

## DESIGNING 21<sup>ST</sup> CENTURY ELECTRICAL SYSTEMS THAT INCORPORATE SYSTEM-WIDE HARMONIC CORRECTION

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### **ABSTRACT**

A hybrid solution consisting of a parallel-connected electronic filter at the point of service and locally applied phase-shifting distribution transformers delivers a cost effective and complete system-wide harmonic correction solution. This approach takes advantage of transformer configurations placed close to the loads to cancel commonly found characteristic harmonic currents by creating quasi higher pulse systems and then uses a small electronic filter to address the residual harmonic currents inherent to multi-pulse systems. This hybrid solution enables any corporation to consistently meet IEEE-519 harmonic limits for current and voltage on a facility-wide basis as well as deal with harmonics not easily mitigated using conventional passive technology.

### **KEYWORDS**

Harmonics, switchmode power supply, 6-pulse, active filter, phase multiplication, IEEE-519

### **INTRODUCTION**

One of the requirements in electrical system design is to meet the recommended levels set out in IEEE Std 519-1992 "IEEE RECOMMENDED PRACTICES AND REQUIREMENTS FOR HARMONIC CONTROL IN ELECTRICAL POWER SYSTEMS" [1]. This standard sets out limits for both voltage and current harmonic levels at different points in an electrical system. For the benefit of both the loads and the electrical system, a variety of approaches have been implemented that reduce harmonic levels in electrical systems. Without some form of corrective action in place, harmonics produced by

nonlinear loads can permeate throughout an electrical system with a variety of consequences including overheating and premature failure of components in an environment of increased system losses and voltage distortion.

For decades, electromagnetics have been used to deliver cost-effective and reliable transformer-based harmonic current and voltage distortion reduction. An example of such an approach is the implementation of phase multiplication, a technique whereby separate but similar harmonic-producing loads are fed through transformers having different relative phase-shifts [2,3,4]. The effectiveness of a phase multiplication strategy varies as a function of load balance between the sources and similarity of load profile, making it very difficult to meet the current distortion limits with a reasonable degree of certainty. Another method of harmonic treatment is the active filter, the most popular is a current harmonic treatment that involves injecting the appropriate magnitude of harmonic current out of phase with that produced by the load, thereby canceling load-produced harmonic currents. This approach is able to provide very effective and predictable harmonic current reduction across the frequency spectrum, delivering a predictable reduction of current THD to typically below 5%, thereby meeting even the tightest harmonic current limit set out in IEEE Std 519-1992. There are several drawbacks to using this approach on a system-wide approach, including high price.

This paper describes how both electromagnetic-based and active filters have been applied, and proposes a method of integration of the two technologies on an electrical system basis so as to deliver reliable harmonic correction that predictably meets IEEE-recommended limits.

### ***PHASE MULTIPLICATION (ELECTROMAGNETIC-BASED TECHNOLOGY)***

The effectiveness of the phase multiplication technique is well documented in many hundreds of publications in the electrical industry, and in fact is described in IEEE Std 519-1992 as a method to reduce harmonic current levels in a system [1].

Phase multiplication essentially creates quasi higher pulse systems out of lower pulse loads with the result of reduced harmonic content. For example, this strategy can be implemented for multiple rectifier loads by using the following relationships:

1. the required number of 6-pulse loads = desired pulse number / 6
2. required relative phase-shift =  $360/p$  degrees, where  $p$  is the desired pulse number of the system

So to create a quasi 18-pulse system,  $18/6 =$  three 6-pulse rectifier loads are required, having a relative phase angle difference of  $360/18 = 20$  degrees.

The theoretical characteristic harmonics produced by rectifiers can be determined by the formula  $h = k p \pm 1$ ,

where  $h$  = harmonic order

$k$  = any integer, 1, 2, 3, .....

