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IEEE Guide for Application and Specification of Harmonic Filters

IEEE Power Engineering Society

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IEEE Guide for Application and Specification of Harmonic Filters

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**Transmission & Distribution Committee
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IEEE Power Engineering Society**

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Abstract: Guidelines for specification of components, protection, and control of harmonic filters are provided. This guide applies to the use of 50 Hz and 60 Hz passive shunt power harmonic filters on low- and medium-voltage electric power systems. This document is the first guide specifically created for harmonic filters, although standards do presently exist for most of the components that are used in a filter. Applications including industrial low-voltage facilities, utility medium-voltage systems, and arc furnace installations are covered.

Keywords: capacitors, harmonic filters, inductors, notch filters, passive filters, power filters, power system harmonics, reactors, switched capacitor filters

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Introduction

(This introduction is not part of IEEE Std 1531-2003, IEEE Guide for Application and Specification of Harmonic Filters.)

This guide addresses the specification of the (1) components, (2) protection, and (3) control of harmonic filters. It does not address the proper sizing or configuration of harmonic filters to achieve desired performance. This document provides guidelines for passive shunt harmonic filters for use on 50 Hz and 60 Hz power systems. No specific standards exist for harmonic filters, although standards do exist for virtually all of the components that are used in a filter.

Participants

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Ignacio Ares
Steve Ashmore
Jim Barcus
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Van Wagner
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IEEE Guide for Application and Specification of Harmonic Filters

1. Scope

This guide addresses the selection of the (1) components, (2) protection, and (3) control of harmonic filters. It does not address the engineering required to establish the proper size and configuration of harmonic filters to achieve desired performance. This document provides guidelines for passive shunt harmonic filters for use on 50 Hz and 60 Hz power systems to reduce harmonic distortion on the system(s). (No specific standards exist for harmonic filters, although standards do exist for most of the components that are used in a filter. This guide references standards where they exist and gives typical criteria where appropriate standards do not exist.)

2. References

This guide shall be used in conjunction with the following publications. The dates shown indicate the current version of the standard at the time of publication of this guide. Except for the quotations from IEEE Std 18-2002, any version of the referenced publications published since 1 January 1990 is an appropriate reference. In all cases, reference to the most recent approved version is preferred, regardless of the date shown in this guide.

ANSI C37.06-2000, American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.¹

ANSI C37.66-1969 (Reaff 1997), American National Standard for Requirements for Oil-Filled Capacitor Switches for Alternating-Current Systems.

IEEE P519.1/D8b, Draft Guide for Applying Harmonic Limits on Power Systems.²

IEEE Std C37.012™-1979, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.^{3, 4}

¹ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²This IEEE standards project was not approved by the IEEE-SA Standards Board at the time this publication went to press. For further information about obtaining a draft, contact the IEEE.

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IEEE Std C37.04™-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.

IEEE Std C37.48™-1997, IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.99™-2000, IEEE Guide for the Protection of Shunt Capacitor Banks.

IEEE Std C57.12.00™-2000, IEEE General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01™-1998, IEEE General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings.

IEEE Std C57.16™-1996 (Reaff 2001), IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

IEEE Std C57.110™-1998, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.

IEEE Std C62.22™-1997, IEEE Guide for Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

IEEE Std 18™-2002, IEEE Standard for Shunt Power Capacitors.

IEEE Std 32™-1972 (Reaff 1997), IEEE Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices.

IEEE Std 141™-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book™*).

IEEE Std 399™-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (*IEEE Brown Book™*).

IEEE Std 519™-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 1036™-1992, IEEE Guide for Application of Shunt Power Capacitors.

NEMA MG 1-1998, Motors and Generators.⁵

NFPA 70-2002, National Electrical Code® (NEC®).^{6, 7}

UL 508-1999, Standard for Safety for Industrial Control Equipment.⁸

UL 508A-2001, Standard for Safety for Industrial Control Panels.

UL 810-1995, Standard for Safety for Capacitors.

⁵NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

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⁷NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://www.nfpa.org/>).

⁸UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

UL 1561-1999, Standard for Dry-Type General Purpose and Power Transformers.

