Identification of Individual Contributions to Total Flicker Levels in Electric Power Systems

by

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Abstract

Total flicker levels in an electric power system can be contributed to from multiple sources of flicker. Methodologies for allocating portions of this total flicker level to the responsible loads are studied. The representation of flicker is expanded upon for data generation purposes. Software necessary to both generate and measure the necessary data is developed. A digital IEEE 1453 flickermeter is examined and implemented as a tool to analyze the total flicker level in an electric power system. Techniques for identifying individual contributions to total flicker levels are proposed, tested, and analyzed. The two methodologies explored are examination of the line current and voltage difference. Test scenarios compare sources of no flicker, single sources of flicker, and multiple sources of flicker. Tests range across both lab tests and computer simulations. The results show evidence of possible statistical correlation across a range of testing scenarios and identification methodologies for purely resistive line impedance. Use of more practical RL line impedance appears to discredit the possibility of correlation for certain identification methodologies.

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Chapter 1

Introduction

Flicker is the term used to describe voltage fluctuations in AC power systems that are significant enough to cause disturbance. The disturbance is most notably of visual or perceived nature stemming from lighting systems but it can sometimes affect equipment operation [1]. Flicker can be caused by many sources. This is often from industrial facilities that use large induction machines and non-linear, time-varying loads such as arc welding furnaces [1]. Cyclic flicker can be represented in the form of rectangular amplitude modulation. Flicker severity cannot exceed a certain level without disturbing other loads on the power system. This severity depends largely on the regularity of voltage fluctuations and the magnitude of voltage change. The frequency range of the phenomenon is very important as the human eye is most susceptible to flicker in the frequency range of 5-10Hz while the typical observable range is 0.5-30Hz [1]. Though flicker is described in terms of voltage fluctuations, analysis of fluctuations in the current will also be explored.

In large power systems there are often multiple sources of flicker. The problem arises when trying to detect how much of the total flicker level an individual load is responsible for. Such a system can be seen in Figure 1.

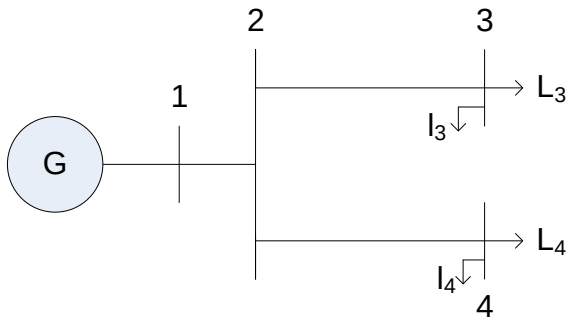

Figure 1: Example Power System Diagram

Looking at the simple diagram in Figure 1 it becomes obvious that nodes within the system affect one another. Simple representations of the node voltages can be seen in (1), (2), and (3).Let [Z] be the bus impedance matrix. L_3 and L_4 represent high power loads that can generate flicker. I_3 and I_4 represent a residential consumer that would be affected by the generated flicker. $\overline{V}_2$, $\overline{V}_3$, and $\overline{V}_4$ are the respective node voltages.

$$\overline{V}_2=f_1([\overline{Z}], \overline{L}_3,\overline{L}_4) \quad (1)$$
$$\overline{V}_3=f_2([\overline{Z}], \overline{L}_3, \overline{V}_2) \quad (2)$$
$$\overline{V}_4=f_3([\overline{Z}], \overline{L}_4, \overline{V}_2) \quad (3)$$

The manner of influence is not as important as the simple fact that since nodes in a power system are interconnected the node voltages involved are functions of one another. Before examining an entire utility power system this problem can be scaled down to allow feasible testing and exploration of various

methodologies for analyzing flicker. The small scale problem used to represent the larger issue at hand can be seen in Figure 2.

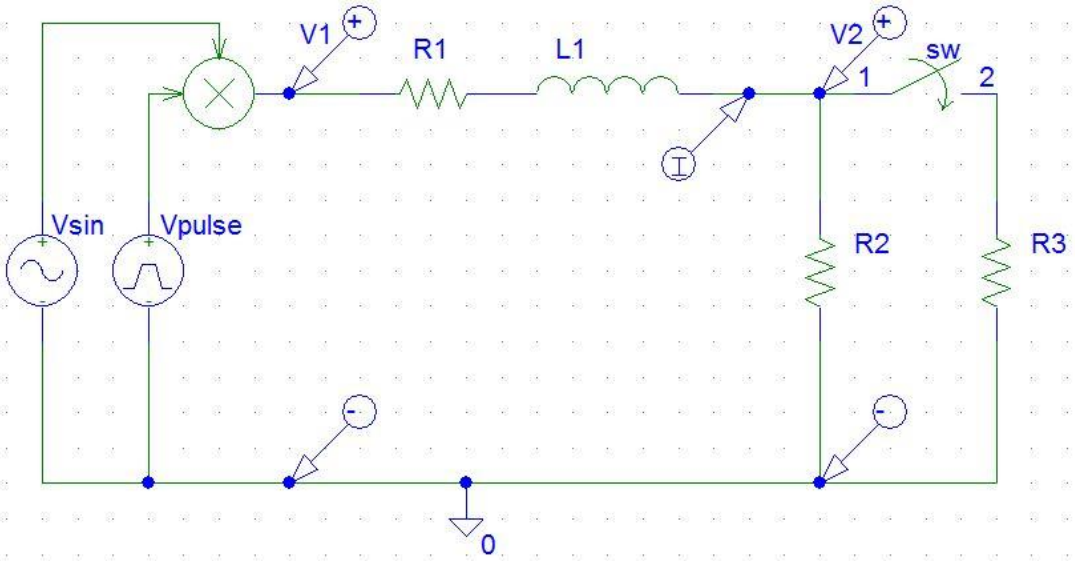

Figure 2: Simple Circuit Diagram of Small Scale Problem

This small scale problem reduces the system seen in Figure 1 from a large utility power system to one with just a source, line impedance, and a load impedance. The source will be able to generate a flicker signal defined as the time-domain voltage v_1 in Figure 2. The line impedance matrix has been reduced to an impedance defined as $R_1+j\omega L_1$. The load impedance needs to fluctuate so as to generate a flicker signal at the load. This can be accomplished by switching two impedances in parallel at a certain frequency. These resistances are defined as R_2 and R_3. The time-domain voltage v_2 at the load will then be affected by a combination of the source flicker, load flicker, and line impedance.

As flicker in one area of the power system could be caused from multiple other areas, methodologies that can be employed to allocate portions of the total flicker to the responsible individual sources would be extremely helpful. Proposed

methodologies include examining fluctuations in the line current. The results of subtracting the source and load voltages will be analyzed. Direct analysis of the voltage present at the source and load shall also be performed. This will allow for the statistical analysis of the results from a range of tested methodologies by using the implemented flickermeter to examine current, voltage difference, and standardized voltage flicker signals. It is important to examine, analyze, and compare various configurations of flicker sources within the system. The proposed problem and test setup provides for this eventuality by allowing for regulation of flicker generation at both the source and load.

With multiple sources of flicker present within the small scale problem it is necessary to examine how to go about measuring and analyzing this phenomenon. Standards for measurement of flicker exist both in the US and Europe. These are the IEEE 1453 [2] and IEC 61000-4-15 Ed. 2 [4] standards respectively. There are both hardware and software concerns with constructing the measurement instrument specified by these standards. The flickermeter that will be proposed is a digital implementation using MATLAB and Simulink similar to that explored in [3]. There are other possible implementations of the flickermeter such as those explored in [5], [6], and [7]. Hardware devices necessary include National Instruments DAQ cards, computer hardware, and other equipment in the lab. This setup and digital implementation allows for the measurement, data storage, and analysis of the current and both relevant voltages in the test system.

The flickermeter itself is designed to manipulate and analyze a data signal spanning a set amount of time. The first part of the flickermeter is designed to simulate the lamp-eye-brain chain response. The second part of the flickermeter is for statistical analysis of flicker and providing the corresponding results [2]. Short-term flicker severity, P_{st} , is the ultimate output of the flickermeter. The flickermeter's process of determining P_{st} provides other meaningful data in the form of P_{inst} (instantaneous flicker sensation), which can be examined with several statistical methods. The results of node voltage and current analysis from a system that has multiple sources of flicker may provide insight into finding the portion of flicker disturbance for which each source is responsible.

In Chapter 2 the representation of flicker is explored along with designing and testing means to gather data. Next, in Chapter 3, design and implementation of the digital flickermeter is presented. The method of testing and results obtained are presented and analyzed in Chapter 4, followed by conclusions and implications of future research in Chapter 5.

Chapter 2

Data Generation and Gathering

The first step in solving the problem presented in the Introduction is being able to generate a flicker waveform. As such it is necessary to expand upon the representation of flicker. After generating data to act as input into the system it will be necessary to measure and gather data from the points of interest within said system. The means of gathering this data should be tested and function properly so as not to corrupt or influence the results obtained from the measurement.

2.1 Flicker Waveform Generation

For the purpose of testing the initial flickermeter model, “perfect” data will be generated to use as input to the model as opposed to real sampled data. The representation is that of rectangular amplitude modulation of a sinusoidal waveform. As is standard in the United States the combination of r.m.s. voltage and utility frequency examined is 120 V_{ac}/60 Hz. Equation (6) can be used to generate the voltage fluctuation waveform.

$$v(t)=170\cdot\sin(2\cdot\pi\cdot60\cdot t)\cdot\left\{1+\frac{\Delta V}{V}\cdot0.5\cdot\text{signum}[\sin(2\cdot\pi\cdot f_f\cdot t)]\right\} \quad (4)$$

Where $\Delta V/V$ (%) is the relative voltage change for unit flicker severity and f_f (Hz) is the fluctuation frequency. These values are taken from the IEEE Standard table of rectangular voltage fluctuation test points shown in Table 1 [2]. The test points provided will generate a flicker waveform that produces a unit flicker severity result (P_{st}=1) in a working flickermeter. Note that different average peak voltage levels are used in later testing as the voltage sampled by the DAQ card is normalized by the flickermeter.

Changes per minute	Fluctuation Frequenzy (Hz)	P_{st}=1 Relative voltage changes for unit flicker severity for 120 V_{ac} lamps $\Delta V/V$ (%)
0.1	0.000833	8.202
0.2	0.001667	5.232
0.4	0.003333	4.062
0.6	0.00500	3.645
1	0.00833	3.166
2	0.01667	2.568
3	0.02500	2.250
5	0.04167	1.899
7	0.05833	1.695
10	0.0833	1.499
22	0.1833	1.186
39	0.3250	1.044
38	0.4000	1.000
68	0.5667	0.939
110	0.9167	0.841
176	1.4667	0.739
273	2.2750	0.650
375	3.1250	0.594
480	4.0000	0.559
585	4.8750	0.501
682	5.6833	0.445
796	6.6333	0.393
1020	8.5000	0.350
1055	8.7917	0.351
1200	10.000	0.371
1390	11.583	0.438
1620	13.500	0.547
2400	20.000	1.051
2875	23.9583	1.49

Table 1: Rectangular Voltage Fluctuations for P_{st}=1 Test Points [2]

It is beneficial to examine a test point that will be used throughout later sections. Looking at Table 1 it can be seen which values correspond to 1620 changes per minute for a 120 V_{ac}/60 Hz system: $\Delta V/V$=0.547 % and f_f=13.5 Hz. To make the voltage fluctuation more visible $\Delta V/V$ has been scaled by a factor of 100. The resulting waveform for this scaled test point can be seen in Figure 3.

