NISTIR 8248

A NIST Testbed for Examining the Accuracy of Smart Meters under High Harmonic Waveform Loads

Richard Steiner
Michael Farrell
Shannon Edwards
Joni Ford
Sumaiyah Sarwat
Thomas Nelson

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8248

National Institute of
Standards and Technology
U.S. Department of Commerce

NISTIR 8248

A NIST Testbed for Examining the Accuracy of Smart Meters under High Harmonic Waveform Loads

Richard Steiner
Michael Farrell
Shannon Edwards
Thomas Nelson
Quantum Measurement Division
Physical Measurement Laboratory

Joni Ford
The University of Ohio State

Sumaiyah Sarwat
University of Maryland

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8248

May 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Interagency or Internal Report 8248
Natl. Inst. Stand. Technol. Interag. Intern. Rep. 8248, 18 pages (May 2019)

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8248

Abstract

Household and industrial electrical energy measurements are advancing into a Smart Grid stage, using solid-state watt-hour meters with communication capability, called smart meters. As electrical products become heavily based on solid-state designs, such as LED lighting and dimmers, electrical loads are not purely resistive, but contain voltage and current spikes, introducing relatively high harmonic power to the grid. This paper describes a testbed laboratory that attempts to model LED household lighting loads, measure the energy by smart meter and power analyzer, and correlate offsets to the waveform variations. Results show that with large current crest factors up to 9, two meters (same manufacturer) out of eight tested show an error near 4 %, with a combined uncertainty of ±0.18 %. Three meters showed no variation outside a 0.07 % standard deviation that was typical for their normal repeatability.

Key words

crest factor; power quality; power system harmonics; power system measurements; smart grid; smart watt-hour meters; watt-hour meters.

Table of Contents

List of Tables

List of Figures

Glossary

AC: alternating current

LED: light emitting diode

LED bulb: a commercial light bulb containing LED(s) and control circuitry

rms: root mean square

1. Introduction

Electrical energy usage is measured with watt-hour meters. The present generation of meters with a solid-state design, and additional features such as digital panel display and internet or wi-fi or cellular communications, are called smart meters. A recent test conducted in Europe on European watt-hour meters [1,2] found that when some smart meters measured energy usage under AC waveforms that were extremely non-sinusoidal, the reported energy usage had very large measurement errors, up to 500 %. That test subjected the smart meters to electrical waveforms with voltage and current spikes of short duration and high amplitude, such as produced with light emitting diode (LED) lights that are dimmed with solid-state electronic switches with dimmer control. Thus, there is a question about whether very high number of harmonics contained in these waveforms are measured consistently by the electronics in some smart meters. This would not only affect the accuracy of electrical energy billing, but also communicate wrong information on actual energy usage to the control algorithms used in the future Smart Grid, affecting power station operations. With this report in mind, the National Institute of Standards and Technology (NIST) is developing a Smart Meter Testbed for examining the power measurement response of solid-state watt-hour meters to the influence power spikes (AC power with high harmonic content).

This paper starts with Section 2, a brief background on measuring electrical power and energy to introduce the complications that this system is trying to examine. Section 3 contains a brief description of the measurement procedures used to obtain the smart meter data. Section 4 reports on the measured accuracy of the smart meters under test, with conclusions mentioned in Section 5. A reader with experience in AC electrical measurements or not interested in the technical details of the experimental design can skip ahead.

2. Background

2.1. Electric power and measurement

In the ideal electric grid, electricity arrives as a voltage potential, a pure sine wave oscillating at a frequency of 60 Hz (or 50 Hz outside the USA). Devices draw current to operate, where the instantaneous power used is equal to voltage times current, V times I. To measure the average power, it is convenient to consider root mean square (rms) of the voltage and current over an oscillation period. This is the square root of the mean of the sine wave squared, as is shown in Fig. 1. Slightly different from instantaneous power, the total rms power is

$$\text{rms}\,Power = P_{\text{rms}} = (V_{\text{rms}} \times I_{\text{rms}}) \times \cos\theta\ , \tag{1}$$

where θ it the phase of the current relative to voltage. When the rms value for a sine wave is calculated, the peak positive amplitude is equal to $\sqrt{2} = 1.414$ times the rms value. The ratio of peak amplitude to rms value is called a crest factor. Since the line voltage in the tests reported here is only slightly distorted, the crest factor was computed in Eq. 2 from the peak current, I_{p}, and rms current, I_{rms}, as measured by the power analyzer