UL 1562-1999, Standard for Transformers, Distribution, Dry-Type—Over 600 Volts.

3. Definitions

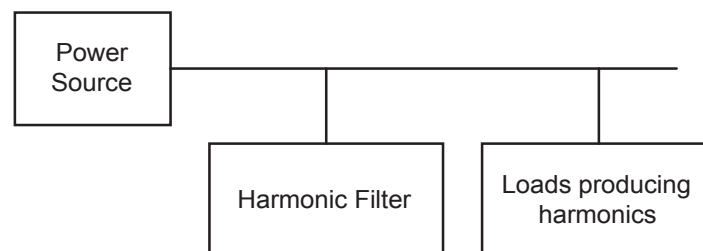
3.1 kvar: (Pronounced kay var, with emphasis on the first syllable) **a)** The size or magnitude of a reactive power source, which would usually be measured in (units of) kilovar. **b)** Abbreviation for kilovar, a unit of reactive power.

3.2 Mvar: (Pronounced em var, with emphasis on the first syllable) **a)** The size or magnitude of a reactive power source, which would usually be measured in (units of) megavar. **b)** Abbreviation for megavar, a unit of reactive power.

The meaning of other terms used in this standard shall be as defined in *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B1]⁹.

4. Harmonic filter design considerations

Harmonic distortion on the power system is caused by nonlinear devices that produce distorted or nonsinusoidal waveforms. Examples include electronically controlled devices (such as rectifiers and power controllers), arcing loads (such as arc furnaces and arc welders), and magnetic devices to a lesser degree (such as rotating ac machinery and transformers). Excessive harmonic voltage and/or current can cause damage to equipment and the electrical system. IEEE Std 519-1992¹⁰ gives application guidelines. One of the common ways of controlling harmonic distortion is to place a passive shunt harmonic filter close to the harmonic-producing load(s). The harmonic-producing device can generally be viewed as a source of harmonic current. The objective of the harmonic filter is to shunt some of the harmonic current from the load into the filter, thereby reducing the amount of harmonic current that flows into the power system (see Figure 1). The simplest type of shunt harmonic filter is a series inductance/capacitance (LC) circuit as illustrated in Figure 2. More complex harmonic filters may involve multiple LC circuits, some of which may also include a resistor. Some commonly used harmonic filter arrangements are shown and discussed in Annex B.



NOTE—A harmonic filter in the vicinity of the harmonic-producing loads shunts some of the harmonic current, thereby reducing the amount of harmonic current flowing from the loads into the power source.

Figure 1—Harmonic filter shunting harmonic current between harmonic-producing loads and power source

⁹The numbers in brackets correspond to the numbers of the bibliography in Annex A.

¹⁰Information on references can be found in Clause 2.

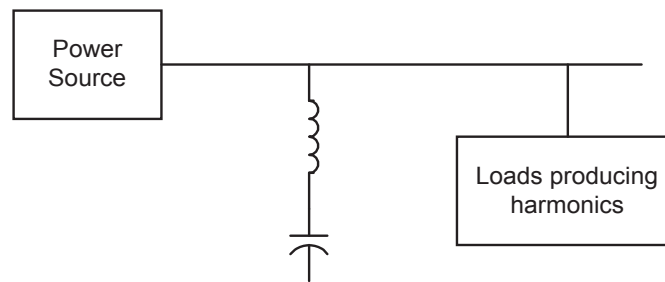


Figure 2—Single-tuned harmonic filter

Key filter design considerations include the following:

- a) Reactive power (kilovar) requirements
- b) Harmonic limitations
- c) Normal system conditions, including ambient harmonics
- d) Normal harmonic filter conditions
- e) Contingency system conditions, including ambient harmonics
- f) Contingency harmonic filter conditions

These considerations can be grouped into performance and rating criteria. The performance criteria relate to normal expected operating conditions and include capacitive reactive power requirements, harmonic limitations, normal system conditions, and normal harmonic filter conditions. The rating criteria relate to unusual conditions that may place a more severe duty on the equipment. These unusual conditions include contingency system conditions and contingency harmonic filter conditions. Under the contingency conditions, it may be acceptable to have a more relaxed harmonic limitation. These six design considerations are discussed in 4.1 through 4.6.

