1C.4.1—Harmonic Distortion

1. Scope

This handbook section contains of PacifiCorp's standard for harmonic distortion (electrical pollution) control, as well as a brief explanation for its use at a typical customer site. The intended audience for this document is a customer who is considering the installation of equipment that could produce harmonic distortion.

2. General

Harmonic distortion is commonly produced by customer equipment injecting current harmonics causing electrical noise in the power system. The current harmonics will degrade PacifiCorp's voltage quality to other customers. Maintaining electrical noise within tolerable limits will allow PacifiCorp to provide quality electrical service to all its customers as partially specified in Section 7. *PacifiCorp requires that a customer's facility must stay within all limits described in Sections 5, 6, and 8, as measured at the point of common coupling* (see Section 4). The customer shall take necessary action, at the customer's sole expense, for the customer's facility to stay within these limits. Failure to operate within these limits can result in termination of electrical service or other remedial action as provided by state regulatory authority. Help in managing this noise at a tolerable level is found in Sections 9-12.

3. References and Resource Documents

This handbook reflects the requirements of the industry documents listed below that were in effect at the time of publication. When a referenced document is superseded by an approved revision, the revision shall apply.

IEEE Standard 519, *IEEE Recommended Practices and Requirements for Harmonic Control in Power Systems*.

IEEE Standard C57.110, *IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents*.

IEEE Standard 2800, *Interconnection and Interoperability of Inverter-Base Resources (IBRs) Interconnecting with associated Transmission Electric Power Systems*.

IEEE Standard 1543, *IEEE Standard 2800, Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interface*.

4. Definitions and Abbreviations

The following definitions and abbreviations pertain to this standard.

Characteristic harmonics (h). "Those harmonics produced by semiconductor converter equipment in the course of normal operation" (see IEEE 519). These are given by the equation $h = kq \pm 1$, where k is any integer and q is the pulse number. In a six-pulse converter these are the 5^{th}, 7^{th}, 11^{th}, 13^{th}, and so forth.

Distortion. Any corruption of the 60-hertz sinusoidal voltage or current waveform.

Harmonic. A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency (see Section 3).

Inverter-based resource (IBR). Any source of electric power that is connected to the transmission or distribution system via power electronic interface, and that consists of one or more IBR units capable of exporting active power from primary energy source or energy storage system to the Company electrical grid.

Low voltage. In a three-phase system, low voltage is an rms phase-to-phase voltage 600 volts or less.

Point of common coupling (PCC). The point on the utility power system, electrically nearest a particular load, at which other loads are, or could be, connected.

Pulse number (q). In a rectification circuit, the number of pulses (lobes) seen in the dc output per ac input cycle.

Total demand distortion (TDD). The same as THD for current except the denominator is I_L, the average of monthly peak 60 Hz kW demand load currents over preceding 12 months.

Total harmonic distortion factor (THD). Can apply to a voltage, current, or power waveform. It is the square root of the sum of the squares (rss) of the root-mean-square (rms) values of nonfundamental harmonics, divided by the rms value of the fundamental.

Total rated-current distortion (TRD). The non-fundamental frequency RMS current flowing (including harmonics, interharmonics, and noise) between the transmission system and the inverter-based resource with respect to the rated RMS current capacity I_{rated}.

5. Transformer Harmonic Damage Limits

Harmonic loading on the transformer that serves the customer must be considered because harmonic currents produce more heat per ampere than fundamental current. *If the THD of the current passing through the transformer windings is greater than five percent of the fundamental at rated transformer current the heating effect of this current must be further evaluated by PacifiCorp if the transformer serving the PCC is owned by PacifiCorp*. If the customer owns the transformer, further evaluation is still recommended. Guidance as to how to evaluate transformers for harmonic heating can be found in IEEE C57.110, or by contacting PacifiCorp. Also, certain harmonics tend to collect in some types of transformer connections, so this should be evaluated as well.

