A New World – A New Challenge to Metering

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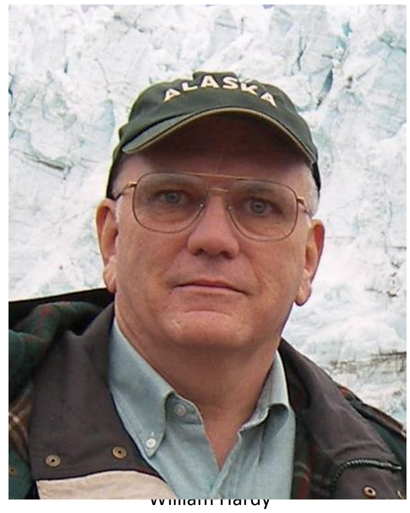
The first three phase electric power system was built in Great Barrington, Massachusetts in 1886. For the next hundred years the nature of loads didn't change very much: incandescent lighting, motor loads, resistive heating – all nice linear loads. Yes there were a few special loads, like arc furnaces, that presented special challenges, but they were few and far between.



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Then in the 1980's, a century after the first AC electric power system, the world began to change. The driver of that change was the invention of the transistor and the myriad of other semiconductor devices that followed. Though the invention of the transistor occurred in 1947, its affect on the power grid really started in the 1980's and has accelerated ever since. Solid state electronics generated the need for low cost, high power density DC power supplies. The rapid advances in solid state technology led to an explosion of technology and a flood of consumer and industrial devices.

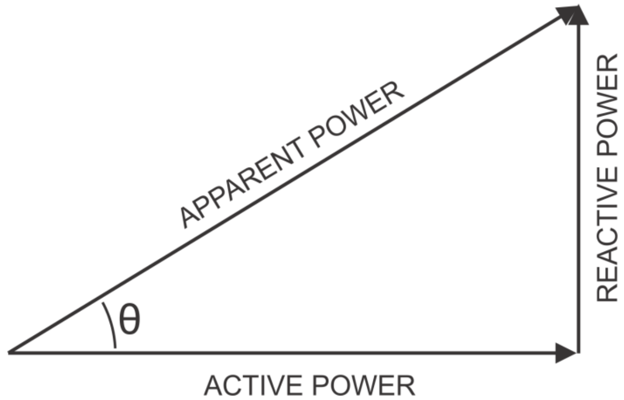
From the point of metering these were radically different loads. They were non-linear, i.e. the loads did not result in sinusoidal current flows. In the beginning these non-linear loads represented only a small fraction of the total, but today these non-linear loads are becoming the dominant load. This presents challenges to the very definitions we use for the measurement of power, VA and VAR.

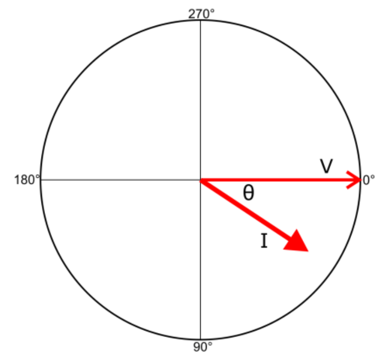
What makes these "solid state electronic loads" so challenging?

Today our standards, the ANSI C12 family, do not apply to non-sinusoidal waveforms. This means that when meters are type tested they are not tested under non-sinusoidal conditions. This is changing but the changes are still in progress. Here we will discuss those pending changes.

Non-sinusoidal Power Theory

We are all familiar with the classic theory of sinusoidal power where the voltage is sinusoidal and the current is sinusoidal with possibly a shift in phase. These very simple conditions can be addressed by a very straight forward set of math.





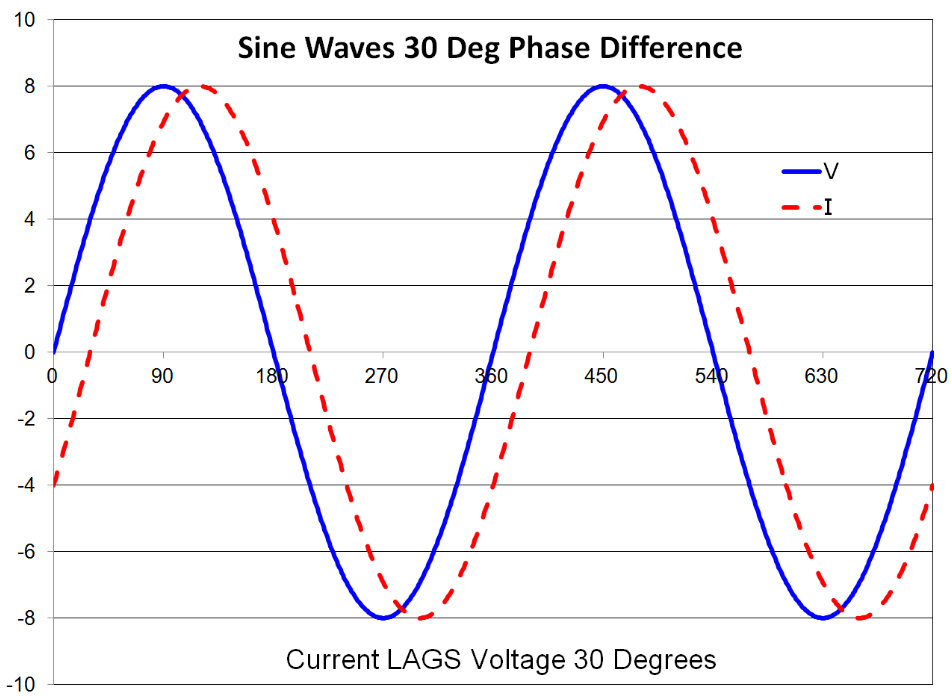
In this simple model, which represented reality fairly well for over a century, power is simply:

$$P = \text{Active Power} = VI\,\text{Cos}(\theta)$$

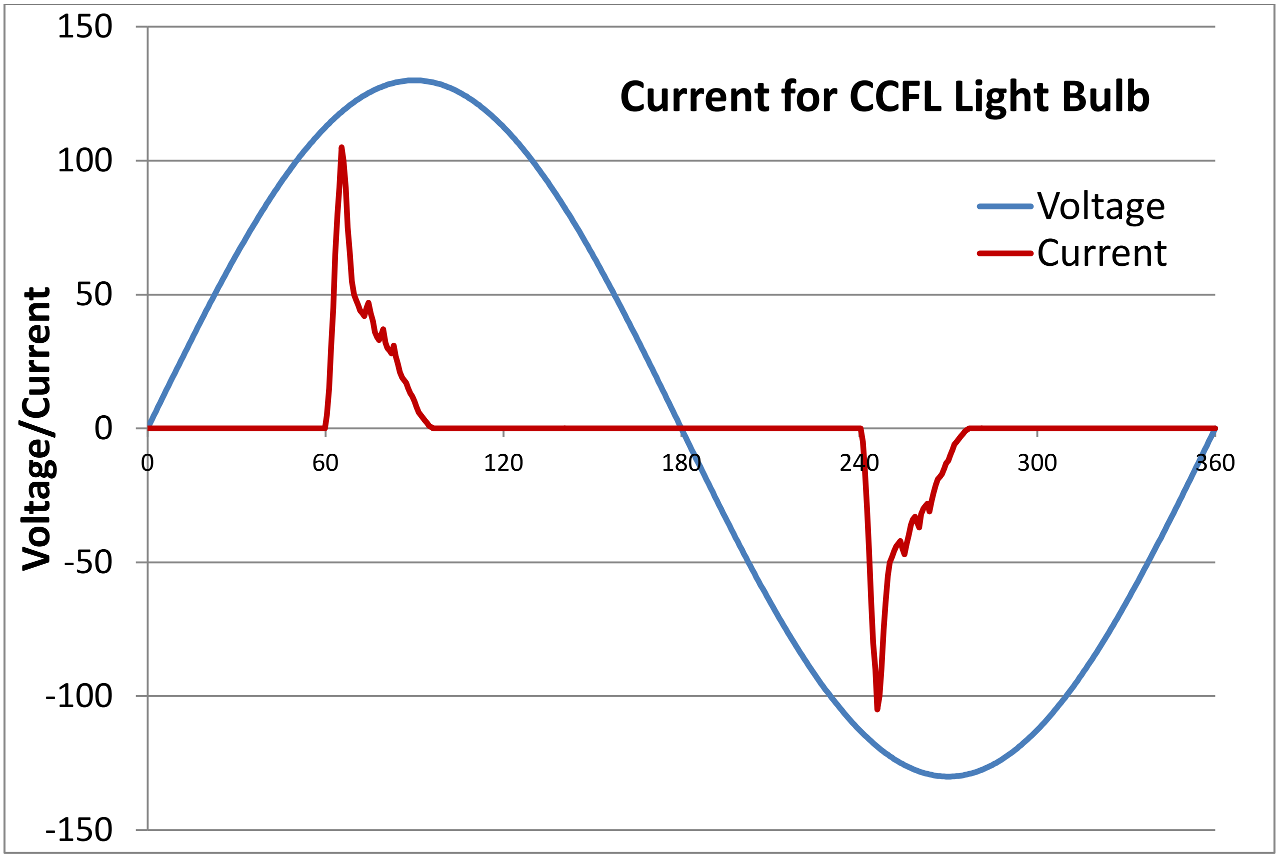
$$Q = \text{Reactive Power} = VI\,\text{Sin}(\theta)$$

