Questions and Answers for Applying IEEE 519-1992 – Part 1

Mark McGranaghan, Electrotek Concepts, Inc., Knoxville, Tennessee

Many of you who know me are probably wondering how I have been able to write this column so far without contributing a single article on harmonics issues. Well, I'm finally doing one. The only danger is that once I get started, I may never get back to other more important power quality concerns. Since this is my first article on harmonics, I have to focus on the application of IEEE 519 – *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.*

The current version of IEEE 519 was introduced in 1992. Since that time, many utilities have adopted the standard as the basis for evaluating harmonic interaction concerns between customers and the power system. It has also influenced harmonic standards that are being developed throughout the world. Despite being widely applied, there are still many questions that continue to come up regarding interpretation and application of the standard. We on the standards committee are currently completing an application guide that should help with most of these questions. In the meantime, in this article I will try to address some of the most common questions.

One of the things I like about IEEE 519 is that it is one of the first standards in the power quality area to define responsibilities on both sides of the meter in order to achieve *compatibility* between the power system and customer loads. The utility is responsible for the quality of the *voltage* being supplied, and the customers are responsible for the *current* distortion in their load currents. If all the customers meet the current distortion requirements, the utility should be able to maintain a power system design that will assure the quality of the voltage. So let's get to the questions.

Where is the point of common coupling for most facilities?

The harmonic limits in IEEE 519-1992 were meant to be applied at the point of common coupling (PCC) between the utility system and multiple customers. The definition used in the IEEE P519A application guide under development is that the PCC is the location on the system where another customer can be served from the system. The standard allows for the same procedure to be applied by the customer at other locations within a facility but different current limit values could apply in these cases.

The PCC can be located at either the primary or the secondary of a supply transformer depending on whether or not multiple customers are supplied from the transformer. *Figure 1* illustrates the two possibilities. Note that when the high side of a supply transformer is the PCC, current measurements for verification can still be performed at the transformer low side. Low side measurements can be used (at a metering location, for instance), and the results can then be referred to the transformer high side by the turns ratio of the transformer, keeping in mind the effect of the transformer connection on the zero sequence harmonic components. For example, a delta-wye transformer will not allow zero sequence components to flow from the secondary to the primary system (they will be trapped in the primary delta winding). Therefore, zero sequence components (e.g., balanced triplen harmonic components) measured on the secondary side would not be included in the evaluation for a PCC on the primary side. If the utility owns the stepdown transformer, the harmonic currents can be evaluated at the transformer secondary, but the short circuit ratio (SCR)

should be calculated at the primary side PCC.

What load current and system short circuit current should be used to calculate the short circuit ratio (SCR)?

The SCR is calculated as the ratio between the short circuit current at the PCC and the customer's maximum load current, or in this case, the average maximum demand load current, I_L. The SCR is used as a measure of the customer's size in relation to the system capacity. The smaller the customer, the less likely the customer can cause harmonic voltage distortion problems on the overall power system. For this reason, smaller customers can have a somewhat higher level of harmonic current expressed as a percentage of their total load current. This assumes that there will be some amount of diversity or cancellation as harmonic currents from these customers are combined on the power system.

IEEE 519 gives a procedure for calculating I_L, which is to average the maximum demand current from billing records for 12 consecutive months. Obviously, this is not possible if you are evaluating IEEE 519 compliance for a new customer or for a customer where the facility is being expanded or changed. In these cases, the maximum load current must be estimated. Sometimes, you may just want to use a rated current, such as the transformer rating. The important thing is to have a consistent method for choosing this current and to have the utility and the customer agree on which value will be used.

The short circuit current for the calculation should be the minimum short circuit current for normal conditions at the PCC. Note that this is different from the short circuit current normally used for protection studies, in which the maximum short circuit current is most important. The minimum short circuit current results in the most voltage distortion for a given amount of harmonic current injection.

