Development of an Automated Efficiency and Loss Measurement System for High-Efficiency Power Converters

by

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Abstract

When building a high performance power converter system, characterization becomes a significant task in and of itself. This thesis addresses the development of an automated efficiency and loss measurement system for high-efficiency power converters. The design, construction, calibration, and evaluation of such a measurement setup is described, including development of software to control the system. Application of the setup to a solar high- efficiency grid-tie inverter system is also addressed.

Thesis Supervisor: David J. Perreault
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Chapter 1. Introduction

Measurement is the process of assigning values to describe observed properties of phenomena. Although seemingly trivial, measurements become increasingly difficult to make when a high level of accuracy is demanded. A measurement is only as good as its measurement system, which depends heavily on the precision of the equipment, technique of acquiring data, and analysis of results. All of these contribute to error, which makes uncertain the true value of the variable measured [1].

Thorough uncertainty analysis allows for the reporting of measured values with confidence. It is comprised of two main components: systematic and random. Systematic uncertainty arises in calibration issues and bias. It encompasses initial design errors, such as instrument selection, data acquisition methodology, and other considerations that need to be undertaken prior to actually performing the measurement. Random uncertainty refers to errors that exist due to repetition in procedure and condition [2].

Measuring the behavior and efficiency of power conversion systems can be challenging, especially when the efficiency of the circuit is high. Small differences in large numbers have a significant impact on calculating efficiency and loss when losses are measured as the difference between input and output power. Small errors in one measurement can propagate to a staggeringly inaccurate calculation of important power converter characteristics, such as efficiency and loss. In order to calculate the efficiency of a converter, one must measure the input and output voltages, as well as the input and output currents. A 1% error in any one of these four measurements leads to an approximately 1% error in calculated efficiency. For a high efficiency converter (e.g. 98% nominal), this can represent as much as a factor of two error in calculated loss. Thus, being able to take measurements accurately, although difficult, becomes very desirable.

Automation is important for improving accuracy and increasing effectiveness. When recording voltage and current data by hand, there exists a time lag between reading the voltage and reading the current. For power systems in which the operating point moves slightly over time, recording data by hand this way results in incorrect associations of voltage and current. This propagates to errors in calculating the efficiency and loss. Automating the system allows for simultaneous readings of voltages and currents, which eliminates this time lag and fixes this problem.

There are also major advantages to automating measurements of systems that have to be evaluated across a wide range of operating conditions. For example, in measuring the efficiency of micro-inverters for photovoltaic applications, at least forty different operating points must be measured to provide a data set for one power level for efficiency calculation. For each operating point, four measurements are taken of the input voltage and current, and the output voltage and current. This comes out to at least one hundred and sixty measurements that must be taken at each power level. Doing this by hand becomes tedious and introduces error, so automation becomes increasingly attractive.

The goal of this thesis is to develop an automated system for measuring the efficiency and loss of high-efficiency power converters.

1.1. Solar High-Efficiency Grid-Tie Inverter System

The measurement system proposed here will be implemented for measuring high-efficiency grid-tie inverters for photovoltaic (PV) applications, but is meant to be easily generalized to similar converter systems, including power converters with more than two ports. The circuit topology for the first inverter to be tested is shown in Figure 1.1 [3],[4],[5].

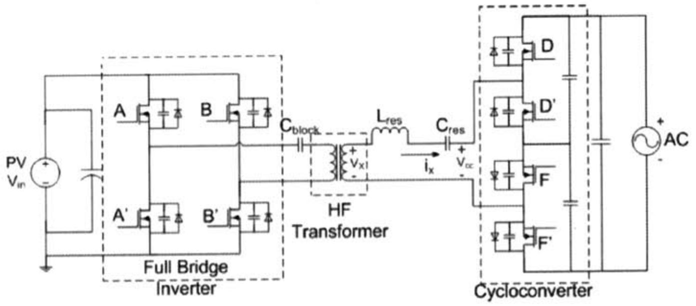

Figure 1-1: Circuit Topology of Solar Micro-Inverter

This solar micro-inverter, presented in [4], [5], and [6], has the following specifications:

Input Voltage	25V - 40V dc
Output Voltage	240V ac RMS
Maximum Output Power	175 W
Efficiency	> 97% C.E.C

Table 1.1: Specifications for Solar Micro-Inverter.

1.1.1. CEC Efficiency

The efficiency cited follows the metrics outlined by the California Energy Commission (CEC) for rating efficiency. The CEC considers the efficiency of a PV inverter as a weighted average of its efficiency at six different power and input voltage levels, expressed as percentages of the maximum average power. The proposed system will measure the voltage and current at each port to calculate the average power. Following the CEC's metric of efficiency, the converter will be run over a wide range of operating points, across input voltage, line cycle position, and power levels.

The voltage and current will be measured at multiple ports for the ranges of interest, and will go into calculating the output power and CEC efficiency. A more detailed look at the CEC efficiency calculation is presented in Chapter 1.

The inverter application does not require measuring efficiency by looking at ac. Instead, discrete points along the line cycle are picked and evaluated. These then are used to calculate the overall efficiency of the inverter by integrating over the line cycle.

1.1.2. Choosing Operating Points

Let the term "operating point" be defined as a unique point on the ac line cycle for a given input voltage and power component to the converter. This means an operating point defines the input voltage, output voltage, and instantaneous power over the line cycle.

Each of the three input voltage levels has to sweep through fifteen output voltage levels. This process is repeated for each of the six average power levels. Overall, this produces an estimated one thousand individual measurements, which drives the need for automation.

1.2. Automation of Hardware

The control system sets the operating point, records data, and archives that data. The micro-inverter setup utilizes the following equipment:

Equipment Name	Description
HP 6030A	Input Power Supply (200V, 17A)
HP 6632A	Output Power Supply (20V, 5A)
HP 6015A	Output Power Supply (500V, 5A)
Agilent 34401A (x3)	Digital Multimeter
Agilent 34330A	Current Shunt (30A, 1mV/A)
Prologix	GPIB-USB Controller

Table 1.2: List of Equipment Used

The dc input voltage, and the voltages at one or more output ports must be varied. In order to do this, operating commands to the power converter itself are developed, as well as methods for driving and loading the converter in an automated fashion.

On the output side of the solar micro-inverter, the HP 6015A is able to reach 240V, but lacks GPIB control. However, it does have analog programming capabilities. Thus, the HP 6632A, which has GPIB ability, is connected to the HP 6015A and controls the output voltage of the HP6015A from commands sent by the computer.

The GPIB commands to all the power supplies set their voltages and currents, which are verified by the multimeters that feed back to the computer. Input current levels reach as high as 14A, which exceeds the current limit ratings on the Agilent 34401A. Thus, the Agilent 34330A current shunt is included to measure the input current. The final setup is represented in the following block diagram:

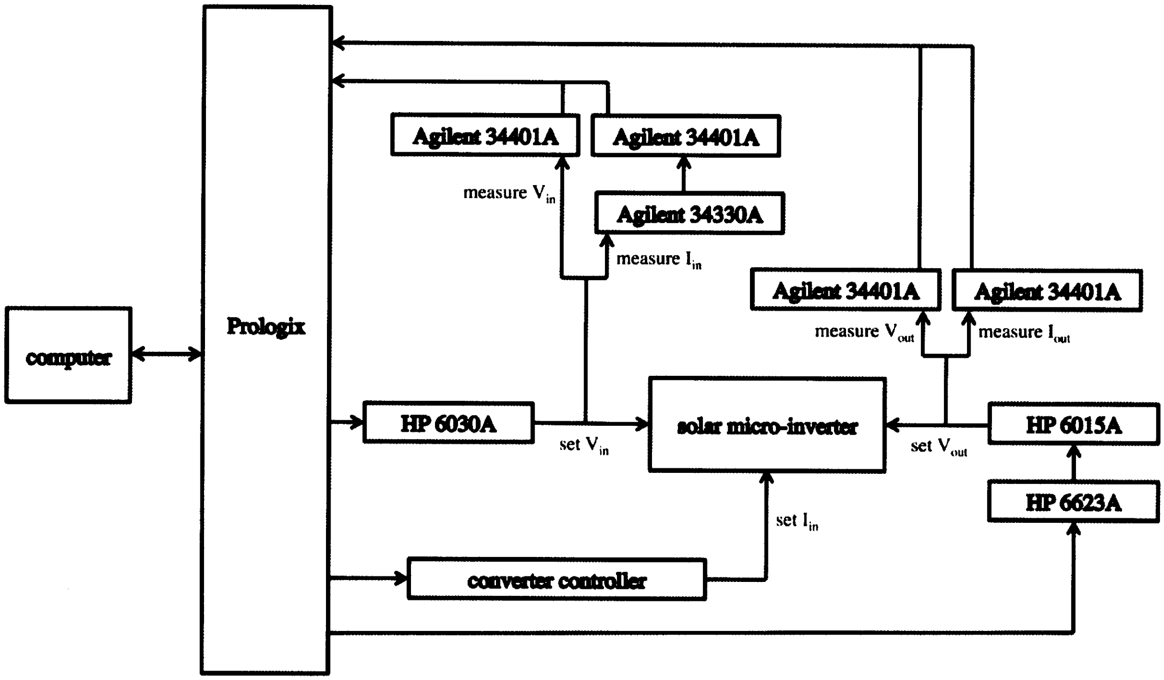

Figure 1-2: Overall System Block Diagram

1.3. Organization of the Thesis

Chapter 2 explores how efficiency is measured and loss calculated. A discussion follows on sources of error outside of the power converter itself, such as error introduced by the hardware, and how these errors propagate.

Chapter 3 describes the automation and synchronization of all the hardware. This control scheme, although specifically designed for the solar micro-inverter, can be easily modified to accommodate any power converter.

Chapter 4 discusses the testing performed on the system to evaluate the measurement setup and validate its accuracy. A resistor test board is used to compare manual measurements to automated measurements. Sample test data acquired from the solar micro-inverter is analyzed using the CEC efficiency half of the automation script. The hand-calculated CEC efficiency is compared to the result outputted by the automation script.

Chapter 5 summarizes the thesis and suggests directions for continued work based on the limitations of this system.

The appendices document all the MATLAB script and data generated in the validation tests. Appendix A contains the script that controls the whole measurement system. Appendix B includes the necessary functions called on by the master loop measurement system. Appendix C lists all the possible operating points for the solar micro-inverter. Appendix D shows the data points generated by the automated tests described in Chapter 4. Appendix E comprises of the CEC calculation part of the automation code, which was run on sample test data from the solar micro-inverter.

Chapter 2. Efficiency and Accuracy Calculation

This chapter discusses the error introduced by the hardware, how this error propagates, and what that means for calculating efficiency. Three methods for calculating error propagation are investigated and analyzed.

2.1. Sources of Error in Agilent 34401A

There are two major sources of error in this measurement system. The first is the offset error, and the second is noise in the measurement. Both of these come from the multimeters, which have accuracy specifications that make it easier to quantify the error.

2.1.1. Measurement Noise and Offset

Offset error is inherent and is hard to remove unless the equipment is taken in for calibration. Even then, after some time has passed, offset creeps back in. Although offset poses a problem, it does stay consistent, which means measurements with offset will remain relatively accurate, if not absolutely accurate. Consider a voltage measurement that initially reads 10.0356V and then a later voltage measurement reads 22.4598V. It can be said with certainty that the voltage has increased, even if the absolute values of those readings cannot be deduced.

Measurement noise is modeled as Gaussian, and thus can be eliminated by the Root-Sum Squares Method, introduced in Section 2.2.2. This is essentially eliminated by the multimeter itself, since the Agilent 34401A has built in functionality to take long term measurements and internally average them to significantly reduce measurement noise.

Another source or error, although not as prominent, is error incurred with changes in temperature. One way to overcome this is by trying to keep the temperature constant, which means operating the hardware at its steady state, after it has warmed up to some asymptotic temperature. This will cause the drift rate to be small, and thus cut out error associated with temperature change. However, this does not make the reading more accurate, but instead, more consistent.

2.1.2. Multimeter Accuracy

The three power supplies used (HP 6030A, HP 6015A, and HP 6632A) may have error in the sense that the value each indicates it is outputting is not the real voltage value sourced. Since multimeters are used to measure the real voltages and currents inputted and outputted from the power converter, and it is these measured values which are used to calculate power and efficiency, and thus that power supply error is not a problem, and does not factor in to the overall analysis of the measurement system.

However, the multimeters themselves have error in that they have accuracy limitations, and this does indeed play a big role. The Agilent 34401A has a different error associated with its measurement depending on the voltage level, frequency, and type of measurement. The accuracy specifications are summarized in the following table [6]:

Function	**Range**	**90 Day 23°C ± 5°C**
dc Voltage	100.0000 mV	0.0040 + 0.0035
	1.000000 V	0.0030 + 0.0007
	10.00000 V	0.0020 + 0.0005
	100.0000 V	0.0035 + 0.0006
	1000.000 V	0.0035 + 0.0010
dc Current	10.00000 mA	0.030 + 0.020
	100.0000 mA	0.030 + 0.005
	1.000000 A	0.080 + 0.010
	3.00000 A	0.120 + 0.020

Table 2.1: Agilent 34401A Accuracy Specifications ± (% of reading + % of range)

The uncertainty is comprised of two parts, the first being the percentage of the reading, and the second the percentage of the range. For example, consider the case where the Agilent 34401A reads a dc voltage level of "33.2345mV." The error associated with this measurement is: ±[(0.000040*0.0332345)+(0.000035*0.1)]= ±4.82938e-6 V, which is 0.01453% of the nominal 33.2345mV value.

The current shunt reads out a voltage proportional to the amount of current it measures, by a 1mV/A ratio. The accuracy specifications for the Agilent 34330A is summarized below [7]:

Frequency Range	**Uncertainty**
dc – 1kHz	0.3%
1kHz – 5kHz	5%

Table 2.2: Agilent 34330A Accuracy Specifications

The 1kHz-5kHz range gives a very substantial 5% error, but since all measurements taken are at dc, the error introduced from the shunt is always only 0.3%. However, it is important to realize that this is extra error added on to the error from the multimeter, not the overall error for the current measurement. Take, for example, a dc current measurement using the Agilent 34401A and the Agilent 34330A. If the multimeter displays "33.2345 mV," this corresponds to a current reading of 33.2345A. The error associated with this measurement is comprised of ±(0.003*33.2345) = ±0.09970 A from the current shunt, and ±[(0.000040*0.0332345) +(0.000035*0.1)] = ±4.82938e-6 A from the multimeter.

Now that the error from the measurements has been explored, the next step is to see how these errors grow as power loss is analyzed.

2.2. Error Analysis

Three different methods for modeling how the measurement error propagates are explored. The first, a derived approach [8], starts with basic equations and develops a worst-case formula for power loss. The second, the Root-Sum-Squares Method [9], assumes a Gaussian distribution error to calculate its propagation. The last utilizes interval analysis [10],[11] to define arithmetic operations on bounded intervals.

2.2.1. Derivation Method

Error introduced by small incorrect measurements in the voltages and currents leads to a propagation of error in calculating the total power loss. Power loss is defined as the difference between the input and output power [8]:

$$P_{loss} = P_{in} - P_{out} = V_{in}I_{in} - V_{out}I_{out} \tag{2.1}$$

A measured value is equal to the actual value plus the difference between the actual value and the measured value. In the case of voltage and current measurements, the measurement is a function of the actual values, as defined in Equations 2.2 and 2.3.

$$V_{meas} = V(1+\frac{\Delta V}{V}) \qquad I_{meas} = I(1+\frac{\Delta I}{I}) \qquad (2.2),(2.3)$$

Each element of error (voltages and currents) in the measurement of power combines to increase the uncertainty of the overall measurement. Therefore, the measured power can be derived from Equations 2.2 and 2.3 to arrive at Equation 2.4.

$$P_{meas} = VI(1+\frac{\Delta V}{V}+\frac{\Delta I}{I}+\frac{\Delta V \Delta I}{VI}) \approx VI(1+\frac{\Delta V}{V}+\frac{\Delta I}{I}) \qquad (2.4)$$

The last term, $\frac{\Delta V \Delta I}{VI}$, approaches zero for $\frac{\Delta V}{V},\frac{\Delta I}{I} << 1$. Thus, for small percentage errors in voltage and current, the total percent error in power is approximately the sum of the linear percent errors in voltage and current. This is the worst-case error in measured power, and is the metric by which power loss is calculated.

2.2.2. Root-Sum-Squares Method

Another method for analyzing error assuming random, independent errors is proposed by S. Figliola and D.E. Beasley in *Theory and Design for Mechanical Measurements* [9]. This analysis supposes a Gaussian distribution for the variation in error over repeated measurements. For a measured variable x with k elements of error e_i, where $i = 1, 2, 3, \ldots k$, the uncertainty in the measurement, u_x, can be computed using the root-sum-squares method (RSS):

$$u_x = \pm\sqrt{e_1^2 + e_2^2 + e_3^2 + \ldots + e_k^2} \qquad (2.5)$$

Take for example the calculation of loss in a system from input power and output power. Measurements on input voltage, input current, output voltage, and output current require four different multimeters (one of which also includes the current shunt), each with their own measurement errors. The loss in the system can be derived from Equation 2.5 in the following manner:

$$\%\Delta P_{loss} = \pm\sqrt{(\%\Delta V_{in})^2 + (\%\Delta I_{in})^2 + (\%\Delta V_{out})^2 + (\%\Delta I_{out})^2} \tag{2.6}$$

The percentage of error in power loss is the square root of the sum of the squares of the percentage of error in each element that contributes, which in this case is the measured values of input voltage and current, and output voltage and current.

2.2.3. Interval Analysis

A third way of calculating error propagation is through interval analysis, as described by R. Moore, R. Kearfott, and M. Cloud in *Introduction to Interval Analysis* [10], as well as by M. Petrovic and L. Petrovic in *Complex Interval Arithmetic and Its Applications* [11]. If it is known with absolute certainty that an interval contains the exact value for some desired quantity, then interval analysis provides a way to perform arithmetic operations on this interval. This analysis provides rigorous bounds on the solution, because computing with bounds is equivalent to computing with sets.

Consider a real number A that resides in the range of $[a_1, a_2]$, and another real number B that exists in $[b_1, b_2]$. Then the following four basic arithmetic operations hold true:

$$A+B \in [a_1+b_1, a_2+b_2] \tag{2.7}$$

$$A-B \in [a_1-b_1, a_2-b_2] \tag{2.8}$$

$$A*B \in [\min(a_1b_1, a_1b_2, a_2b_1, a_2b_2), \max(a_1b_1, a_1b_2, a_2b_1, a_2b_2)] \tag{2.9}$$

$$A/B \in [\min(a_1/b_1, a_1/b_2, a_2/b_1, a_2/b_2), \max(a_1/b_1, a_1/b_2, a_2/b_1, a_2/b_2)] \tag{2.10}$$

Section 2.1 provides the look-up tables for the accuracy specifications on the Agilent 34401A and the Agilent 34330A. From these, error bounds are determined for voltage and current measurements made. Interval analysis gives error bounds on calculations of input and output power, and ultimately efficiency. The limitation of this approach is that it always provides the worst-case error bounds, which may be much more pessimistic than typical error levels. However, Section 2.4.1 steps through an example of efficiency calculation for one set of voltage and current measurements for input and output, and shows that one efficiency calculation is less than 1% off in accuracy. Section 2.3 explains how total efficiency of a PV inverter is calculated, and thus the complete efficiency calculation across a variety of average power levels will always be within 1%. For a more detailed explanation, see the interval analysis discussion immediately following the example in Section 2.4.1. Interval analysis may be impractical in some cases because it is very conservative, but it is reasonable for the purposes of this measurement system.

Since this method is the simplest and the most complete of the three, it is this method that is used to calculate the power loss and efficiency in the measurement system.

2.3. Efficiency Analysis

The efficiency of a power converter is defined as the difference between the input power and output power divided by the input power:

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.11}$$

The California Energy Commission (CEC) considers the efficiency of a PV inverter as a weighted average of its efficiency at different percentages of the maximum average power [3],[4],[5]. At unity power factor, the power into the grid averaged over a switching cycle is:

$$P_{out} = \frac{(V_{peak}\sin(\omega_{line}t))^2}{R_{equivalent}} = 2P_{ave}\sin^2(\omega_{line}t) \tag{2.12}$$

For U.S. standards, ω_{line} is 377 rad/s, and V_{peak} represents the peak line voltage, about 339V. The CEC efficiency metric assigns different weights to different percentages of the maximum average power. Table 2.3 shows these weights for the given percentages, where 100% corresponds to 175W, the highest average power level of interest.

