Guide for Applying Harmonic Limits on Power Systems

P519A/D5
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Prepared by the P519A Task Force

of the

Harmonics Working Group (IEEE PES T&D Committee)
and SCC22 - Power Quality

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1. INTRODUCTION AND SCOPE

IEEE Standard 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, provides procedures for controlling harmonics on the power system along with recommended limits for customer harmonic injection and overall power system harmonic levels. This document provides example applications of the procedures and limits in IEEE 519-1992.

The following are specific objectives for this guide:

1. Provide general harmonic evaluation procedures for different classes of customers (industrial, commercial, residential) and for the application of equipment on the utility system.

2. Illustrate methods for evaluating harmonic levels at the point of common coupling (PCC). Examples should illustrate the concepts of the PCC, direction of harmonic current flow, the average maximum demand load current, the short circuit ratio (SCR), and the total demand distortion (TDD).

3. Provide examples of measurement procedures for evaluating harmonic voltages and currents at the PCC. The measurement procedures should address the time variations and the statistical characteristics of the harmonic levels.

4. Illustrate evaluation of harmonic levels for existing and new customers.

5. Illustrate methods of harmonic control at the customer level and on the utility system. Describe possible concerns for filter applications and possible interaction with other customers.

2. REFERENCES

[1] IEEE 519-1992.

[2] IEC 1000-2-2

[3] IEC 50(161)(1990) - International Electrotechnical Vocabulary, Chapter 161: Electromagnetic Compatibility.

[4] IEEE STD 100-1992, IEEE Standard Dictionary of Electrical and Electronic Terms (ANSI).

[5] IEC Task Force Publication on Harmonic Limits for Medium Voltage Customers

[6] 'Application of Steady-State Harmonic Limits to the Time-Varying Measured harmonic Distortions' by Wilsun Xu, December 1993.

[7] IEC 1000-4-7 or 1000-4-13. Harmonic measurement guidelines.

[8] Effect of different sampling durations on the harmonic statistics. Con Ed paper from IAS meeting or similar reference.

[9] IEEE/ANSI C57.110. Transformer harmonic limits.

[10] PQA 95 paper on active filters

[11] B. Banerjee et al, "Design of an Active Series/Passive Parallel Harmonic Filter for ASD Loads at a Wastewater Treatment Plant," PQA 92, Atlanta, 1992.

[12] R.A. Adams, et. al., "Power Quality Issues Within Modern Industrial Facilities, " IAS Textile Film and Fiber Meeting, Atlanta, GA., 1990.

[13] L. Tang, et al., "Voltage Notching Interaction Caused by Large Adjustable Speed Drives on Distribution Systems with Low Short Circuit Capacities, " 1995 IEEE PES Summer Power Meeting.

[14] R. Zavadil, et al., Commercial facility harmonic paper, PQA 91, Paris.

[15] IEC 1000-3-2.

[16] Draft version of IEC 1000-3-4.

[25] Rory Dwyer paper on harmonic simulation techniques.

[26] Transmission SVC harmonic control

[27] Arc furnace SVC harmonic control

[28] Distribution system harmonic control, Dugan, et al

[29] Mack Grady, et al, Optimizing Active Filter sizes and locations on distribution systems

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3.0 BACKGROUND

3.1 Basic Responsibilities

Harmonics are created by nonlinear loads and devices on the power system. There are a wide variety of devices that generate harmonics and they can be connected to the power system at any voltage level. The one line diagram in Figure 3.1 provides a conceptual system illustrating the interconnection of different harmonic-producing devices on the power system. The procedures outlined in IEEE 519-1992 are designed to limit harmonic currents from individual customers and equipment so that harmonic voltage levels on the overall power system will be acceptable. The approach involves a divided responsibility between the customer and the utility.

1. **The customer**. For individual customers, the revised standard limits the level of harmonic current injection at the point of common coupling between the customer and the utility. Recommended limits are provided for individual harmonic components and for the Total Demand Distortion (TDD). These limits are expressed as a percentage of the customer's demand current level, rather than as a percentage of the fundamental, in order to provide a common basis for evaluation over time.

2. **The utility**. The utility system is the transmission and/or distribution system that serves multiple customers. The utility is responsible for the voltage distortion at the point of common coupling. For most systems (below 69 kV), the Total Harmonic Distortion (THD) should be less than 5%. This means that the utility must make sure that system resonance conditions do not result in unacceptable voltage distortion levels, even if all customers are within the recommended guidelines for harmonic current generation.

Figure 3.1.1
Illustration of the variety of nonlinear loads connected at different levels of the power system (conceptual diagram only).

3.2 IEEE 519 Application Concerns

In applying the recommendations of IEEE 519-1992, many questions have come up requiring interpretation. The examples presented in this guide are meant to illustrate some of these application concerns and possible approaches for resolving them. Some of the more important concerns addressed in the examples include the following:

- Selecting the point-of-common-coupling.
- Measurement methods, problems, limitations.
- Calculation and simulation methods.
- Assumptions for harmonic studies (background harmonic levels, system impedance characteristics)
- Impacts experienced due to harmonic distortion (Effects of harmonics).
- Calculating the customer demand current (changing load characteristics, energy conservation impacts, power factor correction impacts).
- Power factor correction considerations (evaluating limits, resonance concerns, measurement considerations, direction of harmonic flows).
- Effect of unbalanced harmonic generation.
- Evaluating the time-varying characteristics of harmonics (design stage, measurements).
- Evaluating non-integer harmonic components (cycloconverters, arc furnaces).
- Application of multi-pulse systems.
- Applying limits for small customers and in cases with large numbers of harmonic generating customers (e.g. residential).
- Cost of Problems/Cost of Solutions (Cost/Benefit Analysis).

3.3 The Harmonic Limits

The most important concepts to be illustrated involve the evaluation of harmonic current limits at individual customers and harmonic voltage limits on the overall system. These limits are typically evaluated at the point of common coupling (PCC) between the supplier and the customer (see Section 3.4).

3.3.1 Voltage Distortion Limits

The utility is responsible for maintaining the quality of voltage on the overall system. Table 3.3.1 summarizes the voltage distortion guidelines for different system voltage levels.

Table 3.3.1
Harmonic voltage distortion limits
in % of nominal fundamental frequency voltage.

Bus Voltage at PCC (V_n)	**Individual Harmonic Voltage Distortion (%)**	**Total Voltage Distortion - THD_{Vn} (%)**
$V_n \le 69kV$	3.0	5.0
$69kV < V_n \le 161kV$	1.5	2.5
$V_n > 161kV$	1.0	1.5

$$THD_{V_n} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_n} \times 100\%$$

where:

V_h = magnitude of individual harmonic components (rms volts)
h = harmonic order
V_n = nominal system rms voltage (rms volts)

Note that this definition is slightly different than the conventional definition for total harmonic distortion, which expresses the distortion as a function of the fundamental frequency voltage magnitude at the time of the measurement. The definition used here allows the evaluation of the voltage distortion with respect to fixed limits rather than limits that fluctuate with the system voltage. A similar concept is applied for the current limits.

3.3.2 Current Distortion Limits

The harmonic currents from an individual customer are evaluated at the PCC where the utility can supply other customers. The limits are dependent on the customer load in relation to the system short circuit capacity at the PCC. Note that all current limits are expressed as a percentage of the customer's *average maximum demand load current.*

Table 3.3.2
Harmonic current distortion limits (I_h) in % of I_L

$V_n \le 69kV$						
I_{sc} / I_L	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	*TDD*
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
$69kV < V_n \le 161kV$						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4.0
50-100	5.0	2.25	2.0	1.25	0.35	6.0
100-1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_n > 161kV$						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≤ 50	3.5	1.75	1.25	0.5	0.25	4.0

* All power generation equipment applications are limited to these values of current distortion regardless of the actual short circuit ratio I_{SC}/I_L.

The following notes are provided for the harmonic current limits in Table 3.3.2. Some of these notes are the topic of further discussion in this application guide. A few very brief comments are provided in italics with the notes themselves.

Notes to current distortion limits:

- I_{SC} is the short circuit current at the point of common coupling. *The question of what system conditions to use for this calculation often arises. Generally, the normal system conditions that result in minimum short circuit capacity at the point of common coupling should be used since this results in the most severe system impacts. It is not recommended that contingency conditions that should be very rare be used to apply the current limits, although they may need to be evaluated to make sure severe problems are avoided during these conditions.*
- I_L is the maximum demand load current (fundamental frequency component) at the point of common coupling. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated. *The information needed for this calculation is often not available (e.g. a new customer). In these cases, some estimate of the maximum load current must be used based on the predicted load profiles.*
- The tables of individual harmonic component limits apply to the odd harmonic components. Even harmonic components are limited to 25% of the limits in the tables. *It is usually not necessary to apply this 25% limit to even harmonics unless the application of harmonic filters results in a resonance that magnifies one of the even harmonics and causes unacceptable voltage distortion levels.*
- Current distortion which results in a dc offset is not allowed.
- Total Demand Distortion (*TDD*) is defined as:

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

  where:

  I_h = magnitude of individual harmonic components (rms amps)
  h = harmonic order
  I_L = maximum demand load current (rms amps) defined above

- If the harmonic producing loads consist of power converters with pulse number (q) higher than six, the limits indicated in the table are increased by a factor equal to

$$\sqrt{\frac{q}{6}}$$

  provided that the magnitudes of the non-characteristic harmonics are less than 25% of the limits specified in the table.

3.4 Point of Common Coupling Assumption

The current limits in IEEE 519-1992 were meant to be applied at the point of common coupling (PCC) between the utility system and multiple customers. In other words, the PCC is the location where another customer can be served from the system. The standard allows for the same procedure to be applied by the customer at other locations within a facility but different current limit values could apply in these cases. Unless otherwise noted in this document, it is assumed that the PCC is the location on the system where another customer can be served.

The PCC can be located at either the primary or the secondary of a supply transformer depending on whether or not multiple customers are supplied from the transformer. Figure 3.4.1 illustrates the two possibilities. Note that when the high side of a supply transformer is the PCC, current measurements for verification can still be performed at the transformer low side. Low side measurements can be used (at a metering location, for instance) and the results referred to the transformer high side by the turns ratio of the transformer, keeping in mind the effect of the transformer connection on the zero sequence harmonic components (see Section 4.3.1). For instance, a delta-wye transformer will not allow zero sequence components to flow from the secondary to the primary system (they will be trapped in the primary delta winding). Therefore, zero sequence components measured on the secondary side would not be included in the evaluation for a PCC on the primary side. Sometimes, if the utility owns the stepdown transformer, a secondary side PCC is used to help limit the harmonic currents that the transformer must withstand. In this case, the harmonics can be evaluated at the transformer secondary but the short circuit ratio (SCR) should be calculated at the primary side PCC.

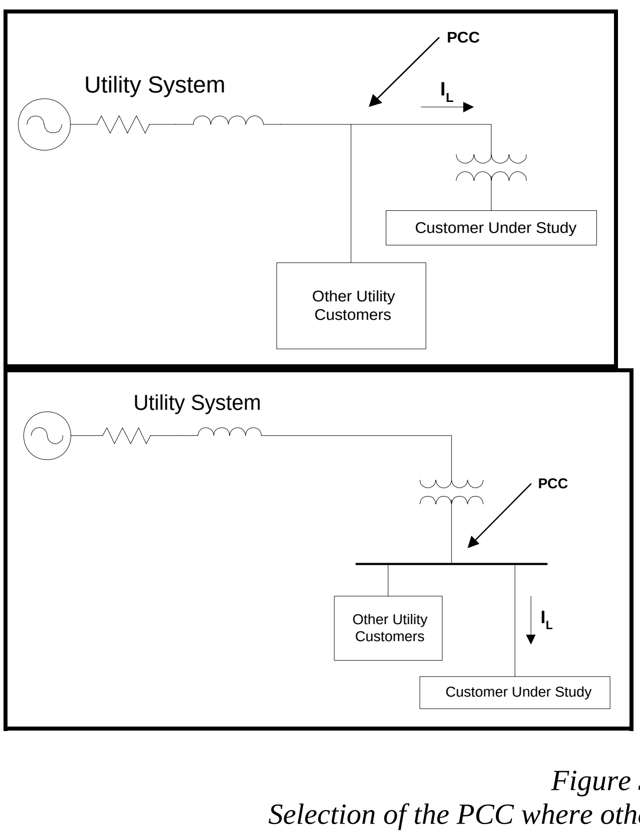


Figure 3.4.1.
Selection of the PCC where other customers can be supplied.

4.0 GENERAL PROCEDURE FOR APPLYING HARMONIC LIMITS

The general procedure for applying harmonic limits involves characterizing the harmonic sources, evaluating the impact on the system, and implementing methods for harmonic control, if necessary. This must be a cooperative effort of all the parties involved in the problem. Most importantly, it will usually involve the electric utility and the customer. Through the customer, the manufacturer of equipment that generates harmonics will also be involved in the evaluation.

4.1 General Evaluation Procedure

It is unrealistic to perform a detailed evaluation of every customer with respect to harmonic concerns. These evaluations can be limited to facilities that have installed or are installing equipment that has nonlinear characteristics (e.g. adjustable speed drives, converters, induction furnaces, arc furnaces, etc.). It is useful to develop some rules for an initial evaluation stage that would allow for acceptance of most customers without detailed measurements or calculations. A general two stage procedure for evaluating customer harmonic injection is illustrated in Figure 4.1.1.

The evaluation requirements of the two stages are described in more detail below.

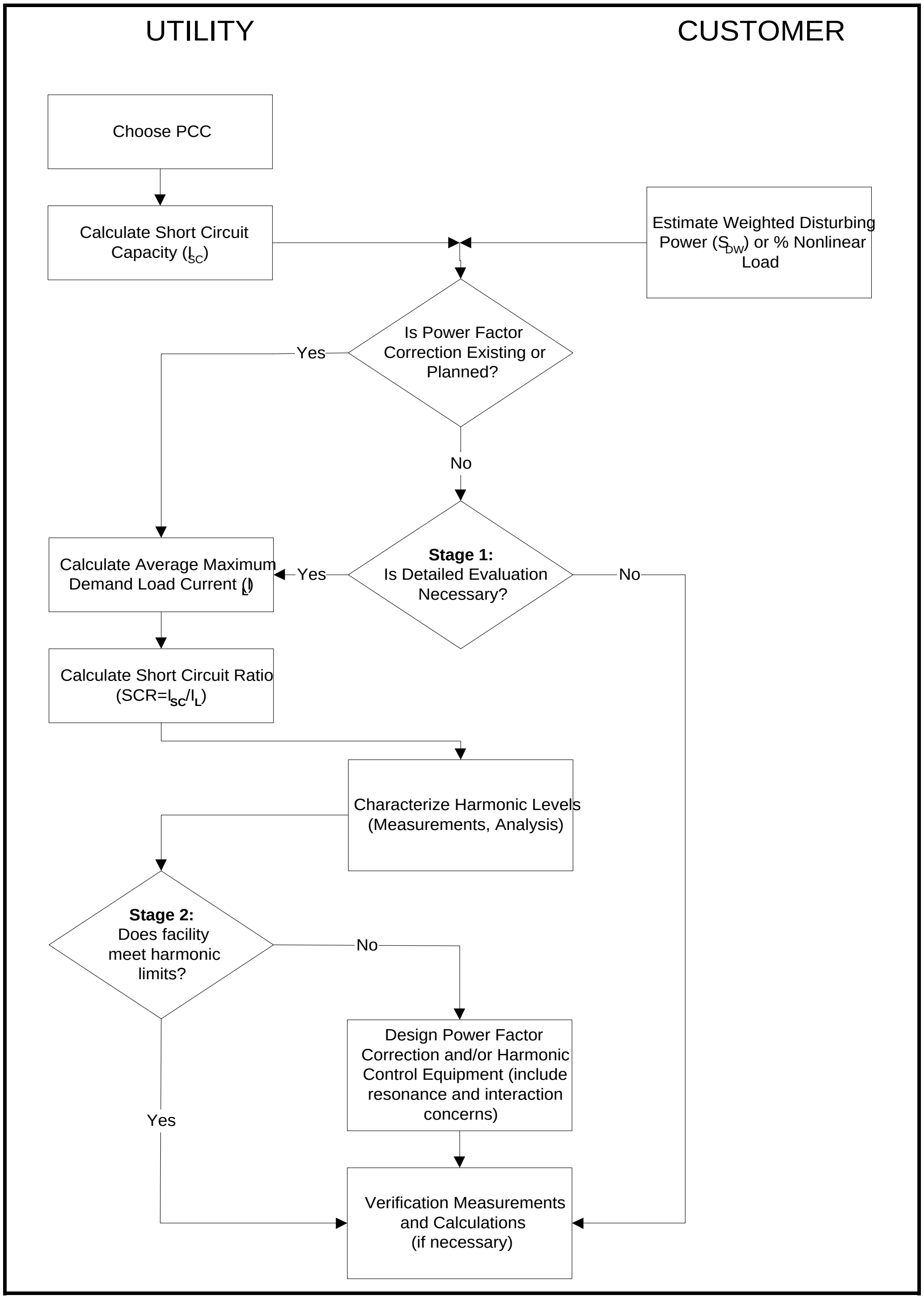


Figure 4.1.1.
General procedure for harmonic limit evaluations.

4.1.1 Stage 1: Automatic Acceptance

In Stage 1, harmonics from small customers or customers with only a limited amount of disturbing load can be accepted without detailed evaluation of the harmonic generating characteristics or the supply system response. One approach for this initial evaluation involves calculating a "weighted disturbing power", S_{Dw} to characterize the amount of disturbing load within the customer facility. This can be done using the weighting factors in Table 4.1.1 for common types of harmonic producing loads.

The weighted disturbing power is calculated as follows:

$$S_{Dw} = \sum_i (S_{Di} \times W_i) \quad \text{for all the disturbing loads in the facility}$$

where:

S_{Di} = power rating for an individual disturbing load (kVA)
W_i = weighting factor for the disturbing load (pu)

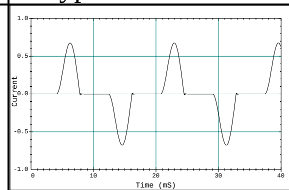
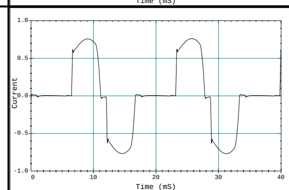
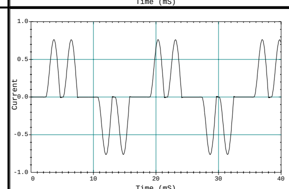
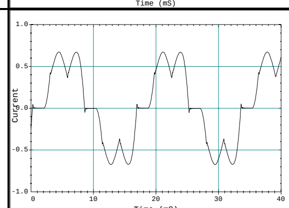
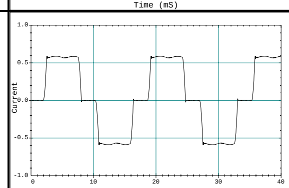
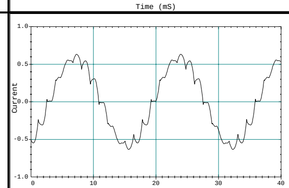
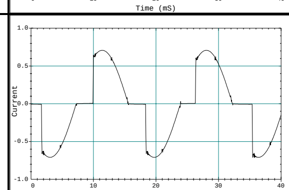
If the portion of the total load which is nonlinear is not known, it can be assumed that all the load is harmonic producing with a weighting of 1.0. This sets a limit for the size of the customer that would require harmonic evaluation, regardless of the type of equipment used. Applying harmonic limits for very small customers can be better accomplished by promoting equipment that has reduced harmonic generation characteristics.

The acceptability of the customer in Stage 1 can be evaluated by comparing the weighted disturbing power with the short circuit capacity at the point of interconnection. The following criteria is proposed by an IEC task force [5] for this evaluation:

If $S_{Dw} / S_{SC} < 0.1\%$, then automatic acceptance.

A simpler Stage 1 evaluation can be performed using the percentage of the total facility load that is nonlinear. If the majority of the nonlinear load is one of the types in the first three rows of Table 4.1.1, a detailed harmonic evaluation should only be necessary if the load is more than 5% of the total facility load. For other types of loads, this percentage can be as high as 10%. It is important to note that a more detailed harmonic evaluation should always be performed if the customer has or is considering power factor correction capacitors. The potential for resonance concerns and harmonics from the supply system should be evaluated regardless of the percentage of nonlinear load in the facility.

Table 4.1.1.
Weighting factors for different types of harmonic producing loads.

Type of Load	Typical Waveform	Current Distortion	Weighting Factor (W_i)
Single Phase Power Supply		80% (high 3rd)	2.5
Semiconverter		high 2nd,3rd, 4th at partial loads	2.5
6 Pulse Converter, capacitive smoothing, no series inductance		80%	2.0
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%	1.0
6 Pulse Converter with large inductor for current smoothing		28%	0.8
12 Pulse Converter		15%	0.5
ac Voltage Regulator		varies with firing angle	0.7
Fluorescent Lighting		17%	0.5

4.1.2 Stage 2: Evaluation According to the Current Limits

Stage 2 involves application of the current limits specified in IEEE 519-1992. The current limits are dependent on the customer size, the short circuit capacity at the PCC, and the individual harmonic components involved. Harmonic limits are expressed as a percentage of the customer's average maximum demand load current.

If some type of harmonic control is needed (e.g. passive harmonic filters), the design should be a cooperative effort to avoid interaction problems between the power system and the equipment.

The utility may elect to allow conditional acceptance of harmonic injection levels from a facility that exceed the levels specified in the standard. In some cases, this could be advantageous if the costs of reducing the harmonic injection levels are prohibitive and there are no adverse impacts associated with the higher levels of harmonic current injection (i.e. they will not cause the voltage distortion to exceed allowable levels). Acceptance of higher harmonic injection levels would be subject to revision if adverse impacts are associated with these harmonics at a later date. For instance, harmonic control could be required in the future if additional facilities add harmonic generating equipment that increases the overall system distortion levels.

4.2 Evaluating the Time Varying Characteristics of Harmonics

Harmonic limits are generally developed with the assumption that harmonic injection levels are relatively constant. However, it is important to remember that harmonic levels have important **time varying** characteristics. The steady state harmonic limitations are reasonable to apply at the design stage for a facility but they may be difficult to apply to actual measurements unless the time varying nature of the harmonics is addressed.

Any limits on the short duration harmonic levels should be based on the possible impacts of these harmonic levels. There are two types of impacts to consider. Effects such as metering error and accelerated equipment aging are the accumulated result of harmonic levels over time. Other effects such as the malfunction of sensitive electronics may be caused by only a short burst of high harmonic levels. Two approaches are proposed here for dealing with the time varying characteristics of the harmonic levels.

4.2.1 Probability Distributions

IEEE 519-1992 introduced the concept of probability distribution plots to characterize variations in harmonic levels. Figure 4.2.1 is an example of this type of plot. A reasonable method of using these types of plots to evaluate harmonic levels would be to compare the steady state harmonic limits with the measured harmonic level that is **not** exceeded 95% of the time (the 95% probability point). This is consistent with the evaluation of compatibility levels in IEC standards [2].

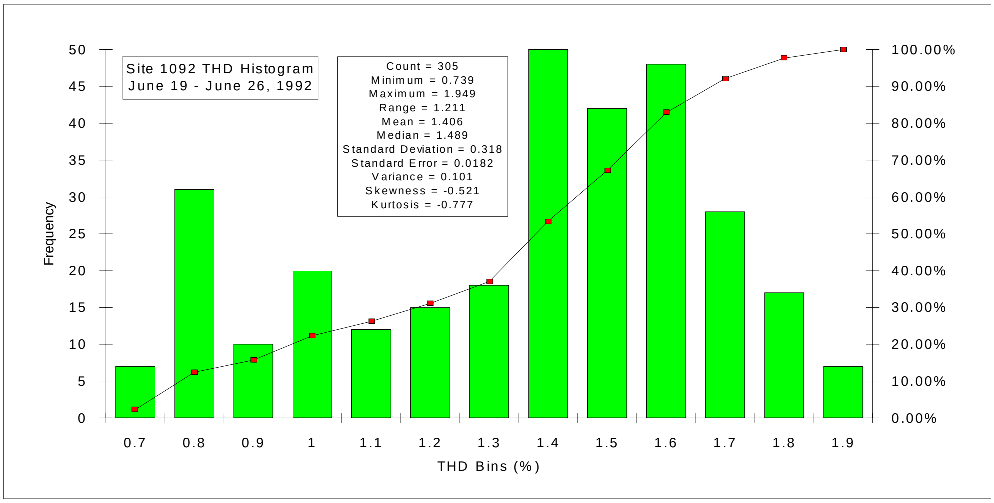


Figure 4.2.1.
Probability plot illustrating variable nature of harmonic levels.

