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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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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.

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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]

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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.

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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

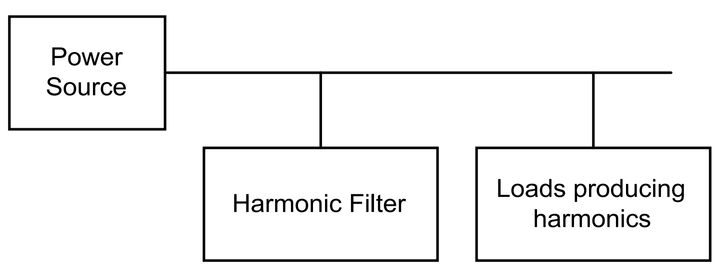
3.1 kvar: (Pronounced kay var, with emphasis on the first syllable) **a)** The size or magnitude of a reactive power source, which would usually be measured in (units of) kilovar. **b)** Abbreviation for kilovar, a unit of reactive power.

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 519-1992[10] 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

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

[10]Information on references can be found in Clause 2.

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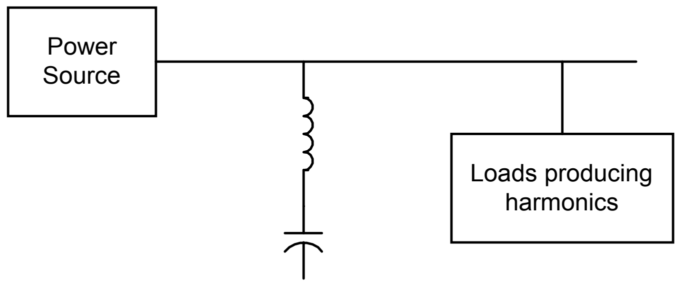

Figure 2—Single-tuned harmonic filter

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.

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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 18-2002[13] 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 x (square root of two) x 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.

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

[12]See footnote 11.

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

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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):

$$\text{Dielectric Loss} \propto fCV^2 \tag{1}$$

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

$$Q = (V)(I) \tag{2}$$

$$= (V)(2\pi fCV) \tag{3}$$

$$= 2\pi fC(V)^2 \tag{4}$$

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

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

or

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

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

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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/D8b[14]).

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.

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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

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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.

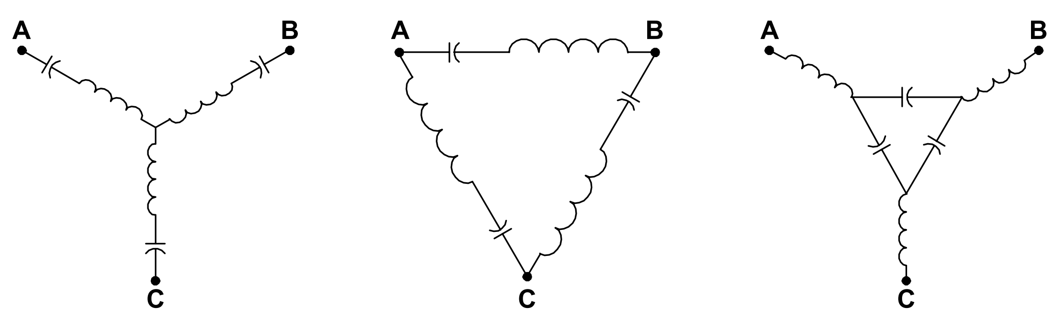

Figure 3—Different configurations that give identical filtering performance

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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 5^{th} harmonic filter may also absorb significant quantities of the 7^{th} harmonic. However, the application requirements may dictate the use of multiple-tuned harmonic filters and/or high-pass sections.

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5.2 Technical specifications

General requirements for harmonic filter components and construction are give 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 18-2002[15] 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 × rated rms voltage (ac test) or 4.3 × 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.

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

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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):

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

where

$I(h)$	is the current at the h^{th} harmonic (A rms),
h	is the harmonic number $h = 1, 2, ...$,
$P_{\text{eddy}}(h)$	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),

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$P_{stray}(h)$ is the loss at the h^{th} harmonic and the rated operating temperature (W),

$R_{ac}(h)$ is the conductor resistance at the h^{th} harmonic and the rated operating temperature (Ω).

Core and gap power losses are greatly influenced by harmonic current frequencies and their amplitudes. The core and gap losses should be determined at the fundamental frequency and at each of the harmonic frequencies. The losses at each frequency should be numerically added to determine the total loss. The total core power loss should be less than 40% of the coil power loss. Gap power losses are also a function of the harmonic frequencies and their amplitudes. The gap loss should be determined at the fundamental frequency and at each of the harmonic frequencies. These losses should be numerically added to determine total gap power loss. The total gap power loss should be less than 20% of the coil loss.

Saturation is not typically a problem with low-voltage harmonic filter reactors.

The dc resistance of the harmonic filter reactor should be determined at 25 °C.

Inductance is determined by the number of turns, the core cross-sectional area, and the width of the air gap.

Using finite element analysis, the design can be optimized adjusting all these factors until the desired inductance, losses, and temperature rise are obtained. Once the harmonic filter reactor has been built, fine-tuning is typically done by adjusting the air gap. When the gap is adjusted on a three-phase harmonic filter reactor, it changes for all three phases. However, with a three-phase harmonic filter reactor, the fringing characteristics that will affect the flux density and inductance of each phase are different for the center leg from what they are for the outer legs. Such differences create a challenge because all three gaps should be the same for a three-phase core. Fringing effects are less significant with a distributed air gap. With single-phase harmonic filter reactors, each phase may be individually tuned and adjusted.

5.2.2.3 Testing

To assure proper tuning, inductance should be measured at rated current. Inductance of harmonic filter reactors should not be measured on an instrumentation bridge. Harmonic filter reactors are not field adjustable.

For low-voltage applications, harmonic filter reactors do not typically undergo a basic impulse insulation level (BIL) test. As a minimum, the insulation should have a low-frequency voltage test (Hi-Pot), phase-to-phase (three-phase harmonic filter reactors) and phase-to-ground. This test is typically on the order of 10 times the rms voltage rating. IEEE Std C57.12.01-1998[16] suggests a test voltage of 4 kV rms on 480 V systems. If a similar field test is to be performed, consult with the harmonic filter manufacturer on the values to expect and the procedure to be used.

5.2.2.4 Protection

The primary cause of harmonic filter reactor failure is over-heating of the insulation system. Iron core harmonic filter reactors typically have a 180 °C to 220 °C rated insulation system. Normal overcurrent protection is inadequate to properly protect the harmonic filter from overload. At least one phase of a harmonic filter section should have a thermal cutout or thermistor imbedded near the hot spot, which will disconnect the harmonic filter section when the hot spot temperature approaches 180 °C. The temperature of the hot spot is higher than any other location in the harmonic filter reactor winding.

5.2.3 Capacitor and reactor tolerances

Both harmonic filter reactors and harmonic filter capacitors have tolerances. However, when constructing a harmonic filter, the combination of these tolerances is more significant than individual tolerances.

[16]This information is from the referenced standard(s) and does not transplant these limits to this guide.

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Capacitor tolerances typically permit capacitance to exceed the nominal value. Capacitor units built according to IEEE Std 18-2002 since 2002 have a manufacturing tolerance of –0% to +10% at 25 °C uniform case and internal temperature. Older capacitors may have tolerances as high as –0% to +15% for the capacitance of individual units. Because capacitors are mass-produced, the filter manufacturer typically has very little control on the capacitor value.

No standard presently exists for harmonic filter reactors, although IEEE Std C57.16-1996 is often referenced.

An example of the effect of tolerances is shown in Equation (8).

$$f_{\text{tuned}} = f_{\text{nominal}}\left(\frac{1}{\sqrt{(1+t_{\text{r}})(1+t_{\text{c}})}}\right) \tag{8}$$

where

f_{tuned} is the actual tuned frequency,
f_{nominal} is the specified tuned frequency,
t_{r} is the reactor tolerance (per unit),
t_{c} is the capacitor tolerance (per unit).

For a filter that has been specified for 4.7$^{\text{th}}$ harmonic tuning, the tuning point ranges have been calculated using Equation (8). In both cases the capacitor tolerance used are –0%/+15% with an expected value of +8% from nominal. The inductance range example shows a ± 2.5% tolerance with the target inductance at nominal. This calculation results in a filter tuning range from the 4.33$^{\text{rd}}$ to the 4.76$^{\text{th}}$ and an expected value near the 4.52$^{\text{nd}}$. A second example shows a –0%/+10% tolerance with the targeted inductance to be at 5% above nominal. This calculation results in a tuning range from the 4.38$^{\text{th}}$ to the 4.95$^{\text{th}}$ and an expected value near the 4.64$^{\text{th}}$ harmonic. These results show the need to be aware of component tolerances.

Another concern in low-voltage applications is the feeder inductance from the filter unit to where it is connected to the power system. The inductance of reactors for these systems will be on the order of hundreds of microhenries. It is not unusual for long cable inductance to be at least a few microhenries. This inductance can significantly affect the tuned frequency of the filter. When determining what frequency a harmonic filter needs to be tuned for, do not forget to allow for inductance of the feeder cable.

Because the manufacturer has more control over the reactor tolerance than the capacitor tolerance, it is recommended that a range of acceptable tuning points for the assembly be provided (i.e., 4.33 to 4.76) instead of tolerances for individual components.

5.2.4 Contactors

Contactors are often incorporated into a harmonic filter assembly to enable it to be switched on and off with the filtered load, or as load levels vary in the case of a bus mounted filter. Contactors should be either IEC or NEMA rated, and UL-listed or CSA-certified. The contactor should be rated, considering both system normal and contingency conditions, for the following:

a) Maximum system voltage
b) Maximum continuous current (fundamental current and all harmonic currents)
c) Number of switching operations (Frequent switching suggests a more conservative approach to sizing contactors than the normal current criteria would dictate. Note that the inrush current experienced when capacitors are switched is limited by the series tuning reactor. Therefore, the contactors can be sized using the manufacturer’s inductive switching rating.)
d) Capacitor switching duty

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5.2.5 Fuses

Each phase of each filter step should be protected by fuses. Fuses should be current limiting, rated for the available fault current at the fuse location. Fuses should be UL-listed Class J or T, CSA-rated HRC-1, or equivalent. The current rating of the fuses should be a minimum of two times the capacitor current calculated from its rated reactive power and its rated voltage. The voltage rating of the fuses should be greater than or equal to the system voltage. Fuses internal to the capacitor should not be accepted as the primary means of filter protection. In a harmonic filter assembly containing more than one capacitor per reactor, a single set of fuses, one per phase, should be provided. The current rating of the fuses should be at least equal the total filter current including all harmonics, with margin (typically 35%) to cover contingency conditions.

Fuses should be located after the harmonic filter main lugs or main disconnect and before the contactor/reactor/capacitor assemblies.

In addition to fusing, some harmonic filters may be protected by devices that detect phase loss or thermal overload and trip the step/unit off line. Such devices are not meant to replace fuses.

The fuses should be rated for the following conditions:

a) Maximum system voltage
b) Maximum continuous filter current, including fundamental and harmonics
c) Interrupting rating, equal to or greater than the available short-circuit current at the fuse location
d) Sized to limit the fault current to a level consistent with the capabilities of the harmonic filter components
e) Sized to withstand inrush currents when the harmonic filter is energized

5.2.6 Circuit breakers

Circuit breakers may be used in place of fuses to provide the primary means of overcurrent protection (i.e., thermal/magnetic trip). Alternately, circuit breakers or molded case switches may serve in addition to fuses to provide a primary means of disconnect (i.e., manual switch) or to provide overload (i.e., thermal trip) and/or short-circuit (i.e., magnetic trip) protection for the complete harmonic filter.

Circuit breakers should be rated for the following conditions:

a) Maximum system voltage
b) The harmonic filter current spectrum, including the fundamental and harmonics (Note that this current spectrum should be determined based on the maximum system operating voltage and maximum positive capacitor tolerance. The heating of the circuit breaker may be greater at higher frequencies than at the fundamental frequency because of eddy currents and the skin effect. It is not sufficient to specify only the rms value of the circuit breaker current.)
c) Interrupting rating, equal to or greater than the available short-circuit current at the harmonic filter
d) Sized to limit the fault current to a level consistent with the capabilities of the harmonic filter components.
e) Sized to have sufficient short-time current rating to withstand inrush currents when the harmonic filter is energized
f) The number and the frequency of switching operations

5.2.7 Connections

UL 508-1999 and UL 508A-2001 should be followed in the design and construction of harmonic filter banks. The harmonic filter should be electrically connected to the three-phase bus through mechanical lugs or compression lugs. All code requirements regarding internal grounding of the enclosure must be followed.

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It is important that mechanical connections to the electrical elements of the harmonic filter exhibit low electrical resistance and be mechanically secure. All distribution blocks, lugs, and terminal strips should utilize threaded studs with lock nuts or screw compression type connections. Terminal lugs used on wires should be pressure crimped to the wires. Locking spade or ring terminal lugs are recommended for current-carrying conductors.

Power conductors should use insulation rated 90 °C or higher. Control and signal wire should be 600 V, 90 °C rated, or multiple conductor double jacketed with 300 V 80 °C insulation (see UL 508-1999 and UL 508A-2001).

5.2.8 High-pass harmonic filter resistor assemblies

Resistors are generally not required in single-tuned low-voltage harmonic filters. Typically, the value of the resistance in the filter consists primarily of the resistance in the inductor. The low resistance value enhances the harmonic filter's effectiveness, while simultaneously minimizing power losses.

Resistor assemblies are required in high-pass harmonic filters. A high-pass harmonic filter has low impedance at frequencies higher than the tuned frequency. (It "passes" these higher frequencies.) The resistor in this type of harmonic filter creates a low impedance at the rated frequency and nearly constant impedance at higher frequencies. This type of harmonic filter has been effectively used to attenuate commutation notches and is sometimes applied in lieu of or in combination with single-tuned filters (see Ludbrook [B4]).

5.2.9 Enclosure and general construction

The enclosure should be NEMA rated, suitable for the intended environment. Where applicable, screened or louvered openings should be provided for ventilation. Harmonic filter reactors add substantially to the heat generated inside the filter enclosure. Because the longevity of a capacitor is temperature critical, special attention should be given to the ambient environment and cooling requirements for harmonic filter capacitor banks. Systems are typically designed for a maximum ambient temperature of 40 °C.

Cooling may be provided by convection or fan forced as necessary to maintain the harmonic filter components below their rated operating temperatures. Extremely hot environments may require auxiliary cooling. Thermostatically controlled heaters should be provided to maintain proper component operating temperature in cold climates and to prevent the formation of condensation on the components. An enclosure that is equipped with air filters should be maintained regularly to ensure proper airflow.

5.2.10 Integrated harmonic filter assembly

Harmonic filter equipment may be integrated as part of a freestanding switchboard or switchgear assembly. Components typically include iron core reactors, power capacitors, contactors, fuses, controller, and bus. Main switchgear generally consists of molded case or power circuit breakers, relays, meters, controls, and bus. The harmonic filter assembly may also be added to existing switchgear equipment.

5.3 General design considerations

Several factors influence the design and location of a harmonic filter. The primary motivation is the removal of harmonic currents produced by specific nonlinear loads, or power factor correction and harmonic attenuation of dispersed loads within the plant. Equipment that is overheating or malfunctioning will also be a factor in deciding where to locate a harmonic filter. Refer to Wagner [B7] for more information regarding the effects of harmonics. IEEE Std 519-1992 and utility requirements should provide a basis for performance criteria.

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5.3.1 Selecting the point of connection

Low-voltage harmonic filters may be connected at an individual load or to a distribution bus. Both locations have advantages and disadvantages, which must be weighed with the application objectives to select the most appropriate point of connection for a particular installation. In general, load-connected harmonic filters are more effective at mitigating harmonics while bus-connected harmonic filters are typically a better choice to improve the overall plant power factor. Both options provide reactive compensation, mitigate harmonics, and are subject to overload.

5.3.1.1 Harmonic filter at an individual load

Points B and Points C in Figure 4 illustrate load-connected harmonic filters. This approach can be cost effective when the original equipment manufacturer supplies the harmonic filter as an integral part of supplied equipment or when a few loads require harmonic filtering. The installation and maintenance costs can become prohibitive if a large number of harmonic filters are to be retrofitted to an existing installation. A load-connected harmonic filter provides reactive and harmonic compensation at the source, offering the following advantages:

a) The need to oversize distribution equipment is eliminated.

b) System losses are minimized.

c) Voltage distortion at the point of utilization is minimized.

d) The harmonic filter can be sized specifically for the load.

e) The harmonic filter can be switched on and off with the load.