Average Power (%)	100	75	50	30	20	10
Weight	.05	.53	.21	.12	.05	.04

Table 2.3: CEC Coefficient Weights

The inverter application does not require measuring efficiency by looking at ac. Instead, discrete points along the line cycle are picked and evaluated. These then are used to calculate the overall efficiency of the inverter by integrating over the line cycle. Since all measurements are taken at dc, the only error on the multimeters is in the range of their dc readings, and error bounds in ac can be ignored.

2.3.1. Determining Operating Points

The input voltage is independent of the output voltage and instantaneous power, so the first step in choosing an operating point is to pick an instantaneous output voltage, $V_{out,1}$. For an average power level of interest, the output voltage must be swept through its entire range over the line cycle. For each output voltage $V_{out,1}$, there is an associated instantaneous power. This P_{inst} then defines the instantaneous $I_{out,1}$ from $V_{out,1}$. Sweeping for values of input voltage provides corresponding values for input current given this P_{inst}. The efficiency is calculated for each operating point, knowing the input voltage, input current, output voltage, and output current. This same process is repeated for the whole range of output voltages to calculate input and output power. In order to estimate the equivalent ac efficiency over a quarter of the line cycle, trapezoidal approximation is used to estimate integration of the input and output power with respect to time obtained at discrete points along a quarter of the line cycle. Dividing these two values results in an efficiency calculation for one average power level.

Given the CEC standards, this same procedure is performed for each average power level of interest (100%, 75%, 50%, 30%, 20%, 10% of 175W). Thus the overall efficiency of the solar inverter system is:

$$\eta = 0.05\eta_{100\%} + 0.53\eta_{75\%} + 0.21\eta_{50\%} + 0.12\eta_{30\%} + 0.05\eta_{20\%} + 0.04\eta_{10\%} \qquad (2.13)$$

The intended inverter application does not require measuring efficiency by looking at ac. Instead, discrete points along the line cycle are picked and evaluated. These then are used to calculate the overall efficiency of the inverter by integrating over the line cycle.

Please refer to Appendix A for the MATLAB code that calculates the efficiency, with associated error bars derived from the uncertainty on the measurements of voltages and currents themselves.

2.4. Example of Error Propagation in Measurement System

In an effort to make the error analysis more apparent, this section steps first through an example of a set of measurements for input and output voltages and currents, and shows the error propagation for the calculation of efficiency. The second part of this section explores the use of a current shunt in conjunction with the multimeter on the output current measurement to determine whether including the shunt decreases uncertainty in the measurement.

2.4.1. Operating Point with Efficiency Calculation

Consider the case where the following measurements are taken at the max average power of 175W:

Parameter	Measured Value
input voltage, V_{in}	25.0038 V
input current, I_{in}	6.99712 A
output voltage, V_{out}	226.272 V
output current, I_{out}	0.62304 A

Table 2.4: Sample Data for Solar Micro-Inverter

The current shunt is used on the input current side because of the 3A limit on the Agilent 34401A. The shunt allows the multimeter to display the current in a 1mV/A ratio. Thus, the input current multimeter in actuality would display 6.99712mV.

These measured values have uncertainty, which can be determined from Tables 2.1 and 2.2. These error bars are summarized below:

Parameter	Measured Value	Uncertainty	Range
input voltage, V_{in}	25.0038 V	±0.0015 V	[25.0023, 25.0053] V
input current, I_{in}	6.99712 A	±0.0212 A	[6.9759, 7.0183] A
output voltage, V_{out}	226.272 V	±0.0179 V	[226.2541 226.2899] V
output current, I_{out}	0.62304 A	±6.8691e-4 A	[0.6224, 0.6237] A

Table 2.5: Sample Data with Uncertainty and Ranges for Measured Values

Using interval analysis, most notably Equations 2.9 and 2.10, we can compute the valid range of input and output power and efficiency.

Parameter	**Nominal Value**	**Range**
input power P_{in}	174.9546 W	[174.4124 175.4969] W
output power, P_{out}	140.9756 W	[140.8099, 141.1431] W
efficiency, η_{175W}	80.58%	[80.23% 80.92%]

Table 2.6: Input, Output Power and Efficiency Range for Sample Data

From this example, it is important to notice that the accuracy on the efficiency calculation is within less than 1%.

Given the CEC efficiency rating, consider the case where each efficiency calculation is not less than 1%, but is actually 1%. Also assume for a worst-case calculation, that the efficiency for each average power level is 100%. Using interval analysis, the error on the CEC efficiency will be 0.05(0.01)+0.53(0.01)+0.21(0.01)+0.12(0.01)+0.05(0.01)+0.04(0.01) = 0.01. Thus, the measurement system will always provide a CEC efficiency calculation within 1% error.

2.4.2. Current Shunt on Output Current Measurement Analysis

Another interesting test is to see whether or not the shunt and the multimeter (reading voltage) combined provide better accuracy than just the multimeter (reading current). From Table 2.1, it is clear that dc voltage measurements in the range of [100mV, 1V] are more accurate than dc voltage measurements in the range of [0V, 100mV]. Thus, if another Agilent 34330A current shunt were to be used to measure the output current, which can reach values up to around 3A, then the accuracy on the current shunt and multimeter combination may be better than the accuracy on just the multimeter. To determine whether better accuracy on the output current measurement can be obtained by the combination, consider another Agilent 34330A current shunt included used to measure the output current. The following table lists a representative output current value for every range possible for the accuracy specifications of the voltage and current readings on the Agilent 34401A.

Measurement Range [A]	Nominal Iout [A]	Uncertainty w/o Shunt [A]	Range w/o Shunt [A]	Uncertainty with Shunt [A]	Range with Shunt [A]
0.010	0.00623	±3.869e-6	[0.006227, 0.006234]	±2.244e-5	[0.00621, 0.00625]
0.1	0.06230	±2.369e-4	[0.06228, 0.06233]	±1.929e-4	[0.06211, 0.06250]
1	0.62304	±5.984e-4	[0.62244, 0.62364]	±1.895e-3	[0.62115, 0.62493]
3	1.62304	±2.548e-3	[1.62049, 1.62559]	±4.952e-3	[1.61809, 1.62799]

Table 2.7: Comparison of Accuracy with and without Current Shunt

It is interesting to notice that for the [0.010 0.01] A range, the shunt provides less uncertainty. However, the case without the shunt outperforms on every other range, and it is not feasible to switch between using the shunt and not with an automated system. Also, since the majority of current measurements are taken in the range of [0.1, 3] A, it is more practical to have the output current measurement not utilize a current shunt. For the MATLAB script written to compare the performance of both cases, please refer to Appendix B.

Chapter 3. Hardware Automation

This chapter discusses the control scheme for the automation of the hardware. The first section provides motivation for why automation is desirable. The second section describes the algorithm used to take all the measurements necessary for completing one CEC efficiency calculation. The third section depicts the equipment setup.

3.1. Need for Automation

The solar-micro-inverter can change its average power level by adjusting the input current to the converter. Setting the input current is outside of the scope of this project, and is thus not addressed in this thesis. However, assuming that input current is set externally from this system, it is possible to achieve varying average power.

A "CEC efficiency" rating requires measuring the efficiency of the solar micro-inverter for six different average (over a line cycle) power levels. As described in Chapter 2, these cases are at six different percentages of the maximum average power. Given that the maximum average power is 175W, Table 3.1 shows the different average power levels of interest.

Case	% of Maximum Average Power	Average Power
1	100%	175 W
2	75%	131.25 W
3	50%	87.5 W
4	30%	52.5 W
5	20%	35 W
6	10%	17.5 W

Table 3.1: Six Different Average Power Levels

For each of these six different average powers, there are three different input voltage levels at which measurements are taken. These are summarized in Table 3.2.

Case	Input Voltage
1	25 V
2	32.5 V
3	40 V

Table 3.2: Three Different Input Voltage Levels

For each of these three different input voltages, there are fifteen different output voltage levels at which measurements are taken corresponding to fifteen points in the line cycle. These are summarized in Table 3.3.

Case	Output Voltage
1	22.6274 V
2	45.2548 V
3	67.8823 V
4	90.5097 V
5	113.137 V
6	135.765 V
7	158.392 V
8	181.019 V
9	203.647 V
10	226.274 V
11	248.902 V
12	271.529 V
13	294.156 V
14	316.784 V
15	339.411 V

Table 3.3: Fifteen Different Output Voltages

The power at a specific output voltage/point in the cycle is not the average power over a line cycle, but is directly related to it.

Altogether, six different power levels, each with three different input voltage levels, and each with fifteen different output voltages gives two hundred seventy different operating points. Each of these operating points requires four different measurements to be taken: input voltage and current, and output voltage and current. This makes one thousand eighty individual measurements that need to be recorded. Obviously, taking all one thousand eighty readings by hand is cumbersome and tedious, and automation is definitely desirable.

Even after all these one thousand-some measurements are taken, there still needs to be data analysis, such as calculating instantaneous input and output power, computing efficiency for each operating point, and computing a weight average CEC efficiency rating, as discussed in Chapter 2.

3.2. Automation Algorithm

Figure 3.1 shows a flow diagram of the hardware automation process. The first step is to pick the first average power level. At this power level, the first input voltage is chosen, and then the first output voltage is chosen. Next, the power supplies are set to deliver this input and output voltage. The four multimeters measure and record the input and output voltage and current. As described in Chapter 2, there are associated error bounds for different voltage and current readings on the multimeters depending on range. Thus, error bounds are calculated for these measured nominal voltage and current levels. Input and output power are computed, and through interval analysis, the error bounds on those values are found. Efficiency is calculated next, and again, using interval analysis, the error range on that nominal efficiency is calculated. This completes the measurements for that output voltage. The program repeats for the next output voltage, and iterates through the whole process again until all output voltages have been measured. At this point, the input power supply steps to the next input voltage, and the whole process is repeated for every output voltage. Once all input voltages have been measured, then the next average power level is chosen, and the whole process repeats. Thus, there are three loops. The innermost loop sweeps through all the output voltages, the middle loop sweeps through all the input voltages, and the outermost loop sweeps through all the average power levels. When the program calculates input and output power as well as efficiency, running figures of this data, with their error bounds, are plotted.

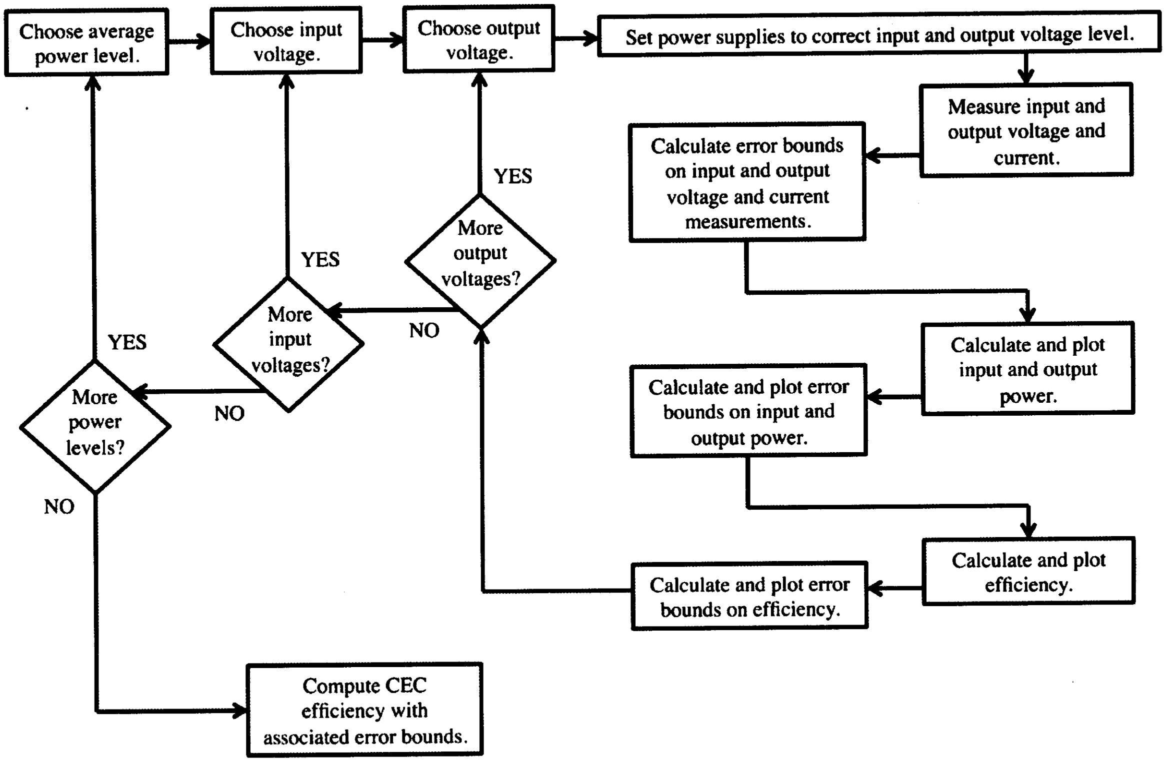

Figure 3-1: Hardware Automation Algorithm

For each operating point, the input voltage and current, output voltage and current, input and output power, and efficiency are recorded with their associated error bounds. After all average power levels have been cycled through, these input and output power values are used to calculate the CEC efficiency of the solar micro-inverter.

The goal of this algorithm is to be applicable not only to the solar micro-inverter, but also to other high frequency power converters. The MATLAB script, which commands this whole automation process, is easily adapted for other such converters. The only difference would be in removing the CEC efficiency calculation at the end. The solar micro-inverter has six distinct average power levels, three distinct input voltages and fifteen distinct output voltages, but the script can take in any number of average powers, input voltages, and output voltages.

Appendix A documents the MATLAB code written to control this whole master triple loop automation. Special functions were written in order to calculate the error bounds on current and voltage measurements involving the Agilent 34401A look-up tables, which are provided in Appendix B. Other functions that are called in the master loop code, such as opening and closing the port, are presented in Appendix B as well.

3.3. Equipment Setup

A list of equipment used, as described in the Introduction, is reproduced below for convenience.

Equipment Name	Description
HP 6030A	Input Power Supply (200V, 17A)
HP 6632A	Output Power Supply (20V, 5A)
HP 6015A	Output Power Supply (500V, 5A)
Agilent 34401A (x4)	Digital Multimeter
Agilent 34330A	Current Shunt (30A, 1mV/A)
Prologix	GPIB-USB Controller

Table 3.4: Equipment List

The master loop program commands the power supplies and multimeters through the Prologix GPIB-USB controller, and is compatible on both Mac and Windows platforms. As mentioned in the Introduction, the HP 6015A lacks GPIB control, but has analog programming capabilities. The HP 6632A controls the voltage outputted from the HP 6015A by a 1:10 ratio. Thus, if the HP 6632A outputs 0.1 V, the HP 6015A outputs 10 V. Hooking up the sensing terminals on the power supplies to their output terminals ensures that the voltage commanded is the voltage sourced.

Input current levels reach as high as 14A, which exceeds the current limit ratings on the Agilent 34401A. Thus, the Agilent 34330A current shunt is included to measure the input current. The current shunt attached to the Agilent 34401A gives a voltage reading in a 1mV:1A ratio.

The four multimeters (one which has the current shunt) measure the input and output current and voltages, and it is these measurements that are used to calculate the efficiency. The overall system diagram is shown below in Figure 3.2.

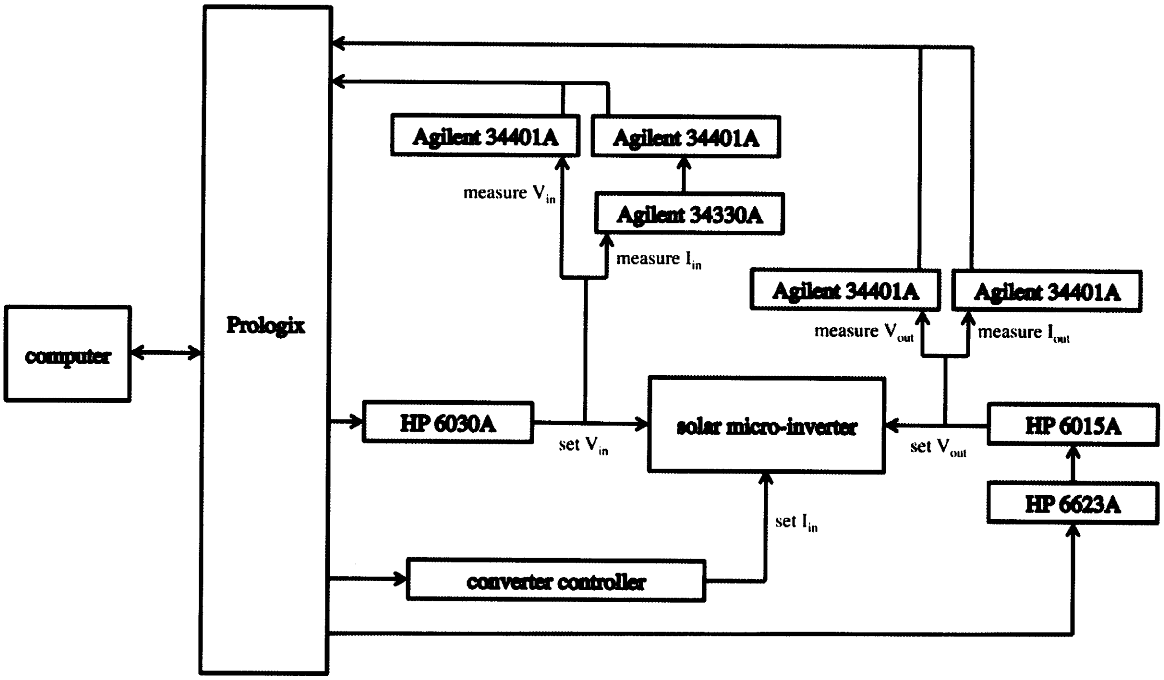

Figure 3-2: Overall System Diagram

Chapter 4. System Test and Validation

Verifying the measurement system involves analyzing two separate cases and comparing the results. The first case is the "control," where measurements are taken and recorded by hand. The second case is the "automation," which takes the same measurements but uses the automated system. The test board used is essentially two power resistors, one connected to the input voltage supply, and the other connected to the output voltage supply. Figure 4.1 shows the basic topology of the test board.

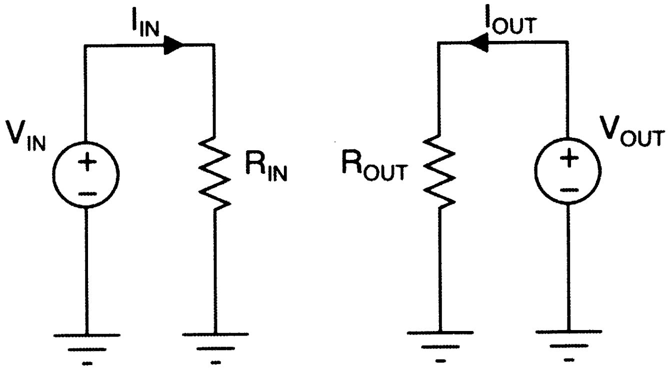

Figure 4-1: Resistor Test Board Topology

The point of the test board is to operate it at points of interest in the micro-inverter topology. Thus, different values were chosen for R_{in} and R_{out} depending on the currents needed. The current levels were chosen to span the complete range of current for the micro-inverter (i.e. from ~50mA to 15A for input current, and ~10mA to 2A for output current). The voltage levels chosen for V_{in} and V_{out} spanned the range of voltages on input and output of the micro-inverter as well. Given these ranges on current and voltage, three resistors were chosen for R_{in} and R_{out}. Their resistance and current limits are summarized in Table 4.1.

Resistor	Resistance	Current Limit
A	1.6 Ω	22A
B	1.435 kΩ	0.54A
C	2.87 kΩ	0.38A

Table 4.1: Resistor Values and Limits for Test Board

A complete listing of all the possible operating points of interest for the micro-inverter is included in Appendix C.

After verification of the measurement system, sample test data taken from manual measurements of the input and output voltages and currents is processed by the measurement system in order to verify the working state of the CEC efficiency calculation.

4.1. Control Measurements

The control measurements looked at different voltage and current pairs, chosen because they were boundary points. That is, the nominal input voltage was either 25V or 40V, and the nominal output voltage was either 29V or 340V. Using different resistors for the same input and output voltages provides variety in the power level.

Table 4.2 lists the voltages, and based on the resistance, the expected current.