IEEE 519-1992 states that the steady state harmonic limits can be exceeded by 50% for short periods of time (up to one hour per day). One hour per day is approximately 4% of the time. Therefore, this limitation is consistent with using the design limits as the 95% probability of not being exceeded. The higher limit (1.5 x the design limits) can be compared with the measured harmonic level that is not exceeded 99% of the time (the 99% probability point).

4.2.2 Magnitude/Duration Limits for Short Duration Harmonic Levels

The probability distributions do not distinguish between many short bursts of harmonics and one longer burst of harmonics that may exceed a specified threshold. Figure 4.2.2 provides an exaggerated comparison of two time trends of harmonic levels illustrating the difference. Both of the cases have the same total duration where the harmonics exceed a threshold (e.g. 8%) but they may have significantly different impacts on motor or transformer heating.

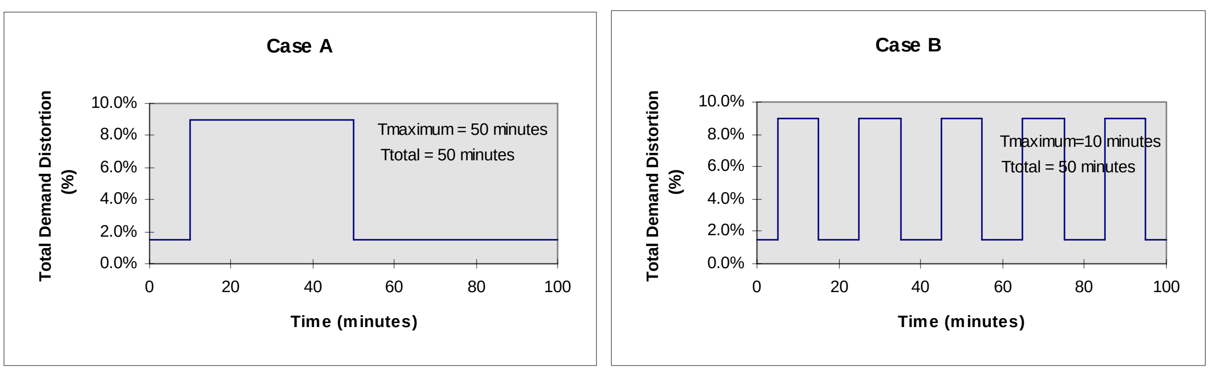


Figure 4.2.2.
Exaggerated comparison for two different harmonic distortion time trends.

There are two indices that can be calculated to characterize the time varying nature of the harmonics and take into account both of these cases:

1. The total duration of harmonic bursts (T_{total}) is the summation of all the time intervals in which the measured level exceeds a particular level during a specified measurement period.

2. The maximum duration of a single burst ($T_{maximum}$) is the longest time interval in which the measured distortion level continuously exceeded a particular level during the specified measurement period.

Both T_{total} and $T_{maximum}$ are functions of the threshold selected. Specific limits can be developed for ranges of these indices and then the limits can be plotted on a magnitude duration plot (see example in Section 5) for comparison with the measurement results. Table 4.2.1 provides example magnitude/duration limits that can be used to include the time varying nature of harmonics in the evaluation [6]. They use the steady state limits from IEEE 519-1992 as a basis (referred to as design limits in the table). Note that harmonic bursts with durations less than 5 seconds are ignored. While these short duration bursts of harmonics could be very important, it is difficult to apply steady state limits to control them. While reference [6] uses 5 seconds as the defining period for these short bursts, it may be desirable to use 3 seconds since that is the sampling period used in IEC 1000-4-7.

Table 4.2.1.
Short duration harmonic distortion limits based on a 24 hour measurement period.

Acceptable harmonic distortion level (individual or TDD)	**Maximum duration of a single harmonic burst ($T_{maximum}$)**	**Total duration of all harmonic bursts (T_{total})**
3.0 x (design limits)	1 sec < $T_{maximum}$ < 5 sec	15 sec < T_{total} < 60 sec
2.0 x (design limits)	5 sec < $T_{maximum}$ < 10 min	60 sec < T_{total} < 40 min
1.5 x (design limits)	10 min < $T_{maximum}$ < 30 min	40 min < T_{total} < 120 min
1.0 x (design limits)	30 min < $T_{maximum}$	120 min < T_{total}

4.3 Measurement Considerations

There are a number of general considerations that are important for harmonic measurements, especially when they are being used as part of an evaluation to apply harmonic limits. The most important of these are discussed briefly here and addressed in more detail with examples throughout this guide.

4.3.1 Where to Measure

Harmonic limits are evaluated at the PCC. Measurements to evaluate compliance with the harmonic limits should therefore be made at the PCC, if possible. Measurements at other locations throughout a facility can help in the overall evaluation of harmonic concerns. For instance, measurements at nonlinear loads are used to characterize these loads as part of the overall facility load, including the time varying nature of the harmonic currents produced. Measurements for portions of a facility (e.g. individual branch circuits) can help illustrate the cancellation achieved due to harmonic injection from multiple nonlinear loads within the facility.

For many customers, the PCC will be at the high side of a step down transformer but it would be more convenient to perform measurements at the transformer low side to take advantage of existing CTs that can be used for the current measurements. The low side measurements should be quite adequate for evaluating the harmonic currents but cannot be easily used to evaluate the harmonic voltage distortion characteristics on the primary side. The harmonic currents measured on the transformer secondary can be referred to the primary side by the transformer turns ratio. However, the effect of the transformer connection on the zero sequence harmonic components must be considered.

The transformer connection will only affect the zero sequence harmonic current magnitudes. If the harmonic currents consist of only positive and negative sequence components (this may be the case for many industrial facilities that are dominated by three phase loads), then the transformer connection will only affect the phase angles of the harmonic currents. However, if the facility includes single phase loads that can generate triplen harmonics (that become zero sequence components in a balanced three phase system), the transformer connection must be considered. Delta-wye transformers will trap the zero sequence components in the delta primary winding and they will not show up in the primary system (Figure 4.3.1 illustrates this effect for a load that has significant third harmonic current). Wye grounded-wye grounded transformers will allow these zero sequence components to flow into the primary system.

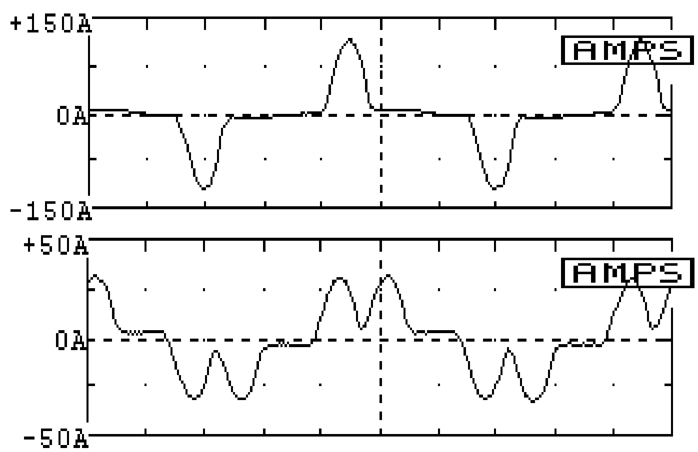


Figure 4.3.1.
Effect of delta-wye transformer connection on harmonic currents that include zero sequence components (top current is the secondary and bottom is the primary of a 480/208 volt delta wye transformer).

4.3.2 Harmonic Voltage Measurements

Harmonic voltage measurements can be made on low voltage systems with a direct connection to the bus. At higher voltages, potential transformers (PTs) are used to provide a lower voltage signal for the measurement equipment. PTs usually have good frequency response characteristics up to 3000 Hz. Capacitively coupled voltage transformers (CCVTs) should not be used for harmonic measurements. They use a tuned circuit for accuracy at the fundamental frequency but can have large errors at harmonic frequencies [1].

4.3.3 Harmonic Current Measurements

Measurements to evaluate compliance with harmonic limits require measurement of harmonic currents. The most important concept to remember when making these measurements is that the harmonic current limits are expressed in percent of a **fixed** current value (the average maximum demand load current). This means that the current limits are essentially fixed ampere limits at each harmonic and for the total demand distortion. In order to compare measurements with these limits, the measurements must be made in actual amperes, **not percent of the fundamental current**. The fundamental current is continually varying due to load variations and power factor correction changes. Harmonic currents expressed as a percentage of this changing fundamental current may be difficult to convert to actual amperes and the results can be misleading. For instance, the harmonic distortion levels expressed as a percentage of the fundamental current could be quite high during light load conditions, but the actual amperes of harmonic current may be quite acceptable.

When measuring harmonic currents within the facility, it may be important to include the phase angles of the individual harmonic components. This permits a better evaluation of harmonic cancellation between different loads within the facility. The phase angles must all be related to the same reference. This is commonly selected to be the zero crossing of the fundamental frequency voltage on phase A.

Current transformer (CT) characteristics can also be important for harmonic current measurements. The frequency response characteristics of the CTs should be evaluated for the measurements being performed. The CTs should have less than 3dB of attenuation for frequencies up to 3000 Hz. Usually, the CT characteristics have a more important impact on the harmonic current phase angle than the magnitude.

4.3.4 Monitoring Durations

Measurements should be performed over a period of time to characterize the variable nature of the harmonic levels. Section 4.2 described different methods to consider the time-varying nature of the harmonic levels in the evaluation procedure. These methods require that the harmonic levels be trended over time (using actual amperes for the harmonic currents). The time trends can then be used to develop a magnitude/duration plot or a probability histogram (Figure 4.2.1) that summarizes the harmonic levels vs. time.

For very stable processes, measurements over a single day may be adequate to characterize harmonic level variations. More commonly, measurements should be performed over a period of at least one week during normal operation of the facility. For facilities like steel plants with arc furnaces that can have characteristics that vary from day to day, monitoring over longer durations is recommended.

Permanent monitoring of harmonic levels can be used to flag abnormal conditions and for ongoing evaluation of compliance with harmonic standards. Monitoring over some initial period of time will establish the normal harmonic variations that can be expected at a facility. If the harmonic levels fall outside these normal variations, it is an indication that something has changed either within the facility or on the power system (e.g. a filter failure, new capacitor bank, new harmonic producing load, etc.).

4.3.5 Important System Conditions

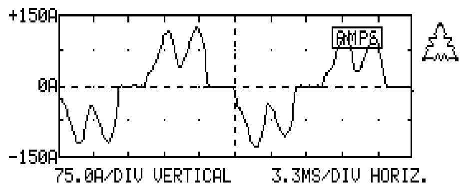
Besides the random time variations of the harmonic levels, it is important to evaluate the impact of different system conditions on the harmonic levels, both within the facility and on the power system. These can be evaluated with a combination of measurements and simulations, if necessary. The measurements are used to verify a model for specific system conditions and then the model can be used to evaluate the impact of other system conditions that cannot be immediately tested in the field. Important conditions to consider include:

- effect of power factor correction capacitors in the customer facility
- effect of harmonic filter out of service
- effect of power factor correction capacitors on the utility supply system
- effect of alternative sources from the utility (e.g. alternate feeders)
- effect of different load combinations than can be evaluated in the field tests
- effect of nearby customers with significant harmonic production

4.3.6 Presentation of Measurement Results

The results of harmonic measurements can be presented in a variety of different ways. Different methods are recommended for different objectives. The following list summarizes the main methods of presenting the measurement data along with the uses of each method.

- **Snapshots.** Snapshots of individual measurement samples are presented as waveform pictures with the associated harmonic spectrum (Figure 4.3.2). The phase angles of the individual harmonic components should be included in the harmonic spectrum so that the issues of cancellation between different harmonic sources can be considered and so that the information can be used directly in simulations. Snapshots are used to characterize performance for specific conditions. For instance, snapshots may be used to characterize a harmonic producing device at light load, normal load, and full load conditions.



PHASE B CURRENT SPECTRUM 2:23:40 PM
Fundamental amps: 61.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	−128°	2nd	1.0%	145°
3rd	3.9%	−149°	4th	0.4%	−57°
5th	39.7%	−122°	6th	0.8%	175°
7th	18.9%	122°	8th	0.2%	10°
9th	0.8%	47°	10th	0.2%	159°
11th	6.8%	67°	12th	0.4%	−27°
13th	3.8%	−118°	14th	0.3%	111°
15th	0.4%	−140°	16th	0.4%	6°
17th	3.2%	−144°	18th	0.4%	109°
19th	2.3%	10°	20th	0.3%	2°
21st	0.3%	29°	22nd	0.2%	141°
23rd	1.8%	11°	24th	0.2%	−79°
25th	1.7%	145°	26th	0.2%	124°
27th	0.2%	−165°	28th	0.1%	−81°
29th	1.1%	160°	30th	0.1%	68°
31st	1.3%	−74°	32nd	0.1%	−112°
33rd	0.2%	−32°	34th	0.1%	81°
35th	0.7%	−49°	36th	0.1%	−114°
37th	1.0%	67°	38th		
39th	0.2%	153°	40th		
41st	0.5%	96°	42nd	0.1%	−1°
43rd	0.8%	−147°	44th	0.1%	134°
45th	0.2%	−59°	46th		
47th	0.4%	−112°	48th		
49th	0.7%	−5°	50th		
ODD	45.1%		EVEN	1.6%	
THD:	45.1%				

Figure 4.3.2.
Snapshot illustrating current waveform and harmonic spectrum for specific conditions.

- **Time Trends.** Time trends of harmonic levels show the variations over a specified period of time. Figure 4.3.3 illustrates the harmonic current distortion variations over the period of one week. Maximum and minimum harmonic levels can be determined and the data can be used to generate statistics of the harmonic levels. The time trends are needed to evaluate individual bursts of harmonic current vs. total duration that harmonics exceed a specified threshold (see Section 4.2).

Figure 4.3.3.
Example time trend illustrating harmonic current distortion at a facility over a one week period.

- **Probability histograms.** The probability of a specified harmonic level being exceeded can be evaluated with histograms and cumulative probability distribution plots (Figure 4.3.4). The histograms are useful for determining the harmonic levels that are most likely to exist and the overall variation of the levels. The shape of these histograms can also provide information about the loads and the system. For instance, Figure 4.3.4 shows two distinct peaks in the distribution. One of the peaks represents the harmonic levels when a capacitor bank is in service and the other peak represents the conditions when the capacitor bank is out of service.

(bimodal distribution - Chris Melhorn)

Figure 4.3.4.
Example probability histogram for harmonic current distortion levels illustrating two distinct system conditions.

- **Magnitude/duration plots.** Magnitude/duration plots provide a method to present the time varying nature of the harmonic levels in summary form. The plot is essentially a cumulative distribution of the data presented in the probability histogram. Figure 4.3.5 is an example. These allow direct evaluation of the harmonic levels that are not exceeded 95% of the time and 99% of the time (probability points used in the IEC standards).

Figure 4.3.5.
Example of cumulative distribution of harmonic current distortion levels (magnitude vs. cumulative duration).

4.3.5 Sampling Requirements

Since harmonic levels are continually changing with time, a single sample cannot be used to evaluate compliance with harmonic limits or to describe the harmonic levels on the system. Multiple samples over time are required until the time varying nature of the harmonic levels is adequately characterized. IEC working groups have developed draft recommendations for essentially continuous monitoring of harmonic levels and then development of appropriate statistics to describe the harmonic performance [7].

The same statistical information describing the harmonic levels can be obtained with individual harmonic samples separated in time, as long there are sufficient samples to adequately characterize the harmonic variations. Measurements at customer service entrance locations and on primary distribution systems have shown that the harmonic variations can usually be accurately characterized in less than one month with samples that are separated in time by about one half hour [8].

4.4 Finding the Source of Harmonics

When harmonic problems are caused by excessive voltage distortion on the supply system, it is important to locate the source of harmonics in order to develop a solution to the problem. Usually, problems with high voltage distortion involve a combination of excessive harmonic injection from one or more facilities and a system response characteristic that causes magnification of specific harmonic components. The system response characteristics can be evaluated with simulations and varying the status of capacitor banks. Finding the actual source of the harmonics can be more difficult.

There are two basic approaches to finding the source of harmonic currents on the power system:

1. **Compare the time variations of the voltage distortion with specific customer and load characteristics.** Harmonic distortion that comes and goes with normal times for shift changes, lunch breaks, etc. may be due to industrial or commercial power consumers. There are also

patterns that can be correlated with particular types of loads such as mass transit, rolling, mill drives, and arc furnaces, all of which have peculiar intermittent behavior. Arc lighting harmonics can be recognized from the dusk-to-dawn timing patterns.

Figure 4.4.1 illustrates the time variations of the voltage distortion on a distribution system that supplies a number of industrial customers. One of these customers was unable to operate his computerized lathes during normal business hours because of the high voltage distortion. The lathes would shut down when voltage distortion exceeded 5.5%. The second trend in Figure 4.4.1 gives the loading characteristics of a customer with induction furnace loads. The correlation of the customer load characteristics with the voltage distortion timing pattern indicates that this customer is the main source of the harmonic currents.

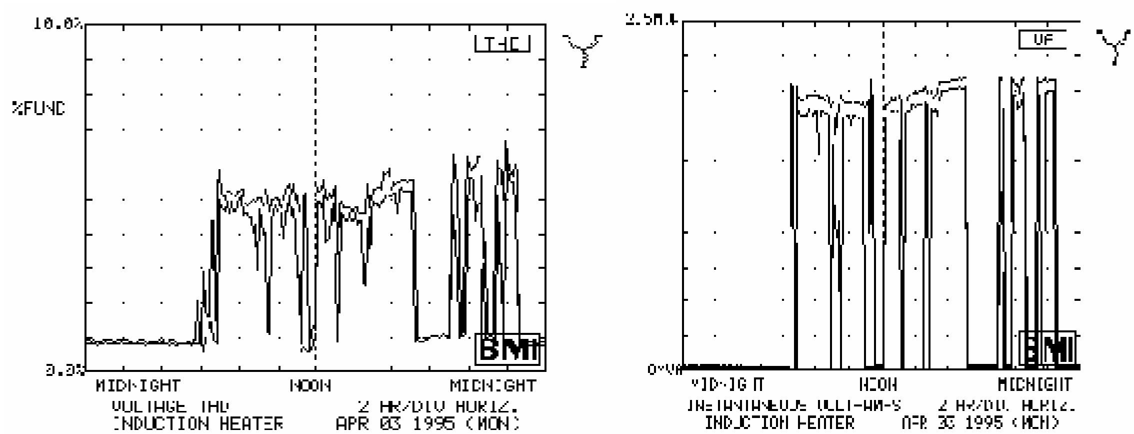


Figure 4.4.1.
Voltage distortion vs time on the distribution system and the load profile(volt-amperes) for a particular customer that is causing the harmonic distortion.

2. **Monitor flow of harmonic currents on the feeder with capacitor banks off.** The normal flow of harmonic currents will be from the nonlinear load to the utility supply system as shown in Figure 4.4.2. With this in mind, the harmonic source can be located by measuring the harmonic currents on the feeder starting at the substation and going towards the source of harmonics. It is important to note that this method will only be effective if all capacitor banks have been removed from the feeder. Capacitors will cause local resonances which hide where the source is really located.

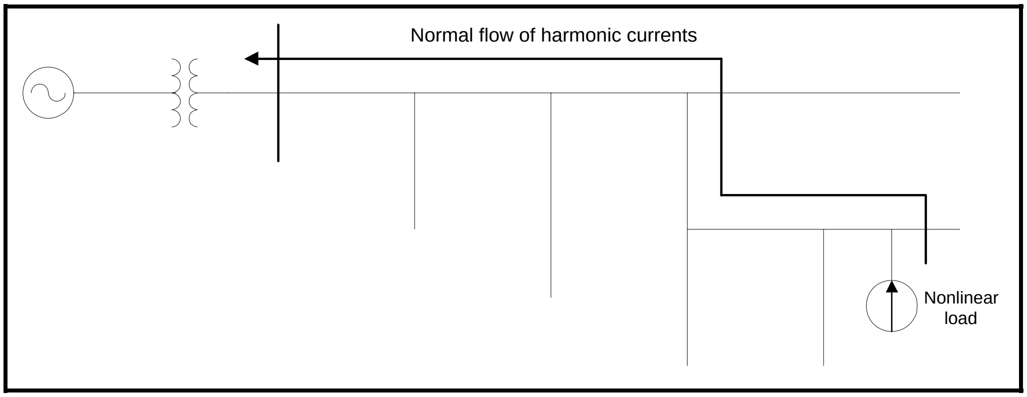


Figure 4.4.2.
Normal flow of harmonic currents on a feeder without capacitor banks.

If neither of these methods is effective in locating a particular source of harmonics that is the cause of the distortion, then the cause may be distributed harmonic sources throughout the distribution system. In this case, it may not be possible to solve the problem at individual harmonic sources and changing the response of the system or filtering may be necessary on the distribution system.

5.0 APPLYING HARMONIC LIMITS FOR INDUSTRIAL FACILITIES

Most harmonic problems are associated with harmonics from nonlinear loads used in industrial facilities. There are a few important reasons for this:

1. Many industrial processes involve the application of nonlinear loads. These include adjustable speed motor drives, large rectifiers for dc processes such as aluminum pot lines, induction furnaces, arc furnaces, and dc drives. These loads can be a significant portion of the total facility load for many industrial plants.

2. Industrial facilities often have power factor correction capacitors. Industrial loads, such as motors, often have relatively low power factor. Depending on the utility rate structures, it is often economical to correct the power factor with capacitors. These capacitors create resonance conditions that can magnify harmonic currents from the nonlinear loads.

3. Industrial loads are often dominated by motors and other loads that do not provide much resistive damping of resonance conditions at harmonic frequencies. Therefore, the application of capacitors can create more problems in an industrial facility than they would on a distribution system with significant resistive load.

Most harmonic problems show up within the industrial facility before they create prob1ems on the utility supply system. Resonance conditions created by the application of capacitors within an industrial plant will result in the highest voltage distortion levels at the customer's low voltage bus where the capacitors are applied. Problems are likely to show up in the plant with motors overheating, transformer heating, and misoperation of electronic equipment before problems show up on the utility system. Therefore, it is in the customer's best interest to understand the possible harmonic problems and make sure the harmonic distortion levels are not excessive.

IEEE 519-1992 recommends that voltage distortion at the PCC be limited to 5% for most medium voltage systems. This provides some margin to allow for higher voltage distortion levels within a customer facility. In general, voltage distortion levels should be less than 8% to prevent excessive motor heating, probably the most important concern for most industrial customers. This 8% voltage distortion level is specified as the compatibility level in IEC 1000-2-2 [1].

Evaluation of harmonic concerns for industrial facilities requires an understanding of the different types of loads that are used in the facility. Most integrated industrial plants have many different sources of harmonics (nonlinear loads) and the combined effect of these different sources may be difficult to calculate. Measurements are usually required to characterize these sources and their interaction. At the design stage, evaluations often require conservative assumptions in order to estimate expected harmonic levels. Section 5.1 provides a case study for an industrial facility that illustrates many of the concerns involved. Subsequent sections give more detailed information on specific types of nonlinear loads, the impact of power factor correction equipment, designing harmonic filters, and concerns for voltage notching.

A general procedure for evaluating harmonic limits at an industrial facility is outlined here. This procedure is illustrated by the case study in Section 5.1.

1. **Step 1: Choose PCC.**

   Most industrial facilities are supplied by one or more dedicated transformers. Therefore, the PCC is normally be on the high side of the step down transformer where other customers can be served. Measurements to evaluate compliance can be made on the low side of the transformer and converted to the high side.