4.1 Filter capacitive reactive power

The major components of a harmonic filter generally include capacitors, reactors, and resistors (if any) designed to achieve acceptable harmonic control. Because of the capacitors, the harmonic filter provides power frequency capacitive reactive power to the power system. In order to optimize the system costs, it is important to know how much capacitive reactive power (kilovars) is needed (if any) and what savings can be obtained by adding the capacitive reactive power. The reactive power and voltage control requirements may dictate that the harmonic filter bank be switched in steps. IEEE Std 1036-1992 indicates that the maximum capacitive reactive power (kilovars) step size is typically limited to a value so that the fundamental frequency voltage change is no greater than 2% to 3% in order to have a minimal effect on system loads. Consequently, the total and step kvar sizes are generally determined by the fundamental frequency load flow and the voltage control requirements.

4.2 Harmonic limitations

Harmonic limitations are defined in terms of system limitations and equipment withstand capabilities, as summarized in 4.2.1 and 4.2.2.

4.2.1 System limitations

System harmonic limitations are generally defined to ensure that equipment does not malfunction or fail due to excessive harmonic distortion. System limitations are recommended in Clause 10 and Clause 11 of IEEE Std 519-1992.¹¹ IEEE Std 519-1992 recommends that the total voltage distortion at the point of common coupling to the utility be limited to 5% or less, depending upon the system voltage level and other factors; and 8% or less for most user busses at less than 1 kV. The total demand current distortion at the point of common coupling to the utility is limited to the range of 2.5% to 20%, depending upon the size of the customer's harmonic-producing load and other factors. (See IEEE Std 519-1992 for details.) The document also gives higher limits for conditions lasting less than 1 hour.

4.2.2 Equipment withstand capabilities

Some of the withstand capabilities that are described in existing equipment standards are summarized in this subclause.

When transformers are operating at rated load, the total harmonic current distortion should be limited to 5% as defined in IEEE Std C57.12.00-2000 and IEEE Std C57.12.01-1998.¹² IEEE Std C57.110-1998 defines the method for derating transformers when supplying nonsinusoidal loads. UL 1561-1999 and UL 1562-1999 define the transformer K-rating that is intended for use in high harmonic environments.

IEEE Std 18-2002¹³ states that “[c]apacitors are intended to be operated at or below their rated voltage. Capacitors shall be capable of continuous operation under contingency system and bank conditions provided that none of the following limitations are exceeded:

- “a) 110% of rated rms [root-mean-square] voltage
- “b) 120% of rated peak voltage, i.e., peak voltage not exceeding $1.2 \times (\text{square root of two}) \times \text{rated rms voltage}$, including harmonics, but excluding transients
- “c) 135% of nominal rms current based on rated kvar and rated voltage
- “d) 135% of rated kvar”

Additional application guidelines for capacitors are given in IEEE Std 1036-1992. It should be noted that capacitor fuses should be rated for the voltage and current, including harmonics, in a filter application.

The limitation to 135% of rated kvar in IEEE Std 18-2002 is based on dielectric heating at fundamental frequency and is based on the thermal stability test in that standard. The 135% limit in IEEE Std 18-2002 is based on a maximum operating voltage of 110% of rated voltage and a maximum capacitance tolerance of +15% (the maximum allowable tolerance at the time the 135% limit was set). ($1.1^2 \times 1.15 \approx 1.35$, thus 135%.)

The total dielectric heating in a capacitor is a function of the force between the electrodes, the capacitance of the dielectric, and the number of force reversals per second.

The force is the result of the attraction of the positive and negative charges on the electrodes. The magnitude of the charge Q on each of the electrodes is proportional to the voltage difference V between the electrodes. The force is proportional to the product of the charge magnitudes. Because the positive and negative charges are equal to each other and are proportional to the applied voltage, the force (and losses) varies as the square of the applied voltage.

¹¹This information is from the referenced standard(s) and does not transplant these limits to this guide. See the first paragraph of Clause 2.

¹²See footnote 11.