$$Crest\ factor = I_{\text{p}}/I_{\text{rms}}\ . \tag{2}$$

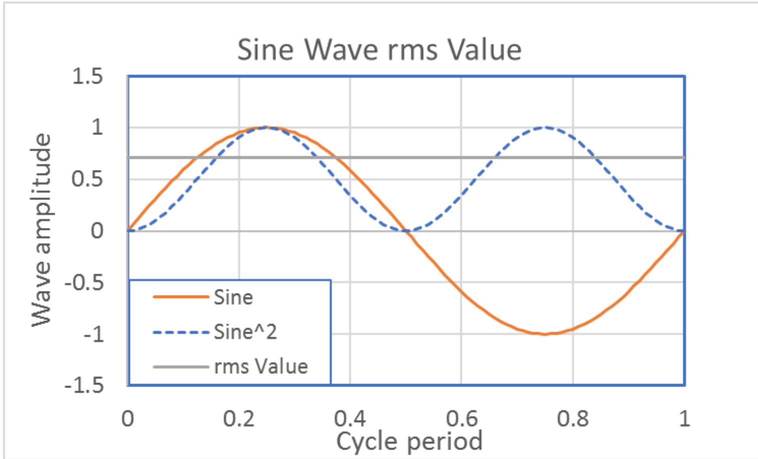

Figure 1. The rms value for a sine wave is equal to the peak positive amplitude divided by √2.

2.2. Electrical distortions from modern lighting devices

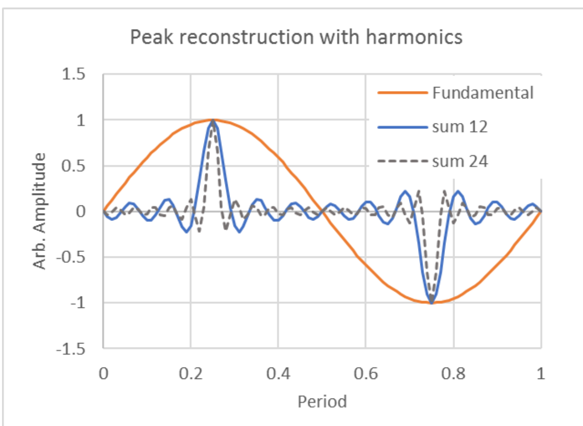

Figure 2. A spiked waveform, computed as the sum of a few higher harmonics of the fundamental frequency, including 12 and 24 harmonics for this example.

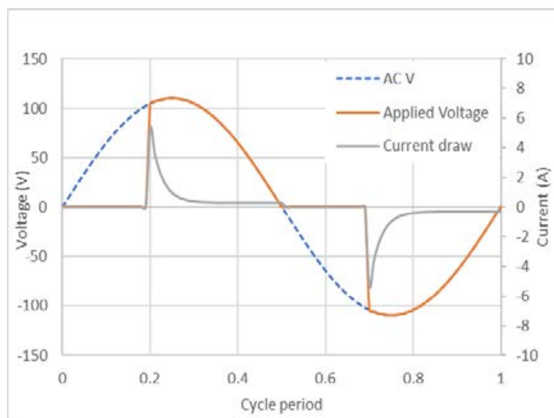

Figure 3. A schematic on the effect of a time-division dimmer, generating a current spike, as the voltage is turned on.

Now consider a current spike as shown in Fig. 2. It can be mathematically treated as a sum of higher harmonic frequencies. The sharper the spike, the higher the harmonic components needed to reproduce it mathematically. In Fig. 2, the 12th harmonic is 720 Hz, while the 24th harmonic is 1440 Hz. A very sharp and narrow spike might require several hundred harmonics to accurately characterize it and thus, high data rates are needed to calculate the rms value of the power from the current and voltage. This test system is not yet capable of such high frequency analysis. Using the crest factor to investigate the harmonic dependence is only an approximation to complicated structure and fast rise times of spike waveforms.

Electrical power is becoming ever more distorted with the use of digital electronics, such as the lighting combinations that are of interest in this testing procedure. Older dimmers used resistive circuits to restrict the current to incandescent light bulbs. Modern dimmers usually use a technique called phase control, in either a forward or reverse phase mode. Fig. 3 shows one full cycle of an AC voltage signal. A forward phase control dimmer will turn on at some fraction of the half-period after a zero crossing, turn off at the next zero crossing, then turn on again at the same time fraction on the reverse part of the voltage cycle. (A reverse phase controller would do the opposite. Our test concerned forward phase control dimmers.) At the time of "turn on", the dimmer switches on a steep and fast voltage rise. A typical LED bulb would draw a sudden and large amount of current before settling into normal operation. And thus, a spike is produced on the electrical waveforms.