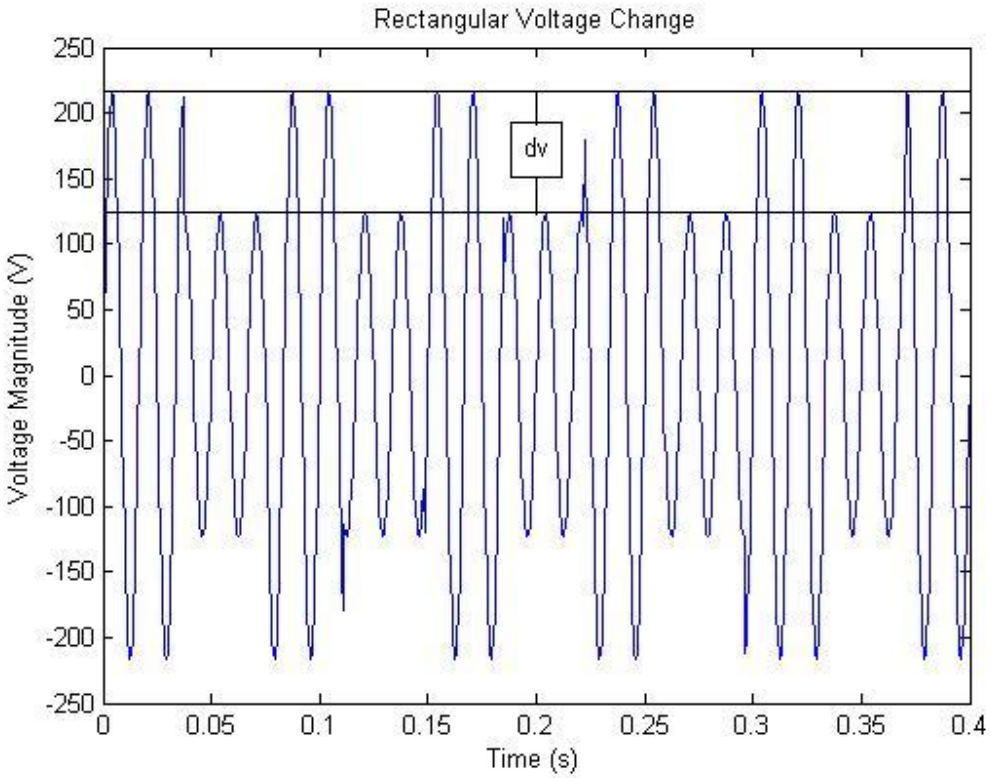

Figure 3: Rectangular Voltage Modulation for 1620 Changes per Minute Test Point [2]

From this plot it is possible to calculate that $\Delta v/v=93/170=0.547$ and that the two distinct rectangular voltage changes per period of 0.0741 seconds results in 27 changes per second, or 1620 changes per minute.

2.2 Sampling

After waveform generation the signal can be output through a DAQ card. For testing this signal will then be amplified, applied to the system, and then various data will be sampled from the system for analysis. The means for acquiring this data was accomplished with MATLAB and the Data Acquisition Toolbox. When generating data, sampling the data, and then writing it to hard-

disk, an important concern is the possibility of missed samples. Thus a method for checking the acquisition and file writing process was employed.

The process for checking for missed samples consists of comparing the approximate derivative of the sampled data to the maximum analytical derivative of the generated signal. For these tests a simple sine wave shown in (5) was used.

$$A\sin(\omega t) \tag{5}$$

Where A is the amplitude and $\omega=2\pi f$ with f being the frequency in Hz. From this it is easy to determine the analytical derivative and solve for the maximum value.

$$\frac{d}{dt}(A\sin(\omega t))=A\omega\cos(\omega t) \tag{6}$$

$$\max_t (A\omega\cos(\omega t)) = A\omega \tag{7}$$

Next it is necessary to calculate the approximate derivative from sampled data. This can be done by taking the difference between two sampled data points and dividing by the sample time, seen in (8), where **v** is a vector of sampled data points, T_s is the sample time, n is the number of samples in vector **v**, and **d** is the resulting vector of approximate derivatives.

$$d_k=\left|\frac{V_{k+1}-V_k}{T_s}\right| \text{ for } k=1,2,\cdots,n-1 \tag{8}$$

Now, compare the approximate and analytical derivatives. To do this find all $d_k>A\omega s$ with s being a scaling factor used to exclude measurement error from

the result. By using a range of scaling factors in vector **s**, the threshold for measurement error can also be examined.

$$\mathbf{s} = [1 \quad 1.025 \quad 1.05 \quad 1.075 \quad 1.1 \quad 1.125 \quad 1.15]$$

For analysis it will be helpful to represent the number of approximate derivatives that exceed the analytical derivative as a percentage of the total approximate derivatives.

With this information an actual test can be performed. The input signal $2.96\sin(116\pi t)$ will be sampled at a rate of 1920 samples per second by four different channels on the DAQ card simultaneously. Testing multiple channels simultaneously is necessary as in lab testing there will be three data channels. Every two seconds the data will be written to a file for a total of 200 seconds worth of data. This allows for testing of 100 data acquisition and file writing procedures. This test will be performed 5 times to allow for comparison. The results for two of these five tests are shown in Figures 4 and 5. The remaining tests were very nearly identical. It is also important to note that the largest approximate derivative calculated is only 18.58% greater than the maximum analytical derivative without using any scaling factor. This implies that even at this level the error isn't great enough to be attributed to missed samples.

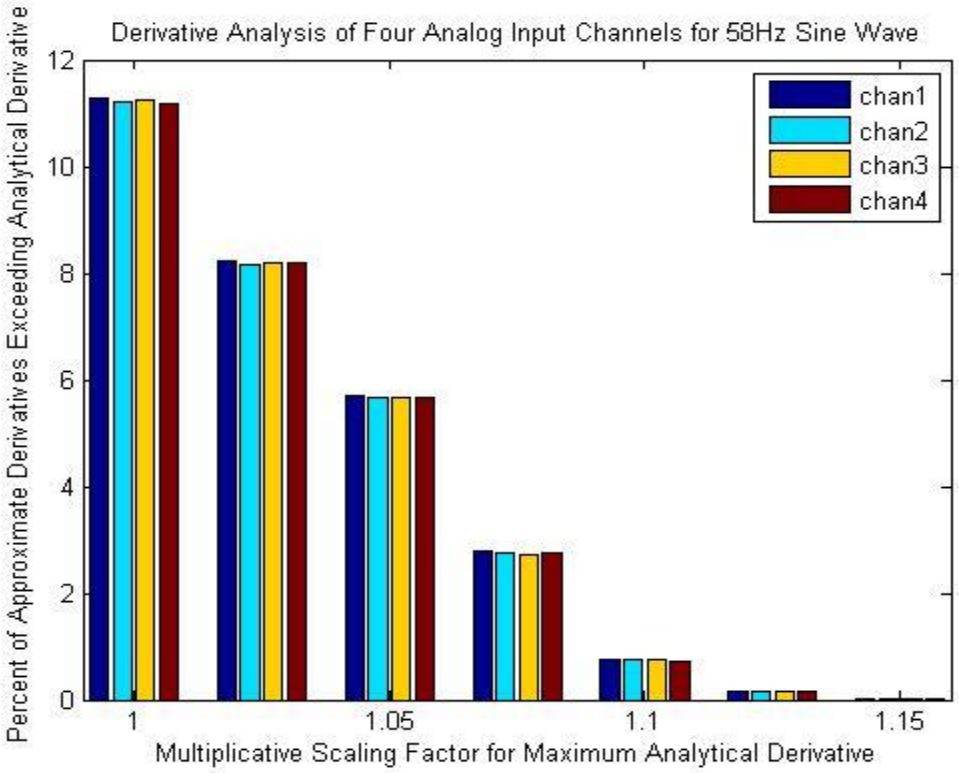

Figure 4: Results of First Round of Testing a 58Hz Sine Wave

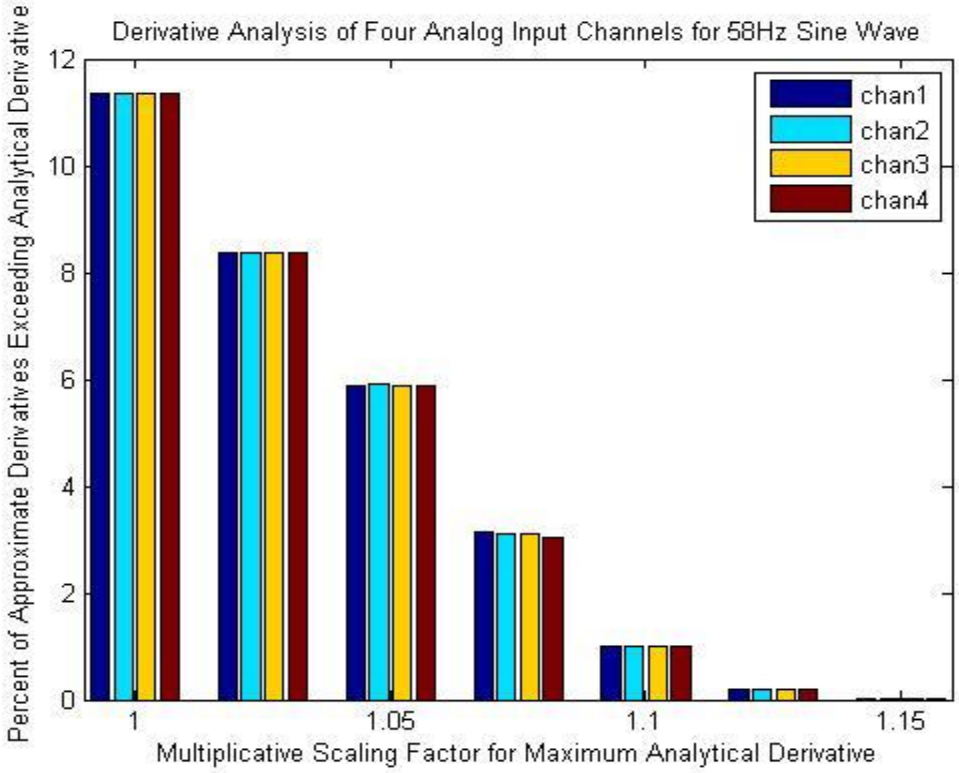

Figure 5: Results for Second Round of Testing a 58Hz Sine Wave

If a sample were missed then the distance between two sampled points would be twice the derivative of the sine wave at that point in time. Depending on when in the cycle this occurs it could cause an approximate derivative to be up to twice as large as the maximum analytical derivative; it's also possible that the resulting approximate derivative could be less than the maximum analytical derivative. If several samples were being missed in every cycle the percentage of approximate derivatives exceeding the analytical derivative would increase relative to the cyclic rate and depending on where in the cycle the sample is missed.

To expand on this point a simple test was run with 200 seconds of a 60Hz sine wave generated in Matlab with a sampling rate of 1920 samples per second. Then 1 random sample per cycle was removed to simulate it being missed in a sampling process. The previously described test was performed. For a scaling factor of 1.1 or less, 4.297% of the approximate derivatives exceeded the maximum analytical derivative. This value is lower than for measured data due to the fact that there is no measurement error with the generated data. For a scaling factor of 1.125 or greater, 3.516% of the approximate derivatives exceeded the maximum analytical derivative.

From these tests it can be concluded that there are no data samples being missed in the acquisition and writing processes. Each test is consistent with itself over a sufficient number of operations. For both tests there is a significantly small amount of approximate derivatives exceeding the maximum analytical derivative for a scaling factor of 10%. This implies that the error in approximate derivatives

in these cases is most likely due to measurement error. It should be noted that these conclusions are dependent upon using the same DAQ hardware and sampling rate tested in this section. If either of these is changed the tests should be repeated.