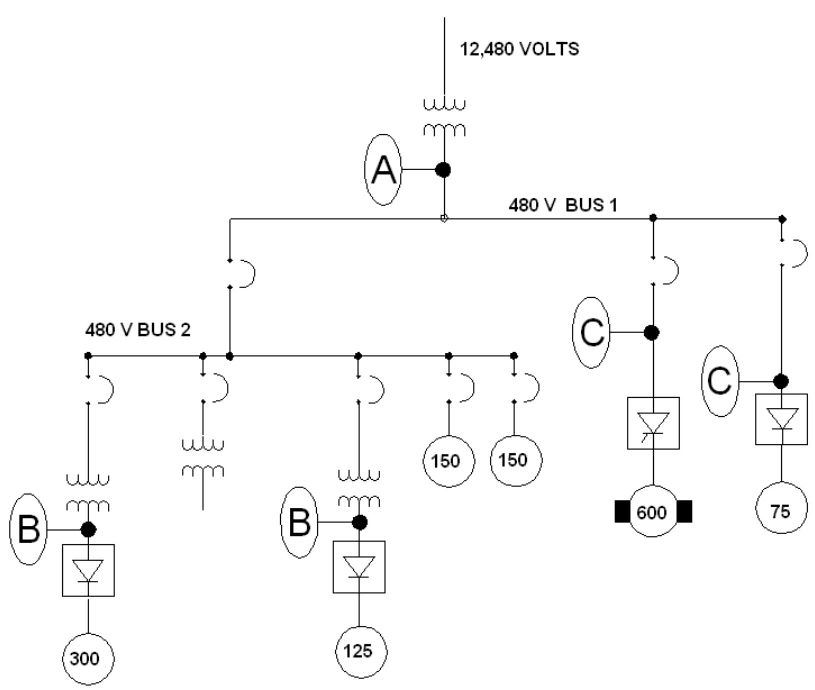

Figure 4—Selecting the point of connection

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When properly applied, a harmonic filter at the load will remove more harmonic current for a given design than will a harmonic filter at the bus. The reason is that the effectiveness of the harmonic filter depends on the current division between the harmonic filter and system. To prevent overloading from other harmonic sources, a load-connected harmonic filter should always be installed on the load side of an isolation transformer or line reactor. The reactive impedance of the transformer or line reactor should be about 5% of the drive's base impedance. This practice substantially increases the driving point impedance at the load and thereby causes more of the harmonic current to flow into the harmonic filter. The isolating impedance will greatly reduce, but not eliminate, the tendency of a filter to draw harmonics from other sources as illustrated in Figure 5.

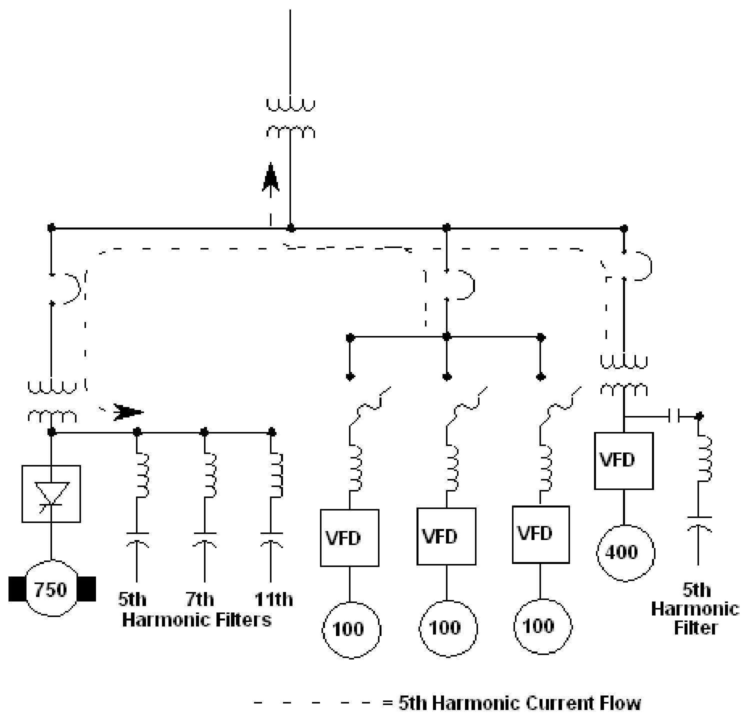

Figure 5—Harmonic current flow

The closer the harmonic filter is tuned to the frequency of a harmonic and the smaller the inductance of the isolating impedance, the greater will be the percentage of that harmonic current from other sources through the harmonic filter. Referring again to Figure 5, the operation of the 300 kW (400 hp) variable-frequency drive (VFD) without its harmonic filter may cause the 5^{th} harmonic filter on the 560 kW (750 hp) dc drive to become overloaded. If detailed site information is available, contingency analysis should be performed to establish anticipated harmonic filter duty.

To the extent practical, safety margins should be included in the harmonic filter design to account for additional harmonic loading. Some installations may require the load be interlocked with its harmonic filter so that the load cannot operate unless the harmonic filter is energized.

Another concern involves the application of multiple single-tuned harmonic filters. The loss of a harmonic filter tuned to a lower harmonic will likely cause another to become severely overloaded. For example, if the 5^{th} harmonic filter is out of service while the 7^{th} harmonic filter is energized for the 560 kW (750 hp) dc drive in Figure 5, a parallel resonance near the 5^{th} harmonic may occur and expose the 7^{th} harmonic filter to amplified levels of 5^{th} harmonic current. In addition, series resonance with the 300 kW (400 hp) VFD could

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expose the 7th harmonic filter to even higher levels of 5th harmonic current. Such a condition reinforces the need for thermal overload protection for the harmonic filter.

5.3.1.2 Harmonic filter at a distribution bus

For certain applications, the most cost-effective solution for poor power factor, excessive voltage distortion, and IEEE Std 519-1992 violations is to install one or more larger harmonic filters at a distribution bus or busses as indicated by "A" in Figure 4. Generally, an automatic harmonic filter bank will be installed on the secondary of each main transformer in the plant requiring power factor and harmonic compensation. Placement of multiple banks on a common low-voltage system can create problems by changing network harmonic flows and thereby increase the potential for overloading some of the filter banks. Therefore, this practice is not generally recommended. Where power factor correction is most important, systems tuned to the 4.2nd harmonic or below can generally be safely applied in this manner. Parallel resonance at the 3rd harmonic must be carefully evaluated.

Caution must be exercised when a harmonic filter is electrically close to the main and is tuned to the 4.7th harmonic or higher. In this case, the potential exists to absorb large amounts of harmonic current from the utility distribution system. Harmonic filters should be designed assuming the distribution system will have up to 3% voltage distortion at the harmonic nearest the tuning frequency per IEEE Std 519-1992. If the harmonic filter reactors are not equipped with taps, as is common with low-voltage filters, a good practice is to over-specify the thermal rating so that additional capacitance may be added to detune the filter in the event a harmonic overload occurs.

If altering the tuning results in unacceptable filtering of in-plant harmonics, the utility can generally help to identify methods for reducing the available harmonic current. Possible utility-side solutions include the following:

- Changing the size or status of capacitor banks to alter the impedance characteristics of the system
- Enforcing IEEE Std 519-1992 limits on customers with excessive harmonic injection
- Circuit reconfiguration to isolate harmonic injectors
- Medium-voltage harmonic filters

During lightly loaded conditions, harmonic filters that are fixed on the bus can produce an overvoltage condition. The maximum per-unit voltage rise caused by the harmonic filter can be estimated as approximately equal to the harmonic filter power system frequency current (i.e., fundamental current) divided by the system three-phase short-circuit current at the harmonic filter location (see IEEE Std 1036-1992). If overvoltage is a concern, an automatically switched harmonic filter should be considered.

Switched harmonic filter(s) comprise a number of steps, each of which is an individually tuned harmonic filter. Reactive current controllers (sometimes referred to as var controllers) that can switch steps in and out automatically as system reactive current (i.e., power factor) changes are readily available. Other switching alternatives include the use of current relays, time-of-day controllers, voltage controllers, or other sensing devices. Switching times become more important as the harmonic filter is tuned closer to its rated frequency. Temporary duties should be evaluated with automatic harmonic filters to ensure steps do not overload before enough compensation is added. Steps should typically be switched in at 10 s to 15 s intervals. If the controller has the capability, the step removal interval should be greater than 1 min to avoid unnecessary "seeking" or "hunting" by the controller. Note that some controllers include algorithms to avoid "seeking" or "hunting."

5.3.1.3 Combined load/bus approach

When harmonic sources constitute only part of a plant system load, harmonic filters connected at individual loads may leave the power factor at the bus lower than desired. A combination of the two methods leads to an acceptable result. Appropriate load-connected harmonic filters are selected for individual

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harmonic-producing loads, and the remaining reactive power (kilovars) needed to achieve the desired power factor is added to the main as a detuned harmonic filter. (A "detuned" harmonic filter is a filter tuned to a frequency so that it will never become tuned with the source impedance at a frequency where there are significant harmonics. These filters are usually tuned below the 5^{th} harmonic, e.g., at the 4.7^{th} or 4.3^{rd} harmonic.)

Rarely can capacitors, which are not a part of a harmonic filter, be installed in the plant to supply the deficit capacitive reactive power. Because only the lower harmonics are typically filtered, capacitors that are not a part of a filter may create an objectionable resonance at a higher harmonic frequency. Connecting capacitors at individual motors is particularly risky because predicting all of the possible system conditions is practically impossible. IEEE Std 141-1993 (*IEEE Red Book*) addresses in detail this concern and others related to connecting capacitors at motor terminals.

5.3.2 Component selection

This subclause provides guidance in selecting harmonic filter capacitors and harmonic filter reactors to achieve the desired performance. For reliability, these and other harmonic filter components should be selected according to the specifications of 5.2. In harmonic filter design, the capacitors are chosen first based on the required reactive power. The inductance of the harmonic filter reactor is then chosen to create the desired tuning. In practice, the selection of harmonic filter components may require several iterations because filter capacitors are typically voltage rated 10% to 25% higher than the system voltage for which they are designed, and the harmonic filter reactor absorbs some reactive power while raising the voltage across the capacitor. Both factors can significantly alter the actual reactive compensation produced from the value stated on the capacitor nameplate. After this initial component selection, computer simulation should be employed to evaluate the ability of the design to achieve the desired harmonic attenuation and verify the adequacy of component thermal and dielectric ratings.

5.3.2.1 Harmonic filter capacitor selection, method 1

This method of sizing the capacitors is more common because it is based on actual measured or predicted operating data. Like sizing capacitors for a normal shunt capacitor application, the displacement power factor is obtained from utility billing data, in-plant power monitoring systems, or temporary monitoring with portable power monitors. For a new system, the power factor must be calculated based on the expected operating characteristics of the load(s). The capacitive reactive power that is required from the harmonic filter to reach the desired power factor is calculated. Standard power factor correction capacitor tables may be used if desired.

5.3.2.2 Harmonic filter capacitor selection, method 2

When sizing harmonic filters for a converter, or group of converters, with a thyristor [e.g., a silicon controller rectifier (SCR)] bridge front end, the following method for capacitor selection can be used if the converter power factor is unknown. The capacitive reactive power in kilovars required to improve power factor to 0.90–0.95 is approximately 40% of the apparent power of the load in kilovolt-amperes. This relationship is valid only if the load power varies proportionally with dc voltage. Larger uninterruptible power supply (UPS) systems often contain a thyristor front end and are an example of a load for which the power can vary significantly without a change in the dc voltage. Such systems can incur high voltage at periods of light load (see 5.3.1.2) if the harmonic filter is sized based on this method.

If other than converter load is present, the system power factor may be less than optimal when applying this method. It is based on the observation that reactive and harmonic compensation for a thyristor rectifier is proportional to the size of the connected load. Empirical data, simulation, and extensive field testing have verified this method. Shunt passive harmonic filters are not recommended for loads with a diode bridge front end such as a pulse-width modulation (PWM) type of variable frequency drive. Such loads exhibit near unity power factor throughout their operating range. The amount of capacitance that would be required for

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effective harmonic filtering will create a potential for high voltage at lower load levels. The magnitude of the voltage and possible adverse system impacts need to be reviewed. Alternate mitigating technologies such as line reactors, multiple pulse configurations, passive broadband harmonic filters, and active harmonic filters may be more appropriate. IEEE P519.1/D8b provides additional information on these alternatives.

5.3.2.3 Harmonic filter reactor selection

After the capacitance is chosen, the reactor inductance is selected to tune the harmonic filter to the desired frequency according to

$$f_{\text{tuned}} = \frac{1}{2\pi\sqrt{LC}} \tag{9}$$

$$h_{\text{tuned}} = \frac{f_{\text{tuned}}}{(\text{power system frequency})} = \frac{1}{2\pi(\text{power system frequency})\sqrt{LC}} \tag{10}$$

where

f_{tuned} is the tuned frequency of the harmonic filter (Hz),
h_{tuned} is the harmonic to which the harmonic filter is tuned,
L is the inductance in the harmonic filter circuit (H),
C is the capacitance in the harmonic filter circuit (F).

Low-voltage harmonic filters are often tuned below the nominal frequency; e.g., a 5^{th} harmonic filter may be tuned to the 4.7^{th} harmonic. The reasons for this practice include the following:

a) Capacitors with metalized film construction lose capacitance as they age, resulting in a gradual increase in tuning frequency when used in harmonic filters. Using capacitor manufacturers' aging tables, a harmonic filter tuned at 6% below its rated frequency will still exhibit acceptable tuning at the end of its 20 yr life. (Nonmetalized electrode capacitors have fairly stable capacitance. Refer to the manufacturers' aging tables.)

b) Tuning a harmonic filter more sharply than required to attain the desired performance unnecessarily stresses the components and generally makes the harmonic filter more prone to overload from other harmonic sources.

c) The manufacturing tolerance of the harmonic filter reactor may result in a tuning frequency higher than nominal.

d) Operation of capacitor fuses on failed capacitor units or elements will result in an increase in tuning frequency.

In some cases where displacement power factor improvement is desired and harmonic removal is secondary, capacitors are tuned 12% or more below their nominal frequency. (The "nominal frequency" is the integer multiple of the fundamental frequency that the filter is primarily intended to remove. When tuned in this fashion, the resultant device is protected against harmonic overload. Such designs can be safely used with harmonic generating loads, but may not absorb enough harmonic current to enable compliance with specified harmonic limits.

5.3.2.4 Computer analysis

As with any design activity, some form of simulation is necessary to verify a device will operate as intended. In order to produce an optimized harmonic filter design, it is essential to develop an accurate mathematical model to describe the harmonic behavior of the system.

The following data are typically incorporated into the model:

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a) Fundamental and individual harmonic current magnitudes and phase angles for the relevant nonlinear loads

b) Source impedance data

c) Feeder impedance (reactance and resistance)

d) Transformer impedance characteristics, size, and winding configuration

e) Size and location of all capacitor banks on the system being modeled (Note that usually this information is limited to capacitors within the plant, although capacitors on the utility system and neighboring facilities can have an impact and should be included if enough information is available.)

f) Harmonic current spectrum of all nonlinear loads

g) Subtransient reactance of all rotating machines on the system being modeled

Field data collection; site monitoring; utility/energy company billing data; system short-circuit capability; drive size and type; motor size; UPS; battery; rectifier; furnace; lighting; telcom/data systems; generators; heating, ventilation, and air conditioning (HVAC); and cable/bus data, along with a single line of the power distribution system, should be reviewed prior to analysis input.

If information about the site is not available in sufficient detail to create a suitable model, conservative assumptions should be made. Additional information regarding harmonic modeling and simulation can be found in IEEE Std 519-1992, IEEE Std 399-1997, and IEEE Catalog Number: 98TP125-0 [B2].

5.4 Case study

A large wastewater treatment plant was undergoing a major capacity expansion. Part of this expansion included the addition of six 150 kW (200 hp) dc adjustable-speed drives and three 225 kW (300 hp) dc drives. Concerns about low power factor and high harmonic voltage distortion resulted in a requirement for harmonic filtering for the new drives.

The facility, shown in outline in Figure 6, was supplied power through two pairs of parallel 1500 kVA transformers, each pair with a separate utility feeder.

Two harmonic filter design schemes were considered. Placement of a large automatically switched harmonic filter bank on each main feeder was first considered. With numerous possible combinations of transformer and generator feed and possible load transfer between buses, it was felt that this design would result in unnecessary control complexities. The final design placed a fixed filter at each of the new drives, with contactors and controls to switch on and off with the drive. The harmonic filters were connected to the drives on the load side of the integrated line reactors.

Harmonic filters were sized using the alternate method for selecting capacitors. Eighty kvar harmonic filters were installed on each 150 kW (200 hp) drive, and 120 kvar filters were installed on each 225 kW (300 hp) drive. Harmonic filters were connected through built-in circuit breakers and protected from overheating with overtemperature sensors in the harmonic filter reactors.

Table 1 contains selected data from preliminary testing upon installation of a 120 kvar harmonic filter on a 225 kW (300 hp) drive. Note that the drive was not operating under the same load for the two measurement conditions.

