Differences Between Medium and Low Voltage Filter Design

Abstract - The use of harmonic filters at both the low and medium voltage level is becoming quite prevalent due to the recent advances in solid-state power converters. The market structure and the real world application of passive harmonic filters is still relatively new, and as such, the real world aspects of the present harmonic filter market is not well understood by many consulting and facility engineers.

The purpose of this paper is to introduce the present harmonic filter market and how harmonic filters are applied, designed, and manufactured in the US. There are many papers written about the subject of harmonics, but there are few, if any, that address the practical aspects of this relatively new market.

Introduction

Wide spread use of harmonic filters on low and medium voltage industrial systems did not occur until the early 80's, when the use of variable frequency drives became quite prevalent and the harmonic problem became widely understood. The development of cost-effective, high-powered, semi-conductor technology is what drove this market. Before this time, harmonic problems were rare and were isolated to a select number of industries using devices such as the Mercury Arc Rectifier. As such, the application and design of harmonic filters were limited, and was done on a job-by-job basis by specialized engineering firms and manufacturers.

The harmonic filter market, being conceived in the early 80's, is relatively young and its market dynamics are not well understood by many engineers. The low, and medium voltage filter markets are different from a technical, marketing, and application standpoint. The aspects of medium voltage (above 600 volts) filters are quite different than low voltage (600 volts and below) filters, while medium voltage (2.4 kV and 4.16 kV filters) filters seem to share commonalities to both voltage levels. There are many papers written about the subject of harmonics, but there are few, if any, that address the practical aspects of this relatively new market. This paper addresses the present harmonic filter market, with an emphasis on "real world" harmonic filters.

II. Primer On Harmonic Filters

Fig. 1 and Fig. 2 show the typical layout of low and medium voltage harmonic filters. In many cases a filter bank may consist of two or more separate stages (smaller banks), connected to a main switch. This is typically done to provide more precise control of voltage and/or power factor, or to limit the size of the contactors or capacitor switches. Except for the reactor(s), the components in a harmonic filter are similar to that of a shunt capacitor bank. In fact, a harmonic filter behaves like a capacitor bank at 60 Hz (it provides leading kvar, and can be used to control power factor and voltage). It is at frequencies above 60 hertz that the two behave differently. Although there are many types of filters, nearly all harmonic filters used in industrial facilities are either single-tuned or high-pass filters as shown in Fig. 3. The more complex filter arrangements, such as the C-form filter are more costly, less effective, (at equal fundamental var ratings), and are rarely furnished. These filters also require much more engineering.

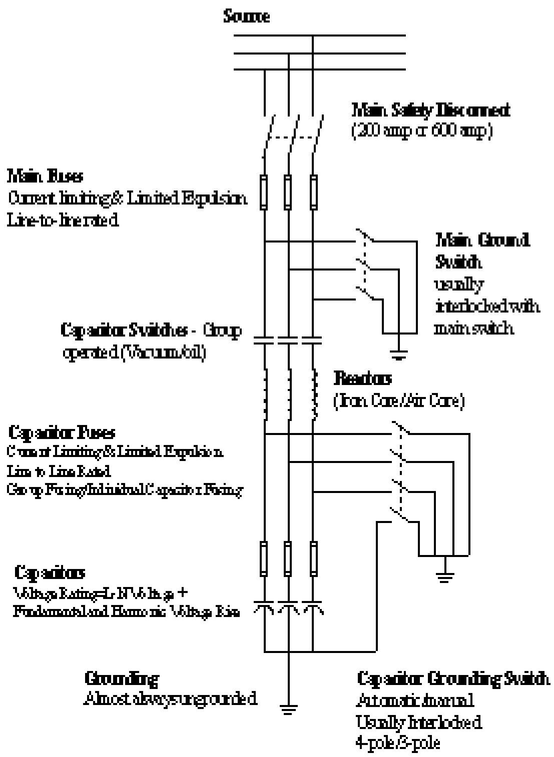

Fig. 1. Typical Medium Voltage Filter Layout

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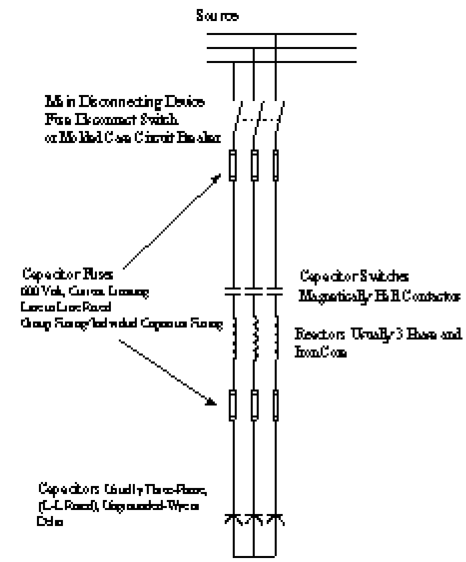

