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NOT ALL 60 Hz AC ELECTRICITY IS THE SAME – COMPLICATIONS IN MEASURING SOLID-STATE LIGHTING PRODUCTS

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NOT ALL 60 HZ AC ELECTRICITY IS THE SAME – COMPLICATIONS IN MEASURING SOLID-STATE LIGHTING PRODUCTS

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Abstract

In January 2010, the National Institute of Standards and Technology (NIST) began to offer a Measurement Assurance Program (MAP) for solid-state lighting (SSL) products to customers of the National Voluntary Laboratory Accreditation Program (NVLAP) under the support of the United States Department of Energy. The MAP program provided proficiency testing complimenting laboratory accreditation to ensure that as SSL products became more prevalent, capable testing laboratories would be available to handle the volume of measurement work. A conclusion of the analysis of the MAP data was that the type of AC power supply may have an influence on the electrical and optical measurement results. While the measurement of Active AC power appears to have a variance consistent with a normal distribution (assumption of randomness implied), the measurement of RMS AC current and power factor is somewhat bimodal. A few potential causes were identified and discussed.

Keywords: Measurement Assurance Program, Proficiency Testing, Solid State Lighting

1 Introduction

In January 2010, the National Institute of Standards and Technology (NIST) began to offer a Measurement Assurance Program (MAP) for solid-state lighting (SSL) products to customers of the National Voluntary Laboratory Accreditation Program (NVLAP) under the support of the United States Department of Energy (DOE). The MAP program provided proficiency testing complimenting laboratory accreditation to ensure that as SSL products became more prevalent, capable testing laboratories would be available to handle the volume of measurement work. At the request of the ENERGY STAR® program, in January 2011 the MAP was opened to any testing laboratories that wanted to participate, independent of accrediting body. In December 2014, the first version of the MAP was closed with 118 participant laboratories representing 13 countries.

In January 2015, NIST started to offer a second version of the MAP (MAP2) with different SSL artefacts meant to evaluate the laboratory's capabilities. The MAP2 artefacts have been updated to represent the current SSL market and were selected to allow the laboratory to diagnose potential deficiencies in its measurement system or to provide diagnostics to improve the lighting measurement standards. MAP2 is expected to run for four years and is available to any testing laboratory for a service fee.

Both MAPs are conducted as a star-type comparison. Along with the measurement results, each laboratory provided information on their measurement procedures, laboratory equipment, and measurement traceability. The difference between the results of the laboratories' measurements and NIST's measurements for each of the eight properties/quantities was calculated and categorized by lamp type. This analysis provides a snapshot of the lighting measurement community's capability to measure SSL products and is presented in such a way that an individual laboratory's results cannot be identified. Individual laboratories have received formal reports describing their results.

An unexpected result of the MAP1 was the large standard deviation and the number of outliers identified for the measurement of AC current. The 30 measurements identified as outliers included the results from 19 different laboratories. Possible causes are investigated.

2 General Results

The results of the MAP1 offered by NIST are a snapshot of lighting testing laboratories' capabilities to measure total luminous flux (lm), RMS voltage (V), current (A), electrical active power (W), luminous efficacy (lm/W), chromaticity coordinates (x, y), CCT (K), and CRI (Ra) according to the procedures described in IES LM-79-08 "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products". (IES, 2008) The results are for the measurements of 118 laboratories located worldwide between the years of 2010 and 2014 and were published in 2016. (Miller et al., 2016)

The results of the comparison are analysed using a normal probability plot. (NIST/SEMATECH, 2013a) The process begins by ordering the differences to the NIST values from smallest to largest. These differences are plot against theoretical normally distributed values (called normal order statistic medians). If the observed differences are normally distributed, then the resulting graph will be linear to a certain significance determined by the correlation coefficient and the number of data points. To calculate the normal order statistic medians of a distribution, the uniform order statistic medians were calculated using equations (1), (2), and (3). The normal order statistic medians were calculated by taking the inverse of the normal cumulative distribution function also known as the percentage point function (NIST/SEMATECH, 2013b) for each of the uniform statistic medians where the mean of the normal cumulative distribution function is zero and the standard deviation is one.

$$U_i = (1 - U_n)\ for\ i = 1 \tag{1}$$

$$U_i = (i - 0.3175)/(n + 0.365)\ \ for\ i = 1, 2, 3, 4, \dots, n - 1 \tag{2}$$

$$U_i = 0.5^{1/n}\ for\ i = n \tag{3}$$

where

U_i is the uniform statistic median for an observed value i in the sequenced function of the differences;

n is the total number of observed values.