2. **Step 2: Characterize harmonic producing loads.**

   Examples of the harmonic generating characteristics of many different types of industrial loads are provided in the subsequent sections. The combined effect of multiple loads may be difficult to determine without measurements.

3. **Step 3: Determine power factor correction needs.**

   Harmonic concerns must be considered as part of the application of power factor correction equipment, regardless of whether or not the facility includes significant harmonic producing loads. If capacitors are needed, the potential for absorbing harmonics from the supply system should be considered, as well as possible resonances that could magnify harmonic currents from the industrial facility.

4. **Step 4: Calculate expected harmonic currents at the PCC.**

   Compliance with harmonic current limits at the PCC can be evaluated using assumptions about the harmonic generation characteristics of plant loads and simple system response characteristics.

5. **Step 5: Design harmonic control equipment, if necessary.**

   Harmonic control equipment will usually be coordinated with power factor correction needs for industrial facilities. In cases where small harmonic filters are needed, active filters may be economical to avoid the possibility of overloading due to voltage distortion on the supply system.

6. **Step 6: Verify harmonic performance with measurements.**

   Measurements over a period of time should be used to verify that harmonic current levels are within limits and that harmonic control equipment is performing as designed. The period of time selected should adequately characterize the time varying and statistical characteristics of the harmonic levels.

5.1 Example Case Study

This case study illustrates many of the important considerations in evaluating harmonic limits for an industrial facility. These include:

- multiple sources, harmonic cancellation effects
- power factor correction/resonance concerns

- choosing the PCC
- design of harmonic filters to control harmonic levels
- evaluating the time varying nature of the harmonic levels

5.1.1 Background

A large industrial customer (battery manufacturing facility) was considering a significant plant expansion. The plant includes significant rectifier load and had experienced harmonic problems due to resonance with shunt power factor correction capacitors in the past. Problems included blown capacitor fuses and process interruptions. Since the plant expansion would result in additional harmonic generation, the customer worked with the utility to develop a solution that would solve the overall harmonic problems for the facility.

5.1.2 System Description

The facility set a peak demand of just over four megawatts in the twelve months prior to the plant expansion work. It contains 831 rectifier circuits, which represent about 60% of the plant load. Production is divided between building the batteries and charging them. The charging load can be varied based on production, or based on other parameters such as the cost of electricity.

The plant is served at 480 volts from a 44-kV sub-transmission system. Prior to the expansion, the utility operated two 1200-kvar switched capacitor banks on the 480-V bus for voltage regulation. This resulted in a number of problems caused by resonance conditions. Figure 5.1.1 illustrates the plant configuration before expansion.

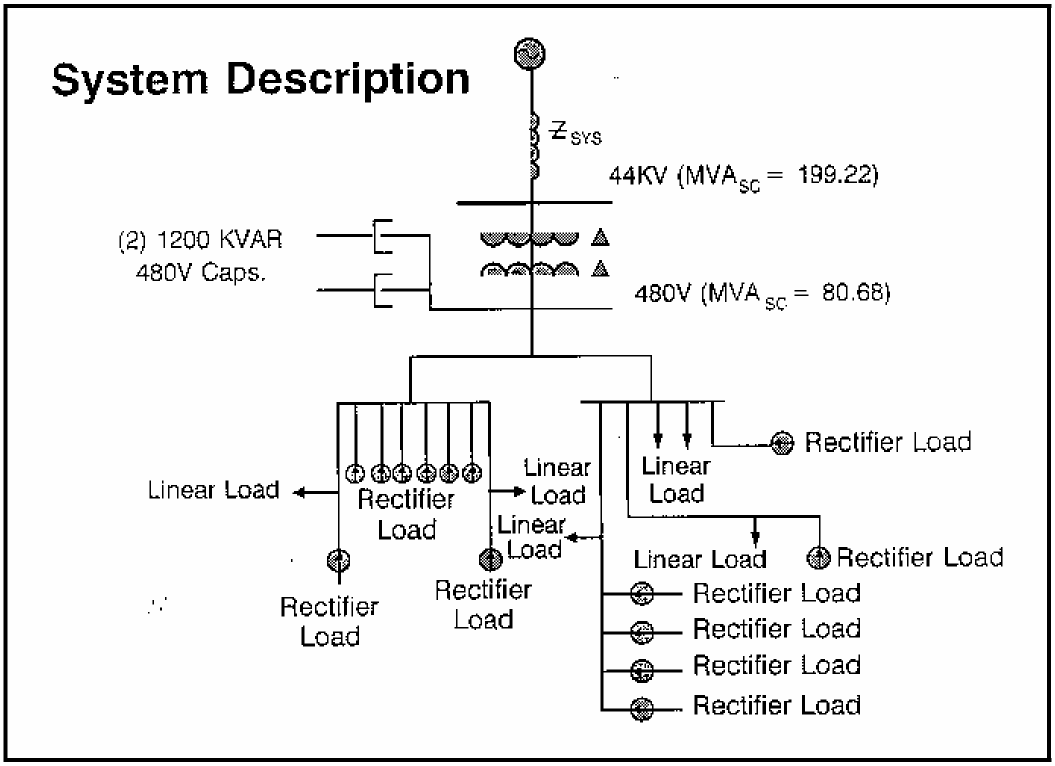


Figure 5.1.1.
One line diagram for example system.

5.1.3 Harmonic Source Characteristics

As mentioned above, the facility includes 831 rectifier circuits. The typical AC system serving rectifiers consists of a 460/230-V transformer, connected wye-delta, rated at 124 kVA. This transformer serves 16 rectifiers, each of which resembles the circuit diagram in Figure 5.1.2. Note that the six-pulse bridge circuit consists of uncontrolled diodes. DC current control is achieved by adjusting current flow through the saturable AC reactors.

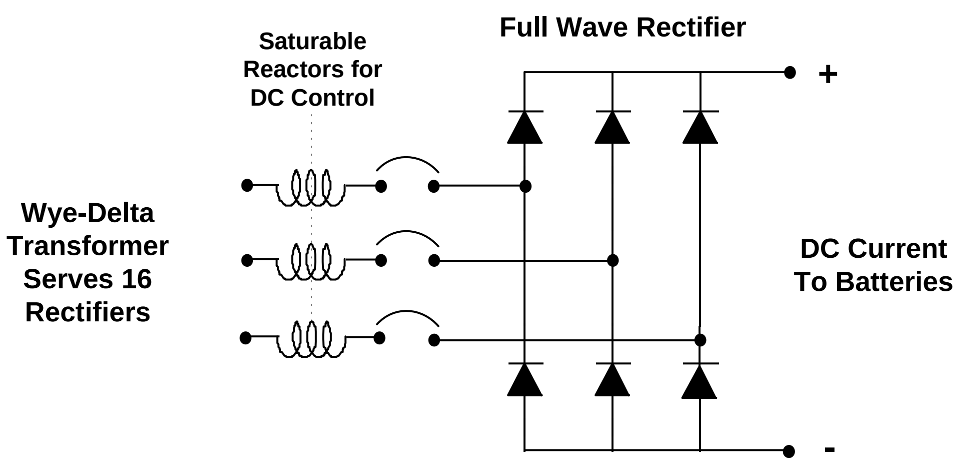


Figure 5.1.2.
Typical rectifier configuration.

The rectifiers are not all operating at the same level at the same time. Therefore, there is significant cancellation between the different rectifier circuits and different levels of harmonic generation depending on the operating conditions. Figure 5.1.3 gives measurement results for a set of 15 rectifier circuits (one of the 16 rectifiers was shut down) at four different levels of rectifier dc current output.

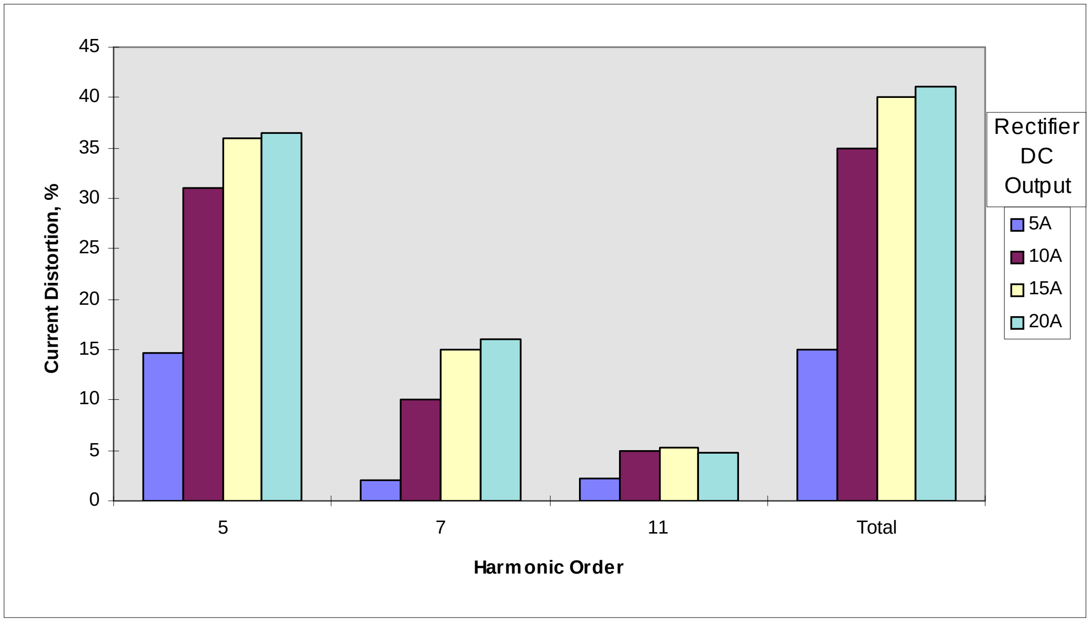


Figure 5.1.3.
Harmonic generation from a group of 15 rectifier circuits
(% of fundamental) for different levels of dc current output.

These harmonic injection characteristics provide a good picture of the harmonic generation from a single group of rectifiers. As multiple groups of rectifiers are considered, diversity results in increased levels of cancellation. It is not uncommon for the harmonic injection levels at the fifth harmonic to be on the order of 10-15% of the fundamental in this type of facility due to cancellation effects (without cancellation, the fifth harmonic would be about 30% of the fundamental).

5.1.4 Selecting the PCC

The assessment begins with an estimate of the short circuit capability of the utility system serving the customer. This calculation is no different than the usual short circuit estimate completed by electric utilities for coordination studies. The value is an indication of the "stiffness" of the utility system serving the plant, and is used in IEEE 519 tables to determine appropriate limits on current distortion. Stiff systems can transmit higher levels of harmonic currents without excessive voltage distortion than weak systems.

IEEE 519 recommends the following limits on harmonic current injection, based on the short-circuit to load current ratio. At this customer, the I_{SC}/I_L is 16 at the 480-V bus, and 38 at the 44-kV bus. According to the IEEE 519 table, Total Demand Distortion should be limited to 5.0% at the 480-V bus, and 8.0% at the 44-kV bus. Since the 44-kV bus was the point at which the other customers could be served (the PCC), 8% was the target limit for current injection onto the utility system

5.1.5 Calculating Compliance with Harmonic Limits

Computer modeling is commonly required when investigating harmonic distortion problems. A model of the supplying power system and important elements of the customer system is developed and used to estimate the effect of different system conditions on the expected harmonic levels.

System capacitor banks have the most important effect on resonance conditions. Frequency scans of the system show the resonance condition with and without the 1200 kvar capacitor bank at the service entrance. The resonance is at the 8.5th harmonic. With both 1200 kvar capacitors in service, the resonance is close to the sixth harmonic.

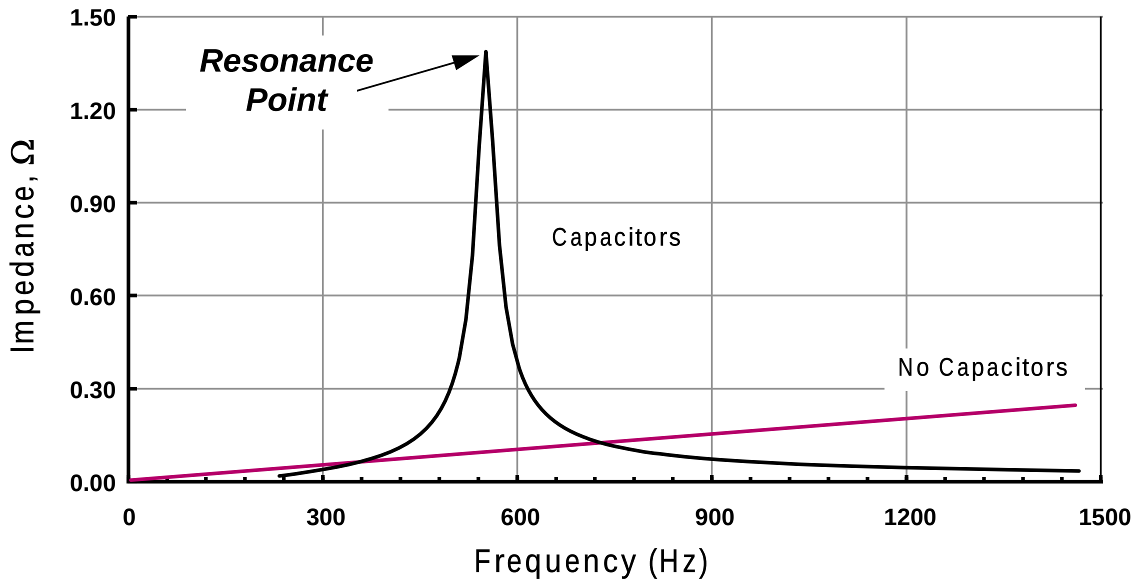


Figure 5.1.4.
Resonance condition with and without a 1200 kvar capacitor banks in service.

In order to evaluate compliance with IEEE 519, the base current for evaluation (average maximum demand load current) must be calculated. This is typically based on historical data but must be adjusted in a case when the plant is considering expansion. There is considerable flexibility in calculating this load current and engineering judgment must be used.

At this facility, the 12-month average monthly demand was 4032 kW and the average power factor was 79%. This yields a peak total power demand of 5104 kVA (4032 / 0.79), and a resulting current of 6,139 amperes (referred to the 480 volt level). This current becomes the denominator for the TDD and individual harmonic limit calculations.

Note that customers with poor power factor are allowed *more* nonlinear current injection, because their TDD is smaller (larger denominator) than a similarly-sized customer with better power factor. This is a point for consideration within individual utilities when calculating the base current value. One suggestion for utilities that do not have significant power factor penalties is that the power factor used in the TDD calculation never be less than 0.85.

The other part of the TDD estimate requires the amount of harmonic current injection. For existing systems, this current injection can be measured directly. For new loads or expansions, models must be used to predict the amount of harmonic current. As discussed earlier, adding all the harmonic currents from loads in the plant will usually overstate the harmonic current.

In order to model the expansion at this facility, the following worst-case assumptions were used:

- 80% of the rectifiers operating at 20 A_{DC} output;
- 1500 kVA of linear load at 0.75 lagging power factor;
- Non-linear load represented as a single current source (no cancellation).

Based on the above assumptions, the simulated TDD at the service entrance, without harmonic filters, would have been 34%. This current distortion would have resulted in 16% voltage distortion! Although conservative assumptions were used in the calculation to obtain worst case estimates, it is clear that some type of harmonic control is needed.

5.1.6 Developing the Solution

Harmonic filters can be applied at industrial sites to improve power factor and limit voltage distortion problems. The beneficial effect of the filters is illustrated by the frequency scan in Figure 5.1.5. The harmonic filter creates a very low impedance close to its tuned frequency and reduces the overall impedance at all higher frequencies. A lower frequency parallel resonance is created, but there should be no harmonic injection to excite the resonance.

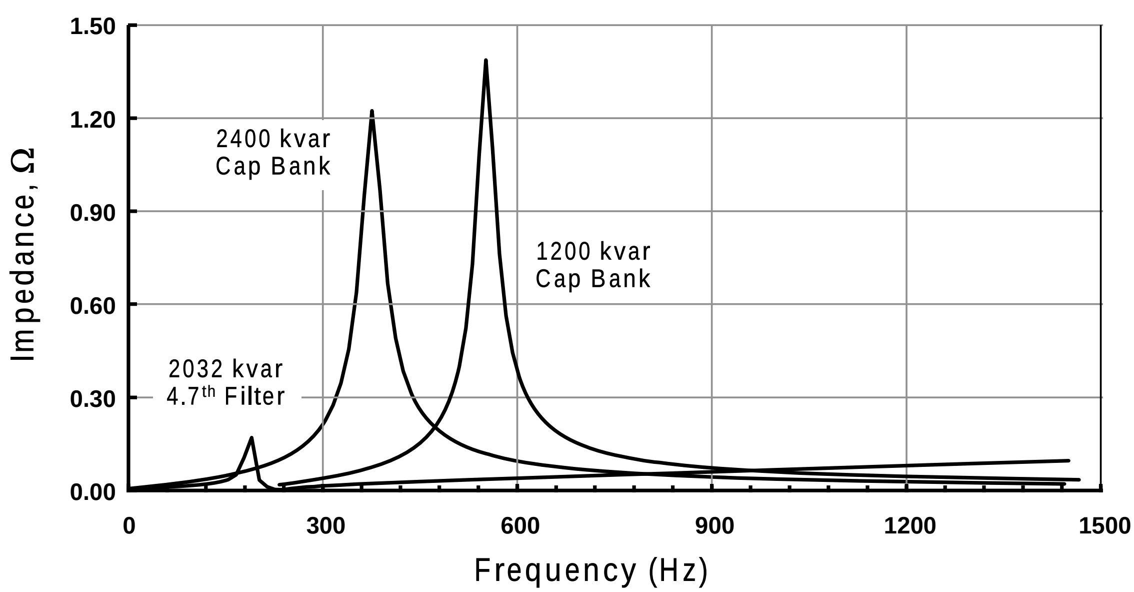


Figure 5.1.5.
Effect of tuned harmonic filter on the frequency response characteristics at the facility.

With two switched harmonic filters, the TDD would be 12.6%, primarily because the 5th harmonic current drops from 31% with no filters to 4.3% with two filters. This 12.6% TDD level is still above the 8.0% limit recommended by the standard, but the resulting voltage distortion is limited to 3.5% due to the beneficial effects of the harmonic filters.

The effects of twelve additional 84-kvar filter banks located close to the rectifier loads within the facility were also evaluated in the analysis. The simulated fifth harmonic current distortion dropped to 3.0%, and the voltage distortion (480-V bus) dropped to 2.8%. These additional filters also bring the overall expected TDD within the 8% recommended maximum TDD for the PCC at the 44kV bus.

5.1.7 Measurement Results/ Time Varying Characteristics

Harmonic currents were measured at the facility to verify the simulations. Harmonic current injection, as summarized in Figure 5.1.6, shows the beneficial effects of the 14 harmonic filters. Total Demand Distortion did not exceed 6% during the monitoring period. TDD is well below the 8% requirement at the 44-kV bus, and is below the 5% level on the 480-V bus most of the time. During the snapshot, the customer's plant demand did not exceed 78% of the 12-month average peak demand.

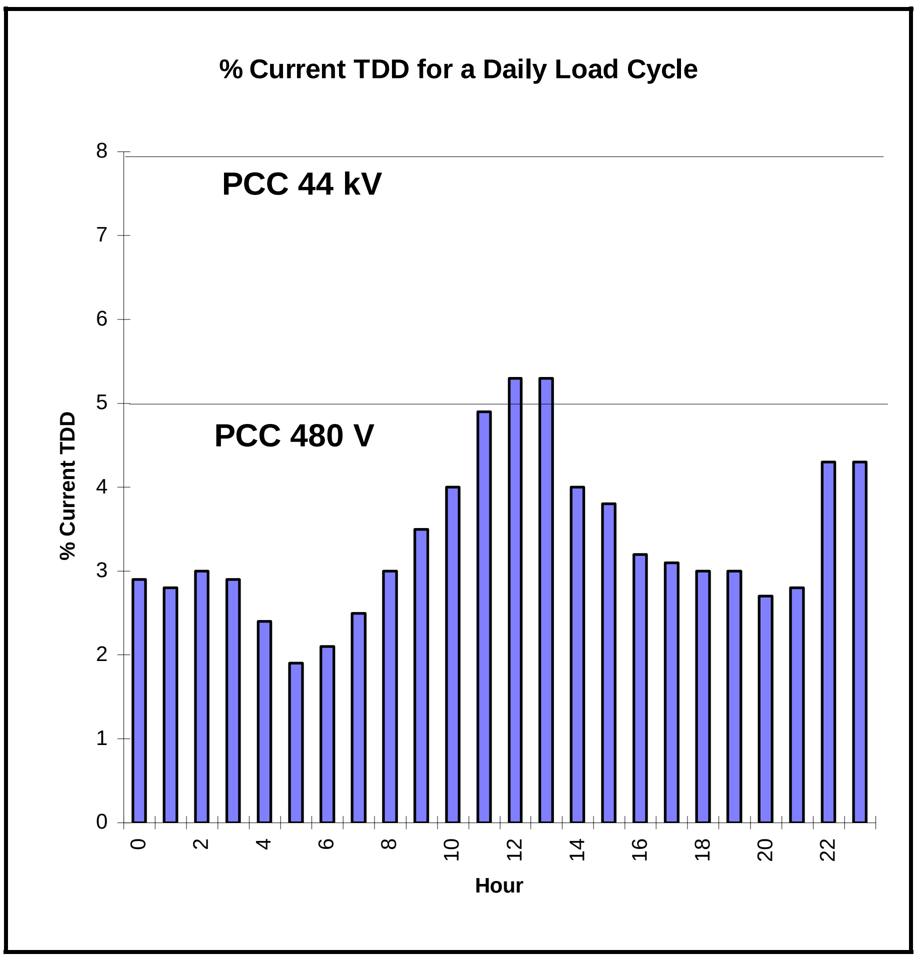


Figure 5.1.6.
Measured harmonic current profile over a 24 hour period.

The final step in the 519 analysis is often to plot a probability distribution of TDD. This graph is used to determine the time distribution of the TDD, or how long the TDD remains at certain levels. Figure 5.1.7 shows that the TDD at the customer is considerably below the 44-kV criterion for both total current distortion and distortion at the fifth harmonic. Many utilities will consider the 519 guideline successfully achieved if the TDD levels specified in IEEE 519 are not exceeded 95% of the time. Utilizing the snapshot results, the customer appears to be well within 519 recommendations.

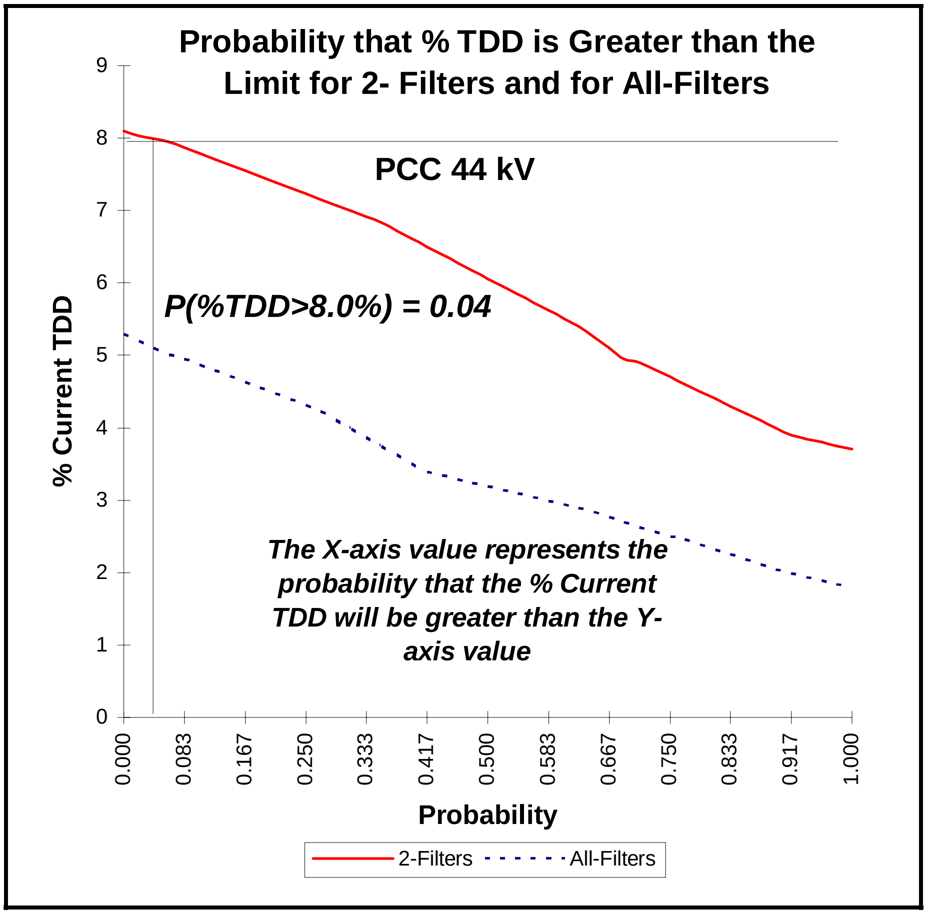


Figure 5.1.7.
Cumulative probability distribution (magnitude/duration plot) of the TDD with all filters in service.

