Modern power electronics enable a wide variety of devices to connect to the power grid—from switch-mode power supplies (SMPS) and variable-frequency drives (VFDs) to uninterruptible power supplies (UPSs) and light-emitting diodes (LEDs) to battery chargers, inverters, and generators. Many of these devices depend on non-linear components to minimize size and cost, and maximize reliability and performance. But this requires the designer to pay special attention to the impact non-linear current flows have on the signal integrity of the input mains power.

SMPS, for example, are common in electronic equipment, such as computers, monitors, and televisions. These devices typically draw non-linear current and are therefore significant sources of harmonics on the power network, as shown in Figure 1. The same applies to VFDs, which are often used with AC motors, such as those found in household appliances and HVAC equipment. And even LED lamps, despite their lower power, can produce significant harmonics if many are used in parallel.

The negative effects of harmonics are well-known: overheating of cabling and transformers, neutral conductor current, nuisance tripping of circuit breakers, higher electromagnetic emissions, and reduced life of motors and transformers. In addition, to handle these harmonics means increasing the rated capacity of transformers and cables, which increases cost. To alleviate these problems in your designs, you must assess the actual harmonic levels, which can be a challenging task.
Good citizens of the power grid

The issue of excessive harmonics extends beyond the device under test, of course. Any voltage distortion or degradation of power quality affects all users connected to the same section of the grid. Harmonic currents and voltages can have complex interactions with other equipment on the power network, leading to operational issues that may be difficult to debug.

To minimize these issues, power engineers validate that their devices are good citizens of the power network, so that they don’t degrade the signal integrity of AC waveforms for other users. Measuring the Total Harmonic Distortion (THD), power factor, and harmonic levels of the input mains provides a good indicator of how the device under test impacts power quality.

IEEE and IEC guidelines describe how measurements must be made and also specify maximum harmonic levels for power electronics connected to the power network (IEEE 519, IEC 61000-3-2). Many standards related to power quality are written in reference to harmonics, because this provides a rational way to specify testable limits on distortion. For example, Table 1 shows the current harmonic limits specified by IEC 61000-3-2 Class A (equipment that draws <16A per phase).
Harmonic analysis provides an excellent tool to help identify the source of signal integrity issues and meet the specifications that standards require.

### Table 1: Maximum current draw for harmonics as specified by IEC 61000-3-2 Class A

<table>
<thead>
<tr>
<th>Harmonics (n)</th>
<th>Max Current (A)</th>
<th>Even Harmonics (n)</th>
<th>Max Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.3</td>
<td>2</td>
<td>1.08</td>
</tr>
<tr>
<td>5</td>
<td>1.14</td>
<td>4</td>
<td>0.43</td>
</tr>
<tr>
<td>7</td>
<td>0.77</td>
<td>6</td>
<td>0.30</td>
</tr>
<tr>
<td>9</td>
<td>0.40</td>
<td>8-40</td>
<td>0.23*8/n</td>
</tr>
<tr>
<td>11</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-39</td>
<td>0.15*15/n</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If a power supply meets the above limits, it will be a minimal burden to power quality. Harmonic analysis provides an excellent tool to help identify the source of signal integrity issues and meet the specifications that standards require.

## Review of harmonic analysis

Harmonic analysis uses Fourier series to decompose a complicated periodic waveform into a set of simple sinusoids. The original waveform may be arbitrarily complex and most likely doesn’t have an analytical equation. The waveform can be digitized, however, and run through a harmonic analysis to generate a set of sinusoids (harmonics) that, when added together, approximate the original waveform. Figure 2 illustrates this process.

![Harmonic analysis](image)

**Figure 2** Harmonic analysis decomposes an arbitrarily complex periodic waveform into sinusoids.

You may recall that harmonics are organized by frequency. The lowest non-zero frequency harmonic is the fundamental (or 1st harmonic). All the other harmonics have frequencies that are integer multiples of the fundamental. The 2nd harmonic is twice the fundamental frequency, the 3rd is three times, and so on.
Voltage and current harmonics and power transfer
Now consider a simple system of an AC source and a load. The average power delivered
to the load from the source over one power line cycle is given by the following equation:

\[ P_{\text{avg}} = \frac{1}{T} \int_0^T v(t)i(t) dt \quad (1) \]

where \( T \) is the period of the power line cycle, \( v(t) \) is the voltage across the load, and \( i(t) \) is
the current through the load. Substituting the harmonics formulation for the \( v(t) \) and \( i(t) \)
waveforms gives the following result:

\[ P_{\text{avg}} = V_0 I_0 + \sum_{n=1}^{\infty} \frac{V_n I_n}{2} \cos(\phi_n - \phi_{in}) \quad (2) \]