In legacy electromechanical watt-hour meters, a wheel rotated at a speed proportional to the rms power coming through the meter and was measured by counting the revolutions. The number of rotations as counted over time resulted in the amount of energy used,

$$P_{rms} \times time = energy \text{ (watt-hours)}. \qquad (3)$$

The slow mechanical response guaranteed that current spikes could not be accurately measured. Modern smart meters are designed to measure more complicated waveforms. The built-in electronic circuits start by reducing the line voltage to digital logic levels (3 V to 5 V). The current must also be transformed into a voltage signal. (The type of transformer used is possibly a cause of the issues mentioned in the European paper. The root cause of meter errors is presently beyond the scope of this test.) Then in the meter, the voltage, V, and current, I, are separately and digitally measured at a rate higher than the fundamental frequency. Algorithms in the microchip logic are needed to compute V_{rms} and I_{rms} to calculate the rms power for waveforms other than sinusoid. Each stage of the smart meter energy measurement has possible errors due to limits in the hardware. In addition, there are electronics for the digital display, timing, and some method of communicating to the meter user or power supplier. One way to get energy information from a smart meter is via an infrared pulse system. That is the method by which this testbed obtained the watt-hour data, as described in Section 3. The accuracy of the numerical displays or other communication modes on the meters were not tested and are presumed to be consistent with the infrared pulse system.

Electric light loads were almost exclusively resistive incandescent lights. The heated and glowing filament of an incandescent responds slowly to the 60 Hz cycling and therefore does not blink on and off at 120 Hz. They act as natural P_{rms} converters without extra electrical components to convert the incoming AC voltage signal. LED devices do need complex electrical components to adjust and filter the incoming AC voltage waveform. Briefly described here, an LED needs a positive voltage above a certain level (typically a few volts) to turn on, and thus the bulb has additional circuitry to rectify the AC voltage. Circuitry also limits the voltage applied to the device. LEDs respond rapidly to the AC signal, so there must be additional inductance or capacitive components to smooth out the on/off switching of the AC period, keeping the device turned on longer to minimize blinking effects.

Now consider adding a dimmer to control a light bulb. Older dimmers worked compatibly with incandescent bulbs by varying the voltage amplitude to the bulb, thus limiting the current draw synchronously. As mentioned above, modern dimmers switch the power on for a fractional phase of the voltage waveform period (a time delay, as opposed to the current-voltage phase mentioned in Eq. 1). These dimmers are still compatible with incandescent bulbs, but an LED draws a large spike of current at the sudden voltage rise, then takes time to recover to a low current level, as shown in Fig. 3. A non-dimmable LED bulb has minimal current limiting circuitry, and thus draws a large current at each voltage turn-on transition. Dimmable LED bulbs and LED compatible dimmers have extra circuitry to limit the current spike. In severe cases, the current spikes do not just settle slowly, but ring down with very high oscillation frequencies. The current also affects the voltage supplied to the lighting device, an effect discussed later concerning crest factor determination.

3. Watt-hour Energy Accuracy Measurement

3.1. Smart meter testing

Smart meters are designed to be read in several ways. Some transmit information to readers of some sort (RF, ethernet, USB, signal on power line transmission, etc.). They also can be read by eye from the digital readout. As mentioned earlier, there is also an infrared pulse port for testing and readout purposes that is used in this procedure. Each pulse registers an energy value as specified by its Kh factor (a constant 'Kh' number of watt-hours per pulse). To automate this test platform, optical detectors were used to sense the infrared pulses. The pulses were recorded (see Fig. 4) and time-stamped via software. The electrical energy used is the total number of pulses for a test time multiplied by the Kh factor. Each smart meter reading is then compared to the measurement from a separately calibrated power analyzer.