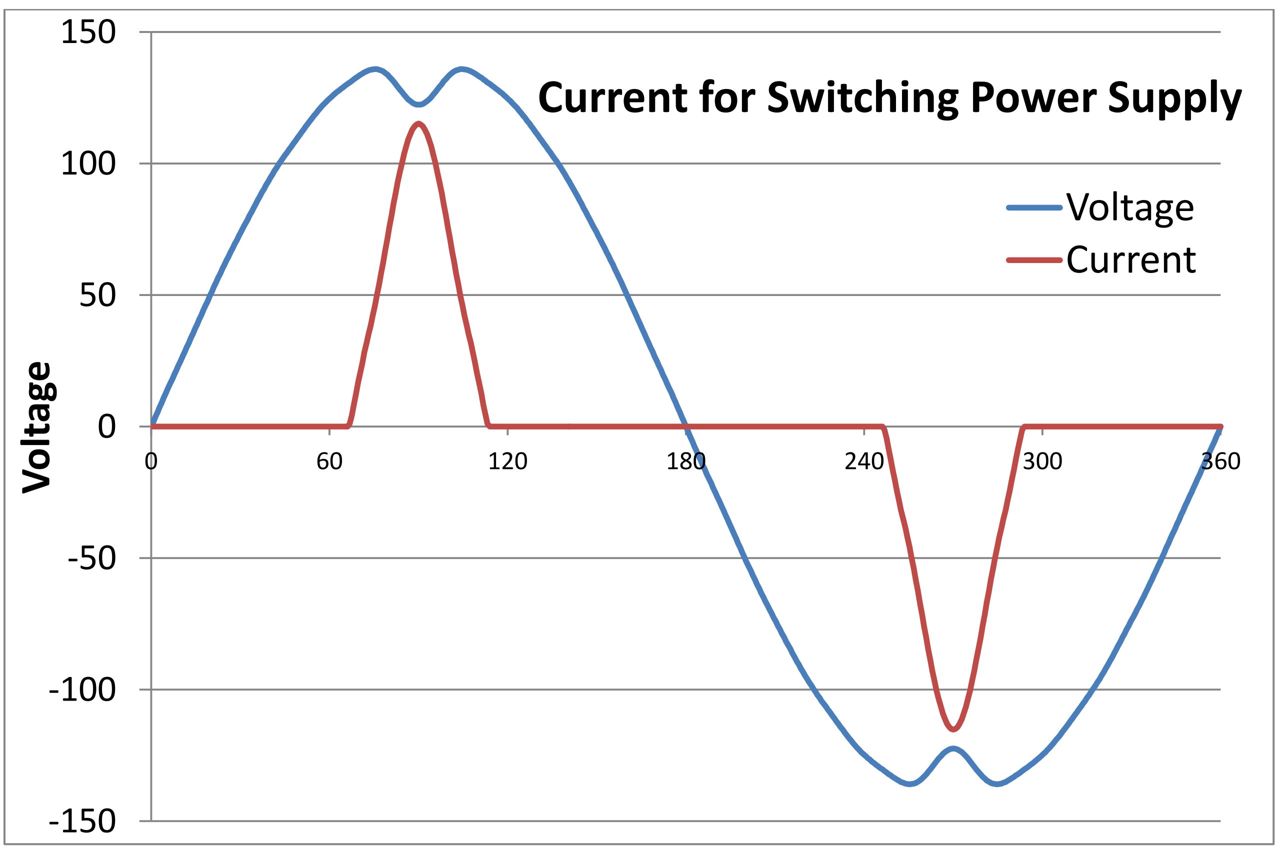
$$S = \text{Apparent Power} = VI$$

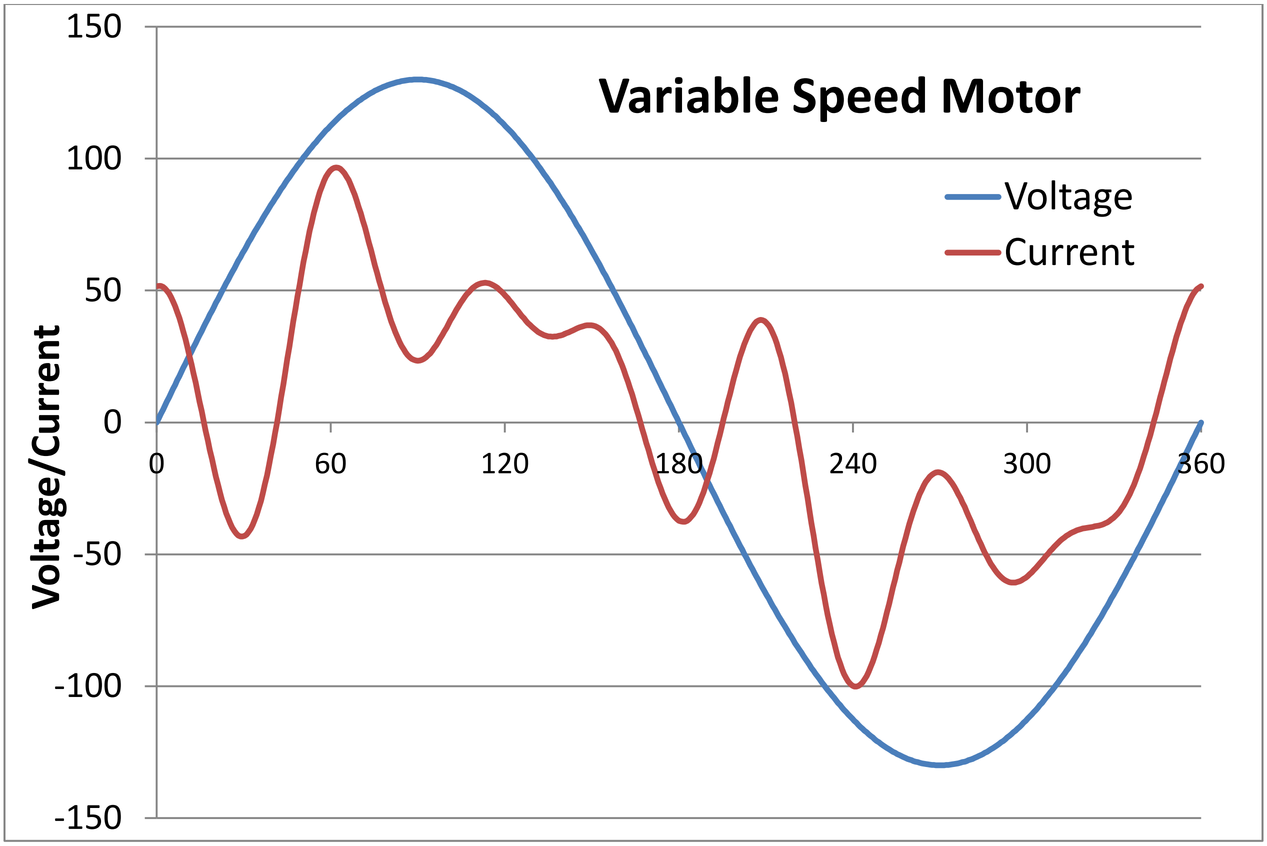
This approach to power measurement works just fine when our loads are sinusoidal as shown below, but that is a rare situation today.