Resistor A			
	V_{in} = 25 V	I_{in} = 15.625 A	P_{in} = 390.625 W
Resistor B			
	V_{in} = 25 V	I_{in} = 0.0174 A	P_{in} = 0.435 W
	V_{in} = 40 V	I_{in} = 0.0278 A	P_{in} = 1.112 W
	V_{out} = 29 V	I_{out} = 0.2567 A	P_{out} = 7.444 W
	V_{out} = 340 V	I_{out} = 0.0206 A	P_{out} = 7.004 W
Resistor C			
	V_{in} = 40 V	I_{in} = 0.0139 A	P_{in} = 0.556 W
	V_{out} = 29 V	I_{out} = 0.0103 A	P_{out} = 0.299 W
	V_{out} = 340 V	I_{out} = 0.1183 A	P_{out} = 40.222 W

Table 4.2: Control Operating Points

Measurements were taken by manually adjusting the power supplies to the correct voltage, and then manually reading the measurements off the multimeters. The results are shown in Table 4.3.

Resistor A			
	V_{in} = 24.8139 V	I_{in} = 15.6690 A	P_{in} = 388.809 W
Resistor B			
	V_{in} = 24.9964 V	I_{in} = 0.0184 A	P_{in} = 0.4599 W
	V_{in} = 39.9488 V	I_{in} = 0.0295 A	P_{in} = 1.1785 W
	V_{out} = 29.8312 V	I_{out} = 22.4476 mA	P_{out} = 0.6696 W
	V_{out} = 340.312 V	I_{out} = 256.679 mA	P_{out} = 87.3509 W
Resistor C			
	V_{in} = 39.9502 V	I_{in} = 0.0152 A	P_{in} = 0.6072 W
	V_{out} = 29.8972 V	I_{out} = 11.42676 mA	P_{out} = 0.3416 W
	V_{out} = 339.4113 V	I_{out} = 130.152 mA	P_{out} = 44.1751 W

Table 4.3: Control Measurements and Power Calculation

4.2. Automated Measurements

The automated measurements were taken for the same ranges that the micro-inverter operates. Two distinct tests were run. The first went through the full range of input and output voltages of interest, and the second went through the full range of input currents of interest. This second test was performed because the current shunt limits the input current to be above 50mA in order to still remain measureable. Thus, the second test sets the input current across its full range.

4.2.1. Test 1: Sweeping All Possible Voltages

The first automated test measures the full voltage ranges on input and output side of the micro-inverter. These values are shown below.

V_{in}	V_{out}
25 V	22.6274 V
32.5 V	45.2548 V
40 V	67.8823 V
	113.1371 V
	135.7645 V
	158.3919 V
	181.0193 V
	203.6468 V
	226.2742 V
	248.9016 V
	271.5290 V
	294.1564 V
	316.7838 V
	339.4113 V

Table 4.4: Operating Voltages for Automated Test 1

The same resistor test board was used for the automated test, with R_{in} = 2.87 kΩ and R_{out} = 1.435 kΩ. The input and output voltage, current, and power are shown in the next eight figures. Error bars have been added to the figures to show the uncertainty in the measurement. For each current and voltage pair, the automated system takes two of the same measurements. The full list of data is available in Appendix D.1.

The automated measurement system also plots efficiency and associated error bars, but since the resistor test board has input completely independent from the output, the calculation of efficiency here is meaningless and is omitted.

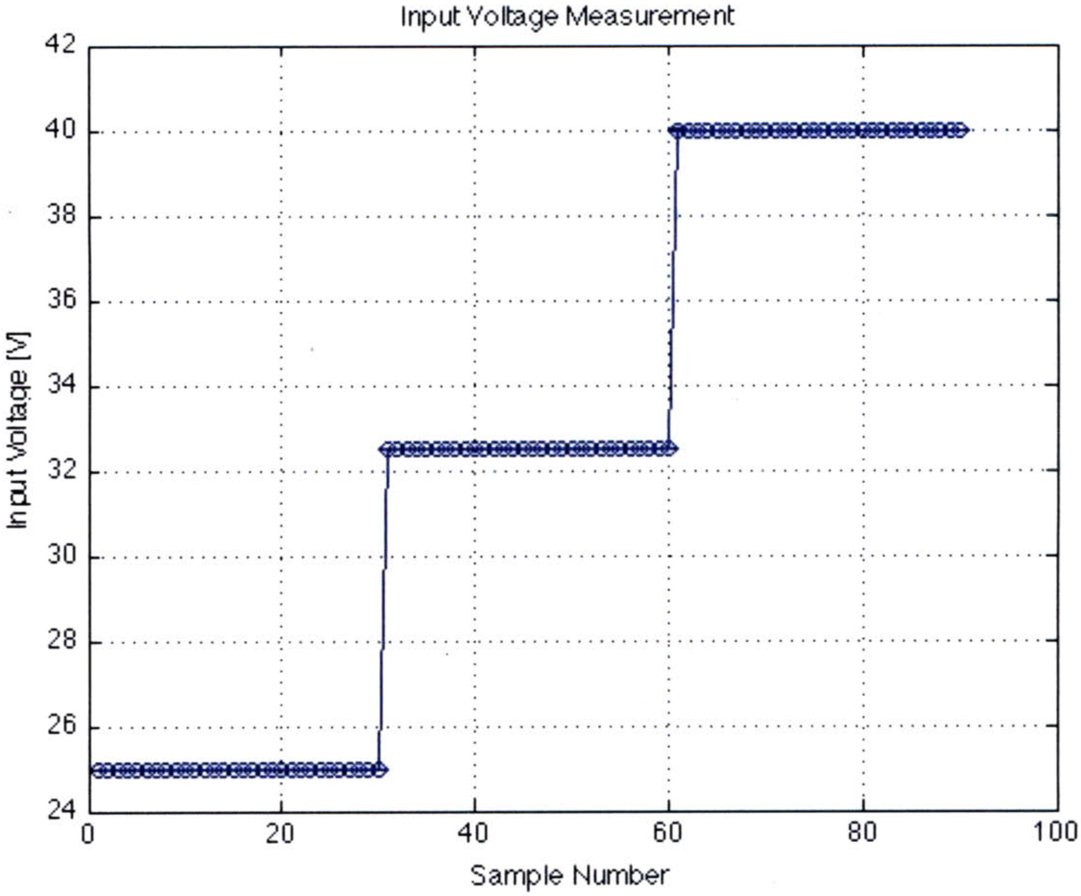

Figure 4-2: Test 1 Input Voltage Measurement

The error bars on the figure are so small that they are not easily noticeable. Figure 4-3 shows a zoomed in version of the Test 1 input voltage measurement.

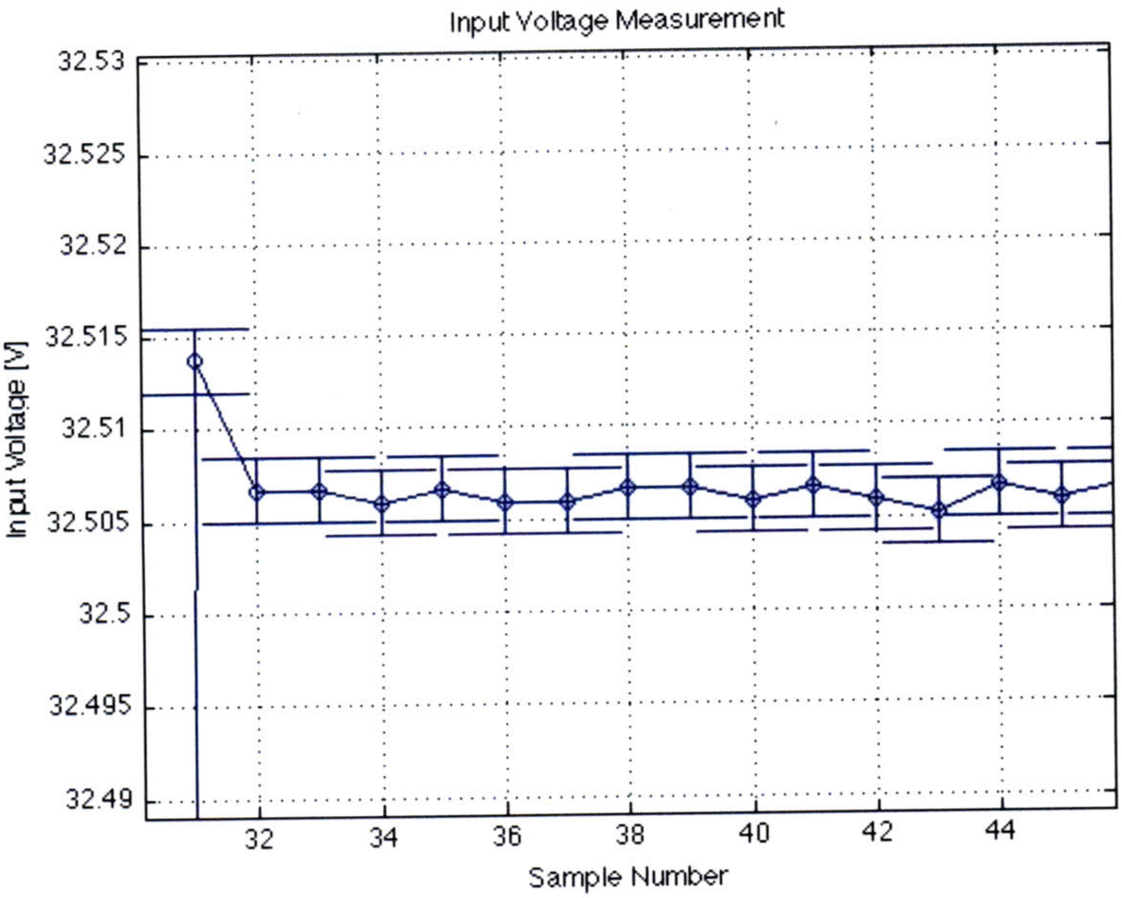

Figure 4-3: Test 1 Input Voltage Measurement Zoomed in

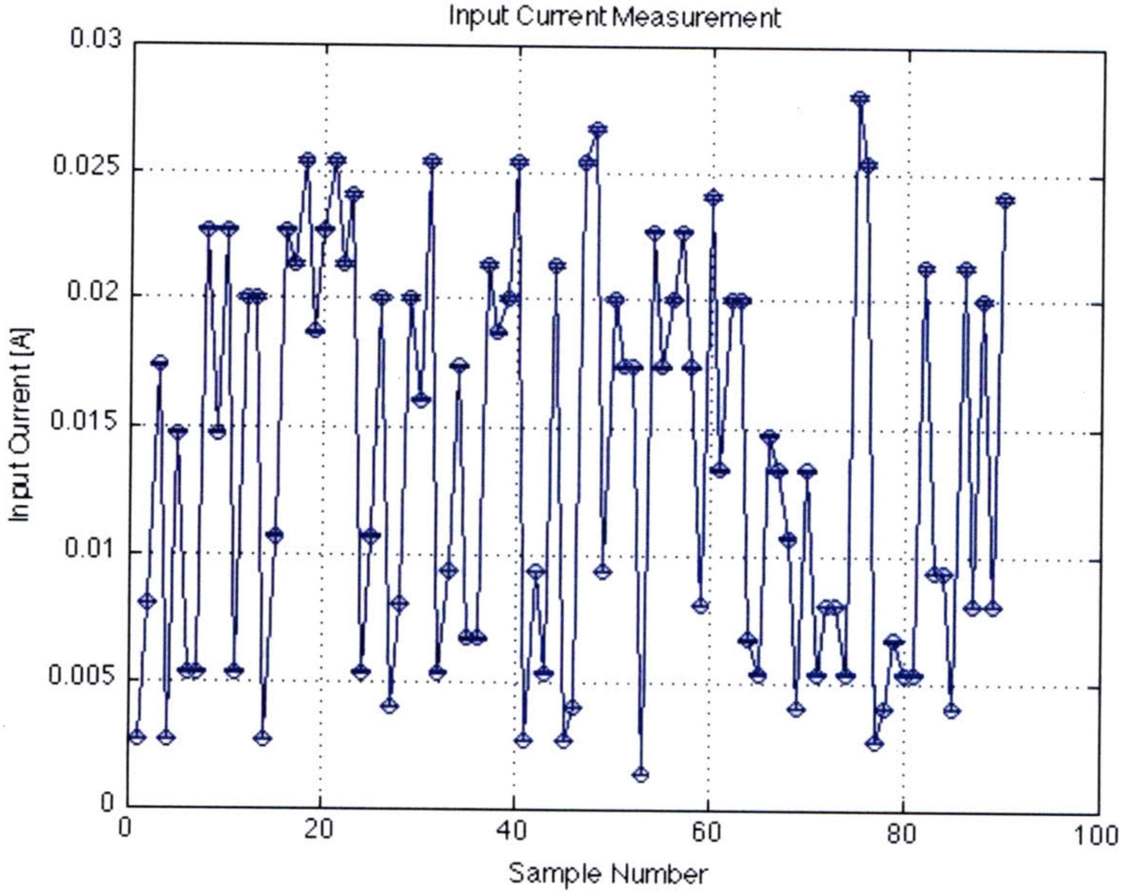

Figure 4-4: Test 1 Input Current Measurement

The input current measurements seem unstable, but that is due to the fact that the shunt just cannot measure such small current values. The lowest the shunt can read accurately is around 50mA, which accounts for the wide swings in input current. This is not a big problem because the majority of the input currents of interest are at currents significantly higher than 50mA.

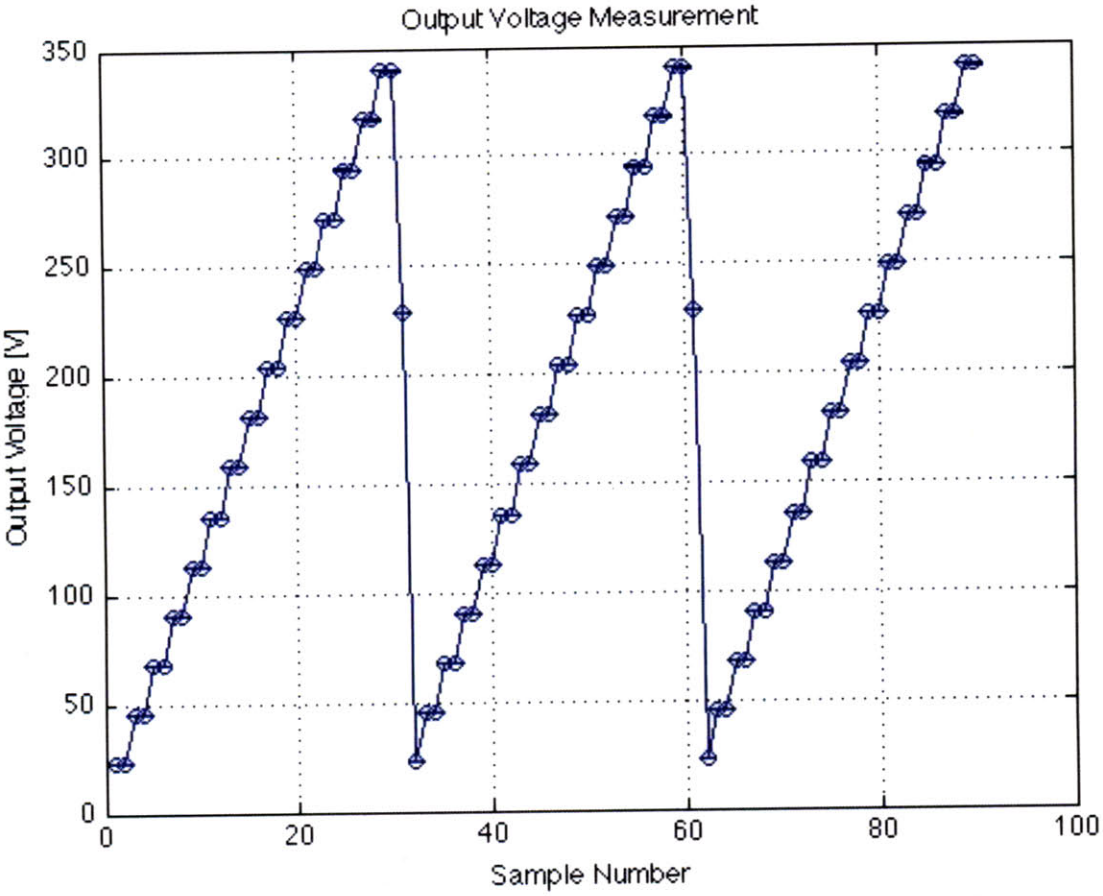

Figure 4-5: Test 1 Output Voltage Measurement

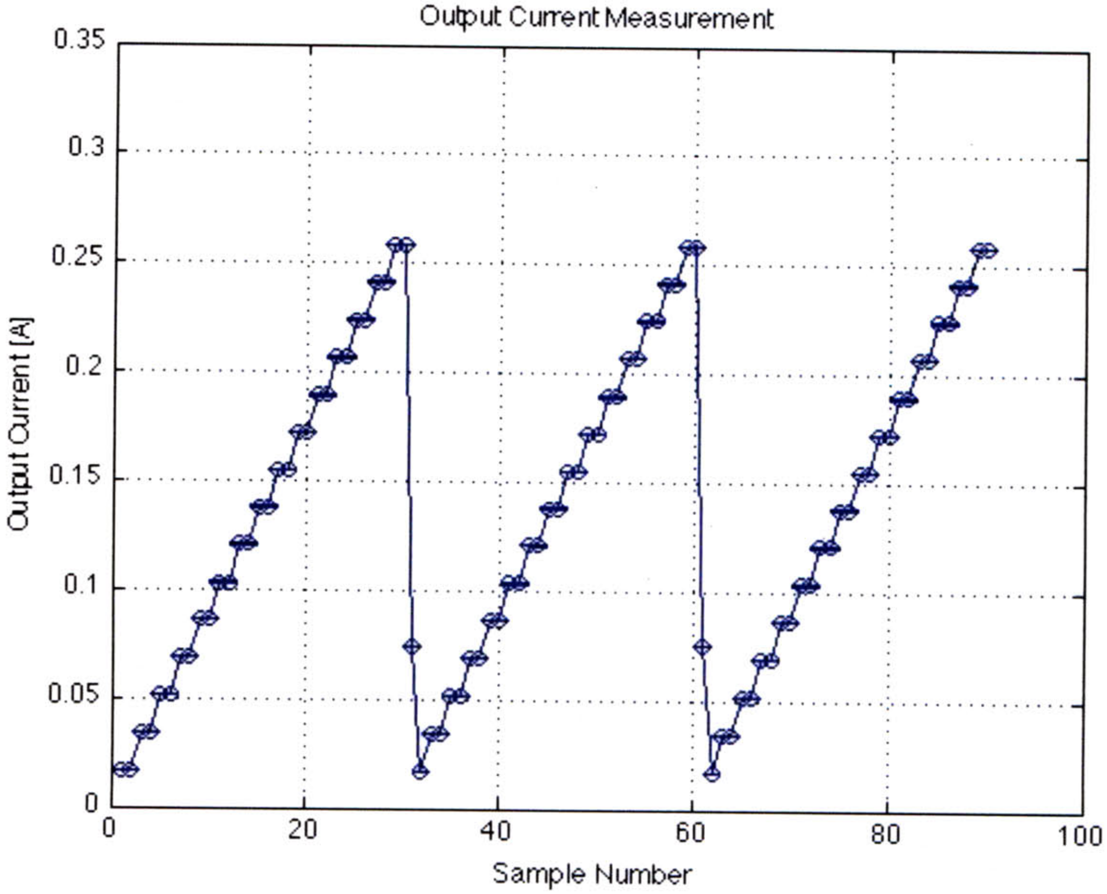

Figure 4-6: Test 1 Output Current Measurement

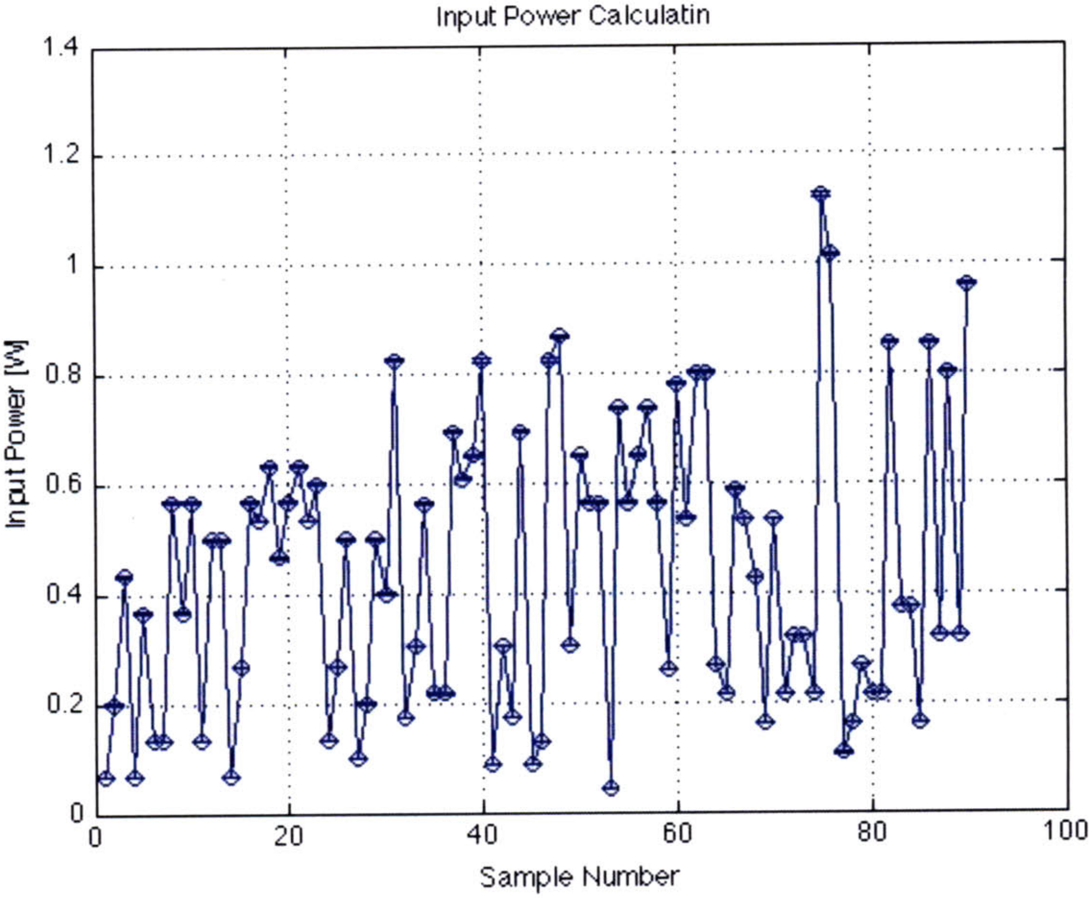

Figure 4-7: Test 1 Input Power Calculation

The input power varies wildly because the input current varies wildly. Again, this is not a problem because the solar micro-inverter will operate at power levels much higher than 2W.