For example, Figure 1 shows the sequenced distribution of all the observed differences between laboratories' measurements and NIST's measurements of luminous flux, and Figure 2 shows the normal probability plot of the data in Figure 1.

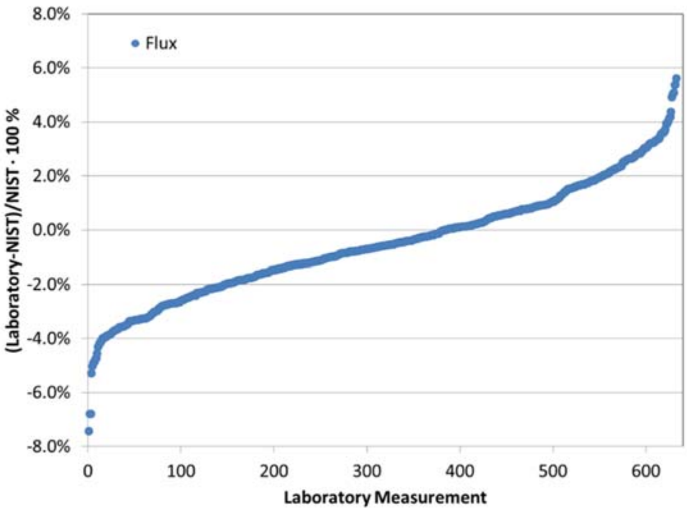

Figure 1 – The sequenced distribution of all the measured total luminous flux differences

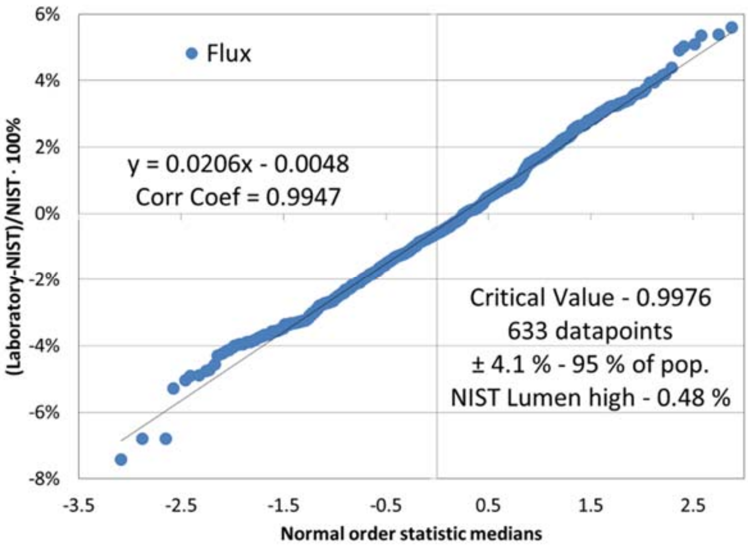

Figure 2 – A Normal Probability Plot of all the observed differences in luminous flux measurements which has been fit to a linear function.

The normal order statistic medians have been calculated using the method described above and plotted on the horizontal axis against the observed normalized differences. The hypothesis is that the measurement differences come from a normal distribution. The correlation coefficient *R* is calculated for the observed values with respect to a linear fit line. A critical value (NIST/SEMATECH, 2013c) is established based on the number of points and significance level. The correlation coefficient *R* is compared to the critical value and, based on the results, the hypothesis can be confirmed or rejected. For Figure 2 the number of points is 700 and the significance level is chosen as 5%, which gives a critical value of 0.9978. The correlation coefficient is $R = \sqrt{R^2}$ = 0.9963, which is lower than the critical value, meaning that the sequence does not come from a normal distribution. However, it is very close implying that the process is quite random.