$p$  = pulse number of the rectifier circuit

So for a 6-pulse rectifier, the characteristic harmonic currents are 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, 13<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup> and so on. By increasing the effective pulse of a system, the lower order characteristic harmonics are eliminated. For example, using the above formula, we see that for a 12-pulse system the first pair of characteristic harmonics are 11<sup>th</sup> &

13<sup>th</sup>. Therefore by creating a quasi 12-pulse system by phase-shifting two 6-pulse rectifiers, the 5<sup>th</sup> & 7<sup>th</sup> harmonic currents, while still produced by each individual rectifier, are eliminated at the common point feeding the two rectifiers (assuming similar load profiles). As a result of the elimination of the 5<sup>th</sup> & 7<sup>th</sup> harmonic currents, the harmonic current distortion is typically reduced from the 30-40% range to 15-20%. Following Ohm's Law, this reduction in current harmonics will deliver a drop in voltage THD at the loads. The degree of reduction is a function several variables including the proportion and similarity of the treated loads relative to the size of the system, the system impedance, and the proportion of remaining untreated harmonic-producing loads, as well as the baseline voltage THD at the Utility/customer interface.

While both the loads and the electrical system benefit from such a reduction in harmonic current and voltage levels, real life performance varies continuously as a function of several typically dynamic variables, especially in industrial systems, and as a result the phase multiplication approach may fall short of what is ultimately required on an ongoing basis.

### ***ALTERNATE HARMONIC TREATMENT***

There are of course other well established alternatives to the previously described phase multiplication method for harmonic reduction. Perhaps the best known is the tuned filter, a capacitor/inductor combination that produces a low impedance at or near a targeted harmonic frequency. Design, implementation, and application issues have been and continue to be widely published in the industry and are outside of the scope of this paper [6]. Some issues relating to tuned filters include the potential for resonance and the need for stable harmonic loading.

The simple reactor should also be mentioned as it has a place in the arena of harmonic

current reduction. Reactors are often used with variable frequency drives as the default way to “treat” their harmonic currents. When installed in-line with a harmonic producing source, a reactor reduces current harmonics, as a function of its reactance, although this achievement is at the expense of an increase in voltage distortion on the load side of the reactor. Reactors cost much less than perhaps any other form of harmonic mitigation, but because of the undesirable increase in voltage distortion at the load, their use as a full harmonic treatment should be carefully evaluated with respect to whether or not the load can operate satisfactorily under such conditions.

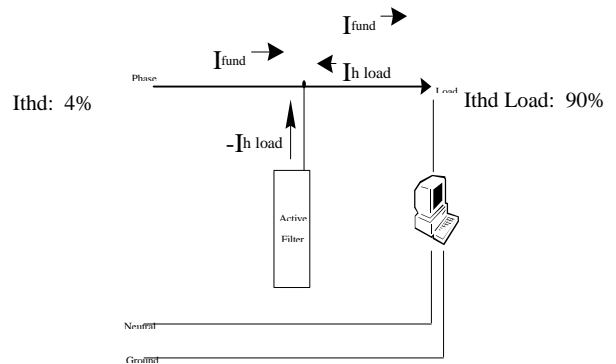
In response to the need for predicable harmonic reduction, active (electronic-based) harmonic correction has been developed to address either current or voltage waveforms or both. Active harmonic filters, originally developed for military requirements, are gradually becoming an accepted solution for commercial and industrial applications. As the technology becomes more reliable and cost effective there will be many opportunities to utilize this approach both on a stand alone basis as well as in conjunction with passive electromagnetic solutions to create a hybrid harmonic treatment, and therefore more description of the approach is appropriate.

**ACTIVE FILTERS (ELECTRONIC-BASED TECHNOLOGY)**

The active approach is not encumbered by some of the shortcomings of other harmonic treatments such as load imbalance for phase multiplication or fixed target harmonic frequencies for tuned filters. Different configurations of active technology exist and have been described in detail in industry publications for the past several years [7,8]. The most popular is a current harmonic treatment that involves injecting the appropriate magnitude of harmonic current out of phase with that produced by the load, thereby canceling load-produced harmonic currents. This approach is able to provide very

effective and predictable harmonic current reduction across the spectrum. Reductions of current THD to typically below 5% is quite achievable thereby meeting even the tightest harmonic current limit set out in IEEE Std 519-1992.

FIGURE 2: ACTIVE FILTER DIAGRAM



The concept of active harmonic cancellation, CWACS™ (Current Wave Active Correction System™), in simplest terms involves injecting a waveform that is out of phase with the non 60Hz portion of the load profile. Up to the point of connection of the CWACS to the system, the demand on the electrical system is essentially reduced to delivering the 60Hz component. Improved power factor results as a function of reducing the distortion power factor and is a natural positive by-product of harmonic cancellation. CWACS does not change the displacement power factor.