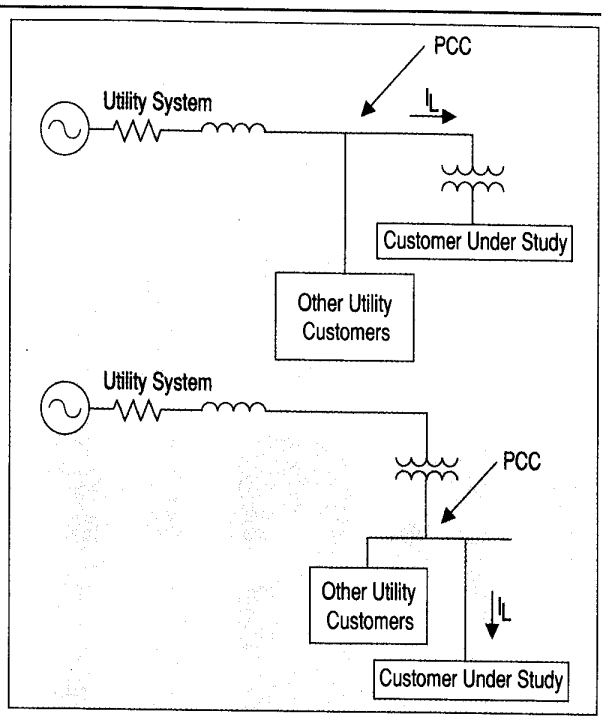


Figure 1. Selection of the PCC where other customers can be supplied.

What is Total Demand Distortion (TDD)?

TDD is a new term introduced in IEEE 519. It is a very important concept. Here's the formula:

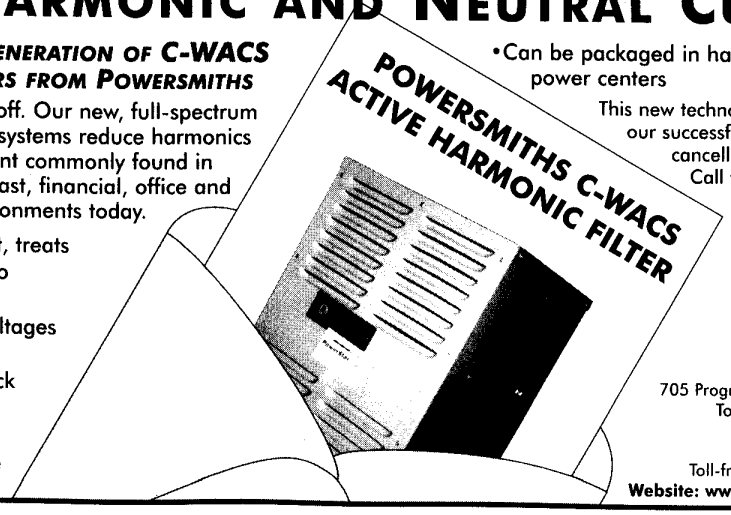
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$$TDD = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_L} \times 100\%$$

where:

I_h = magnitude of individual harmonic components (rms amps)

h = harmonic order

I_L = maximum demand load current (rms amps) defined above

Look familiar? It's the same formula used to calculate the total harmonic distortion (THD), except here the denominator is the maximum demand load current (a constant), rather than the fundamental value of the load current for a particular measurement (a value that will change with each measurement).

All the limits for harmonic currents are expressed in % of the maximum demand load current, I_L. This allows harmonic currents to be evaluated over a wide variety of load conditions with a constant base value. If we used the fundamental component of the current as the base, the distortion values at light load might look very high but would not have a significant impact on the power system. The method of expressing everything in % of I_L allows evaluation of the actual amps of harmonic current being injected onto the power system.

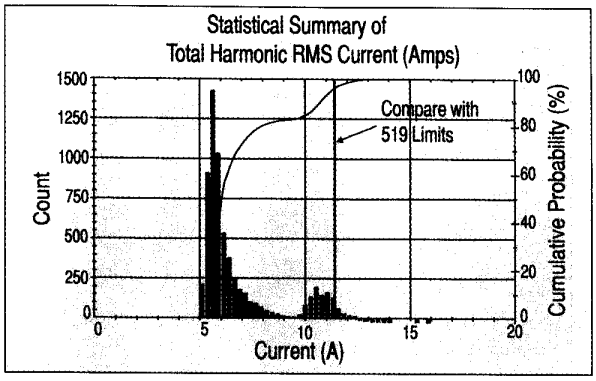


Figure 2. *Representing the harmonic distortion as a statistical distribution for comparison with IEEE 519 limits.*