This is more useful. Decomposing the \( P_{\text{avg}} \) into sums of harmonics now lets you compute
the power being delivered by a particular harmonic frequency. For example, if you want
to know how much power the 9th harmonic is delivering, you can compute it directly by
multiplying the amplitudes of the 9th harmonics’ voltage and current times the cosine of
the angle difference between them:

\[ P_{\text{avg}} = \frac{V_9 I_9}{2} \cos(\phi_9 - \phi_{in}) \]

An interesting prediction from the above decomposition is that both voltage and current
must have corresponding harmonics present. Otherwise there will be no average power
transfer from that particular harmonic. For example, if the voltage contains just the
fundamental, and the current contains just the 3rd harmonic, the average power will be
zero, as shown in Figure 3.

Figure 3. A power analyzer is a useful tool for measuring the power of a test set-up. Here a function generator
outputs a voltage signal with just the fundamental (60 Hz), and a current signal with just the 3rd harmonic (180
Hz). The bottom trace shows the power waveform. Note that the average power transferred per 60-Hz cycle is
effectively zero even though the voltage, current, and power traces have significant amplitude.
If the voltage is a clean sine wave, and the current waveform is non-sinusoidal, power will be transferred only by the fundamental. All the higher harmonics in the current waveform will be unproductive.

One goal of power system design is to maximize the power factor, which is defined as:

\[
\text{Power Factor} = \frac{W}{VA} = \frac{P_{avg}}{V_{rms}I_{rms}}
\]

But the harmonics that don’t transfer power work against this goal. They don’t contribute to \( P_{avg} \), but they increase the \( V_{rms}I_{rms} \). The extra harmonic voltage and/or current is not used, but the power system still has to carry the extra voltage and/or current from these harmonics and incur the associated losses. To maximize power transfer efficiency, it’s therefore beneficial to minimize higher harmonics.

**Harmonic measurements made simple**

A sensible first step before harmonic analysis is to measure the THD, especially if the purpose is to troubleshoot power quality problems. This can be done with a True-RMS digital multimeter with high enough bandwidth and sampling rate to measure the higher harmonic frequencies. If the THD level is low enough (< 3-5 percent depending on amplitude), then you have no harmonics issues to deal with. However, if either THD is too high or you want to characterize the performance of your device, the THD measurement is not enough. You need the full breakdown of harmonic amplitudes.

You may also want to conduct multiple runs, evaluating the device at different operational modes and load conditions. With general-purpose instruments (digital multimeters, spectrum analyzers, or scopes), you may find the data collection and post-processing required for harmonics analysis extremely time-consuming. In addition, comparing the harmonic levels to published standards can be tedious.

A modern power analyzer, such as the Keysight IntegraVision PA 2201A, simplifies and speeds up the process with features specifically intended for harmonic analysis. Data collection, frequency domain processing, and harmonics analysis are built-in. Power analyzers typically have high sample rates and a graphical display that lets you see the waveform, like a scope does. This visualization is invaluable, because you can quickly verify that you are measuring what you think you are measuring and that cabling or misconnections aren’t causing issues.

The power analyzer can display other relevant information, such as THD, frequency, amplitude, phase of the voltage, current, and power waveforms all at the same time. Once the measurement set-up is verified, you can simply turn on the harmonic analysis and the power analyzer will display the harmonics in a table and/or visual bar graph format.

Many power analyzers also have built-in pass/fail limits based on popular standards. This makes for quick, convenient, and immediate feedback on how the harmonics of the device under test stack up against the compliance limits.
Using a power analyzer to address the problem posed above—minimizing higher harmonics to maximize power transfer—lets you quickly investigate the harmonic content. Given a device that has the harmonics shown in Figure 4, for example, you can see that the current waveform contains mostly the odd harmonics, as expected. However, the 15th harmonic is uncharacteristically high, failing against the IEC 61000-3-2 specification. If your device must meet this specification, you’ve identified the problem to address.

Conclusion

Harmonic analysis can provide actionable guidance to address signal integrity issues in power systems with periodic switching waveforms. Using a modern power analyzer simplifies measurements and lets you model complicated interacting voltage and current waveforms in a way that is easy to understand. Harmonic analysis will help you design a device that minimizes higher order harmonics, meets required specifications, and acts as a good citizen on the power grid.
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