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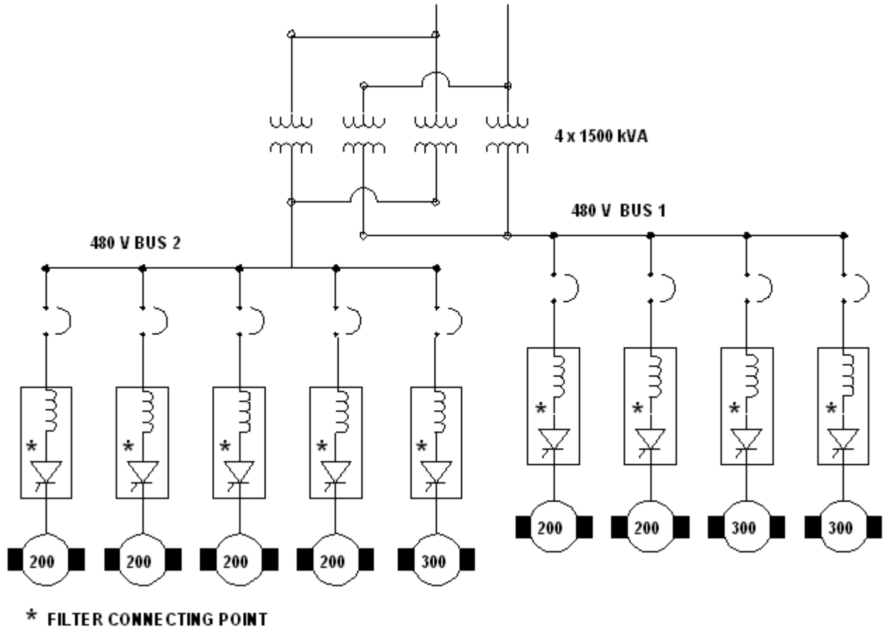

Figure 6—Water treatment facility renovation

Table 1—Water treatment plant

	RSS current (A rms)	60 Hz current (A rms)	Displacement power factor	True power factor
Drive without filter	177	168	0.28	0.26
Drive with filter	139	118	0.82	0.70

6. Medium- and high-voltage harmonic filters

This clause applies to harmonic filters installed at bus voltages above 1 kV. Harmonic filters are exposed to many of the same duties to which normal capacitor banks are exposed. The stresses are usually intensified, however, in a harmonic filter. This clause will briefly review the major considerations, describe their effect on the capacitor and other components, present requirements for properly specifying and operating the components, and conclude with an example of how to specify a single-tuned harmonic filter.

6.1 Introduction

The performance of the components that make up a harmonic filter bank is related to the operating temperatures of the various components and to the voltage stress levels, especially on the capacitor dielectric. Excessive operating temperatures can lead to dielectric damage, corrosion of parts exposed to air, annealing of connections, etc. Overheated fuses may eventually fail with either nuisance operation or malfunction. For large conductors, eddy current heating causes an apparent rise in resistance at higher harmonics, thus increasing the operating temperature on these conductors. Excessive voltages can cause dielectric breakdown, corona damage, etc. Corona at harmonic frequencies is more intense and damaging than at the normal power frequency.

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Specifications provided to the equipment manufacturer must state the operating conditions in such a way that temperatures can be predicted in the various components and that the dielectric stress and corona performance can be adequately predicted for design purposes. The performance specifications need to account for normal continuous operation, background harmonics (from other harmonic generators in the vicinity), temporary harmonic overloads, regular energizing transients, various contingencies as they occur (e.g., transformer energization, system faults, reclosing), and an estimate of future increases in harmonic loading from the addition of harmonic-generating loads in the vicinity.

Rather than specify the total rms current, it is much more appropriate to specify the harmonic current spectrum from which the total heating and dielectric stress can be calculated. For example, a certain leg of the filter may have an I_1 fundamental, I_2 of the 2nd harmonic, I_3 of the 3rd harmonic, I_5 of the 5th harmonic, etc. Dielectric stresses in capacitors can be determined by calculating the capacitor voltage at each harmonic. By summing the voltages, the worst-case peak voltage and dielectric stress can be calculated. Heating in harmonic filter reactors, resistors, fuses, etc., are also calculated for each frequency and summed for the total effect. Similar calculations are made for magnetic materials that may be used in the structure. The estimation of magnetic heating requires knowledge of the harmonic current spectrum.

Detailed specification requirements for each component of the harmonic filter and for the harmonic filter's operation are provided in 6.3.

6.2 Harmonic overload considerations

Harmonic filters are generally designed to provide fundamental frequency reactive power compensation for inductive loads and to control harmonic currents and voltages. It is usually desirable to build the harmonic filter with greater capability than is required for continuous duty of the identified harmonic loads. Other harmonics on the system will be drawn from the system and may lead to overloading. In addition, as loads are added to the power system, harmonics may increase. The additional harmonics may increase the current through the filter and cause an overloaded condition in the harmonic filter. The incremental cost of adding capacity to a harmonic filter for unanticipated harmonic absorption is much lower than the average cost of the harmonic filter. A generous margin in specifying the harmonic duty is desirable. A minimum of 10% margin above the maximum anticipated duty from all sources is suggested.

Additional harmonic loading can come from nearby transformers. System events that cause transformer saturation (e.g., transformer energizing, clearing of nearby faults) will lead to a temporary surge in the filter harmonic current. If the harmonic filter remains connected to the system during and following a fault, harmonics generated by transformer saturation may lead to short-time overloading of the harmonic filter when the system is re-energized. If a harmonic filter is not going to be removed automatically during a system outage, it is probably desirable to do a system study to determine the filter performance during this event. Similarly, nearby faults that do not cause a system outage but cause a voltage excursion may result in some transformer saturation and temporary increasing of the loading of the harmonic filter. The duty imposed on the harmonic filter by these transient conditions needs to be specified in a way that the proper components for the filter can be selected.

Unfortunately, the effect of the transients is not easily defined because of the random variation of the harmonic magnitude during the period of the transient decay. For this reason, it is frequently desirable to provide the designer with data (such as an oscillogram) from the study that gives the worst-case harmonic loading expected during this type of transient along with an identification of the magnitudes of the current by harmonic order at the beginning or worst part of the transient.

Normally the switching of a single-tuned harmonic filter does not result in any unusual duty to the capacitors or reactors over what would normally be expected in a shunt capacitor bank. However, for harmonic filters that are tuned for multiple frequencies, the transient duty on the components during routine capacitor bank switching and system faults may be magnified and should be studied.

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For design purposes, it is desirable to provide the current magnitudes, by harmonic order, through each leg of the harmonic filter both continuously and, as a function of time, for the worst-case short-term overloading resulting from switching or a contingency. Resistors are sometimes used to dampen transients and reduce the short-time overloading.

6.3 Major component specifications

The major components of the harmonic filter bank generally include the capacitors, reactors, resistors (if any), protective relaying, and the main switchgear. In specifying this type of equipment, the normal ratings must be specified with the additional requirements of harmonic current spectrums and tighter tolerances on component parameters, specifically capacitance, inductance, and resistance. Harmonic currents result in higher peak voltage, increased heat generation, and higher noise generation than most other power system applications. The applicable standards are noted below for each component with additional comments related to the harmonic filter application as needed.

6.3.1 Harmonic filter capacitor assemblies

The capacitor should be designed so that operation during normal conditions should not result in voltages or reactive power that exceed 100% of the filter capacitor unit nameplate rating. IEEE Std 1036-1992 gives continuous operating limits in excess of 100% nameplate rating. However, these limits are overload capabilities and should be reserved for contingency operation only.

IEEE Std 18-2002 gives the following limits for capacitor units:

"Capacitors 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 voltage

"b) 120% of rated peak voltage, i.e., peak voltage not exceeding 1.2 x (square root of two) x 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"

Some of the key information related to capacitors is summarized as follows:

a) *Overload capabilities.* The overload capabilities given above are generally used for contingency conditions. These contingencies include system overvoltages, harmonic filter capacitor bank unbalance conditions, and other contingencies. Special consideration needs to be given to the harmonic filter tuning during harmonic filter capacitor bank unbalance conditions (refer to 6.5.4) as the fundamental and harmonic currents may increase significantly in all or in part of the harmonic filter capacitor bank.

b) *Specification items.* Specifications for harmonic filter capacitor equipment for these applications should include the following:

    1) The maximum system line-to-line operating voltage
    2) Power system fundamental frequency
    3) System BIL
    4) Total three-phase effective power frequency capacitive reactive power (megavars) at rated voltage, and the rated voltage of the filter
    5) Tuned frequency(ies) of the harmonic filter
    6) Installation type (e.g., indoor, outdoor, metal enclosed)

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7) Environmental conditions [e.g., ambient temperature range, creepage requirements (industrial pollution), maximum wind velocity, ice loading, seismic requirements, altitude greater than 1800 m above sea level]
8) Harmonic filter capacitor bank capacitance (microfarads) and tolerance
9) The individual harmonic voltage peaks applied to the capacitors or individual harmonic currents through the capacitors, including the fundamental, during the various conditions in which the filter will operate (i.e., steady-state, normal, contingency)
10) Transient and dynamic voltage peaks for switching operations (e.g., switch restrike during harmonic filter deenergization, transformer energiziation)
11) The expected duty cycle or repetition rate and duration of the voltages and currents of Item 9 and Item 10.
12) Harmonic filter capacitor bank configuration (e.g, grounded wye, ungrounded wye, or delta)

c) *Voltage rating*. The rms voltage rating, V_r, of capacitors used in harmonic filter banks is specified as the greater of Item 1, Item 2, or Item 3 as follows:
   1) Steady-state fundamental-frequency voltage plus the voltages due to the harmonic currents through the capacitors. Such voltage should be calculated by the arithmetic sum of the power frequency and harmonic voltages as shown in Equation (11) [or Equation (12)].

$$V_r = \sum_{h=1}^{\infty} I(h) X_C(h) \tag{11}$$

where

V_r is the rms voltage rating of the capacitor,
h is the harmonic order,
$I(h)$ is the rms current through the capacitor at the given harmonic order,
$X_C(h)$ is the capacitive reactance at the harmonic order.

or

$$V_r = V_C(1) + \sum_{h=2}^{\infty} I(h) X_C(h) \tag{12}$$

if fundamental current through the capacitor is not specified.

where

$$V_C(1) = V_S\left(\frac{h^2}{h^2 - 1}\right) \tag{13}$$

and where

$V_C(1)$ is the maximum power frequency rms voltage across the capacitor,
V_S is the maximum system voltage across the capacitor, not including the voltage rise across the tuning reactor,
h is the tuned harmonic order of single-tuned filter (i.e., 4.3^{rd}, 4.7^{th}, 5^{th}, 7^{th}, and so on).

   2) For transient events (generally less than 1/2 cycle of the power frequency, such as capacitor bank switching, circuit breaker restrike, etc.), the voltage rating of the capacitor is calculated by Equation (14).

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$$V_r = \frac{V_{tr}}{\sqrt{2}\,k} \tag{14}$$

where

- V_r is the voltage rating (rms) of the capacitor,
- V_{tr} is the peak transient voltage,
- k is the multiplier from Figure 7.

In using Figure 7 to determine the minimum acceptable capacitor voltage rating to accommodate the expected transient voltages, enter Figure 7 at the maximum number of transients of approximately the expected magnitude in a year. Go up to the curve and across to the y axis to determine the appropriate *k*.

IEEE Std 1036-1992 states that a capacitor unit may reasonably be expected to withstand the transient overvoltages indicated in Figure 7.

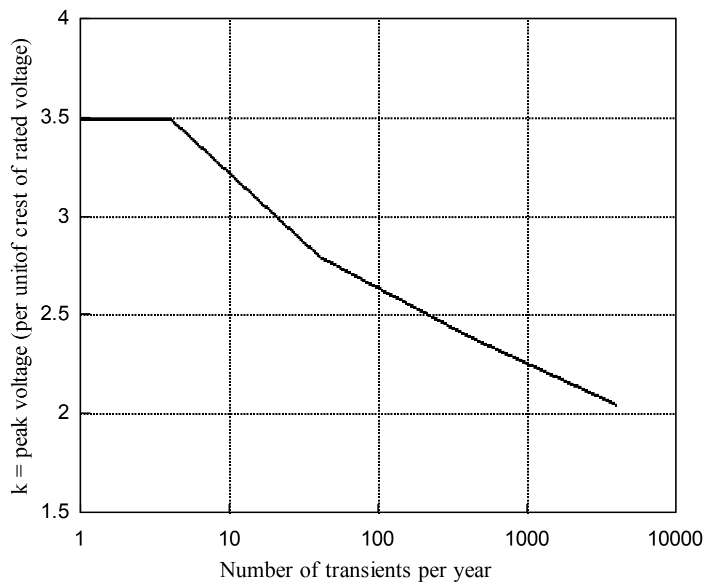

Figure 7—Transient overvoltage capability of capacitors

3) For dynamic events (generally lasting from more than a few fundamental cycles to several seconds, such as transformer energization, bus and line fault clearing, etc.), the voltage rating on the capacitor is calculated using Equation (15).

$$V_r = \frac{V_d}{\sqrt{2}} \tag{15}$$

where

- V_r is the voltage rating of the capacitor,
- V_d is the peak voltage across the capacitor reached during dynamic event.

For infrequent contingencies (e.g., system faults), the contingency overvoltage capability discussed in Item e) may be used to reduce the rated capacitor voltage. This figure is based on a total of 300 contingencies over the life of the installation. For resonant overvoltages occurring

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with some regularity in the operation of the harmonic filter, the voltage rating to endure resonant overvoltages calculated in Equation (15) is recommended.

The unit voltage ratings obtained from Equation (11) through Equation (15) may not result in typical capacitor unit ratings as shown in IEEE Std 18-2002. This result is not unusual. Manufacturers can usually supply the required voltage ratings.

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 component will also be increased according to Equation (13). Other issues [including reactive power (kilovars) and current] as presented in this guide must also be considered.

d) *Capacitance tolerance.* The following capacitor parameters must be defined when designing a filter to achieve a specified tuning point:

— Capacitance variation with temperature

— Capacitance manufacturing tolerance

The effect of the capacitance tolerance on the performance of the harmonic filter must be evaluated. Capacitor units built according to IEEE Std 18-2002 since 2002 have a manufacturing tolerance ranging from –0% to +10% at 25 °C uniform case and internal temperature. Older capacitors may have tolerances as high as –0% to +15% for the capacitance of individual units. While this range may be acceptable for shunt capacitor banks, it may be unacceptable for some harmonic filter applications.

In harmonic filter designs, the capacitor manufacturer must select a tolerance for individual units so that the filter capacitor bank capacitance tolerance is met. The capacitance tolerance of the individual units should not exceed ± 5% of the rated unit capacitance. A reasonable tolerance for a full capacitor assembly is 4% (± 2%, or –0% +4%), measured at 25 °C. Tighter capacitance tolerance may be achieved through consultation with the manufacturer.

Capacitance variation over the operating temperature range may be significant. Capacitor manufacturers can usually provide the variation of capacitance with temperature.

e) *Power frequency short-time overload capability.* As given in IEEE Std 1036-1992,[17] capacitor units may reasonably be expected to have a short-time overload capability for 300 applications of power frequency overvoltage, without superimposed transients or harmonic content, of the magnitude and duration specified in the curve shown in Figure 8.

In using Figure 8, the overvoltage capability is for the capacitor unit, not the capacitor bank. Evaluation of capacitor unit overvoltage exposure should include allowance for any voltage unbalance in the capacitor bank

The time axis of Figure 8 indicates the maximum duration for a single event. Capacitor unit damage tends to escalate during an event, so that damage is happening more rapidly at the end of the event than at the beginning. Two continuous seconds at 1.73 per unit is *much* more severe than two separate events of 1 s each, with a time in between to allow for localized cooling, absorption of corona gasses, etc. The curve should not be used to estimate the effect of contingency overvoltage events exceeding the maximum time indicated by the curve.

For event times shorter than indicated by the curve, the times of the individual events can be accumulated to estimate the effect of the shorter events. Ten 1.73 per-unit events of 0.1 s each (shorter than the allowable 1 s limit of the curve) would create equal or less damage to the capacitor unit than one 1.73 per-unit event of 1 s duration.