6. Voltage Notching Limits

Whenever ac voltage is rectified to dc with solid state switching devices, a phenomenon called *commutation notching* can occur. The duration of these notches in each ac voltage cycle is typically only a few microseconds, but they can last longer and cause equipment malfunction or resonance with attendant damage or loss to neighboring electrical equipment or the processes they control. PacifiCorp's limits for this are the same as in IEEE 519 and are shown in Table 1.

Table 1—Low-Voltage System Classification and Distortion Limits

	Special Applications*	General System	Dedicated System†
Notch Depth	10%	20%	50%
Notch Area (A_N)‡	16 400	22 800	36 500

Note: The value A_N for other than 480-volt systems should be multiplied by V/480.

* Special applications include hospitals and airports.

† A dedicated system is exclusively dedicated to the converter load.

‡ In volt-microseconds at rated voltage and current.

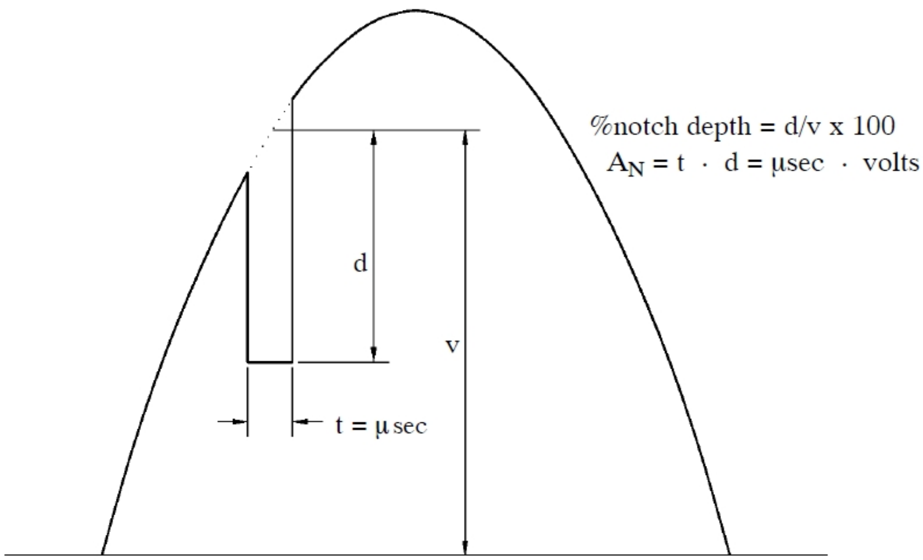


Figure 1—Definition of Notch Depth and Notch Area

7. Voltage Distortion Limits (PacifiCorp's Responsibility)

It is PacifiCorp's responsibility to provide quality voltage to all its customers. Customers keeping the current distortion within the limits of Section 8 will allow PacifiCorp to provide this service. This service is defined as voltage having distortion levels within the limits of Table 2. These limits are the same as in IEEE 519 and are for normal operation. During start-ups, shutdowns or unusual non-steady state conditions these limits may be exceeded up to 50%.

- Daily 99th percentile very short time (3 s) values shall be less than 1.5 times the values given in Table 2.
- Weekly 95th percentile short time (10 min) values shall be less than the values given in Table 2.

Table 2—Harmonic Voltage Distortion Limits in Percent of Nominal Fundamental Frequency Voltage

Bus Voltage at PCC	Individual Harmonic Voltage Distortion (%)	Total Voltage Distortion THD (%)
1.0 kV and below	5.0	8.0
1.0 ≤ 69 kV	3.0	5.0
69 kV < V_{rms} ≤ 161 kV	1.5	2.5
V_{rms} > 161 kV	1.0	1.5

8. Current Distortion Limits

Current distortion occurs when customer equipment draws current from the utility in a nonlinear or choppy manner. It always produces harmonics in the load current waveform and can produce significant harmonics in the voltage waveform at the PCC and elsewhere. Current distortion limits for PacifiCorp are the same as in IEEE 519 and are described in Table 3. This table applies to steady state operation and general distortion situations.