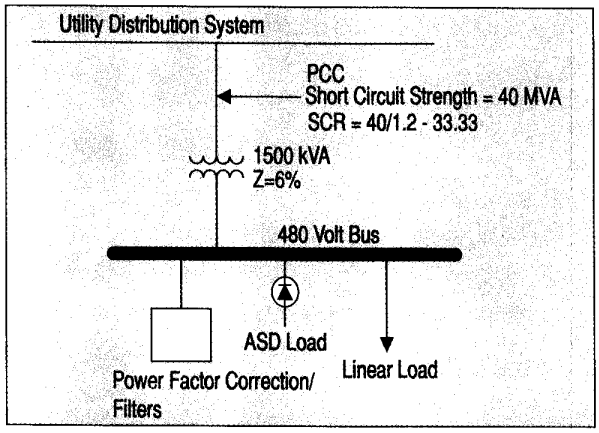


Figure 3. *One-line diagram for example evaluation of IEEE 519 limits.*

How long should harmonics be measured to evaluate compliance with IEEE 519 guidelines?

Remember, harmonics are continuous. Harmonic distortion levels are changing all the time, just like the overall load and the rms voltage magnitude. You cannot evaluate harmonics with a single snapshot of the voltage and the current any more than you can evaluate voltage regulation with this approach. IEC guidelines for evaluating harmonics

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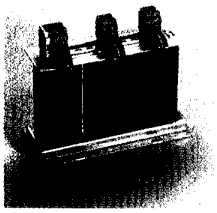
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recommend measurements over a minimum one-week period in order to characterize the daily and weekly variations in the load levels. The important thing is to get enough samples so that you characterize the overall statistical nature of the harmonic levels (*Figure 2*).

Once you have determined the statistical characteristics of the harmonic distortion levels, what value should you use to compare with the IEEE 519 limits? IEEE 519 states that the limits specified can be exceeded for up to one hour per day (4.2% of the time). IEC guidelines use the 95% probability point (level that is exceeded 5% of the time) for many evaluations. At least remember that it's okay to exceed the limits for short periods since most of the impacts of harmonics are time related (e.g., overheating of motors and transformers).

How much nonlinear load can I have in my plant without exceeding IEEE 519 guidelines?

It is useful to look at a simple example system to help answer this question. Assume an industrial customer is supplied by a 1500kVA transformer and that his average maximum demand load is 1200kVA (*Figure 3*). How much of this 1200kVA of load could be adjustable speed motor drives without causing the plant to exceed IEEE 519 guidelines?

First, identify an adjustable speed drive current waveform that could be representative of ASD loads in the facility. The waveform in *Figure 4* is typical of most modern ASDs with pulse-width-modulated inverters and diode-bridge-rectifier front ends. The waveform assumes that a choke inductance is part of the design. If this waveform is characteristic of all the ASDs in the facility (not too bad an assumption for drives with diode-bridge-rectifier front ends), then the relationship plotted in *Figure 5* can be derived. It shows that the site reaches the IEEE limit for the fifth harmonic current injection when the ASD load becomes about 20% of the plant load.

Note that a higher percentage of ASD load might be acceptable in terms of the voltage distortion created in the plant (typically, about 40% of the plant load could be ASDs without exceeding 5% voltage distortion). The IEEE 519 limits were developed to prevent problems from the combination of all customers injecting harmonics onto the power system, not to prevent problems within a single customer facility.

A higher percentage of ASD load would be acceptable if 12-pulse drives were used or if harmonic filters were applied. Conversely, if power factor correction is applied (not as filters), resonance problems could cause the limits to be exceeded for even less ASD load.

What if voltages inside my facility exceed the voltage distortion guidelines provided in IEEE 519?

The IEEE 519 voltage distortion guidelines should be applied at the PCC where multiple customers are supplied,

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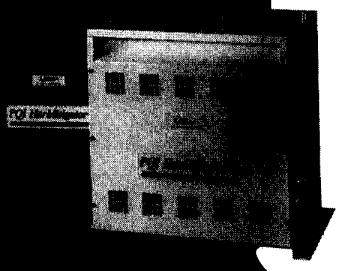
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usually the primary of the distribution system. If individual customers have higher voltage distortion numbers within their facilities, this is not necessarily a problem. Equipment problems are not usually associated with voltage distortion when the distortion level is less than 8%. In fact, the European guidelines for voltage distortion indicate a limit of 8%. This means that it should be acceptable in most cases (in fact, it is quite common) for the voltage distortion inside facilities to exceed 5%.

Why are the limits for even harmonic components more strict than the limits for odd harmonic components?