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

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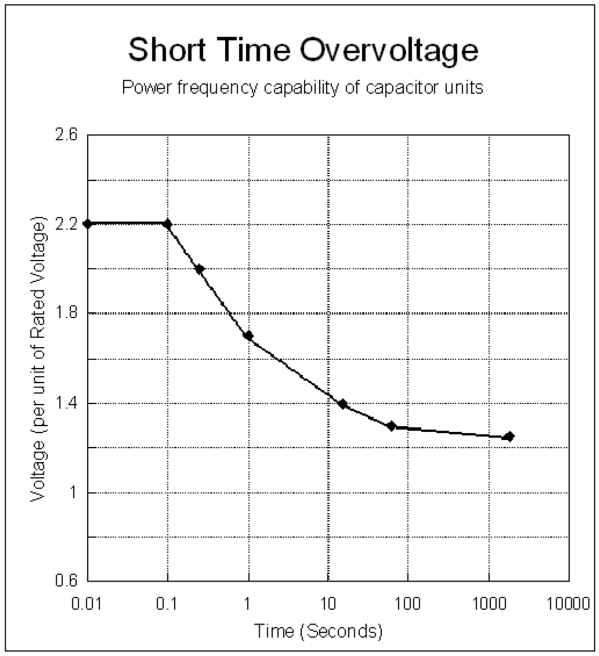

Figure 8—Maximum contingency power frequency overvoltage of capacitor units

Capacitor units in shunt capacitor banks (not harmonic filters) may reasonably be expected to withstand, during normal service life, a combined total of 300 applications of power frequency terminal-to-terminal overvoltages without superimposed transients or unusual harmonic content of the magnitudes and duration in this curve. For harmonic filters with substantial harmonic voltage across the capacitors, the equivalent terminal-to-terminal overvoltage of the capacitor is calculated by arithmetically summing the fundamental and individual harmonic rms voltages appearing across the capacitor terminals [see Equation (12)].

If this capability is needed in a particular application, it is important to be sure that the other equipment also has this short-time overload capability including the reactors, resistors, fuses, switchgear, etc.

f) The temperature rise of the capacitor units results from dielectric heating, resistive (I^2R), and discharge resistor losses. At harmonic frequencies, eddy current heating of the capacitor case may also contribute to heating of the capacitor dielectric. The dielectric loss is related to the operating kvar (sum of the products of voltage and current at each harmonic, including the fundamental) of the capacitor unit. The dielectric and I^2R heating losses depend upon the unit construction (e.g., foil thickness, connections, internal fuses). The discharge resistor losses are determined by the rms operating voltage and the resistance of the resistors. The manufacturer of the capacitor units should be contacted if there is any question concerning a possible undesirable temperature rise in the capacitor units.

g) Bank configuration, whether grounded wye, ungrounded wye, or delta, does not affect performance for positive and negative sequence harmonics. Zero sequence harmonics must be controlled by a grounded bank configuration. The advantages and disadvantages of capacitor bank configuration, as described in IEEE Std 1036-1992, apply equally well to harmonic filter capacitor banks.

The 3rd harmonic is a zero-sequence harmonic during balanced conditions. However, unbalanced loads, such as an electric arc furnace, can produce both positive- and zero-sequence 3rd harmonics. The zero-sequence portion is usually controlled by transformers with delta-connected windings. The zero-sequence portion can be controlled with a grounded-wye harmonic filter capacitor bank. The positive sequence portion can be controlled using a grounded-wye, ungrounded-wye, or delta-connected harmonic filter capacitor bank.

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6.3.2 Harmonic filter reactors

There is no existing ANSI or IEEE standard specifically related to harmonic filter reactors. The closest document is IEEE Std C57.16-1996. The referenced standard includes an annex that provides guidance for applying dry-type air-core filter reactors. Filter reactors generally fall into three categories:

— *Dry-type, air-core reactors.* Generally used in medium- and high-voltage applications.
— *Dry-type, iron-core reactors.* Generally used in low- and medium-voltage applications.
— *Fluid-filled, iron-core reactors.* Generally used in medium-voltage applications.

Some of the key information related to applying harmonic filter reactors that is different from applying other series connected reactors is summarized as follows:

a) *Specification items.* Specifications for harmonic filter reactors should include the following:
   1) The maximum system line-to-line operating voltage
   2) System fundamental frequency
   3) System BIL
   4) Tuned frequency of the filter (hertz)
   5) Installation type (e.g., indoor, outdoor, metal enclosed)
   6) Environmental conditions [e.g., ambient temperature range, creepage requirements (industrial pollution), maximum wind velocity, ice loading, seismic requirements, altitude greater than 1800 m above sea level]
   7) Reactor inductance (millihenries) and inductance tolerance and whether taps are required
   8) Q at the tuned frequency, with its tolerance if critical (Note that Q is the ratio of reactance to effective series resistance, X/R)
   9) Maximum short-circuit current and its duration through the reactor
   10) The individual harmonic currents through the reactor, including the fundamental, during the various conditions in which the filter will operate (i.e., steady-state, normal, contingency)
   11) Transient and dynamic voltage peaks for switching operations (e.g., switch restrike during filter deenergization, transformer energization)
   12) The expected duty cycle or repetition rate and duration of the currents and voltages of Item 10 and Item 11.
   13) BIL rating across the coil and to ground (may be different)
   14) Preferred coil dimensions and mounting arrangements
   15) Audible noise limit (if applicable)

b) *Three-phase, iron-core harmonic filter reactors.* Three-phase (common-core) iron-core harmonic filter reactors should be avoided in situations where the performance of the harmonic filter network is critical. It is very difficult to adjust the inductance of one phase without affecting the inductance of the other two phases. In addition, if the inductance of all three phases is set at the fundamental frequency, there is no guarantee that the inductance of all three phases will remain constant as the frequency is increased.

c) *Inductance, inductance tolerance, and quality factor.* The inductance and the quality factor, Q, for the harmonic filter reactor should be specified at the resonant (tuned) frequency of the harmonic filter network. The tolerance on the inductance should be selected to insure the proper performance of the harmonic filter network across the range of the tolerance. Inductance tolerance is usually available as ± 3% or +0% to –6%. The tolerance on the quality factor, Q, is typically ± 20%.

   Reactor taps, if required, should also be specified. Taps are often included to provide final tuning in the field and to accommodate changes in the capacitance of the harmonic filter capacitor bank. Harmonic filter capacitor banks are frequently built with the capacity for future expansion.

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d) *Harmonic current spectrum.* The harmonic current spectrum should be defined for both continuous and temporary/contingency conditions. Transient conditions should also be provided in applications where the harmonic filter is exposed to frequent transients such as transformer energizing. The duty cycle or repetition rate of the transients and contingency operations should be specified. The harmonic current spectrum is required for the following reasons:

   1) To ensure that the core will not saturate and to determine the core and gap losses in the iron core harmonic filter reactors.

   2) To assist the harmonic filter reactor designer in conductor selection in order to minimize resistive, eddy and stray losses.

   The current specified for the fundamental frequency should account for variations in the line voltage and the tolerance of the harmonic filter capacitance. The fundamental frequency should be clearly stated also.

e) *Voltage specifications.* The (1) fundamental and harmonic voltages, (2) minimum required BIL across the coil, and (3) minimum required BILs from coil high-voltage and low-voltage terminals to ground or core (iron-core harmonic filter reactors) must be specified.

   The rated steady-state voltage is calculated as the arithmetic sum of the fundamental and the harmonics, similar to the capacitor. See Equation (16).

$$V_r = \sum_{h=1}^{\infty} I(h) X_R(h) \tag{16}$$

   where

   V_r is the rms voltage rating of the reactor,
   h is the harmonic order,
   $I(h)$ is the rms current through the reactor at the given harmonic order (h),
   $X_R(h)$ is the inductive reactance at the given harmonic order.

   The required contingency voltage capability is based on the same type of calculation using the contingency current instead of the continuous current.

   The coil-to-ground BIL will usually match the BIL of other equipment on the user's system. If the harmonic filter reactor is located on the neutral side of the harmonic filter capacitor bank and one terminal of the harmonic filter reactor is grounded, the BIL of the grounded terminal may be reduced.

   The terminal-to-terminal BIL across the coil will usually match the system BIL whether the harmonic filter reactor is located on the source side or the neutral side of the harmonic filter capacitor bank because the bulk of the lightning surge voltage will be across the harmonic filter reactor rather than the harmonic filter capacitor. Terminal-to-terminal BIL may be reduced if a surge arrester is connected across the harmonic filter reactor terminals. The coil must then be adequately coordinated with the protective characteristics of the surge arrester (see IEEE Std C62.22-1997).

   The manufacturer should be made aware of frequent switching surge duties to which the harmonic filter may be exposed. Frequent transformer switching on the same bus as the harmonic filter, for example, may result in additional dielectric stresses to the insulation.

f) The maximum short-circuit current available to the harmonic filter reactor and the amount of time the harmonic filter reactor must withstand this current must be specified. The value will vary depending upon the location of the harmonic filter reactor within the equipment. Fault current through the harmonic filter reactor is minimized when the harmonic filter reactor is connected on the neutral side of the harmonic filter capacitor.

g) In configuring the harmonic filter, the mounting arrangement of the reactor and physical size limitations should be specified. The following items are noted:

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1) For medium-voltage applications, the harmonic filter is generally connected in an ungrounded-wye configuration with the harmonic filter reactor located on the source side. The neutral connection is generally conveniently made within the harmonic filter capacitor equipment. The harmonic filter reactor may limit the available fault current for a fault in the harmonic filter capacitor bank if the reactor is located on the source side of the capacitor. However, iron-core reactors may not limit fault current if they saturate. Iron-core and air-core reactors located on the neutral side of the harmonic filter capacitor will not decrease the available phase-to-phase or phase-to-ground fault current level in the harmonic filter capacitor bank.
2) For high-voltage applications, the harmonic filter may be connected in a wye configuration with the harmonic filter reactor located on the neutral side. This filter reactor location may allow heavy harmonic filter reactors to be conveniently mounted at a lower elevation.

   For grounded-wye filters (effectively grounded systems only), this filter reactor location may also allow the BIL of the reactor to be less than the BIL of the system. For this application, an appropriately rated surge arrester should be placed across the harmonic filter reactor.
3) Air-core reactors must be mounted to prevent magnetic flux from producing excessive heating in nearby ferromagnetic materials and/or affecting the harmonic filter tuning.

6.3.3 Harmonic filter resistor assemblies

The majority of passive harmonic filters are connected as high Q, single-tuned harmonic filters. Some applications require the attenuation of more than one harmonic and require additional damping. A resistor often supplies the damping.

There is no existing ANSI or IEEE standard specifically related to harmonic filter resistors. The standard that relates most to resistors in filter applications is IEEE Std 32-1972. Some of the additional considerations for use in harmonic filters are summarized:

a) *Specification items.* The specifications for harmonic filter resistor equipment should include the following:
   1) The maximum system line-to-line operating voltage
   2) System fundamental frequency
   3) System BIL
   4) Installation type (e.g., indoor, outdoor, metal enclosed)
   5) Environmental conditions [e.g., ambient temperature range, creepage requirements (industrial pollution), maximum wind velocity, ice loading, seismic requirements, altitude greater than 1800 m above sea level]
   6) Resistance (ohms) and resistance tolerance
   7) Maximum allowable inductance (if low inductance is required)
   8) Maximum allowable resistance variation with temperature (if resistance variation with temperature is critical)
   9) The magnitude and duration of the maximum short-circuit current through the resistor
   10) The magnitude of the individual harmonic currents through the resistor, including the fundamental, during the various conditions in which the filter will operate (i.e., steady state, normal, contingency)
   11) Transient and dynamic voltage peaks for switching operations (e.g., switch restrike during filter deenergization, transformer energization)
   12) The expected duty cycle or repetition rate and duration of the currents and voltages of Item 10 and Item 11
   13) Energy rating of the resistor (maximum adiabatic energy capability, optional for fluctuating loads only)

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14) Minimum required BIL across the resistor, and minimum required BILs from resistor high voltage and low voltage terminals to ground
15) Preferred dimensions and mounting arrangements

b) The resistor harmonic current spectrum must be defined for continuous and temporary/contingency operation. As with the reactors, this spectrum determines the heat/losses and vibration/noise considerations. Fundamental frequency losses may be substantial in some damped harmonic filter designs.
c) The maximum short-circuit requirement for the resistor is similar to the requirement presented for the harmonic filter reactor in 6.3.2.
d) Some applications may require that the resistor has low series inductance.
e) Voltage requirements are similar to the requirements presented for the harmonic filter reactor in 6.3.2.
f) The tolerance of the resistance with regards to frequency may need to be defined to ensure the desired performance.
g) Mounting arrangements are similar to the harmonic filter reactor. Animal proofing, such as screens or enclosures, may be needed to prevent faults.

6.3.4 Switchgear

In general, the ANSI/IEEE Std C37 series includes guides and standards for switchgear and relays. IEEE Std C37.012-1979 provides guidance on applying high-voltage circuit breakers in switching capacitor banks. ANSI C37.66-1969 provides guidance in applying oil switches for capacitor switching. In Section 460.24 of NFPA 70-2002 (National Electrical Code), there is also information on switching devices for capacitor switching. These documents generally recommend that the device be capable of switching a capacitive current and that the device be rated for at least 135% of the nominal current of the capacitor based on rated reactive power and rated voltage. With high harmonic currents in a filter, the current rating needs to be selected based on the expected continuous and contingency fundamental and harmonic currents.

Special consideration must be given to the specification of switching devices for harmonic filters. The fundamental voltage rise across the reactor results in a higher recovery voltage on the switching device than when switching a capacitor bank without tuning reactors. In addition, some switching devices may have difficulty interrupting the high harmonic currents of a harmonic filter because of the higher rates of rise and possible multiple zero crossings. The switching device manufacturer should be consulted for the application of switching harmonic filters. Refer to IEEE Std C37.04-1999, ANSI C37.06-2000, IEEE Std C37.012-1979, and ANSI C37.66-1969 for guidance with specification of these devices.

As compared with a shunt capacitor, the inrush and outrush currents are greatly reduced in a harmonic filter by the series tuning reactor. Adding a separate inrush or outrush limiting reactor would change the tuning of the filter and is not normally needed.

The specifications for switchgear used in harmonic filter applications should include the following:

a) The maximum system line-to-line operating voltage
b) The harmonic filter capacitor bank grounding (i.e., ungrounded, grounded, or impedance grounded). (If the bank is grounded through an impedance, state the ratings of the impedance.)
c) The grounding of the system (i.e., effectively grounded, impedance grounded, or ungrounded). (If the system is grounded through an impedance, state the ratings of the impedance.)
d) System fundamental frequency
e) System BIL
f) Installation type (e.g., indoor, outdoor, metal enclosed)

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g) Environmental conditions [e.g., ambient temperature range, creepage requirements (industrial pollution), maximum wind velocity, ice loading, seismic requirements, altitude greater than 1800 m above sea level]
h) Maximum short-circuit current—symmetrical and asymmetrical, momentary and interrupting
i) The magnitude and duty cycle or repetition rate and duration of the individual harmonic currents through the switchgear, including the fundamental, during the various conditions in which the harmonic filter will operate
j) Switchgear BIL
k) Duty cycle of switching operations (number and frequency)
l) Capacitor/harmonic filter switching duty, very low probability of restrike
m) The natural frequency of the harmonic filter tuning reactor. (This natural frequency affects the rate of rise of recovery voltage across the circuit breaker for a fault in the harmonic filter.)

None of the ANSI/IEEE Std C37 series addresses circuit breaker action in the presence of high harmonic currents. Interruption of current with higher rates of rise or higher rates of rise of recovery voltage may be more difficult for some switches and circuit breakers. The switchgear supplier should be alerted to the application.

6.3.5 Conductors

Electrical conductors with large cross-sectional areas (e.g., buswork, cables, bushings) may be subjected to eddy current and skin effect heating from harmonic currents. The sizing of conductors based on rms current alone may not be adequate. Conductor sizing should be based on the anticipated continuous and short-time harmonic current duty, including the fundamental.

6.3.6 Grounding switch and key interlock

For servicing and maintaining the equipment, a three-phase and neutral grounding switch is often included when using medium-voltage and high-voltage capacitors. In addition, key interlocks are included, which are tied to the main disconnecting device(s), the ground switch, and the enclosure doors if an enclosure is used.

6.3.7 Surge arresters

Surge arresters are used at a harmonic filter installation to prevent filter component failures or other system equipment failures during switching surges, limit the risk of repetitive circuit breaker restrike, and limit lightning-induced overvoltages. The primary protective function of the arrester will determine its location and rating.

Arresters connected line to ground at the harmonic filter terminals will provide general protection of substation equipment from harmonic filter circuit breaker restrikes and lightning, but may not provide substantial reduction in the transients across the harmonic filter capacitor or the harmonic filter reactor. Arresters connected across the harmonic filter capacitors will provide capacitor protection; the surge arresters, however, are exposed to higher steady-state voltages and may be subject to higher surge discharge energies than arresters located on the bus.

6.3.7.1 Specification items

The specifications for arresters used in harmonic filter applications should include the following:

a) The maximum system line-to-line operating voltage
b) System grounding (i.e., effectively grounded, impedance grounded, or ungrounded)

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c) Environmental conditions [e.g., ambient temperature range, creepage requirements (industrial pollution), maximum wind velocity, ice loading, seismic requirements, altitude greater than 1800 m above sea level]

d) Maximum available short-circuit current

e) Voltage rating or maximum continuous operating voltage (MCOV)

f) Class (e.g., distribution, intermediate, station)

g) Mounting arrangements

6.3.7.2 Surge arrester selection

Arresters located at the line terminals of a harmonic filter, where the harmonic voltage distortion is small, are applied in the same way as other arresters located on a power system. Arrester ratings are selected so that the device is able to withstand the MCOV, temporary overvoltage (TOV), and switching surge energy absorption duties. A detailed description of the selection process is given in IEEE Std C62.22-1997.