¹³This quotation is from the referenced standard(s) and does not transplant these limits to this guide.

The total dielectric heating varies linearly with the capacitance of the dielectric. Changes in capacitance due to change in area of the dielectric, thickness of the dielectric, and changes in the dielectric constant due to small materials variations all affect the total heating linearly.

The dc dielectric losses and resulting heating in a high voltage power capacitor are very small. The dielectric losses are dominated by ac losses. Each time the force is reversed there is an amount of loss. The ac losses are linear function of the applied frequency.

Therefore, for a single frequency, the dielectric losses are proportional to the square of the applied voltage, the capacitance, and the frequency, as shown in Equation (1):

$$\text{Dielectric Loss} \propto fCV^2 \quad (1)$$

Note that, for a capacitor, the reactive power Q is

$$Q = (V)(I) \quad (2)$$

$$= (V)(2\pi fCV) \quad (3)$$

$$= 2\pi fC(V)^2 \quad (4)$$

Note the similarity in the expressions for dielectric loss and Q . For a single frequency, the dielectric heating in the capacitor is proportional to the reactive power (measured in kilovars).

For a capacitor in a filter, there are multiple frequencies generating the dielectric heating. For filter applications where (1) there is no significant dc voltage present, (2) the harmonic voltages across the capacitor are smaller than the fundamental frequency voltage, and (3) the highest significant frequency is less than about 1 kHz, the dielectric heating will be within the 135% limit if

$$\left| 2000 \pi fC \sum_h (hV(h))^2 \right| \leq 1.35|Q_{\text{rated}}| \quad (5)$$

or

$$\left| \sum_h (V(h)I(h)) \right| \leq 1.35|Q_{\text{rated}}| \quad (6)$$

where

- f is the rated frequency of the capacitor and system (Hz),
- C is the actual capacitance of the capacitor (F),
- h is the harmonic order, for all significant harmonics including the fundamental ($h = 1$),
- $V(h)$ is the capacitor voltage (rms) at the h harmonic (kV),
- $I(h)$ is the capacitor current (rms) at the h harmonic (A),
- Q_{rated} is the capacitor rated reactive power (kvar).

The inequality in Equation (6) is the one normally used to determine whether the dielectric heating is acceptable. While dc losses in a capacitor are small, the presence of dc voltage can increase the maximum charge and significantly increase the ac losses. That increase is not reflected in the above inequalities, limiting the use of these inequalities to applications where no significant dc voltage is present.

Higher frequency currents may result in eddy current or induced losses in addition to the dielectric losses. Where the harmonic currents are smaller than the fundamental current, the error caused by ignoring these

losses is negligible. Where the harmonic currents are larger or there are significant harmonic currents above 1 kHz, higher frequency capacitor equipment designs, which are beyond the scope of this guide, may be required.

Proposed derating curves for harmonic voltages for constant speed motors are given in various references (see IEEE Task Force [B3] and Rice [B6]). Typically, these curves indicate that the derating of the motor occurs for voltage distortions greater than 5%. For a typical distribution of harmonics, significant derating of the motor begins at about 8% total harmonic distortion (see IEEE P519.1/D8b¹⁴).

4.3 Normal system conditions

The normal system operating conditions are generally evaluated to assure that the harmonic filter design will meet specific reactive power (kilovars) and harmonic performance requirements for these conditions. These normal system operating conditions include the following:

- a) All harmonic voltages and currents, including
 - 1) *Characteristic harmonics of all expected loads.*
 - 2) *Uncharacteristic harmonics.* Frequencies that are not theoretically characteristic of a perfectly operating device may sometimes occur. (These uncharacteristic harmonic frequencies may include even harmonics, triplen harmonics, and harmonics that are not integral multiples of the power system frequency.) Analysis, experience, and field measurements will often help to quantify these values.
 - 3) *Background and future harmonic loads.* Harmonics generated by other loads near the proposed load location will affect the harmonic current in the harmonic filter. In addition, some future harmonic generating loads should be anticipated to reduce the probability of overloading the harmonic filter.
- b) *System voltage variation.* Overvoltages to +5% are typically considered for normal load conditions and +10% for unloaded system conditions. Undervoltage conditions are generally not critical for harmonic filter design, unless voltage is lost completely. In that case, the harmonic filters should be disconnected from the system immediately until the system is restored to normal conditions.
- c) *System frequency variation.* On the interconnected power system, frequency variations beyond ± 0.1 Hz are rare. Larger frequency variations may occur when the system is fed from a local generator. They can affect the duty of the harmonic filter and can also have a profound impact on the overall harmonic performance of the system.
- d) *Power system configurations.* Possible variations in the power system configuration that may affect the filter should be evaluated. For example, in industrial power systems, changes in the supply transformer and reconfigurations of the medium voltage feeders have the largest effect on the system impedance. Changes in the source power system (e.g., generation, transmission/distribution, transformer changes) may also have a significant impact. These evaluations should include a realistic representation of the system and its components—generators, transformers (with proper winding connections), lines (with conductor skin effect and capacitive charging), capacitors, reactors, and all sources of harmonics electrically close to the proposed filter site.
- e) *Loading conditions.* Variations in the system load, as it affects the harmonic filter design, should be considered. Conditions to be considered include variations in the harmonic-producing loads, in the status of ac motors, and in the status of system capacitor banks and other harmonic filters. Linear (resistive) loads also should be included as they help to dampen harmonic resonant peaks.
- f) *System voltage unbalance.* System unbalance can result in increased harmonic injections from distortion-producing equipment, particularly triplen harmonics, and facilitate their propagation on the system.

¹⁴Numbers preceded by P are IEEE authorized standards projects that were not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining drafts, contact the IEEE.

4.4 Normal harmonic filter conditions

Filters are seldom tuned to their exact calculated values. It is necessary to allow for the following parameter variations when evaluating the performance of the harmonic filters:

- a) *Component tolerances.* Manufacturing tolerances must be considered for the inductance, capacitance, and resistance.
- b) *Ambient temperature variations.* Capacitance and resistance both vary with temperature. The appropriate temperature range depends upon the location. Capacitance variation with temperature is typically in the range of 0.4% to 0.8% decrease per 10 °C increase in temperature.
- c) *Capacitor element or unit failures.* Capacitor failures will result in a change in the harmonic filter tuning and may result in overvoltage on some parts of the capacitor bank. Larger harmonic filters may continue to give acceptable performance with a limited number of failed capacitor elements or units. However, for smaller harmonic filters, the failure of one capacitor element or unit can cause a relatively large change and require the harmonic filter to be immediately disconnected.

4.5 Contingency system conditions

The contingency system operating conditions are generally evaluated to assure that the harmonic filter design will be rated adequately to handle these conditions although the normal system distortion limits may be exceeded. These include the following:

- a) *Switching.* The switching of harmonic filters or other system components may result in significant overvoltage duties for the harmonic filter components.

The energization of large transformers can result in severe dynamic overvoltages on harmonic filter components.

When several single-tuned harmonic filters are energized simultaneously, the transient overvoltages can be very severe on small harmonic filters tuned to relatively low frequencies.

When multiple-tuned steps are switched individually, it may be necessary to assure that they are switched on and off in the proper order so that an undesirable parallel resonance does not occur.

When switching harmonic filters, it is important that an adequate delay time be maintained between an open and a subsequent close. This delay allows time for the trapped charge on the capacitors to decay so that the resultant energizing transient voltages are not excessive. A delay time of 5 min is used with high-voltage capacitors (rated over 1000 V, where IEEE Std 18-2002 requires a discharge to 50 V in 5 min), and 1 min for low-voltage capacitors (rated at 1000 V or less, where IEEE Std 18-2002 requires a discharge to 50 V in 1 min). Shorter time delays may be acceptable if a modest increase in the energizing transient is acceptable. See 5.2.1 and 6.4.

Where very short delays are required, discharge devices to rapidly discharge the capacitors may be used. Switching devices with insertion resistors or reactors, or switching devices designed to close with near-zero voltage across the open contacts, may also be used to control system transient voltages.