The load current, I_L, is defined as the average for the preceding 12 months of the kW portion of the currents measured at the times of monthly peak demand by the demand meter. The demand is found on the monthly bill for the facility (site) being considered. For a balanced three-phase load I_L is calculated as

$$I_L = \frac{kW_{demand}}{\left(kV_{1-1}\sqrt{3}\right)} \qquad \text{Eq (1)}$$

I_L can often be read directly from a facility meter when the facility is at full load. The rms short circuit current, I_{SC}, is found from a recent PacifiCorp fault study for a three-phase fault at the customer's PCC under normal operating conditions. Users should limit their harmonic currents at the PCC as follows:

- Measured over a period of 24 hours, 99th percentile very short time (3 sec.) harmonic currents should be less than 2.0 times the values given in Table 3.
- Measured over a period of 7 days, 99th percentile short time (10 min.) harmonic currents should be less than 1.5 times the values given in Table 3.
- Measured over a period of 7 days, 95th percentile short time (10 min.) harmonic currents should be less than the values given in Table 3.

The statistically oriented measurements just described are intended to allow limited exceedances of base harmonic limits when such excursions are occasional, random, do not cause equipment overheating, and do not adversely affect neighboring customer facilities. However, these emissions must be controlled if the facility regularly emits bursts of harmonics above the levels in Table 3 and cause mis-operation of neighboring customer facilities. Such control will be to levels below the limits of

Table 3 or may be above these limits if the emissions allow the correct operation of neighboring facilities. The above noted statistical measurement protocols do not include start-ups or unusual non-steady state conditions. The limits in Table 3 may be exceeded by no more than 50% in those events.

PacifiCorp may relax the allowable TDD limits in Table 3 if a facility's lower-order harmonics are controlled through filtering or some other method to less than 25% of the individual harmonic limits in Table 3. References in IEEE 519 gives guidance on how this may be done.

Table 3—Harmonic Current Distortion Limits in Percent of I_L

Line No.	I_{sc}/I_L	$h<11$	$11 \le h<17$	$17 \le h<23$	$23 \le h<35$	$35 \le h$	TDD
$V_{rms} \le 69$ kV							
1	<20*	4.0	2.0	1.5	0.6	0.3	5.0
2	20-50	7.0	3.5	2.5	1.0	0.5	8.0
3	50-100	10.0	4.5	4.0	1.5	0.7	12.0
4	100-1000	12.0	5.5	5.0	2.0	1.0	15.0
5	>1000	15.0	7.0	6.0	2.5	1.4	20.0
69 kV < $V_{rms} \le 161$ kV							
6	<20*	2.0	1.0	0.75	0.3	0.15	2.5
7	20-50	3.5	1.75	1.25	0.5	0.25	4.0
8	50-100	5.0	2.25	2.0	0.75	0.35	6.0
9	100-1000	6.0	2.75	2.5	1.0	0.5	7.5
10	>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_{rms} > 161$ kV							
11	<25*	1.0	0.5	0.38	0.15	0.1	1.5
12	25<50	2.0	1.0	0.75	0.3	0.15	2.5
13	≥50	3.0	1.5	1.15	0.45	0.22	3.75

- All power generation equipment is limited to these values of current distortion regardless of the actual short circuit ratio, I_{SC}/I_L. Inverter-based generation is limited to the total rated-current(TRD) in Section 8.1.
- Individual 2nd, 4th, and 6th harmonics are limited to 50% of Table 3 limits.
- Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

8.1. Current Harmonic Distortion - Inverter-Based Resources

This section defines the current harmonic distortion limits for IBRs connected at distribution and transmission systems. Current harmonic distortion from IBRs is determined by TRD, similar in concept to TDD. TRD is the ratio of the current harmonics to the rated output of the inverter resource. IEEE 1547 defines the permitted current harmonic output of distribution IBR with IEEE 2800 managing transmission interconnected IBR plants. The measurement and statistical analysis of both transmission and distribution IBRs shall follow IEEE Std 519 as outlined in Section 8.