For arresters located within a harmonic filter, where the voltage distortion may be substantial, the peak applied voltage and harmonic heating should be considered in selecting the arrester rating. For the peak voltage, the sum of the fundamental and all harmonic voltages at the arrester location (times the square root of 2) gives the maximum peak voltage expected. See Equation (17).

$$V_{\text{peak}} = \sqrt{2}\sum_{h} V(h) \tag{17}$$

In order to avoid peaks of the voltage wave from being high enough above the peak of the arrester MCOV to cause “turn on” (conduction) and excessive heating, the arrester MCOV rating should be selected so that

$$\text{MCOV} \geq \sum_{h} V(h) \tag{18}$$

The harmonic (dielectric) heating of the arrester is proportional to the order of the harmonic and the square of the voltage of each harmonic (including the fundamental). In order that this heating not exceed the heating of the same arrester applied at rated frequency only, the arrester MCOV rating should be selected so that

$$\text{MCOV} \geq \sqrt{\sum_{h} (hV(h)^2)} \tag{19}$$

For continuous operation, the MCOV for arresters located in a harmonic filter should be based on the higher value of Equation (18) and Equation (19). In addition to the continuous capability requirements for the arrester, there may be a contingency overvoltage requirement. If there is substantial short-time overvoltage across the arrester, the short-time overvoltage capability of the arrester should be compared with the expected exposure using peak voltages to determine the required MCOV to meet the short-time overvoltage requirements of the application. Alternatively, if the arrester is modeled in a study of the overvoltage phenomena, the arrester energy may be compared with the energy capability of the arrester, as supplied by the surge arrester manufacturer.

The surge protective level of the selected arrester must coordinate with the surge withstand level (e.g., BIL) of the filter component being protected. Usually a minimum margin of 15% for switching surges and 20% for lightning discharge is required between arrester protective level and equipment withstand level. Methods of calculation of protective margins are contained in IEEE Std C62.22-1997.

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6.4 Harmonic filter switching control

The switching controls are similar to the controls used with standard capacitor banks. These controls are discussed in IEEE Std 1036-1992. The key factors and differences for harmonic filters are summarized as follows:

a) If the harmonic filters are switched, they are commonly controlled based on fundamental frequency reactive power and voltage requirements with consideration for harmonics as required.

b) Although inrush and outrush currents need to be taken into account, they are typically lower in harmonic filter applications due to the presence of the harmonic filter reactor.

c) Undervoltage conditions are generally not critical for harmonic filter design, unless voltage is lost completely. In that case, the harmonic filters should generally be disconnected from the system immediately until the system is restored to normal conditions. Such timely disconnection avoids dynamic overvoltage conditions that can occur when capacitors are energized with transformers. Dynamic overvoltages can also occur when large transformers are energized after the harmonic filter is in service.

d) When a small (kilovar), low-frequency harmonic filter (such as a 3^{rd} harmonic filter) is switched with a much larger higher frequency harmonic filter (such as a 5^{th} harmonic filter), the transient voltage in the 3^{rd} harmonic filter may be excessive, resulting in harmonic filter reactor or harmonic filter capacitor failures in that filter. This type of configuration should be evaluated carefully and the equipment rated as required.

Typical harmonic filter switching controls fall into the same categories as listed in the IEEE Std 1036-1992 for standard capacitor installations. They include the following:

— Voltage control

— Current control

— Reactive current control (sometimes referred to as a var control)

— Time control

— Temperature control

Switched harmonic filters using a voltage, current, or var control are usually switched based on the fundamental voltage and reactive power requirements. Controllers or relays should incorporate proper filtering so that the switching signal is based on the fundamental frequency voltage and current and not on other harmonic components.

The switching control or associated control circuitry is usually set with a 5 min delay between opening and closing. This 5 min delay is based on the requirement of IEEE Std 18-2002 for capacitor units rated above 600 V to have an internal device to discharge the residual voltage to 50 V within 5 min. This 5 min delay allows the trapped charge in each capacitor unit to decay to 50 V or less before the bus voltage is superimposed upon it. (Note that capacitors built to standards other than IEEE Std 18-2002 may have different discharge times and require a different delay before re-energizing.)

Where less delay than 5 min is desired, allowing the trapped charge to decay to 10% of the crest of the rated capacitor unit voltage is usually acceptable. (A trapped change of 10% of the crest of rated voltage results in a 10% increase in inrush current and transient overvoltage.) The decay in voltage is exponential. The time in minutes required to reach 10% of the crest of rated voltage, V_{rated}, expressed in kilovolts (for capacitor units reaching 50 V in 5 min) is shown in Figure 9.

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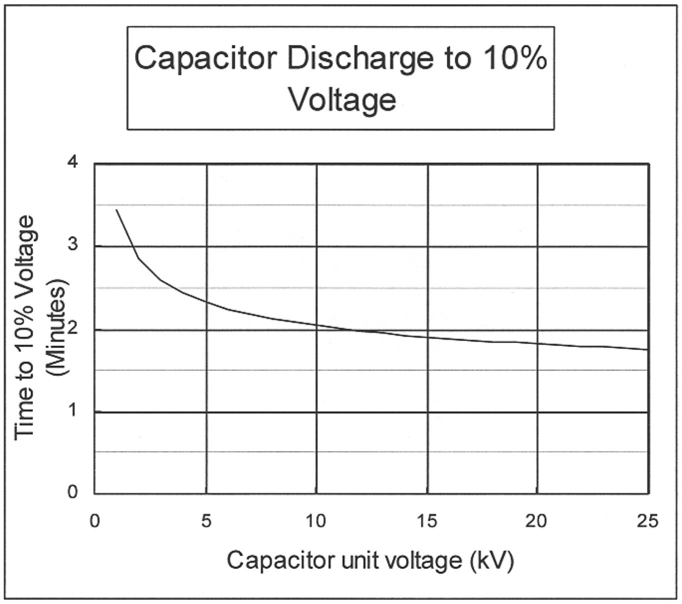

Figure 9—Discharge time to 10% voltage for medium voltage capacitor units discharging to 50 V in 5 min

Transient simulations of the switching event of a harmonic filter or multiple harmonic filter arrangement should be conducted to assure that the specifications for the filter components are adequate for the voltages and currents encountered during switching. Each switching contingency condition, such as switching a multiple harmonic filter arrangement with one or more harmonic filters disconnected, should be simulated so that the voltage and current transients are properly considered when creating component specifications. See IEEE Catalog Number: 98TP125-0 [B2] for a detailed discussion of the importance of transient simulations of harmonic filter arrangements.

6.5 Protection

The purpose of harmonic filter protection is to increase filter availability by providing an alarm to personnel for minor faults and allowing the filter to remain in service and by tripping the bank for greater unbalance before severe damage occurs. Protection of a harmonic filter begins in the filter design stage. Considering the design of the protective relaying scheme during the design of the harmonic filter can result in a more effective protective relaying design. IEEE Std 1036-1992 and IEEE Std C37.99-2000 discuss the details of capacitor bank protection. Issues of special concern for the protection of a harmonic filter are overvoltage, overcurrent, unbalance, and harmonic overloading.

6.5.1 Relay considerations for harmonic filter applications

Relays are usually not specifically designed for harmonic filter protection. Concerns with specific types of relays used in harmonic filters are discussed as follows:

a) *Mechanical overcurrent relays.* The torque imposed on an induction disk per ampere of current decreases as the frequency of the current increases. Thus, the output signal of this type of relay is not a correct representation of reactor rms current. However, a mechanical relay can be used for harmonic filter reactor protection if sufficient margin is added to the reactor current rating to compensate for the relay's inaccuracy. Calculating the margin will generally require testing the specific relay to be used in a harmonic filter application in order to determine its harmonic response, as this information is not typically available from the relay vendor.

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b) *Solid-state relays.* These relays have lower burden and may have better filtering than electromechanical relays.

c) *Digital overcurrent relays.* Most digital relays used for fault protection sample current at a rate that is not sufficient to detect harmonics of interest. Any digital fault relay that is not certified to have true rms measuring capability should not be used in harmonic filter overload applications. Relays that respond to the fundamental current only may be preferred for unbalance protection.

d) *Thermal relays.* Thermal relays that sense temperature directly are effective for enclosed filter designs. These relays may sense the air temperature in the enclosure or the core surface temperature of iron-core, harmonic filter reactors.

   Unenclosed medium-voltage or high-voltage air-core harmonic filter reactors cannot use direct temperature sensing relays because BIL considerations make imbedding sensors in the reactor windings impractical. Such applications can use relays in which the measured current heats a bimetal element or other type of temperature sensor. However, commonly available relays of this type are designed for motor overload protection and tend to be more “inverse” than desirable for harmonic filter protection. To coordinate a motor relay in a harmonic filter subject to varying harmonic filter injection, the harmonic filter reactor current rating must be increased if the motor relay is to protect the harmonic filter reactor against a legitimate continuous overload without tripping during short-term periods of high harmonic load that would not damage the reactor.

e) *Programmable monitor/controller units.* Programmable monitor/controller units usually calculate the harmonic content of the sensed current correctly and provide digital outputs for relay operation. However, some programmable monitors are unsuitable for harmonic filter protection for subtle reasons such as lack of anti-aliasing filters on the monitor inputs.

6.5.2 Overvoltage protection

The key points of overvoltage protection of a harmonic filter are summarized as follows:

a) *Surge protection.* Refer to 6.3.7 for a discussion of this topic.

b) *Bus overvoltage.* The application of capacitors inherently results in a voltage rise at the fundamental frequency. To protect the harmonic filter from abnormal system voltages that could damage filter components, bus overvoltage relays or harmonic filter overcurrent relays designed to derive the true overvoltage on the harmonic filer capacitors may be applied.

c) *Harmonic overvoltage.* Excessive harmonic currents may result in excessive harmonic filter capacitor voltages. Refer to 6.5.5 for further discussion of this topic.

d) *Harmonic filter capacitor bank unbalance.* Unbalances due to external or internal fuse operations or the shorting of elements in a fuseless harmonic filter capacitor bank may result in excessive capacitor voltages in parts of the harmonic filter capacitor bank. Refer to 6.5.4 for further discussion of this topic.

6.5.3 Overcurrent protection

The key points of overcurrent protection of a harmonic filter are summarized as follows:

a) *Harmonic overcurrent.* Excessive harmonic currents may result in excessive harmonic filter capacitor voltages and/or excessive heating in components such as harmonic filter reactors and harmonic filter resistors. Refer to 6.5.5 for further discussion of this topic.

b) *Harmonic filter capacitor fusing.* Capacitor fuses are used to remove faulted capacitor units or elements from service quickly enough to prevent case rupture or damage to other capacitor units or elements. Power fuses are often used to provide major fault protection. Power fuses, individual external capacitor fuses, or internal fuses cannot provide harmonic filter capacitor overload protection. Fuses must be sized, and possibly derated, to withstand, without damage, the harmonic currents and the transient and dynamic overcurrents associated with application in a harmonic filter. In addition, the fuses must be rated for the power frequency and transient recovery voltages occurring in a shunt

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capacitor bank. Refer to IEEE Std C37.48-1997, IEEE Std 1036-1992, and IEEE Std C37.99-2000 for more guidance about fuses for shunt capacitor bank applications.

c) *Major fault protection.* Major fault protection is generally provided by an external device such as a power fuse or switching device with associated relay circuits.

6.5.4 Harmonic filter unbalance and detuning protection

Usually the most critical function of the unbalance protection is to trip the harmonic filter capacitor bank off promptly for a flashover or fault within the bank that may not be detected by the overcurrent protection. Such arcing faults within a capacitor bank frequently create very high transient overvoltages within the capacitor bank and will lead to substantial damage if the capacitor bank is not promptly tripped (refer to IEEE Std C37.99-2000).

Unbalance and detuning protection (hereafter referred to as *unbalance protection*) refers to the detection of and the protective actions taken for external or internal fuse operations or the shorting of elements of a fuseless harmonic filter capacitor bank. Such fuse operations or shorting of elements changes the capacitance of the filter and may result in an increase in fundamental voltage applied to the remaining units/elements. The effects of this capacitance change and potential increase in fundamental voltage must be evaluated to determine the appropriate protective action. Generally, the same methods of unbalance protection used for standard capacitor banks are also used for harmonic filter capacitor banks. The key points of unbalance protection of a capacitor bank used in a harmonic filter are summarized as follows:

a) External or internal fuse operations or the shorting of elements of a fuseless harmonic filter capacitor bank changes the resonant frequency of the harmonic filter from its design point. Fuse operations in a parallel connected harmonic filter capacitor bank result in a decrease in capacitance and a corresponding increase of the resonant frequency. There is also the possibility that the shorting of elements of an externally fused capacitor without the fuse operation will result in an increase in capacitance and a corresponding decrease of the resonant frequency.

   The shorting of elements of a fuseless harmonic filter capacitor bank results in an increase in capacitance and a corresponding decrease of the resonant frequency. Refer to 6.6 for a discussion of the consequences of filter detuning.

   In specifying the unbalance protection requirements for a capacitor bank used in a harmonic filter, it is desirable to indicate the maximum capacitance change (+ and – tolerances) that can be tolerated. The detuning of the filter may be a more stringent condition in the unbalance protection than the resulting overvoltage on the remaining units/elements.

b) Unbalance protection schemes in which ambiguous indications are a possibility are of special concern to the designer of a harmonic filter if the number of capacitor element or unit failures is being used as a criterion to avoid damage due to a change in filter tuning. Ambiguous indications occur when the harmonic filter capacitor bank is “in balance” after more than one fuse operation or element fault. For example, a negligible current should flow through a current transformer connecting the neutrals of a balanced ungrounded-double-wye capacitor bank; however, the same negligible current should flow through the current transformer if an equal number of fuse operations/element failures occur in the same phase of both wye sections. Thus this type of scheme does not indicate that there have been failures.

   Where ambiguous indications are a possibility, it is desirable to have an unbalance detection scheme designed to issue an alarm either upon the first fuse operation of either an externally or internally fused harmonic filter capacitor bank or upon the first failure of an element in a fuseless bank. Having such a sensitive unbalance detection scheme will minimize the probability of having undetected canceling failures that result in detuning of the filter.

c) Arcing faults within the harmonic filter capacitor bank require the bank be removed from service promptly to minimize the damage. As a fault external to a capacitor unit can result in a large change in the filter capacitance and thus significantly detune the filter, the effects of such a fault need to be examined by the filter designer. Although the primary protection in the event of an arcing fault is

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generally the unbalance protection, certain harmonic filter capacitor bank configurations provide no unbalance signal for some faults within the harmonic filter capacitor bank. In these cases, the following may provide protection:

1) Separating the portions of the harmonic filter capacitor bank that, if faulted together, would result in no unbalance signal.
2) Reconfiguring the harmonic filter capacitor bank.
3) Designing the phase overcurrent relaying scheme to protect in the event of such an arcing fault. (Refer to IEEE Std C37.99-2000 for further discussion on this topic.)
4) In order to assure that harmonic voltages or currents do not adversely affect trip or alarm levels, relays for unbalance protection may need to be filtered so that operation is based only on fundamental voltage or current.

6.5.5 Harmonic filter overload protection

Harmonic filters may be subject to overloading from unanticipated harmonic sources, unanticipated resonance, or other contingencies. There are two types of overload protection with which the designer of a filter may be concerned:

a) *Thermal overload.* High harmonic currents can result in thermal overload of filter components such as reactors, resistors, instrument transformers, and fusing and switching devices. Although the capacitor units are typically designed with ample current-carrying capacity, even they can be thermally overloaded if the currents are high enough. The losses internal to a capacitor unit include the following:

   — Dielectric losses
   — I^2R losses of the conductor
   — I^2R losses of any internal fuses
   — I^2R losses of the discharge resistor

   All of these losses are affected by harmonic currents. The heat resulting from the harmonic filter capacitor unit internal losses combined with a high ambient temperature may result in excessive capacitor unit internal temperatures. Refer to IEEE Std 18-2002 for more information on the maximum ambient temperature conditions under which capacitor units may be applied. Refer to the capacitor unit manufacturer for guidance on selecting capacitor units for harmonic filter applications.

   Metal-enclosed harmonic filters, or similar installations, may require forced ventilation to ensure the ambient temperature in the enclosure where the harmonic filter capacitors are mounted does not become excessive. Iron-core harmonic filter reactors are often used in metal-enclosed harmonic filters. If iron-core harmonic filter reactors are used in an enclosed harmonic filter, it is recommended that they be placed above the harmonic filter capacitor units or in a separate compartment. Air-core harmonic filter reactors may be used inside an enclosure with the same consideration as iron-core harmonic filter reactors. However, additional component clearances must be allowed due to the external magnetic fields that are present in air-core harmonic filter reactors.

b) *Voltage overload.* Voltage overload due to excessive harmonic currents is a concern for the harmonic filter capacitor units and the harmonic filter reactors. As harmonic filter reactors are typically designed with robust turn-to-turn insulation, voltage overload is typically not a problem except in cases of dynamic events such as transformer energization.