Significant levels of even harmonics in the voltage or the current are quite rare. You can tell there are even harmonic components present when the positive half cycle is different from the negative half cycle (waveform is not symmetrical). Even harmonics are often associated with transformer saturation (transformer inrush currents have high levels of even harmonics but this is a transient condition) which can be caused by DC currents. This association between DC currents and even harmonics resulted in a stricter limit on even harmonic components in the IEEE 519 standard. In fact, it is usually not necessary to apply this stricter limit because the impacts of even harmonic components are not any different than the impacts of odd harmonic components (at least at the levels specified as limits in IEEE 519). The presence of significant even harmonic components can make filter design to control harmonics very difficult because new resonance frequencies introduced by the filter can often magnify the even harmonic components.

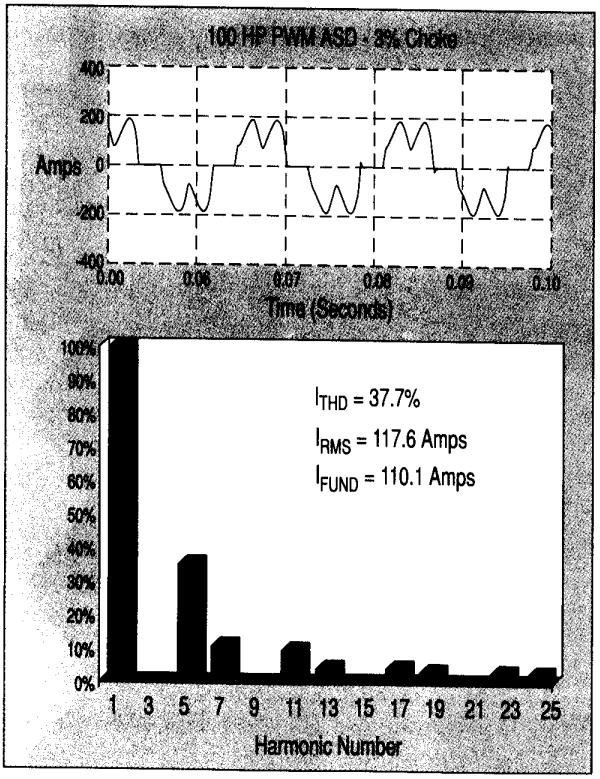


Figure 4. Adjustable speed drive current waveform assumed for the analysis.

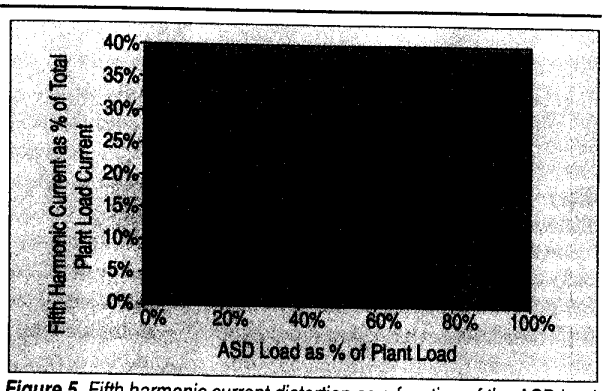


Figure 5. Fifth harmonic current distortion as a function of the ASD load in the facility.

Are there any guidelines for acceptable levels of interharmonic components?

This is an issue that really only comes up with loads like cycloconverters and arc furnaces. Interharmonics are frequency components in the voltage or current that are not integer multiples of the fundamental frequency. Unfortunately, IEEE 519 doesn't provide any guidance here. There is an IEEE task force working on developing some guidelines on control of interharmonics. It is also an active topic in IEC; however, there are no well-accepted standards for interharmonic levels at this time. One design objective used for some arc furnace applications is to limit the interharmonic components to less than 25% of the corresponding integer harmonic limits specified in IEEE 519-1992.

How can we apply the IEEE 519 limits when we have power factor correction capacitors or harmonic filters?

Capacitors and filters make the application of the 519 limits difficult to evaluate because these components will absorb harmonics from the power system. In fact, customers need to be careful when applying power factor correction or filters to make sure they are designed for the harmonics they will absorb from the power system. The customer shouldn't be penalized for acting like a filter to the power system. Unfortunately, meters can't tell which direction the harmonics are going when they make a measurement at a single point. There are ways to get around this by measuring over time, but that topic goes beyond the scope of Part 1 of this article.