Fig. 2 - Typical Low Voltage Filter Layout

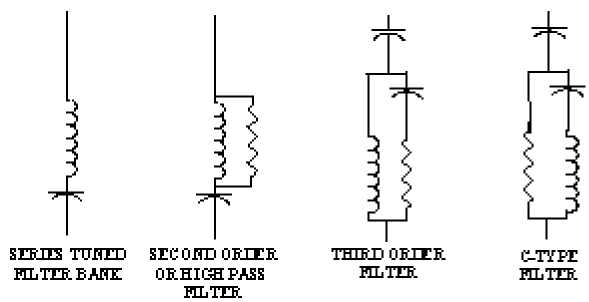

Fig. 3 - Types of Harmonic Filters

Harmonic filters function by providing a low impedance path for harmonic currents generated by non-linear loads, as shown in Fig. 5 for the system shown in Fig. 4. The filter impedance at the tuned frequency is much lower than the system/source impedance. The net effect (parallel combination of the harmonic filter impedance and the source impedance at the 5th harmonic) is much less impedance at the fifth harmonic. This effect is illustrated in Fig. 6 for all frequencies up to the 25th harmonic. The plot shows three harmonic impedance scans (looking from the drive) of a typical industrial facility. As shown, the impedance for the system with a harmonic filter, is much lower at its tuned frequency (5th harmonic in the plot). This is particularly true at the 5th and 7th harmonic where a significant amount of harmonic current would be present for a 6-pulse rectifier. A low net system impedance is desirable at all frequencies where harmonic currents are present since many non-linear loads act as ideal current sources, and a lower impedance would result in a lower voltage distortion.

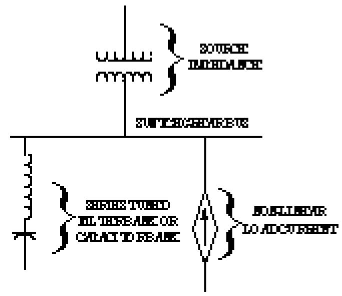

Fig. 4- Simplified System Diagram

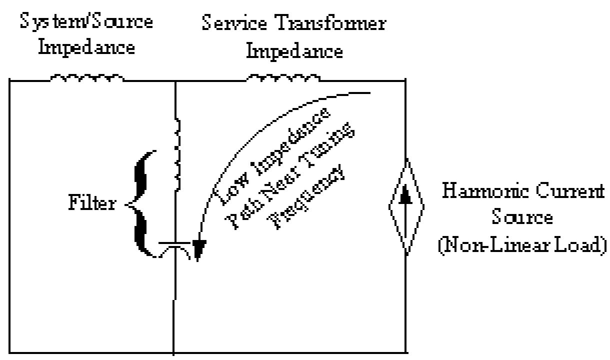

Fig. 5 - Equivalent Circuit of System Shown in Fig. 4

Other important points that should be noted in Fig. 6 are as follows:

- A system resonance exists below the tuned frequency of the harmonic filter. This resonance is often termed the "anti-resonant" point and is an important consideration in applying harmonic filters. Generally, as the source impedance increases, the "anti-resonant" frequency decreases.

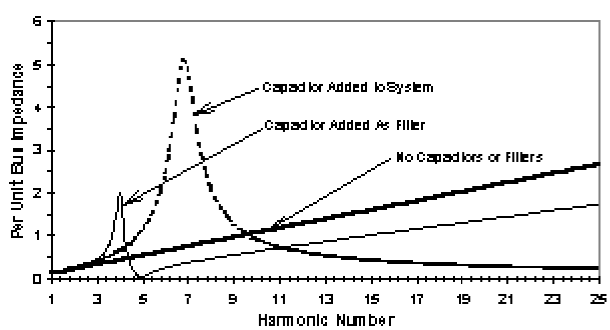

Fig. 6- Harmonic Impedance Scan

- For the addition of a capacitor, there is a resonance near the 7th harmonic. In general, as the capacitance kvar is increased, the frequency of the resonance will decrease.