Loads with complex harmonic spectrums and/or electrical systems where even harmonics are but two examples where active technology can be very cost effective on a stand alone basis. While the precision of active harmonic correction is very desirable, its high cost per harmonic amp can sometimes make it prohibitively expensive to implement on a facility-wide basis.

**HYBRID HARMONIC TREATMENT**

The combination of different methods of harmonic reduction can also be implemented in order to improve the overall effectiveness of the total harmonic treatment. In many facilities a hybrid approach may be a cost effective and reliable approach that meets all the requirements for harmonic current and voltage limits as prescribed by IEEE Std 519-1992.

At first glance, tuned filter banks at the building entrance looks like an attractive complimentary approach to electromagnetic-based phase multiplication. However, the weaknesses inherent to capacitor-based filters combined with the varying level of residual harmonic currents after phase multiplication make this combination far from ideal.

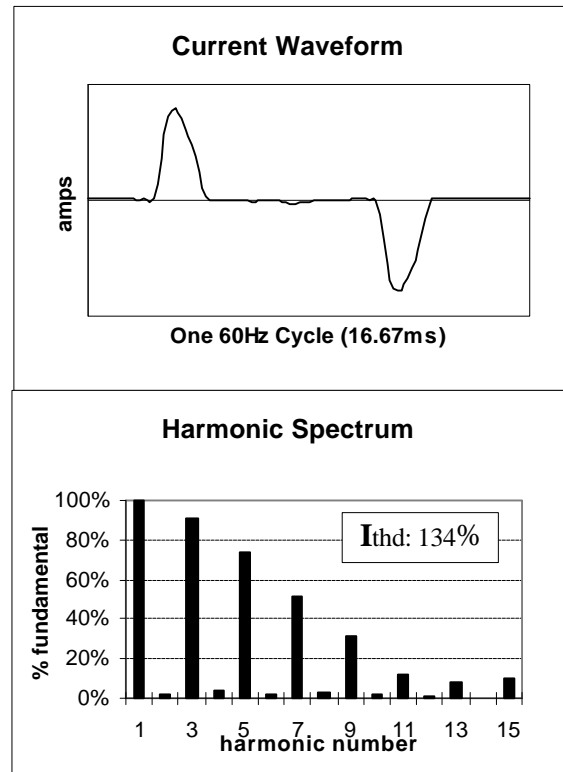
Active harmonic cancellation systems, on the other hand, make a good partner with phase multiplied systems. By playing the “clean up” role, active technology can address the residual current left over from electromagnetic cancellation, resulting in predicable harmonic correction even with a dynamic electrical system. Under this strategy the cost of total harmonic treatment is provided at a relatively small premium to the low cost phase multiplication treatment.

**CASE STUDY - TREATING PERSONAL COMPUTER LOAD HARMONICS**

Let’s look at an industrial example of how the different approaches to harmonic cancellation compare. We analyzed the implementation of hybrid harmonic cancellation to a system feeding personal computer loads. This equipment is like most phase-neutral electronic equipment in that is powered by a switchmode power supply that has a characteristically high harmonic content.

The baseline data is the untreated computer load (figure 3). The rich harmonic spectrum is typical of phase-neutral electronic equipment. Note the high levels of lower order odd harmonics beginning with the 3<sup>rd</sup>.