After examining the flicker waveform in greater detail, a work means of accurately generating a flicker signal was implemented and tested. With the ability to generate the necessary flicker signal and store measured data for analysis, it is possible to proceed to examining the tools for analyzing flicker.

Chapter 3

Flickermeter Design

The flickermeter design itself has several key components. The flickermeter design process is broken up into several sections represented by different “blocks” in the system. A general block diagram of the flickermeter is provided in Figure 6 [2].

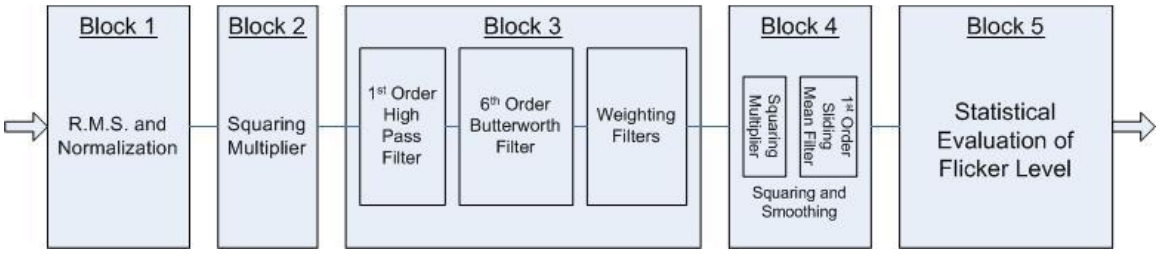

Figure 6: Block Diagram of IEC Flickermeter

The model of blocks 2, 3, and 4 correspond to the lamp-eye-brain chain response. Block 1 controls the r.m.s. calculation and normalization of the input voltage signal. Block 5 is responsible for the statistical evaluation necessary to calculate P_{st}.

As this is a digital implementation that will ultimately gather and process data the first consideration is that of sampling rate. It is important to sample fast enough to retain the integrity of the waveform but without obtaining too many

samples to practically handle in a ten minute span of data. The rate is also somewhat controlled by hardware limitations of the DAQ cards. For this implementation the rate of 1920 samples per second will be used. This is the equivalent of 32 samples per cycle (one complete period that repeats) in a 60 Hz system. Not only will this provide accuracy but the cyclic rate being a power of two will allow for relatively easy data manipulation in the future, such as Fourier Transforms. This could be helpful if other design alternatives that implement Fourier Transforms were explored such as in [5], [7], and [8].

3.1 Block 1 – R.M.S. and Normalization

Once a signal has been acquired for processing the next necessary step is normalization of the waveform. Through normalization the magnitude of the flickermeter input becomes a non-factor. Normally this normalization process is a simple matter of calculating the r.m.s. value, multiplying it by the square root of two, and dividing each sample in the time function by the result. To be able to use this simpler method it must be assumed that the r.m.s. value for the entire time function is constant. This is not the case for the problem at hand. It must be kept in mind that the ultimate goal is to examine a utility power system. Over the period of time required to sample enough data it is quite possible that the signal level could be altered by a percent significant enough to impact the resulting analysis. Such changes often occur during particularly high or low load times on a utility power system. Thus it is necessary to calculate an r.m.s. value

corresponding to every sample in the time function. For accurate calculation a full cycle worth of data must be used. Note that the resulting calculation is only valid at the point in time for which it is calculated. This leaves the first cycle without a "valid" r.m.s value; it is necessary to retroactively use the first calculated value for the entire first cycle.

After the r.m.s. calculation is completed it is necessary to filter the result to keep it at a constant reference level corresponding to the input. The only changes that should affect the calculation are magnitude shifts of a relatively permanent nature. Higher frequency changes will be filtered out to prevent modification of the flicker modulating fluctuation. This is necessary to follow any slow changes that occur during the measurement process. The filter has a 10% to 90% response time step variation equal to 1 minute. The IEEE 1453 standard stipulates these required specifications [2]. This is accomplished through the use of a 2nd order low-pass filter. The transfer function (9) was implemented where s is the Laplace complex variable. A step response of the implemented filter can be seen in Figure 7.

$$\frac{1}{336.3s^2+36.67s+1} \tag{9}$$

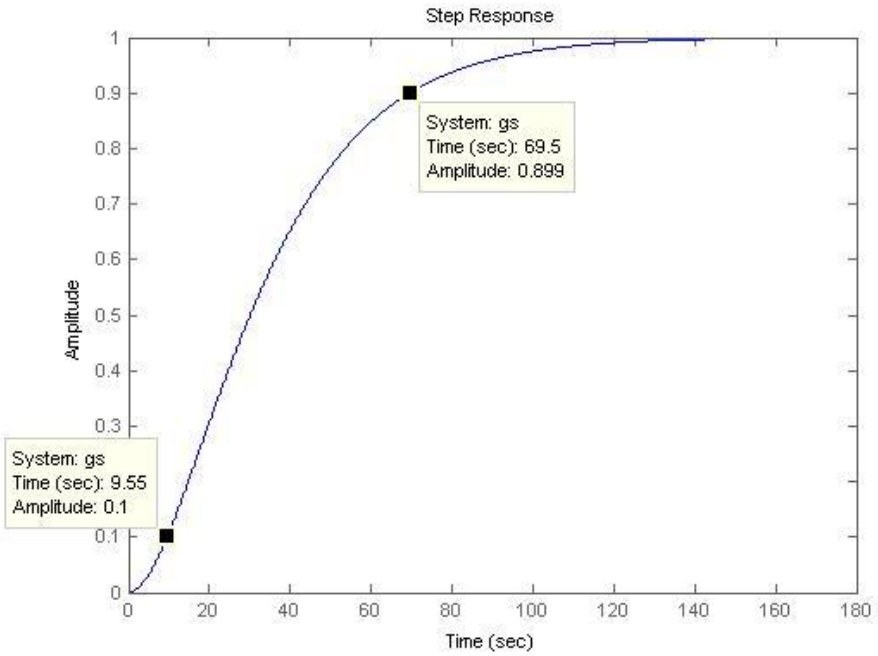

Figure 7: R.M.S. Filter Step Response

3.2 Blocks 2, 3, and 4 – Lamp-Eye-Brain Chain Response

This series of blocks is responsible for taking the normalized input waveform and manipulating it in such a way as to provide an accurate simulation of the human response to a visibly fluctuating light source. The combined non-linear response of blocks 2, 3, and 4 simulates human flicker sensation. The first component of this process, block 2, is a square law demodulator. By squaring the normalized input voltage the voltage fluctuation is recovered; this, when filtered, simulates the behavior of a lamp output (light) response. Implementation of this in Simulink is straightforward as math-function blocks are available.

Contained within block 3 is a series of two sets of filters. The purpose of the first set is to eliminate the d.c. and double mains frequency ripple components of the block 2 output [2]. This is accomplished through the use of a first order high-pass filter and a low-pass section implemented as a 6^{th} order Butterworth filter. The high-pass filter is suggested to have a 3 dB cut-off frequency of about 0.05 Hz. The transfer function (10) was implemented where s is the Laplace complex variable. A magnitude response of this filter can be seen in Figure 8.

$$\frac{s}{s+0.3142} \tag{10}$$

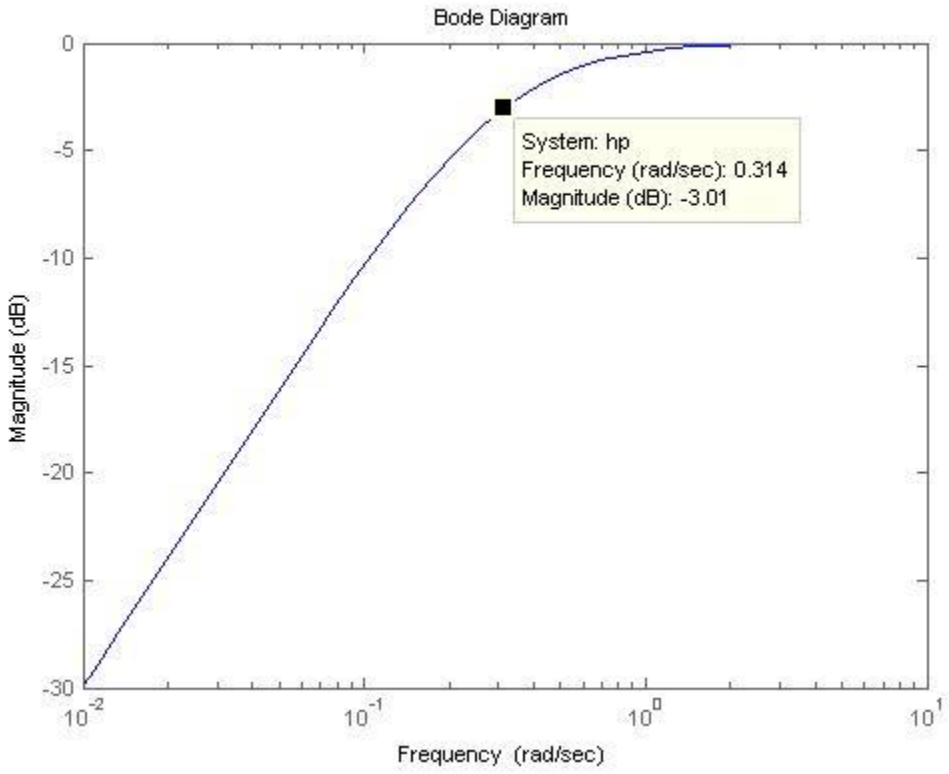

Figure 8: Bode Magnitude Plot of the Block 3 High-pass Filter

The Butterworth filter is suggested to have a 3 dB cut-off frequency of 42 Hz for 120 V_{ac}/60 Hz systems. The following transfer function (11) was implemented where s is the Laplace complex variable. A magnitude response of this filter can be seen in Figure 9.

$$\frac{69640}{s^2+136.59s+69640} \times \frac{69640}{s^2+373.20s+69640} \times \frac{69640}{s^2+509.82s+69640} \quad (11)$$