- The impedance scan for the installation of a capacitor bank shows less impedance (than the impedance scan for the addition of harmonic filters) for currents above the 11th harmonic. This implies that a capacitor bank can actually reduce the overall voltage distortion on a facility if the resonant frequency of the system is not near a harmonic current produced by the system load.

III. Major Application and Construction Features of Medium and Low Voltage Harmonic Filters

Table 1 summarizes the major application and construction features of low and medium voltage harmonic filters. Only the more pertinent aspects are discussed in this paper.

A. Capacitor Design

Most (if not all) capacitors used in harmonic filters at the low voltage level make use of a “metalized” electrode. A metalized electrode has a “self-healing” characteristic, and offers the advantage that a dielectric fault inside the capacitor does not translate into a faulted capacitor, but rather a small loss of capacitance. Thousands of such dielectric faults can occur before there will be any measurable change in capacitance. The main concern with the use of a self-healing capacitor in low voltage harmonic filters is the change in tuning frequency, and the shift in the anti-resonant frequency from the unpredictable loss of capacitance over time. This is illustrated in Fig. 7. Low voltage manufacturers compensate for this problem by tuning their filter banks away from the 5th harmonic, usually to a frequency near the 4.7th, but some tune down to 4.1. Tuning down to 4.1 can cause the anti-resonant frequency to shift down near the 3rd, and can cause problems with 3rd harmonics generated by the magnetizing reactance of motors and transformers. The one draw back in tuning away from the fifth harmonic is that it causes unnecessarily high filter impedance at the 5th harmonic (less filtering capability).

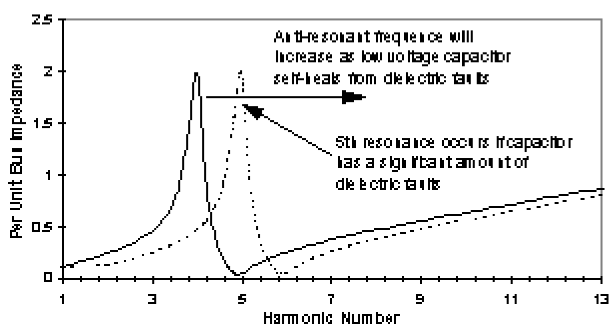

Fig. 7 - Shift in Tuning Frequency Due to Loss of Capacitance in Low Voltage Capacitors

At the medium voltage level, the capacitor usually consists of a separate film/foil design, in which the electrode is totally separate from the capacitor dielectric. These capacitors are not self-healing and therefore, their capacitance changes very little with time. This offers a very stable tuning point, but does not provide protection from dielectric faults. There is no industry data, however, that suggests medium voltage capacitors are less reliable than low voltage, metalized film capacitors.

In addition to electrode design, some low voltage manufacturers have begun to manufacture dry-type capacitors. The use of a dry dielectric in harmonic filter capacitors is relatively new, and the technology is somewhat unproven in electric power applications.

B. Capacitor Connection

Due to economics, low voltage capacitors are generally three phase, and are internally connected as ungrounded wye or delta. The internal connection makes for a more compact design, but it conceals the neutral and removes the possibility of utilizing neutral unbalance voltage detection schemes and the choice of putting the reactor on the load side of the capacitor bank. The neutral detection scheme, commonly used on medium voltage banks, protects capacitors from elevated voltages due to blown fuses on parallel, ungrounded-wye connected (split-wye) capacitors banks. Elevated voltage on unbalanced capacitor banks is not a problem if the capacitors are delta connected. This is not the case for all low voltage manufacturers as some capacitors are connected internally in a wye configuration to alleviate the voltage stress associated with harmonic filters.