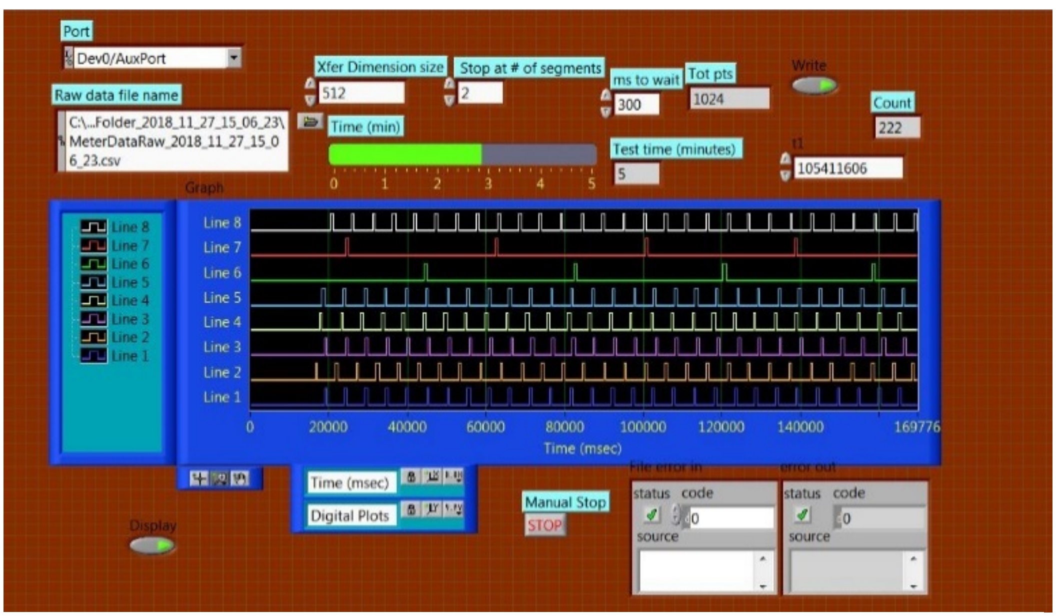

Figure 4. A sample of the program interface that records the smart meter energy pulses for 8 separate meters.

3.2. Power analyzer reference standard

Briefly described, the power analyzer monitors multiple phase line voltages and currents, digitizing the signals and calculating the various parameters, much like the inner working of the smart meters, but recording at a much higher rate of about a mega-sample per second.

The power analyzer was calibrated using a custom-built NIST sampling wattmeter, an instrument that has been upgraded to provide calibration capability for power with higher harmonic components. These calibration measurements are based on techniques reported previously [3]. For a general test, the power analyzer was checked on its high current input elements 2 and 3, 120 V at 60 Hz and at 5 A using a pure sine wave at phases 0°, +60°, -60°.

To match the typical test conditions of the testbed, the power analyzer ranges were set to 150 V and 10 A. The power analyzer was tested with a calibrated output current waveform with a peak current of 28 A and rms value of 4 A; a crest factor of 7:1. The spiked waveform was generated by using a 99 harmonic Fourier reconstruction, thus a 6 kHz frequency response limit. The current rate of rise for 1 A was 24 kA/s. The calibration tests showed that the power analyzer was repeatably within its accuracy specification rating of 0.01 % for the 60 Hz sinusoid test. For the 6 kHz harmonics of the spiked signal calibration, there is a higher uncertainty in the measurement, but the power analyzer's results agreed with the calibrated test signal to better than its general specification:

0.01 % of reading +0.03 % of range at 45 Hz $\leq$ f $\leq$ 66 Hz,
0.05 % of reading +0.05 % of range at 66 Hz < f $\leq$ 1 kHz,
0.15 % of reading +0.05 % of range at 1 kHz < f $\leq$ 10 kHz.

The higher frequencies contribute less to the total power measurement, so these accuracy specifications are not significant contributors to the total uncertainty. However, the actual testbed spiked waveforms contained even higher harmonic frequencies, so as seen in the conclusions, future test instruments working at higher frequencies will be needed to have a clearer picture of the total uncertainty.

3.3. Light fixtures board wiring schematic

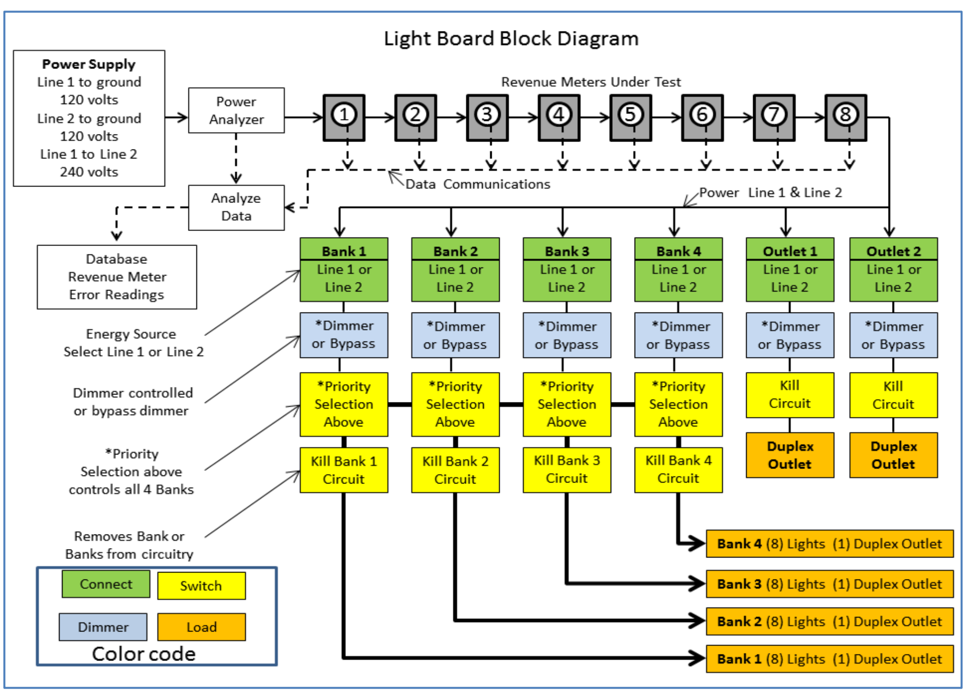

Figure 5. Lightboard layout and data paths.