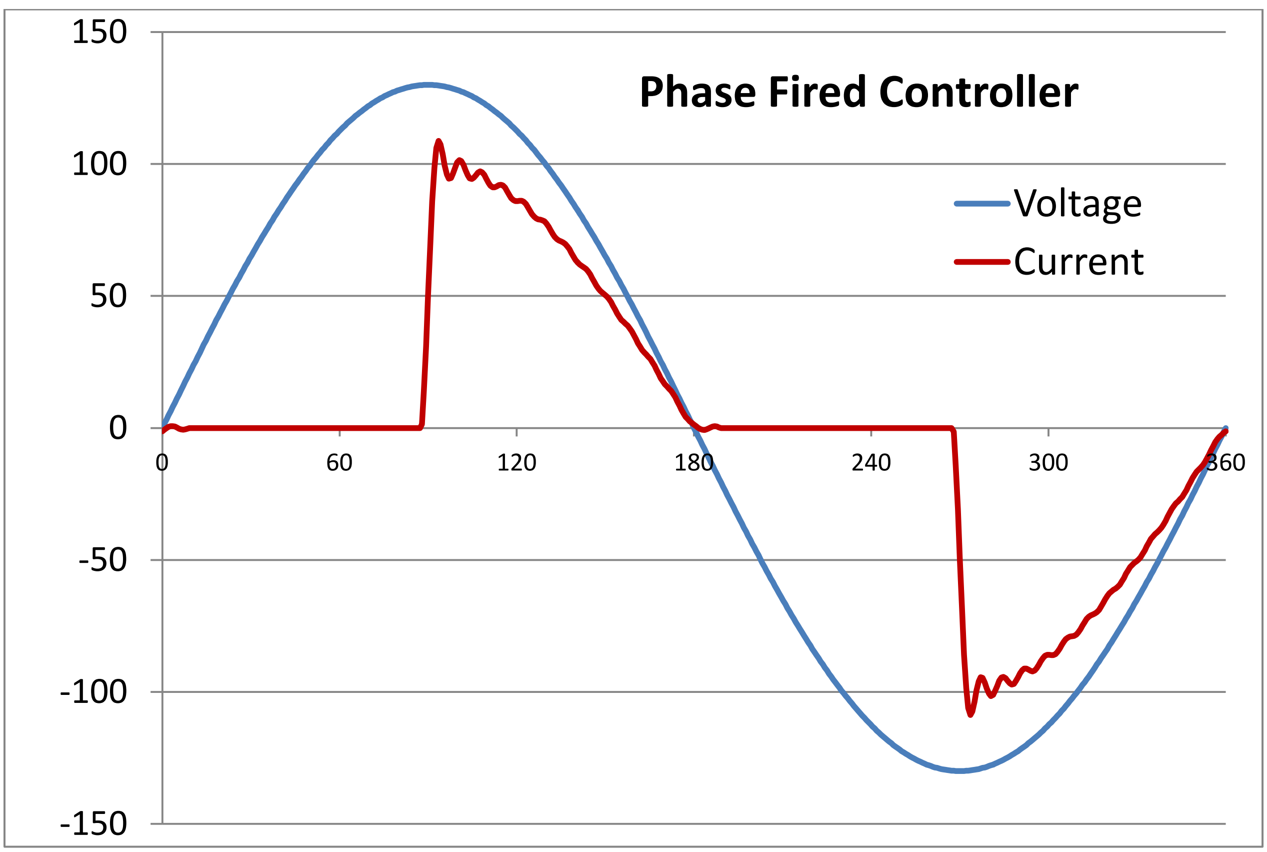


Here are just a few examples of modern loads.


Current for CCFL Light Bulb
Voltage
Current
Voltage/Current
150
100
50
0
-50
-100
-150
0
60
120
180
240
300
360


Current for Switching Power Supply
Voltage
Current
Voltage
150
100
50
0
-50
-100
-150
0
60
120
180
240
300
360


Variable Speed Motor
Voltage
Current
Voltage/Current
150
100
50
0
-50
-100
-150
0
60
120
180
240
300
360


Phase Fired Controller
Voltage
Current
150
100
50
0
-50
-100
-150
0
60
120
180
240
300
360

When loads are non-sinusoidal like those above, then we have to extend our definitions to cover these situations. For active power there is solid agreement as to the definition.

From ANSI C12.1 Code for Electricity Metering we have:

2.45 Power – active: The time average of the instantaneous power over one period of the wave. (Note: For sinusoidal quantities in a two-phase circuit, it is the product of the voltage, the current and the cosine of the phase angle between them. For nonsinusoidal quantities, it is the sum of all of the harmonic components, each determined as above.)

$$P = \frac{1}{T}\int_{a}^{a+T} vi\,dt$$

Integral over a cycle.

Most modern meters are digital making many measurements of voltage and current each cycle. In a sampled system the integral above becomes.

$$P = \frac{1}{N}\sum_{i=0}^{nN} V_i I_i$$

Where the summation is over an exact number of cycles.

