7. Standards and Solutions

7.1. IEEE 519

The most often quoted harmonics standard is IEEE 519, "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems." IEEE 519 attempts to establish reasonable harmonic goals for electrical systems that contain nonlinear loads. The objective is to propose steady-state harmonic limits that are considered reasonable by both electric utilities and their customers. The underlying philosophy is that

- customers should limit harmonic currents,
- electric utilities should limit harmonic voltages,
- both parties share the responsibility for holding harmonic levels in check.

IEEE 519 applies to all voltage levels, including 120V single-phase residential service. While it does not specifically state the highest-order harmonic to limit, the generally accepted range of application is through the 50^{th} harmonic. Direct current, which is not a harmonic, is also addressed and is prohibited. Since no differentiation is made between single-phase and three-phase systems, the recommended limits apply to both.

It is important to remember that IEEE 519 is a recommended practice and not an actual standard or legal document. Rather, it is intended to provide a reasonable framework within which engineeers can address and control harmonic problems. It has been adopted by many electric utilities and by several state public utility commissions.

Definitions and Terms

THD. Total Harmonic Distortion (or Distortion Factor) of voltage or current is the ratio of the rms value of harmonics above fundamental, divided by the rms value of the fundamental.

PCC. Point of Common Coupling is a point of metering, or any point as long as both the utility and the customer can either access the point for direct measurements of the harmonic indices meaningrul to both, or estimate the harmonic indices at the point of interference through mutually agreeable methods. Within an industrial load, the point of common coupling is the point between the nonlinear load and other loads.

There is some flexibility in determining the PCC, but in most instances, it is at the meter. An electric utility might also interpret the PCC to be on the high-voltage side of the service transformer, which would have the effect of allowing a customer to inject higher harmonic currents.

ISC. Maximum short circuit current at the PCC.

IL. Maximum demand load current (fundamental frequency component) at the PCC, calculated as the average current of the maximum demands for each of the preceeding twelve months. For new customers, this value must be estimated.

TDD. Total demand distortion, which is the THD of current (using a 15 or 30 minute averaging measurement period) normalized to the maximum demand load current IL.

Utility Limits

Electric utilities are responsible for maintaining voltage harmonics and THD_V. The limits are divided into two categories: voltages 69kV and below, and voltages above 69kV. For electric utility distribution systems (i.e., corresponding to 69kV and below), the limits are

For Voltages 69kV and Below

Individual Voltage Harmonic %	Total Harmonic Distortion THD_V %
3.0	5.0

Customer Limits

Customers are responsible for maintaining current harmonics and THD_I. Again, the limits are divided into two categories: voltages 69kV and below, and voltages above 69kV. For 69kV and below, the limits are

For PCC Voltages 69kV and Below
Maximum THD_I in % of IL for Odd Harmonics k

ISC/IL	$k < 11$	$11 \le k < 17$	$17 \le k < 23$	$23 \le k < 35$	$35 \le k$	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

* All power generation equipment is limited to these values of THD_I, regardless of the actual ISC/IL.

Even-ordered harmonics are limited to 25% of the odd harmonic limits given in the tables. Loads that produce direct current offset, e.g. half-wave converters, are not allowed.

7.2. Public Utility Commission Standards

Several states, including Texas and Oklahoma, have adopted harmonic standards. These standards are based upon IEEE 519. Texas state ruling 25.51, “Power Quality,” permits an electric utility to charge a fee for having to investigate and remedy a customer-created excessive harmonics condition. The fee is limited to actual cost incurred plus a reasonable administrative cost.

7.3. Interacting with Customers

It is wise for an electric utility to develop a written document of harmonics policy that can be distributed to large industrial customers as the need arises. While a good basis for the document is IEEE 519, other procedural items should also be addressed. The following key points should be considered for inclusion in the document.