- b) *Application of filters tuned to the same frequency.* When harmonic filters are applied at the same location and are tuned to the same frequency, care must be taken to assure that there is acceptable sharing of the harmonic currents among the harmonic filters. This current sharing is a function of the differences in the impedances of the harmonic filters.
- c) *System frequency variation.* Frequency variations greater than the frequency variations for the normal system conditions are generally considered.
- d) *Power system configurations.* Single and double contingency conditions, which are more severe than the normal operating conditions, are evaluated. Sometimes it may be desirable that these conditions also meet the harmonic distortion criteria that were considered for normal operating conditions. Changes in system configuration (including connection/outage of harmonic filters) often

result in significant shifts of harmonic resonant peaks, thus affecting the duties and design of multiple harmonic filter installations.

- e) *Characteristic and uncharacteristic harmonics.* Higher values than the values used to evaluate performance are typically used for the rating of the equipment.
- f) *Unknown harmonic sources.* It is best to identify all of the significant harmonic sources on the power system. Sometimes such identification may be difficult and carefully conducted and documented field measurements may be helpful in resolving this issue. It is often advisable to add a factor to the calculated harmonic duties to account for unknown or future harmonic sources when rating the equipment.

4.6 Contingency harmonic filter conditions

When rating the harmonic filter components, the same factors that were given in 4.4 for normal harmonic filter conditions (without any failure or abnormality in the harmonic filter) are typically used, but with wider ranges. In addition, when multiple harmonic filters are applied at the same location, the outage of a complete harmonic filter is often considered in rating the filter components. In some applications, the outage of a single harmonic filter may require that the other harmonic filters be disconnected so that their ratings are not exceeded.

4.7 Harmonic filter locations

Harmonic filters may be located at individual devices or at a common bus that feeds many loads. They may be located at low voltage (e.g., 480 V) or at higher voltages (e.g., 4.16 kV or 12.47 kV). The alternatives in a given application should be evaluated based on meeting the acceptable harmonic voltages and currents and the effect of the resulting harmonic load flows on the affected equipment and conductors (e.g., losses, heating).

4.8 Harmonic filter configurations

For ungrounded filters, the same filtering effectiveness can be achieved with a variety of wye and/or delta configurations. The ratings and the capability of the available hardware will often dictate the selection of the arrangement. Figure 3 illustrates configurations that are indistinguishable in terms of their filtering characteristics.

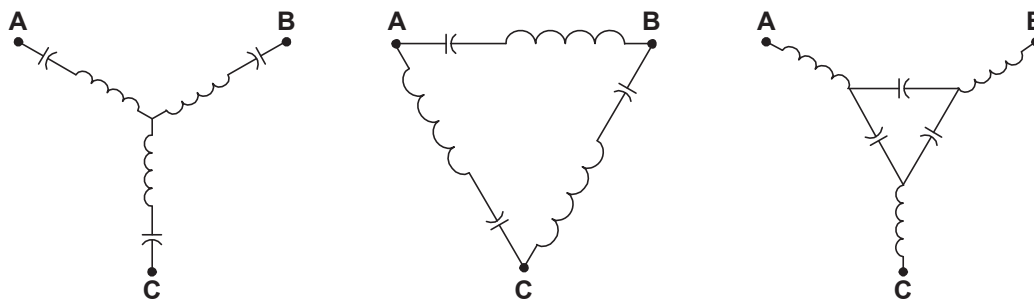


Figure 3—Different configurations that give identical filtering performance

The schematic to be used and the relative positions of the components are generally dictated by construction and/or protection considerations. The filters illustrated are all single-frequency harmonic filters, tuned for one frequency. A wide variety of schematics are also available for multiple-tuned harmonic filters.

4.9 Using existing capacitor banks

Occasionally, consideration will be given to converting an existing capacitor bank to a harmonic filter capacitor bank. It is important to compare the unit ratings of the existing bank with the required ratings for a harmonic filter capacitor bank.

In addition to increased harmonic voltage stresses, the fundamental frequency component will also be increased according to the equation for $V_C(1)$ as shown in Item c)1 in 6.3.1. Other issues, including reactive power (kilovars) and current, as presented in this guide, must also be considered.