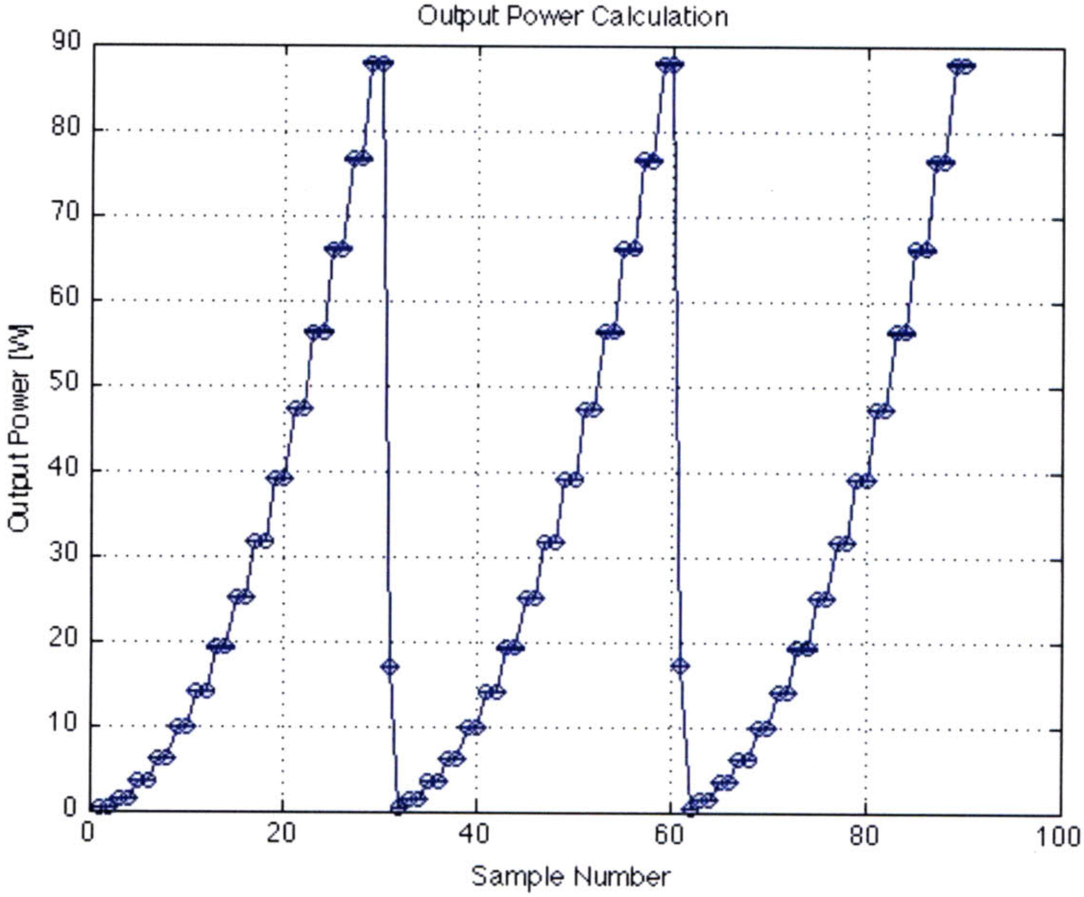

Figure 4-8: Test 1 Output Power Calculation

The maximum uncertainty for each parameter is shown in Table 4.5.

Parameter	Maximum Uncertainty
input voltage	0.004 V
input current	1.7762e-4 A
output voltage	0.0438 V
output current	6.1368e-4 A
input power	0.0072 W
output power	0.2198 W

Table 4.5: Maximum Uncertainty for Automated Measurements Test 1

The uncertainty on output power may seem high, but considering that this error occurs at the maximum output power calculated, which is around 90W, this uncertainty of 0.2198 is not particularly troublesome.

4.2.2. Test 2: Sweeping All Possible Input Currents

Previous automated measurements for input current have been focused on currents in a range that cannot be measured, given the limitation of the current shunt. Thus this second automated test shows the measurement system operating at input current levels at which the solar micro-inverter would be operating. A list of the operating input currents is shown below.

Associated Input Voltage	**Input Current**
1 V	0.625 A
5 V	3.125 A
10 V	6.25 A
15 V	9.375 A
20 V	12.5 A
25 V	15.625 A

Table 4.6: Operating Input Currents and Associated Input Voltage, for $R_{in} = 1.6\Omega$

The input resistance is 1.6Ω, which allows for the current to span from approximately 1A to 16A. The following three figures show plots of the input voltage, input current, and input power. Error bars have been added to the figures to show the uncertainty in the measurement.

For each current and voltage pair, the automated system takes two of the same measurements. The full list of data is available in Appendix D.2.

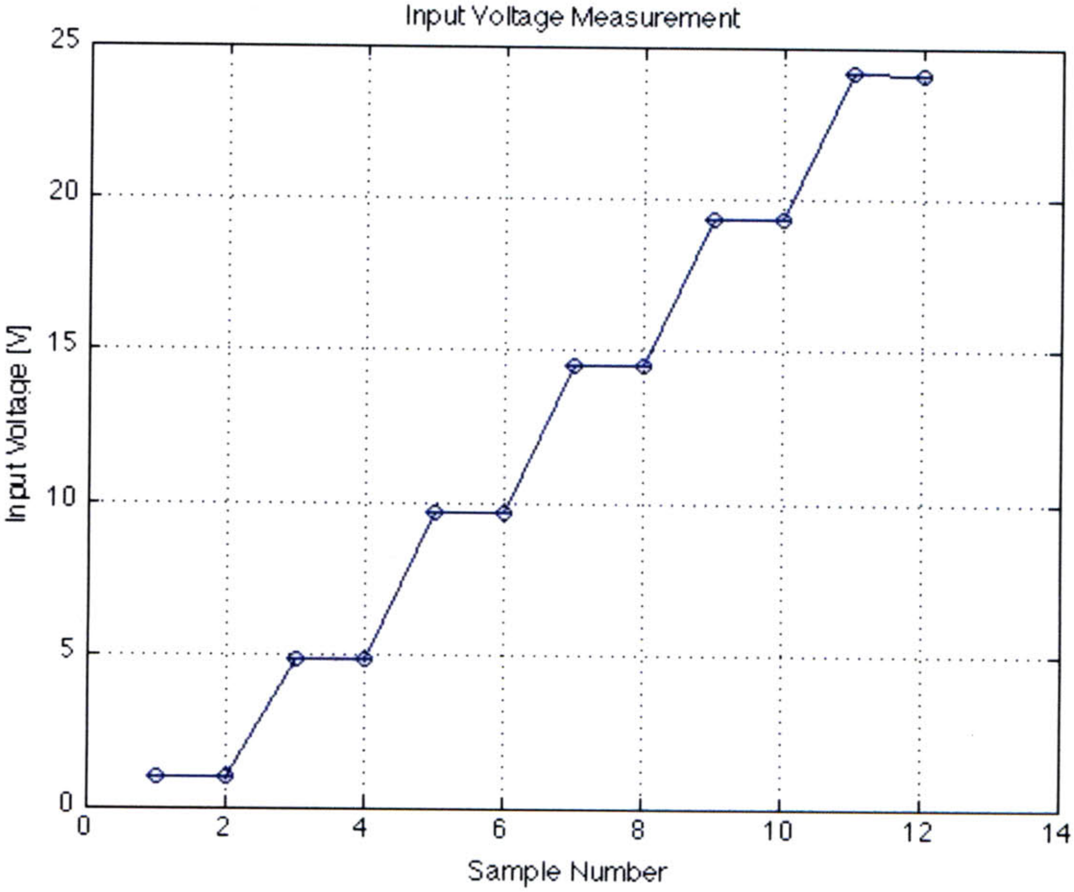

Figure 4-9: Test 2 Input Voltage Measurements

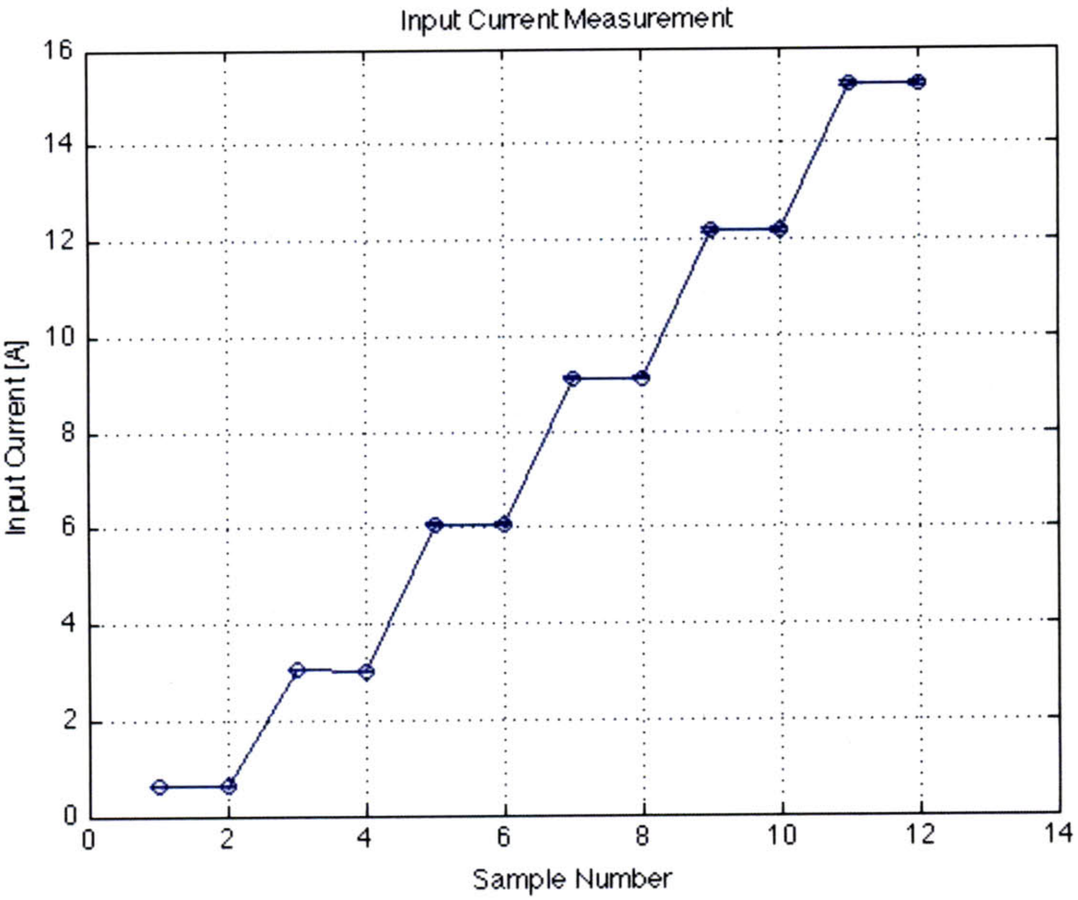

Figure 4-10: Test 2 Input Current Measurements

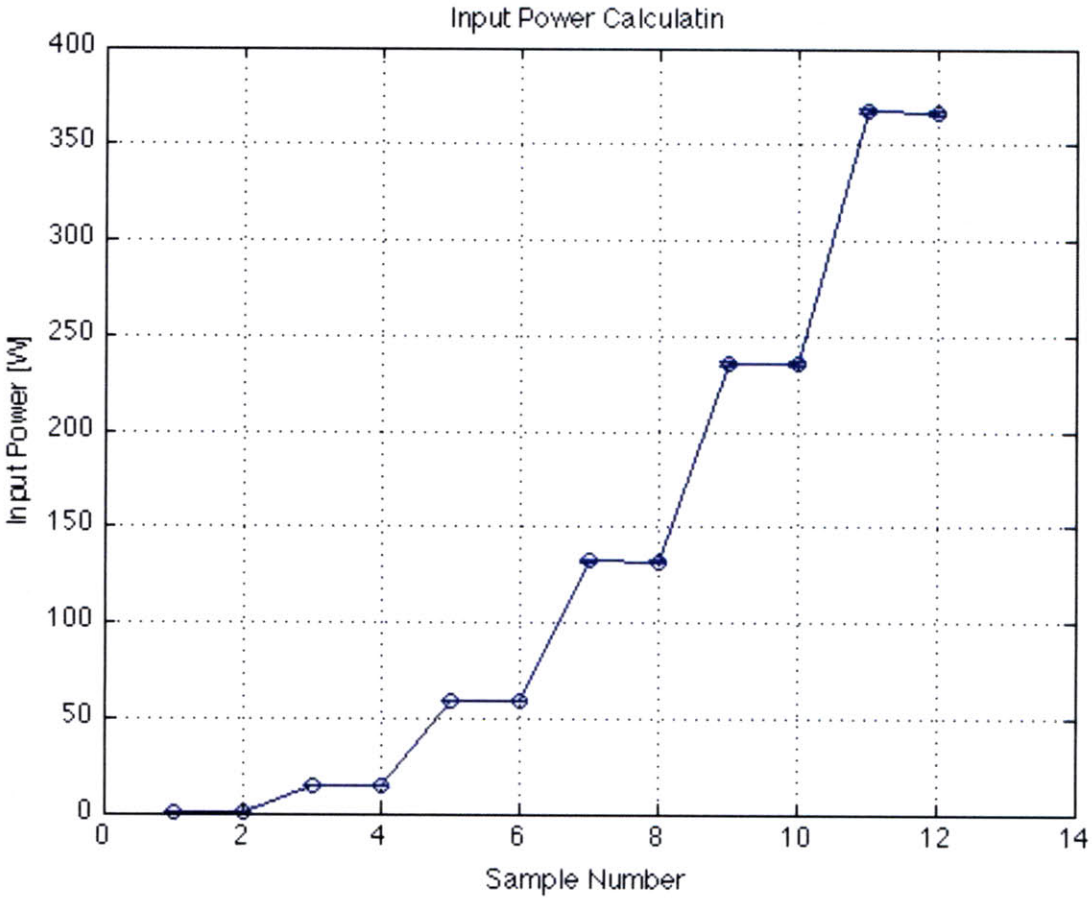

Figure 4-11: Test 2 Input Power Calculations

Parameter	Maximum Uncertainty
Input Voltage	0.0029 V
Input Current	0.0936 A
Input Power	2.3042 W

Table 4.7: Maximum Uncertainty for Automated Measurements Test 2

The input power has a maximum uncertainty of 2.3042W, but this occurs at the maximum input power of around 366 W, so relatively speaking, this is acceptable.

From the measurements presented in the previous two sections, it is clear that the automated system provides measurements that are as good as, if not better, than measurements taken manually. The 50mA minimum on the input current provides a limitation on the measurement system, but it is possible to just not use the current shunt if input current values do not exceed 3A.

4.3. Solar Micro-Inverter Test Data Analysis

Now that the measurement setup proves to be a reliable system, some sample test data from the solar micro-inverter was acquired to run the code on. Unfortunately, the test data has some serious flaws. First, the test data was taken with a different set of multimeters than the Agilent 34401A that the measurement code was written for. Second, there are an uneven number of input voltage and output voltage pairs for each average power level. Third, only five of the six power levels were swept through. Thus, analyzing this test data with the CEC efficiency calculator part of the measurement code will not provide exactly the same results as those that were manually calculated, but it does provide a nearest answer approximation.

Table 4.8 shows the test data for the solar micro-inverter. The code for analyzing this data, which basically is only the CEC efficiency calculation part of the automation code, is included in Appendix E.

% Average Power	Input Voltage [V]	Input Current [A]	Output Voltage [V]	Output Current [A]
100	34	9.74	333.66	0.919
100	34	8.79	314.69	0.879
100	34	5.41	240.53	0.7
100	34	1.65	130	0.383
100	25	7.13	240.53	0.687
100	25	2.22	130.26	0.385
75	34	7.63	333.54	0.725
75	34	6.86	314.56	0.689
75	34	4.14	240.42	0.538
75	34	1.21	130.18	0.276
75	25	11.2	333.58	0.788
75	25	9.39	314.57	0.703
75	25	5.6	240.43	0.542
75	25	1.67	130.19	0.289
50	34	5.46	333.39	0.519
50	34	4.85	314.42	0.487
50	34	2.82	240.3	0.363
50	34	0.663	130.09	0.14
50	25	8.13	333.44	0.578
50	25	6.89	314.44	0.517
50	25	3.93	240.32	0.38
50	25	1.01	130.11	0.169
30	34	3.45	333.27	0.321
30	34	2.97	314.28	0.291
30	34	1.46	240.19	0.177
30	34	0.646	130.08	0.128
30	25	5.66	333.33	0.4
30	25	4.71	314.33	0.351
30	25	2.42	240.22	0.229
30	25	0.572	130.47	0.0833

Table 4.8: Sample Test Data for Solar Micro-Inverter

The next six plots show these measurements and the input and output power and efficiency calculations with their associated error bars.