   Relays that respond to the true rms current can be used to protect harmonic filter reactors and harmonic filter resistors from excessive fundamental and harmonic currents. Other relaying schemes are sometimes used, particularly for installations tuned to several frequencies.

   Harmonic filter capacitor overload protection can be provided by current integration methods to calculate the voltage applied to the capacitors by the fundamental and harmonic currents.

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One method of detecting possible excessive harmonic overloading of metal-enclosed equipment is by the use of temperature relays monitoring the temperature in the enclosure. Note that power capacitors are intended to operate in a maximum ambient temperature of 40 °C, while most other metal-enclosed switchgear can operate in a 55 °C ambient.

6.6 Harmonic filter design procedure

The purpose of this subclause is to illustrate the design process for harmonic filters in a systematic manner showing how the information from the previous subclauses is used. It is not intended that the method for harmonic simulations and modeling be detailed. Other references [e.g., IEEE Std 399-1997 (*IEEE Brown Book*)] provide adequate detail for modeling a power system and performing power frequency and harmonic analysis. Instead, the subclause will focus on the conditions to consider when performing the studies and how the data are used to specify harmonic filtering equipment.

The design of a harmonic filter requires information about the power system and the environment in which the harmonic filter will be installed. This information includes system characteristics such as nominal system line-to-line voltage, typical equipment BIL for the system voltage level, and fundamental frequency. Environmental data such as ambient temperature, wind loading, etc., should be available. The owner should make decisions, such as equipment location (indoor versus outdoor) and operating constraints, before the design begins, as these decisions will affect certain aspects of the design. A clear understanding of the equipment's current duty cycle and switching repetition rates is also important for the design.

Harmonic filter design requires basic information on the power system and the local harmonic generation. This information includes system configurations, impedance of system components (e.g., transformers, lines, sources, capacitors, harmonic filters, shunt reactors), nominal and maximum voltage, load power ratings and power factors, and harmonic generation. Harmonic measurements at the site are the most accurate means of getting harmonic information if the loads are already installed. If not, then the equipment manufacturer should supply the harmonic characteristics.

6.6.1 Step 1: Determine harmonic filter bank kvar size

In addition to harmonic filtering, the filter equipment will provide the system with capacitive reactive power that will improve the power factor and help maintain voltage during heavy loads. The capacitive reactive power requirements for power factor and voltage control generally determine the "effective kvar" size of the harmonic filter. The effective kvar of the harmonic filter is always less than the nameplate kvar of the harmonic filter capacitor because of the subtractive effect of the filter reactor. The rated kvar is calculated in Step 4 of the design process (see 6.6.4).

Power flow programs are often used to determine the capacitive reactive power requirements. The factors that should be considered when performing these studies are explained in 4.1, 4.3, and 4.5. These factors are summarized as

- Number of harmonic filter capacitor steps to be switched
- Range of system voltage variation
- Range of load variation
- Power system configurations—normal and contingency, existing and planned

6.6.2 Step 2: Select initial harmonic filter tuning

Based on the harmonic generation, an initial estimate of the harmonic filter tuning is made. The tuning is usually designed to reduce harmonic voltage and current distortion to meet specified harmonic performance criteria. To meet this objective, the harmonic filter will typically be tuned to the lowest frequency of the most significant harmonics. For example, if the highest harmonic current levels were for the 5^{th} and 7^{th}

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harmonics, a single filter tuned near the 5th harmonic may be sufficient for control of the distortion. Later evaluations with a harmonic analysis program may determine that other harmonic filters are required also.

Harmonic filters are not usually tuned to exact harmonic frequencies. Tuning directly to the harmonic frequency may have two undesirable consequences:

a) The low impedance at resonance can result in nearly all harmonic current at that frequency being absorbed by the harmonic filter. The harmonic filter is required to be larger and more expensive than is needed to achieve the required harmonic performance.

b) The harmonic filter interaction with the system impedances results in a parallel resonance at a frequency just lower than the tuned frequency. If a harmonic filter is designed exactly at the harmonic frequency, a variation in the impedance values of the actual equipment from the design values could retune the harmonic filter and place the parallel resonant frequency very close to the harmonic. Instead of low impedance, the combined harmonic filter-system impedance becomes resonant at the harmonic frequency, distortion levels become unacceptable, and damaging voltage amplification may result in severe cases. Changes in the system supply can shift the parallel resonance also. The most common mechanisms that cause a shift in the resonance are as follows:

    1) *Harmonic filter capacitor unit/element failure.* Externally and internally fused banks have fuses that operate when a unit or element shorts. The fuse operation, which reduces the total capacitance, increases the resonant frequency of the harmonic filter. On the other hand, shorted elements in a fuseless harmonic filter capacitor bank (or in an externally fused harmonic filter capacitor bank prior to fuse operation) are not removed from the circuit. The capacitance rises and the resonant frequency decreases.

    2) *Tolerances.* Manufacturing tolerances in both the harmonic filter reactors and the harmonic filter capacitors, and capacitance change due to temperature variations in the capacitors.

    3) *System variations.* Power system configurations are not static.

        — The loss of one of two parallel transformers or of one of two supply feeders can weaken the source and shift the parallel resonance to a lower frequency.
        — Routine maintenance can often result in a "weakening" of the source supplying the harmonic-producing load.
        — Portions of overhead circuits may be replaced with underground lines, and lines may be relocated.

    These changes will impact the impedance between the source and the load.

It is often advantageous to tune the harmonic filter to approximately 3% to 15% below the desired frequency. This tuning will provide for sufficient harmonic filtering, yet will also provide allowance for the detuning of the harmonic filter.

For some installations with multiple harmonic filters tuned at different frequencies, tuning individual harmonic filters below the harmonic frequency may not be advantageous. Harmonic filter performance across the entire harmonic frequency spectrum at the harmonic filter location under both normal and contingency conditions should be considered.

The reactance of the harmonic filter capacitor is determined by the var size of the harmonic filter. The inductive reactance is selected to create a series resonance with the harmonic filter capacitor at the tuned frequency. The series resonance provides a low impedance path to neutral for the harmonics of the system.

A simple equation to calculate the capacitive reactance (for a filter tuned to the *h* harmonic) at power frequency is Equation (20).

$$X_C = \left(\frac{h^2}{h^2 - 1}\right) X_{eff} \tag{20}$$

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where

$$X_{\text{eff}} = \frac{kV_{\text{LLsys}}^{2}}{Q_{\text{eff}}\ (\text{Mvar})} \tag{21}$$

A simple equation to calculate the inductive reactance at power frequency is Equation (22).

$$X_{\text{L}} = \frac{X_{\text{C}}}{h^2} \tag{22}$$

where

X_{eff} is the effective reactance of the harmonic filter,
Q_{eff} is the effective reactive power (Mvar) of the harmonic filter,
V_{LLsys} is the nominal system line-to-line voltage,
X_{C} is the capacitive reactance of the harmonic filter capacitor at the fundamental frequency,
X_{L} is the inductive reactance of the harmonic filter reactor at the fundamental frequency,
h is the harmonic number.

If the harmonic filter tuning is chosen to be slightly less than the harmonic frequency as suggested, the *h* of Equation (22) will be noninteger. For example, *h* will equal 4.7 for a 5^{th} harmonic filter tuned to 282 Hz on a 60 Hz system.

An alternative objective in harmonic filter tuning may be to avoid harmonics rather than reduce them. This alternative is sometimes used where the harmonic distortion levels are not critical, but the user wants to avoid overloading the harmonic filter capacitor with harmonic currents and avoid creating a harmonic resonance in the power system. In this case, the harmonic filter is ungrounded (to avoid 3^{rd} harmonic resonance with the system) and tuned below the 5^{th} harmonic (i.e., 4.3^{rd} or 4.7^{th}) to avoid resonance at a characteristic harmonic (e.g., 5^{th}, 7^{th}).

6.6.3 Step 3: Optimize the harmonic filter configuration to meet harmonic guidelines

IEEE Std 519-1992 provides guidelines for harmonic distortion limits. The harmonic filter must limit both voltage and current distortion over a range of normal system configurations as well as abnormal conditions. The analysis can be done by hand calculations for simple systems. Usually, however, a harmonic simulation program is required to adequately assess each of the possible operating conditions over the frequency spectrum of the harmonic loads. IEEE Std 519-1992 and IEEE Std 399-1997 provide guidance on performing the required studies.

The harmonic studies will finalize the number of harmonic filters, harmonic filter tuning, and the location of the harmonic filters based on compliance with the harmonic guidelines. The factors that should be considered when performing these studies are summarized as follows (see 4.3 through 4.7 for more information):

a) Number of harmonic filter steps to be switched
b) Outage of a harmonic filter, if more than one harmonic filter is used
c) Range of system voltage variation
d) Range of load variation
e) Power system configurations—normal and contingency
f) Detuning of the harmonic filter by changes in system frequency, range of component manufacturing tolerances, capacitance variation with severe temperatures, and harmonic filter capacitor unit outages
g) Characteristic and uncharacteristic harmonics
h) System background harmonics

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If distortion levels are still too high, it may be because the addition of a harmonic filter has caused a new parallel resonance with the system near one of the lower frequency harmonics. In this case, a retuning of the harmonic filter to the lower harmonic frequency can sometimes be adequate. If it is not, then multiple-tuned harmonic filters may be needed.

The broadness of the tuning can be increased to account for capacitance and inductance deviations by increasing the filter kvar size.

Harmonic analysis can finalize the tuned frequency or frequencies and values of the capacitance(s), inductance(s), and resistance(s) (if needed). Allowable tolerances for capacitance, inductance, and resistance may be established. The Q (X/R ratio) of the harmonic filter reactor at the tuned frequency and the steady-state energy dissipation requirements for the harmonic filter resistors can be determined by the analysis.

An outcome of the analysis will be harmonic spectra for voltage across and the current through each filter component (e.g., capacitor, inductor). A typical harmonic spectrum includes the fundamental and all significant harmonic frequencies. Spectra for normal and contingency conditions are usually included in the results.

6.6.4 Step 4: Determine the component ratings

Once the harmonic filter performance is optimized, the component ratings are determined. The process is sometimes an iterative one requiring adjustments to the harmonic filter design if component standards cannot be met.

Harmonic filter capacitor ratings are usually the first to be determined followed by harmonic filter reactor, harmonic filter resistor, and switch ratings. The harmonic duties used in the rating process should be the highest values determined from Step 3 (see 6.6.3).

Transient simulations may also be desirable to determine component ratings for some harmonic filter designs, particularly where harmonic filters tuned to different frequencies will be connected to the same bus. The effect of transformer energizing is also evaluated in transient simulations.

6.6.4.1 Harmonic filter capacitors

Capacitors are rated by voltage and kvar. These ratings are usually determined by the capacitor manufacturer based on the harmonic spectra, transient overvoltages, var requirements, and system data specified by the user.

Subclause 6.3.1 states that the capacitor voltage rating is determined from the greater of three types of voltage stresses: steady-state (including harmonics), transient (lasting less than half a cycle), and dynamic (lasting up to several seconds). Transient overvoltages are associated with harmonic filter switching and sometimes circuit breaker operations. Transient overvoltages are not usually severe unless multiple harmonic filters with different resonant frequencies are connected to the same bus. In general, dynamic overvoltages can be avoided by not energizing transformers and capacitors simultaneously (see 6.4). See 6.6.4.4 for additional details on switching related overvoltages.

In most single-tuned filter applications, the harmonic filter capacitor voltage rating is based on steady-state duties. The phase-to-neutral voltage rating for the harmonic filter capacitor is calculated using Equation (11) (from 6.3.1).

$$V_{\mathrm{r}} = \sum_{h=1}^{\infty} I(h) X_{\mathrm{C}}(h) \tag{11}$$

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The capacitor voltage ratings should be specified so that the highest peak voltage applied to the harmonic filter capacitors (i.e., fundamental plus harmonics) is not greater than 100% of the peak of the voltage rating of the capacitors. Exception can be made for infrequent contingencies per Item c)3 in 6.3.1. (The rated voltage of the harmonic filter capacitors from this calculation will never be less than the value calculated across the capacitors at maximum bus voltage, including the voltage rise across the harmonic filter reactor.) The voltages across the harmonic filter capacitor (i.e., combined fundamental and harmonic) must be computed from the worst case determined in Step 3 (see 6.6.3). The worst case is generally a contingency case rather than a normal operating condition. In the absence of a digital computer program, a reasonable estimate of the rated line-to-neutral voltage may be obtained by summing just the fundamental frequency voltage and the tuned frequency voltage. See Equation (23) through Equation (25).

$$V_C(1) = I_f(1)X_C \tag{23}$$

$$V_C(h) = I_f(h)\frac{X_C}{h} \tag{24}$$

$$V_r = V_C(1) + V_C(h) \tag{25}$$

where

- $V_C(h)$ is the voltage across the harmonic filter capacitor caused by the harmonic current,
- $I_f(h)$ is the harmonic current,
- $V_C(1)$ is the fundamental frequency voltage across the harmonic filter capacitor,
- $I_f(1)$ is the fundamental frequency current through the harmonic filter capacitor,
- X_C is capacitive reactance at the fundamental frequency.

The approximations in the these equations are based on the fact that in most applications the harmonic filter capacitor voltage is dominated by the fundamental and the harmonic closest to the resonant frequency of the harmonic filter.

The fundamental frequency current, $I_f(1)$, can be calculated by Equation (26).

$$I_f(1) = \frac{V_S}{(X_C - X_L)} \tag{26}$$

where

- V_S is the voltage across harmonic-filter-capacitor–harmonic-filter-reactor circuit,
- X_C is the capacitive reactance at fundamental frequency,
- X_L is the inductive reactance at fundamental frequency.

Tuned frequency current assumes $I_f(h)$ = maximum harmonic current available from the system at the resonant frequency of the harmonic filter (e.g., 5^{th} harmonic).

The fundamental frequency current flowing in the harmonic filter capacitor can be computed easily from Equation (26). The harmonic currents are a part of the design criteria for the harmonic filter (see Annex C). The total rms current in the harmonic filter is calculated by

$$I_{rms} = \sqrt{\sum_{1}^{\infty} I(h)^2} \tag{27}$$

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The total rms current through the harmonic filter capacitor units should be less than 135% of the capacitor unit nominal current based on the rated kvar and the rated voltage. In addition, the current should be kept within the capability of the harmonic filter capacitor fuses. Actually, the current is seldom a limiting factor when the lower order harmonics are involved. It is difficult to exceed the current limitation without exceeding the other limitations unless the harmonic order is high.

The final check in the harmonic filter design is to see that the dielectric heating of the harmonic filter capacitor is acceptable. The dielectric heating is evaluated by the inequality [see Equation (6) in 4.2.2].

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

where

$V(h)$ is the voltage drop (kV) across the harmonic filter capacitor at harmonic number h,

$I(h)$ is the current (A) flowing through the harmonic filter capacitor at harmonic number h,

h is the all harmonics [including the fundamental ($h = 1$)],

Q_{rated} is the the capacitor bank rated kvar, based on nameplate data.

It is important to note that the rated kvar of the harmonic filter capacitor bank is not the same as the effective reactive power of the harmonic filter because of the effect of the reactor.

For continuous duty, it is very desirable to build the harmonic filter with more capability than is required for the identified harmonic loads. Other harmonics on the system will be drawn from the system and may lead to overloading. Some overrating should allow for this overloading. The incremental cost per kilovar of adding capacity for harmonic absorption is much lower than the average cost per kilovar of the harmonic filter. Therefore, a generous margin in specifying the harmonic duty is generally desirable.

The basic information supplied to the harmonic filter capacitor manufacturer should include the specification items listed in 6.3.1.

6.6.4.2 Harmonic filter reactors

Items to include in harmonic filter reactor specifications are listed in 6.3.2. Many of these items are the same as specified for harmonic filter capacitors. In Step 3 of the design process (see 6.6.3), harmonic analysis determined the tuned frequency, inductance, Q (X/R ratio), and the acceptable degree of tolerance in the inductance and Q values for harmonic filter reactor. The fundamental and harmonic current spectra for normal and contingency cases were also determined. Step 4 of the design process involves the following:

a) Determine the location of the harmonic filter reactor physically and electrically with respect to the harmonic filter capacitor. As explained in 6.3.2, the location of the harmonic filter reactor in the circuit influences thermal issues, magnetic flux heating, reactor short-circuit rating, and reactor BIL.

   The heating due to fundamental and harmonic currents in an iron-core harmonic filter reactor should be considered in designing metal-enclosed filters. Excessive heating can lead to component degradation. The effect of eddy current losses induced in surrounding metallic structures by an air-core harmonic filter reactor's magnetic flux must be considered. Heating effects in building structural steel, concrete imbedded steel (rebar), electrical grounding systems, and the equipment frame can be substantial. Additional details are provided in Item g) in 6.3.2 and Item a) in 6.5.5.