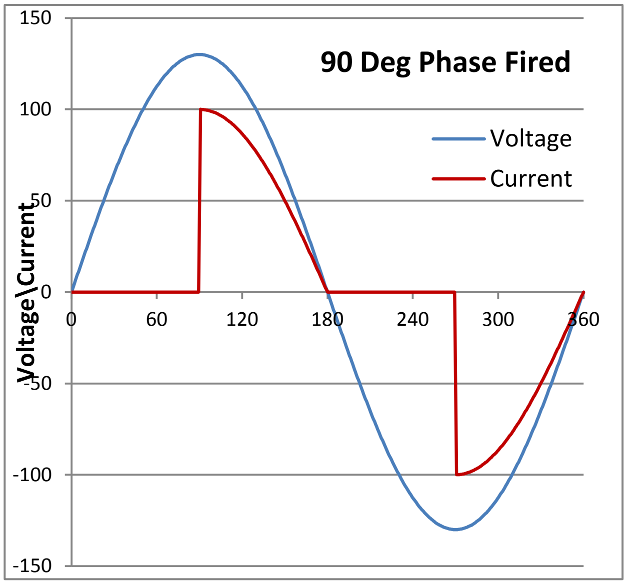
This definition works whether the loads are sinusoidal or non-sinusoidal. Some high end meters use Fourier transform mathematics to compute power quantities. For FFT technology to be accurate the waveforms must be repetitive. The wave form is represented by the summation of a number of sine waves at multiples of the fundamental frequency.

$$V(t) = \sqrt{2}\sum_{n=1}^{\infty}\left(V_n Sin(n\omega_0 t - \alpha_n)\right) = \sum_{n=1}^{\infty}\left(a_n Cos(n\omega_0 t) + b_n Sin(n\omega_0 t)\right)$$
$$I(t) = \sqrt{2}\sum_{n=1}^{\infty}\left(I_n Sin(n\omega_0 t - \beta_n)\right) = \sum_{n=1}^{\infty}\left(c_n Cos(n\omega_0 t) + d_n Sin(n\omega_0 t)\right)$$

Using these definitions for voltage and current then active power is:

$$P = \sum_{n=1}^{\infty} V_n I_n Cos(\theta_n) = \sum_{n}\left[a_n c_n + b_n d_n\right] \qquad \text{where} \qquad \theta_n = \alpha_n - \beta_n$$

Generally for the computation of active power the definitions are not the problem. When meters have difficulties making accurate measurements the problems are generally in the Implementation of the algorithms. Lea Wren of WECO did a number of tests on meters to determine whether they had problems measuring active power for waveforms like those above. Most meters were quite accurate; however, a few had severe errors. The nature of the errors was review by ANSI C12 working group C12.24 which published a technical report. The Harmonics Working Group of ANSI C12.16 has produced a set of tests for performance under harmonic conditions. The waveforms used in the proposed tests are shown below.

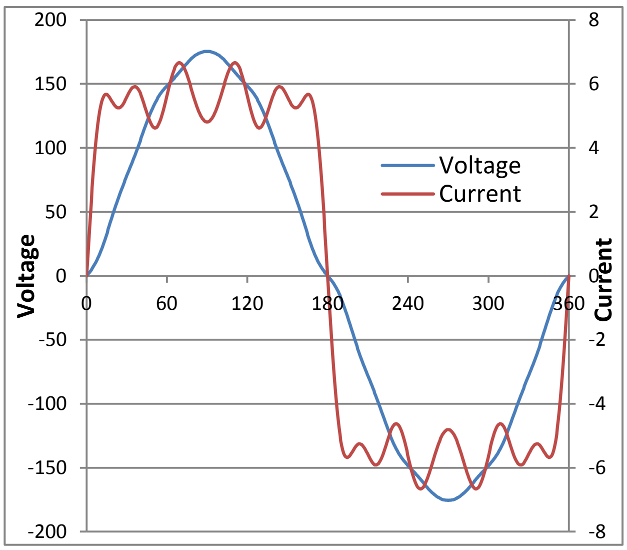


90 Degree Phase Fired Waveform

This waveform is one of the IEC test waveforms. It has two aspects which are problematic for some meters:

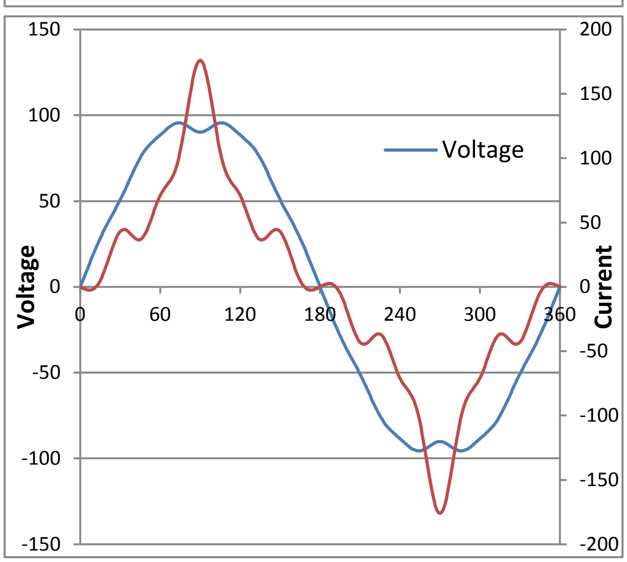
(1) Some meters have trouble with the flat (zero current portion of this waveform).
(2) Others have trouble with the very rapidly rising currents.

This waveform mimics the behavior of SCR switched loads. There is ongoing discussion about the details of the specifications of the test waveform, i.e. bandwidth.