$\%TRD = 100 \times \sqrt{(I_{rms}^2 - I_1^2)}/I_{rated}$

Where

I_{rms} is the IBR's current, inclusive of all frequency components up to 50th order

I_1 is the fundamental frequency current

I_{rated} is the IBR's rated current capacity based on MVA rating at the PCC

As harmonics originating from generation sources can elevate voltage harmonics in the electrical grid IBR the allowable level of current harmonic distortion has specific limits in the supplemental IEEE 1547 and 2800 standards. Section 8.2 and 8.3 define the limits for single harmonic groupings and specific even harmonics.

8.2. Distribution Interconnected Inverter-Based Resources

Distribution IBR current harmonics are limited to the lowest permitted level of IEEE 519. The 2nd, 4th, and 6th have a progressive allowable limit, see in Table 4, rows 3 and 4, where current harmonic loads are limited to 50% of the limits of Table 3. All other even harmonics, 8th through 50th, match the corresponding single harmonic group in rows 1 and 2 of Table 4. The statistical evaluation from IEEE 519 and Section 8 is still utilized to determine compliance.

Table 4—Distribution IBR Current Harmonic Distortion as a Percentage of I_{rated}

	Individual Odd Harmonic Order						
1	Harmonic Order (h)	h < 11	11 ≤h < 17	17 ≤h < 23	23 ≤h < 35	35 ≤h < 50	Total rated current distortion (TRD)
2	Percentage (%)	4.0	2.0	1.5	0.6	0.3	5.0
	Individual Even Harmonic Order						
3	Harmonic Order (h)	h = 2	h = 4	h = 6		8 ≤h < 50	
4	Percentage (%)	1.0	2.0	3.0		Range specified in rows 1 and 2	

8.3. Transmission Interconnected Inverter-Based Resources

Transmission IBR current harmonics limits have fewer single harmonic groups and permit higher single harmonics to have a higher percentage of the IBR rated output. The 2nd, 4th, and 6th even single harmonics have a progressive allowable limit, see in Table 5, rows 4 and 5. Even harmonics greater than the 8th are limited to the appropriate single harmonic grouping in Table 5, rows 1-3. The statistical evaluation from IEEE 519 and Section 8 is still utilized to determine compliance.

Table 5—Transmission IBR Current Harmonic Distortion as a Percentage of I_{rated}

	Individual Harmonic Order *(h)*				
	PCC LL Voltage (kV)	h < 11	11 ≤h < 17 (%)	17 ≤h < 50 (%)	Total rated current distortion (TRD) percentage (%)
1	≤69	4.0	2.0	1.5	5.0
2	69.001 to 161	2.0	1.0	1.0	2.5
3	> 161	1.5	1.0	1.0	2.0
	Certain Even Harmonic Order *(h)*				
4	h = 2 (%)	h = 4 (%)	h = 6 (%)		
5	1.0	2.0	3.0		

9. Recommended Full-Load Harmonic Current Limits for Equipment

Some customers may want rules-of-thumb to help keep their harmonic distortion under control without formal analysis. PacifiCorp suggests that harmonic producing devices used by these customers be limited or filtered at the individual device or equipment level. PacifiCorp's recommended maximum individual full load equipment limits are given in Table 6. *Staying within these limits does not remove the responsibility from the customer to conform to the facility limits described in Sections 5-8*.