A testbed was built just before the summer of 2018 to mimic a household lighting system that uses combinations of electronic dimmer switches and various types of light bulbs: incandescent, LED. It also has the capability to set up different electrical loads with sinusoidal or distorted waveforms, and to simultaneously test the measurement accuracy of multiple smart meters (see Fig. 5). A 110:220 V transformer sends power to the smart meters, which have a 2S form factor operating configuration of single-phase, three-wire, 240 V (ANSI C12 Code). The power lines are split into two 120 V lines and a neutral (180° out of phase), so the smart meter can be balanced or unbalanced with loads on either or both lines. Eight smart meters are wired in series with the entire electrical load.

4. Results

4.1. Smart meter baseline and data scatter

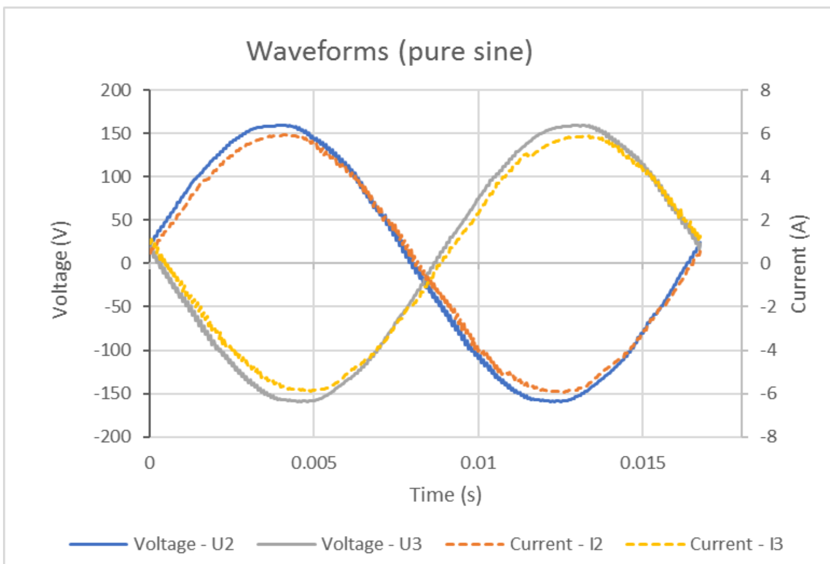

Figure 6. Waveform: pure sine wave. Line voltages are U2 and U3, line currents are I2 and I3, for lines 1 and 2 respectively. (Channels 2 and 3 are for higher currents than channel 1 on the power analyzer.)

A series of measurements were taken with incandescent lights as a resistive load as a baseline with which to compare changes between the smart meters in a consistent manner. As mentioned previously, there are two 120 Vrms lines on the smart meters, as seen by the familiar sine waveforms of the electrical voltage and current as shown in Fig. 6. The baseline plots for six of the eight smart meters under test are shown in Fig. 7. Meters made by the same manufacturer (numbered as models 1, 2, 3, other) are combined to show that they react similarly within the model type. The numeric average meter offset, at an average of 650 W, is listed in Table 1. These smart meters have an accuracy rating of 0.5 %. The smart meters plotted in Fig. 7a showed slightly more dependence on the load power than the rest of the smart meters. For the smart meter deviation data of the later graphs, the average of the baseline offset was subtracted from the subsequent test results. Thus, the graphed results display the relative change from the baseline for each meter.

Table 1. Baseline accuracy of meters under test at about 600 W and their scatter under this test (standard deviation).

Meter ID	Avg offset	Std. Deviation (1σ)
ID 1147	0.12 %	0.06 %
ID 7667	0.07 %	0.07 %
ID 7668	0.05 %	0.07 %
ID 0767	0.11 %	0.07 %
ID 2372	-0.01 %	0.06 %
ID 8729	0.07 %	0.06 %
ID 2370	0.05 %	0.07 %
ID 6318	-0.19 %	0.07 %