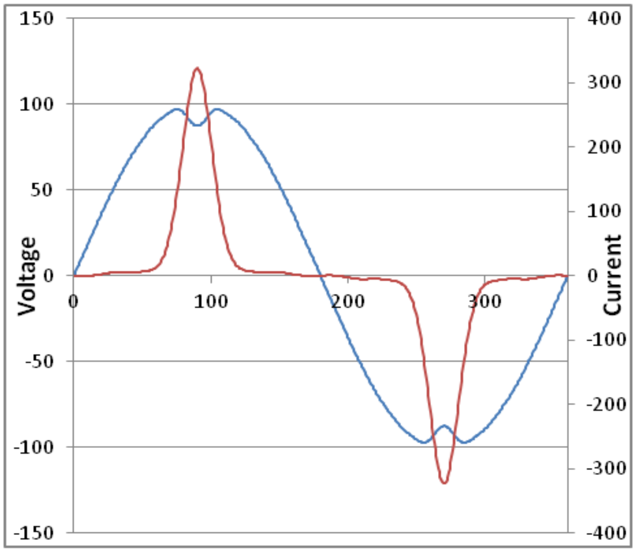
Quadriform Waveform

This waveform is one of the IEC test waveforms. There is low level distortion in the voltage and moderate harmonic content in the current. Actual active power is 98.023 % of the undistorted case.



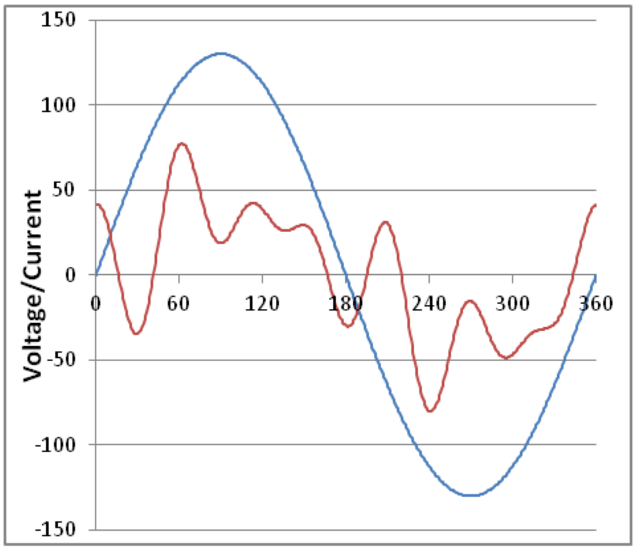
Peaked Waveform

This wave form is one of the IEC test waveforms. It has some distortion on the voltage and moderate distortion on the current. It also has a small multiple zero crossing on the current.



Pulse Waveform

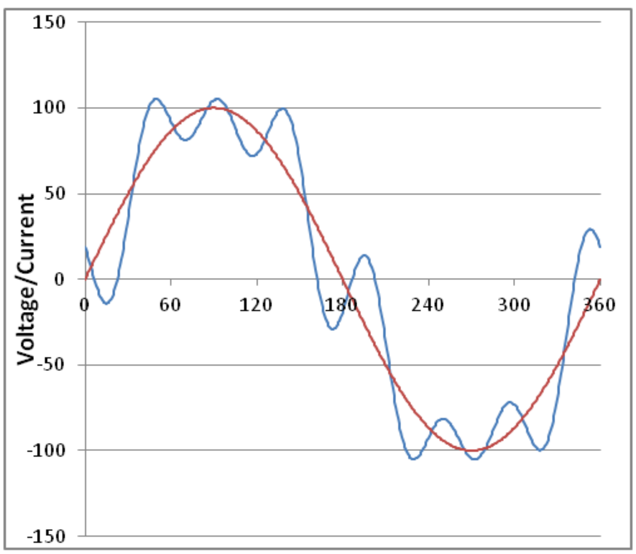
This test waveform was added by the ANSI C12 working group. It has very high harmonic content on the currents. It closely resembles the very common switching power supply load



Multiple Zero Crossing on Current

This test waveform was added by the ANSI C12 working group. It has very high harmonic content on the currents. The issue this wave form is intended to test is response to multiple zero crossings on the current. This is a "null" test. Because the voltage has no harmonic content, the active power should be the same as when all harmonics are removed.

The multiple zero crossing on the current confused some meters.



Multiple Zero Crossing on Voltage

This test waveform was added by the ANSI C12 working group. It has very high harmonic content on the voltage. The issue this wave form is intended to test is response to multiple zero crossings on the voltage. This is a "null" test. Because the current has no harmonic content, the active power should be the same as when all harmonics are removed.The multiple zero crossing on the voltage confused some meters.