There are many other harmonics topics to discuss in Part 2 of this article, which will appear in the next issue. I've been wanting to cover the topic of active filters versus passive filters anyway, and it is part of this overall topic. I warned you that, once I got started, I wouldn't be able to get off the topic of harmonics.

Anyway, I hope this article might have addressed some of your burning questions on IEEE 519. If you have others, I encourage you to contact me.

If you found this article useful, circle 204 on the inquiry card.

Applying IEEE 519 – Part 2: Controlling Harmonic Distortion Levels

Mark McGranaghan, Electrotek Concepts, Inc., Knoxville, Tennessee

Last issue we discussed some of the concerns associated with applying IEEE 519, but I couldn't fit everything I wanted to say into one column, so I had to defer to this issue for the conclusion. Basically, we covered the most important concerns associated with applying the limits, but we didn't get to the topic of reducing harmonic levels if they turn out to be a problem. In this issue, we will focus on the different methods available for controlling harmonic levels. It is a timely topic because active filters are finally becoming a viable alternative to passive filters for controlling harmonic levels. It is worthwhile to look at where it makes sense to consider this new technology.

Harmonic problems can be solved or prevented at a number of different levels of the system. Here are the key options:

- Purchasing equipment with reduced harmonic generation. This decision usually must be made at the design stage of a facility, since it is difficult to modify or replace the equipment once it is in service.
- Applying technologies (e.g., magnetics) that can achieve cancellation of harmonics from different loads. This can often be done with standard transformer connections.
- Changing the system configuration to avoid the resonance conditions that magnify the harmonic levels.
- Applying power factor correction as passive harmonic filters This is the best approach when power factor correction is needed and harmonics are a concern. I will talk about some basic filter design guidelines later.
- Applying active filters. If power factor correction is not needed and harmonics are a concern, this may be the best approach. This technology has come a long way and appears to finally be a realistic economic alternative for controlling harmonic levels.

Each option is worth considering, and each could be the best approach depending on the specific circumstances. In the end, the choice will be determined by the economics of the different alternatives. Let's look at each of these options in a little more detail for a better idea of when each option might make sense.

Buying Equipment With Reduced Harmonic Generation

The most effective way to solve harmonic problems is often right at the source of the harmonics. The Europeans use this as the basic approach for controlling harmonic levels from single phase equipment that gets applied in

offices and residential applications. Standard IEC 1000-3-2 (formerly 555-2) specifies allowable harmonic generation for single phase equipment up to 16 amps. Design of equipment with reduced harmonic generation involves additional costs, and some manufacturers claim this may not always be the most economical method of dealing with the harmonic issue.

One example of reducing harmonic generation at the equipment level is the application of inductive chokes for adjustable speed motor drives. Without the chokes, harmonic currents for adjustable speed drives can have distortion levels of 80% and higher. A simple 3% choke can reduce the harmonic current distortion to less than 40%, which might be enough to prevent problems in many cases. *Figure 1* illustrates the effect of a choke on the harmonic current distortion levels for a typical pulse-width-modulation (PWM) type adjustable speed drive. Note that the distortion levels without the choke are dependent on the size of the drive with respect to the supply transformer. If the drive is big enough, the supply transformer looks like the choke. Many adjustable speed drive manufacturers now include a choke in the DC link of the drive, producing the same effect – check on it before you buy your next drive.

Harmonic Cancellation

Another method for controlling harmonic generation at the source is to buy adjustable speed drives or other rectifier equipment with higher pulse numbers. The pulse number refers to the number of commutations, or steps, in the AC waveform to a rectifier load. A six pulse device has six steps. The harmonics generated by these loads are related to the pulse number. A six pulse drive or rectifier has its first two characteristic harmonics at the fifth and seventh harmonics. A twelve pulse drive has the first two characteristic harmonics at the eleventh and thirteenth harmonics, and the magnitudes are much lower.

You can make multiple drives look like higher pulse number loads when they are combined through judicious application of transformers with different connections. The basic principle is illustrated in *Figure 2*. One drive is connected through a transformer with a delta-delta connection, and another drive is connected through a transformer with a delta-wye connection. The resulting phase shift changes the waveform at the primary of the transformer and results in cancellation of the fifth and seventh components. The combined waveform for the two drives is much cleaner, but this technique probably will not produce perfect cancellation, so be careful in applying harmonic filters in a situation like this (more about this later).