5.2 Characteristics of Most Important Load Types

The following sections provide background information describing a number of important load types that are found in industrial facilities and may cause harmonic concerns.

5.2.1 Adjustable Speed AC Drives

The characteristics of the input current for ASDs depend on the drive type, drive loading, and the characteristics of the system supplying the drive. The harmonic distortion in these currents can vary over a wide range. However, it is possible to identify two basic waveform types that can be used for analysis purposes:

TYPE 1: High Distortion Current Waveform
This is characteristic of virtually all ASDs that have voltage source inverters (either stepped wave or pulse width modulated) that do not have additional choke inductance for current smoothing. The total harmonic distortion for the example waveform is 80%. Actually, it can be higher for small drives but this waveform is a good representation for larger drives or groups of smaller drives.

TYPE 2: Normal Distortion Current Waveform
This waveform represents dc drives, large ac drives with current source inverters, and smaller ac drives with voltage source inverters and added inductance for current smoothing. The example waveform has a distortion level of 38%, which is obtained from a 100 hp PWM drive with a 3% choke inductor.

Example waveforms and harmonic spectrums for the two waveform types are given below. These waveform characteristics are used throughout the analysis that follows to develop some general guidelines for harmonic control requirements.

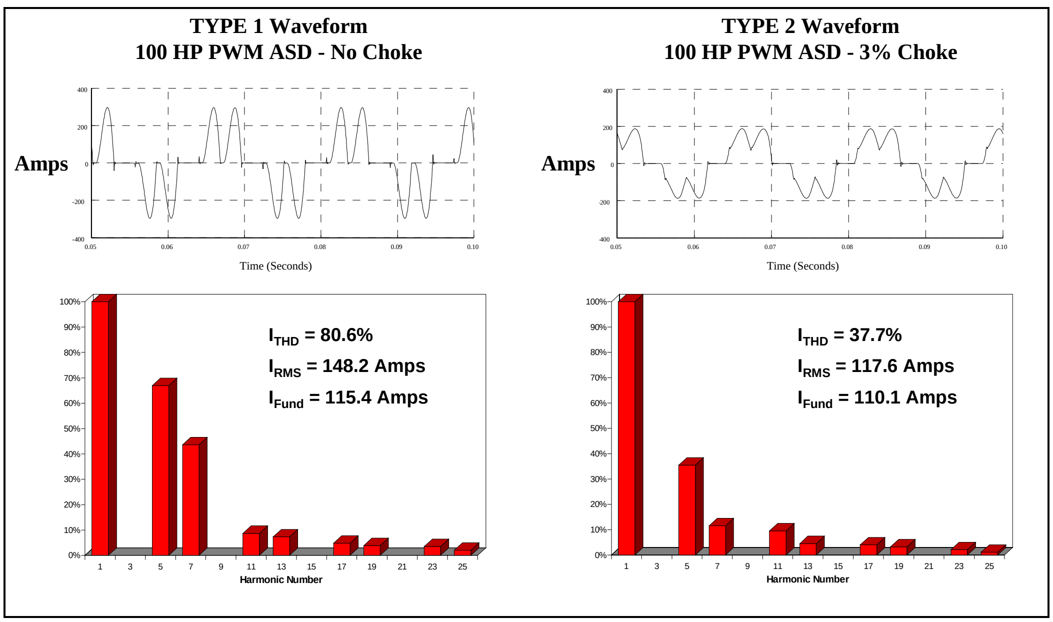


Figure 5.2.1. Example ASD current waveforms used for analysis.

The first observation from these two waveform types is the significant harmonic reduction that can be obtained for PWM type ASDs just by adding a choke inductance at the input. The figure below illustrates the effect of choke inductor size on input current distortion levels for a typical drive. Some drive manufacturers are starting to include this choke inductance in the dc link of the drive, providing the same harmonic current reduction benefit.

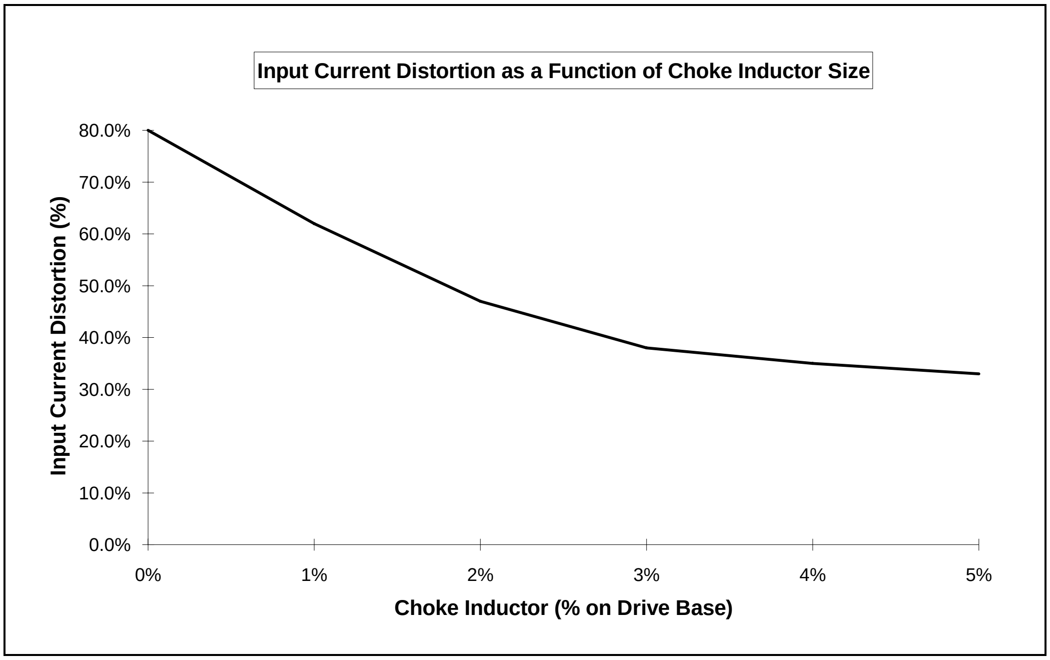


Figure 5.2.2. Effect of input choke on ASD current distortion.

Example System. Many conclusions regarding harmonic control requirements for facilities with ASDs can be developed from analysis of a very simple circuit (Figure 5.2.3).

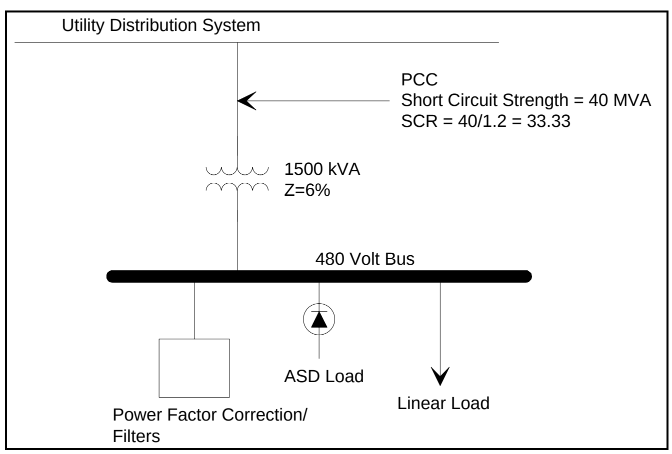


Figure 5.2.3. Example system used for analysis.
Note: Customer Avg. Max. Demand Load = 1200 kVA

Evaluating Harmonic Limits Without Power Factor Correction Capacitors. Since most ASDs have relatively high displacement power factor, power factor correction capacitors may not be required where ASDs are a significant part of the plant load. This analysis deals with the case where the plant does not have power factor correction. The case with power factor correction is evaluated in Section 5.3.

Without power factor correction, the harmonic currents generated by ASD loads can be assumed to flow through the step down transformer and on to the primary system (i.e. no magnification and no filtering). With this assumption, limits for ASD plant loading can be derived using the current waveforms provided previously.

The ASD plant loading needs to be expressed as a percentage of the average maximum demand load used to evaluate the harmonic limits (1200 kVA in this case). Once this is done, the ASD harmonics can be compared with the limits in IEEE 519-1992. The fifth harmonic current component will usually be the limiting factor for this evaluation. The figure below gives the fifth harmonic current for the entire plant as a function of the plant ASD loading for the two characteristics waveforms.

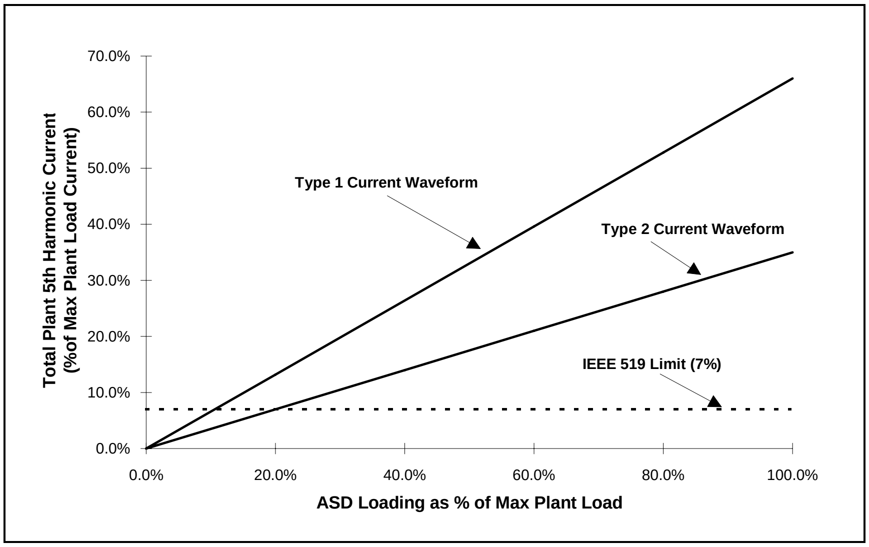


Figure 5.2.4. Evaluation of Fifth Harmonic Current as a Function of the Total ASD Plant Load

In this example, only a small percentage of the plant load can be ASDs:

≈ 10% for TYPE 1 currents
≈ 20% for TYPE 2 currents

An assumption inherent in this simple evaluation is that the harmonics from multiple ASDs add directly. This is approximately true for the lower order harmonic components from PWM-type ASDs. Other types of ASDs that have phase-controlled rectifiers may have significant cancellation of lower order harmonic components.

Effect of Higher Pulse Number Configurations. One effective method to control harmonics from ASDs is to use higher pulse number configurations (e.g. 12 pulse or 18 pulse). A 12 pulse configuration can be achieved by supplying one drive through a delta-wye transformer and another drive through a delta-delta transformer. The impact on the waveshape at the transformer primaries is illustrated below.

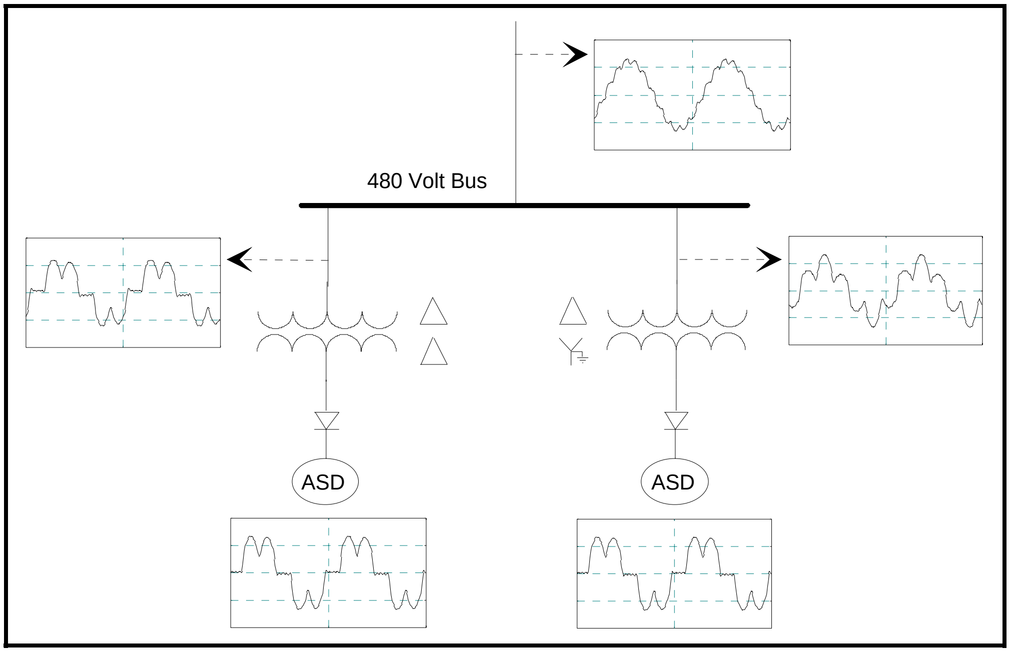


Figure 5.2.5 .12 pulse configuration for harmonic control.

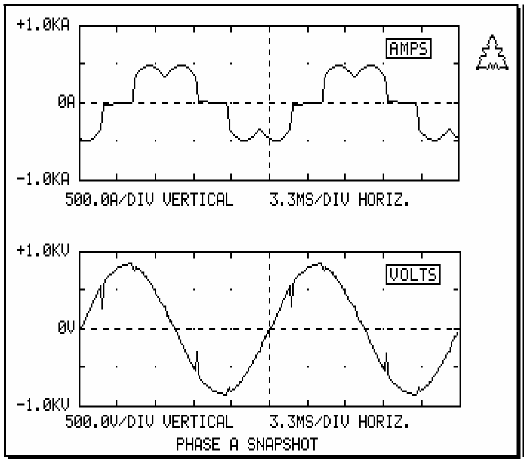
Using the same simple model described above, the harmonic limits for ASDs in a 12 pulse configuration can be evaluated. With cancellation of the fifth and seventh components, the 11th harmonic component is the limiting factor. The IEEE 519-1992 limit at the 11th harmonic is 3.5% of the average maximum demand load current. However, this limit is increased by a factor of 1.4 for 12 pulse drives, resulting in a limit of 4.9%. Using a typical 11th harmonic current component of 8% for the ASDs, this means that the total ASD loading should not exceed **60%** of the total plant load when 12 pulse drives are used.

5.2.2 DC Drives

DC drives can be a significant percentage of plant load in many industrial facilities. They are commonly used in the plastics, rubber, paper, textile, printing, oil, chemical, metal, and mining industries. These drives are still the most common type of motor speed control for applications requiring very fine control over wide speed ranges with high torques.

Power factor correction is particularly important for dc drives because phasing back of the SCRs results in relatively poor power factor, especially when the motor is at reduced speeds. Additional transformer capacity is required to handle the poor power factor conditions (and the harmonics) and more utilities are charging a power factor penalty that can significantly impact the total bill for the facility.

The dc drives also generate significant harmonic currents. An example current waveform and harmonic spectrum for a dc drive load is given above. The harmonics make power factor correction more complicated. Power factor correction capacitors can cause resonant conditions which magnify the harmonic currents and cause excessive distortion levels.



PHASE A CURRENT SPECTRUM 2:51:53 PM
Fundamental amps: 346.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-43°	2nd	0.3%	68°
3rd	0.4%	-126°	4th	0.2%	30°
5th	25.3%	-30°	6th	0.1%	61°
7th	5.5%	-122°	8th	0.2%	10°
9th	0.6%	37°	10th	0.2%	-45°
11th	8.2%	-102°	12th	0.1%	-37°
13th	3.9%	170°	14th	0.2%	-65°
15th	0.3%	-40°	16th	0.2%	-119°
17th	5.0%	-179°	18th	0.1%	-126°
19th	2.9%	93°	20th	0.2%	-136°
21st	0.3%	-44°	22nd	0.2%	167°
23rd	3.4%	109°	24th	0.1%	162°
25th	2.1%	14°	26th	0.2%	150°
27th	0.2%	-144°	28th	0.2%	100°
29th	2.7%	39°	30th	0.1%	86°
31st	1.9%	-59°	32nd	0.2%	74°
33rd	0.2%	99°	34th	0.2%	29°
35th	2.1%	-35°	36th	0.1%	6°
37th	1.7%	-135°	38th	0.2%	3°
39th	0.3%	41°	40th	0.2%	-42°
41st	1.8%	-110°	42nd	0.2%	-72°
43rd	1.5%	150°	44th	0.2%	-70°
45th	0.5%	-30°	46th	0.3%	-113°
47th	1.7%	177°	48th	0.2%	-146°
49th	1.4%	70°	50th	0.2%	-142°
ODD	28.9%		EVEN	1.0%	
THD:	28.9%				

Figure 5.2.6. Example dc drive current waveform and harmonic spectrum.

There is significant cancellation of harmonic currents resulting from the different dc drives fed from a common bus in most facilities with multiple drives. This is due to the fact that not all drives are operating with the same phase angle on the phase-controlled rectifier front ends. Cancellation of about 50% at the lower order characteristic harmonics is typical with plants that have 5 or more dc drives and the cancellation at higher order harmonics (e.g. above the 13th) is even greater. Even better cancellation can be achieved if isolation transformers are used for the dc drives with different connections (delta-wye, delta-delta) throughout the plant. This design causes the overall facility to approach 12 pulse operation with cancellation of the 5th and 7th harmonic components if there is nearly equal loading for the two connections.

Due to the cancellation, harmonic control may not always be required at facilities with dc drives. However, the poor power factor usually warrants power factor correction. It is convenient to implement the power factor correction in the form of tuned banks tuned below the fifth harmonic to make sure that the power factor correction does not create a resonance problem at a characteristic harmonic frequency. This is almost always sufficient for harmonic control in these types of facilities. Multiple step filters are seldom required.

Sometimes higher harmonic levels and non-characteristic harmonics may be associated with regeneration conditions. In this mode, the drive is actually acting as a generator and the flow of power is from the load to the source. These are usually short bursts during deceleration and the harmonics should be evaluated based on the durations involved.

5.2.3 Heating Processes

Induction heating. Induction heating processes, while clean, quick, and efficient, can be a major source of harmonics on a power system. Industrial applications of induction heating include hardening, forging, annealing, and soldering electrically conducting workpieces. The workpiece is heated by circulating currents which are electromagnetically induced.

Induction heaters typically employ a 6-pulse SCR rectifier front-end which results in the generation of significant harmonic currents. The harmonic spectrum and waveforms provided below were taken from the primary side of a delta-wye transformer feeding a 3000KW induction heater utilized to harden metal tubing used in drilling oil and gas wells.

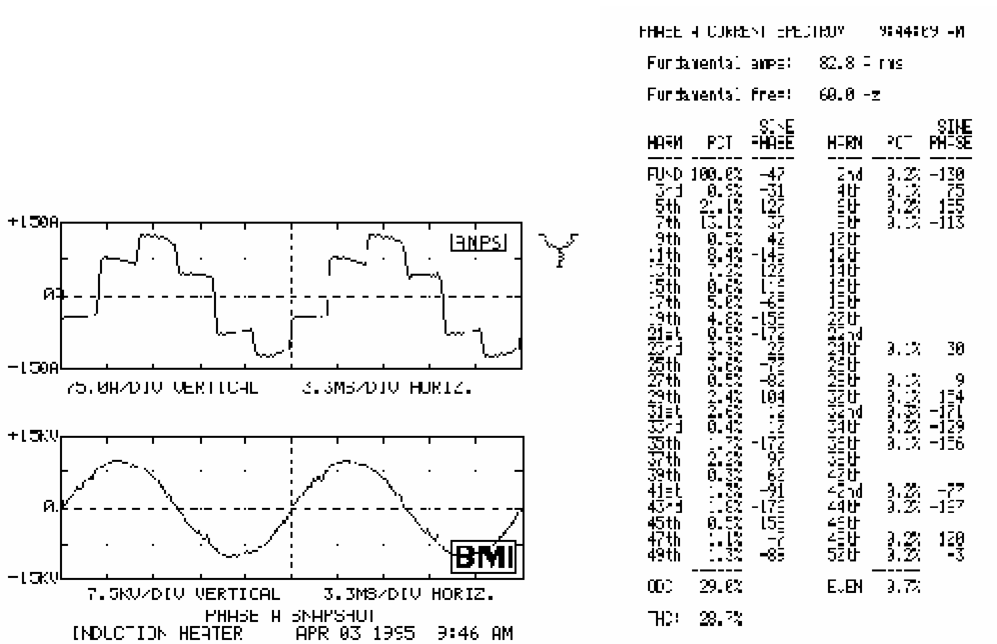


Figure 5.2.7. Example waveform and harmonic spectrum for induction heating load (primary of delta-wye step down transformer)

Control of induction heaters is achieved by delaying the firing angle of the SCRs resulting in the same poor power factor as DC drives. Power is only required when material is being heated. Therefore, the demand of an induction heater can be very sporadic depending on the continuity of material flow. This is illustrated in the power trend below.

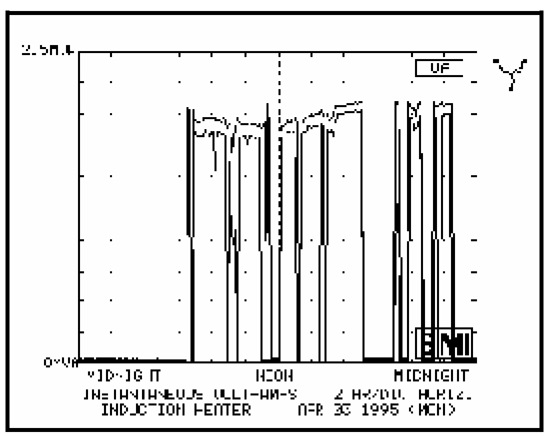


Figure 5.2.8. Induction heating load as a function of time (24 hour period).

SCR Controlled Resistive Heating. Diffusion furnaces in semiconductor manufacturing facilities often use resistance heaters with SCR controls. These are also important sources of harmonics (as well as voltage notching). The circuit for this type of load is quite simple. It is basically the same as a light dimmer, except it is a three phase load. The harmonic current components for this type of load are a function of the SCR firing angle which varies with the load. The figures below provide an example waveform and spectrum for a specific firing angle (Figure 5.2.9) and a plot of the harmonic current as a function of the SCR firing angle (Figure 5.2.10).

Figure 5.2.9. Example waveform and spectrum for SCR-controlled resistance heater (diffusion furnace).

Figure 5.2.10. SCR-controlled resistance heater harmonic current components as a function of the SCR firing angle (note that the harmonic currents are referred to the full load current with the SCRs turned completely on)

Other Heating Processes. Other types of heating processes that can result in significant harmonic generation include microwave heating, infrared heating, and plasma heating. Most of these electro-technologies use ac/dc converters as part of the power supply. Therefore, the characteristics are often similar to the characteristics discussed for induction heating.

5.3 Power Factor Correction Considerations

Power factor correction is often an important consideration for industrial facilities. Harmonic concerns should always be evaluated as part of a power factor correction evaluation, regardless of whether or not the facility has harmonic producing loads.