The normal probability plot also provides the mean and standard deviation of the sequenced distribution because of the fit where the mean is estimated by the y-intercept and the standard deviation is approximated by the slope of the fit. The y-intercept of the graph shows how far the laboratories' measurements fall from NIST's measurements altogether. In this case, the intercept is −0.0048, meaning that, in general, laboratories measured luminous flux is about 0.48% lower than NIST. The standard deviation of the measured differences is ±2.1%.

In general, independent of the lamp type, laboratories were able to measure the total luminous flux and the luminous efficacy within ±4% (k = 2, representing a 95% confidence interval). The laboratories were able to measure the active power within ±1% (k = 2) for most of the lamps. The one type of lamp, which has an active feedback, and another type of lamp, which is a 12 V DC lamp (uncommon for many laboratories), have a larger spread.

3 AC Current Measurement

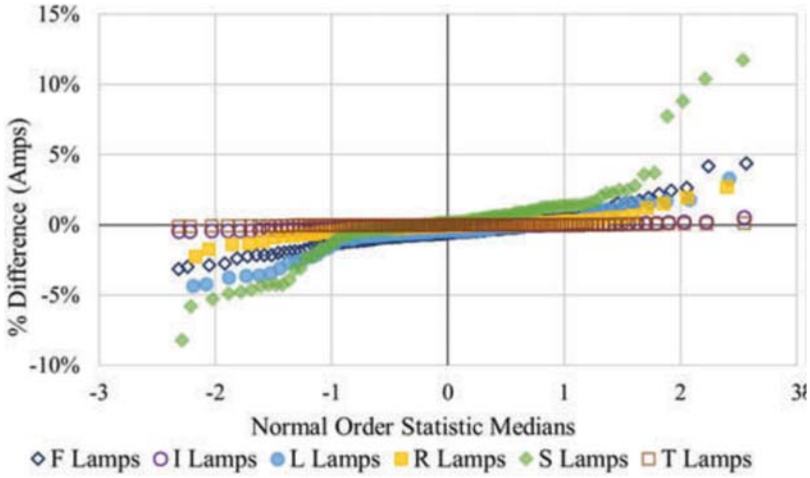

Figure 3 – Normal Probability Plots for the differences in RMS current measurements for each lamp type except the T type lamp which is a difference in voltage measurements.

Figure 3 shows the normal probability plots for the difference of AC current measurements for each lamp type in the MAP set. The F-lamp is a recessed ceiling luminaire that was chosen because of its physical size (large enough to cause self-absorption concerns with sphere measurements) and because it has a chromaticity stabilization feedback loop. The L-lamp has a large remote phosphor enclosure that may cause potential self-absorption concerns in a small sphere measurement system. The S-lamp has a sharp peaked current wave that has a maximum when the voltage wave is at a maximum, which makes the measurement of the current and power factor of the lamp challenging. The R-lamp is a 30° spot lamp that requires the laboratory to correct for angular nonuniformity of sphere responsivities or angular sampling frequency for a goniometric-based measurement. The I-lamp is an incandescent halogen lamp used to evaluate the luminous flux scale of the laboratory. These five lamps are operated with 120 V of 60 Hz AC electricity. The sixth lamp, the T-lamp, is a 24-in. under-cabinet-type lamp that is operated with 0.2250 A of constant current DC electricity with an approximate compliance voltage of 12 V. The T-lamp has a high correlated color temperature near 7000 K.