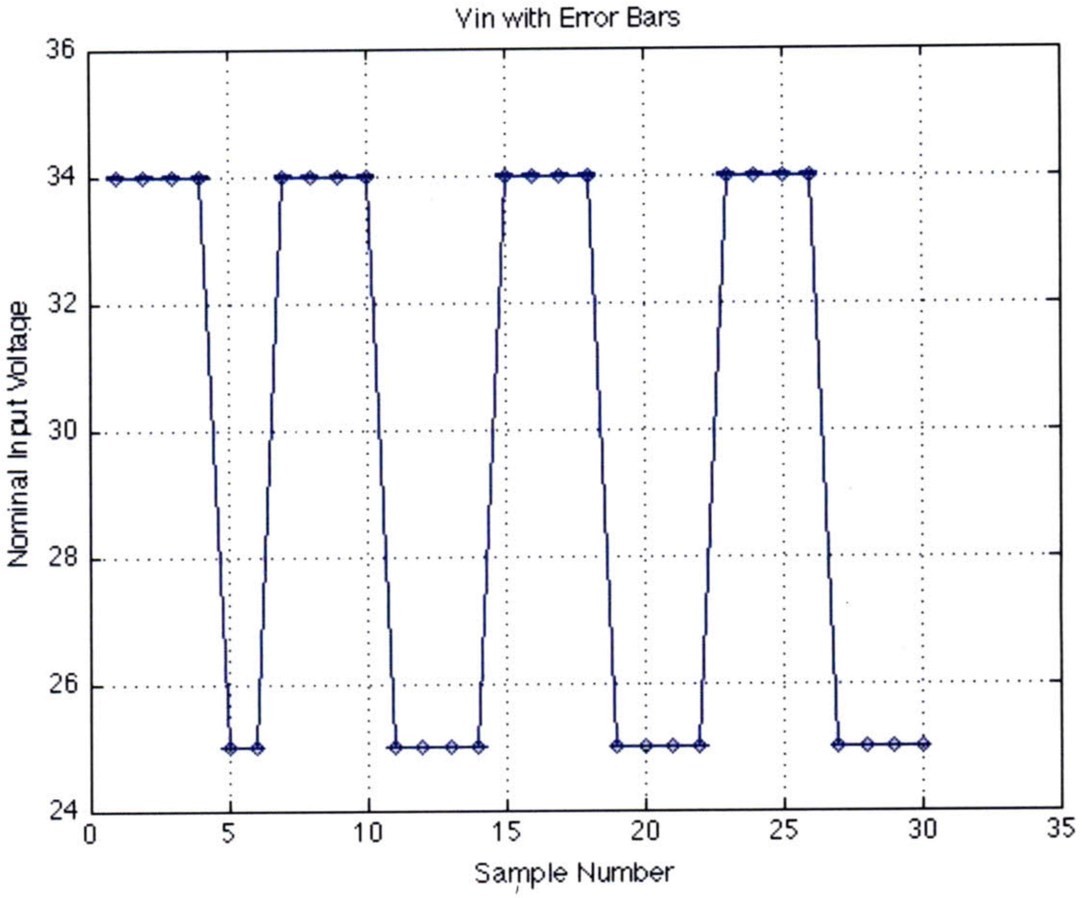

Figure 4-12: Test Data Input Voltage Measurement

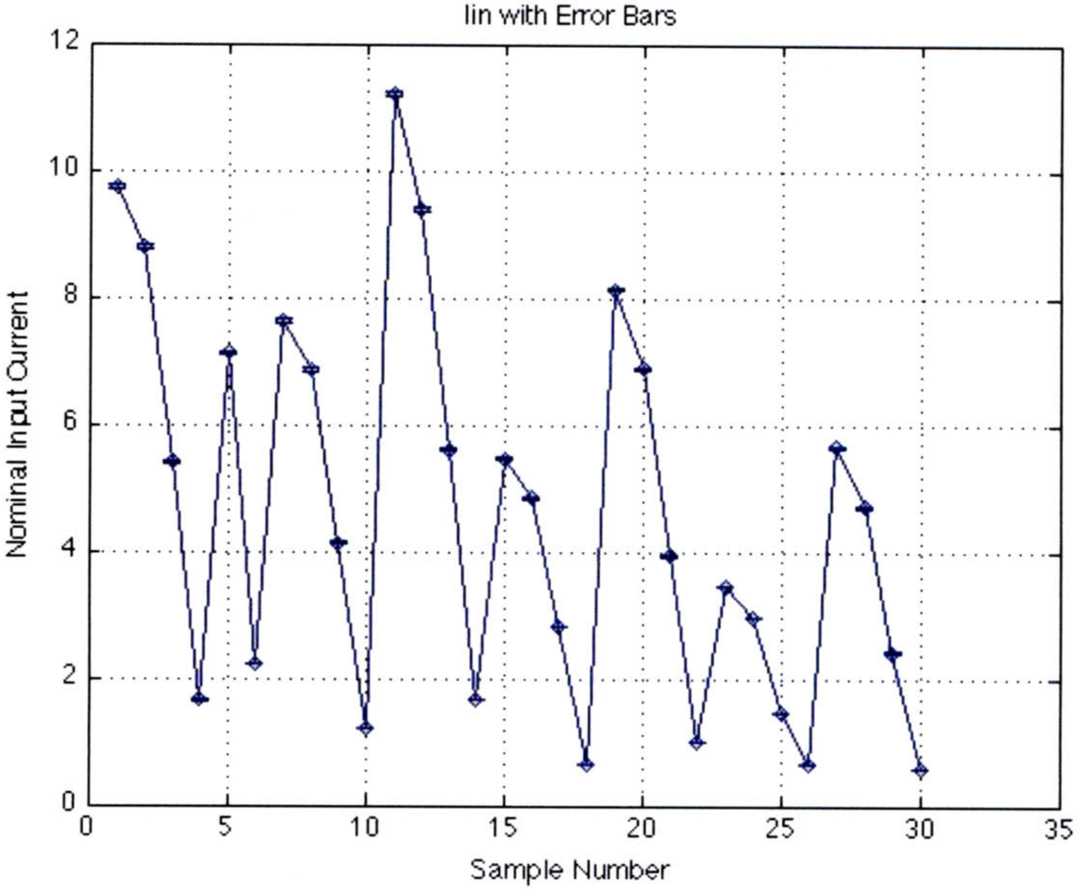

Figure 4-13: Test Data Input Current Measurement

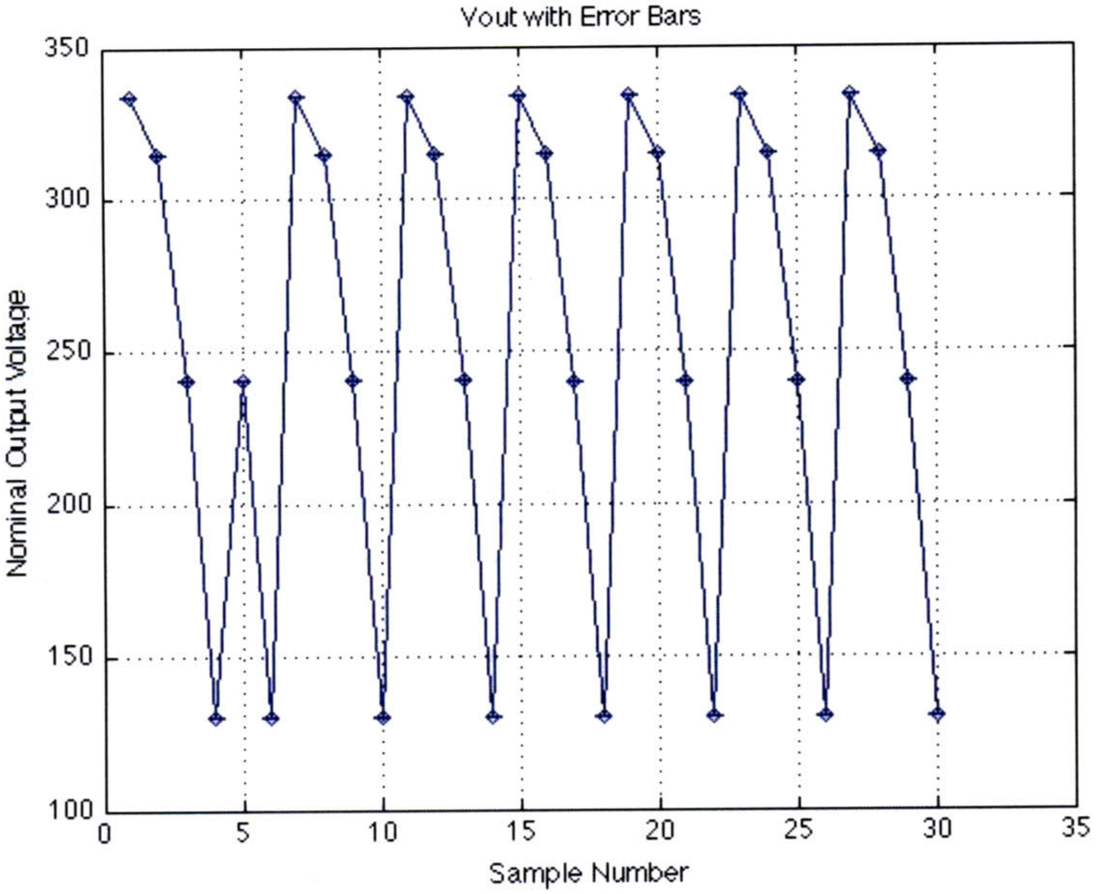

Figure 4-14: Test Data Output Voltage Measurement

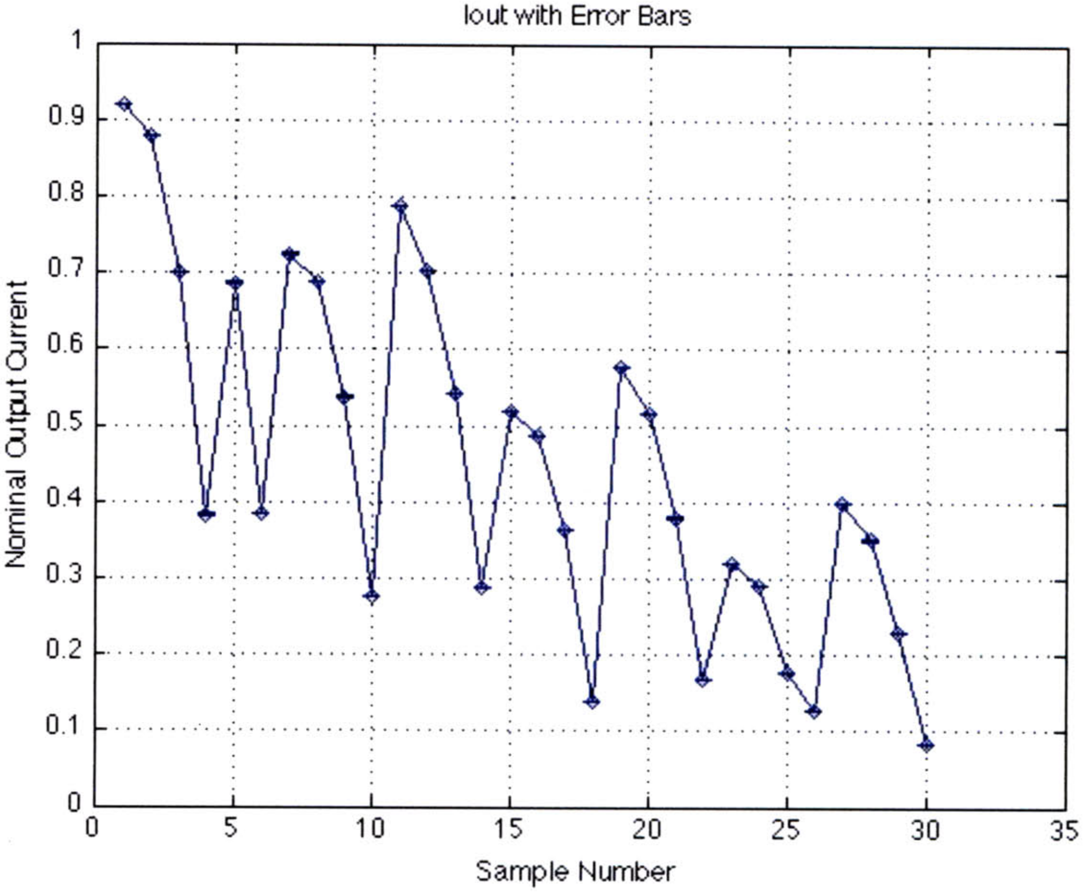

Figure 4-15: Test Data Output Current Measurement

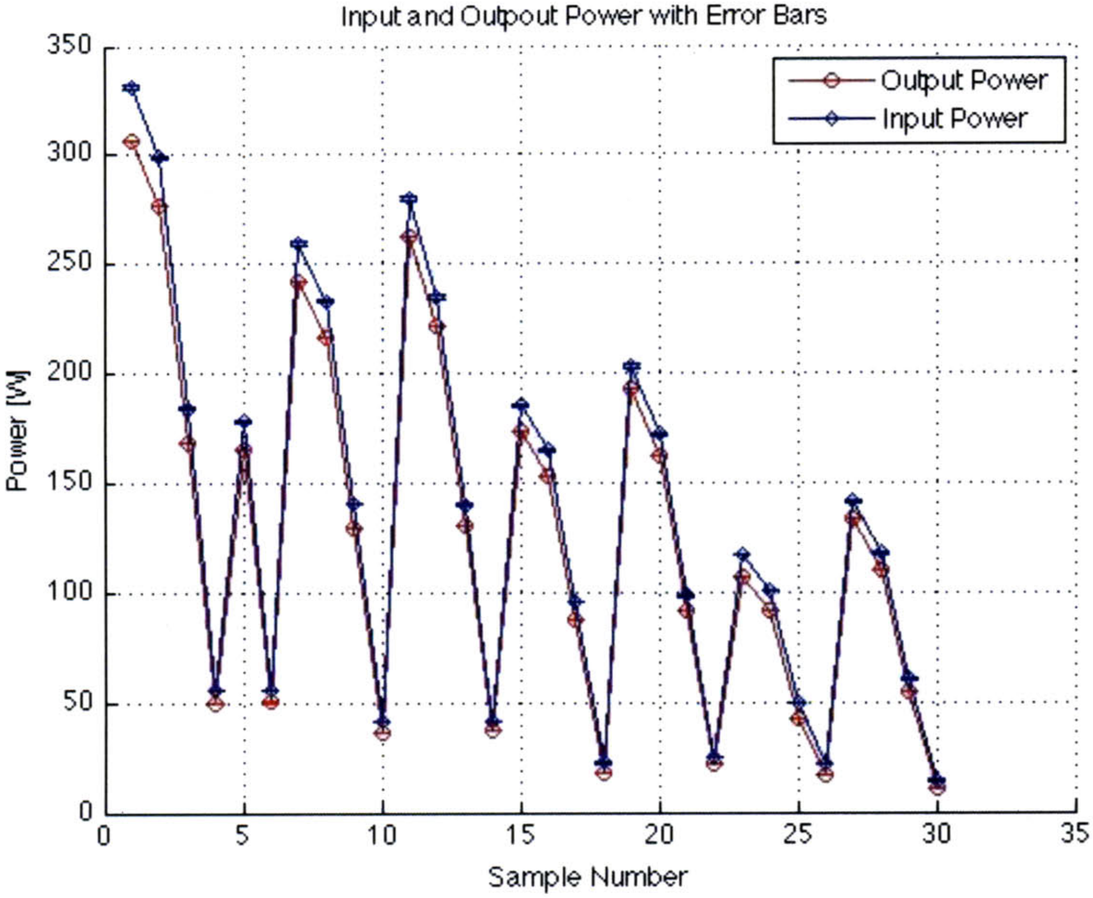

Figure 4-16: Test Data Input and Output Power Calculations

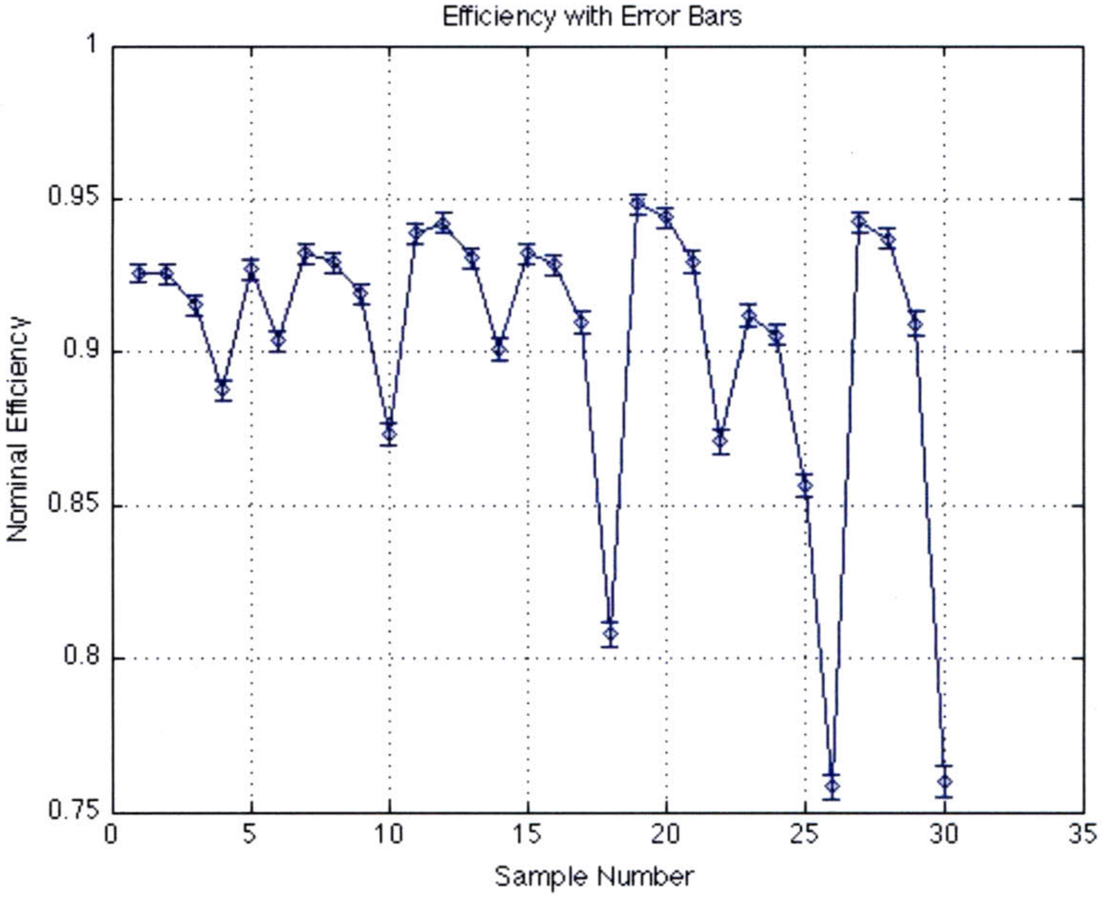

Figure 4-17: Test Data Efficiency Calculations

It is now quite easy to see that the efficiency calculation with error bars is functional. The next calculation of interest is the CEC efficiency. Table 4.9 shows the trapezoidal integration of the efficiencies for each average power level.

% Avg Power	Trapezoidal Integration Efficiency
100	0.922901553
75	0.925138854
60	0.924867344
50	0.92165876
30	0.916015128

Table 4.9: Calculated Efficiency for each Average Power Level

Table 4.10 compares the hand-calculated CEC efficiency with the result from the automated system. Due to the previously mentioned limitations of the sample data, the hand-calculated value and the automation-calculated value are not quite the same, but are compatible.

CEC efficiency by hand	CEC efficiency by code		
	low bound	nominal	high bound
0.923622468	0.920042795	0.923353931	0.926685136

Table 4.10: Hand-Calculated vs Code-Calculated CEC Efficiency

This final CEC efficiency value calculated by MATLAB gives an uncertainty of about 0.66%. In Chapter 1, the worst-case estimate of the uncertainty for CEC efficiency calculation was 1%. Interval analysis gives a worst-case absolute limit on the error, which may be impractical for some applications, but given that the calculated CEC efficiency is reported to be within 0.66% of the actual value, it is a fitting choice for error analysis.

Chapter 5. Summary and Conclusions

5.1. Thesis Conclusions

This thesis documents the design and implementation of an automated measurement system specifically for high frequency power converters. The system measures input and output voltages and currents, and calculates the uncertainty on these values based on the specific hardware used. From this data, input power, output power, and efficiency are calculated with their associated error bars. The system is written in MATLAB script, and provides real-time plots of the input power, output power, and efficiency. All the data is archived for future processing.

5.2. Thesis Summary

Chapter 1 provides an overview of the thesis, starting with the motivation for an automated efficiency and power loss measurement system. This system has a very specific solar micro-inverter application in mind, and the specifications on this micro-inverter are presented.

Chapter 2 discusses in detail the various approaches used to calculate uncertainty. The first approach is a linearization method, which starts out with foundational equations such as Ohm's Law, and develops a model for the uncertainty. The second approach assumes a Gaussian distribution of error, and takes a root-sum-squares method. The third approach utilizes interval analysis, and provides formulas for keeping track of the error after basic mathematical operations.

The method for calculating efficiency as per CEC standards is explored. Accuracy of the hardware is analyzed, which leads to a discussion on just using a multimeter, or combining a multimeter with a current shunt in order to measure current. An example details the propagation of error from the input and output voltage and current measurements all the way to efficiency.

Chapter 3 details the algorithm for hardware automation. The main code runs the master loop for the measurement system. It takes in vectors of values for average power, input voltage, and output voltage. For each average power, it sweeps through all input voltages. For each input voltage, it sweeps through all output voltages. This uniquely defines one set of distinct (P_{avg}, V_{in}, V_{out}). For each set, the code commands the power supplies to output the correct voltages, and measures input and output voltages and currents. From these measurements, it calculates input and output power as well as efficiency. Using interval analysis functions, it determines the uncertainty on all the measured and calculated values. At the very end, it calculates the CEC efficiency, and the error bars on that value.