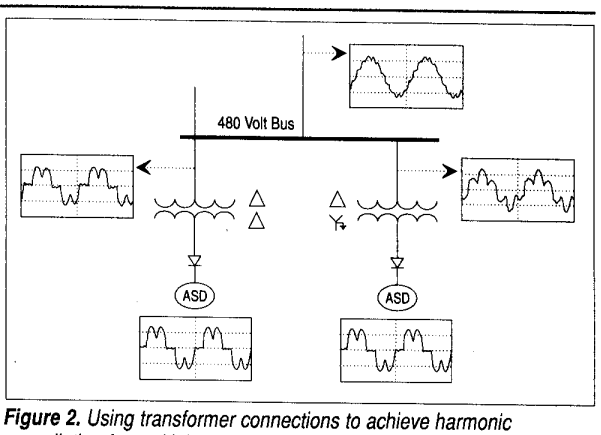


Figure 2. *Using transformer connections to achieve harmonic cancellation for multiple adjustable speed drives.*

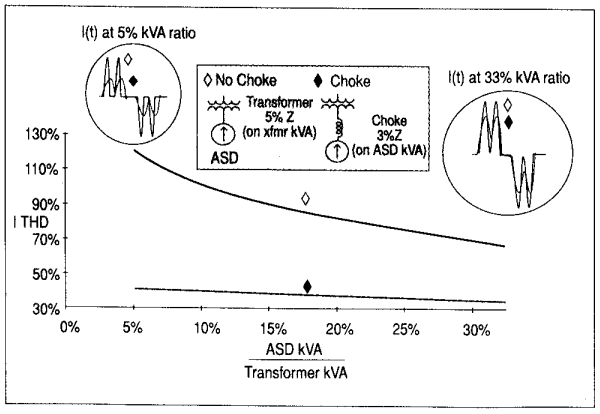


Figure 1. *Effect of an AC line choke on the harmonic current distortion levels for a PWM-type ASD.*

Avoiding Resonance Problems

Be careful in applying power factor correction capacitors. Hopefully, that message was clear in my column in the last issue. Capacitors combine with the system source inductance to cause a parallel resonance. The basic circuit is illustrated in *Figure 3*. A parallel resonance means a high impedance at the resonant frequency. Remember that nonlinear loads look like harmonic current sources (the basis of the IEEE 519 standard). When these harmonic currents see a high impedance near the resonant frequency for the circuit, they cause high voltage distortion and magnified harmonic currents in the capacitor bank and the source. *Figure 4* illustrates the effect of different capacitor bank sizes on the magnification of the harmonic currents for a typical case (1500kVA transformer supplying a facility).

How do we avoid this problem of magnified harmonic currents and high voltage distortion levels? Don't apply

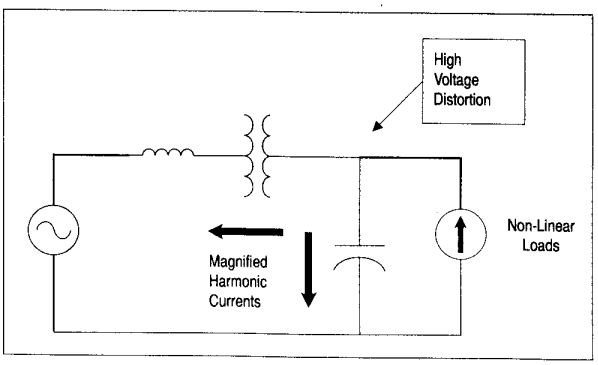


Figure 3. *Basic circuit illustrating concern for parallel resonance.*

capacitor banks that result in a resonance near one of the characteristic harmonics for the nonlinear loads (usually the fifth or seventh). You can avoid problems of magnification in most cases by limiting the size of power factor correction capacitors to less than 20% of the transformer kVA rating. For example, if the facility is supplied with a 1500kVA transformer, don't apply power factor correction of more than 300kVAR. *Figure 4* shows that 300kVAR results in a resonance near the eighth harmonic. You don't want to get any closer to the seventh than that.

Oftentimes, you don't have a harmonic problem unless you create one with a resonance condition. Be careful.