Modeling

Data are needed to determine whether a proposed customer's facility will cause harmonic limits to be exceeded. These data include

- One-line drawings of the customer's facilities, showing ratings and connections of all electrical equipment,
- Location, connection, size, and control method of capacitors,
- Conductor sizes and impedances,
- Location and type of nonlinear loads,
- Overall plant load and portion that is nonlinear,
- Location, rating, connection, and impedance of transformers.

Customers should be responsible for modeling their systems to project harmonic levels and determine whether the utility's harmonic limits will be exceeded.

The utility should provide information regarding the local power system to support the customer's modeling efforts. This information should include

- Available fault duty at customer's location,
- Ultimate available fault current,
- Impedance and ratings of service transformers,
- Possible voltage range variation.

Filter modeling should include the utility's background voltage distortion allowed by IEEE 519, which is 3% for a single harmonic and 5% THD_V . Failure to include this allowed background distortion may result in inadequate filter designs.

The utility may need copies of the customer's harmonic analysis for review prior to approving the customer's proposed facilities. The utility may need the customer to submit manufacturer's documentation and test data demonstrating the harmonic content of nonlinear loads.

Measurements

The utility should reserve the right to measure the amount of a customer's harmonic current injection at any time at the point of common coupling (normally the electric meter). These measurements are usually spot checks, but additional monitoring may be required.

Mitigation Devices and Methods

The customer should be responsible for the design, installation, operation, and maintenance of mitigation devices required to meet the utility's harmonic limits. Mitigation devices may include current limiting reactors, passive filters, active filters, or other devices that minimize the flow of harmonic currents onto the utility's distribution system.

The customer should submit mitigation device maintenance records to the utility upon request. The installation and testing of mitigation equipment should be subject to the approval of the utility. The mitigation devices must be capable of handling the IEEE 519 permitted background voltage distortion that can exist on the utility's distribution system.

The utility will likely reconfigure the distribution system regularly in response to load changes and to resolve outages. The mitigation equipment should operate independently of these changes.

7.4. Solutions

Solution techniques fall into two broad categories – preventive and remedial.

Preventive Measures

Preventive measures focus on minimizing the harmonic currents that are injected into power systems. Preventive measures include

- Strict Adherence to IEEE 519.

- Phase Cancellation. The use of twelve-pulse converters instead of six-pulse converters should be encouraged. Most utility harmonic problems are associated with high 5^{th} and 7^{th} harmonic currents, and if they are eliminated through phase cancellation, harmonic problems rarely develop. In situations where there are multiple six-pulse converters, serving half of them (in terms of power) through delta-delta or wye-wye transformers, and the other half through delta-wye or wye-delta transformers, achieves net twelve-pulse operation.

- Encouragement of Low Distorting Loads. Because of IEEE 519, increasing attention is being given to the THD_I of distorting loads. A customer often has a distortion choice in loads. For example, twelve-pulse (or higher) ASDs and low-distortion fluorescent lamp ballasts can be purchased.

- Computer Simulations. It is always better to simulate the impact of a large distorting load before it is ordered and installed. Solutions can be proposed and evaluated "on paper" and perhaps implemented when the load is installed. Once the distorting load is connected, the customer will likely be under considerable pressure to operate it and perhaps less likely to commit additional funds to deal with a distortion problem.

Remedial Measures

Remedial measures include

- Circuit Detuning. By using only field measurements such as capacitor current waveforms and search coil readings, it is possible to identify the capacitor banks that are most affected by resonance. As a temporary measure to "buy time" before a real solution can be found, the affected capacitor bank can be switched off to see if the resonance problem subsides. Of course, the problem may simply transfer to another capacitor bank, so post-switching measurements at other capacitor banks must be made to see if the temporary solution is satisfactory. If switching a capacitor bank off temporarily solves the problem, computer simulations may be in order to test filtering options and possible re-location of the capacitor bank.

- Passive Filters. These are widely used to control harmonics, especially the 5^{th} and 7^{th} harmonics. Most filters consist of series L and C components that provide a single-tuned notch with a low-impedance ground path. At 50/60Hz, these filters are, for all practical purposes, capacitors. Thus, passive filters provide both power factor correction and voltage distortion control.