Chapter 4 provides the validation of the automated system. A resistor test board is used to test two different cases. The first is manually measuring operating points, and the second is automating the process. The results show that the automated system provides a more efficient and accurate method for data collection.

This is followed up by running sample test data from the solar micro-inverter on the measurement system and calculating the CEC efficiency with error bounds. These results are compared to a known manually calculated CEC efficiency rating as a check.

5.3. Future Work

While the measurement system here provides a convenient solution to taking multiple measurements on high efficiency power converters, there are some limitations. It is constrained to the use of the power supplies and multimeters mentioned, and the input current cannot fall below about 50mA, in order to be within a readable range using the current shunt.

Appendix A Master Loop Code

```
%% Measurement System for Power Loss and Efficiency
% Master Loop Control

% This code runs the master loop for the measurement
system.
% It takes in a vector of values for average power, input
voltage, and
% output voltage. For each average power, it sweeps through
all input
% voltages. For each input voltage, it sweeps through all
output voltages.

% This uniquely defines one set. For each set, this code
commands the power
% supplies to their correct voltages, and measures Vin,
Iin, Vout, Iout.
% From these measurements, it calculates Pin, Pout, and
efficiency. Using
% interval analysis, it determines the uncertainty on all
the measurement
% values and calculated values.

% At the very end, it calculates the California Energy
Commission (CEC)
% Efficiency, and returns the error bars on that value.


%% Initilialize the Prologix GPIB-USB serial port
%clear all;
close all; clc; clearvars -except sport;

format long;

while(not(exist('sport')))
    sport = initGPIB('mac'); % for mac
    %sport = initGPIB('win'); % for windows
end

%% setting up instruments (2 power supplies, 4 multimeters)

% There are four miltimeters and two power supplies.
% They are used to set and measure:
%       input voltage, output voltage, input current,
```

```
output current
% The GPIB addresses used by each are set with the
following variables:

psin_gpib = 4; %input voltage power supply(HP 6030A)
psout_gpib = 6; %output voltage power supply of master (HP
6632A)
voltin_gpib = 16; %input dc voltage (Agilent 34401A)
currin_gpib = 15; %input dc current (Agilent 34401A +
34330A)
voltout_gpib = 23; %output dc voltage (Agilent 34401A)
currout_gpib = 5; %output dc current (Agilent 34401A)


filename = 'Power_Eff_Measurements'; %name of file to be
saved
filename2 = 'Trapz Approx for Eff per Avg Power';

fname_counter = 1;
while(exist([filename '.mat']))
    filename = [filename num2str(fname_counter)];
    fname_counter = fname_counter + 1;
end
while(exist([filename2 '.mat']))
    filename2 = [filename2 num2str(fname_counter)];
    fname_counter = fname_counter + 1;
end



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Configure input power supplies (HP 6643A)
fprintf(sport,['++addr ' num2str(psin_gpib)]); %address the
power supply (master)
%fprintf(sport,'*RST');
%fprintf(sport,'*CLS');
%fprintf(sport, 'OUTP OFF'); %disable output
fprintf(sport, 'VSET 20'); %set the voltage
fprintf(sport, 'ISET 16'); %set the current
%fprintf(sport, 'VOLT?'); %read back programmed voltage
%fprintf(sport, 'CURR?'); %read back programmed current
%fprintf(sport, 'OUTP ON'); %enable output
%fprintf(sport, 'MEAS:VOLT?'); %read back outputs from
sense terminals
%fprintf(sport, 'MEAS:CURR?');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Configure output power supplies (HP 6632A)
%vout_desired=30; %desired output voltage
%vout_factor=100; %factor by which 6632A must turn up to
get vout_desired
%vout_master=vout_desired/vout_factor; %appropriate voltage
level for 6632A


fprintf(sport,['++addr ' num2str(psout_gpib)]); %address
the power supply
%fprintf(sport,'*RST');
%fprintf(sport,'*CLS');
%fprintf(sport, 'OUTPUT 706');
%fprintf(sport, 'OUT 0'); %disable output
%fprintf(sport, 'OVSET 5'); %set overvoltage protection,
enabled until RST command given
fprintf(sport, 'VSET 0.1'); %num2str(vout_master)]); % set
the voltage
fprintf(sport, 'ISET 4');
%fprintf(sport, 'OUT 1'); %enable output
%fprintf(sport, 'VOUT?'); %read back voltage
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Configure DC output voltage measurement (Agilent
34401a)
fprintf(sport,['++addr ' num2str(voltout_gpib)]); %address
the proper instrument
fprintf(sport,'*RST'); %reset the meter to its power-on
state
fprintf(sport,'*CLS'); %clear the status registers
fprintf(sport,'CONF:VOLT:DC 1000,1e-3'); %set the range and
resolution
%sets the integration time in number of power line cycles,
max=100
fprintf(sport,'DET:BAND 3');%set AC filter to slow (3Hz)
%CONF sets filter to 20Hz

% fprintf(sport,'TRIG:SOUR BUS'); %bus triggering
% fprintf(sport,'TRIG:COUN 1'); %one trigger per init cycle
% fprintf(sport,'TRIG:DEL:AUTO ON'); %automatic delay after
```

```
trigger
% fprintf(sport,'SAMP:COUN 1'); %samples per trigger

%%%%% Configure DC input voltage measurement (Agilent
34401a)
fprintf(sport,['++addr ' num2str(voltin_gpib)]); %address
the proper instrument
fprintf(sport,'*RST'); %reset the meter to its power-on
state
fprintf(sport,'*CLS'); %clear the status registers
fprintf(sport,'CONF:VOLT:DC 100,1e-3'); %set the range and
resolution
%set the integration time in number of power line cycles,
max=100
fprintf(sport,'DET:BAND 3');%set AC filter to slow (3Hz)
%CONF sets filter to 20Hz

%%%%% Configure DC input current measurement (Agilent
34401a)
fprintf(sport,['++addr ' num2str(currin_gpib)]); %address
the proper instrument
fprintf(sport,'*RST'); %reset the meter to its power-on
state
fprintf(sport,'*CLS'); %clear the status registers
fprintf(sport,'CONF:VOLT:DC 0.1,1e-6'); %set the range and
resolution
%set the integration time in number of power line cycles,
max=100
fprintf(sport,'DET:BAND 3');%set AC filter to slow (3Hz)
%CONF sets filter to 20Hz

%%%%% Configure DC output current measurement (Agilent
34401a)
fprintf(sport,['++addr ' num2str(currout_gpib)]); %address
the proper instrument
fprintf(sport,'*RST'); %reset the meter to its power-on
state
fprintf(sport,'*CLS'); %clear the status registers
fprintf(sport,'CONF:CURR:DC 1,1e-6'); %set the range and
resolution
%set the integration time in number of power line cycles,
max=100
fprintf(sport,'DET:BAND 3');%set AC filter to slow (3Hz)
%CONF sets filter to 20Hz
%7seconds/reading settling time for 3Hz
```

```
%% Loopy Loopy

%%%%% Create a timer object
t = timer('TimerFcn','disp(''Just Hanging
Around'')','StartDelay',8);

avgpower_levels = [10 20 30 50 75 100];
%voltin_levels = [25 32.5 40];
%voltout_levels = 0.01*[6:6:90]/90*240*sqrt(2);
%Vout=[6:6:90]/90*240*sqrt(2);
voltin_levels = [5];
voltout_levels=0.01*[339.4113];
numptsperavgp=length(voltin_levels)*length(voltout_levels);

counter=1; %counts every set of measurements taken

%efficiencies contains trapezoidal integration for each avg
power level
efficiencies = zeros(length(avgpower_levels),1);
efficiencies_error = zeros(length(avgpower_levels),2);

Vpeak=240*sqrt(2); %240 rms
theta=asin(Vout./Vpeak); %angle

for i = 1:length(avgpower_levels)
    avgpower_amplitude = avgpower_levels(i);
    %%%talk to alex
    for j=1:length(voltin_levels)
        vin_amplitude = voltin_levels(j);
        for k=1:length(voltout_levels)

            vout_amplitude = voltout_levels(k);

            textstrng = ['Present Pavg is ' ...
                num2str(avgpower_amplitude)];
            disp(textstrng);

            textstrng = ['Present Vin is ' ...
                num2str(vin_amplitude)];
            disp(textstrng);

            textstrng = ['Present Vout is ' ...
                num2str(vout_amplitude)];
            disp(textstrng);

            % address the input power supply
            fprintf(sport,['++addr ' num2str(psin_gpib)]);
```

```
            fprintf(sport,['VSET '
num2str(vin_amplitude)]);

            % address the output power supply
            fprintf(sport,['++addr ' num2str(psout_gpib)]);
            fprintf(sport,['VSET '
num2str(vout_amplitude)]);

            clear voltout voltin currout currin
shuntvolt...
                vout_error vin_error iout_error
iin_error...
                pout_error pin_error eff_error


            measuring = 1;
            meas_count = 1;
            while(measuring)

                %%%% Trigger then fetch the results from
each instrument
                fprintf(sport,['++addr '
num2str(voltin_gpib)]);
                fprintf(sport,'INIT');
                fprintf(sport,'FETC?');
                fprintf(sport,'++read 10');
                voltin = str2num(char(fread(sport,16))');

                fprintf(sport,['++addr '
num2str(currin_gpib)]);
                fprintf(sport,'INIT');
                fprintf(sport,'FETC?');
                fprintf(sport,'++read 10');
                %dccurr{meas_count} = char(fread(sport))';
                %dccurr_temp(meas_count) =
str2num(char(fread(sport))');
                shuntvolt =
str2num(char(fread(sport,16))');
                currin=shuntvolt*1000;

                fprintf(sport,['++addr '
num2str(voltout_gpib)]);
                fprintf(sport,'INIT');
                fprintf(sport,'FETC?');
                fprintf(sport,'++read 10');
                voltout = str2num(char(fread(sport,16))');
```

```
                fprintf(sport,['++addr '
num2str(currout_gpib)]);
                fprintf(sport,'INIT');
                fprintf(sport,'FETC?');
                fprintf(sport,'++read 10');
                currout = str2num(char(fread(sport,16))');

                % Print the results and then wait 5s for
the measurement
                textstrng2 = ['Trial Number = ' ...
                    num2str(meas_count)];
                disp(textstrng2);
                start(t)
                wait(t)

                % Print the measurement results
                textstrng3 = ['measured Vin is: '
num2str(voltin)];
                disp(textstrng3);
                textstrng4 = ['measured Iin is: '
num2str(currin)];
                disp(textstrng4);
                textstrng5 = ['measured Vout is: '
num2str(voltout)];
                disp(textstrng5);
                textstrng6 = ['measured Iout is: '
num2str(currout)];
                disp(textstrng6);


                meas_count = meas_count + 1;
                if meas_count > 2 %number of samples per
output voltage
                    measuring = 0;
                end

                %calculate input power, output power,
efficiency
                powerout=voltout*currout;
                powerin=voltin*currin;
                eff=powerout/powerin;


                % adding error bars
                vin_error=vget_errorbars(voltin);
                iin_error=iget_errorbars_input(currin);
```

```
                vout_error=vget_errorbars(voltout);
                iout_error=iget_errorbars_output(currout);

                pin_error=interval_multiply(vin_error,
iin_error);
                pout_error=interval_multiply(vout_error,
iout_error);

                eff_error=interval_divide(pout_error,
pin_error);

                figure(1);
                hold on; grid on;
                errorbar(counter, powerout,...
                    powerout-pout_error(1),pout_error(2)-
powerout,'ro-');
                errorbar(counter, powerin, ...
                    powerin-pin_error(1),pin_error(2)-
powerin,'bd-');
                xlabel('Sample Number');
                title ('Running Plots of Input and Outpout
Power');
                ylabel('Power [W]');
                legend('Output Power', 'Input Power');

%                 figure(2);
%                 hold on; grid on;
%                 errorbar(counter, eff, ...
%                     eff-eff_error(1), eff_error(2)-eff,
'bd');
%                 xlabel('Sample Number');
%                 ylabel('Nominal Efficiency');
%                 title('Running Plots of Efficiency');

                %update measurements
                voltout_meas(counter,1)=voltout;
                voltout_error_meas(counter,:)=vout_error;

                voltin_meas(counter,1)=voltin;
                voltin_error_meas(counter,:)=vin_error;

                currout_meas(counter,1)=currout;
                currout_error_meas(counter,:)=iout_error;

                currin_meas(counter,1)=currin;
                currin_error_meas(counter,:)=iin_error;
```

```
                powerout_meas(counter,1)=powerout;
                powerout_error_meas(counter,:)=pout_error;

                powerin_meas(counter,1)=powerin;
                powerin_error_meas(counter,:)=pin_error;

                eff_meas(counter,1)=eff;
                eff_error_meas(counter,:)=eff_error;

                counter=counter+1;

            end

            save(filename,...
                'voltin_meas','voltin_error_meas',...
                'currin_meas','currin_error_meas',...
                'voltout_meas','voltout_error_meas',...
                'currout_meas', 'currout_error_meas',...
                'powerin_meas', 'powerin_error_meas',...
                'powerout_meas', 'powerout_error_meas',...
                'eff_meas', 'eff_error_meas')
        end
        disp('output voltage sweep completed');
    end
    disp('input voltage sweep completed');

    %calculate efficiency for each average power level
    %calculate the start and stop bounds
    %powerin_meas, etc appends new measurements, so pull
out data of
    %interest
    start=(i-1)*numptsperavgp+1;% # distinct Pins
    stop=i*numptsperavgp;


    % extract # of distinct measurements per avg power
level, sorts that
    % interval
    theta_i = theta(start:stop);
    powerin_error_meas_i =
powerin_error_meas(start:stop,:);
    powerout_error_meas_i =
powerout_error_meas(start:stop,:);
    powerin_meas_i = powerin_meas(start:stop);
    powerout_meas_i = powerout_meas(start:stop);

    [theta_i,ind] = sort(theta_i);
```

```
    powerin_error_meas_i = powerin_error_meas_i(ind,:);
    powerout_error_meas_i = powerout_error_meas_i(ind,:);
    powerin_meas_i = powerin_meas_i(ind);
    powerout_meas_i = powerout_meas_i(ind);


    in=trapz(theta_i,powerin_meas_i);
    in_error1=trapz(theta_i,powerin_error_meas_i(:,1));
    in_error2=trapz(theta_i,powerin_error_meas_i(:,2));
    in_error=[in_error1 in_error2];

    out=trapz(theta_i,powerout_meas_i);
    out_error1=trapz(theta_i,powerout_error_meas_i(:,1));
    out_error2=trapz(theta_i,powerout_error_meas_i(:,2));
    out_error=[out_error1 out_error2];

    effavgp=out./in; %stores efficiencies for each avg
power level
    effavgp_error=interval_divide(out_error, in_error);

    efficiencies(i) = effavgp;
    efficiencies_error(i,:) = effavgp_error;

    save(filename2, 'efficiencies','efficiencies_error')
end
disp('all measurements completed');

%address the input power supply
fprintf(sport,['++addr ' num2str(psin_gpib)]);
fprintf(sport,'VSET 0');
fprintf(sport,'ISET 0');
%address the output power supply
fprintf(sport,['++addr ' num2str(psoutmaster_gpib)]);
fprintf(sport, 'VSET 0');
fprintf(sport, 'ISET 0');
%fclose(sport); % close the serial connection

%% Calculate CEC Efficiency with error bars

%effs=[0.1 0.2 0.3 0.5 0.75 1] of max average power

weights=[0.04 0.05 0.12 0.21 0.53 0.05];
CECeff=dot(weights,efficiencies')

CECefflow=weights.*efficiencies_error(:,1)';
CECeffhigh=weights.*efficiencies_error(:,2)';
CECefferror=[sum(CECefflow) sum(CECeffhigh)]
```

Appendix B Associated Functions Code

B1. Opening the Port

```
%%%%% Initialize the controller

%clear all
%clc

function [sport] = initGPIB(OStype)

if OStype == 'mac'
    %sport = serial('/dev/tty.usbserial-PXEIYCJE');
    sport = serial('/dev/tty.usbserial-PXENMLS9');
    %sport = serial('/dev/cu.usbserial-PXENMLS9');
elseif OStype == 'win'
    sport = serial('COM3');
else
    disp('Invalid operating system specification.  Choose
''mac'' or ''win.''');
end
sport.Terminator = 'LF';
sport.Timeout = 0.5;

fopen(sport);

fprintf(sport, '++mode 1');
fprintf(sport, '++addr 10');  %% set default gpib address
fprintf(sport, '++auto 0');
fprintf(sport, '++eoi 1'); % turn on end-of-line character
fprintf(sport, '++eos 2'); % send a line-feed (ASCII 10)
character at end of line
```

B2. Interval Multiply Code

```
function [interval] = interval_multiply(intervalA,
intervalB)

%This script does the following interval analysis:
% Let a fall in the range of [a1, a2], and b in the range
of [b1, b2]
%
%a/b= [min(a1*b1, a2*b2, a1*b2, a2*b1), max(a1*b1, a2*b2,
```

```
a1*b2, a2*b1)]

a = intervalA(1)*intervalB(1);
b = intervalA(1)*intervalB(2);
c = intervalA(2)*intervalB(1);
d = intervalA(2)*intervalB(2);

interval=[min([a b c d]), max([a b c d])];
```

B3. Interval Divide Code

```
function [interval] = interval_divide(intervalA, intervalB)

%This script does the following interval analysis:
% Let a fall in the range of [a1, a2], and b in the range
of [b1, b2]
%
%a/b= [min(a1/b1, a2/b2, a1/b2, a2/b1), max(a1/b1, a2/b2,
a1/b2, a2/b1)]

a = intervalA(1)/intervalB(1);
b = intervalA(1)/intervalB(2);
c = intervalA(2)/intervalB(1);
d = intervalA(2)/intervalB(2);

interval=[min([a b c d]), max([a b c d])];
```

B4. Comparison of Current Measurement using Multimeter with and without Current Shunt

```
function [ioutput] = iget_errorbars_output_compare(ivalue)

%This script compares uncertainty on measurements in two
cases:
% Case 1: multimeter
% Case 2: multimeter + current shunt

%multimeter = Agilent34401A, shunt = Agilent 34330A

%Case 1, multimeter only
noshunt = iget_errorbars_output(ivalue)
noshunt_error=0.5*(noshunt(2)-noshunt(1))

%Case 2, multimeter + current shunt
```

```
shunt = iget_errorbars_input(ivalue)
shunt_error=0.5*(shunt(2)-shunt(1))
```

B5. Error Bars on Input and Output Voltages

```
function [voutput] = vget_errorbars(vvalue)

% vget_errorbars takes in Agilent 34401A's reading of DC
voltage level and
% outputs the range of possible values based on error

% 90 day, 23 degrees C +- 5 degrees C

format long;
len = length(vvalue);

vlow = zeros(len,1);
vhigh = zeros(len,1);
for i=1:len


    dc_volt_measurement=vvalue(i);

    %range for dc voltage and associated accuracy
    %uncertainty=(%reading + %range)
    dc_volt=[0.1 1 10 100 1000]';
    dc_volt_accuracy=...
        [0.0040e-2*vvalue+0.0035e-2*0.1;
        0.0030e-2*vvalue+0.0007e-2*1;
        0.0020e-2*vvalue+0.0005e-2*10;
        0.0035e-2*vvalue+0.0006e-2*100;
        0.0035e-2*vvalue+0.0010e-2*1000];

    %lookup where measured value falls in table

dc_volt_index=length(find(dc_volt<=dc_volt_measurement))+1;

    dc_volt_lookup=dc_volt_accuracy(dc_volt_index);
    dc_volt_low_bound=dc_volt_measurement-dc_volt_lookup;
    dc_volt_high_bound=dc_volt_measurement+dc_volt_lookup;

    %range for actual dc voltage
    %dc_volt_range=[dc_volt_low_bound dc_volt_measurement
dc_volt_high_bound];
```

```
        vlow(i)=dc_volt_low_bound;
        vhigh(i)=dc_volt_high_bound;
    end

    voutput = [vlow,vhigh];
```