Usually the existing capacitor banks cannot be used in a harmonic filter unless the capacitor units were over-rated in the original installation.

5. Low-voltage shunt harmonic filters

This clause applies to harmonic filters installed at bus voltages up to and including 1 kV. The components, protection, and general design of low-voltage harmonic filters are discussed. The clause concludes with an application design example of multiple harmonic filters installed at a water treatment facility. Applicable codes and standards are mentioned where appropriate.

5.1 Introduction

Application of harmonic filters at low voltage is required when any of the following conditions exists:

- a) Harmonic voltages appearing across the low-voltage distribution system result in voltage distortion at a point of utilization that is incompatible with connected loads.
- b) Harmonic currents exceed specified limits.
- c) Harmonic currents exceed the thermal capability of distribution equipment.
- d) Power factor correction at the low-voltage bus is desired in a harmonic-rich environment.

Like conventional shunt capacitors, which are not a part of a harmonic filter, passive harmonic filters improve power factor ahead of the point of connection and thereby reduce the fundamental current, release capacity in the distribution system, and reduce losses. Unlike conventional shunt capacitors, which are not a part of a filter and can create an undesirable resonance and thus amplify harmonic currents, harmonic filters control the resonant frequencies and shunt harmonic currents out of the system and thereby further reduce losses and improve voltage quality.

Both fundamental and harmonic components must be considered in selecting equipment ratings. Capacitors and reactors should not operate above their nameplate ratings under normal conditions. Overload capabilities should be reserved for contingency operation only. A harmonic filter should be adequately protected so that a severe overload condition does not result in equipment damage.

Harmonic filters may be installed at the load or an upstream bus. They may be fixed or switched. Harmonic filters are typically single-tuned, series LC devices where the absorption spectrum will include more than one harmonic. For example, a 5th harmonic filter may also absorb significant quantities of the 7th harmonic. However, the application requirements may dictate the use of multiple-tuned harmonic filters and/or high-pass sections.

5.2 Technical specifications

General requirements for harmonic filter components and construction are given in 5.2.1 through 5.2.10.

5.2.1 Harmonic filter capacitors

Capacitors are generally rated for the system line-to-line voltage (e.g., 240 V, 480 V). However, in a harmonic filter application, they should be selected to withstand overvoltages and overcurrents caused by fundamental and harmonic current flow through the series connected tuning.

IEEE Std 18-2002 requires shunt capacitors, under contingency conditions, to withstand continuous voltages up to 110% of rated rms voltage and continuous currents up to 135% of nominal rms current based on rated kvar and rated voltage. When applied in harmonic filters, the normal voltage and current may exceed these levels even before system contingencies are considered. Consequently, capacitors selected for use in normal shunt capacitor applications may not be suitable for use in harmonic filters. Harmonic filter capacitors should be selected based on their expected duty under normal and contingency conditions. The capacitor manufacturer should be consulted when specifying capacitors for harmonic filter applications.

Capacitors should be manufactured in accordance with UL 810-1995. Capacitors should be protected by a UL-listed/recognized protective device. For capacitors that do not contain a UL-listed/recognized protective device, the capacitors should be protected with external current limiting fuses or other external protective devices that are UL-listed. Capacitor cells connected with a wiring harness may also be protected with UL-listed current limiting fuses (even if they have internal pressure sensitive interrupters) to protect in the event of a failure of external resistors, bushings, or connecting wires.

IEEE Std 18-2002¹⁵ specifies that the terminal-to-case test for the internal insulation of indoor capacitors should be performed at 3 kV rms (capacitors rated 300 V or less) or 5 kV rms (capacitors rated 301 V to 1199 V) for 10 s. The terminal-to-terminal test should be 10 s at $2 \times$ rated rms voltage (ac test) or $4.3 \times$ rated rms voltage (dc test).

Each capacitor rated 600 V or less must be provided with a discharge resistor(s) to reduce the residual voltage from peak of rated to less than 50 V within 1 min of de-energization (5 min for capacitor units rated higher than 600 V) to meet the requirements of IEEE Std 18-2002 and Article 460-6 of NFPA 70-2002 (National Electrical Code®).