Table 1 – Major Design and Construction Features of Medium and Low Voltage Harmonic Filters

	Medium Voltage Filter Characteristics	**Low Voltage Filter Characteristics**
Construction	Metal enclosed / Rack	Metal enclosed
	Indoor / Outdoor	Indoor / Outdoor (usually indoor)
Capacitors	Film / Foil	Metalized film or foil (self-healing dielectric)
	Single phase cans	Usually three-phase cans, internally connected (neutral not available)
	Connected wye & L-N rated	Connected delta & L-L rated
	Internal discharge resistor 5 minute discharge time	Internal / External discharge resistors 1 minute discharge time
Capacitor Voltage Rating	Rated at System Voltage to + 15% depending upon the design engineer and the harmonic voltage duties	480 volt filter may consists of either 480 volt, 600 volt or special, "harmonic rated" capacitors
Reactors	Iron core for metal enclosed (air core for rack mounted banks)	Iron Core
	3ϕ and 1ϕ	3ϕ and 1ϕ (mostly 3ϕ)
	Commonly tapped	Not usually tapped
Capacitor Protection	Current limiting (CL) fuses for metal enclosed banks / expulsion fuses for rack mounted banks (usually L-L rated)	Current limiting fuses (usually 600 volt rated)
	Neutral unbalance detection	

Reactor Protection	Current limiting fuses or power fuse	CL fuses
	Upstream protective device	Upstream protective device
	RMS sensing overload relay	Thermistors in reactors
Filter Bank Protection	Fuse(s) disconnect switch	Fuse(s) disconnect switch
	Vacuum breaker / Overcurrent relay	Molded case circuit breaker
Blown Fuse Detection	Neutral unbalance detection	Blown fuse indicators – by measuring fuse voltage
	Blown fuse detection – by ejection feature on fuses	
Grounding	Ungrounded on resistance grounded systems	Ungrounded
	Grounded / Ungrounded on solidly grounded systems	
Engineering Design	Custom	Nearly all are standard off the shelf designs
Filter Types	5th, 7th, 11th, and high pass filter designs	5th is most common
Commonly Switched By	200 amp oil / vacuum switch	Magnetically held contactors
	Vacuum breakers	Molded case / Power circuit breaker
Safety Interlocks	Key interlocks (i.e. Kirk Key)	Electrical door interlocks (door only)
	Electrical interlocks	
Grounding Switch	Very common	Uncommon, if ever
Safety Disconnect With Visible Break	Usually provided by either air-disconnect switch or roll-out breaker (required by NEC)	Not provided and not required by NEC
Typical Size	1 to 15 Mvar	Less than 1 Mvar

Since medium voltage capacitors are typically single phase and may have two bushings, they can be connected in any manner. The most common is the ungrounded-wye connection due to the simplicity in bus work. This permits the detection of blown fuses by a neutral voltage relay.

C. Capacitor Voltage Rating

Depending upon the manufacturer, low voltage filter manufacturers may use 480-volt, 600-volt, or "harmonic-hardened" capacitors. The harmonic-hardened capacitors are rated to carry excess harmonic currents and voltages. The problem with the harmonic-hardened capacitor concept is that a comparison between the capacitors of one manufacturer and that of another are difficult to evaluate, and are based on claims.

To make the comparison even more difficult, the ANSI/IEEE shunt capacitor standard does not really apply to low voltage capacitors, and therefore, there is not really a standard for shunt capacitors at the low voltage level. Underwriters Laboratories provides a standard, but this standard is for safety only.

At the medium voltage level, harmonic filters make use of standard, "off-the-shelf" capacitors. The capacitors are usually rated at about 115% of the systems nominal voltage rating to account for the fundamental voltage rise and harmonic voltages.

The actual voltage rating used is determined by the design engineer, and varies depending upon the tuned frequency, philosophies of the engineer, harmonic current levels, and the interpretation of the standards. This does not present a problem from an evaluation standpoint because medium voltage capacitors are more likely to adhere to the ANSI/IEEE shunt capacitor standard and therefore, can be evaluated based on nameplate data.

D. Capacitor Protection

Capacitor protection at the low voltage level is simple and straightforward. Low voltage capacitors, unlike medium voltage capacitors, fail open and contain pressure interrupters to prevent case rupture. A common rule of thumb used by most manufacturers would be to fuse the capacitor at 250% to 300% of the capacitor's rated current.

At the medium voltage level, capacitors are more difficult to fuse because they fail shorted, and do not contain pressure interrupters. Therefore, there is a higher risk for case rupture. The fuse must be sized low enough to detect low level, evolving faults, but high enough to prevent spurious fuse blowings. In addition, the application of fuses at the medium voltage level is more complex than at the low voltage level. There is no simple rule of thumb. For example, a medium voltage current limiting fuse can be classified as either "general purpose" or as "back up current limiting". They can also be classified as either "limited expulsion" or "expulsion" and can have slant voltage ratings. The application and operating characteristics of these fuses are considerably different.