   The harmonic filter reactor can be on the source side of the harmonic filter capacitor or the neutral side. If the harmonic filter reactor is located between the bus and the harmonic filter capacitor, it should be rated to withstand a short circuit to ground at the junction between the harmonic filter reactor and the harmonic filter capacitor.

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The BIL rating of the phase-to-ground insulation of the harmonic filter reactor should be similar to the rating of the power transformers connected to the same voltage level. However, a reduction in BIL may be appropriate for a harmonic filter reactor terminal that is connected to ground (solidly grounded harmonic filters). Insulation across the coil may be different from the phase-to-ground insulation. It is designed for the voltage drop (i.e., fundamental frequency and harmonics) and transients across the coil. The coil BIL can be reduced if the coil is protected by a surge arrester connected terminal to terminal. See Item e) and Item g) in 6.3.2.

b) Evaluate the transient and dynamic overvoltages, if necessary. As discussed with the harmonic filter capacitors, switching multiple-tuned harmonic filters and frequent transformer switching can create excessive stresses on the harmonic filter capacitor and the harmonic filter reactor unless these stresses are accounted for in the design. Transient studies may be necessary to determine the magnitude and duration of the overvoltages. Transient studies determine proper arrester protection for reduced BIL designs. Further details are available in 6.6.4.4.

c) Calculate the short-circuit current rating for the harmonic filter reactor. The short-circuit current should be calculated based on the maximum system operating voltage. Both rms symmetrical and crest asymmetrical fault current is needed. The duration of the fault due to tripping delay and circuit breaker interrupting time is also needed. See Item f) and Item g) in 6.3.2.

6.6.4.3 Harmonic filter resistors

Items to include in harmonic filter resistor specifications are listed in 6.3.3. Many of these items are the same as specified for harmonic filter capacitors. If harmonic filter resistors are included in the design, Step 3 of the design process (see 6.6.3) would have defined the resistance, the acceptable resistance tolerance, the maximum allowable series inductance in the resistor and the power rating of the resistor. The fundamental and harmonic current spectra for normal and contingency cases were also determined.

Step 4 of the design process involves the following:

a) Determine the location of the harmonic filter resistor physically and electrically with respect to the harmonic filter capacitor. As explained in 6.3.3, the location of the harmonic filter resistor in the circuit influences thermal issues, resistor short-circuit rating, and resistor BIL.

The heating due to fundamental and harmonic currents in a harmonic filter resistor should be considered in designing metal-enclosed harmonic filters. Excessive heating can lead to component degradation. Animal proofing may be needed for outdoor installations. Additional details are provided in Item g) in 6.3.3.

The location of a harmonic filter resistor in a damped harmonic filter is quite variable depending upon the design. Annex B shows several examples of damped harmonic filters. The harmonic filter resistor should be rated to withstand the maximum short-circuit current that can flow through it during a harmonic filter fault.

The BIL rating requirements may also be affected by the position of the harmonic filter resistor within the harmonic filter as with the reactor. Similar considerations apply.

b) Evaluate the transient and dynamic overvoltages, if necessary. As with harmonic filter reactors, transient studies may be necessary to determine the magnitude and duration of the overvoltages and to design adequate arrester protection, especially if reduced BILs are to be used. Further details are available in 6.6.4.4. Transient studies also determine the resistor energy associated with transient and dynamic overvoltages.

c) Calculate the harmonic filter resistor short-circuit current rating. The shortcircuit should be calculated based on the maximum system operating voltage. Both the rms symmetrical and the asymmetrical fault current are needed. The duration of the fault due to tripping delay and circuit breaker interrupting time is also needed. See Item c) in 6.3.3.

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6.6.4.4 Circuit breaker or switch

Items to include in switchgear specifications are listed in 6.3.4. Step 3 of the design process (see 6.6.3) developed the harmonic current spectra from which the rms continuous current rating can be determined. In Step 4 of the design process, the maximum short-current rating is calculated based on system data. The short-circuit current for the switching device is essentially the bus fault current and is not the same as the short-circuit current for the harmonic filter reactor specification. Although a capacitor switch is not required to interrupt short-circuit current (as opposed to a circuit breaker, which is required to do so), a capacitor switch must be able to handle short-circuit current flow through it for the close-and-latch and momentary requirements.

The capacitive current switching requirement must be based on the worst combination of maximum system voltage, capacitance tolerances, and harmonics. Current transformers and relays must be able to function properly in the presence of harmonics.

As discussed in 6.3.4, filter banks develop a higher recovery voltage across a switch than a shunt capacitor bank. This higher recovery voltage is especially true of 2^{nd} and 3^{rd} harmonic filters in which the dc voltage on the harmonic filter capacitor following interruption is 133% (2^{nd} harmonic) and 112% (3^{rd} harmonic) of nominal power system line-to-neutral voltage. The switchgear manufacturer should be made aware of the additional recovery voltage stress.

6.6.4.5 Switching transients

Back-to-back switching current magnitudes and frequencies are much lower for harmonic filters than for shunt capacitor banks because of the harmonic filter tuning reactor. Consequently, additional current limiting reactors are not needed.

Normally the switching of a single-tuned harmonic filter does not result in any unusual duty to the capacitors or inductors over what would normally be expected in a shunt capacitor bank. However, harmonic filters with several legs may need to be studied for transient performance to assure that there are no unusually high voltages or currents during the initial energization. Restriking during harmonic filter de-energizing can result in particularly high overvoltages across the capacitor and reactor. A transient analysis may be required to determine the switching surge duties.

If the harmonic filter is connected to the system when it is first energized following a system outage, harmonics generated by transformer saturation may lead to short-time overloading of the harmonic filter. If a harmonic filter is not going to be removed automatically during a system outage, it is probably desirable to do a transient study to determine the harmonic filter performance during this event. Similarly, nearby faults that do not cause a system outage but cause a voltage excursion may result in some transformer saturation and a temporary increase in the loading of the harmonic filter. The duty imposed on the harmonic filter by these transients needs to be specified in a way that the proper harmonic filter components can be selected.

These transformer caused overvoltages are frequently referred to as dynamic overvoltages. The saturated transformer core generates low-order harmonic currents (e.g., 2^{nd}, 3^{rd}, 4^{th}, and 5^{th}), which can overload harmonic filters tuned to the same low-order frequencies. The most common source of saturation harmonics is the inrush current associated with transformer energizing. If the harmonic filter is routinely subjected to high inrush harmonic currents from the regular switching of large transformers (often the case in steel mills, see 6.6.6.1.3), then this duty should be included in the specifications.

The transients are not usually easily definable both because of the randomness of the occurrences and because of the decay that occurs over a period of time. Frequently it is desirable to provide the designer with data (such as an oscillogram) from the transient study that gives the worst-case harmonic loading expected during this type of transient along with an identification of the magnitudes of the current by harmonic order at the beginning or worst part of the transient.

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Generally, thus, for design purposes it is desirable to provide current magnitude through each leg of the harmonic filter by harmonic order, both continuously and as a function of time, for the worst-case design basis.

6.6.5 Numerical example

A 30 MVA industrial load is supplied from a 34.5 kV bus. The three-phase fault level at the bus is 10.0 kA rms symmetrical. The load has a power factor of 0.85. It is desired that the power factor be raised to 0.95. The load is a source of harmonic current. The magnitude of the harmonic current suggests that the capacitor should be designed as a harmonic filter.

6.6.5.1 Step 1: Determine filter bank reactive power (var) size

The filter bank size is calculated based on the amount of capacitive compensation needed to raise the power factor from 0.85 to 0.95. IEEE Std 1036-1992 provides load power (kilowatts) multiplying factors for calculating compensating reactive power (kilovar) for simple circuits such as the circuit being considered in this example. Power (kilowatts) can be calculated from the apparent power (kilovoltamperes) by multiplying by the uncompensated power factor. See Equation (28) and Equation (29).

$$Q_{\text{eff}} \text{ (in kvar)} = \text{(multiplying factor)(load power in kilowatts)} \tag{28}$$

$$Q_{\text{eff}} = (0.291)(30\,000 \text{ kVA})(.85) = 7420 \text{ kvar} \tag{29}$$

The load will need a 7.4 Mvar filter bank to raise the power factor to 0.95. The 7.4 Mvar is the "effective" compensation of the filter bank. The addition of the tuning reactor causes the rated reactive power (megavars) of the capacitor to be different from the effective reactive power of the reactor-capacitor combination.

6.6.5.2 Step 2: Select initial filter tuning

The filter will typically be tuned to the lowest frequency of the most significant harmonics. Harmonic filters are often tuned to a frequency approximately 3% to 15% below the selected harmonic frequency. For example, this "5^{th}" harmonic filter will be tuned to about 6% below 300 Hz. This value is 4.7 times the fundamental frequency on a 60 Hz system.

Using Equation (21) (from 6.6.2), the effective impedance of the filter bank is

$$X_{\text{eff}} = \frac{V_{\text{LLsys}}^2 \text{ (kV)}}{Q_{\text{eff}} \text{ (Mvar)}} \tag{21}$$

$$= \frac{(34.5 \text{ kV})^2}{7.4 \text{ Mvar}} = 160.8 \tag{30}$$

Equation (20) and Equation (22) (both from 6.6.2) can be used to calculate the capacitive reactance and the inductive reactance of the harmonic filter at fundamental frequency.

$$X_{\text{C}} = \left(\frac{h^2}{h^2 - 1}\right) X_{\text{eff}} \ \Omega \tag{20}$$

$$X_{\text{C}} = \frac{4.7^2}{4.7^2 - 1} \times 160.8 = 168.4 \ \Omega \tag{31}$$

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$$X_L = \frac{X_C}{h^2}\ \Omega \tag{22}$$

$$X_L = \frac{168.4}{4.7^2} = 7.62\ \Omega \tag{32}$$

where

X_C is the capacitive reactance at fundamental frequency,
X_L is the inductive reactance at fundamental frequency,
h is the harmonic number to which the filter is tuned.

In this example, the value of h is 4.7.

6.6.5.3 Step 3: Optimize filter configuration to meet harmonic guidelines

Once the harmonic filter inductance and capacitance are determined, harmonic analysis can be performed to determine whether the design adequately controls the harmonics to meet the limits. IEEE Std 519-1992 and IEEE Std 399-1997 (*IEEE Brown Book*) provide guidance on performing the required studies. IEEE Std 519-1992 provides guidelines for harmonic distortion limits. If distortion levels are not adequate, the harmonic filter capacitance can be increased, the filter may need to be tuned to a different frequency, or multiple harmonic filters with different resonant frequencies may be needed.

6.6.5.4 Step 4: Determine component ratings

6.6.5.4.1 Capacitors

The voltage rating for capacitors is calculated by Equation (11) (from 6.3.1):

$$V_r = \sum_{h=1}^{\infty} I(h) X_C(h) \tag{11}$$

The worst-case fundamental and harmonic voltages across the capacitors can be calculated from the worst-case current spectrum and the harmonic filter capacitive reactances. All significant harmonics will be included in the calculation of the voltage rating. The fundamental frequency current for a wye-connected harmonic filter is calculated by Equation (26) (from 6.6.4.1).

$$I_f(1) = \frac{V_S}{(X_C - X_L)} \tag{26}$$

$$I_f(1) = \frac{\left(\frac{34.5\ \text{kV}}{\sqrt{3}}\right)}{(168.4 - 7.62)} = 124\ \text{A} \tag{33}$$

where

V_S is the maximum system operating voltage, phase to neutral,
X_C is the capacitive reactance at fundamental frequency,
X_L is the inductive reactance at fundamental frequency.

The estimate of worst-case harmonic current through the harmonic filter is beyond the scope of this guide. See Annex C. The harmonic currents for this example are as follows:

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— 5^{th} harmonic: 60.3 A
— 7^{th} harmonic: 17.3 A
— 11^{th} harmonic: 8.0 A
— 13^{th} harmonic: 6.5 A

Calculate the total rms current and harmonic voltages as follows:

$$I_{rms} = (I_{f1}^2 + I_{f5}^2 + I_{f7}^2 + I_{f11}^2 + I_{f13}^2)^{1/2} \text{ A} \tag{34}$$

$$I_{rms} = (124^2 + 60.3^2 + 17.3^2 + 8.0^2 + 6.5^2)^{1/2} = 139.3 \text{ A} \tag{35}$$

$$V_C(1) = I_f(1)X_C \text{ V} \tag{36}$$

$$V_C(1) = 124 \times 168 = 20\ 832 \text{ V} \tag{37}$$

$$V_C(h) = \sum_h I_f(h)\left(\frac{X_C}{h}\right) \text{ V} \tag{38}$$

$$V_C(h) = 60.3 \times \frac{168}{5} + 17.3 \times \frac{168}{7} + 8.0 \times \frac{168}{11} + 6.5 \times \frac{168}{13} = 2647 \text{ V} \tag{39}$$

Note that the individual harmonic voltages on the capacitor unit are (60.3 × 168 ÷ 5) or 2026 V rms 5^{th} harmonic, 415.2 V rms 7^{th} harmonic, 122.2 V rms 11^{th} harmonic, and 84.0 V rms 13^{th} harmonic.

$$V_r = [V_C(1) + V_C(h)] \text{ V} \tag{40}$$

$$V_r = (20\ 832 + 2647) = 23\ 479 \text{ V} \tag{41}$$

The voltage rating is greater than the rating required for a shunt capacitor bank applied to the same system because of the 60 Hz voltage rise across the tuning reactor and the harmonic voltage resulting from the harmonic current. Although IEEE Std 1036-1992 allows for continuous operation of the capacitor at a voltage 110% above the rms-rated voltage and 120% above the peak of the rated voltage, these margins should be reserved for contingency operation. Consequently, the design for the harmonic filter rates the capacitor voltage at 100% of the most severe operating condition.

Based on the line-to-line rated voltage of the harmonic filter capacitor and the impedance of the harmonic filter capacitor bank, the rated three-phase Mvar of the capacitor bank is

$$Q_{rated} = \frac{(\sqrt{3}V_r)^2}{X_C} \tag{42}$$

where
Q_{rated} is the three-phase rating of capacitor bank (Mvar),
X_C is the impedance of capacitor bank, per phase, (Ω).

$$Q_{rated} = \frac{(\sqrt{3} \times 23.479)^2}{168.4} = 9.82 \text{ Mvar} \tag{43}$$

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This value is significantly greater than the required effective reactive power (megavars) calculated at the beginning of the example (7.4 Mvar, in 6.6.5.1). The reason is that the capacitor voltage rating is higher than nominal system voltage as explained previously.

The nominal capacitor current based on rated voltage and rated kvar is calculated to be

$$I_{\text{nom}} = \frac{Q_{\text{rated}}\ (\text{kvar})}{\sqrt{3}\ V_{\text{rated}}\ (\text{kV})} \tag{44}$$

$$I_{\text{nom}} = \frac{(9.82\ \text{Mvar} \times 1000)}{\sqrt{3} \times (\sqrt{3} \times 23.5\ \text{kV})} = 139.3\ \text{A} \tag{45}$$

The actual rms current that will flow in the harmonic filter was calculated in Equation (35) as 139.3 A.

Based on IEEE Std 1036-1992,[18] the total rms current through the harmonic filter capacitor units should be less than 135% of the capacitor unit nominal current based on rated kvar and rated voltage. The nominal current for the sample design is 139.3 A rms. The I_{rms}, current duty, with harmonics is 139.6 A rms. Therefore, the current duty is 100.2% of nominal current and meets the IEEE Std 1036-1992 requirement.

The final check in the harmonic filter design is to see that the dielectric heating of the harmonic filter capacitor is acceptable. The dielectric heating is evaluated by the inequality in Equation (6) from (4.2.2):

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

To compare against the three-phase rating of the capacitor bank, the left-hand side of the inequality is multiplied by three.

$$|3 \times (20.8 \times 124 + 2.0 \times 60.3 + 0.4 \times 17.3 + 0.1 \times 8.0 + 0.1 \times 6.5)| \le |1.35 \times 9820| \tag{46}$$
$$8124 \le 13\ 257$$

The inequality is satisfied with substantial margin, the dielectric heating of the proposed design is satisfactory.

It appears that the harmonic filter capacitor is conservatively designed and meets all requirements. Additional capability can be built in to handle other harmonics on the system from unidentified sources that will be drawn to the harmonic filter and could otherwise lead to overloading. Also, as additional loads are added in the area, the new harmonics will be drawn to the low impedance of the filter and may lead to harmonic overloading. Some overrating should be built into the design to allow for this contingency. The incremental cost per kilovar of adding capacity for harmonic absorption to a harmonic filter is much lower than the average cost per kilovar of the harmonic filter. Therefore, a generous margin in specifying the harmonic duty is generally desirable.