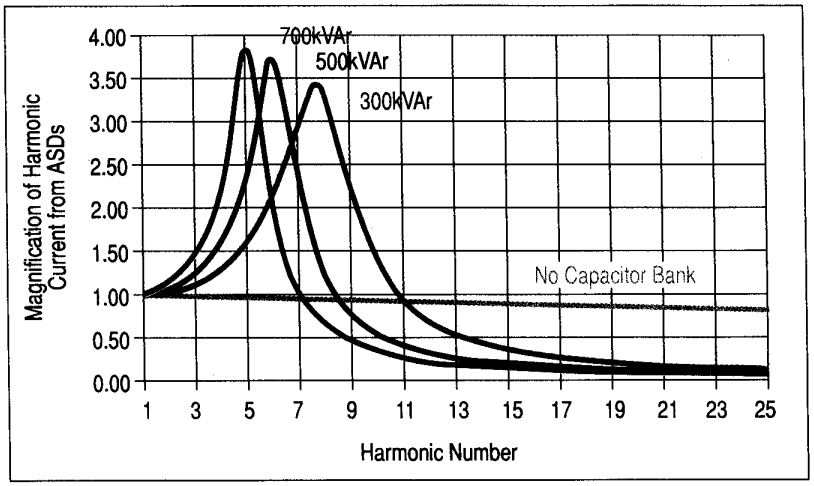


Figure 4. *Magnification of harmonic currents caused by power factor correction capacitors (for the case of a facility supplied by a 1500kVA step-down transformer with 6% impedance).*

Designing Passive Harmonic Filters

Passive shunt harmonic filters are the traditional method of controlling harmonic distortion levels. A single-tuned filter consists of tuning reactors in series with a capacitor bank. This series combination results in a low impedance at the resonant frequency. Therefore, we choose this resonant frequency to match up with one of the characteristic harmonics we want to control. Then the filter will absorb the harmonic currents at this frequency and prevent them from flowing onto the supply system. The effect of the filter on the frequency response of the system is shown in *Figure 5*.

Here are a few important principles to keep in mind when designing passive harmonic filters:

- Always design the harmonic filters for the lowest order harmonic component generated by the nonlinear loads. You can see in *Figure 5* that the filters create a new parallel resonance at a frequency below the series resonance frequency. This was the concern I was talking about when discussing the application of filters for 12-pulse loads earlier. You might think you could design an eleventh harmonic filter for these loads. However, you have to be careful you don't create a new resonance near the fifth or seventh harmonics, because the 12-pulse configuration will not result in perfect cancellation of these components, and you don't want the filter to magnify them.
- Remember that a filter is a filter. It's a low impedance at the filter frequency, regardless of where the harmonics are coming from. It can absorb harmonics from other nonlinear loads in your facility, and it very likely will absorb harmonics from the power system. Unfortunately, the filter must be designed to handle harmonics from all these sources, making it very difficult to apply generic filters for individual loads – they have to be derated too much for all the other harmonic sources that could affect them.
- You don't always have to tune the filter right on the harmonic component of interest. It is usually sufficient to tune the filter somewhere below the lowest characteristic harmonic (e.g. tuned to 4.7th harmonic). This helps reduce the impact of harmonics from the power system and from other loads. When applying the power factor correction as a tuned bank, the most important thing is to not create a parallel resonance that makes things worse.
- Be careful in applying filters in combination with shunt capacitor banks. The capacitors create another resonance that can cause problems at other characteristic harmonics. If you are using a tuned capacitor bank to prevent resonance problems, apply

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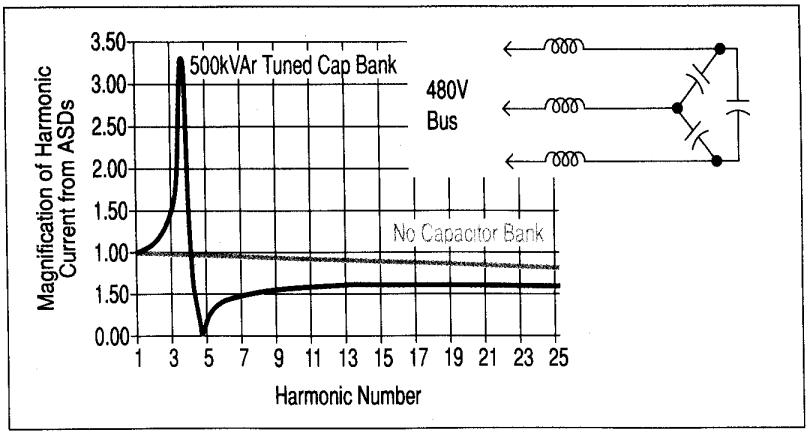


Figure 5. *Effect of a tuned capacitor bank on the magnification of harmonic currents from nonlinear loads.*

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all of your power factor correction as tuned capacitor banks.