  5^{th} harmonic filtering is usually adequate in distribution systems. However, in some cases it may be necessary to add 7^{th}, 11^{th}, and 13^{th} harmonic filters, in that order. In general, harmonics may not be "skipped." For example, if the problem harmonic is the 7^{th}, both 5^{th} and 7^{th} harmonic filters must be added because the 7^{th} filter alone would aggravate the 5^{th} harmonic voltage. Filters tuned near the 3^{rd} harmonic must be avoided because transformers and machines located throughout distribution feeders are sources of third harmonics, and their currents will easily overwhelm 3^{rd} harmonic filters.

  Usually, the higher the harmonic, the fewer kVArs needed for a filter. For multiple filter installations, a good practice is to stairstep the kVAr as follows: if Q kVArs are used for the 5^{th} harmonic, then Q/2 should be used for the 7^{th}, Q/4 for the 11^{th}, and Q/8 for the 13^{th}. Of course, actual sizes must match standard kVAr sizes. For best performance, a filter should be at least 300 kVAr.

  It may be possible to add low-voltage filters within the confines of an industrial customer without performing computer simulations, as long as all shunt capacitors in the facility are filtered. However, in a utility distribution system, it is always prudent to perform computer simulations to make sure that a filter does not aggravate the harmonics situation at a remote point. This is especially true if the feeder also has unfiltered capacitors.

Some problems associated with passive filters are that

- their effectiveness diminishes over time as their capacitors age, losing μF and thus raising their notch frequency,

- they attract harmonic currents from all sources in the network – new, known, and unknown, so that they may become overloaded.

- Active Filters. This is a new and promising technology, but there are as yet few distribution feeder installations. Active filters are power electronic converters that inject equal-but-opposite distortion to yield more sinusoidal voltage waveforms throughout a network. Active filters have the advantages of

    - time-domain operation so that they automatically "tune" to the problem harmonic or harmonics,

    - current limiting capability to prevent overload by new or unknown sources of harmonics on the network,

    - multi-point voltage monitoring so that they can simultaneously minimize distortion at local and remote busses.

The performance of mitigation equipment must be verified by extensive monitoring, both before and after commissioning. At least two days of recordings before commissioning, and one week after, should be made to assure that the mitigation equipment is performing as planned. One week of measurements is needed so that the entire weekly load cycle can be observed. Monitoring should include time traces of voltage and current THD, spectra, sample waveforms, power, and harmonic power.

Economic Justification of Mitigating Measures

From a customer's perspective, the most common economic justification of harmonics mitigation is in minimizing down-time due to nuisance tripping of senstive loads. This cost is totally customer-dependent.

From a loss perspective, harmonics can be considered as a reduction in power factor. In Section 3, true power factor was shown to be

$$pf_{true} \approx \frac{dpf_1}{\sqrt{1 + THD_I^2}}.$$

Thus, the true power factor of nonlinear loads is limited by THD_I. Consider a nonlinear load with perfect displacement power factor (dpf_1). When current distortion is included, the true power factor degrades, as shown in Table 7.1.

Table 7.1. Maximum True Power Factor for Nonlinear Loads

THD_I %	Maximum pf_{true}
10	0.99
20	0.98
30	0.96
50	0.89
100	0.71

Since the true power factors given above are for the special case of unity dpf_1, they represent *maximum* true power factors for nonlinear loads. Actual true power factor is the product of *maximum* true power factor and *displacement* power factor, and the product can be significantly lower.

The power factor comparison presents a rather optimistic picture, because harmonic currents actually cause more losses per ampere than do fundamental currents.

Voltage harmonics have been shown to cause additional losses in motors, especially high-efficiency single-phase motors. Voltage harmonics induce harmonic currents that increase motor losses and insulation temperature. Research by Dr. Ewald Fuchs at the University of Colorado at Boulder has shown that voltage distortions in the 6% range with predominant 3rd and 5th harmonics can reduce the expected lifetime of single-phase motors by 25%-30%.