B6. Error Bars on Output Current

```
function [ioutput] = iget_errorbars_output(ivalue)

% iget_errorbars takes in Agilent 34401A's reading of DC
current level and
% outputs the range of possible values based on error

% 90 day, 23 degrees C +- 5 degrees C

format long;

len=length(ivalue);

ilow=zeros(len,1);
ihigh=zeros(len,1);
for i=1:len

    dc_i_measurement=ivalue(i);

    %range for dc current and associated accuracy
    %uncertainty = (%reading + %range)
    dc_i=[10e-3 100e-3 1 3]';
    dc_i_accuracy=...
        [0.030e-2*ivalue+0.020e-2*10e-3;
        0.030e-2*ivalue+0.005e-2*100e-3;
        0.080e-2*ivalue+0.010e-2*1;
        0.120e-2*ivalue+0.020e-2*3];

    %lookup where measured value falls in table
    dc_i_index=length(find(dc_i<=dc_i_measurement))+1;

    dc_i_lookup=dc_i_accuracy(dc_i_index);
    dc_i_low_bound=dc_i_measurement-dc_i_lookup;
    dc_i_high_bound=dc_i_measurement+dc_i_lookup;

    %range for actual output current
    dc_i_range=[dc_i_low_bound dc_i_measurement
dc_i_high_bound];
```

```
        ihigh(i)=dc_i_high_bound;
        ilow(i)=dc_i_low_bound;
    end

    ioutput=[ilow,ihigh];
```

B7. Error Bars on Input Current

```
function [ioutput] = iget_errorbars_input(ivalue)

% iget_errorbars takes in Agilent 34401A's reading of DC
current level and
% outputs the range of possible values based on error

% 90 day, 23 degrees C +- 5 degrees C

% this includes agilent 34330A current shunt
% The shunt provides a voltage reading based on the current
level, with the
% ratio being 1mV/A. Thus, in order to calculate the output
current
% accuracy, we need to look at the voltage accuracy of the
Agilent 34401A

%this gives uncertainty on voltage measurement from
multimeter
vrange=vget_errorbars(ivalue);

%add uncertainty from shunt
shunt_error=0.003;
ilow=vrange(:,1)*(1-shunt_error);
ihigh=vrange(:,2)*(1+shunt_error);

ioutput=[ilow,ihigh];
```

Appendix C Generating Operating Points for Solar Micro-Inverter

C1. Code to Determine Operating Points

```
%Calculates the operating points to be tested
%inputs:
Vpos = (5:5:90)./90;  %set the positions along the line (in
degrees, from 0 to 90) to test
Vinput = [25 32.5 40];    %set the input votlages
PercentPower =[.1 .2 .3 .5 .75 1]; %set the power levels

Pave_max = 175;
Vrms = 240;

PowerPercentLineCycle = sin(Vpos*pi/2).^2;
Rlprime = 66./PercentPower;

LPP = length(PercentPower);
pl = length(PowerPercentLineCycle);
LV = length(Vinput);

PTT = zeros(LPP*LV*pl,6);
row = 1;

for pm = 1:LPP
    Pout_max = 2*Pave_max.*PercentPower(pm);
    Rldprime = Rlprime(pm);

    LineCyclePosition = sqrt(PowerPercentLineCycle);
    Vline = LineCyclePosition.*Vrms*sqrt(2);
    Pout = PowerPercentLineCycle.*Pout_max;

    for vi = 1:LV
        for np = 1:pl
            Vout = Vline(np);
            %Perecent average power, Vin, Vout, Pout
            Iout = Pout(np)./Vout;
            Iin =  Pout(np)./Vinput(vi)/0.95;       %0.95 -
some efficiency
            PTT(row,1:6) = [PercentPower(pm), Vinput(vi),
```

```
Vout, Pout(np), Iin, Iout];
            row = row+1;
        end
    end
end
```

C2. First Few Samples from List of Generated Operating Points (PPT Matrix)

% Avg	Vin	Vout	Pout	Iin	Iout
0.1	25	29.58164002	0.265864322	0.011194287	0.008987477
0.1	25	58.93814591	1.055379136	0.044437016	0.017906555
0.1	25	87.84609691	2.344555434	0.098718124	0.026689352
0.1	25	116.0854861	4.094222245	0.172388305	0.035269028
0.1	25	143.4413946	6.25121683	0.26320913	0.043580285
0.1	25	169.7056275	8.75	0.368421053	0.051559869
0.1	25	194.6782981	11.51464749	0.484827263	0.059147052
0.1	25	218.1693493	14.46115689	0.608890816	0.06628409
0.1	25	240	17.5	0.736842105	0.072916667
0.1	25	260.0041058	20.53884311	0.864793394	0.078994303
0.1	25	278.0294234	23.48535251	0.988856948	0.084470745
0.1	25	293.9387691	26.25	1.105263158	0.089304314
0.1	25	307.6110634	28.74878317	1.210475081	0.093458222
0.1	25	318.9422517	30.90577775	1.301295905	0.096900858
0.1	25	327.8460969	32.65544457	1.374966087	0.099606019
0.1	25	334.2548354	33.94462086	1.429247194	0.101553118
0.1	25	338.1196927	34.73413568	1.462489923	0.102727337
0.1	25	339.411255	35	1.473684211	0.103119739
0.1	32.5	29.58164002	0.265864322	0.00861099	0.008987477
0.1	32.5	58.93814591	1.055379136	0.03418232	0.017906555
0.1	32.5	87.84609691	2.344555434	0.075937018	0.026689352
0.1	32.5	116.0854861	4.094222245	0.132606389	0.035269028
0.1	32.5	143.4413946	6.25121683	0.202468561	0.043580285
0.1	32.5	169.7056275	8.75	0.28340081	0.051559869
0.1	32.5	194.6782981	11.51464749	0.372944048	0.059147052
0.1	32.5	218.1693493	14.46115689	0.468377551	0.06628409
0.1	32.5	240	17.5	0.566801619	0.072916667
0.1	32.5	260.0041058	20.53884311	0.665225688	0.078994303
0.1	32.5	278.0294234	23.48535251	0.760659191	0.084470745
0.1	32.5	293.9387691	26.25	0.850202429	0.089304314
0.1	32.5	307.6110634	28.74878317	0.931134678	0.093458222
0.1	32.5	318.9422517	30.90577775	1.00099685	0.096900858
0.1	32.5	327.8460969	32.65544457	1.057666221	0.099606019
0.1	32.5	334.2548354	33.94462086	1.099420919	0.101553118
0.1	32.5	338.1196927	34.73413568	1.124992249	0.102727337
0.1	32.5	339.411255	35	1.133603239	0.103119739
0.1	40	29.58164002	0.265864322	0.00699643	0.008987477
0.1	40	58.93814591	1.055379136	0.027773135	0.017906555
0.1	40	87.84609691	2.344555434	0.061698827	0.026689352
0.1	40	116.0854861	4.094222245	0.107742691	0.035269028

Appendix D Data Points from Automated Tests

D1. Code for Analyzing Data

```
%% Data Analysis for Measurements

clc; clear all; close all;

load 'Analyze2.mat'; % name of measurement file
x=(1:1:12); % set to the number of samples

figure(1)
vin=errorbar(x,voltin_meas,...
    voltin_meas-voltin_error_meas(:,1), ...
    voltin_error_meas(:,2)-voltin_meas,'bo-');
grid on; title('Input Voltage Measurement');
xlabel('Sample Number'); ylabel('Input Voltage [V]');
vinerror=max(voltin_error_meas(:,2)-voltin_error_meas(:,1))

figure(2)
iin=errorbar(x,currin_meas,...
    currin_meas-currin_error_meas(:,1), ...
    currin_error_meas(:,2)-currin_meas,'bo-');
grid on; title('Input Current Measurement');
xlabel('Sample Number'); ylabel('Input Current [A]');
iinerror=max(currin_error_meas(:,2)-currin_error_meas(:,1))

figure(3)
vout=errorbar(x,voltout_meas,...
    voltout_meas-voltout_error_meas(:,1), ...
    voltout_error_meas(:,2)-voltout_meas,'bo-');
grid on; title('Output Voltage Measurement');
xlabel('Sample Number'); ylabel('Output Voltage [V]');
vouterror=max(voltout_error_meas(:,2)-
voltout_error_meas(:,1))

figure(4)
iout=errorbar(x,currout_meas,...
    currout_meas-currout_error_meas(:,1), ...
    currout_error_meas(:,2)-currout_meas, 'bo-');
grid on;  title('Output Current Measurement');
xlabel('Sample Number'); ylabel('Output Current [A]');
iouterror=max(currout_error_meas(:,2)-
currout_error_meas(:,1))
```

```
figure(5)
pin=errorbar(x,powerin_meas,...
    powerin_meas-powerin_error_meas(:,1), ...
    powerin_error_meas(:,2)-powerin_meas,'bo-');
grid on; title('Input Power Calculatin');
xlabel('Sample Number'); ylabel('Input Power [W]');
pinerror=max(powerin_error_meas(:,2)-
powerin_error_meas(:,1))

figure(6)
pout=errorbar(x,powerout_meas,...
    powerout_meas-powerout_error_meas(:,1), ...
    powerout_error_meas(:,2)-powerout_meas,'bo-');
grid on; title('Output Power Calculation');
xlabel('Sample Number'); ylabel('Output Power [W]');
pouterror=max(powerout_error_meas(:,2)-
powerout_error_meas(:,1))
```

D2. Test 1: Input Voltage and Error Bars, Input Current and Error Bars

Vin low [V]	Vin [V]	Vin high [V]	Iin low [A]	Iin [A]	Iin high [A]
24.97667776	24.978152	24.97962624	0.002661385	0.002673	0.002684637
24.99088027	24.992355	24.99382973	0.007990137	0.008018	0.008045886
24.99017029	24.991645	24.99311971	0.017315702	0.017372	0.017428323
24.99017029	24.991645	24.99311971	0.002661385	0.002673	0.002684637
24.99017029	24.991645	24.99311971	0.014650827	0.014699	0.014747197
24.98946032	24.990935	24.99240968	0.005325262	0.005345	0.00536476
24.98946032	24.990935	24.99240968	0.005325262	0.005345	0.00536476
24.99017029	24.991645	24.99311971	0.022644454	0.022717	0.022789573
24.99088027	24.992355	24.99382973	0.014650827	0.014699	0.014747197
24.98946032	24.990935	24.99240968	0.022644454	0.022717	0.022789573
24.99017029	24.991645	24.99311971	0.005325262	0.005345	0.00536476
24.98946032	24.990935	24.99240968	0.019979579	0.020044	0.020108447
24.99017029	24.991645	24.99311971	0.019979579	0.020044	0.020108447
24.99017029	24.991645	24.99311971	0.002661385	0.002673	0.002684637
24.98946032	24.990935	24.99240968	0.010654014	0.01069	0.010726009
24.98946032	24.990935	24.99240968	0.022644454	0.022717	0.022789573
24.99088027	24.992355	24.99382973	0.021311518	0.02138	0.021448508
24.98946032	24.990935	24.99240968	0.025308331	0.025389	0.025469696
24.99017029	24.991645	24.99311971	0.01864764	0.018708	0.018768385
24.99017029	24.991645	24.99311971	0.022644454	0.022717	0.022789573
24.98946032	24.990935	24.99240968	0.025308331	0.025389	0.025469696
24.98946032	24.990935	24.99240968	0.021311518	0.02138	0.021448508
24.99017029	24.991645	24.99311971	0.023976392	0.024053	0.024129635

24.99017029	24.991645	24.99311971	0.005325262	0.005345	0.00536476
24.99088027	24.992355	24.99382973	0.010654014	0.01069	0.010726009
24.98946032	24.990935	24.99240968	0.019979579	0.020044	0.020108447
24.98946032	24.990935	24.99240968	0.003993324	0.004009	0.004024698
24.99017029	24.991645	24.99311971	0.007990137	0.008018	0.008045886
24.99017029	24.991645	24.99311971	0.019979579	0.020044	0.020108447
24.99017029	24.991645	24.99311971	0.015982766	0.016035	0.016087259
32.51204302	32.513781	32.51551898	0.025308331	0.025389	0.025469696
32.50494227	32.50668	32.50841773	0.005325262	0.005345	0.00536476
32.50494227	32.50668	32.50841773	0.009322075	0.009354	0.009385948
32.50423129	32.505969	32.50770671	0.017315702	0.017372	0.017428323
32.50494227	32.50668	32.50841773	0.006657201	0.006681	0.006704822
32.50423129	32.505969	32.50770671	0.006657201	0.006681	0.006704822
32.50423129	32.505969	32.50770671	0.021311518	0.02138	0.021448508
32.50494227	32.50668	32.50841773	0.01864764	0.018708	0.018768385
32.50494227	32.50668	32.50841773	0.019979579	0.020044	0.020108447
32.50423129	32.505969	32.50770671	0.025308331	0.025389	0.025469696
32.50494227	32.50668	32.50841773	0.002661385	0.002673	0.002684637
32.50423129	32.505969	32.50770671	0.009322075	0.009354	0.009385948
32.50352132	32.505259	32.50699668	0.005325262	0.005345	0.00536476
32.50494227	32.50668	32.50841773	0.021311518	0.02138	0.021448508
32.50423129	32.505969	32.50770671	0.002661385	0.002673	0.002684637
32.50494227	32.50668	32.50841773	0.003993324	0.004009	0.004024698
32.50494227	32.50668	32.50841773	0.025308331	0.025389	0.025469696
32.50494227	32.50668	32.50841773	0.02664027	0.026725	0.026809758
32.50494227	32.50668	32.50841773	0.009322075	0.009354	0.009385948
32.50494227	32.50668	32.50841773	0.019979579	0.020044	0.020108447
32.50494227	32.50668	32.50841773	0.017315702	0.017372	0.017428323
32.50423129	32.505969	32.50770671	0.017315702	0.017372	0.017428323
32.50423129	32.505969	32.50770671	0.001328449	0.001336	0.001343572
32.50423129	32.505969	32.50770671	0.022644454	0.022717	0.022789573
32.50423129	32.505969	32.50770671	0.017315702	0.017372	0.017428323
32.50423129	32.505969	32.50770671	0.019979579	0.020044	0.020108447
32.50423129	32.505969	32.50770671	0.022644454	0.022717	0.022789573
32.50423129	32.505969	32.50770671	0.017315702	0.017372	0.017428323
32.50494227	32.50668	32.50841773	0.007990137	0.008018	0.008045886
32.50423129	32.505969	32.50770671	0.023976392	0.024053	0.024129635
39.99698904	39.998989	40.00098896	0.013318889	0.013363	0.013407136
39.99059726	39.992597	39.99459674	0.019979579	0.020044	0.020108447
39.99130723	39.993307	39.99530677	0.019979579	0.020044	0.020108447
39.99130723	39.993307	39.99530677	0.006657201	0.006681	0.006704822
39.98988728	39.991887	39.99388672	0.005325262	0.005345	0.00536476
39.99059726	39.992597	39.99459674	0.014650827	0.014699	0.014747197
39.99059726	39.992597	39.99459674	0.013318889	0.013363	0.013407136
39.99059726	39.992597	39.99459674	0.010654014	0.01069	0.010726009
39.99059726	39.992597	39.99459674	0.003993324	0.004009	0.004024698
39.99130723	39.993307	39.99530677	0.013318889	0.013363	0.013407136
39.99059726	39.992597	39.99459674	0.005325262	0.005345	0.00536476
39.99130723	39.993307	39.99530677	0.007990137	0.008018	0.008045886
39.99059726	39.992597	39.99459674	0.007990137	0.008018	0.008045886
39.99059726	39.992597	39.99459674	0.005325262	0.005345	0.00536476

39.99059726	39.992597	39.99459674	0.027973205	0.028062	0.028150822
39.99130723	39.993307	39.99530677	0.025308331	0.025389	0.025469696
39.98988728	39.991887	39.99388672	0.002661385	0.002673	0.002684637
39.99130723	39.993307	39.99530677	0.003993324	0.004009	0.004024698
39.99130723	39.993307	39.99530677	0.006657201	0.006681	0.006704822
39.99059726	39.992597	39.99459674	0.005325262	0.005345	0.00536476
39.99130723	39.993307	39.99530677	0.005325262	0.005345	0.00536476
39.99130723	39.993307	39.99530677	0.021311518	0.02138	0.021448508
39.99130723	39.993307	39.99530677	0.009322075	0.009354	0.009385948
39.99059726	39.992597	39.99459674	0.009322075	0.009354	0.009385948
39.98988728	39.991887	39.99388672	0.003993324	0.004009	0.004024698
39.99059726	39.992597	39.99459674	0.021311518	0.02138	0.021448508
39.99130723	39.993307	39.99530677	0.007990137	0.008018	0.008045886
39.99059726	39.992597	39.99459674	0.019979579	0.020044	0.020108447
39.98988728	39.991887	39.99388672	0.007990137	0.008018	0.008045886
39.99059726	39.992597	39.99459674	0.023976392	0.024053	0.024129635

D3. Test 1: Output Voltage and Error Bars, Output Current and Error Bars

Vout low [V]	Vout [V]	Vout high [V]	Iout low [A]	Iout [A]	Iout high [A]
22.58059963	22.58199	22.58338037	0.017172395	0.01718255	0.017192705
22.59731905	22.59871	22.60010095	0.017176904	0.01718706	0.017197216
45.15957934	45.16176	45.16394066	0.03431889	0.03433419	0.03434949
45.14298992	45.14517	45.14735008	0.03431789	0.03433319	0.03434849
68.20878259	68.21177	68.21475741	0.051849919	0.05187048	0.051891041
68.19556305	68.19855	68.20153695	0.05184491	0.05186547	0.05188603
90.75967328	90.76345	90.76722672	0.068989645	0.06901535	0.069041055
90.739084	90.74286	90.746636	0.068990525	0.06901623	0.069041935
113.2817047	113.29567	113.3096353	0.086122254	0.0861531	0.086183946
113.2641153	113.27808	113.2920447	0.086114736	0.08614558	0.086176424
135.8860935	135.90085	135.9156065	0.103163383	0.10334606	0.103528737
135.8686241	135.88338	135.8981359	0.103159496	0.10334217	0.103524844
158.9457564	158.96132	158.9768836	0.120680388	0.12087709	0.121073792
158.9355267	158.95109	158.9666533	0.120681647	0.12087835	0.121075053
181.555355	181.57171	181.588065	0.137857755	0.13806821	0.138278665
181.5353857	181.55174	181.5680943	0.137851251	0.1380617	0.138272149
204.0256985	204.04284	204.0599815	0.154933594	0.15515772	0.155381846
204.0097291	204.02687	204.0440109	0.154927339	0.15515146	0.155375581
226.5645196	226.58245	226.6003804	0.172059402	0.17229724	0.172535078
226.5513001	226.56923	226.5871599	0.17204926	0.17228709	0.17252492
249.1022108	249.12093	249.1396492	0.189165796	0.18941733	0.189668864
249.0863613	249.10508	249.1237987	0.189164917	0.18941645	0.189667983
272.1315647	272.15109	272.1706153	0.206657402	0.20692294	0.207188478
272.1164652	272.13599	272.1555148	0.20664752	0.20691305	0.20717858
294.7093145	294.72963	294.7499455	0.223804123	0.22408339	0.224362657