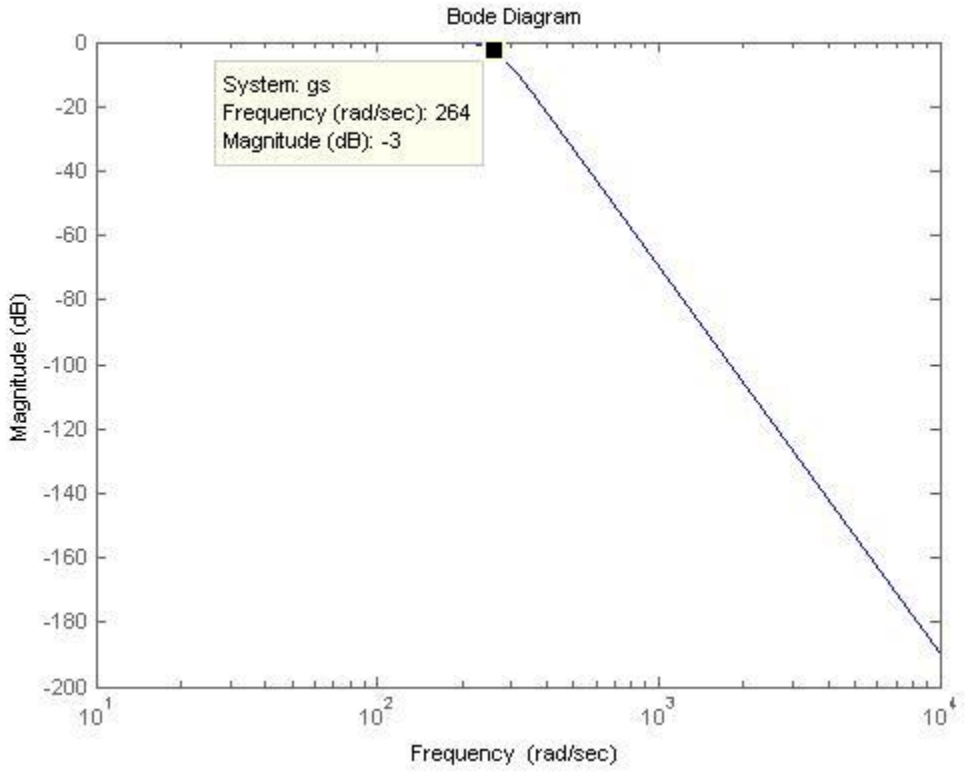

Figure 9: Bode Magnitude Plot of the Block 3 Low-pass Section

The next set of filters is designed to weight the voltage fluctuation according to the eye-brain sensitivity [2]. The overall transfer function implemented to accomplish this is specified in the IEEE 1453 standard and given in (12) where s is the Laplace complex variable [2]. Values required in (12) for a 120 V_{ac}/60 Hz

system are specified in the IEEE 1453 standard and given in Table 2. The bode magnitude plot of the implemented filter can be seen in Figure 10.

$$\frac{k\omega_1 s}{s^2+2\lambda s+{\omega_1}^2} \times \frac{1+\frac{s}{\omega_2}}{\left(1+\frac{s}{\omega_3}\right)\left(1+\frac{s}{\omega_4}\right)} \tag{12}$$

Variable	**120 V_{ac} lamp 60 Hz system**
κ	1.6357
λ	2·π·4.167375
ω_1	2·π·9.077169
ω_2	2·π·2.939902
ω_3	2·π·1.394468
ω_4	2·π·17.31512

Table 2: Necessary Values for Block 3 Weighting Filters; Parameters of Lamps [2]

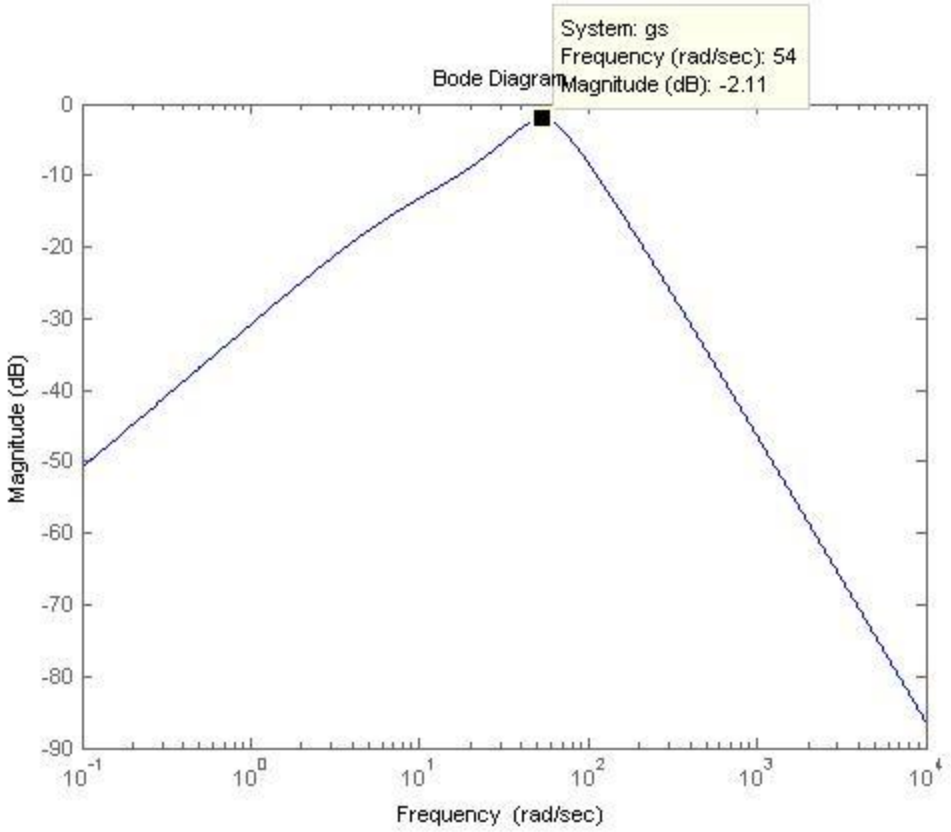

Figure 10: Bode Magnitude Plot of the Block 3 Weighting Filter

The final portion of the lamp-eye-brain chain response is composed of two sections, a squaring multiplier and a 1st order sliding mean filter [2]. This simulates the non-linear eye-brain perception and brain storage effect respectively. As previously implemented the squaring operator can be taken care of with a squaring math function block. The averaging operator must have the transfer function of a first order low-pass RC filter with a time constant of 300 ms as specified in the IEEE 1453 standard [2]. Equation (12) is the transfer function implemented where s is the Laplace complex variable.

$$\frac{1}{0.3s+1} \tag{13}$$

The output of block 4 is the instantaneous flicker sensation P_{inst}. This output is defined as one unit of perceptibility which corresponds to the reference human flicker perceptibility threshold [2]. It is necessary to test this point across a range of input voltage fluctuations provided in the IEEE 1453 standard. The peak values from each individual test point were averaged together to calculate the scalar necessary to achieve a unity peak value. Results for the entire range of test points are given in Table 3. The calculated scalar was 1.24×10^{6}. A plot of P_{inst} for the 0.5 Hz test point can be seen in Figure 11. This better illustrates how P_{inst} relates to the input voltage fluctuations.

Modulation Frequency (Hz)	Voltage fluctuation (%)	P_{inst} Peak Value Results
0.5	0.600	1.0034
1.0	0.547	0.9935
1.5	0.504	1.0020
2.0	0.471	1.0064
2.5	0.439	0.9965
3.0	0.421	1.0053
3.5	0.407	0.9900
4.0	0.394	0.9993
4.5	0.371	0.9864
5.0	0.349	1.0016
5.5	0.323	0.9873
6.0	0.302	0.9964
6.5	0.282	0.9870
7.0	0.269	0.9922
7.5	0.258	0.9943
8.0	0.255	1.0101
8.8	0.253	1.0072
9.5	0.257	0.9858
10.0	0.264	0.9865
10.5	0.280	1.0092
11.0	0.297	1.0262
11.5	0.309	1.0065
12.0	0.323	0.9920
13.0	0.369	1.0072
14.0	0.411	0.9992
15.0	0.459	1.0058
16.0	0.513	1.0139
17.0	0.580	1.0158
18.0	0.632	1.0105
19.0	0.692	1.0073
20.0	0.752	1.0133
21.0	0.818	1.0100
22.0	0.853	1.0151
23.0	0.946	1.0048
24.0	1.072	1.0273
40.0	3.460	1.3701

Table 3: P_{inst} Peak Value Results After Scaling

Note that the 40 Hz test point doesn't fall within the specified P_{inst} peak range. This is most likely due to the Butterworth filter implemented in block 3. The IEEE 1453 standard only recommends a 6^{th} order filter but it may be necessary to implement a higher order filter for the results to be within the

desired range for the higher frequency test points. This isn't necessary for the focus of this implementation.

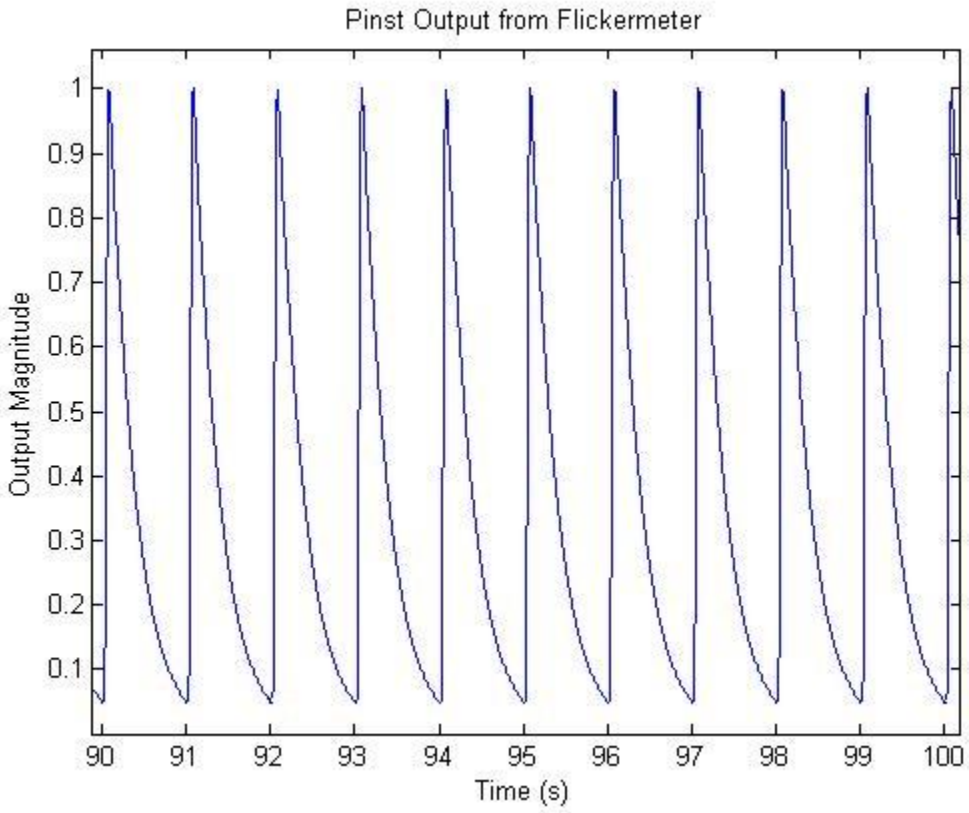

Figure 11: P_{inst} for the 0.5 Hz Test Point

Note that the peak values here are scaled to unity. This will not be the case in the unity P_{st} test points. Scaling from P_{inst} testing allows the instantaneous flicker output to be at a proper level for calculating P_{st}. The importance of this plot becomes clear upon examining where in time each peak occurs: they correspond to the number of changes per minute in the input voltage fluctuation waveform. Two rectangular voltage changes at a frequency of 0.5 Hz correspond to 2 changes per period of 2 seconds, or 60 changes per minute. A

P_{inst} plot of a unity P_{st} test point is presented in Figure 12 from which statistical evaluation will be performed in the following section.