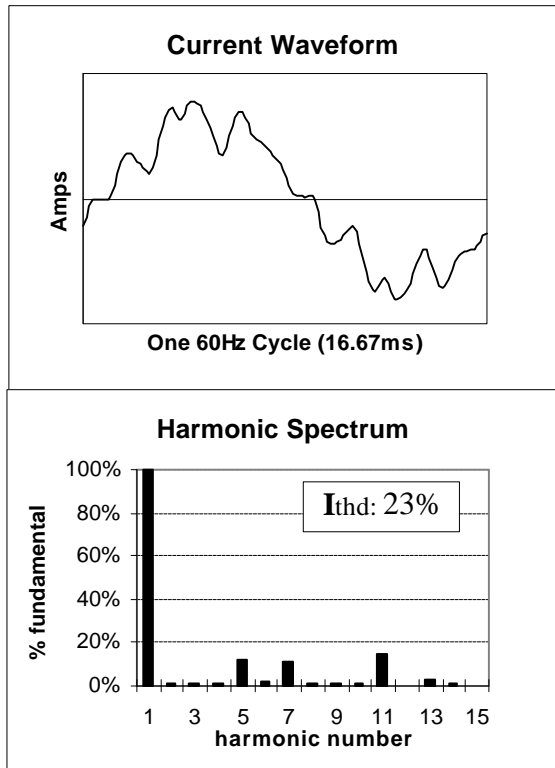
FIGURE 3: UNTREATED PERSONAL COMPUTER LOAD PROFILE



The next step is to implement phase multiplication (figure 4). For treatment of the major harmonics, we used a dual output transformer with a 30 degree phase-shift between the secondary windings for treatment of the 5<sup>th</sup> & 7<sup>th</sup> harmonic currents, combined with low zero sequence impedance in both secondary windings to deliver treatment of the 3<sup>rd</sup>, 9<sup>th</sup>, 15<sup>th</sup>... harmonics. This configuration predictably delivers voltage distortion at the loads well below the IEEE recommended limit. However, as we can see in figure 4, the residual levels of 5<sup>th</sup> & 7<sup>th</sup> that were treated, combined with the untreated 11<sup>th</sup> & 13<sup>th</sup> harmonic currents leave us with harmonic current THD of 23%. This represents an almost 6 times reduction but the remaining harmonic currents

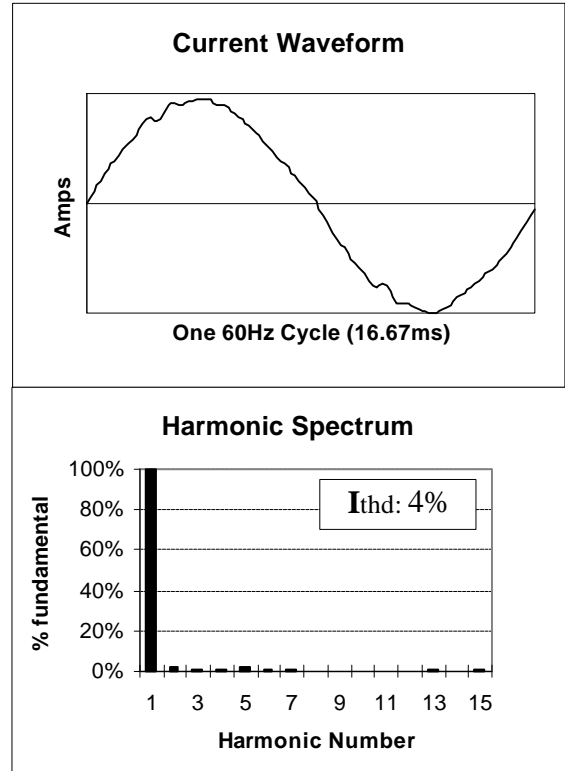
do flow into the upstream system. In some systems, this would not meet the IEEE current limits if this represented the majority of the load profile seen by the utility. This would certainly be uncommon on the commercial side but is a real possibility on the industrial side especially given the rapidly growing variable speed drive load.

FIGURE 4: LOAD PROFILE UPSTREAM OF PHASE MULTIPLICATION AND LOW ZERO SEQUENCE IMPEDANCE TRANSFORMER



The final step adds an active filter (figure 5). With a residual harmonic current THD of only 4%, this load profile meets even the most stringent IEEE current limit.

FIGURE 5: LOAD PROFILE UPSTREAM OF ACTIVE FILTER



### CONCLUSIONS

There are many advantages to the hybrid approach to harmonic cancellation. It will predictably meet the harmonic current limits set out in IEEE Std 519-1992 in a cost effective and reliable manner. Substantial harmonic current reduction can be achieved by using low cost, reliable electromagnetic-based technology, leaving the smaller but more complex job to the active technology.

The biggest limitation is that multiple similar harmonic sources are required to implement the phase multiplication portion of the hybrid approach. Another limitation is that in face of some complex waveforms, the active filter may have to be customized and therefore making it more expensive from a construction and maintenance point of view.

The potential applications are many given the existing densities of nonlinear loads in today's electrical systems such as variable speed drives, welders, arc furnaces, and electronic loads like personal computers and robotics.

Driving forces include increasing densities of nonlinear loads, the increasing sensitivity of these loads to harmonic distortion, and the increasing tendency of electric utilities and service providers to set harmonic limits. Potential industries include military, telecommunications, broadcasting, financial, and high tech manufacturing.

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