harmonic Current Distortion Contributed by each piece of Equipment

Panelboard	**PB -1**			**PB - 2**			
Motor	**100HP**	**10HP**	**5HP**	**125HP**	**200HP**	**100HP**	**150HP**
THD-I w/o Filters	na	81%	114%	65%	52%	na	60%
THD-I with Filter	na	35%	44%	5%		na	12%
THD-I at PB w/o Filters	**14.8% THD-I**			**47.9% THD-I**			
THD-I at PB with Filters	**4.9% THD-I**			**w/o AHF = 5.95% THD-I** **with AHF = < 5.0% THD-I**			

Note: AHF is Active Harmonic Filter
Note: 100HP motors have PF capacitor with Capacitor Protection Reactor (CPR) to block harmonics.
Note: pure motor loads indicate THD-I as "na" because they are not sources of harmonic current.

When the total load consists of both linear and non-linear loads, then at a common point upstream, the harmonic current distortion will depend on the ratio of total rms harmonic current to the total rms fundamental current. Although an individual load may have high harmonic current distortion associated with it, the presence of large linear loads can reduce the impact of the harmonics. Table 2 illustrates the harmonic current distortion at the main switchboard, both with and without harmonic filters. The demonstrated solution meets the most stringent harmonic limit established by IEEE-Std-519. The various IEEE-Std-519 limits (5%, 8%, 12%, 15% or 20% THD-I) are dependent upon certain system conditions. In the event that a higher harmonic limit is acceptable, a lower cost set of distributed mitigation solutions can be used.

Table 2 Total Harmonic Current Distortion (THD-I) at the Main Switchboard (MSB):

Without Harmonic Filters	**With Harmonic Filters (less AHF)**	**With all Harmonic Filters (including AHF)**
42.4% THD-I	**5.77% THD-I**	**< 4.99% or less THD-I**

Since harmonics are reduced to 5.77% using distributed passive filter techniques, if an active filter is used to provide supplemental filtering, it would only need to be sized for 40 amps.

Reducing Harmonics will Increase KVA Available from Power Sources and Transformers
As harmonics are reduced, the true rms (and the peak) current are both reduced. This also reduces the true KVA demanded from the power sources and transformers. Table 3 shows the KVA demand under full load conditions, both with and without harmonic filters, as well as the KVA savings that is realized on each transformer for the solution provided. Transformer KVA savings are also available when power factor is improved.

Table 3 KVA Demand on each Panelboard.

Panelboard	PB - 1	PB - 2
KVA Demand w/o Filters	**120.38 KVA**	**649.43 KVA**
KVA Demand with Filters	**116.05 KVA**	**576.46 KVA**
% KVA Saved	**3.5%**	**11.2%**

Note: Additional KVA was also released due to the installation of the PF improvements capacitors (100HP motors)

For this example, and in most cases, the distributed mitigation approach is the best internal solution and provides the greatest benefit to the facility and electric utility alike. In this case, it also is the lowest initial cost solution as illustrated in Table 4.

Table 4 Harmonic Mitigation Solution Cost Comparison

Bulk Mitigation Solution	Distributed Mitigation Solution (w/o AHF)	Distributed Mitigation Solution (with AHF)
12-15% THD-I	5.77% THD-I	< 4.99% or less THD-I
$55,000.	**$33,500.**	**$51,000.**

Conclusion
Many benefits can be realized when harmonic mitigation equipment is distributed close to the actual non-linear loads. The facility itself gets the best overall value based on multiple internal benefits including the improvement of voltage quality throughout the electrical system as well as reducing the burden on electrical equipment. Electrical equipment maintenance and replacement costs are reduced, energy consumption and losses are reduced and equipment performance and productivity increases. An important factor is that in a system where harmonic mitigation equipment is distributed throughout the facility and close to the non-linear loads, the failure of harmonic mitigation equipment has only a local impact. In the traditional bulk mitigation approach, the entire facility is left vulnerable when an equipment failure occurs. The traditional approach has the disadvantage of requiring re-evaluation and possible upgrade whenever new equipment is added to the facility electrical system. With the distributed mitigation approach, new equipment can be evaluated as an individual piece of equipment and does not affect the distributed mitigation equipment already in place.

Authors

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John Houdek is an electrical engineer (Milwaukee School of Engineering, MSOE) and has a MBA (Keller Graduate School of Management). Houdek has over twenty years experience in the application engineering of sine wave correction techniques for the power electronics industry. He has delivered seminars and technical papers in Europe, Asia, Mexico, Canada and the U.S.A. As an employee of Allied Industrial Marketing, a technical marketing support firm, he provides application engineering support for Beckwith Electric, Inelap's exclusive North American distribution partner. Houdek also teaches a course in electrical power quality at MSOE.