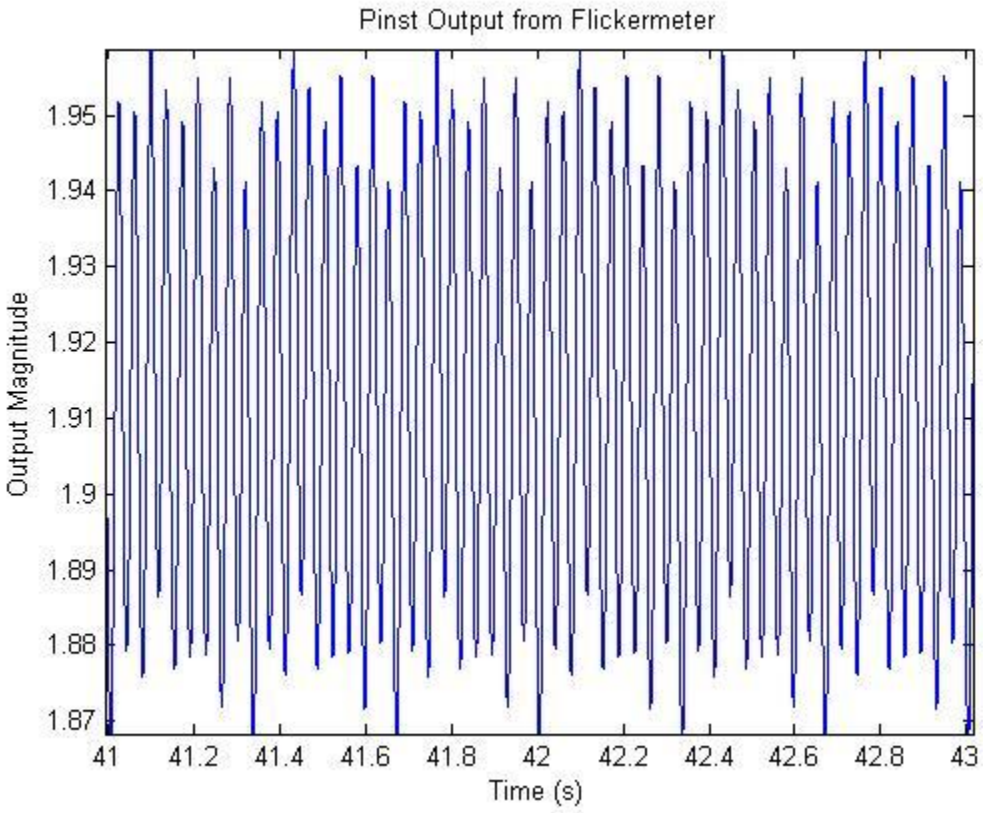

Figure 12: P_{inst} for the 1620 Changes per Minute Test Point

3.3 Block 5 – Statistical Evaluation

The purpose of this block is to determine flicker severity by means of statistical analysis. This is achieved through first sampling the instantaneous flicker signal generated from the output of block 4 discussed in the previous section. These resulting samples are counted into a sufficient number of classes (or 'bins') corresponding to their magnitude. The sampling frequency chosen for

the flickermeter design, 1920 samples per second, is high enough for the resulting histogram to represent the distribution of flicker level duration in each bin [2]. It is then necessary to create a cumulative probability distribution function of the flicker levels by adding each bin count together and dividing by the total number of samples. Note that this implementation uses the complementary cumulative probability distribution. From this distribution function relevant statistical values are easily obtained; this is necessary for calculating P_{st}.

There are mainly two different ways to approach classifying the instantaneous flicker signal, a logarithmic classifier and a linear classifier. This design implements a linear classifier and since it is an off-line flickermeter implementation a large number of bins can be used. Using a large number of bins isn't always practical, particularly in the case of an on-line implementation. In a situation where processing time is an issue it may be necessary to implement a logarithmic classifier which significantly reduces the number of bins required for accuracy.

The statistical evaluation process will be examined in more detail. Assume that the instantaneous flicker signal P_{inst} is available and being run through the classifier. The first step is to create the histogram. This is done through use of the MATLAB "hist" command. With this command the number of bins to be used can be specified. A sufficient number for the purpose of this classifier is 10000 bins. This command now generates 10000 bins centered at linearly spaced intervals ranging from the minimum to the maximum points of the data set. Such a histogram is shown in Figure 13 for the 1620 changes per minute test point.

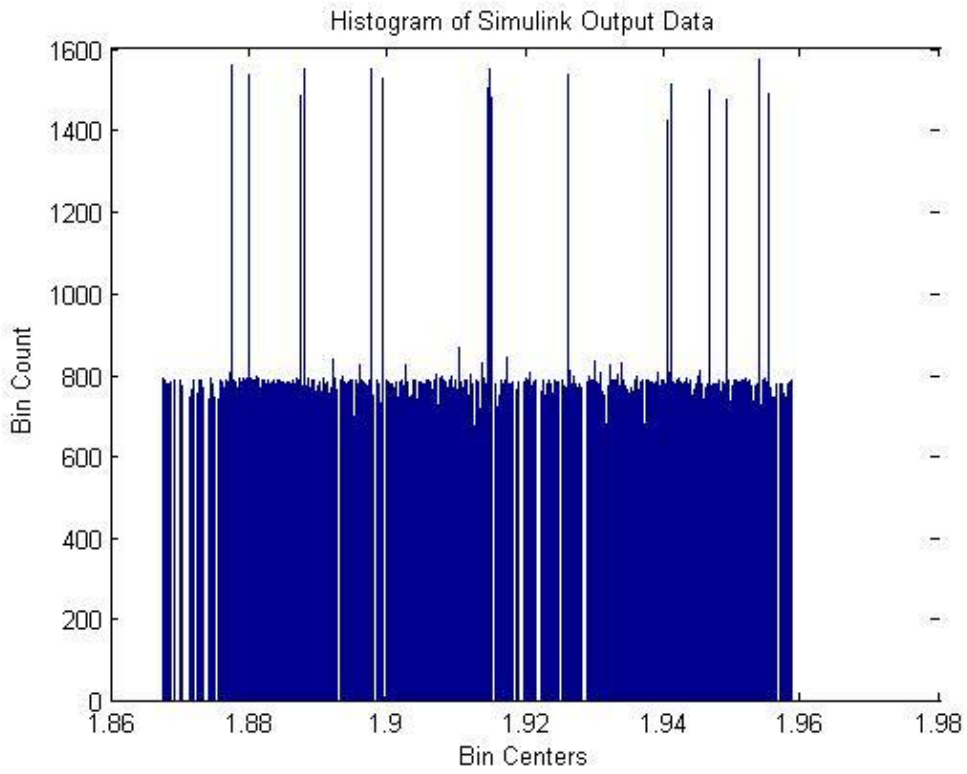

Figure 13: Histogram of Output Data for the 1620 Changes per Minute Test Point

With this data it is possible to calculate the complementary cumulative probability distribution function. Let n be an array of magnitudes corresponding to the count in each bin of the histogram. Let l be the number of bins which is 10000. The cumulative probability distribution function can be defined as (14).

$$p_k = 100 \cdot \left(1 - \frac{\sum_{j=1}^{k} n_j}{\sum_{i=1}^{l} n_i}\right); k = 1,2,\cdots,l \qquad (14)$$

This will result in an array of probabilities that correspond to each bin. Shown in Figure 14 is the result of this process performed on the 1620 changes per minute test point histogram from Figure 13. The y-axis refers to the array of probabilities

while the x-axis refers to the array of magnitudes that correspond to each percentage. Note that the distribution is of the form P(x)>X.

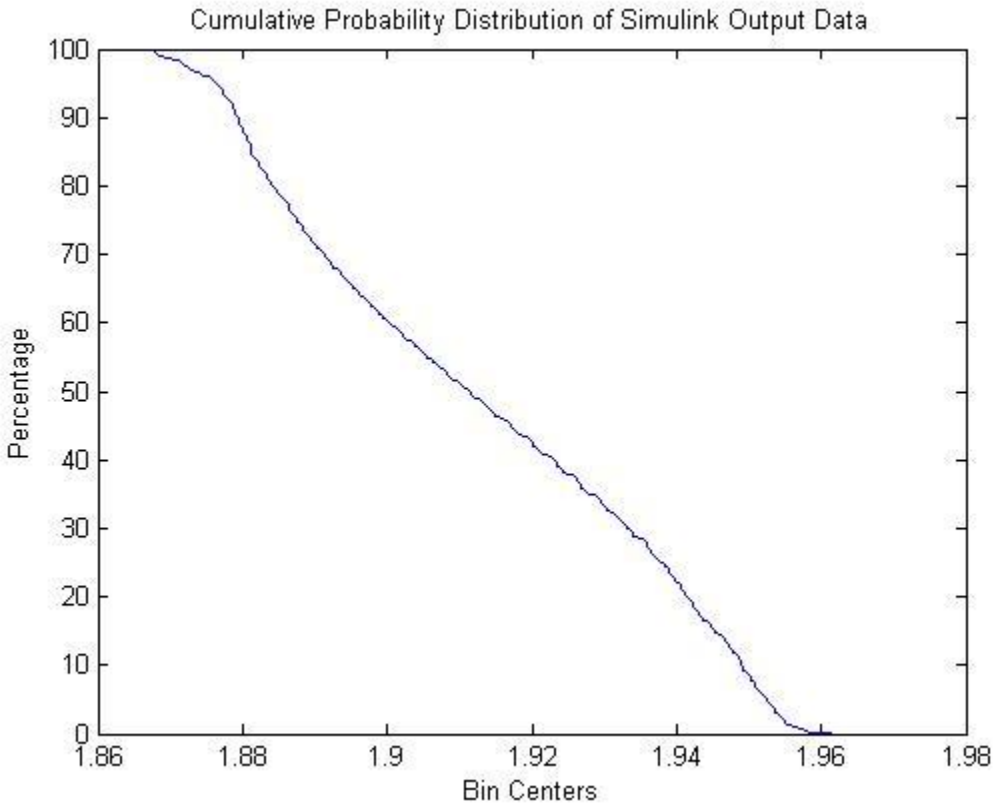

Figure 14: Complementary Cumulative Probability Distribution for the 1620 Changes per Minute Test Point

The amount of bins used provides for a large amount of accuracy in the calculation of P_{st}. It can be calculated from both Figures 13 and 14 that there are about 1300 bins over a spacing of 0.1 in magnitude. This shows that the linear classifier is very accurate when employing a sufficiently large number of bins.

3.3.1 Short-term Flicker Calculation

Short-term flicker is the measure of flicker severity over an observation period of 10 minutes. This measurement is referred to as P_{st} and is calculated from the statistical evaluation acquired from the block 5 classifier examined in the previous section. P_{st} is calculated from the cumulative probability distribution by using (15), specified in IEEE 1453.

$$P_{st}=\sqrt{0.0314\cdot P_{0.1}+0.0525\cdot P_{1s}+0.0657\cdot P_{3s}+0.28\cdot P_{10s}+0.08\cdot P_{50s}} \quad (15)$$

$P_{0.1}$, P_{1s}, P_{3s}, P_{10s}, and P_{50s} are the flicker levels that correspond to the percentiles obtained in the complementary cumulative probability distribution. To obtain an accurate representation of these percentiles it is necessary to use the smoothed value obtained from (16) through (19), specified in IEEE 1453. A smoothed value is not needed for $P_{0.1}$ due to the 0.3 second memory time-constant in the flickermeter.

$$P_{50s}=(P_{30}+P_{50}+P_{80})/3 \quad (16)$$

$$P_{10s}=(P_{6}+P_{8}+P_{10}+P_{13}+P_{17})/5 \quad (17)$$

$$P_{3s}=(P_{2.2}+P_{3}+P_{4})/3 \quad (18)$$

$$P_{1s}=(P_{0.7}+P_{1}+P_{1.5})/3 \quad (19)$$

It is now possible to examine the process for obtaining the percentiles necessary for P_{st} calculation. Let **p** be the vector of probabilities plotted in Figure 14. Let d be the desired percentage; to find P_{50s} three percentages are needed: 30%, 50%, and 80%. To find the magnitude of the bin corresponding to the percentages (20) can be employed.

$$v=\min(|\mathbf{p}-d|) \tag{20}$$

The importance of the value v is only the number of the bin to which it corresponds. The MATLAB “min” function can return the index of v along with the value. This is the index for the magnitude that corresponds to the desired percentage.