Table 6—Equipment Harmonic Current Limits

Equipment	Limit (% THD - Current)
All lighting, motor drives, power supplies, and other equipment sharing a common electrical bus or panel with sensitive electronic loads	15
All fluorescent lighting, including compact fluorescent	30
High efficiency single phase heat pumps and air conditioners	25
Switching power supplies (>500 volt amps), computers, electric vehicles, and so forth	30
Variable frequency drives	No specific equipment limits; total facility to meet standard in Sections 5-8 (same as in IEEE 519)
All other equipment not specified above	30

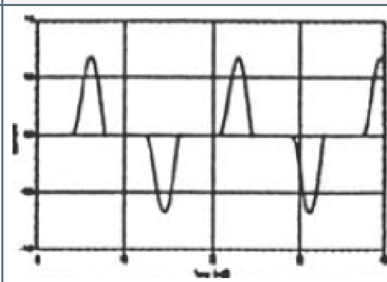
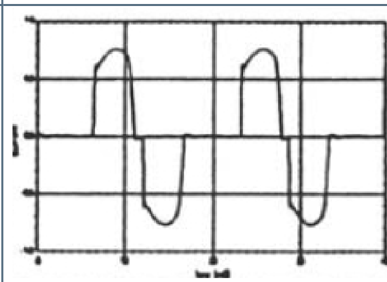
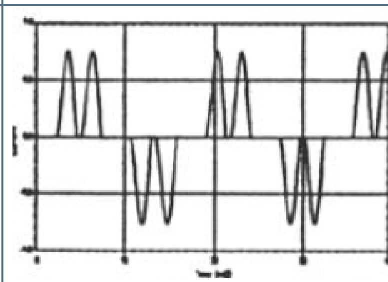
- PacifiCorp may not assist in funding equipment that exceeds the above limits.
- Low quality active filters can introduce higher frequency noise (>3 kHz). This noise can either conduct into the power system, radiate into the atmosphere, or both. Active filters should include noise suppression features. Equipment that omits noise suppression features should be avoided

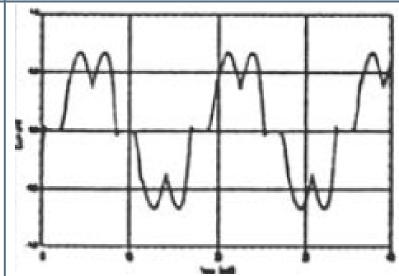
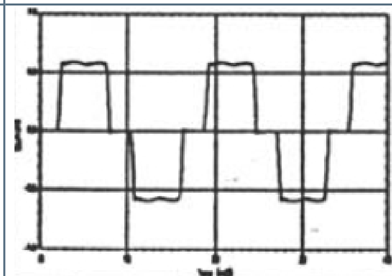
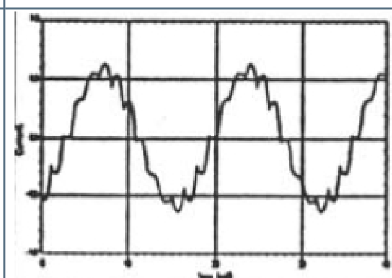
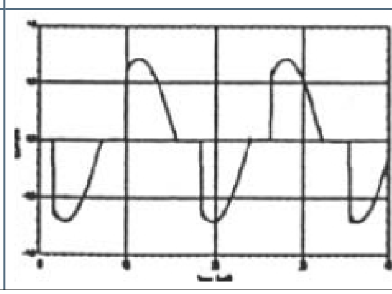
because it can affect other on-site electronic equipment in ways that are sometimes very difficult to predict and troubleshoot.

10. Harmonic Problems—Causes and Solutions

Harmonic problems are caused by one or more nonlinear loads such as adjustable speed drives, switching power supplies, electronic ballasts for fluorescent lighting, and arcing devices such as welders. These devices can cause nearby equipment, such as sensitive computer controls or digital clocks, to malfunction. They can also cause nearby transformers to overheat. It is possible for these devices to cause voltage distortion or trigger a resonance with the utility's or neighbor's, power system equipment and thus cause more widespread problems. Table 7, shown below, lists some common causes of harmonic distortion along with their current waveforms and typical distortion levels.