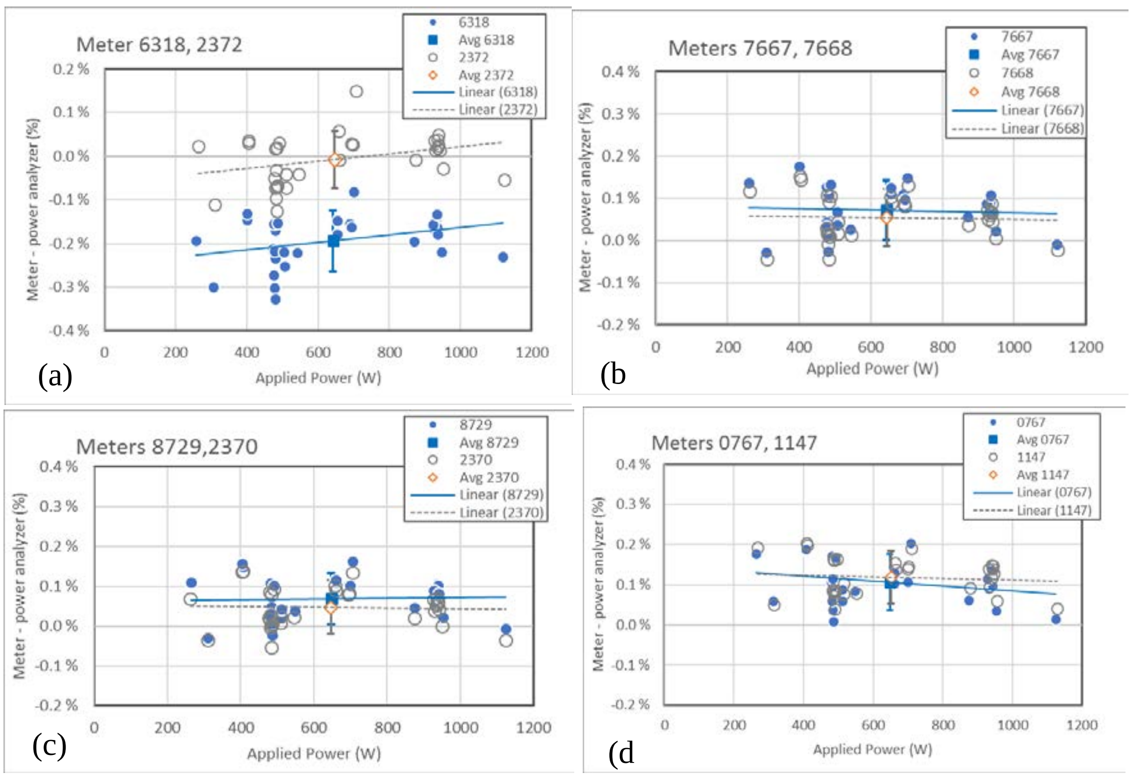

Figure 7. Baseline plot of similar model Type 1 meters. Error bars are 1σ standard deviation. (a) Model 1, (b) model 2, (c) model 3, (d) other models.

To estimate the uncertainty in these tests, we start with the baseline test scatter. The standard deviation of all the meters' data is within 0.07 % (1σ). This is very good repeatability. Some of this scatter is in the resolution limits of the test period, and some from the line voltage variations during the many hours of the test periods.

4.2. Distorted power testing

4.2.1. Balanced loads

The goal of this test was to generate large current spikes using various combinations of non-dimmable LED bulbs and non-LED compliant dimmers. Fig. 8a shows a typical plot of the waveforms, a sinusoid voltage with a large current spike, as recorded from the power analyzer. In this case, as with most of the displayed graph points, the load was balanced between the two input electrical lines. The dimmers were adjusted to maximize the current spikes, and for synchronicity between the two lines. For each test run, a point was obtained for the difference between the energy use as reported by the smart meters and the power analyzer, plotted relative to the crest factor computed using the average of the approximately equal current spikes, as in Eq. 2.

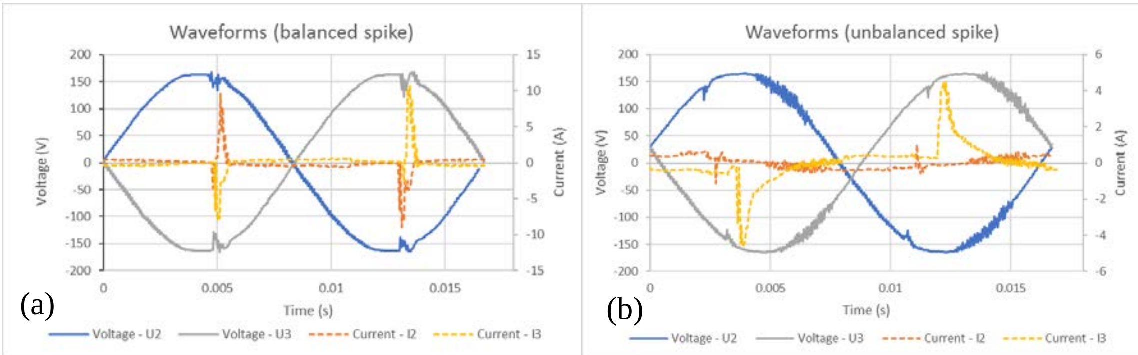

Figure 8. Waveform: (a) balanced current spikes on two lines. (b) unbalanced current spike on one line only.