The values calculated with this process for the flicker levels needed to calculate P_{st} for the 1620 changes per minute test point are P_{50s}=1.9098, P_{10s}=1.9483, P_{3s}=1.9541, P_{1s}=1.9565, and $P_{0.1}$=1.9584. With these values it is possible to calculate P_{st} which results in P_{st}=0.9954. As the test point used was specified to provide P_{st}=1±0.05 it can be seen that the result falls in the required range. This same process is performed for the entire range of test points specified in the IEEE 1453 standard. The results can be seen in Table 4.

Changes per Minute (CPM)	Modulation Frequency (Hz)	Voltage Fluctuation (%)	P_{st} Results
0.1	0.000833	8.202	0.8860
0.2	0.001667	5.232	0.9921
0.4	0.003333	4.062	0.9884
0.6	0.00500	3.645	0.9890
1	0.00833	3.166	0.9928
2	0.01667	2.568	0.9990
3	0.02500	2.250	0.9969
5	0.04167	1.899	0.9969
7	0.05833	1.695	0.9988
10	0.0833	1.499	1.0029
22	0.1833	1.186	1.0028
39	0.3250	1.044	0.9970
48	0.4000	1.000	0.9927
68	0.5667	0.939	0.9941
110	0.9167	0.841	0.9931
176	1.4667	0.739	0.9924
273	2.2750	0.650	0.9954
375	3.1250	0.594	0.9969
480	4.0000	0.559	0.9998
585	4.8750	0.501	0.9968
682	5.6833	0.445	0.9956
796	6.6333	0.393	0.9958
1020	8.5000	0.350	0.9901
1055	8.7917	0.351	0.9894
1200	10.000	0.371	0.9918
1390	11.583	0.438	0.9996
1620	13.500	0.547	0.9954
2400	20.000	1.051	1.0007
2875	23.9583	1.49	0.9973

Table 4: P_{st} Test Results

After testing every provided point in the IEEE 1453 standard it can be concluded that the completed meter is indeed functioning as intended. The P_{st} result for every test point falls within the specified margin of error, $P_{st}=1\pm0.05$, with the exception of the 0.1 CPM (Changes per Minute) test point. For this test point only one change occurs within the 10 minute observation period. Unless the change is perfectly synchronized part of the change will bleed into the next 10 minute period, which is why the P_{st} value is lower than it should be. If measured

continuously the next P_{st} value would be a bit higher than desired. Note that this doesn't impact the results of this implementation.

With these results it is possible to proceed into generating data to analyze the initial problem presented in the Introduction. The P_{st} results from the following sections, presented in Tables 5 and 6, can be compared to the P_{st} results in Table 4 to aid in analysis.

Chapter 4

Testing & Results

With the flickermeter functioning as specified in the IEEE 1453 standard it is necessary to move on to lab testing of the problem initially proposed in the Introduction. This allows for analysis of data that is generated and gathered as it might be in a practical situation. This data can then be used to examine the proposed methodologies for analyzing individual flicker levels within the total flicker signal.

The method of testing should be logically and systematically designed to measure every value of interest while also examining every possible orientation between source and load. It is also necessary to generate realistic data in a lab setting, gather it with the designed meter, and analyze the results. This will be accomplished with a setup that emulates Figure 2 of the Introduction. The source flicker levels will be controlled through the use of a C program via desktop computer and DAQ card. The program is able to generate a flicker waveform from a given set of flicker frequencies and relative voltage modulation levels by using the method described in the flicker waveform generation section. The values for generating these waveforms are contained in Table 1 in the Introduction.

The generated voltage waveform will be amplified to a typical level (~120V_{ac}) and applied to a series of impedances, a purely resistive impedance followed by a variable load resistor bank. The constant impedance is to simulate line impedance. For these tests the impedance is simplified and purely resistive with a value of 1Ω. The variable load bank allows for manual control of flicker generation at a load node by simply varying the resistance every one minute. From this there will be three relevant data points to gather labeled in Figure 2: source voltage (v_1), load voltage (v_2), and current (i). The voltages will be stepped down through a voltage divider and gathered via a laptop running the data gathering program tested in the sampling section. The currents will be obtained through similar use of a current transformer.

With the testing setup completed a list of testing scenarios must be compiled. This list will provide for testing the full range of possible source and load configurations. The source configurations are as follows

- Voltage generated as 120 V_{ac}/60Hz sine wave
- Voltage generated from 2 CPM test point specifications
- Voltage generated from 110 CPM test point specifications
- Voltage generated from 4800 CPM test point specifications

The load configurations are as follows

- Constant 48.8Ω
- Switching 48.8 Ω↔Open circuit every one minute
- Switching 24.5 Ω↔48.8 Ω load resistance every one minute

- Switching 24.5 Ω↔Open circuit every one minute

This results in a total of 16 possible testing configurations. Results from a portion of these testing configurations will be presented in the following section. The presented results are sufficient for comparison and analysis.

4.1 First Round of Results & Analysis

In this section, results are presented that were obtained from the various testing configurations described in the previous section. In most cases plots of both P_{inst} and the corresponding histogram will be presented. It is expected that there can be some statistical correlation found between the various histograms. This would provide insight as to possibilities in determining which portion of the flicker signal is attributed to each of the sources. Values calculated for P_{st} will also be given. Source and load scenarios are kept consistent between testing situations to provide meaningful comparisons. In Table 5 the testing scenarios and P_{st} values are given along with their corresponding figure number. Note that the measurement notation corresponds to the system described in Figure 2 in the Introduction.

LABEL	SOURCE	LOAD	MEASUREMENT	P_{st}
Figure 15	110 CPM	Open	v_1	1.023
Figure 16	60Hz Sine	48.8 Ω Constant	v_1	0.0682
Figure 17			v_2	0.0689
Figure 18			i	0.0874
Figure 19	110 CPM		v_1	1.009
Figure 20			v_2	1.009
Figure 21			i	1.026
Figure 22	60Hz Sine	24.5Ω↔48.8Ω Switch Every 1min	v_1	0.3517
Figure 23				
Figure 24			v_2	1.057
Figure 25				
Figure 26			i	33.64
Figure 27				
Figure 28	110 CPM		v_1	1.037
Figure 29				
Figure 30			v_2	1.384
Figure 31				
Figure 32			i	29.98
Figure 33				
Figure 34	60Hz Sine	48.8Ω↔Open Switch Every 1min	v_1	0.5620
Figure 35			v_2	1.228
Figure 36			i	560.3
Figure 37	110 CPM		v_1	1.148
Figure 38			v_2	1.593
Figure 39			i	525.9

Table 5: Figure List for Obtained Testing Results

Looking at the P_{st} results in Table 5 it can be concluded that the results are as expected. When there is no flicker in the system the P_{st} results are very close to zero. When there is flicker generated only at the source the P_{st} results are very close to unity and agree closely with the P_{st} results in Table 4. This is expected since the source flicker is generated based on the IEEE 1453 standard's specifications. When flicker at the load is introduced it starts to

influence v_1 by increasing the P_{st} result, though the influence of the source still dominates the P_{st} result since v_1 involves only the source impedance whereas v_2 involves both the source and line impedances. The measurement impacted most by the load flicker is the current; the fluctuations resulting from such a large change in load resistance are so severe that it drastically increases the P_{st} value. For the case with no load flicker and a 110 CPM test point as the source, it should be noted that $P_{st}=1$ for the current. This is due to the fact that the voltage is being applied to a fixed resistance of 1Ω. Since current is equal to voltage divided by resistance, if the voltage fluctuates then the current fluctuates in the same manner. The flickermeter examines only the fluctuations and normalizes everything to the same value so internally there is effectively no difference between the current and voltage signals in this case.

It is important to note that the flickermeter only holds to linearity over a certain P_{inst} magnitude range influenced by the type of interpolation and number of bins used in the classifier. In this case linearity describes that if the fluctuation magnitude is doubled the P_{st} result will also be doubled. With the severe fluctuations in the current these magnitudes are so large that it exceeds the flickermeter's linearity in this implementation. This may be why the P_{st} values of the current don't continue to follow linear growth for the largest load fluctuation scenario. The 110 CPM test point from the IEEE 1453 standard is measured directly as output from the amplifier and a histogram of the result is shown in Figure 15.

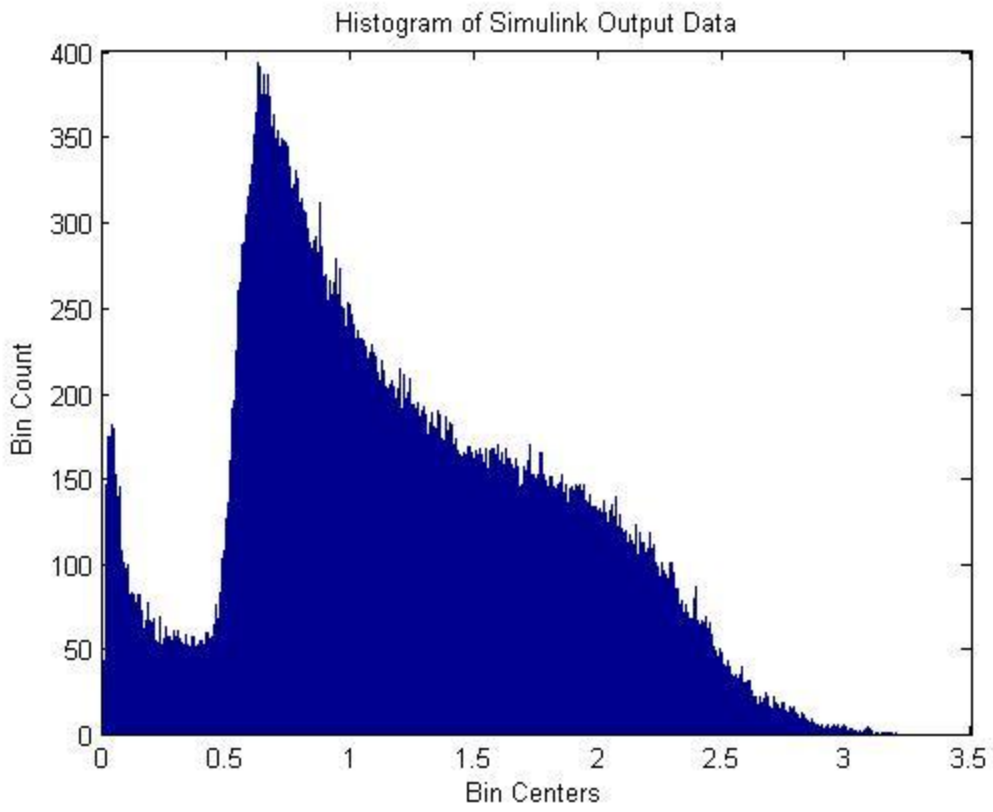

Figure 15: Histogram of P_{inst} of Measured 110 CPM Test Point; P_{st}=1.023

Histograms of the P_{inst} results from a setup where the source output is a 60Hz sine wave from the amplifier while the load is a constant 48.8Ω resistance are given in Figures 16, 17, and 18. Note the magnitude of the bin centers for these plots. Since there is no flicker present at the source or load the majority of the P_{inst} data tends toward zero as expected.