294.6918451	294.71216	294.7324749	0.22378272	0.22406197	0.22434122
317.2674749	317.28858	317.3096851	0.241092102	0.24138521	0.241678318
317.2498855	317.27099	317.2920945	0.241125385	0.24141852	0.241711655
339.7729772	339.79487	339.8167628	0.258231659	0.25853849	0.258845321
339.7565078	339.7784	339.8002922	0.258241052	0.25854789	0.258854728
228.2228916	228.24088	228.2588684	0.074441619	0.07446896	0.074496301
22.60218887	22.60358	22.60497113	0.017185421	0.01719558	0.017205739
45.16007932	45.16226	45.16444068	0.034341053	0.03435636	0.034371667
45.14709978	45.14928	45.15146022	0.034343182	0.03435849	0.034373798
68.21614233	68.21913	68.22211767	0.05187897	0.05189954	0.05192011
68.19905293	68.20204	68.20502707	0.051882469	0.05190304	0.051923611
90.76116323	90.76494	90.76871677	0.06904086	0.06906658	0.0690923
90.74345385	90.74723	90.75100615	0.069035971	0.06906169	0.069087409
113.2835746	113.29754	113.3115054	0.086183476	0.08621434	0.086245204
113.2662352	113.2802	113.2941648	0.086177717	0.08620858	0.086239443
135.898323	135.91308	135.927837	0.103242969	0.10342571	0.103608451
135.8797337	135.89449	135.9092463	0.103230709	0.10341344	0.103596171
158.956356	158.97192	158.987484	0.120762363	0.12095913	0.121155897
158.9411365	158.9567	158.9722635	0.120747095	0.12094385	0.121140605
181.555225	181.57158	181.587935	0.137931347	0.13814186	0.138352373
181.5390056	181.55536	181.5717144	0.137924462	0.13813497	0.138345478
204.0289384	204.04608	204.0632216	0.155018066	0.15524226	0.155466454
204.011349	204.02849	204.045631	0.155014059	0.15523825	0.155462441
226.5661396	226.58407	226.6020004	0.172153637	0.17239155	0.172629463
226.5486802	226.56661	226.5845398	0.172145873	0.17238378	0.172621687
249.1044507	249.12317	249.1418893	0.189287569	0.1895392	0.189790831
249.0852414	249.10396	249.1226786	0.189279555	0.18953118	0.189782805
272.1251949	272.14472	272.1642451	0.206791185	0.20705683	0.207322475
272.1140953	272.13362	272.1531447	0.206778045	0.20704368	0.207309315
294.7075645	294.72788	294.7481955	0.223941913	0.22422129	0.224500667
294.6908451	294.71116	294.7314749	0.223927015	0.22420638	0.224485745
317.265975	317.28708	317.308185	0.24106907	0.24136216	0.24165525
317.2496355	317.27074	317.2918445	0.241062815	0.2413559	0.241648985
339.7733472	339.79524	339.8171328	0.258170838	0.25847762	0.258784402
339.7551378	339.77703	339.7989222	0.258163204	0.25846998	0.258776756
228.8502096	228.86822	228.8862304	0.075169351	0.07519691	0.075224469
22.59918898	22.60058	22.60197102	0.017176284	0.01718644	0.017196596
45.15832938	45.16051	45.16269062	0.034333665	0.03434897	0.034364275
45.14460986	45.14679	45.14897014	0.034326527	0.03434183	0.034357133
68.21040253	68.21339	68.21637747	0.051867823	0.05188839	0.051908957
68.19568305	68.19867	68.20165695	0.051861685	0.05188225	0.051902815
90.75717337	90.76095	90.76472663	0.069021326	0.06904704	0.069072754
90.7419539	90.74573	90.7495061	0.069025335	0.06905105	0.069076765
113.2824546	113.29642	113.3103854	0.086166201	0.08619706	0.086227919
113.2648552	113.27882	113.2927848	0.086158183	0.08618904	0.086219897
135.8934532	135.90821	135.9229668	0.103222196	0.10340492	0.103587644
135.8752339	135.88999	135.9047461	0.103215192	0.10339791	0.103580628
158.9522361	158.9678	158.9833639	0.120748224	0.12094498	0.121141736
158.9342768	158.94984	158.9654032	0.120737832	0.12093458	0.121131328
181.5526051	181.56896	181.5853149	0.137925341	0.13813585	0.138346359
181.5357657	181.55212	181.5684743	0.137925841	0.13813635	0.138346859

204.0264385	204.04358	204.0607215	0.155023822	0.15524802	0.155472218
204.0097291	204.02687	204.0440109	0.155018316	0.15524251	0.155466704
226.5643996	226.58233	226.6002604	0.172152508	0.17239042	0.172628332
226.5470602	226.56499	226.5829198	0.172153637	0.17239155	0.172629463
249.1033307	249.12205	249.1407693	0.18928594	0.18953757	0.1897892
249.0854914	249.10421	249.1229286	0.189279805	0.18953143	0.189783055
272.1323047	272.15183	272.1713553	0.206786928	0.20705257	0.207318212
272.1132154	272.13274	272.1522646	0.206778425	0.20704406	0.207309695
294.7075645	294.72788	294.7481955	0.223927514	0.22420688	0.224486246
294.6898551	294.71017	294.7304849	0.223914005	0.22419336	0.224472715
317.2667249	317.28783	317.3089351	0.24104479	0.24133786	0.24163093
317.2500055	317.27111	317.2922145	0.24101926	0.24131231	0.24160536
339.7717272	339.79362	339.8155128	0.258120029	0.25842677	0.258733511
339.7558878	339.77778	339.7996722	0.258104761	0.25841149	0.258718219

D4. Test 1: Input Power and Error Bars, Output Power and Error Bars

Pin low [W]	Pin [W]	Pin high [W]	Pout low [W]	Pout [W]	Pout high [W]
0.066472553	0.0667666	0.067061222	0.387762981	0.388016172	0.388269391
0.199680551	0.200388702	0.201097509	0.388151977	0.388405385	0.38865882
0.432722334	0.434154857	0.435588175	1.549826624	1.550592449	1.55135834
0.066508462	0.066802667	0.067097447	1.549212164	1.549977699	1.550743301
0.366126669	0.36735219	0.368578466	3.536619842	3.538177252	3.539734783
0.133075432	0.133576548	0.134078278	3.535592853	3.537149849	3.538706968
0.133075432	0.133576548	0.134078278	6.261477676	6.264071269	6.266665056
0.56588875	0.567735199	0.569582524	6.260137055	6.262730097	6.265323332
0.366137071	0.367362626	0.368588936	9.756075749	9.760773187	9.765471486
0.565872673	0.56771907	0.569566343	9.753709421	9.758405903	9.763103246
0.133079213	0.133580343	0.134082087	14.01846913	14.0448174	14.07117106
0.4992789	0.500918301	0.502558537	14.01613882	14.04248336	14.06883328
0.499293085	0.500932532	0.502572815	19.1816356	19.21478178	19.24793409
0.066508462	0.066802667	0.067097447	19.18060118	19.21374549	19.24689592
0.266238065	0.267153095	0.268068821	25.02881373	25.06928099	25.10975513
0.565872673	0.56771907	0.569566343	25.02487995	25.06534186	25.10581066
0.532593591	0.53433655	0.536080364	31.6104347	31.65882184	31.70721666
0.632441533	0.634494849	0.63654908	31.60668442	31.65506676	31.70345678
0.46600771	0.467543695	0.469080495	38.98255581	39.03953077	39.09651426
0.56588875	0.567735199	0.569582524	38.9779836	39.03495332	39.09193156
0.632441533	0.634494849	0.63654908	47.12161802	47.18782141	47.25403421
0.53256333	0.53430619	0.536049906	47.11840083	47.18459993	47.25080845
0.599174126	0.601124037	0.603074844	56.23800207	56.31430367	56.39061563
0.133079213	0.133580343	0.134082087	56.23219257	56.30848771	56.38479321
0.266253193	0.267168275	0.268084052	65.95715975	66.04401462	66.13088085
0.4992789	0.500918301	0.502558537	65.94694278	66.03378715	66.12064287
0.099791002	0.100188658	0.10058691	76.49068237	76.58877051	76.68687103
0.199674878	0.20038301	0.201091797	76.49700084	76.59509284	76.69319722
0.499293085	0.500932532	0.502572815	87.74013965	87.8500526	87.95997898
0.399412045	0.400741028	0.402070786	87.73907788	87.84898839	87.95891233

0.822825546	0.825492386	0.828160387	16.98928161	16.99686096	17.0044413
0.173097345	0.173748205	0.174399857	0.388428139	0.388681668	0.388935226
0.303013525	0.304067485	0.305122311	1.550844682	1.551610863	1.552377111
0.562833573	0.564693693	0.566554828	1.550495085	1.551261085	1.552027153
0.216391936	0.217177129	0.21796314	3.538983211	3.540541466	3.542099844
0.216387203	0.217172379	0.217958372	3.538335255	3.53989321	3.541451288
0.692714506	0.694977617	0.697241816	6.266228766	6.26882399	6.271419408
0.606140475	0.608134969	0.610130502	6.264562493	6.267157067	6.269751835
0.649435067	0.651563894	0.653693784	9.763172197	9.767872635	9.772573934
0.822627844	0.825294047	0.827961411	9.76102561	9.765725184	9.77042562
0.086508163	0.086890356	0.087273293	14.03054641	14.0569068	14.08327258
0.303006897	0.304060834	0.305115638	14.02696128	14.05331669	14.07967749
0.173089778	0.173740609	0.174392234	19.19594511	19.22910514	19.26227129
0.692729658	0.694992818	0.697257066	19.1916805	19.22483528	19.25799619
0.08650627	0.086888455	0.087271384	25.04215665	25.08263578	25.1231218
0.129802754	0.13031928	0.130836575	25.03866968	25.07914421	25.11962562
0.822645838	0.825312099	0.827979521	31.62817148	31.6765746	31.72498542
0.865940429	0.868741023	0.871542803	31.62462737	31.67302574	31.72143179
0.303013525	0.304067485	0.305122311	39.00418489	39.06117903	39.11818171
0.649435067	0.651563894	0.653693784	38.99942032	39.05640865	39.11340552
0.562845884	0.564706045	0.56656722	47.15237581	47.21860634	47.2848463
0.562833573	0.564693693	0.566554828	47.14674366	47.21296748	47.27920073
0.043180221	0.043427975	0.043676448	56.2730914	56.34942302	56.42576502
0.736040556	0.738438098	0.740836752	56.26722066	56.34354614	56.41988198
0.562833573	0.564693693	0.566554828	65.99737577	66.08426545	66.17116649
0.649420862	0.651549643	0.653679487	65.98924126	66.07612233	66.16301475
0.736040556	0.738438098	0.740836752	76.48301361	76.58109497	76.6791887
0.562833573	0.564693693	0.566554828	76.47709029	76.575165	76.67325208
0.259718934	0.26063856	0.261559029	87.71956974	87.82946492	87.93937354
0.7793342	0.781866072	0.784399082	87.71227496	87.82216215	87.93206277
0.532715441	0.53450649	0.536298684	17.20252172	17.21018294	17.21784516
0.798995303	0.801611614	0.804229215	0.38817009	0.388423512	0.388676963
0.799009488	0.801625846	0.804243493	1.550450967	1.551217003	1.551983106
0.266230173	0.267195284	0.268161394	1.54965769	1.550423387	1.551189151
0.212956641	0.213756636	0.214557601	3.537925118	3.539482984	3.541040972
0.585895334	0.587851183	0.589808206	3.536743055	3.538300447	3.539857961
0.532630309	0.534421074	0.536212983	6.26418044	6.266774945	6.269369645
0.42606039	0.427520862	0.42898242	6.263493738	6.26608794	6.268682335
0.159695397	0.160330321	0.160966187	9.761118742	9.765818313	9.770518745
0.532639765	0.534430561	0.536222502	9.758694158	9.763392748	9.7680922
0.212960422	0.213760431	0.21456141	14.02722067	14.05357758	14.07993989
0.319536013	0.320666336	0.321797686	14.02438831	14.05074096	14.077099
0.319530341	0.320660643	0.321791973	19.19320022	19.22635739	19.25952069
0.212960422	0.213760431	0.21456141	19.18938006	19.22253214	19.25569035
1.118665191	1.122272257	1.125880788	25.04070502	25.08118262	25.12166711
1.01211324	1.015390071	1.018668309	25.03847314	25.07894719	25.11942813
0.106428482	0.106898314	0.107369058	31.6289582	31.67736179	31.72577307
0.159698232	0.160333168	0.160969045	31.62524464	31.67364341	31.72204985
0.266230173	0.267195284	0.268161394	39.00362954	39.06062303	39.11762506
0.212960422	0.213760431	0.21456141	39.00090032	39.0578898	39.11488782
0.212964202	0.213764226	0.21456522	47.1517581	47.21798799	47.2842273

0.852275459	0.855056904	0.857839668	47.1468532	47.21307714	47.27931051
0.372801984	0.374097394	0.375393861	56.27340328	56.34973583	56.42607876
0.372795365	0.374090752	0.375387197	56.26714203	56.34346735	56.41980304
0.159692561	0.160327475	0.16096333	65.99313243	66.08001842	66.16691577
0.852260328	0.855041724	0.857824439	65.98518579	66.07206324	66.15895204
0.319536013	0.320666336	0.321797686	76.47549099	76.5735659	76.67165317
0.798995303	0.801611614	0.804229215	76.46336161	76.56142445	76.65949966
0.319524668	0.32065495	0.32178626	87.70188794	87.81176768	87.92166085
0.958830247	0.961941936	0.965055002	87.69261215	87.8024824	87.91236608

D5. Test 2: Input Voltage and Error Bars, Input Current and Error Bars

Vin low [V]	Vin [V]	Vin high [V]	Iin low [A]	Iin [A]	Iin high [A]
0.973608791	0.973645	0.973681209	0.621475263	0.623371	0.625266891
0.973608791	0.973645	0.973681209	0.621475263	0.623371	0.625266891
4.841802161	4.841949	4.842095839	3.045443085	3.054718	3.063993582
4.850323991	4.850471	4.850618009	3.015467882	3.024652	3.033836781
9.688626223	9.68887	9.689113777	6.052303043	6.070686	6.089069986
9.676553464	9.676797	9.677040536	6.053635008	6.072022	6.090410021
14.50343434	14.504542	14.50564966	9.095136035	9.122736	9.15033736
14.50485529	14.505963	14.50707071	9.080481425	9.108037	9.135593968
19.33101137	19.332288	19.33356463	12.14989308	12.187479	12.22507108
19.32106972	19.322346	19.32362228	12.15388991	12.191488	12.22909225
24.13657417	24.138019	24.13946383	15.1813579	15.228172	15.2749929
24.11597989	24.117424	24.11886811	15.16403962	15.210801	15.25756918

D6. Test 2: Input Power and Error Bars

Pin low [W]	Pin [W]	Pin high [W]
0.605073779	0.606942057	0.608810623
0.605073779	0.606942057	0.608810623
14.74543291	14.79078877	14.83615057
14.62599621	14.67098681	14.71598333
58.63850196	58.81808746	58.99769189
58.57832281	58.75772427	58.93714465
131.9107083	132.3211075	132.731588
131.711069	132.1208477	132.5307077
234.8697213	235.611854	236.3542018
234.8261544	235.5681494	236.3103594
366.4259709	367.5779051	368.7301386
365.6956744	366.8453371	367.9952987

Appendix E Solar Micro-Inverter Test Data Analysis Code

```
%% Solar Micro-Inverter Data

close all; clc; clear all;

%% real data taken by Alex Trubitsyn

%Measurement equipment used is NOT 4 Agilent 34401A and
current shunt.
%Therefore error analysis is not correct!!
%Error is calculated here just to test the code.
%Only 4 of the average power values were tested. For CEC
Efficiency
%calculations, 10% and 20% data was conglomerated with 30%

Vin=[34 34 34 34 25 25,...
    34 34 34 34 25 25,...
    25 25 34 34 34 34,...
    25 25 25 25 34 34,...
    34 34 25 25 25 25]';

Iin=[9.74 8.79 5.41 1.65 7.13 2.22,...
    7.63 6.86 4.14 1.21 11.2 9.39,...
    5.6 1.67 5.46 4.85 2.82 0.663,...
    8.13 6.89 3.93 1.01 3.45 2.97,...
    1.46 0.646 5.66 4.71 2.42 0.572]';

Vout=[333.66 314.69 240.53 130 240.53 130.26,...
    333.54 314.56 240.42 130.18 333.58 314.57,...
    240.43 130.19 333.39 314.42 240.3 130.09,...
    333.44 314.44 240.32 130.11 333.27 314.28,...
    240.19 130.08 333.33 314.33 240.22 130.47]';

Iout=[0.919 0.879 0.7 0.383 0.687 0.385,...
    0.725 0.689 0.538 0.276 0.788 0.703,...
    0.542 0.289 0.519 0.487 0.363 0.14,...
    0.578 0.517 0.38 0.169 0.321 0.291,...
    0.177 0.128 0.4 0.351 0.229 0.0833]';

avgp=[100 100 100 100 100 100,...
```

```
    75 75 75 75 75 75,...
    75 75 50 50 50 50,...
    50 50 50 50 30 30,...
    30 30 30 30 30 30]';

%% calculate input and output power, and efficiency
Pin = Vin.*Iin;
Pout = Vout.*Iout;
eff = Pout./Pin;

%% add error bars
vin_error=vget_errorbars(Vin);
iin_error=iget_errorbars_input(Iin);

vout_error=vget_errorbars(Vout);
iout_error=iget_errorbars_output(Iout);


for i=1:length(Pin)

pin_error(i,:)=interval_multiply(vin_error(i,:),iin_error(i
,:));

pout_error(i,:)=interval_multiply(vout_error(i,:),iout_erro
r(i,:));
end

for j=1:length(Pin)
    eff_error(j,:)=interval_divide(pout_error(j,:),
pin_error(j,:));
end

% reformat to be consistent
powerin_meas=Pin;
powerin_error_meas=pin_error;
powerout_meas=Pout;
powerout_error_meas=pout_error;


%% plots

format long;
counter=[1:1:30]';
figure(1)
grid on; hold on;
errorbar(counter, Pout,...
    Pout-pout_error(:,1),pout_error(:,2)-Pout,'ro-');
```

```
errorbar(counter, Pin, ...
    Pin-pin_error(:,1),pin_error(:,2)-Pin,'bd-');
xlabel('Sample Number');
title ('Input and Outpout Power with Error Bars');
ylabel('Power [W]'); hold off;
legend('Output Power', 'Input Power');

figure(2)
errorbar(counter, eff, ...
    eff-eff_error(:,1), eff_error(:,2)-eff, 'bd-');
xlabel('Sample Number');
ylabel('Nominal Efficiency');
title('Efficiency with Error Bars');
grid on;

figure(3)
errorbar(counter, Vin, ...
    Vin-vin_error(:,1), vin_error(:,2)-Vin, 'bd-');
xlabel('Sample Number');
ylabel('Nominal Input Voltage');
title('Vin with Error Bars');
grid on;

figure(4)
errorbar(counter, Iin, ...
    Iin-iin_error(:,1), iin_error(:,2)-Iin, 'bd-');
xlabel('Sample Number');
ylabel('Nominal Input Current');
title('Iin with Error Bars');
grid on;

figure(5)
errorbar(counter, Vout, ...
    Vout-vout_error(:,1), vout_error(:,2)-Vout, 'bd-');
xlabel('Sample Number');
ylabel('Nominal Output Voltage');
title('Vout with Error Bars');
grid on;

figure(6)
errorbar(counter, Iout, ...
    Iout-iout_error(:,1), iout_error(:,2)-Iout, 'bd-');
xlabel('Sample Number');
ylabel('Nominal Output Current');
title('Iout with Error Bars');
grid on;
```

```
%% CEC Efficiency Calculation

avgpower_levels=[100 75 60 50 30];
efficiencies = zeros(length(avgpower_levels),1);
efficiencies_error = zeros(length(avgpower_levels),2);

Vpeak=240*sqrt(2);%240 rms
theta=asin(Vout./Vpeak);


numptsperavgp=6; %length(voltsin)*length(voltsout)


for k = 1:length(avgpower_levels)
    avgpower_amplitude = avgpower_levels(k);

    %calculate the start and stop bounds
    %powerin_meas, etc appends new measurements, so pull
out data of
    %interest
    start=(k-1)*numptsperavgp+1;% # distinct Pins
    stop=k*numptsperavgp;


    % extract # of distinct measurements per avg power
level, sorts that
    % interval
    theta_k = theta(start:stop);
    powerin_error_meas_k =
powerin_error_meas(start:stop,:);
    powerout_error_meas_k =
powerout_error_meas(start:stop,:);
    powerin_meas_k = powerin_meas(start:stop);
    powerout_meas_k = powerout_meas(start:stop);

    [theta_k,ind] = sort(theta_k);
    powerin_error_meas_k = powerin_error_meas_k(ind,:);
    powerout_error_meas_k = powerout_error_meas_k(ind,:);
    powerin_meas_k = powerin_meas_k(ind);
    powerout_meas_k = powerout_meas_k(ind);


    in=trapz(theta_k,powerin_meas_k);
    in_error1=trapz(theta_k,powerin_error_meas_k(:,1));
    in_error2=trapz(theta_k,powerin_error_meas_k(:,2));
    in_error=[in_error1 in_error2];
```

```
    out=trapz(theta_k,powerout_meas_k);
    out_error1=trapz(theta_k,powerout_error_meas_k(:,1));
    out_error2=trapz(theta_k,powerout_error_meas_k(:,2));
    out_error=[out_error1 out_error2];

    effavgp=out./in; %stores efficiencies for each avg
power level
    effavgp_error=interval_divide(out_error, in_error);

    efficiencies(k) = effavgp;
    efficiencies_error(k,:) = effavgp_error;

end

%average powers =
%        [0.01 0.02 0.03 0.05 0.75 1.00];
%weights=[0.04 0.05 0.12 0.21 0.53 0.05];

%partial weights because partial data
weights=[0.05 0.53 0.11 0.21 0.10]; %[0.21 0.21 0.53 0.05];
CECeff=dot(weights,efficiencies')


%% Calculate Error Bounds on CEC Efficiency

CECefflow=weights.*efficiencies_error(:,1)';
CECeffhigh=weights.*efficiencies_error(:,2)';
CECefferror=[sum(CECefflow) sum(CECeffhigh)]
```

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