Table 1 – Normal Probability Plot for AC Current and DC Voltage Measurements

Lamp type	Number of measurements	95 % Confidence Interval	Bias	Correlation Coefficient	Critical value (5%)
AC Current					
F	134	± 2.4 %	-0.46 %	0.9581	0.9897
I	127	± 0.3 %	-0.09 %	0.9791	0.9897
L	89	± 2.6 %	-0.57 %	0.9405	0.9857
R	84	± 1.3 %	-0.09 %	0.9156	0.9850
S	124	± 5.2 %	-0.13 %	0.8937	0.9889
DC Voltage					
T	127	± 1.5 %	-0.02 %	0.9573	0.9897

Table 1 shows the numerical results of the normal probability analysis with the 30 measurements identified as outliers based on ASTM E178-16 removed. (ASTM, 2016) For all types of lamps the correlation coefficient is smaller than the critical values; therefore, the hypothesis that the distributions come from a normal distribution is rejected. The S-type lamp was included in the MAP1 because of its current waveform. The standard deviation for the current measurement of the S-type lamp was twice any of the other types of lamps. One laboratory was a consistent outlier and many times had the largest deviation, measuring a much larger current than NIST. This laboratory identified a wiring problem which has been corrected.

In Figure 3 it visually appears that a fraction of the laboratories' measurements may result from a normal distribution, though the standard deviation is larger than expected. In the wings of the distribution the deviation becomes larger quickly; therefore, there are two types of laboratories. The laboratories with the larger deviations may be due to bad or wrong wiring so that it affects the normal operation of the lamp. NIST is conducting research to determine potential dependencies. Another possible explanation for the differences is improper implementation of using a four-pole or Kelvin socket to eliminate voltage drop from the lamp base all the way to the voltage meter. If a laboratory is measuring the voltage drop across the lamp at a wiring junction outside of the sphere or perhaps at the power supply terminals, the measured lamp voltage will include the voltage drop across the lamp, at any junctions, and through the length of wire. Therefore, the lamp will be operated at a lower than specified voltage. For MAP2 a 12 V, 4.2 A large current incandescent lamp was added to make its measurement results more sensitive to any four-pole socket and/or bad wiring problem.

4 High Frequency AC Current Waveform Component

Drivers for SSL products often have a very fast reaction time. The very fast reaction time may induce a high frequency component in the current waveform, which may result in large measurement errors (Martinsons 2013). Traditional lamps and linear fluorescent tubes using magnetic ballast are operated on 60 Hz or relatively low frequency AC electricity. Most laboratories do not have difficulties in measuring these traditional lamps and low frequency fluorescent tubes. With the development of rapid start and instant start ballasts the 60 Hz electricity is up converted to 20 KHz electricity (even as high as 85 KHz) by an electronics ballast. SSL products that are intended to replace fluorescent tubes and operate with these high frequency electronic ballasts may introduce significant measurement errors. The electronic ballast has a typical output of 300 V RMS at high frequency (20 kHz to 85 kHz). If a laboratory runs, for example, 8 m (about 25 ft) of 14-gauge parallel wire between the ballast and the lamp, 17% of the measured current never reaches the lamp because the capacitance between the two wires shunts the current back directly to the power supply. Measurement of such high frequency lamps is much more difficult; however, in the past only a few laboratories were required to measure such high frequency linear fluorescent tubes or luminaires. The laboratory was aware of this situation and accounted for the higher frequency electricity in their measurement systems.

Certain SSL products manufactured today, while operating on 60 Hz AC electricity, generate a high frequency current component when the driver is reacting to a particular type of AC power supply (usually the higher end power supplies used in metrology laboratories). An AC power supply that uses a digital waveform generator (DWG) to create the 60 Hz AC electricity has small steps in the waveform. Most DWG based AC power supplies use 1024 steps to create one cycle of 60 Hz electricity. The drivers in many of the SSL products react to the flat region of the step by pulling very little current from the power supply. Conversely the driver pulls a large amount of current during the steep region of the step, an indication that impedance of the LED driver becomes very load at a high frequency. The magnitude of current correlates to the slope of the step which ranges from 5 μs to 50 μs. The steeper the step, the more current that is pulled. The rate of change is typically called the slew rate of a power supply.

Figure 4 shows the voltage and current waves for a lamp powered by two different types of AC power supplies and a NIST wall outlet. The current waveform for the lamp using the wall outlet is smooth and only changes level due to the design of the driver in the product. The current waveforms for the lamp using the two AC power supplies are similar but the magnitude of the 'noise' is different by a factor of three. The 'noise' is a repeating high frequency (~60 kHz) waveform. Power supply one has a slope of 5 μs and the power supply two has a slope of 50 μs; therefore, the driver has a larger response to the faster step. This high frequency current wave is susceptible to capacitance and inductance in the electrical wires or cables of the measurement system.