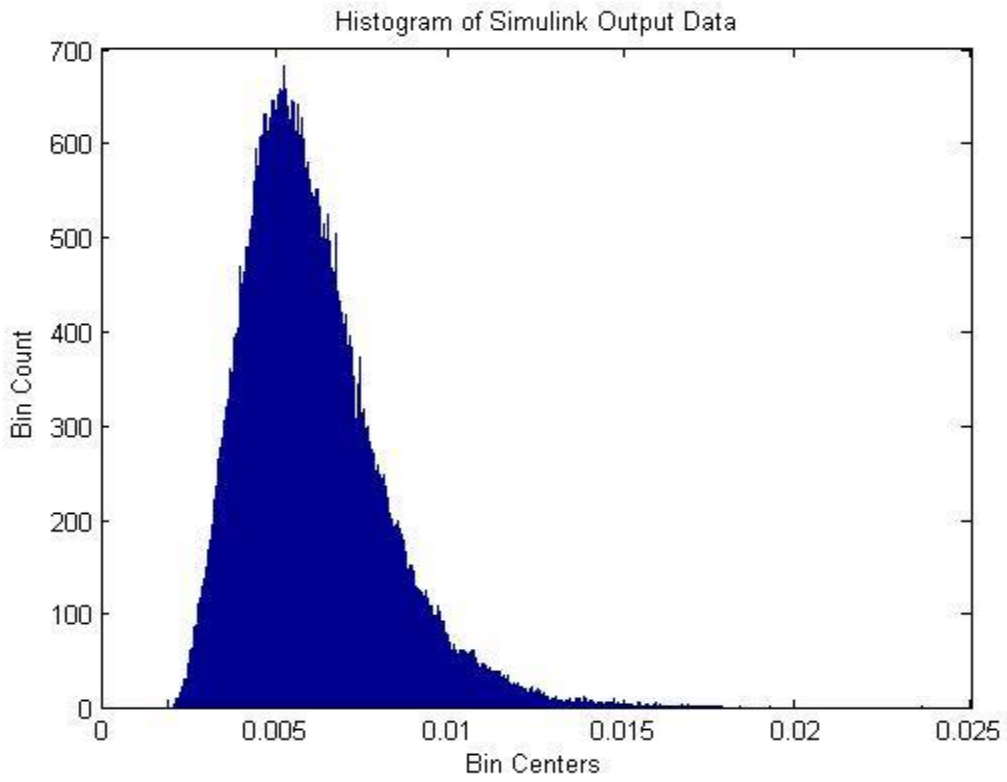

Figure 16: Histogram of P_{inst} of v_1 with Source=60Hz Sine & Load=48.8Ω; P_{st}=0.0682

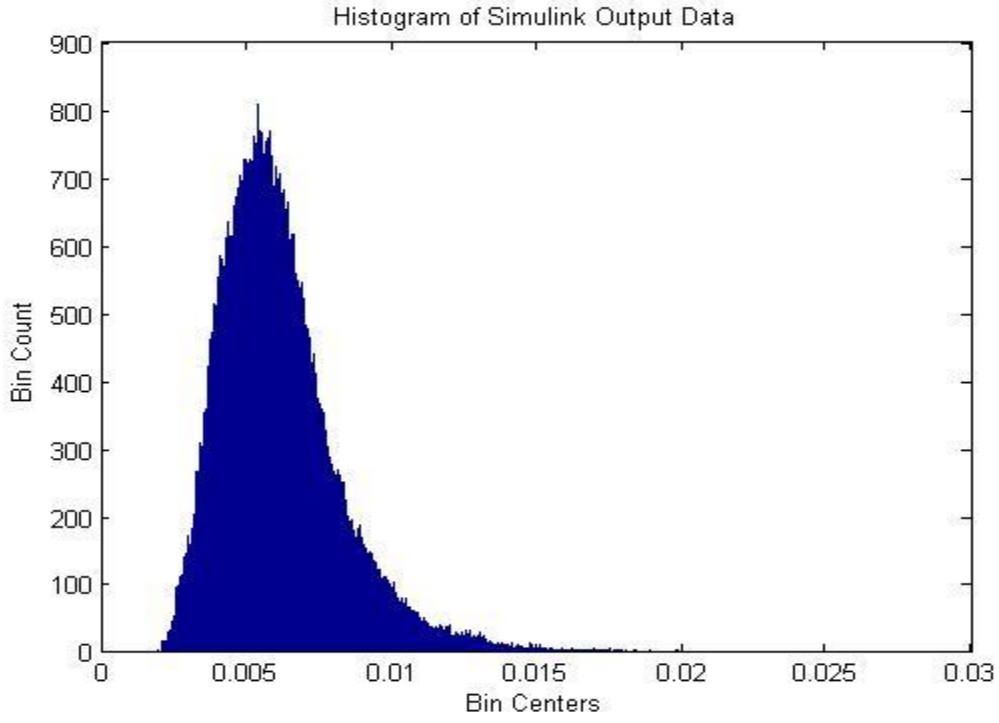

Figure 17: Histogram of P_{inst} of v_2 with Source=60Hz Sine & Load=48.8Ω; P_{st}=0.0689

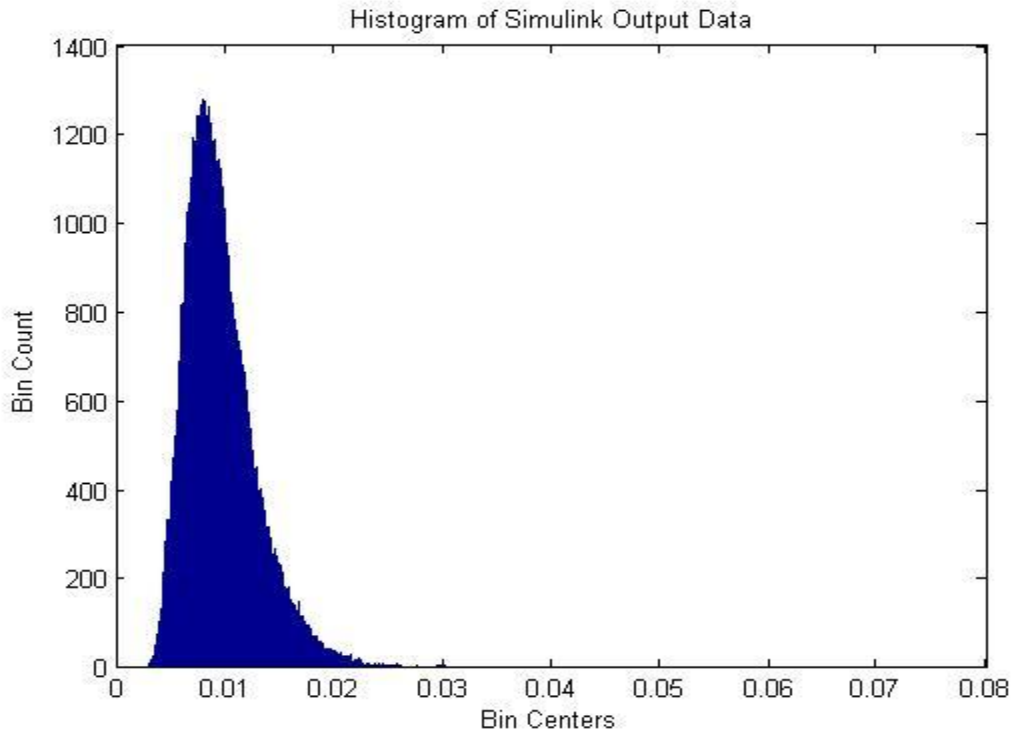

Figure 18: Histogram of P_{inst} of Current with Source=60Hz Sine & Load=48.8Ω; P_{st}=0.0874

Histogram results from a setup where the source output is a 110CPM flicker test point and the load is a constant 48.8Ω resistance are given in Figures 19, 20 and 21. As expected the results are scaled versions of the test point result presented in Figure 15. It also holds true that since there is no flicker present at the load, the histograms of P_{inst} of v_2 and the current are extremely similar to that of v_1.

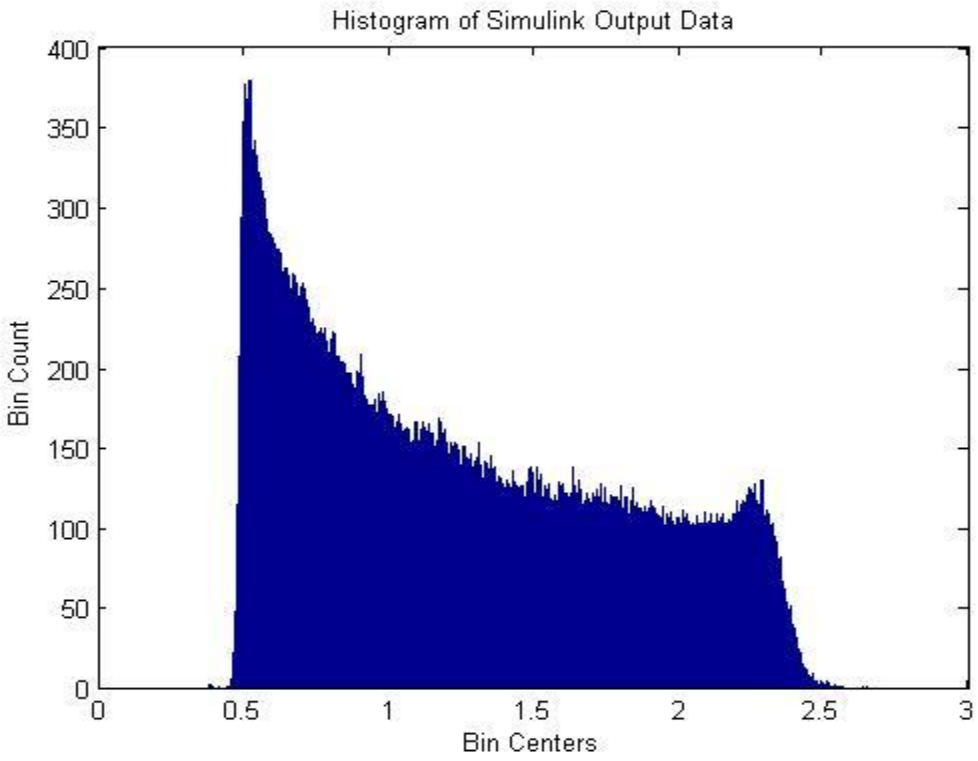

Figure 19: Histogram of P_{inst} of v_1 with Source=110CPM & Load=48.8Ω; P_{st}=1.009

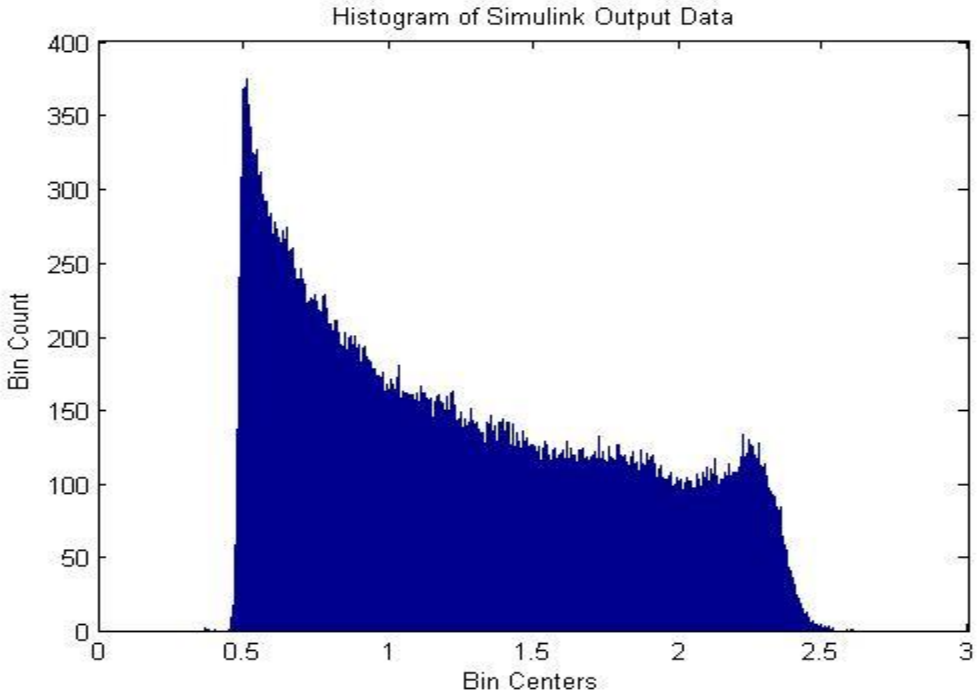

Figure 20: Histogram of P_{inst} of v_2 with Source=110CPM & Load=48.8Ω; P_{st}=1.009