4.2.2. **Unbalanced loads - special case**

One special test configuration requires some extra explanation. Fig. 8b shows a spiked current like most of the test results shown in Fig. 8a, except the load is unbalanced, on only one of the two lines. This was an interesting test condition because it resulted in a crest factor much higher than on the balanced load tests. However, there are two questions that arise in using unbalanced, spiked current loads. First, what is the smart meter correction for an unbalanced spiked load? Second, how is the crest factor calculated when the load is only on one line?

The design of a 2S form factor meter assumes that the voltage is equally split across the two lines. However, an unbalanced, large current reduces the voltage on one line, creating an error within the meter calculations. A calculated correction is derived for sine wave loads [4], which takes the voltage difference between the two lines into account and computes the power from the current and the average voltage between the lines, not the loaded and depressed voltage on one line. To test the correction, an unbalanced resistive load with a sine wave was used. At 12 A and a line voltage difference of 1.5 V, a correction factor of 0.6 % for these points did indeed correct an offset in the meters. These test points are on the Fig 9 graphs, slightly higher than the balanced load points at a crest factor of 1.4.

It is not clear how to calculate an unbalanced line correction for spiked current loads. A simple approximation was to use the sine correction equations with the power analyzer results for the rms current. The voltage waveforms were not severely distorted, and the line voltage difference was only a few tenths of a volt, so the corrections were about 0.1 % to 0.3 %. Test points at a crest factor of about 6.5 compare balanced load results with unbalanced load results plus correction; they are approximately equal. An additional approximation for the unbalanced situation was to weight the crest factor on each line against the total load, instead of averaging two widely dissimilar values. With the maximum test current placed on one line, a larger crest factor of over 9 was obtained.

4.3. Test Results

All the graphs in Fig. 9 are plotted at the same scales to ease comparisons. The points near a crest factor of 1.4 are the baseline checks. Note that two meters with the largest deviations, increasing approximately linearly as a function of the crest factor, were those same meters in Fig. 8a that, coincidentally or not, also had slightly more power dependence than the rest. The meters of Fig. 9b varied less than the other models did and had the flattest response to baseline load power. The meters of Fig. 9c were similarly flat in their response, but with slightly more scatter. The meters of Fig. 9d have some crest factor dependence, one positive deviation and the other with a negative deviation and large scatter.

The meter deviations at the highest crest factor continued along the linear trend of the balanced spike data. Since the highest crest factor points were not considerably outside of the trend lines, it is reasonable to assume that the assumptions made for these extreme test points: approximating an unbalanced line correction, weighting the crest factor, and looking at the crest factor as a variable, are not wildly inappropriate. An additional 0.05 % uncertainty component is added to the overall uncertainty of this test system to account for the approximations.