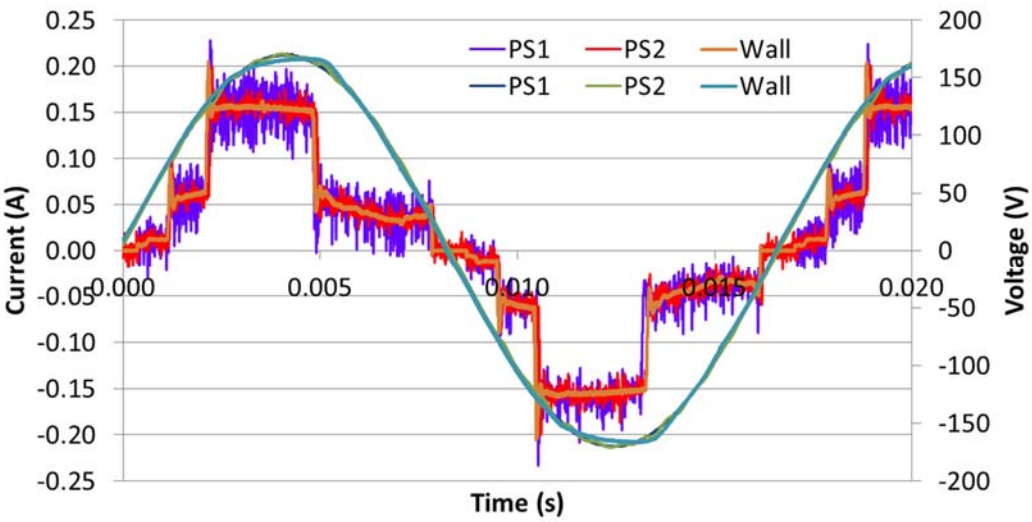

Figure 4 – Voltage and current waves for a lamp under test using two different laboratory power supplies and the laboratory wall outlet.

Measurement of high frequency current is sensitive to test circuit due to its capacitance, which may result from wires running in parallel that are not separated by an appreciable distance. When the SSL device is powered from the wall outlet the high frequency component is very minimal because the output impedance of a wall outlet is much higher compared to that of an ac power supply. As an example, measurements were made with 25 ft of parallel running 14-gauge wire. Table 2 shows the electrical measurement results of a lamp using the wall outlet and two AC power supplies when using parallel wires. The differences of results are with respect to the 'wall' measurements.

Table 2 – Lamp Measurements Using Parallel Wires Using Different Power Supplies

Power Supply	Voltage [V]	Current [A}	% Current Difference	Power [W]	% Power Difference	Power Factor	Pf Difference
Wall	120.1	0.09504		10.378		0.9100	
PS1	120.0	0.09462	0.61 %	10.337	0.80%	0.9081	0.0016
PS2	120.1	0.09444	0.42 %	10.293	0.38%	0.9104	-0.0007

Table 3 shows the results when the same parallel wires have been separated by more than 1 ft of air space. The difference of measurement results between using the wall outlet and using the two power supplies have been significantly reduced. The measured results using the two power supplies approach those using the wall outlet by minimizing the capacitance and inductance within the measurement system, which are more realistic because LED lamps are designed to be operated on wall outlet.

Table 3 – Lamp Measurements Using Separated Wires Using Different Power Supplies

Power Supply	Voltage [V]	Current [A]	% Current Difference	Power [W]	% Power Difference	Power Factor	Pf Difference
Wall	120.05	0.09502		10.376		0.9097	
PS1	120.06	0.09508	-0.06 %	10.366	0.10%	0.9080	0.0018
PS2	120.00	0.09510	-0.08 %	10.391	-0.15%	0.9106	-0.0010

5 Inductance & Resistance Dependency

By separating the current carrying wires and using a power analyser that has an appropriate sampling rate, the problem identified for SSL products in Section 4 is resolved. Other SSL products may have drivers that react very differently to the slew rate and output impedance of a power supply. Figure 5 shows the voltage and current waveforms of another type of lamp powered by two different types of AC power supplies and the wall outlet. The lamp draws current near the peak of the voltage waveform to maximize AC to DC conversion efficiency.