Table 7—Current Waveforms and Distortion Caused by Typical Nonlinear Loads

Type of Load	Typical Waveform	Typical Current Distortion
Single-phase power supply		80% (high 3rd)
Semiconverter		high 2nd, 3rd, 4th at partial loads
6 pulse converter, capacitive smoothing, no series inductance		80%

Type of Load	Typical Waveform	Typical Current Distortion
6 pulse converter, capacitive smoothing, with series inductance > 3% or dc drive		40%
6 pulse converter, with large inductor for current smoothing		28%
12 pulse converter		15%
ac voltage regulator		varies with firing angle

The problem is usually best solved at the source; when specifying equipment, be sure that the supplier provides low harmonic current distortion ratings (see Section 9) as well as high efficiency ratings. This can be done through higher pulse numbers (12 or 18) on drives, or built-in filtering. External filtering or active power line conditioning can be applied where high harmonic producing equipment is already in place. Adding external filtering may have the side benefit of improving facility power factor. A competent consultant can judge which method is best (see Section 12).

11. How to Evaluate a Harmonic Source and Check Compliance with Standard

PacifiCorp can help to assess the type and magnitude of the problem when a customer becomes aware of a harmonic problem in a facility, either at the design phase or after installation. It is the responsibility of the customer to do troubleshooting and take remedial action. PacifiCorp (or a consultant) may be able to help and needs to know the following:

1. The facility's electrical layout (usually with an accurate one-line diagram)
2. The electrical location of nonlinear loads and affected equipment
3. Any relevant misoperation or high-maintenance history

PacifiCorp will review the short circuit current (I_{SC}) at the PCC (see Section 4) and facility average peak demand current (I_L) to ensure compliance with the harmonic standard. Current and voltage distortion, and transformer overload can be checked against acceptable limits with this information, and a harmonic analyzer. A waveform recorder is used to see voltage notching and check against the standard limits (see IEEE 519 and Sections 5, 6, 7 and 8).

12. Selection of Consultants

Selecting a competent consultant to help solve harmonic problems can be a challenging task in itself. PacifiCorp offers a few ideas listed in 12.1 through 12.5 to assist in this effort.

12.1. It's Harder than PF Correction

Harmonic analysis and mitigation is more involved than just installing power factor (PF) correction capacitors. It is a relatively unfamiliar area for many people. Beware of oversimplification and the implication that PF correction capacitors are the complete answer.

12.2. Get a Professional

For a power distribution system of significant size (either by component count or dollar value), ensuring that the consultant performing the study is an engineer with significant experience in the field of harmonics will help avoid financial losses in the long run. One way to do this is to look for a licensed professional engineer with moderate to significant experience in the field of harmonics. While this does not guarantee competence in this specific area, engineers do have the training to handle some of the more technically challenging topics that often come up, such as computer modeling and analysis of resonance. Some non-engineers have developed skill in this area, but may not have professional licensing. Such consultants need proper scrutiny to assure competence. Training, experience, and references are essential credentials of a competent consultant. It is recommended to seek samples of past work to check for quality and attention to detail.

12.3. Make Sure The Problem is Solved

Occasionally a consultant will study a problem, submit a report, and invoice a customer for the study without explaining a down-to-earth real-world solution to the customer. A true professional will always leave the customer with a good grasp of what equipment needs to be bought, approximately how much it will cost, how long it will take to install, and specifically where it should be applied. Be sure your consultant explains the report with a clear understanding of the essentials.

12.4. Beware the Snake Oil Salesmen

Some people make promises that are too good to be true, perhaps citing incompetence or conspiracy as the reason few know about it; unfortunately this also happens with harmonics mitigation. It is necessary to enquire with specific questions to understand the problem and the proposed solutions. Some have claimed that harmonics cause billing meters to significantly over-register, and purchasing their services will ensure significant savings. Meter over-registration due to harmonics has been thoroughly investigated, both in the laboratory and in the field, and the facts simply do not bear this out.

12.5. PacifiCorp is Willing to Help

PacifiCorp deals with harmonic issues on a frequent basis, the company is aware of some of the pitfalls and can suggest ways to help for customers who inquire. For recommendations, ask your PacifiCorp representative.

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