If you keep these few cautions in mind, tuned capacitor banks will be an effective way to avoid harmonic problems. We have a spreadsheet that you can use to help choose the appropriate values and ratings for the components of a simple passive filter – drop me an email (markm@electrotek.com) if you would like a copy of it.

Active Filters

Active filters are the answer to our prayers for a method to control harmonics without worrying about all the side effect problems associated with applying passive filters. The basic concept is illustrated in *Figure 6*. The active filter monitors the load current to be filtered, processes the current to determine the harmonic distortion components that need to be canceled and then produces a current that will cancel the unwanted components in the load current.

The active filter uses the same pulse-width modulation inverter technology that is used in adjustable speed drives. This has helped reduce the costs of the active filter technology substantially and also helps with the reliability of these devices – the components are essentially off the shelf.

Active filters have a number of important advantages over passive filters for many applications:

- You can't overload them, probably their most important advantage. They just produce as much current to cancel harmonics as they can produce. They are not affected by harmonic currents from other nonlinear loads in the facility or by harmonics from the power system. They can be rated just for the loads being compensated. This makes them ideal for OEM applications where they can be applied with individual pieces of equipment.
- They do not result in new resonances. In fact, they don't result in *any* resonances. You don't have to worry about canceling one harmonic and magnifying another harmonic. This makes active filters ideal for application with 12-pulse converter installations. It is difficult to apply passive filters in these cases because they could magnify the fifth or seventh harmonics. The active filter will cancel the eleventh and thirteenth harmonics without magnifying any other harmonics.
- They can be designed with special control strategies to meet specific objectives. The control can be designed to



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control certain harmonics with higher priority than other harmonics. For instance, the control can be designed to control harmonics with weighting factors to match IEEE 519 limits.

- They don't have to compensate for all the harmonics. An active filter will absorb all the harmonics that it can, so it doesn't have to be rated for all the harmonics. It might be sufficient to cut the harmonic currents in half. In this case, you just have to rate the active filter for half the harmonic current from the load.
- Active filters don't have to provide power factor correction. The control can be designed to provide compensation of harmonic components without providing fundamental frequency power factor correction. Many applications with PWM type adjustable speed drives need harmonic control but the displacement power factor is very good. It is difficult to design passive tuned filters in this case because the filters must be sized for the harmonics, and then they make the power factor leading.

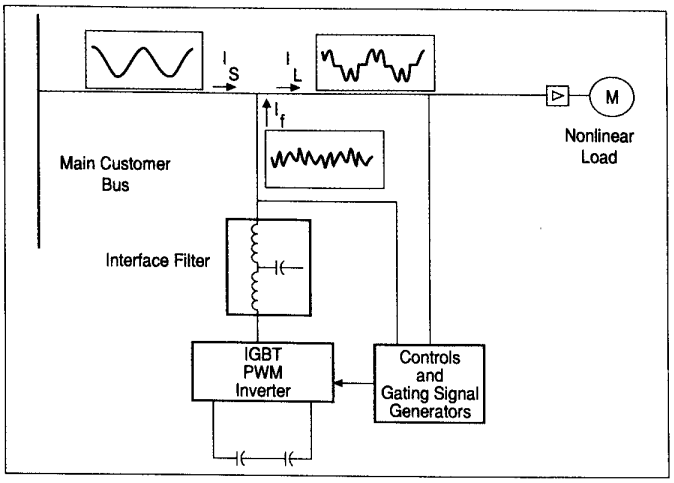
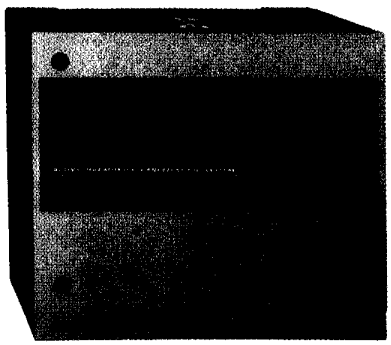


Figure 6. *Basic configuration and operation of a parallel-connected active*

Sound too good to be true? It's not. These active filters are for real. There still will be many applications for passive filters (basically, they will still be preferable when you need power factor correction, anyway). But active filters are going to be an important part of the mix.

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