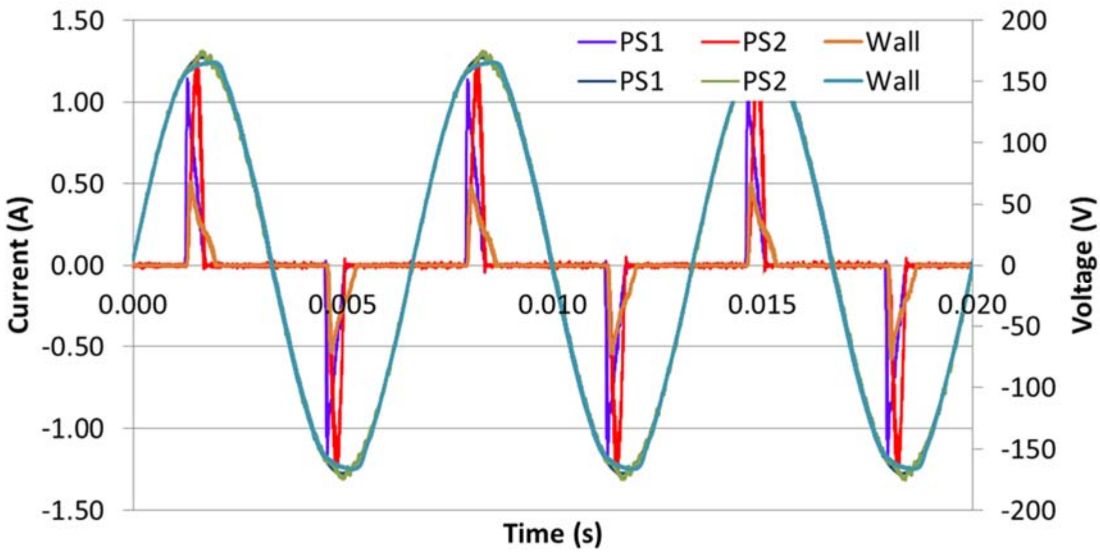

Figure 5 - Voltage and current waves for another type of lamp under test using two different ACpower supplies and the wall outlet.

Table 4 – Lamp Measurements Using Separated Wires Using Different Power Supplies

Power Supply	Volts [V]	Current [A]	% Diff.	Power [W]	% Diff.	Power Factor	Pf Diff.	Lumen [lm]	% Diff.
Wall	120.0	0.1582		10.26		0.5399		293.5	
PS1	120.1	0.2315	46.3 %	12.29	19.8%	0.4422	0.1810	327.1	11.4%
PS2	120.0	0.2841	79.5 %	14.73	43.6%	0.4321	0.1997	360.8	22.9%

Table 4 shows the measurement results of this lamp using the two AC power supplies and the wall outlet. The current waveforms are drastically different under the three different operating conditions, which causes large differences in power consumption and light output. We have made a series of measurements varying the resistance and inductance. Figure 6 and Figure 7 shows the dependence of these variations. By adding the inductors and resistors the agreement to the wall outlet is closer. This is an area of continuing research.