5.2.2 Harmonic filter reactors

5.2.2.1 General construction

Harmonic filter reactors for low-voltage applications are typically dry-type iron-core. No existing standard addresses harmonic filter reactors, but most manufacturers use IEEE Std C57.12.01-1998 as a guideline.

Cores are constructed from silicon sheet steel (such as M-6). The number 6 corresponds to the approximate power loss per pound of steel at a magnetic flux density of 1.5 T, i.e., M-6 has a loss of “0.6 W/lb” or 1.5 W/kg. M-6 is the typical grade of silicon steel used, but both lower and higher grades of steel are available. A manufacturer may choose to use a lower grade steel and either let the harmonic filter reactor operate with a higher temperature rise or use more steel. Conversely, a higher grade of steel can be used and either the harmonic filter reactor may operate with a lower temperature rise or the harmonic filter reactor could be made smaller.

¹⁵This information is from the referenced standard(s) and does not transplant these limits to this guide. See the first paragraph of Clause 2.

The construction may be from individual pieces of cut strip stock or E-I laminations. To create a harmonic filter reactor, it is necessary to have gaps in the core. These gaps are known as *air gaps*, but for physical integrity and rigidity the gaps are filled with hard insulation. This insulation will have permeability similar to air. These gaps can be distributed (many small gaps) or a single larger gap. A single gap will use E-I laminations whereas a distributed gap will be made up of individual cut strips. The E-I construction requires less labor and can be clamped and wedged better than a distributed gap core. However, the distributed gap core will significantly reduce fringing. This reduction in fringing helps control the effective cross-sectional area as well as stray fields that may result in localized heating of the coil. A “C” core may be used, but it will not offer an advantage for harmonic filtering.

Reactor coils may be constructed from sheet conductor or magnet wire. Sheet conductor may be more economical and easier for construction, but reactors with significant harmonic currents can incur heating problems. If not properly designed, sheet copper windings can become annealed due to large localized current densities. Sheet conductor windings should be used only on harmonic filter reactors that have a distributed gap well within the boundaries of the coil. Magnet wire, which is less susceptible to localized heating, is commonly used for harmonic filter reactors. In some cases, it may be desirable to have parallel strands of smaller gauge magnet wire to reduce heating. Although using parallel strands of such wire significantly complicates winding construction, the increase in winding complexity can be justified because coil losses may be significantly reduced.

Clamping is also very important. If a reactor is not properly clamped, the harmonic current can cause laminations to vibrate. Lack of proper clamping could result in a loud audible noise and the breakdown of the insulation coating on the laminations. Laminations are clamped with insulated through-bolts, or bolts that go through clamps, and are external to the laminations. Clamps that bridge air gaps must be of nonferrous construction. Such nonmagnetic clamps are used to avoid shunting the air gap with a magnetic path. Furthermore, ferrous components need to be as far from air gaps as possible to prevent inductive heating of the ferrous material. Coils are held in place with spacers and wedges. The harmonic filter reactor should be vacuum impregnated, preferably vacuum-pressure impregnated with a suitable varnish. Impregnation, however, should not be relied upon as the only mechanical means of support.

5.2.2.2 Properties

The loss calculation should consider the total rms current, including both the fundamental and harmonic currents, which flow through the harmonic filter reactor and harmonic filter capacitor combination. Harmonic filter reactor losses consist of

- Coil loss
- Core loss
- Gap loss

The current should be given as a harmonic spectrum so the manufacturer can calculate losses for each frequency. The rms current is calculated as the geometric sum of the fundamental and all harmonics. Coil power losses should be determined at the expected operating temperature.

The total coil loss is calculated as shown in Equation (7):

$$P_c = \sum [I(h)^2 R_{ac}(h) + P_{eddy}(h) + P_{stray}(h)] \quad (7)$$

where

- $I(h)$ is the current at the h^{th} harmonic (A rms),
- h is the harmonic number $h = 1, 2, \dots$,
- $P_{eddy}(h)$ is the eddy current loss at the h^{th} harmonic and at the rated operating temperature (W),
- P_c is the total coil loss at the rated operating temperature (W),