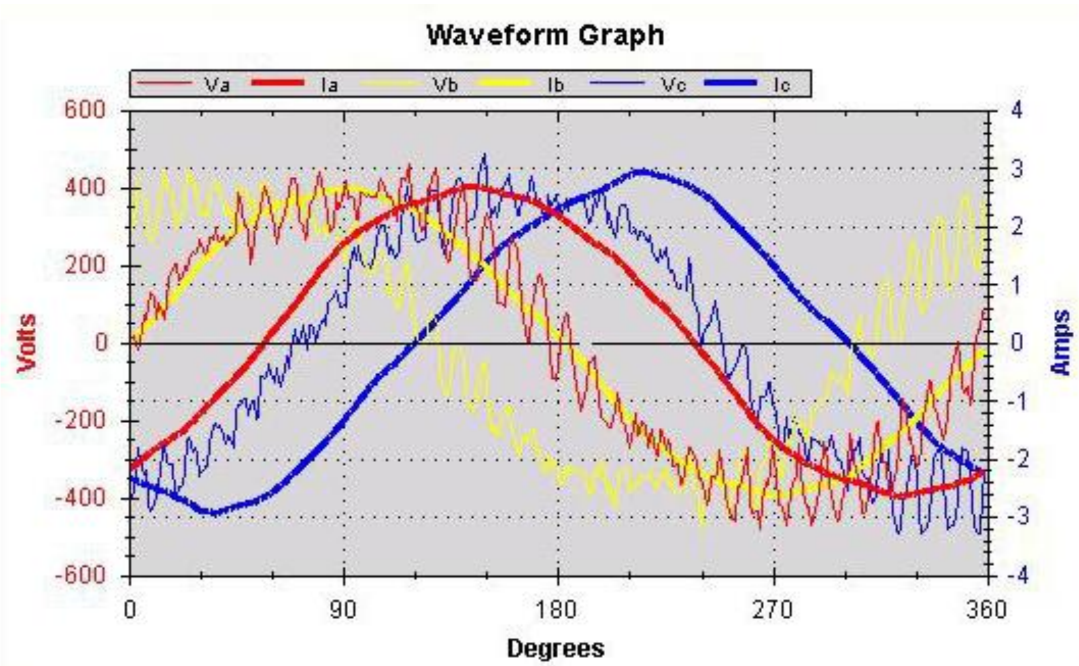
It is the belief of the Harmonics Working Group of C12 SC16 that the tests being proposed will ensure that meters will perform accurately over the full spectrum of non-sinusoidal, repetitive waveforms with regard to active energy metering.

A Couple of Real World Examples

Dan Nordell, XCEL Energy, provided a couple of interesting real world cases.

Case #1: Timing Errors

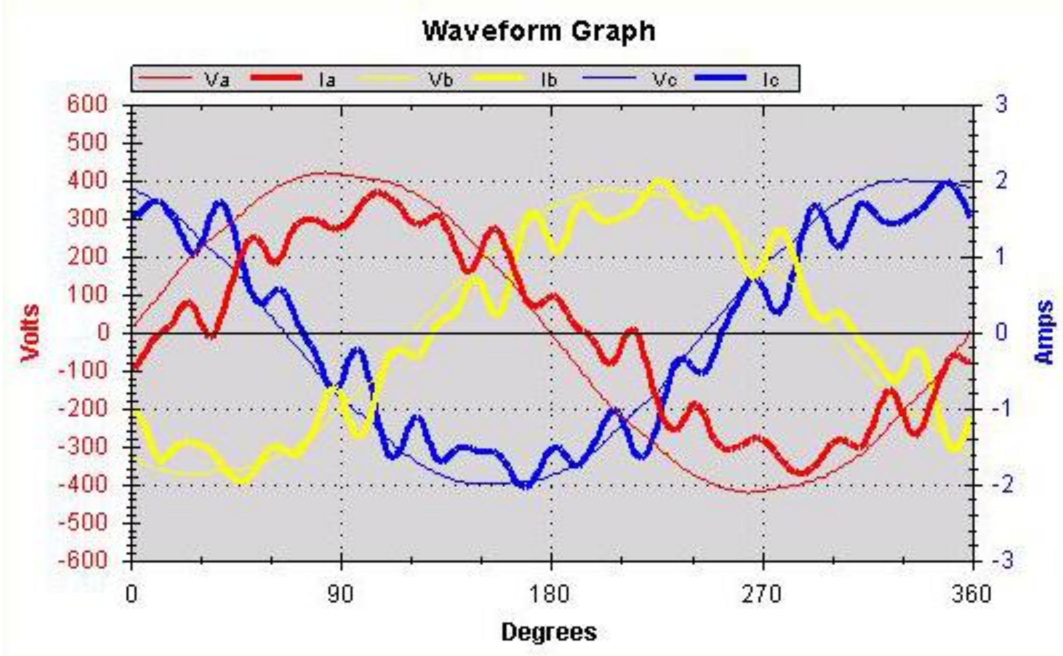
In the first case a load profile meter was exhibiting time discrepancies and erratic results. There were no detailed data available as to the exact source of the problem, but switching to a crystal clock solved the time errors. The underlying problem here was likely multiple zero crossings on the voltage circuits. These may have looked like the waveforms below.



Waveform with high distortion on voltage.

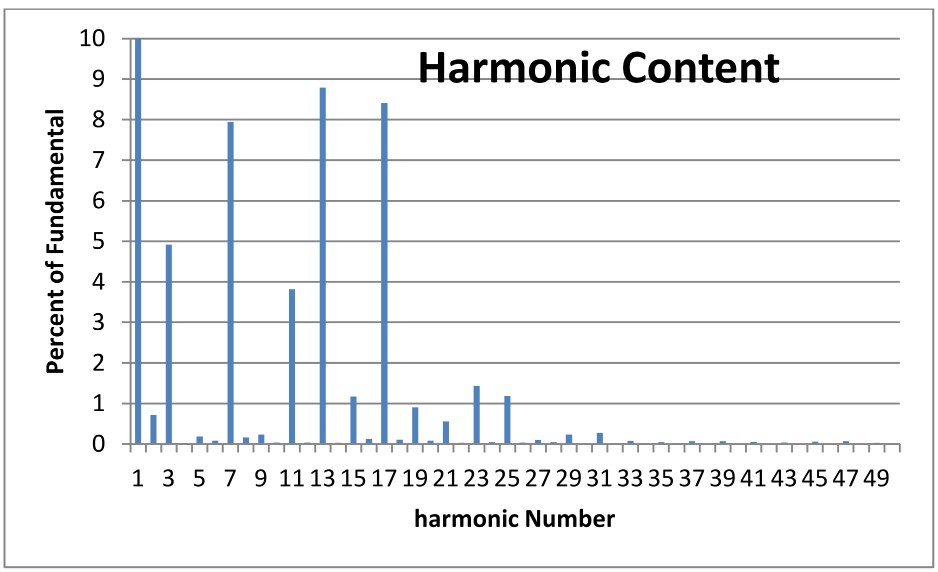
Case #2: Metering Errors

At this industrial site a meter had been installed along with a capacitor system who's vendor had claimed would "demonstrate energy savings". The meter, installed by the vendor, got significantly different answers from the utility's revenue meter. On investigation here's what was found.