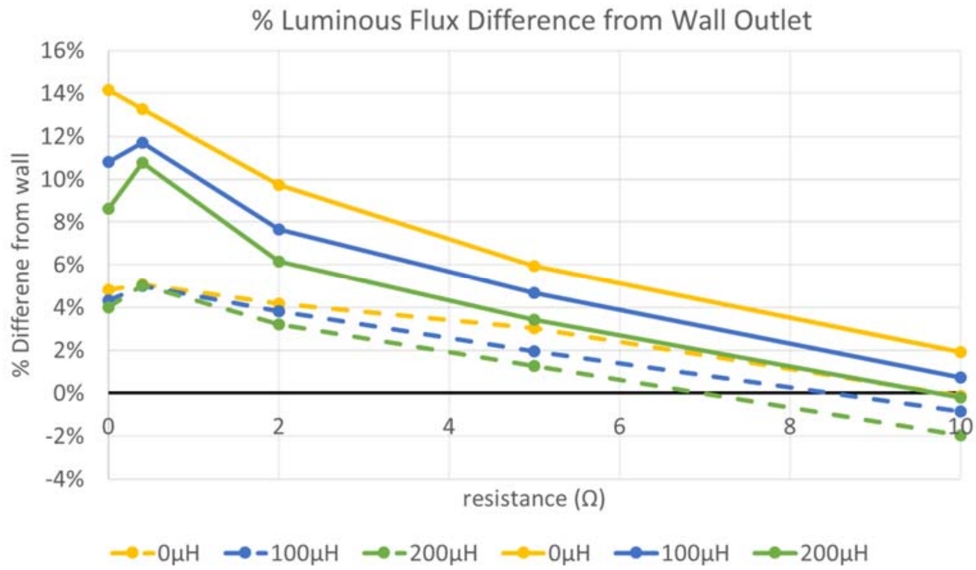

Figure 6 – Percent luminous flux difference from wall outlet under resistance and inductance changes. The dash lines are for power supply one and solid lines are for power supply two.

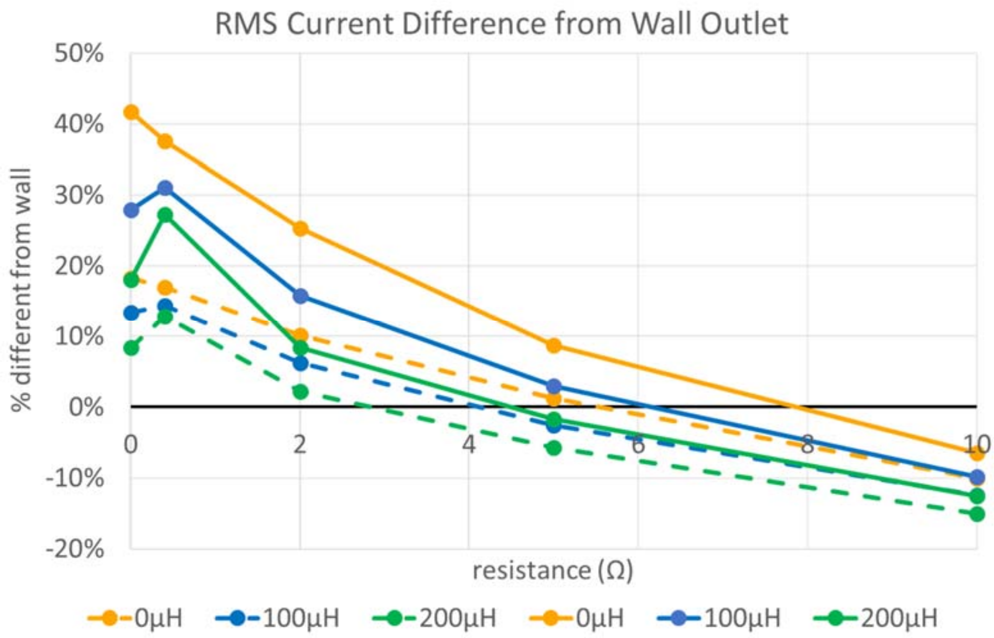

Figure 7 - RMS current difference from wall outlet under resistance and inductance changes. The dash lines are for power supply one and solid lines are for power supply two.

6 Summary

The results of the MAP1 for SSL products offered by NIST were analysed for measurement variation for electrical properties. Besides the bad or wrong implementation of four-pole sockets, two mechanisms of error were identified. The high frequency current wave component uncertainty is mitigated by reducing the capacitance and inductance in the wiring and having a power analyser with a fast sampling rate. The products that are sensitive to the power supply's slew rate and output impedance have been studied by adding inductance and resistance in the circuit, but this issue has not been resolved.

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