E. Engineering Design

Almost all low voltage filter banks are standard, "off-the-shelf" designs. Cut-sheets, catalogs, and list prices are available from most of the major manufacturers. Since the designs are standard, filters can be offered with lead times as little as one week. The disadvantage of the standard design concept is that unusual conditions may not be accounted for. For example, a facility with an unusually high harmonic current level may get the same reactor and capacitor as a facility with an abnormally low current level. This may be true even if a written specification is offered. Some manufacturers may rather assume the risk of filter bank failure instead of offering a custom more costly design.

Rating, rating criteria, and rating standards on low voltage harmonic filters are not readily available and therefore, it is difficult to compare filter ratings between manufacturers.

Most if not all medium voltage filters are built and designed on a job-by-job basis. In many cases the manufacturer follows a specification that was either written by a consultant or A&E firm. Since medium voltage filters are not standard in design, designs can vary considerably from job to job, and lead times are usually on the order of 10 to 15 weeks.

F. Filter Tuning

Almost all filters at the low voltage level are tuned near the 5th harmonic (actually around the 4.7th harmonic). A couple of manufacturers tune their banks lower, but still refer to their filters as 5th harmonic filters. Tuning the bank to a harmonic near the 4th lowers the harmonic current and voltage stress on the filter components. This reduces costs but also reduces filtering capability. This concept is advantageous to a facility looking to improve power factor and avoid resonance rather than improving voltage distortion. Facilities that require filtering should use filters that are tuned near the 5th harmonic. In either case, the end-user should request tuning frequency from the manufacturer.

G. Reactor

Filter reactors can have either an iron-core or air-core. In general, low voltage filters are usually iron-core, while medium and medium voltage filters can be either iron- or air-core. Air core reactors take up more space and are difficult to put into enclosures. They are typically more economical on large filter banks, and are usually applied in conjunction with outdoor rack-mounted filters. Air-core reactors do not saturate and therefore, contribute to a more stable tuning point even for high currents under unusual conditions.

Low voltage iron-core reactors typically make use of a three-phase core as shown in Fig. 8. Reactors built on these cores weigh less, take up less space, have lower losses, and cost less than three single-phase reactors of equal capability.

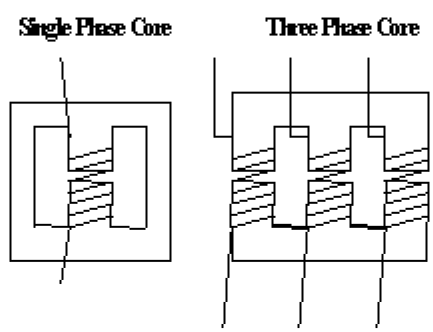

Fig. 8 - Typical Iron Core Designs

Medium voltage iron-core reactors can be either three phase or single phase and are primarily dependent upon the manufacturer and their capabilities.

The primary draw back to iron-core reactors is that they saturate. The saturation level is dependent upon the fundamental current and the harmonic currents that the reactor will see. There is not an ANSI or NEMA standard for rating harmonic filter reactors and therefore, it is difficult to evaluate reactors from different manufacturers. For example, some reactor manufacturers base their core designs (cross sectional area of core) on RMS flux, while other will based it on peak flux (with the harmonic flux directly adding).

There is a significant difference between these two design criteria. For evaluation purposes, reactor weight and temperature rise are a primary indication of the amount of iron that is used.

IV. Conclusion

This paper has illustrated the present harmonic filter market and how filters are designed, manufactured, and applied in the US. It should be quite clear from the paper that the design and manufacturing of medium and low voltage filters are quite different. It should also be clear that there is a lack of standards in the area of harmonic filters, which makes the consistency, and evaluation of harmonic filters difficult. It is hoped that this paper will stimulate an interest in the actual design, application, and manufacturing of passive harmonic filters, and increase the number of papers and standards devoted to harmonic filters.

V. Biography

Paul B. Steciuk - Mr. Steciuk received his BS Degree in Electric Power in 1988 from Rensselaer Polytechnic Institute in Troy, New York and his MS degree from the same institution in 1996. His experience is in the areas of product applications and power system analysis. He has been involved in the design, specification, development and fabrication of harmonic filters and power factor correction equipment. His duties have also included harmonic analysis, the development of harmonic measuring techniques, problem solving in the areas of power factor correction capacitors, performing load flow studies on power systems to establish thermal transfer limits and reactive power flow requirements, and other power system analyses.

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