5.3.1 Resonance Concerns

The addition of power factor correction capacitors at the low voltage level (e.g. 480 volts) causes a parallel resonance between the capacitors and the system source inductance (see below). Harmonic current components that are close to the parallel resonant frequency are magnified. Higher order harmonic currents at the point of common coupling are reduced because the capacitors are a low impedance at these frequencies. At the parallel resonant frequencies, the magnified currents can cause excessive voltage distortion and significant harmonic problems within the facility.

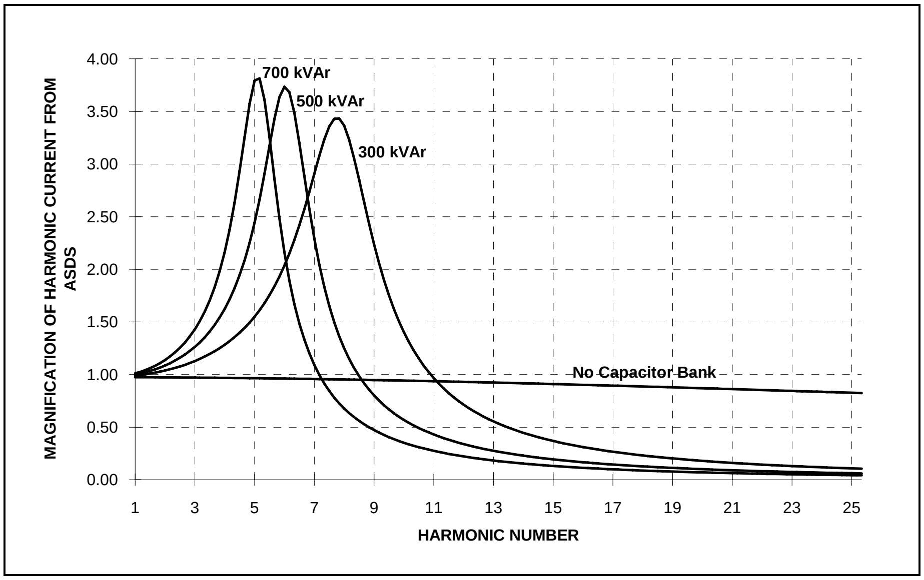


Figure 5.3.1. Effect of capacitor additions on the harmonic current at the PCC (the curves give a magnification factor as a function of frequency for currents generated within the facility)

The figure is based on the circuit parameters for the example system described in Section 5.2.1. It illustrates that typical sizes of power factor correction capacitors will result in magnification of the fifth and seventh harmonic components from ASDs or other nonlinear loads. This makes it even more difficult to meet the IEEE-519 harmonic current limits. Basically, power factor correction capacitors should not be used without tuning reactors if nonlinear loads are a significant percentage of plant load (e.g. > 10%).

5.3.2 Power Factor Correction with Tuned Capacitors

The simplest method to provide some level of harmonic control and also accomplish power factor correction requirements is to add the power factor correction in the form of tuned capacitor banks. This prevents magnification of any characteristic harmonic components from the harmonic producing loads.

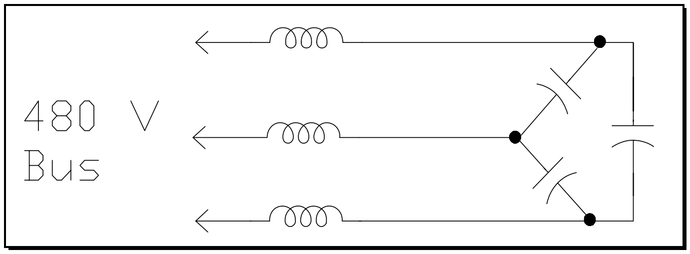


Figure 5.3.2. Typical tuned capacitor bank configuration.

The tuned frequency for the series reactor/capacitor combination is selected somewhere below the fifth harmonic (e.g. 4.7) to prevent a parallel resonance at any characteristic harmonic. The figure below illustrates the effect of the tuned bank on the harmonic currents at the point of common coupling. Significant reduction of the fifth harmonic from the ASDs or other nonlinear load is obtained and there is some reduction at all the harmonic components (i.e. no magnification).

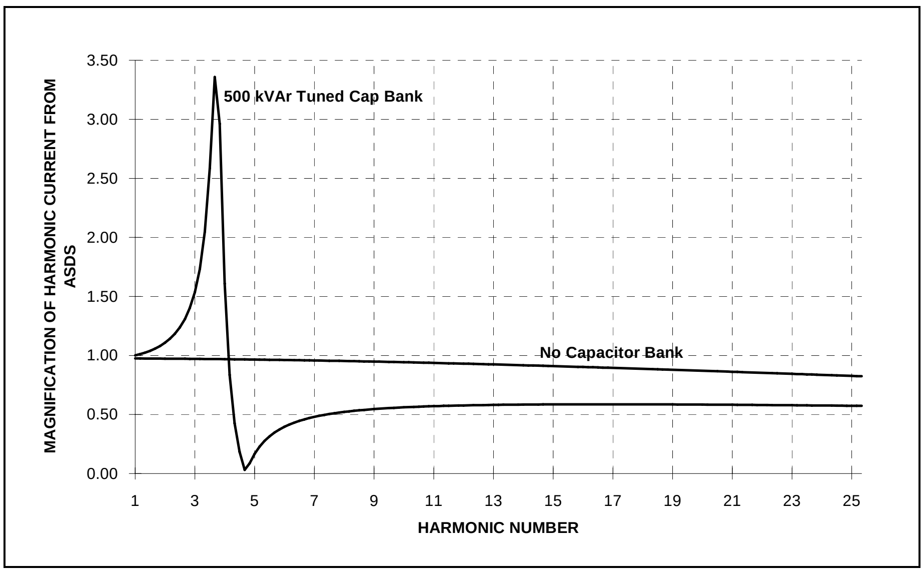


Figure 5.3.3. Effect of tuned capacitor bank on the harmonic current at the PCC (magnification factors for current generated within the facility).

Evaluation for Typical ASD Waveforms. With a tuned capacitor bank, the seventh or the eleventh harmonic component from the ASDs will be the limiting component when evaluating the IEEE-519 limits. Figure 5.3.4 and figure 5.3.5 plot both of these harmonic components at the PCC as a function of the plant ASD loading with a 500 kVAr tuned bank (tuned to 4.7). The figure shows that the seventh harmonic is the limiting case for a TYPE 1 current waveform. The ASD loading should be limited to about 35% of the maximum plant load in this case.

The eleventh harmonic is the limiting case for a TYPE 2 current waveform when a tuned bank is used to control the lower order harmonics. The figure shows that approximately 60% of the maximum plant load can be ASDs in this case. Actually, the ASD loading could even be somewhat higher than this if there are multiple ASDs because some cancellation should be expected at these higher harmonic frequencies.

Design of the 4.7th tuned bank must take into account the maximum harmonic generation levels in the plant and also the harmonics which may be absorbed from the higher voltage power system. It is a good conservative practice to assume that all the fifth harmonic from the ASDs will flow in the tuned bank and then estimate the contribution from the system using a measurement (or estimate) of the system 5th harmonic voltage distortion.

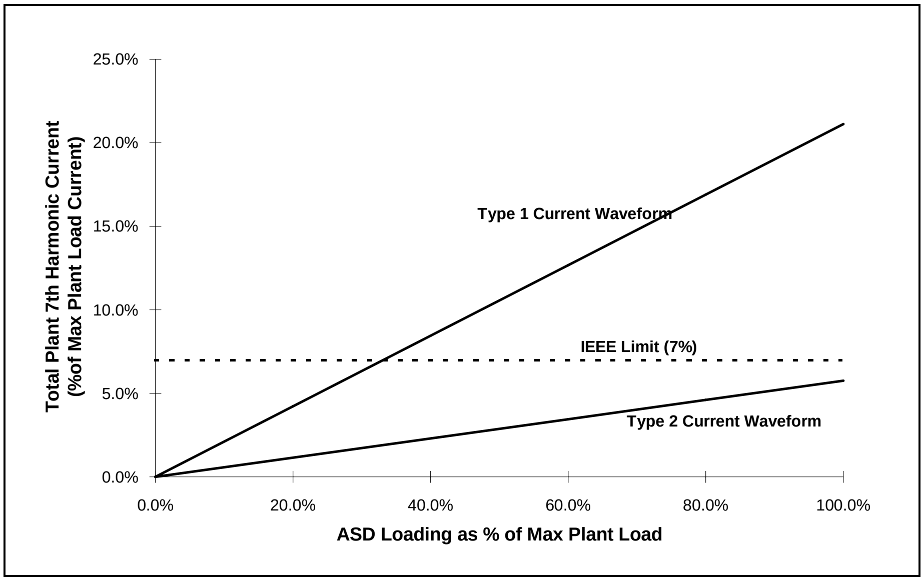


Figure 5.3.4. Seventh harmonic component of the plant load current as a function of ASD loading with a 4.7 tuned bank.

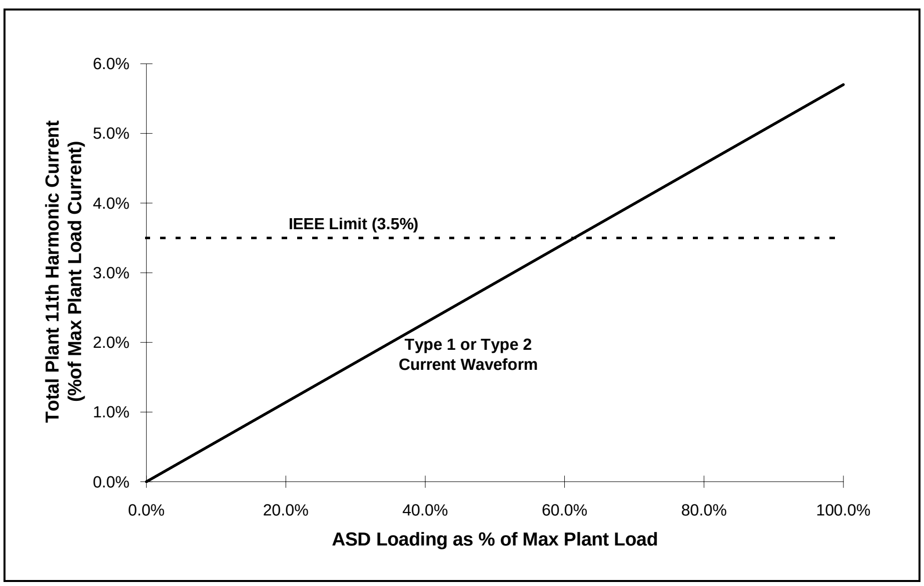


Figure 5.3.5. Eleventh harmonic component of the plant load current as a function of ASD loading with a 4.7 tuned bank.

5.3.3 Absorbing Harmonics from the Supply System

Any time power factor correction capacitors are added, harmonic considerations should be evaluated. Even if no nonlinear loads operate within a facility, a resonant capacitor bank could interact with harmonics from the utility supply system adversely affecting the capacitors as well as other equipment within the facility. Capacitors applied on low voltage systems will be series resonant with the step-down transformer at some harmonic, *h*, where

$h =$ [TKVA (Zpu, Kvar)],

TKVA = Transformer nameplate rating in KVA

Zpu = Transformer impedance in per unit

Kvar = Capacitor bank rating in Kvar.

If *h* is near a predominant harmonic (typically 5th or 7th), the transformer/capacitor combination becomes a sharply tuned filter providing a low impedance path for harmonics near *h*.

Actual case studies reveal when such a resonant condition exists, voltage distortion in excess of the 5% recommended limit is possible on the low voltage bus even if distortion on the utility system is within recommended limits. Nuisance fuse and breaker operations, failed capacitors, and reduced life expectancy of other connected equipment has occurred.

5.3.4 Automatic Power Factor Correction Systems

Automatic Power Factor Systems are most common at facilities where the utility bills on kVA demand. These facilities achieve the greatest savings when they operate at unity Displacement Power Factor (dPF). This is also the operating point to maximize use of transformer capacity.

Example. A facility is served from a 1000 kVA transformer and has a base load of 200 kVA at 0.85 dPF. A 1000 HP DC Drive operates between 150 and 750 kVA. To maintain unity dPF, a 700 kVAr automatic power factor correction system steps in capacitors with fourteen 50 kVAr increments.

Figure 5.3.6 represents the power system configuration for the facility under discussion. As the DC Drive load changes, the automatic power factor correction system adjust to meet the new power requirements. As the amount of capacitance in the system changes, so does the parallel resonance. Figure 5.3.7 shows that 250 kVAr creates a resonance near the 7th harmonic and 500 kVAr resonates near the 5th.

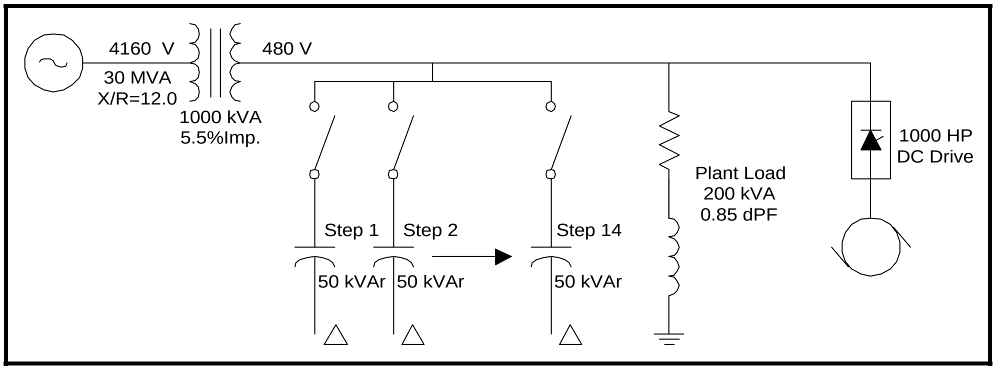


Figure 5.3.6. System One-Line Diagram

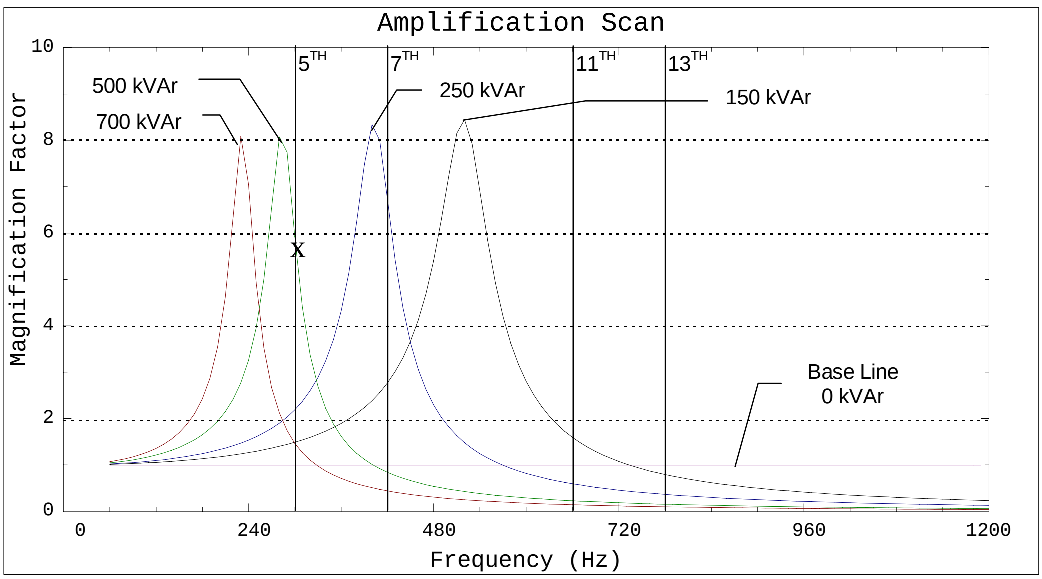


Figure 5.3.7. Magnification factor vs. frequency for multiple steps of capacitance.

The magnification plots give the magnification that can be expected for harmonics produced within the facility. With the automatic system, many resonance points are possible and some of them could cause magnification of harmonic components. The likelihood of problems depends on the operating conditions of the facility and which capacitor configurations occur for extended periods of time (some capacitor conditions may only occur for short periods while the controller is changing from one power factor compensation level to another).

5.4 Filter Considerations

5.4.1 Passive Tuned Filters

The use of tuned capacitor banks for power factor correction and harmonic control was discussed in Section 5.3.2. These tuned capacitor banks act as a harmonic filter for the fifth harmonic. They will have to absorb some percentage of the fifth harmonic current from loads within the facility and also will have to absorb fifth harmonic current due to fifth harmonic voltage distortion on the utility supply system.

IEEE 519-1992 permits the voltage distortion on the supply system to be as high as 3% at an individual harmonic on medium voltage systems. Therefore, this level of fifth harmonic distortion should be assumed for filter design purposes. The filter design spreadsheet below illustrates the calculation of important filter design parameters using this assumption and an assumption that the nonlinear loads in the facility consist of 500 hp of ASDs.

Low Voltage Filter Calculations: Example for Harmonics Application Guide

SYSTEM INFORMATION:

Filter Specification:	5	th	Power System Frequency:	60	Hz
Capacitor Bank Rating:	600	kVAr	Capacitor Rating:	600	Volts
Rated Bank Current:	577	Amps		60	Hz
Nominal Bus Voltage:	480	Volts	Derated Capacitor:	384	kVAr
Capacitor Current (actual):	461.9	Amps	Total Harmonic Load:	500	kVA
Filter Tuning Harmonic:	4.7	th	Filter Tuning Frequency:	282	Hz
Cap Impedance (wye equivalent):	0.6000	Ω	Cap Value (wye equivalent):	4421.0	uF
Reactor Impedance:	0.0272	Ω	Reactor Rating:	0.0720	mH
Filter Full Load Current (actual):	483.8	Amps	Supplied Compensation:	402	kVAr
Filter Full Load Current (rated):	604.7	Amps			
Transformer Nameplate:	1500	kVA	Utility Side Vh:	3.00	% Vh
(Rating and Impedance)	6.00	%	*(Utility Harmonic Voltage Source)*		
Load Harmonic Current:	35.00	% Fund	Load Harmonic Current:	210.5	Amps
Utility Harmonic Current:	134.5	Amps	Max Total Harm. Current:	345.0	Amps

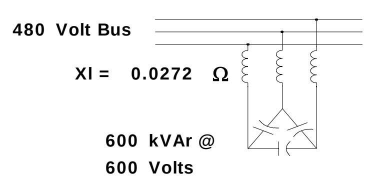
CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	594.2	Amps	Fundamental Cap Voltage:	502.8	Volts
Harmonic Cap Voltage:	71.7	Volts	Maximum Peak Voltage:	574.5	Volts
RMS Capacitor Voltage:	507.8	Volts	Maximum Peak Current:	828.8	Amps

CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	⟷	96%
Current:	180%	⟷	103%
KVAr:	135%	⟷	87%
RMS Voltage:	110%	⟷	85%

FILTER CONFIGURATION:



FILTER REACTOR DESIGN SPECIFICATIONS:

Reactor Impedance:	0.0272	Ω	Reactor Rating:	0.0720	mH
Fundamental Current:	483.8	Amps	Harmonic Current:	345.0	Amps

Figure 5.4.1 Example filter design spreadsheet.

It is usually a good idea to use capacitors with a higher voltage rating in filter applications because of the voltage rise across the reactor at the fundamental frequency and due to the harmonic loading. In the example, 600 volt capacitors are used for a 480 volt application.

In special cases where tuned capacitor banks are not sufficient to control harmonic current levels, a more complicated filter design may be required. Individual tuned steps will be needed to control the individual harmonic components of concern. This is often difficult and a more detailed harmonic study will normally be required. The figure below gives the general procedure for designing these filters.

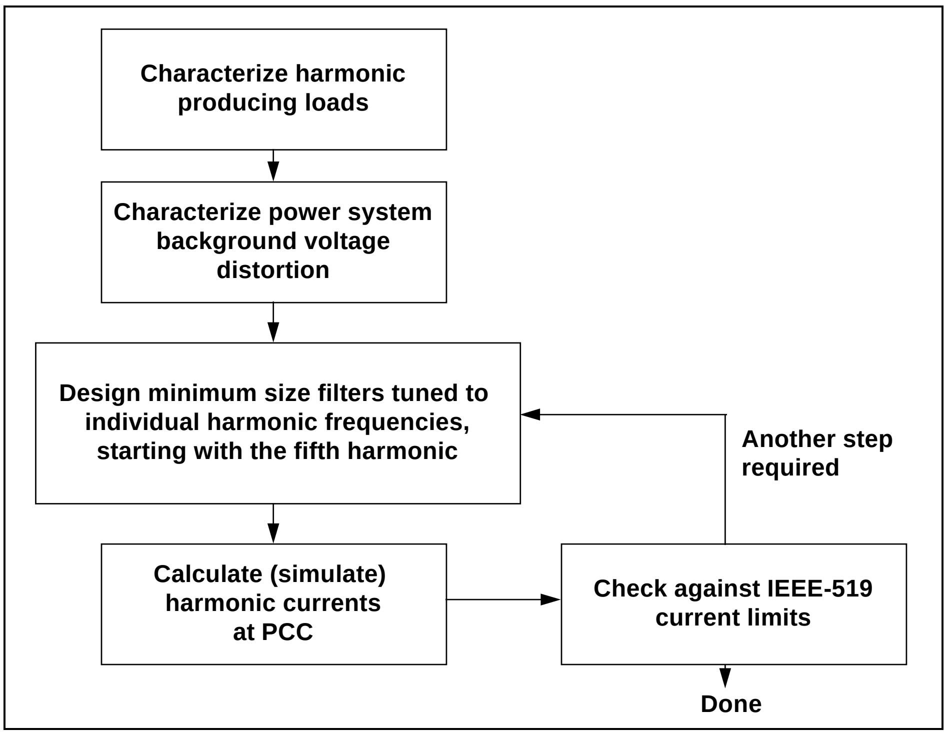


Figure 5.4.2. General procedure for designing individually tuned filter steps for harmonic control.

There are a few important problems with this approach:

- Significant derating of the filters may be required to handle harmonics from the power system. Including the contribution from the power system is part of the process of selecting a minimum size filter at each tuned frequency - they must be large enough to absorb the power system harmonics.
- The design may result in excessive kVAr due to the number of filter steps and filter sizes needed for harmonic control. This would result in leading power factor and possible overvoltages.
- In some rare cases, even three or four steps (5,7,11 or 5,7,11,13) may not be sufficient to control the higher order harmonic components to the levels specified in IEEE 519.

If these problems result in unacceptable filter designs, it may be possible to control the harmonics with modifications to the nonlinear loads (e.g. multi-pulse configurations or active front ends) or electronically with active filters.

Example problem with filter ratings. Before installing a harmonic filter for a 700 HP ASD, facility personnel contacted the local utility to acquire the harmonic distortion limits. The utility engineer referenced the IEEE 519-1981 voltage distortion limits. The filter was designed to meet the specified limits. During start-up of the filter, it was discovered that 5th harmonic distortion on the utility feeder combined with the current being produced by the drive exceeded the filter design limits. The facility was fed through a 750 kVA transformer which was connected to Circuit 2, of a two feeder 20 MVA, 12.47 kV substation served from 138 kV transmission line.

A harmonic summary was collected with a power analyzer. Figure 5.4.3 provides a trend of the fifth harmonic voltage level over a 24 hour period. The motor was only operated between 10:15 and 11:45. The trends revealed that the Voltage THD approached 5.0% and the 5th harmonic voltage exceeded 3%. The notch in the 5th harmonic voltage distortion is during the brief period that the filter was on line. Three phase customers on Circuit 2 were spot checked for harmonic current injection, and no culprit was found. Investigation of Circuit 1 revealed a 2800 kVA customer with the significant load being six-pulse bridge rectifiers for induction furnaces.