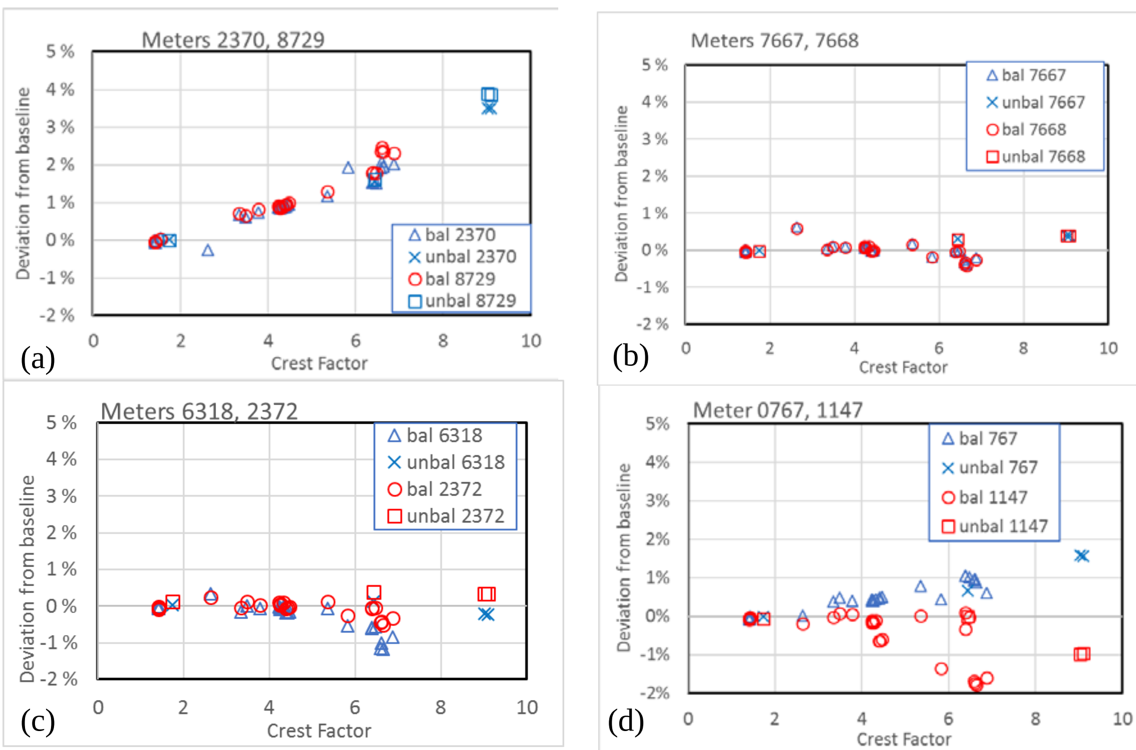

Figure 9. Plot of meter deviations vs crest factors. (a) Model 1, (b) model 2, (c) model 3, (d) other models.

5. Conclusions

The main goal of this testbed was to test for deviations in reported energy usage in smart meters: relative to their baseline offset, with various models of meters, and under extreme non-sinusoidal load waveforms. Only a small sample of smart meters from three manufacturers, or possibly four since some meters were reconditioned, were available for testing. For the baseline offset of each smart meter under normal sinewave loads, all the smart meters are accurate to within their specification of 0.5 %, with a standard deviation of 0.14 % (2σ). This test uncertainty is estimated at about ±0.15 % (k=2) for the balanced test points, ±0.18 % (k=2) for unbalanced test points.

In the case of current spikes under balanced line conditions, two of the tested meters showed errors (deviations from baseline) of a maximum of +2 % (overbilling), and one meter had up to -2 % (underbilling). Three meters showed only variations within their specifications and this test's uncertainty. With extremely large and narrow current spikes (higher crest factor), five of the eight meters tests showed some deviation beyond their typical scatter.

For the special case of the highest crest factor on an unbalanced line, only two meters from the same manufacturer consistently had errors approaching +4 % (overbilling). This is well above the overall relative combined uncertainty estimate of ±0.18 %, and thus statistically significant. However, at least within the parameters of this test, the important take away is that no USA meters had anywhere close to the 500 % errors as reported in the European test. It must also be understood that the larger fraction of normal household power usage is sinusoidal (resistive) or with phase variations due to inductive motor loads, and thus, these tests on relatively low power, spiked current loads are not likely to be seen in real situations.

Future tests are planned and will include more smart meters from the same manufacturers. It appears that similarly manufactured smart meters act the same, but a sample size of two is small. Additional test variations will involve adding long lengths of cable to simulate the added resistance and inductance from typical lengths of house wiring. Plus, different styles of light bulbs, and different dimmer manufacturers can be tested. The uncertainty specification of the power meter only goes to 10 kHz, so it is not certain that the power analyzer, when used to measure very fast rising and large current spikes, will not have its own deviations. Faster measurement electronics to measure the voltage and current of the distorted waveforms at higher frequencies will be needed. This will allow better analyses of the fast rising, spiked waveforms at higher harmonics (up to 1 MHz), and allow a more precise calculation of the P_{rms}, instead of relying upon the lower frequency specifications of the power analyzer and its complicated calibration process.

Acknowledgments

We thank NIST staff Bryan Waltrip for performing the power calibrations, and Michael Berilla for designing and building the latching circuit.

References

[1] Leferink F, Keyer C, Melentjev A (2016) Static energy meter errors caused by conducted electromagnetic interference. *IEEE Electromagnetic Compatibility Mag.*, 5(4): 49–55. https://doi.org/https://doi.org/10.1109/MEMC.2016.7866234

[2] Leferink F, Keyer C, Melentjev A (2016) Runaway Energy Meters due to Conducted Electromagnetic Interference *Proceedings of the 2016 International Symposium on Electromagnetic Compatibility - EMC Europe* (IEEE, New York, NY):172-175.

[3] Stenbakken G N, Dolev A (1992), High-accuracy sampling wattmeter. *IEEE Trans. on Instrum. and Meas.*, 41(6):974–978. https://doi.org/10.1109/19.199445

[4] Edwards S, Wren L (Oct. 13 2011), White paper: Accuracy of energy measurements using the Form 2S three-wire self-contained meter in the presence of voltage imbalance. From minutes of *C12 Accredited Standards Committee on Electricity Metering Subcommittee 16, Solid State Watt-hour Meters*, Dallas, TX.