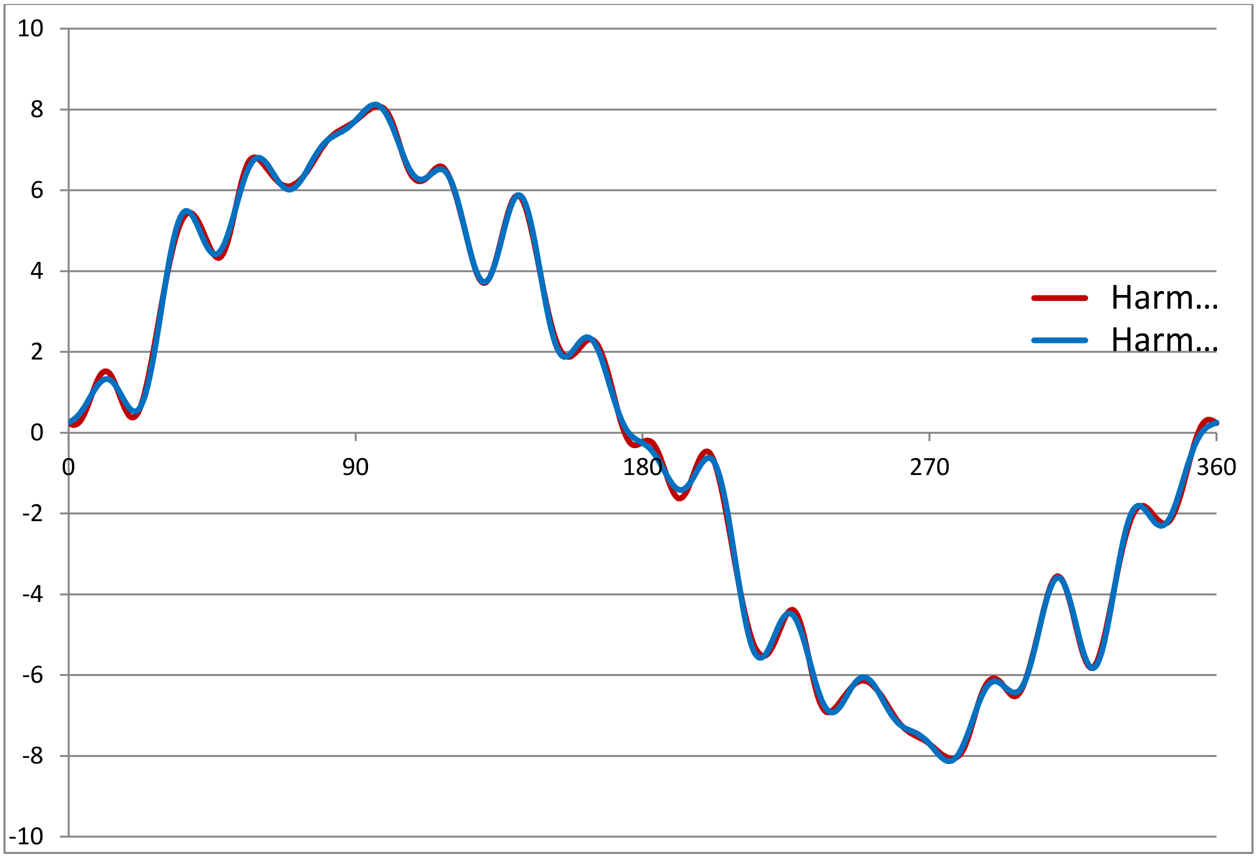
Case #2 Industrial waveform with large variable speed drives

This load shows a lot of low to moderate amplitude harmonics in the currents. The voltages are not very distorted. The harmonic content was analyzed with the following results.



Harmonic analysis of current phase A

As can be seen, there is very little harmonic content above the 25th. In the establishment of the test waveforms for C12 the issue of what the maximum harmonic included in the tests was one of the areas of significant discussion. The final was to generally limit the upper limit to the 19th harmonic. Below is a plot showing this waveform with 50 harmonics included (red) and with only 1 through 19 included (blue). There is no significant difference.



Comparison of waveform with harmonics 1-19 and 1-49

In general this level of distortion on the current should not be expected to cause any issue with metering of active energy. In this case, the meter used by the vendor was of "low quality". When replaced by a revenue grade digital meter the issue was resolved.

Additional Challenges

There are several additional challenges that we face with non-sinusoidal loads.

(1) We still have no definition for VA, VAR or power factor in non-sinusoidal conditions. Testing has shown that different meters get dramatically different answers under these conditions.

(2) Solid state electronics have made it possible to completely switch on and off large loads almost instantly. This has lead to situations where the entire metering load may vary dramatically from second to second. All meter testing is done under stable load conditions. Field testing under the sometimes rapidly varying conditions suggests that different meters get significantly different answers, even for active power under these rapidly changing conditions. There is no work presently under way to address this issue.