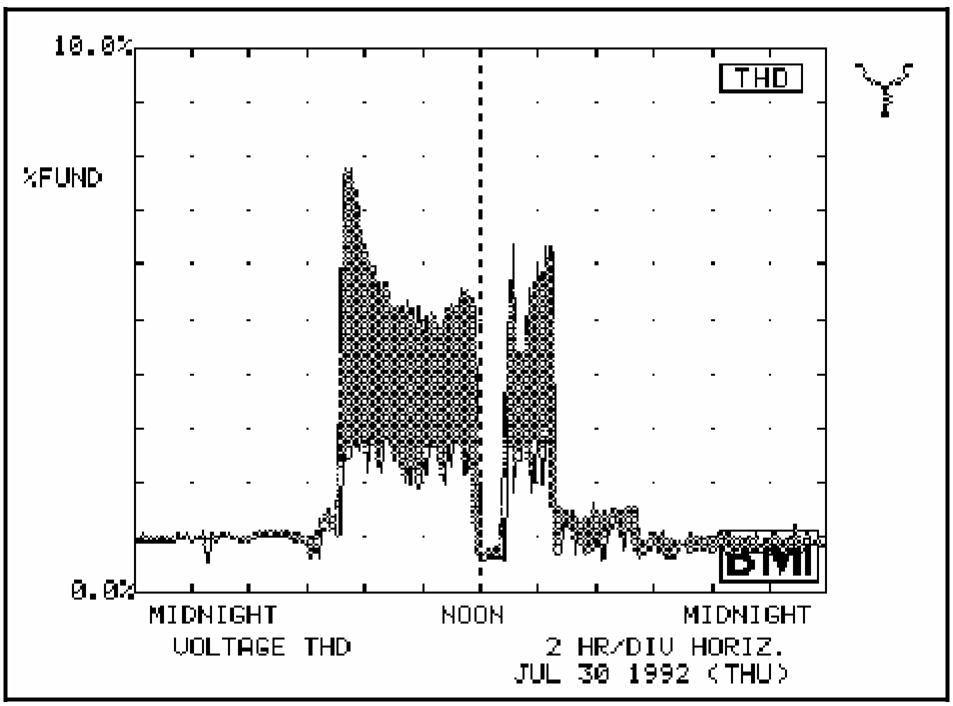


Figure 5.4.3. Trend of 5th harmonic voltage over a 24 hour period showing the effect of the filter around noon.

The induction furnaces did not inject enough current to create the measured voltage distortion. With Circuit 2 having several capacitors connected, it was suspected that the circuit was in resonance. To resolve the resonance problem, all but one capacitor bank was removed from both circuits. Computer simulations showed that strategic switching of the capacitors bank could not guarantee avoiding resonance. The induction furnace facility was requested to install filters to minimize the harmonic current injected to limit the effect of the resonance condition on the utility feeder.

When applying a harmonic filter, there is no guarantee that the measured utility voltage distortion at the time of design will remain at that level. For instance, once the induction furnace plant installs harmonic filters, the utility distortion may fall to one or two percent. A filter designer assumes that this will always be the distortion level. Six months later a customer adds a large harmonic load without installing filters and excites the resonance condition causing the filter to overload. To reduce the risk of this occurring, filters need to be designed expecting that the filter will have to endure the IEEE 519 voltage distortion limits, even if measured values are less.

5.4.2 Filter Performance Verification Measurements

Once a harmonic filter is installed, it is important to verify its performance and the magnitude of critical parameters of the individual components. Verifying the performance of the filter assures that it is doing what the manufacturer said it would, along with providing valuable information to improve computer simulations. Measurement of critical parameters is important to assure that the filter rating is not exceeded. In addition, this gives a bench mark for evaluating the filters condition as it remains in service.

Example performance evaluation. Figure 5.4.4 shows the meter setup for measuring the harmonic filter performance. The diagram shows the ideal situation where one current transformer (CT) is used to measure the load, one for the filter, and one CT for the transformer. Space constraints and load connection points may make this connection more difficult. It is important to use a meter that will sample all of the transducer channels simultaneously and that all the probes be connected to a common phase so that a correlation between the three currents may be made. The values in Table 5.4.1 were taken when the Sample System, shown in Figure 5.4.4, had a drive operating at 500 kVA and 500 kVAr of harmonic filter was connected.

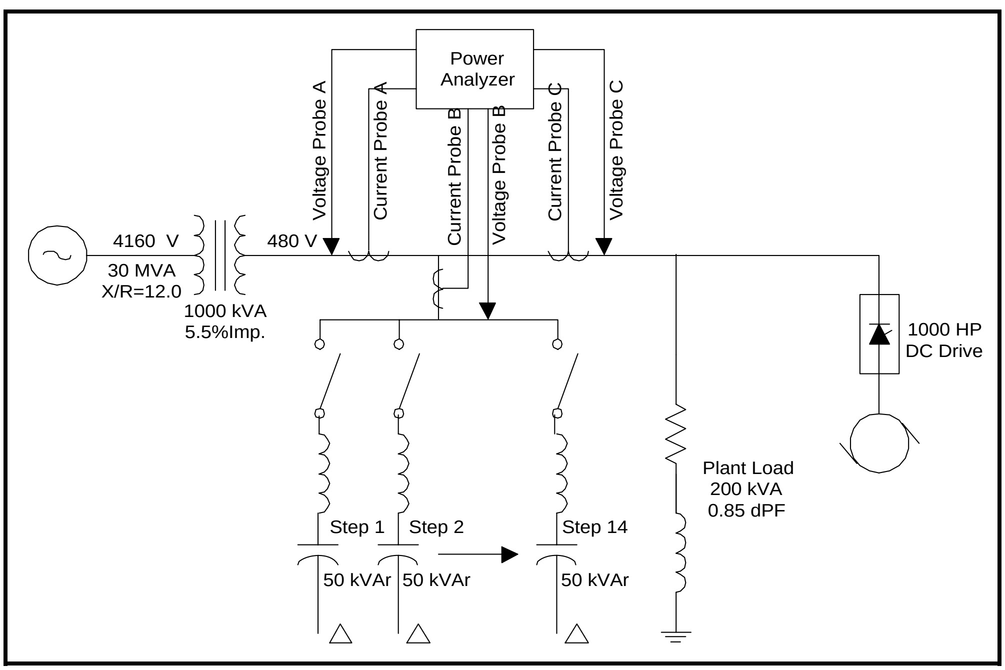


Figure 5.4.4. Meter setup for filter performance measurements.

Table 5.4.1. Shunting of Harmonic Current by the Filter

Harmonic	Transformer Current Probe A (Amps)	Filter Current Probe B (Amps)	Load Current Probe C (Amps)
5	8	130	138
7	22	43	65
11	12	16	28
13	9	12	21

Table 5.4.1 shows that of the 138 A of 5th harmonic current being injected into the system, the filter shunts away 130 A, leaving 8 A to the utility power system. For this simple example, the phase angles have been omitted. If utility voltage distortion were present, the filter would absorb additional harmonic current from the power system.

To create a bench mark for comparison with future tests, critical parameters should be recorded. Table 5.4.2 shows typical measurement results from such a test. The filter manufacture needs to provide the information shown in the rated column. The measured values are obtained using the following techniques.

Table 5.4.2. Example filter verification table.

Parameter	Rated	Measured
Wye Equiv. Cap. Range (uF)	575 - 633	610
Peak Voltage (Vpk)	800	692
Current (Arms)	108	64
Reactive Power (kVAr)	68	56
RMS Voltage (Vrms)	528	500
Inductance (uH)	498 - 553	524
5th Harmonic Current (Arms)	45	13
7th Harmonic Current (Arms)	10	5
11th Harmonic Current (Arms)	5	2
13th Harmonic Current (Arms)	5	2
Total Current (Arms)	80	64
Harmonic Filter Tuned Harmonic	4.48 - 4.95	4.69

To find the capacitor parameters, the meter setup in Figure 5.4.5 is used. It is important that the voltage probes be connected at the terminals of the capacitor. The power analyzer will display the values of Peak Voltage, Current, Reactive Power, and RMS Voltage. These values are recorded and compared with the rated values provided by the manufacturer.

A capacitance meter is used to measure the terminal to terminal capacitance. The capacitance should be converted to the single phase wye equivalent so that the filters tuned frequency may be easily calculated. If the terminal to terminal capacitance values are well balanced, the single phase wye equivalent will be two times that measured.

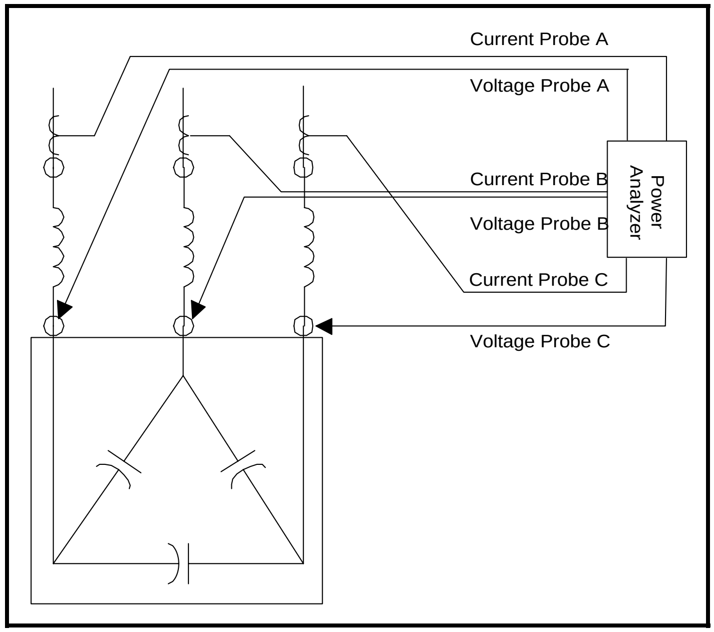


Figure 5.4.5. Meter setup for capacitor limit measurement.

To measure the reactor parameters, the meter is setup in the single phase mode as shown in Figure 5.4.6. The impedance of the reactor will be measured at the frequency the filter was designed to shunt harmonic current. For this example this is the 5th harmonic and the results were:

$$V_{LN} = 12.8\angle 171^0 V$$
$$I_{5th} = 12.95\angle 82^0 A$$
$$Z_{\mathrm{Re}actor} = 0.988\angle 89^0 \Omega$$
$$X_{\mathrm{Re}actor} = j0.987\Omega$$
$$L = \frac{X_{\mathrm{Re}actor}}{2\pi f\, h} = \frac{0.987}{377\cdot 5} = 524\mu H$$

For automatic systems, it is important to take measurements at different operating points. The characteristics of iron core reactors will change slightly as the load current changes. It is recommended that the test be done at the two extreme operating conditions. The reactors will continue to handle less current as more steps come on line. The reactor current spectra are displayed by the Power Analyzer.

The frequency which the filter is tuned for may be determined by the equation:

$$h_{Filter} = \frac{1}{2\pi f\sqrt{L\cdot C}} = \frac{1}{377\sqrt{524\cdot 610\cdot 10^{-12}}} = 4.69$$

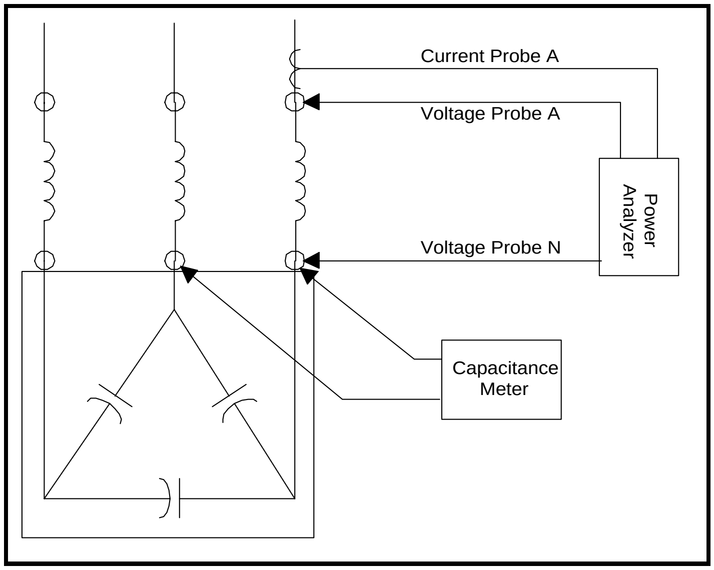


Figure 5.4.6. Meter setup for reactor limit measurement.

In the example of Table 5.4.1, the filter absorbs 94% of the harmonic currents generated from the drive. This is atypical, due to the weakness of the utility power system in this example. Expected performance from a harmonic filter, tuned near the 5th harmonic, would be to shunt 70% to 85% of the 5th harmonic current being injected into the system. A filter creates a current divider with the impedance of the transformer feeding the load bus and the utility feeder. In the case above, if the utilities three phase fault MVA were 130 instead of 30 and the transformer were 2500 kVA instead of 1000 kVA (a stiffer power system) the harmonic filter would only absorb 80% of the 5th harmonic current injected. For this reason, it is important for the filter designer to consider the system characteristics so that the desired performance may be achieved.

5.4.3 Active Filters

The active filter concept uses power electronics to produce harmonic components which cancel the harmonic components from the nonlinear loads. These active filters are relatively new and a number of different topologies are being proposed. Within each topology, there are issues of required component ratings and methods of rating the overall filter for the loads to be compensated. The most common active filter configuration is based on a pulse-width modulated (PWM) voltage source inverter that interfaces to the system through a system interface filter as shown in Figure 5.4.7 [10]. In this configuration, the filter is connected in parallel with the load being compensated. Therefore, the configuration is often referred to as an active parallel filter. Figure 5.4.7 illustrates the concept of the harmonic current cancellation so that the current being supplied from the source is sinusoidal.

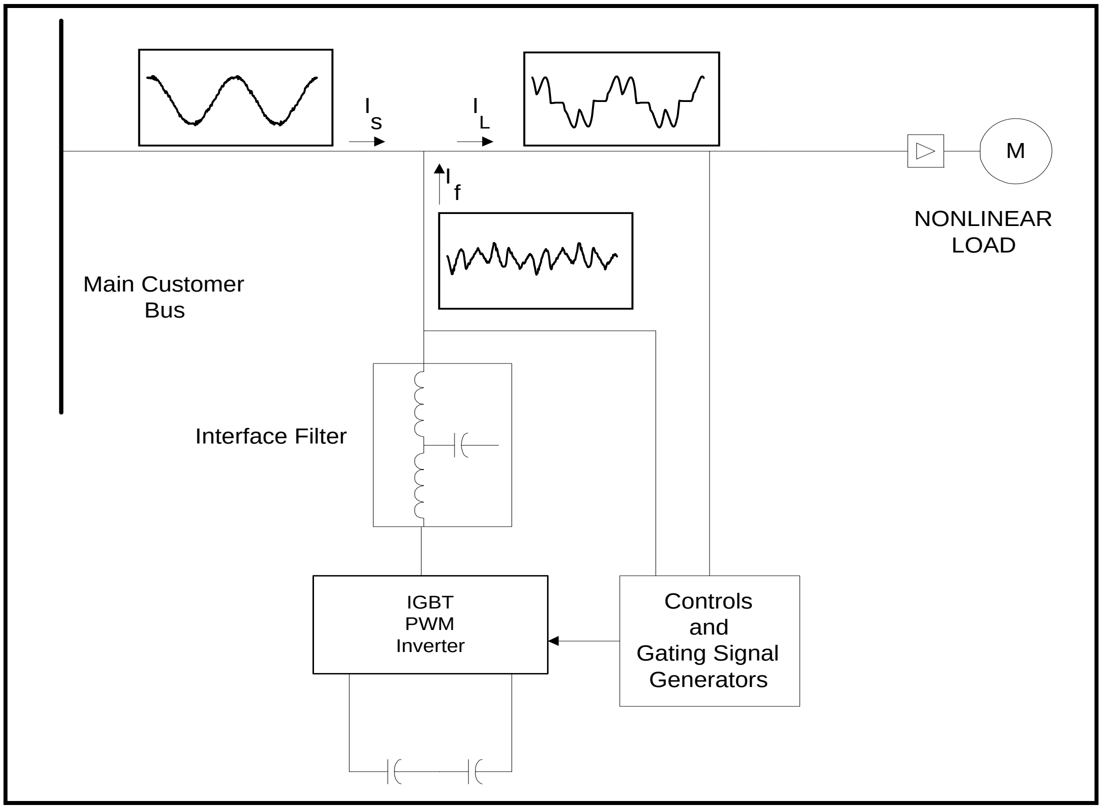


Figure 5.4.7. Diagram illustrating components of the shunt connected active filter with waveforms showing cancellation of harmonics from an ASD load.

Passive filter ratings must be coordinated with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

Another configuration that has been successfully demonstrated involves a series connected active filter designed to be a high impedance to harmonic currents and parallel connected passive filters to absorb the harmonic currents [11].

5.5 Voltage Notching Concerns

Adjustable speed ac drives (ASDs) 1000 hp and larger typically use phase-controlled rectifiers (SCRs) and a large dc link inductor to supply a relatively constant dc current to the inverter. This is known as a current source inverter (CSI) configuration. The input rectifier may be configured as a six pulse, twelve pulse, or even higher pulse number rectifier, depending on harmonic control requirements. For dc drive applications, phase-controlled rectifiers are used to supply the dc current directly to the dc motor.

All of these rectifier configurations result in voltage notching due to the commutating action of the controlled rectifier. Whenever the current is commutated from one phase to another, there is a momentary phase-to-phase short circuit through the rectifier switching devices (SCRs, in this case). For a six pulse converter, this happens six times each cycle. The voltage notch is defined by its duration and its depth. The duration (commutation period) is determined by the source inductance to the drive and the current magnitude. The depth of the notch is reduced by inductance between the observation point and the drive (e.g. isolation transformer or choke inductance). An example waveform illustrating simple notches resulting from a drive operation is shown in Figure 5.4.8.

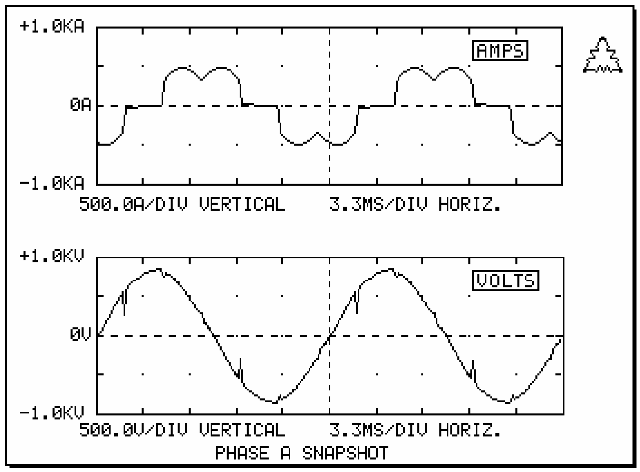


Figure 5.4.8. Example of voltage notches caused by converter commutation.

On most systems, problems with voltage notching can be minimized by applying sufficient isolation reactance at the drive. This limits the notch magnitude on the source side of the isolation reactance [12]. However, on some systems, the notches that appear at the system level can still be significant. If there is not much resistive load on a system like this, the notches can excite the natural frequency of the distribution system (determined by the capacitance of lines, cables, and capacitor banks in parallel with the system source inductance) and cause significant distortion in the voltage waveform [13].

Example of distribution system oscillations caused by notching. Figure 5.4.9 shows an example 25 kV distribution system supplied through a 10 MVA transformer from the 144 kV transmission system. The customer causing the notching problems has a 6000 hp induction motor supplied through an adjustable speed drive. This drive is at a 4.16 kV bus supplied through a 7.5 MVA transformer. Harmonic filters (5th, 7th, 11th) are included to control the lower order characteristic harmonics of the six pulse drive.

Another customer on a parallel feeder supplied from the same 25 kV bus has motor loads at both 4.16 kV (800 hp motor) and 480 volts. The 800 hp motor includes surge capacitors for transient protection. The customer also has power factor correction capacitors at the 480 volt bus. These lower voltage surge capacitors and power factor correction capacitors have the potential to magnify the oscillations which occur on the distribution system.

Operation of the 6000 hp motor and drive resulted in significant oscillations on the 25 kV supply system. These oscillations caused clocks to run fast at the customer with the 6000 hp motor (clocks were fed separately from the 25 kV system) and failure of surge capacitors on the 800 hp motor at the customer located on the parallel feeder.

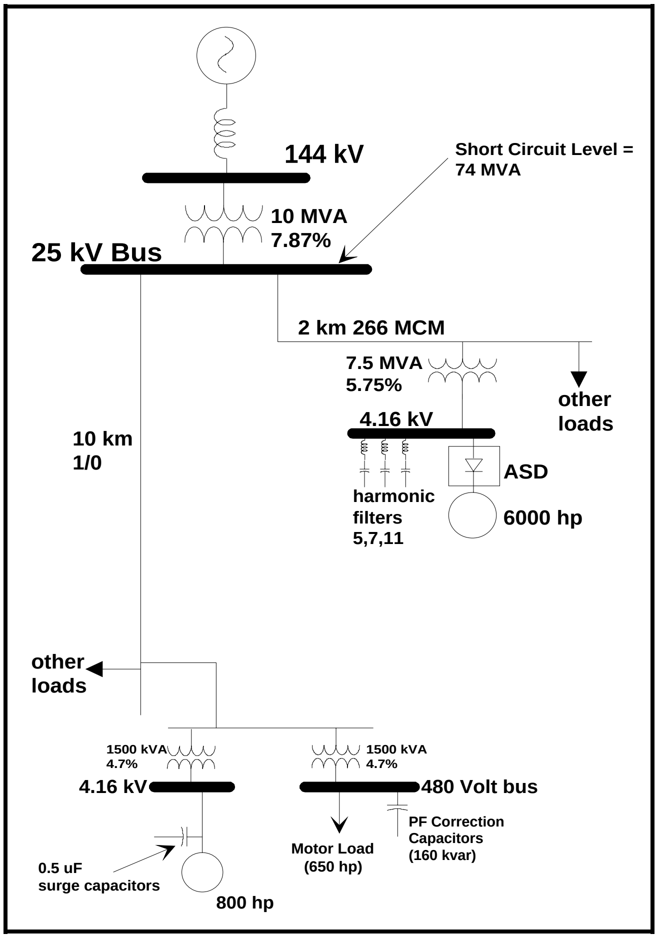


Figure 5.4.9. One line diagram for the example system illustrating a notching problem.

Figure 5.4.10 illustrates the measured waveforms on the 25 kV supply system. The oscillations have a primary frequency component near the 60th harmonic. In this case, the natural frequency is the result of the line capacitance from approximately 12 km of overhead line in parallel with the system source inductance. Note that the oscillations are excited six times per cycle corresponding to the six-pulse operation of the drive. This problem was resolved by adding a shunt capacitor bank on the distribution system to chnage the system resonance to a lower frequency. This solution must be implemented carefully to avoid exciting a lower order characteristic frequency of the rectifier operation [13].

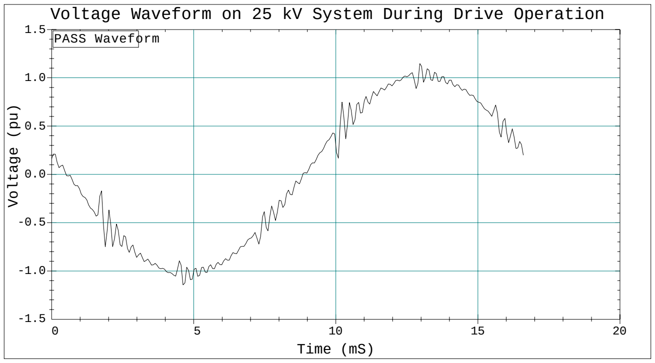


Figure 5.4.10. Voltage waveform on the 25 kV system illustrating oscillations excited by the notching.