6.6.5.4.2 Harmonic filter reactors

In this example, the reactance has already been calculated (7.62 Ω). The harmonic current spectrum was also previously calculated. The short-circuit current at the bus was given as 10 kA. However, this value is not the short-circuit current rating of the harmonic filter reactor. The symmetrical short-circuit current for the harmonic filter reactor is calculated based on the harmonic filter reactor impedance in series with the source impedance (when the harmonic filter reactor is mounted on the source side of the harmonic filter capacitor). The source impedance is as follows:

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

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$$X_S = \frac{\left(\frac{V_{\text{ll nom}}}{\sqrt{3}}\right)}{I_{\text{SCBUS}}} \tag{47}$$

$$X_S = \frac{\left(\frac{34.5\ \text{kV}}{\sqrt{3}}\right)}{10\ \text{kA}} = 1.99\ \Omega \tag{48}$$

where

$V_{\text{ll nom}}$ is the nominal system line-to-line voltage,
I_{SCBUS} is the available short-circuit current at the bus.

The symmetrical short-circuit rating of the harmonic filter reactor is

$$I_{SC} = \frac{\left(\frac{V_{\text{ll nom}}}{\sqrt{3}}\right)}{X_S + X_L} \tag{49}$$

$$I_{SC} = \frac{\left(\frac{34.5\ \text{kV}}{\sqrt{3}}\right)}{1.99 + 7.63\ \Omega} = 2.07\ \text{kA} \tag{50}$$

The harmonic filter reactor symmetrical short-circuit rating must be at least 2.07 kA. The fault duration will depend upon protective relaying and circuit breaker operating times. The asymmetrical short-circuit rating can be calculated based on the X/R ratio of the system. The Q of the harmonic filter reactor is usually above 50. The exact number is not critical in many designs. Digital simulations (Step 3 of the design process; see 6.6.3) may be used to assess the sensitivity to the value.

6.6.5.4.3 Circuit breaker or switch

The short-circuit current for the switching device is essentially the bus fault current (10 kA) and is not the same as the short-circuit current for the harmonic filter reactor specification. Although a capacitor switch is not required to interrupt short-circuit current (as opposed to a circuit breaker, which is required to do so), it must be able to handle short-circuit current flow through it for the close-and-latch and momentary requirements.

The capacitive current switching requirement must include consideration for the worst combination of maximum system voltage, capacitance tolerances, and harmonics.

6.6.6 Specific filter application information

6.6.6.1 Arc furnaces

6.6.6.1.1 General

Arc furnace installations employ various types of harmonic filters based on a variety of application objectives. Arc furnaces operate around a power factor of 0.7 to 0.85 lagging and require reactive compensation to correct the power factor. In order to apply power factor correction to a furnace circuit, capacitor banks are generally applied in single-tuned passive harmonic filter configurations. The harmonic filters will improve the circuit power factor and mitigate harmonics generated by the arc furnace and static var compensator (SVC) equipment that might have been installed to control voltage flicker. The result is improved power factor and a reduction in harmonic distortion levels. In addition to the harmonic filters applied on the arc

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furnace circuit, the rolling mill of the steel manufacturing facilities will also employ harmonic filters to improve power factor and also to mitigate the harmonics generated by the drive systems in the rolling mill.

The design of the harmonic filters will require knowledge of the actual harmonics generated by the furnaces. In most applications, multiple harmonic filters are needed. They can be designed based on the harmonic duty at the filter installation location. The total amount of reactive compensation needed from the filters can be divided into a number of filters based on the percent harmonic current. The tuned frequencies and the number of filters needed are usually based on the plant operating objectives, such as power factor requirements, harmonic limits, voltage flicker limits, SVC limits, etc.

The harmonic filters used in arc furnace applications are typically connected permanently to the furnace circuit. Some installations employ a switching scheme where the harmonic filters will be switched based on the furnace loading.

6.6.6.1.2 Harmonic sources in arc furnace applications

A variety of different arc furnace types are utilized by steel manufacturers based on the plant production. They can be generally divided into two main types: ac furnaces and dc furnaces. Large steel manufacturers use ac furnaces. These ac furnaces can be scrap furnaces or ladle furnaces. The scrap furnaces generate the most significant amount of harmonics, and these furnaces are generally large. The ladle furnaces also generate harmonics, but are less severe compared to the scrap furnaces. Large steel manufacturers also use the dc furnaces, and they are a popular application now. The dc furnaces are typically 12-pulse types, and they can be operated as 6-pulse systems. There are also dc furnaces that are higher pulse order, such as 48 pulse, and they can operate as various lesser pulse systems in abnormal conditions. The principal harmonics generated by the dc furnaces are the typical $h = p \pm 1$ harmonics, where the magnitude of each harmonic is approximately the fundamental current divided by the order of the harmonic $[I(h) \approx I(1)/h]$. Both ac and dc arc furnaces also generate some level of noncharacteristic and interharmonics that must also be addressed or accounted for in the design of the harmonic filters. The presence of noncharacteristic harmonics and interharmonics suggest that it may be necessary to control the parallel resonance modes at those frequencies to avoid excessive amplifications of harmonics, which may produce visible flicker from beating frequencies.

6.6.6.1.3 Arc furnace transformer energizations

Another common harmonic source in an arc furnace installation is the energization of the arc furnace transformer, typically 50 to 100 times a day. Although a transformer energization is a quasi-transient event, it could last from as short as 20 cycles to as long as minutes based on the circuit. These energizations events result in inrush currents that are rich in harmonics. The furnace transformer energization inrush currents should also be considered as a primary source of harmonics when evaluating harmonic filter component ratings.

6.6.6.1.4 Harmonic filter types

The harmonic filter types used are generally based on the arc furnace type. In some applications, other objectives, such as minimizing the total harmonic voltage distortion at the point of common coupling, could also be a factor in the type of harmonic filters used. It should also be noted that some installations would have combinations of furnace types (e.g., ac-scrap, ac-ladle, dc) connected at the same bus. In this case, the overall system should be evaluated for the most effective harmonic filtering scheme. Double-tuned harmonic filters are also used in some applications.

a) *AC arc furnaces—scrap furnaces and ladle furnaces.* The scrap furnaces employ 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} harmonic filters. Based on the installation, any combination of these filters can be found. The lower order harmonic filters, mainly the 2^{nd} and the 3^{rd} harmonic filters, have to be sized to absorb the furnace transformer energization inrush currents and the resulting overvoltages in addition to the

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steady-state arc furnace arcing conditions. The harmonic filters are generally passive, single-tuned, shunt filters. More complex dual frequency and C-type harmonic filters are also employed.

b) *DC arc furnaces.* The dc furnaces employ 5^{th}, 7^{th}, and 11^{th} harmonic filters as a minimum to filter the harmonics generated by the rectification. Due to the harmonics generated by the arcing process, 2^{nd}, 3^{rd}, and/or 4^{th} harmonic filters are frequently used. The harmonic filters are generally passive, single-tuned, shunt filters. More complex harmonic filters tuned to multiple frequencies are also employed.

6.6.6.1.5 Harmonic filter ratings

The harmonic filter ratings should be evaluated based on various operating conditions. The conditions that the harmonic filter should withstand include the following:

a) *No load condition.* This condition is when the harmonic filter is connected to the system with the arc furnace not operating. The bus voltage will increase, and the increased bus voltage will increase the harmonic filter current. In this case, it can be assumed that the harmonic currents are reduced because the arc furnace is off line.

b) *Worst-case steady-state arcing condition.* The most unstable arcing, with the greatest harmonic generation, occurs at the beginning of the melt cycle, when the arcing is to unmelted scrap. During a typical melt cycle, which normally lasts approximately 1 hr, the furnace is charged (i.e., scrap metal is added) twice. Each time the worst-case steady-state arcing (bore-in) lasts approximately 5 min to 15 min, depending on numerous variables. The harmonic filter should be able to withstand the harmonic currents absorbed due to this condition.

c) *Momentary condition for furnace transformer energizations.* This condition is the most limiting, especially when lower order harmonic filters (e.g., 2^{nd}, 3^{rd}, 4^{th}) are present. The harmonic filter should be rated to handle this condition.

d) *Switching the circuit breaker or vacuum switch.* The harmonic filter should be able to withstand the transients created by these switching events.

e) *Back-to-back switching of harmonic filters on the same bus.* The transients created by harmonic filters (or capacitor banks) switched on the same bus should be evaluated. The harmonic filter should be able to withstand these transients, which are not a concern in switching harmonic filters due to the inductance of the harmonic filter reactors.

6.6.6.2 Steel rolling mills

The rolling mill of a steel manufacturing facility will typically include a variety of 6-pulse and 12-pulse drive systems. The harmonics generated by these drive systems are typically the $1/h$ type harmonics.

The rolling mills typically employ 5^{th}, 7^{th}, and 11^{th} harmonic filters as a minimum. The harmonic filters are generally passive, single-tuned, LC shunt filters. More complex harmonic filters tuned to multiple frequencies are also employed. Some installations will also have lower order harmonic filters installed.

Some rolling mills utilize cycloconverters instead of traditional 6-pulse or 12-pulse drives. A cycloconverter may produce typical $1/h$ harmonics at times, but also produces interharmonics. Harmonic filter design must accommodate both $1/h$ harmonics and interharmonics.

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Annex A

(informative)

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Annex B

(informative)

Harmonic filter types

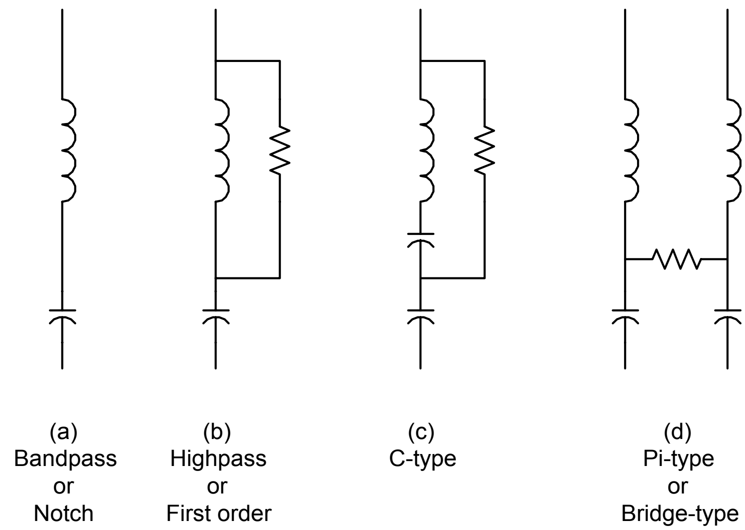

Figure B.1—Commonly applied harmonic filter types

a) The band-pass harmonic filter is the simplest type and widely applied. Its advantage is almost zero impedance at the resonant frequency, yielding almost perfect filtering at this frequency. A drawback is the high value of parallel resonance with the network at some frequency below the tuning point, which may seriously amplify other harmonics, possibly creating a new harmonic problem. It has poor filtering of harmonics much above the tuning point.

b) The high-pass harmonic filter can be an effective compromise between filtering a target frequency and all others above it. It is typically suitable for tuning at 7^{th} or 11^{th} harmonics and higher, and also can effectively dampen high frequency notch-type oscillations. The selection of the resistor can also be adjusted to dampen lower order parallel resonance. The resistor may consume substantial fundamental power; therefore, it is not usually applied at or below the 5^{th} harmonic (see C-type filter).

c) The C-type harmonic filter has very similar performance characteristics to the high-pass harmonic filter, with the advantage that the resistor consumes no fundamental losses at the nominal parameters. For this reason, it is mainly applied where substantial damping is required on filters tuned at or below the 5^{th} harmonic. It is often used in electric arc furnace or cycloconvertor applications to avoid amplifying low-order and noninteger harmonics.

d) The Pi-type harmonic filter is essentially two band-pass harmonic filters tied at the midpoints with a resistor. The main advantage of this harmonic filter is good filtering performance at both resonant frequencies, with very good parallel resonance damping. Typically the resistor can have a lower power rating than a high-pass or C-type harmonic filters. It can sometimes save one resistor as compared to installing two high-pass or C-type harmonic filters. A restriction is that the two harmonic filter legs must be switched as one filter group.

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Annex C

(informative)

Estimating harmonic filter currents

The estimation of harmonic filter currents is not a part of this guide. For the selection of components for a harmonic filter, the harmonic currents in the harmonic filter are provided by a harmonic analysis of the electrical system where the harmonic filter will be applied.

For purposes of illustration, one simple estimate will be shown in this annex and will provide the inputs for the numerical example in 6.6.5.

Where three-phase (6-pulse) rectifiers dominate the harmonic generation, the harmonic currents generated by the rectifiers can be estimated as follows. The principal harmonics generated are 5^{th}, 7^{th}, 11^{th}, 13^{th}, and so on (6 ± 1, 12 ± 1, and so on). These harmonics are common for adjustable-speed drives.

The amount of current generated at each harmonic is estimated as a fraction of the fundamental current to the rectified load. The 5^{th} harmonic current is estimated as 1/5 of the fundamental current, the 7^{th} harmonic is 1/7 of the fundamental current, the 11^{th} is 1/11 of the fundamental, etc.

Usually harmonics higher than the 11^{th} are not calculated for this type of system, where a simple harmonic filter tuned to the 4.7^{th} harmonic is used. The contribution of higher order harmonics to the design of the filter is negligible.

The harmonic currents generated by the rectified load do not all flow through the harmonic filter. Some will be absorbed by parallel load and some will go into the utility source. The worst case for the harmonic filter design is with negligible parallel load and a high impedance (low fault current) source, so that most of the current will flow through the harmonic filter.

Consider the circuit in Figure C.1, which ignores the parallel load.

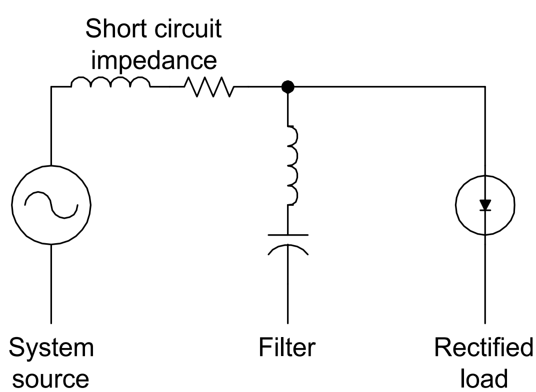

Figure C.1—Simple circuit for estimating harmonic filter harmonic currents

An analysis of this circuit can be used to estimate how much of the harmonic current (at each harmonic) will flow through the harmonic filter and how much will go through the source.

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The system source short-circuit impedance is determined at the bus where the harmonic filter will be installed. The short-circuit impedance of interest is the highest (lowest short-circuit current) that will occur during a contingency when the plant is still operating, considering possible changes in the utility source configuration, single versus paralleled source transformers, etc.—anything that will affect the source impedance. The usual short-circuit diagram only shows the maximum short-circuit current, which is important for equipment selection and short-circuit coordination, but not for harmonic filter design.

The effective rating of the filter (kilovars) is determined by the system requirements for voltage support, elimination of power factor penalty, etc.

The rated current of the rectifier load should be generously overestimated to account for possible additions to the plant and for other sources of harmonic current on the electrical system that may contribute harmonic current to the harmonic filter.

The harmonic currents generated by the rectified load are estimated as indicated near the beginning of this annex (e.g., $1/5^{th}$ for the 5^{th} harmonic). Using these harmonic currents and the parallel impedance of the filter and source, the harmonic voltage may be estimated at each harmonic order (voltage = current × impedance).

Using the harmonic voltage and the harmonic filter impedance at a given harmonic, the harmonic current through the harmonic filter at that frequency may be estimated.

Figure C.2 presents a spreadsheet that illustrates these calculations.

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Harmonic current estimate

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11:43 AM

			Harmonic order			
System	**Fundamental**		**5th**	**7th**	**11th**	**13th**
System voltage	34.5	kV (phase to phase)				
Short circuit current	10	kiloamperes				
Impedance	1.992	Ohms				
X/R ratio	10					
System reactance	1.982	Ohms				
System resistance	0.198	Ohms				
Filter						
Size	7420	rated kvar				
Current	124.2	Amperes				
Impedance	160.4	Ohms	4.4	29.2	68.4	86.0
Tuning	4.7	Harmonic order				
Capacitive reactance	168.0	Ohms	33.6	24.0	15.3	12.9
Inductive reactance	7.6	Ohms	38.0	53.2	83.7	98.9
Rectified load						
Total including factor of safety	30000	kva				
Current	502.0	Amperes	100.4	71.7	45.6	38.6
System						
Parallel impedance		Ohms	3.07	9.45	16.61	19.92
Voltage (line to ground)	19918.6	Volts	308.0	677.9	758.1	769.2
Filter Harmonic current		Amperes	69.6	23.2	11.1	8.9
Total harmonic voltage	1311.7	Volts (rms)				
Voltage THD	6.59	Percent				

Figure C.2—Spreadsheet illustrating estimated harmonic current

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