5.6 Other Harmonic Producing Loads

5.6.1 Arc Furnaces

Inter Harmonics

Time Varying

Mike Stears - NIPSCO

5.6.2 Semiconverters

Even Harmonics

Rubber and Plastics paper

5.6.4 Cycloconverters

Interharmonics

Rolling Mill Applications - Trico Steel

60 Hz/25 Hz applications - PECO

5.6.5 Aluminum Rectifier Loads

high current, dc processes

very high pulse numbers

6.0 APPLYING HARMONIC LIMITS FOR COMMERCIAL CUSTOMERS

Evaluation of harmonic distortion in commercial buildings is becoming increasingly important for a number of reasons:

- An increasing percentage of building load consists of electronic equipment supplied by switched-mode power supplies. These power supplies can have input currents with very high harmonic content.

- New high efficiency fluorescent lighting uses electronic ballasts and can have higher harmonic content than conventional fluorescent lighting using magnetic ballasts.

- Much of the HVAC load in buildings is being converted to adjustable speed motor drives in order to improve overall efficiency. These drives produce significant harmonic currents.

The harmonic currents from these different sources can result in concerns for neutral conductor overheating, transformer overheating, and interference with communication systems. The cumulative effects of the different sources depends on the equipment characteristics and the overall system design.

The overall harmonic levels depend on how the individual harmonics from these different loads combine. In fact, there is usually significant harmonic cancellation in commercial facilities due to the variety of different load types. Most harmonic problems are localized to specific 120/208 systems that supply a significant percentage of single phase electronic load. The harmonic current limits specified in IEEE 519-1992 for the overall facility are very seldom exceeded.

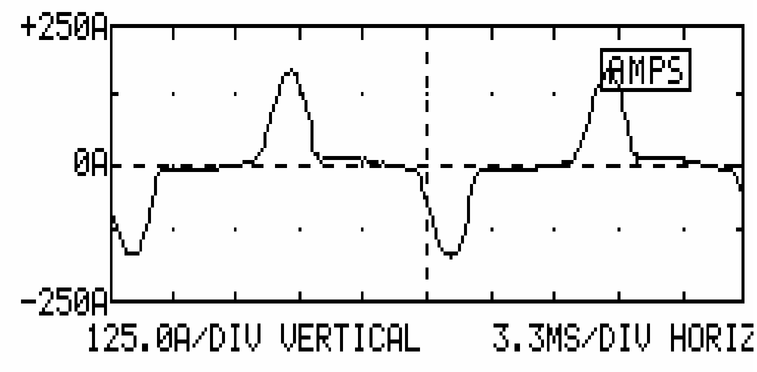
The voltage distortion levels depend on the circuit impedances as well as the harmonic generation characteristics. The circuit impedance is usually dominated by step down transformers and conductor impedances because power factor correction is not commonly applied within commercial facilities. If power factor correction is considered for a commercial application, the resonance concerns described in Section 5.3 should be evaluated carefully.

This section provides some guidelines for evaluating harmonic concerns in a commercial facility even though the IEEE 519 limits at the service entrance usually are not exceeded. These guidelines are equally applicable to office loads within industrial facilities.

6.1 Important Load Types for Commercial Facilities

In commercial buildings, sources of harmonic current generation are usually small in size and large in number. Most nonlinear loads in a commercial facility fall into one of three categories:

- **Electronic Power Supplies**. Almost all productivity equipment used in the modern office environment falls into this category. Personal computers, workstations, and peripheral devices such as printers and copiers all contain circuitry for converting utility-supplied ac voltage to dc which is supplied to microelectronics components. These loads are normally single-phase (although power supplies for larger mainframe or minicomputer systems may be three-phase) and are supplied from receptacles at 120 v. UPS systems providing backup power to a wide variety of loads also fall in this category. Rated power for single-phase electronic power supplies can range from 200 W, typical of many personal computer systems, to several kW, as might be found in a sophisticated engineering workstation or file server. A line current measurement from a branch circuit serving exclusively computer load is shown below.

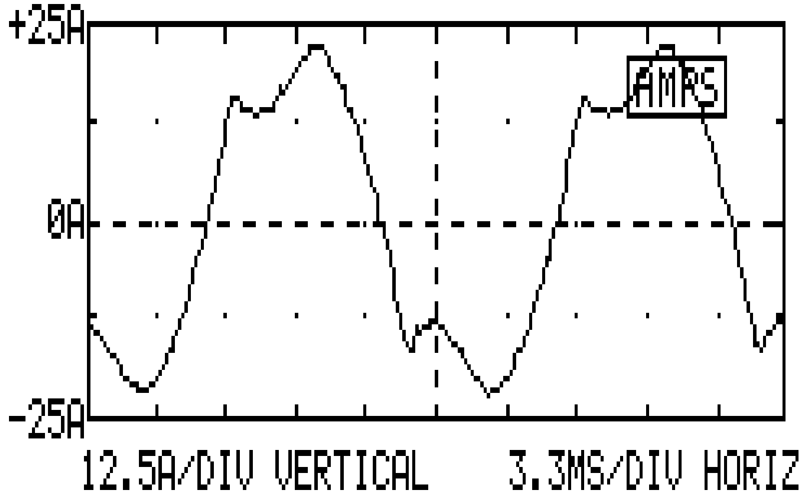


Fundamental amps: 58.5 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-37°	2nd	0.2%	65°
3rd	65.7%	-97°	4th	0.4%	-72°
5th	37.7%	-166°	6th	0.4%	-154°
7th	12.7%	113°	8th	0.3%	112°
9th	4.4%	-46°	10th		
11th	5.3%	-158°	12th	0.1%	142°
13th	2.5%	92°	14th	0.1%	65°
15th	1.9%	-51°	16th		
17th	1.8%	-151°	18th		
19th	1.1%	84°	20th		
21st	0.6%	-41°	22nd		
23rd	0.8%	-148°	24th		
25th	0.4%	64°	26th		
27th	0.2%	-25°	28th		
29th	0.2%	-122°	30th		
31st	0.2%	102°	32nd		
33rd	0.2%	56°	34th		

Figure 6.1.1. Phase Current Waveform and Spectrum for Circuit Supplying Electronic Loads

- **Fluorescent Lighting**. The relationship between voltage across and current through a fluorescent lamp is nonlinear due to the characteristics of the electrical arc which is responsible for illumination. However, harmonic current generation by fluorescent lighting systems is strongly influenced by the type of lamp ballasts used. Although fluorescent lamps with magnetic ballasts draw nonsinusoidal currents, there is currently more concern about electronic ballasts. The harmonic generating characteristics of electronic ballasts vary over a range from about 8-35%. Harmonic current generation in electronic ballasts is due to the operation of a single-phase diode-bridge rectifier, just as is found in electronic power supplies. Passive power factor correction circuitry is usually used to reduce the distortion levels in the input current. A line current from a lighting circuit serving one common type of electronic ballast is shown below.

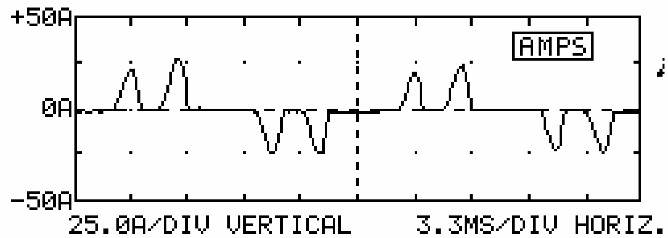


Fundamental amps: 15.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-124°	2nd	0.2%	136°
3rd	19.9%	-144°	4th		
5th	7.4%	62°	6th		
7th	3.2%	-39°	8th		
9th	2.4%	-171°	10th		
11th	1.8%	111°	12th		
13th	0.8%	17°	14th		
15th	0.4%	-93°	16th		
17th	0.1%	-164°	18th		
19th	0.2%	-99°	20th		
21st	0.1%	160°	22nd		
23rd	0.1%	86°	24th		
25th			26th		
27th	0.1%	161°	28th		
29th			30th		
31st			32nd	0.1%	156°

Figure 6.1.2. Input Current and Harmonic Spectrum for a Typical Fluorescent Light with Electronic Ballast

- **Adjustable-Speed Drives (ASDs) for HVAC**. Induction motors are being replaced by ASDs in fan and compressor applications for increased energy efficiency. A typical ASD for HVAC systems connects to the ac power system through a three-phase diode bridge rectifier circuit. An input current waveform to a small ASD in an HVAC application is shown below. On line UPS systems with three phase input rectifiers could have similar characteristics.



PHASE A CURRENT SPECTRUM 12:29:46 PM
Fundamental amps: 6.6 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-14°	2nd	3.8%	-85°
3rd	8.5%	-114°	4th	3.5%	-103°
5th	79.5%	145°	6th	0.3%	25°
7th	66.0%	124°	8th	2.5%	55°
9th	2.7%	11°	10th	1.7%	68°
11th	36.0%	-92°	12th	1.2%	132°
13th	21.8%	-118°	14th	1.2%	156°
15th	2.4%	22°	16th	0.3%	-136°
17th	10.4%	-23°	18th	0.8%	-92°
19th	8.0%	-79°	20th	0.9%	-117°
21st	1.4%	131°	22nd	0.5%	-105°
23rd	6.7%	39°	24th		
25th	4.5%	-2°	26th	0.3%	-12°
27th	0.9%	143°	28th	0.2%	76°
29th	3.7%	83°	30th	0.3%	42°
31st	3.1%	29°	32nd	0.4%	10°
33rd	0.4%	-110°	34th	0.1%	31°

Figure 6.1.3 Typical ASD Input Current and Harmonic Spectrum for HVAC Applications

A common element associated with the dominant sources of harmonic current generation in commercial facilities is the diode bridge rectifier. The "pulsed" nature of the ac input current is due to filter capacitance on the dc-side of the rectifier circuit. Another important feature of these loads is their displacement power factor. Since the individual diodes in the rectifier circuit cannot be controlled, and turn on and off in response to the voltages on the ac and dc sides of the bridge, the phase displacement between the fundamental frequency ac voltage and fundamental frequency ac current will remain nearly constant, at a value very close to zero. The corresponding fundamental frequency power factor, or displacement power factor, is then very near unity.

True power factor is a measure of the ratio between the actual power delivered and the product of rms voltage and rms current and can be quite poor for these nonlinear loads. This is mostly due to the high harmonic content in the current. Traditional utility schemes for metering reactive power respond to fundamental frequency phase displacement and will, for these loads, indicate a power factor very close to unity. The true power factor will be much lower, and will have effects on the power system similar to poor displacement power factor. In the case of an aggregate load consisting almost entirely of computers, for example, the displacement power factor may be above 0.95, with a true power factor as low as 0.6 to 0.7.

Because the displacement power factor for diode bridge rectifier load is constant, the input current waveshape to an aggregate load of one of the three types described will look very much like the input current to an individual load. The waveform for a circuit serving electronic load given above is an example of this phenomena. This makes the task of computing the "equivalent" harmonic current sources within the facility much easier. By assuming a single, representative harmonic current spectrum for each of the described classes of nonlinear loads, an aggregate source as seen from the main can be approximated from the connected kVA or kW demand for each type of load.

6.2 Typical Harmonic Current Levels for Commercial Buildings

Based on the high harmonic content that is characteristic of a large percentage of the commercial facility load, it would not be surprising to find relatively high harmonic current distortion levels for the whole facility. However, this is not usually the case. Cancellation between the different types of loads is the main reason that the totalized current for most commercial facilities does not exceed the harmonic limits specified in IEEE 519-1992. The situation could change as more facilities convert to adjustable speed drives for the HVAC loads.

Figure 6.2.1 illustrates harmonic current measurements at various locations in a commercial office building. This building has a high percentage of electronic load, conventional magnetic ballasts, and only uses adjustable speed drives for air handling equipment (not pumps) in the HVAC system. The waveforms at various locations in the building demonstrate the high current distortion levels that can exist on circuits that serve electronic loads but that these harmonic currents are cancelled and attenuated by the time they reach the service entrance.

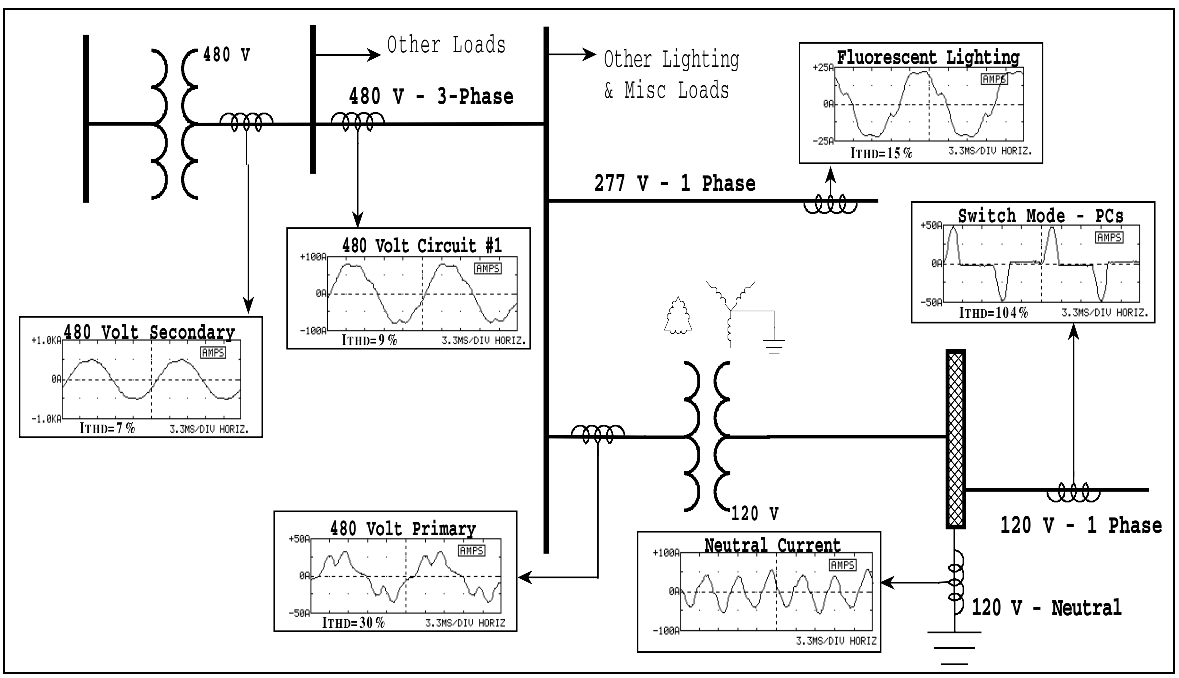


Figure 6.2.1. Example of harmonic cancellation in a commercial building.

The net effect of the different load types can often be analyzed with a relatively simple system representation such as the one in Figure 6.2.2 below [14].

Figure 6.2.2. Simplified representation for commercial building loads

Using this model and assuming a 6% impedance for the stepdown transformer, the harmonic content at the service entrance can be estimated. Table 6.2.1 gives results for a couple of different loading characteristics.

Table 6.2.1. Estimated harmonic current content for commercial buildings with different load characteristics.

Case	Description	Nonlinear Load Levels (% of total load)			Harmonic Distortion Levels of Service Entrance (% of fundamental)	
		Electronic	Lighting	ASDs	Voltage	Current
1	Base Case	20%	30%	5%	3.5%	14.5%
2	High Lighting Load	20%	60%	5%	3.9%	17.1%
3	High Electronic Load	40%	30%	5%	5.7%	21.8%
4	High ASD Load	20%	30%	10%	5.1%	20.3%

6.3 Example Problems and Solutions

Most commercial building harmonic problems are localized within the facility. The cases described here are typical of problems experienced with harmonics in commercial facilities.

6.3.1 Neutral Conductor Overloading

When single phase electronic loads are supplied with a 3-phase, 4-wire circuit, there is a concern for the current magnitudes in the neutral conductor. Neutral current loading in 3-phase circuits with linear loads is simply a function of the load balance among the three phases. With relatively balanced circuits, the neutral current magnitude is quite small. This has resulted in a practice of undersizing the neutral conductor in relation to the phase conductors.

With electronic loads supplied by switch-mode power supplies, the harmonic components in the load currents can result in much higher neutral current magnitudes. This is because the odd triplen harmonics (3, 9, 15, etc.) produced by these loads show up as zero sequence components for balanced circuits. Instead of cancelling in the neutral (as is the case with positive and negative sequence components), zero sequence components add directly in the neutral. The third harmonic is usually the largest single harmonic component in single phase power supplies or electronic ballasts.

The impact on the required rating for the neutral conductor can be estimated using the typical waveform given previously. For this waveform, the third harmonic is approximately 70% of the fundamental. If we assume that the loads on the three phases are balanced and all have this same characteristic, then the rms phase current and rms neutral current can be approximated as follows:

$$I_{phase} = (I_1^2 + I_3^2)^{1/2} = (1.0^2 + 0.7^2)^{1/2} = 1.22$$

$$I_{neutral} = (I_3 + I_3 + I_3) = (0.7 + 0.7 + 0.7) = 2.1$$

$$I_{neutral} / I_{phase} = 2.1/1.22 = 1.72$$

The neutral current in this case will be 172% of the rms phase current magnitude. The conclusion from this calculation is that neutral conductors in circuits supplying electronic loads should not be undersized. In fact, they should have almost twice the ampacity of the phase conductors. An alternative method to wire these circuits is to provide a neutral conductor with each phase conductor. The figure below illustrates how the neutral current is dominated by the third harmonic component in this type of circuit.

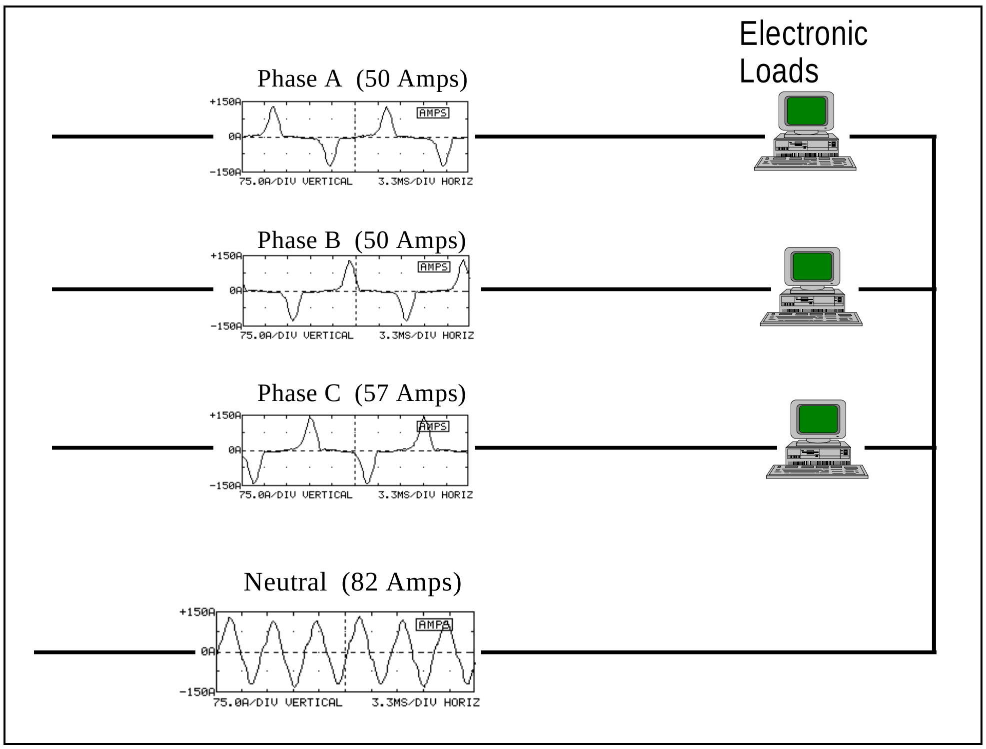


Figure 6.3.1. Phase currents and neutral current for a circuit supplying electronic loads.

An approximate formula for calculating the neutral current magnitude as a percentage of the rms phase current is given below. The formula is based on the assumption that the circuit loading is balanced, that the nonlinear load watts are a fraction p_{nl} of the total load, and that the load current has a third harmonic component equal to 70% of the fundamental.

$$Ineutral_{rms} = 3\sqrt{\frac{0.56 p_{nl}^2}{1 + 0.56 p_{nl}^2}} Iphase_{rms}$$

This relationship is illustrated in graphical form in Figure 6.3.2.

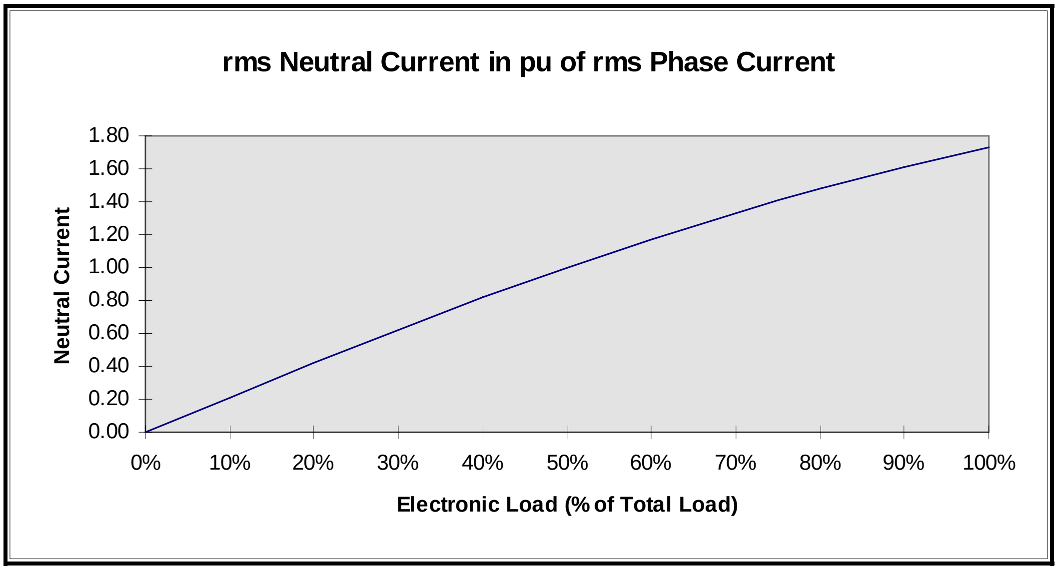


Figure 6.3.2. *Rms neutral current as a function of the portion of electronic load in the circuit.*

Solutions to the overloaded neutral conductor problem include the following:

- increased neutral conductor rating
- double neutral conductor
- neutral conductor with each phase conductor
- zig zag transformer on the load side of the affected neutral conductor
- parallel connected third harmonic filter on the load side of the affected neutral conductor
- series filter to block third harmonic currents in the neutral

It is worth noting here that the neutral current concern is not as significant on the 480 Volt system. The zero sequence components from the power supply loads are trapped in the delta winding of the step down transformers to the 120 volt circuits. Therefore, the only circuits with any neutral current concern are those supplying fluorescent lighting loads connected line-to-neutral (277 Volts). In this case, the third harmonic components are much lower. A typical electronic ballast should not have a third harmonic component exceeding 30% of the fundamental (the waveform given previously has only 20% third harmonic). For this worst case analysis, the neutral current can be calculated as above:

$$I_{phase} = (I_1^2 + I_3^2)^{1/2} = (1.0^2 + 0.3^2)^{1/2} = 1.04$$

$$I_{neutral} = (I_3 + I_3 + I_3) = (0.3 + 0.3 + 0.3) = 0.9$$

$$I_{neutral} / I_{phase} = 0.9/1.04 = 0.87$$

This means that the neutral current magnitude should always be less than the phase current magnitude in circuits supplying fluorescent lighting load. In these circuits, it is sufficient to make the neutral conductors the same size as the phase conductors.

6.3.2 Transformer Heating

One of the important impacts of harmonic currents from nonlinear loads is additional heating in transformers. Transformers which are not specifically designed to supply nonlinear loads must be derated to account for the additional winding eddy current losses caused by harmonic currents. A procedure for establishing transformer capability for supplying nonsinusoidal load currents is defined in ANSI/IEEE Std C57.110. Alternatively, transformers with a *k-factor* rating are designed to be operated up to their full nameplate capacity with currents that have distortion levels defined by the *k-factor* rating.

Example of transformer derating. As an example of applying the procedure outlined in the standard, the figure below illustrates the required transformer derating (for a transformer with an eddy current loss factor of 8%) as a function of the percentage of the load made up of electronic power supplies. The figure illustrates that transformers supplying virtually all electronic loads may have a capability less than 50% of the nameplate rating. This would apply to stepdown transformers (480/208 volts) within a commercial facility. Requirements for derating the main service transformer are much less severe as a result of harmonic cancellation within the commercial building.

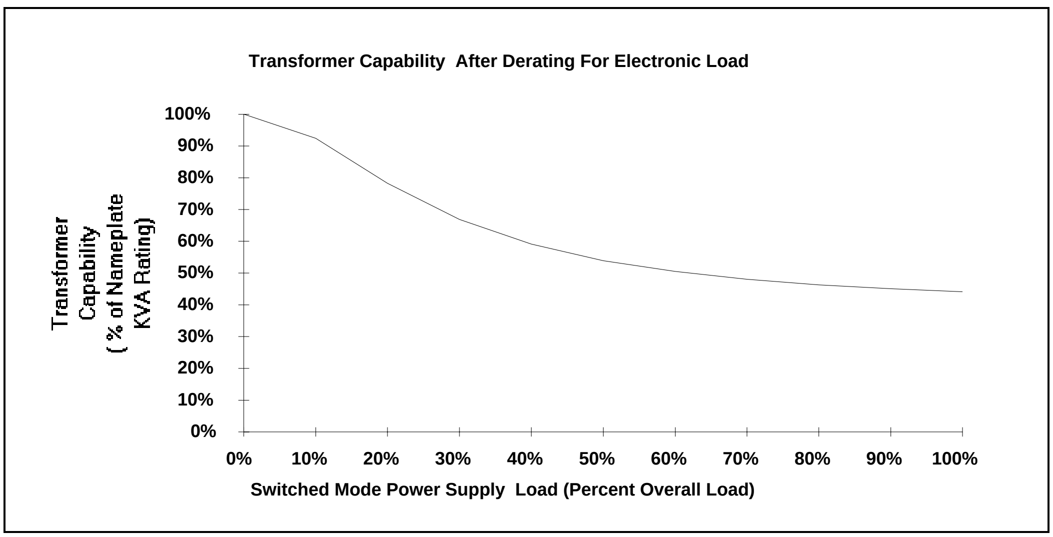


Figure 6.3.3. Transformer Capability for Supplying Electronic Loads

Add effect of Pec-r.

Example of transformer k-factor calculation.

Example k-factor calculation for a transformer supplying a pc-type waveform.

Solutions for overloaded transformers include the following:

- Use transformers that have a *k-factor* rating that is sufficient for the types of loads that are being supplied. A k-factor of 13 is usually sufficient for a transformer that has to supply 100% electronic load. A k-factor of 7 is sufficient if the load consists of a mix between linear loads and electronic loads.
- Passive or active filters on the load side of the transformer. These reduce the harmonic currents that the transformer must supply.
- Zig zag transformer or a neutral blocking filter to limit the zero sequence harmonic components (third harmonic) that the transformer must supply. The harmonics from electronic loads are dominated by the third harmonic. Just by reducing the third harmonic component, the transformer heating can be reduced significantly.

6.3.3 ASD Applications for HVAC

As an energy saving measure, adjustable speed drives are becoming more common for motors on pumps, compressors, and fans in commercial facility HVAC applications. As these applications become significant portions of an overall commercial facility load, the adjustable speed drives may become the dominant source of harmonics in the building. The analysis in Section 5.2.1 is directly applicable to these applications.

These adjustable speed drives should always include an isolation inductance (choke). This could be an input line reactor, an isolation transformer, or an inductance inside the ASD. This inductance reduces the harmonic generation by smoothing the input current waveform. In Section 5.2.1, the input current waveform with an input inductance was called a Type 2 waveform. The analysis showed conventional 6 pulse ASDs of this type could be as much as 20% of the facility load without causing the overall facility to exceed the IEEE 519-1992 current distortion limits. Without the input inductance, the limit would be about 10%.

If the ASDs become more than 20% of a facility load, the harmonic generation can be reduced in a number of ways:

- Harmonic filters, as discussed in Section 5.4.1. A single tuned filter can increase the allowable level of 6 pulse ASDs to about 60% of the facility load, depending on the filter rating.
- Active filters, as discussed in Section 5.4.3.
- 12 pulse ASDs, as discussed in Section 5.4.1. 12 pulse ASDs can be about 60% of the facility load without filters.
- Advanced ASDs with harmonic control in the input rectifiers. These ASDs use pulse width modulation (PWM) techniques in the input rectifier that make the input waveform very clean. Input current distortion levels less than 5% of the fundamental can be achieved with this approach.

6.3.4 Lighting Retrofits

examples from NYPA, PG&E.

6.3.5 Harmonic Control for UPS Systems

Orange book?

6.3.6 Standby Generators

Caterpillar, IPM

7.0 APPLYING HARMONIC LIMITS FOR RESIDENTIAL CUSTOMERS

It is difficult to apply harmonic limits at the residential level in the same way they can be applied for industrial and commercial facilities. The logistics of verifying harmonic performance of each residence makes applying specific limits for residences almost impossible. In some countries, this difficulty is resolved by applying harmonic limits to the actual appliances used in residences rather than to the residence itself. IEC 555-2 (now IEC 1000-3-2) provides harmonic limits which will be applicable for appliances up to 16 Amps at 240 volts [15]. A new standard (IEC 1000-3-4) is under development for appliances with current ratings up to 75 Amps [16].

In most cases, several residences are supplied from the same distribution transformer, as illustrated in Figure 7.0.1 below. It is clear from this configuration that the PCC for residential evaluations must be at the individual service entrances (the metering point). Harmonic current levels from each residence can be evaluated at this point. Harmonic voltage levels will be a function of the harmonics on the overall distribution system and the combined effect of harmonic currents injected from each of the residences supplied from a common distribution transformer.

Figure 7.0.1. One line diagram illustrating typical residential supply configuration.

A range of values for the short circuit ratio at a residence can be estimated using typical distribution transformer sizes and characteristics. For instance, a typical customer size on a 50 kVA transformer might be 5 kVA. The short circuit capacity at the residence in this case would probably be about 2000 kVA, resulting in a short circuit ratio of 400. Using the harmonic current limits from IEEE 519-1992, this would mean that the total demand distortion for the customer current should be less than 15% (short circuit ratios from 100 to 1000).

With existing load characteristics, the current distortion for residences rarely approaches 15%. However, a growing percentage of the load in a household is electronic and may use switch mode power supplies. ASDs for heat pumps and air conditioners, compact fluorescent lights (electronic ballasts), and electric vehicle battery chargers also use diode bridge rectifiers in the front end. All of these new loads have the potential to cause residential loads to become a significant source of harmonics on a distribution system.

A major concern associated with the proliferation of electronic loads on the distribution system is that all of these loads tend to draw current waveforms that are similar and in phase with each other. This is an inherent characteristic of the diode bridge rectifier with capacitive smoothing. As a result, the lower order harmonics from these loads tend to add on the distribution system with little cancellation. The triplen harmonics can be of particular concern on systems that supply single phase loads line-to-neutral on the transformer primary. Some analytical cases evaluating the possible impacts of this increasing penetration of nonlinear loads are provided in this section.

7.1 Harmonic Characteristics of Residential Loads

Mack Grady survey data

Examples of residential load and whole house harmonic current characteristics are given in Table 7.1.1 below. Some of these households have high current distortion levels as a result of ASD heat pump applications.

Table 7.1.1. Examples of residential load and whole house harmonic current characteristics.

Type of Load	RMS Load Current	THDi (%)	I3(%)	I5(%)	I7(%)	I9(%)
Clothes Dryer	25.3	4.6	3.9	2.3	0.3	0.3
Stovetop	24.3	3.6	3.0	1.8	0.9	0.2
Refrigerator #1	2.7	13.4	9.2	8.9	1.2	0.6
Refrigerator #2		10.4	9.6	3.7	0.8	0.2
Desktop Computer & Laser Printer	1.1	140.0	91.0	75.2	58.2	39.0
Conventional Heat Pump #1		10.6	8.0	6.8	0.5	0.6
Conventional Heat Pump #2		13.1	12.7	3.2	0.7	
ASD Heat Pump #1	14.4	123.0	84.6	68.3	47.8	27.7
ASD Heat Pump #2	27.7	16.1	15.0	4.2	2.3	1.9
ASD Heat Pump #3	9.7	53.6	61.1	26.0	13.7	4.0
Color Television		121.0	84.0	60.5	35.0	15.0
Microwave #1		18.2	15.8	5.2	3.3	2.3
Microwave #2		26.4	23.4	9.8	2.3	1.9
Vehicle Battery Charger		51.8				
House #1		4.9				
House #2		7.7				
House #3		11.0				
House #4		6.4				
House #5		16.3				
House #6		8.5				
House #7		11.9				
House #8		31.6				

7.2 Examples of Equipment Harmonic Limits

IEC 1000-3-2

7.3 Cancellation Effects with Dispersed Sources of Harmonics

Mack Grady/Arshad Mansour work

7.4 Examples of Important Load Types

7.4.1 Compact Fluorescents

Pileggi reference

SCE/Electrotek reference

7.4.2 ASD Heat Pumps

Mack Grady reference

Univ of Arkansas reference

Rao Thallum presentation

7.4.3 Electric Vehicle Battery Chargers

Jeff Bohn presentation

Southern Company info

8.0 UTILITY SYSTEM CONSIDERATIONS

The electric utility is responsible for the quality of the voltage supplied to its customers. This voltage can become distorted due to harmonics introduced by nonlinear loads within customer facilities, due to harmonics introduced by nonlinear devices applied directly on the power system (e.g. static var systems, high voltage dc converters, traction power rectifiers, etc.), or due to resonance conditions on the system. IEEE 519-1992 was developed to help with the coordination that is needed to keep voltage distortion levels on the overall system within reasonable limits.

8.1 General Considerations

The level of service quality provided to customers has always been a concern for electric utilities. Utilities and their customers continue to work together to address service quality problems. With the increasing utilization of loads that include electronics that can be sources of harmonics and can also be sensitive to disturbances, the utility industry concern for service quality continues to grow.

Harmonic distortion is one of the many types of power quality variations present on the power system that can degrade service quality. This section of the application guide discusses the various measures that utilities can consider to minimize the effects that harmonic distortion has on the overall service quality provided to customers. Many of these considerations have already been addressed in previous sections.

8.2 Using the Harmonic Distortion Limits as a Control Measure

Application of the harmonic distortion limits from IEEE 519-1992 is one means by which an electric utility can provide and maintain acceptable service quality to all customers. By applying the harmonic current distortion limits for individual customers and controlling resonance conditions on the overall system, the utility can assure that the voltage distortion levels on the overall system will be acceptable for all customers.

8.2.1 Voltage Distortion Limits

Section 11 of IEEE 519-1992, entitled "Recommended Practices for Utilities," contains harmonic voltage distortion limits which are intended to be used by utilities as a measure of the service quality provided to customers and by utility customers as a system design parameter (see Section 3.1.1). Harmonic voltage distortion levels, which are a function of the system impedance as well as the harmonic currents injected by nonlinear loads, can be easily measured on the power system and evaluated when designing harmonic control equipment.

Both utilities and their customers may experience operational problems if the voltage distortion levels exceed the specified limits. If problems are encountered, detailed system studies should be conducted and corrective actions taken (see Section 8.4). The voltage distortion limits for the utility supply system should also be considered by customers when designing harmonic control equipment, such as harmonic filters. The filters will have to operate with the specified levels of voltage distortion on the supply system, imposing an additional duty on the filter design (see Section 5.3.3).

8.2.2 Current Distortion Limits

The harmonic distortion of the system voltage is a product of the flow of harmonic currents on the system and the impedances of the system elements. Any electrical system can tolerate only a certain amount of harmonic current flow before the harmonic voltage distortion exceeds the recommended limits.

The harmonic current distortion limits (see Section 3.1.2) are intended to be applied at the utility/customer interface where other customers could be supplied as a means of equitably allocating the limited harmonic current-carrying capability of the electrical system. The recommended limits take into account the size of the users' loads relative to one another and relative to the strength (i.e. short circuit capacity) of the electrical system to which they connect.

Current distortion, while influenced somewhat by system impedance, can be easily measured with commercially available monitoring equipment at the point of common coupling and is determined by the characteristics of the load equipment. When multiple harmonic-producing loads are present in a user's facility, the totalized harmonic current for the facility usually involves some cancellation of the harmonic components between the individual loads. Therefore, the harmonic current seen at the point of common coupling can be considerably less than the algebraic sum of harmonic currents from individual loads within the facility.

The application of the IEEE 519-1992 harmonic current distortion limits in the design of new facilities or expansion of existing facilities can be beneficial in minimizing future problems on both utility and customer systems. By knowing the type of harmonic-producing equipment within a customer's facility, the harmonic current distortion levels can be predicted and a determination made at the design stage whether or not control measures are needed. Potential customer problems associated with internally generated harmonics can also be evaluated at the design stage in a similar manner.

As discussed in Section 10.2 of IEEE 519-1992, the current distortion limits are derived from the voltage distortion limits such that several customers can inject harmonic currents into the power system without causing unacceptable levels of harmonic voltage distortion. Hence, it is in the interest of both the utilities and their customers to follow the harmonic current distortion limits. By working together, acceptable levels of service quality can be provided to all customers.

8.2.3 Exceptional Circumstances

Sometimes, even with all customers operating within the recommended current distortion limits, the recommended voltage distortion may be exceeded. The installation of capacitor banks for power factor correction and voltage control can cause resonance conditions that magnify specific harmonic current components and may cause unacceptable voltage distortion. When this type of problem occurs, measurements can be performed to help characterize the problem. Harmonic current measurements can help identify the important sources of harmonics and voltage distortion measurements with different system configurations can help identify important resonance conditions that should be avoided.

8.3 Power System Equipment Application Considerations

Many new types of equipment are being designed and applied to improve the power system performance. Power electronics is a common denominator for many of these devices and, therefore, they often have nonlinear characteristics that result in the generation of harmonics. Examples of this equipment include static var compensators (SVCs), HVDC converters, Flexible AC Transmission Systems (FACTS), electric traction supply stations, and Customer Power equipment for distribution systems. When specifying the equipment design parameters, utilities normally include voltage and current distortion limits. As a general rule, the operation of these devices should not result in IEEE 519-1992 limits being exceeded.

Normally, when applying harmonic producing equipment directly on the power system, utilities require that the vendor perform in depth harmonic studies. As part of these studies, utilities and equipment suppliers jointly evaluate the various system parameters that can affect distortion levels and the resulting impacts. These studies usually involve the development of relatively detailed system models and the use of harmonic simulation tools. [25]

The simulations include frequency scans to characterize the response of the power system to harmonic injection by the nonlinear devices. The results of these frequency scans are often presented as plots of the system impedance vs. frequency looking from the location of the harmonic producing device (Figure 8.3.1). Resonance points where harmonic components can be magnified and voltage distortion problems could result are easily identified in these plots as a function of the system conditions. The individual series (low impedance) and parallel (high impedance) resonance points are determined by the interaction of the system inductance with capacitor banks and line or cable capacitance. Load tends to have a damping effect on these resonances. Many different system conditions (e.g. capacitor configurations, load conditions, source conditions) may need to be evaluated to make sure problem resonances are avoided.

Figure 8.3.1. Example frequency scan illustrating the response of a distribution system with multiple capacitor banks to a particular harmonic source.

Detailed harmonic simulations are also performed to evaluate the harmonic voltage profiles for the system and the flow of harmonic currents throughout the system. The frequency scan cases can identify the system conditions of most concern and the detailed simulations can predict the actual voltage and current distortion levels around the system caused by one or more harmonic-producing devices. These detailed simulations are used to make sure acceptable voltage distortion limits are not exceeded throughout the system and current distortion levels will not result in equipment overloading or communication interference problems.

8.3.1 Example - Static Var System Application

Static var compensators (SVCs) are applied on transmission systems to improve voltage control and system stability during both normal and contingency system conditions. They are also used at arc furnaces to control flicker and provide power factor correction and can be applied at distribution voltages for similar reasons. Most SVCs use a thyristor-controlled reactor configuration to provide continuous control of the reactive compensation level. Figure 8.3.2 is a typical one-line diagram.

Figure 8.3.2. One line diagram for a typical SVC configuration.

The thyristor-controlled reactor (TCR) produces harmonic currents because the thyristors only allow conduction in the reactor for a portion of the cycle. For a single TCR, the harmonic components include all odd harmonics (assuming balanced firing on the two half cycles). In a balanced three phase configuration, the triplen harmonics (3,9,15,etc.) are cancelled. The harmonic current magnitudes vary as the firing angle of the thyristors is varied as shown in Figure 8.3.3.

Figure 8.3.3. Variation of harmonic components for a TCR as a function of firing angle.

A comprehensive harmonic study will include evaluation of possible harmonic concerns over the full range of firing angles and all possible system conditions. Generally, harmonic filtering will be accomplished with capacitors that are applied in parallel to the TCRs. For transmission applications, the filters might include tuned filters at the fifth and seventh harmonics along with a high pass filter for higher order components. [26] For an arc furnace application, filtering would normally include a third harmonic filter with a damping resistor to avoid magnification of non-characteristic harmonics that can be generated by the arc furnace operation. [27] It is important that the SVC be designed so that these filters are always in service when the TCR is operating.

The harmonic performance criteria for the investigation would be to assure that IEEE 519-1992 voltage distortion limits are not exceeded at the point of connection. The investigation must include the evaluation of harmonic currents that are introduced by other harmonic-producing devices (customer loads) throughout the system in addition to the SVC.

8.4 Harmonic Mitigation Techniques

Excessive harmonic levels (voltage and/or current) on the utility system can result in increased equipment heating, equipment malfunction and premature equipment failure, communication interference, fuse blowing in capacitor banks, and customer equipment and process problems. When the distortion levels on the utility system are a problem, mitigation measures need to be implemented. IEEE 519-1992 helps identify reasonable limits for the individual customers on the system. If specific customers are causing the unacceptable harmonic levels, the mitigation may be best applied at those customers. If the overall system response is causing unacceptable distortion levels, mitigation measures may be required on the utility system. Some specific measures that can be considered are discussed here.

8.4.1 Removal or Relocation of Shunt Capacitor Banks

Excessive harmonic distortion levels on the utility system are usually associated with a resonance condition. It may be possible to avoid the resonance problem by removing or relocating specific capacitor banks. It may also be possible to detune the system by changing the capacitor bank size (adding or removing cans). Evaluation of the effect of different capacitor configurations and conditions can be performed with harmonic simulation tools.

8.4.2 Application of Passive Filters

If the harmonic levels cannot be adequately controlled by changing capacitor configurations or applying harmonic controls at individual customers, it may be possible to apply shunt passive filters on the distribution system. In general, a filter should be applied at the lowest harmonic component where there is significant harmonic generation on the system. For systems that supply mostly industrial and commercial load, this would probably be the fifth harmonic. For systems with significant single phase residential load, this could be the third harmonic.

This filter will consist of a reactor in series with a conventional capacitor bank. The capacitor bank will typically require a higher voltage rating due to the normal voltage rise across the tuning reactor.

The best location for the passive filter is close to the harmonic producing loads. If the loads are distributed throughout the system, filtering can be applied near the ends of feeders to control distortion on the overall feeder [28].

Example distribution system filter application. (Bill Winnerling (Western Resources) case or John Kennedy case (Georgia Power)

8.4.3 Application of Active Filters

Passive tuned filters introduce new resonances which can cause additional harmonic problems. New power electronics technologies are resulting in products that can control harmonic distortion on the utility system with active control. These active filters will provide compensation for harmonic components on the utility system based on the existing harmonic generation at any given moment in time. Research has been performed into methods of optimizing the sizes and locations of these devices on the distribution system that could lead to cost-effective methods of applying active filters in the future [30].

8.5 Economic Considerations

The presence of harmonic distortion on the utility system results in incremental costs in the operation of the system. Categories for these losses include:

- costs of harmonic mitigation measures (filtering)
- increased losses in conductors, transformers, motors, etc.
- engineering effort to diagnose problems
- accelerated aging of equipment due to heating and other harmonic effects
- derating and oversizing of equipment to withstand harmonic duties

Results of preliminary efforts to characterize these costs have been published [31]. This study showed that the most important cost component is likely to be the costs associated with applying mitigation measures, such as harmonic filtering, to reduce harmonic levels. Based on these incremental costs alone, substantial investment in mitigating harmonic generation in the end use equipment could be justified.

This philosophy of controlling harmonic distortion levels by applying limits at the end use equipment level has been adopted in IEC 1000-3-2 [15].

8.6 Other Considerations

These are many other considerations that can be related to the utility system harmonic levels. Some of these are discussed here.

8.6.1 Telephone Interference

Telephone or communication system interference can be a very important concern related to harmonic current levels on the power system. Interference problems are most prevalent on overhead distribution systems that share right-of-way with communication circuits. Problems are usually associated with capacitor banks and resonance conditions that cause higher current flows along the right-of way. Telephone interference concerns are discussed in IEEE 519-1992 and other references. Problems are generally solved by evaluating the effect of different system modifications, such as adding a neutral reactor to a capacitor bank. This should be done in cooperation with the telephone company.

8.6.2 Tariff Considerations

Tariffs may offer an opportunity to encourage and economically justify the application of harmonic control measures, such as filters or higher pulse number converters. Many of the industrial and commercial tariffs include demand charges and power factor penalties. It should be possible to construct a tariff that also includes a charge for harmonic current components injected onto the power system. This would allow customers to make economic decisions regarding the harmonic control. If the customer does not control the harmonic injection, the utility would have the funds to control the harmonics on the utility system in a similar manner to the application of power factor correction capacitors.

The benefits of controlling the harmonic levels on the customer side would include the following:

- The application of harmonic filters should improve the power factor and reduce the MVA demand for the facility. If the demand charge is based on peak MVA (as opposed to MW), it would be economically attractive for a customer to install harmonic filters to reduce the demand charge. The economic benefits derived from the filter installation can be determined by comparing the reduction in the annual bill to the cost of the filters. The impact of a filter installation on power factor penalties can be evaluated in a similar manner.
- The filtering will reduce the harmonic voltage distortion within the plant and the harmonic currents injected onto the power system.
- The customer should be less susceptible to transient voltages during switching of larger capacitor banks on the utility system. The filters provide damping for these types of transients.

8.6.3 DSM Programs and Equipment Incentives

Many utilities have demand side management programs and energy efficiency incentives that encourage customers to apply new technologies that will reduce energy use during peak times or overall. Incentives in these programs can be structured to encourage the use of equipment with low harmonic generation characteristics. This can have a very important effect on overall harmonic levels for a facility.

Many DSM programs recommend the installation of electronic ballasts and compact fluorescent lamps. If these programs encourage the use of ballasts and lamps with low harmonic current distortion (for instance, many programs will only provide rebates if the ballasts have less than 20% or 30% THD in the current waveform), the overall harmonic levels in the facility and injected onto the power system can be reduced. Adjustable speed drives are another type of energy saving equipment with important harmonic generating characteristics that could be influenced through rebate or incentive policies.

8.6.4 Torsional Interaction Concerns

The use of large cycloconverters (static frequency changers) in rolling mill and mining applications is becoming more widespread. A cycloconverter converts the fundamental frequency ac to a variable frequency ac output at a lower frequency using power electronics. The manner in which the frequency conversion is accomplished and the variable loading of the motors being driven result in a wide range of sub-harmonic and inter-harmonic components.

Sub-harmonic components which propagate to system generators can produce pulsating torques that, in some cases, can result in equipment damage. Most problems occur when these torques align with natural mechanical frequencies of the turbine-generator system.

Analytical studies should be conducted to assess the potential impact of sub-harmonic components on the overall turbine-generator electrical/mechanical system. The evaluation should be performed over the full range of possible system conditions since problems are likely to be associated with particular frequencies and resonance conditions.

8.6.5 Other Concerns

Local resonances (e.g. high frequency)

Overexciting distribution transformers

Distribution automation considerations

Substation transformer overloading (zero sequence) - Roger Dugan

Stray voltage and EMF concerns - Larry Conrad