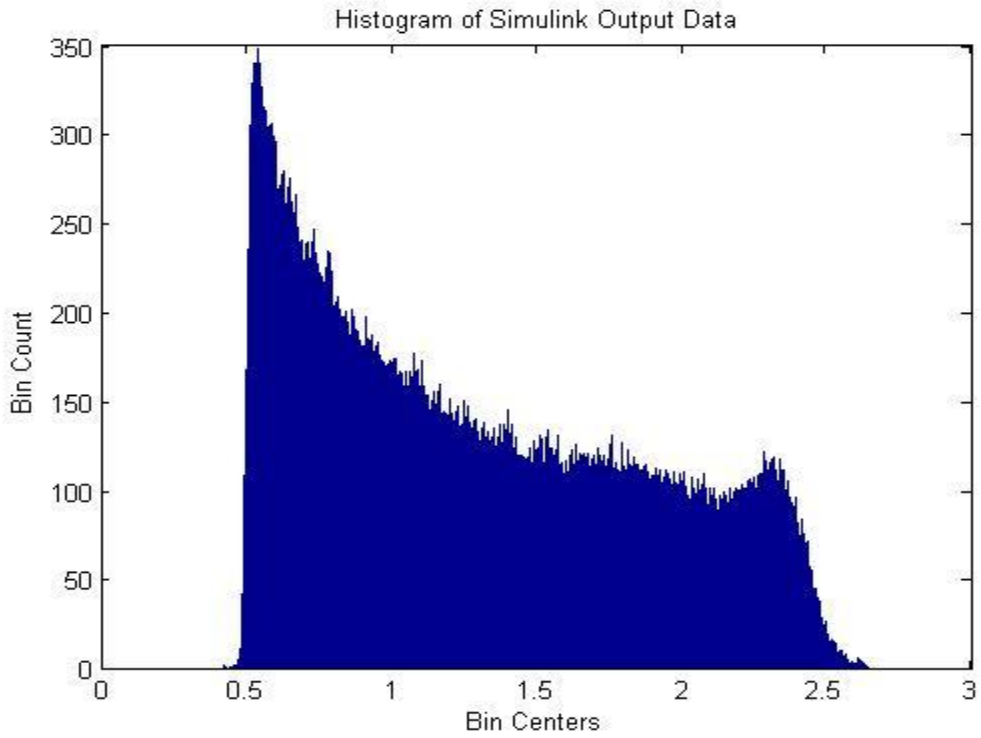

Figure 21: Histogram of P_{inst} of Current with Source=110CPM Sine & Load=48.8Ω; P_{st}=1.026

Histogram and P_{inst} results from a setup where the source output is a 60 Hz sine wave and the load changes between 24.5Ω and 48.8Ω every one minute are given in Figures 22 through 27. The large fluctuations of the load provide for better visual indicators of what is occurring in the flickermeter output. To further illustrate effects of the load flicker, instantaneous flicker plots have also been included. The spikes shown in these correspond exactly to the switching points of the load resistance as expected. Effectively the flickermeter P_{inst} result is the same as that from a 60 Hz sine wave with peaks corresponding to the load flicker. The spikes are so large though that they skew the histogram, forcing the majority of the information into the first few bins. Note that several histograms have logarithmic scaling along the x-axis due to this.

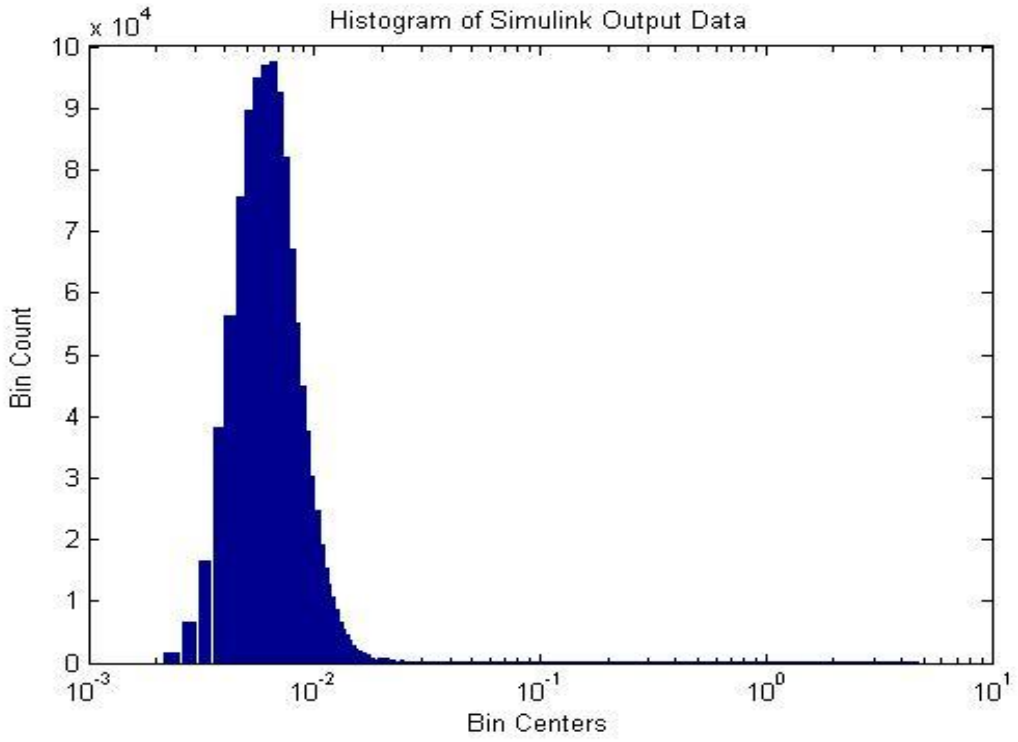

Figure 22: Histogram of P_{inst} of v_1 with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=0.3517

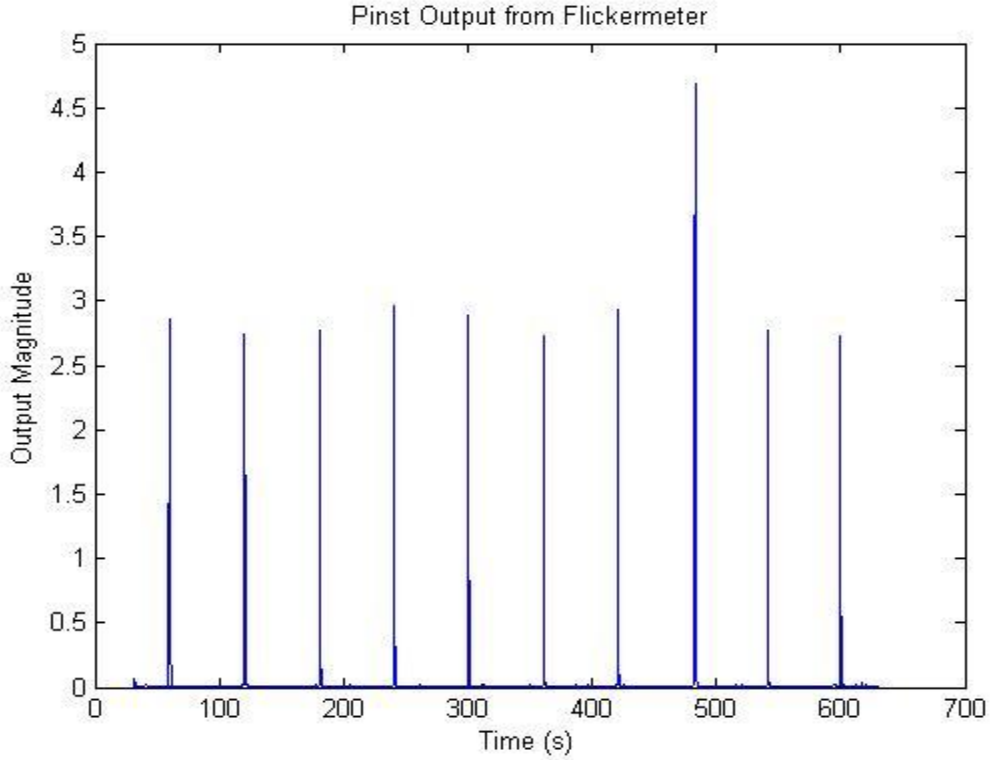

Figure 23: P_{inst} of v_1 with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=0.3517

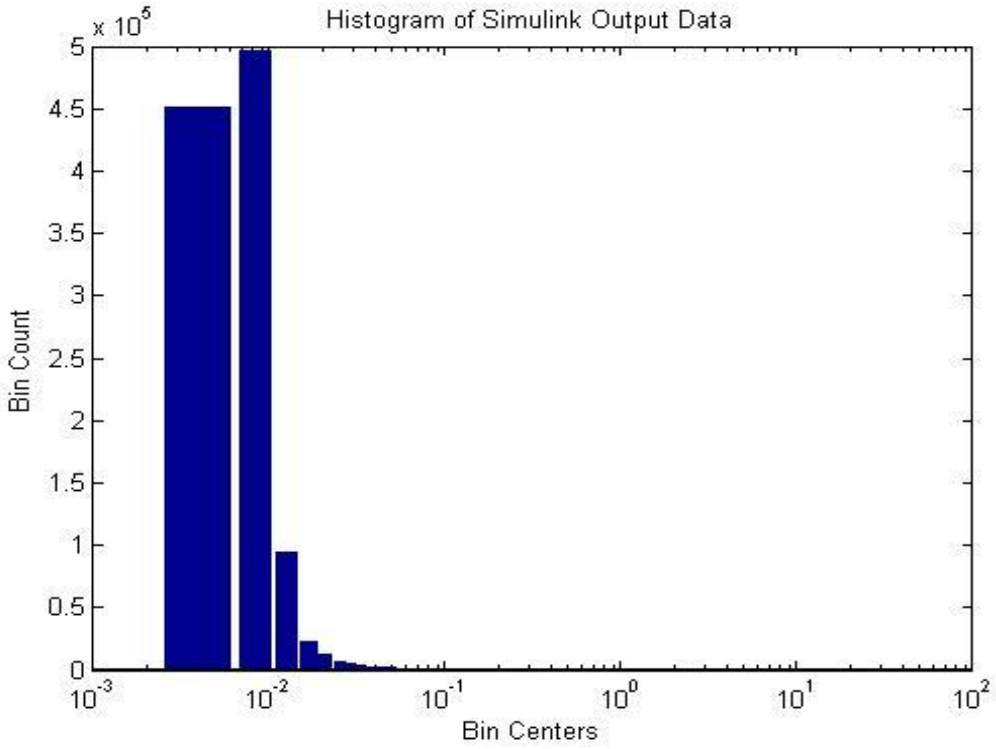

Figure 24: Histogram of P_{inst} of v_2 with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.057

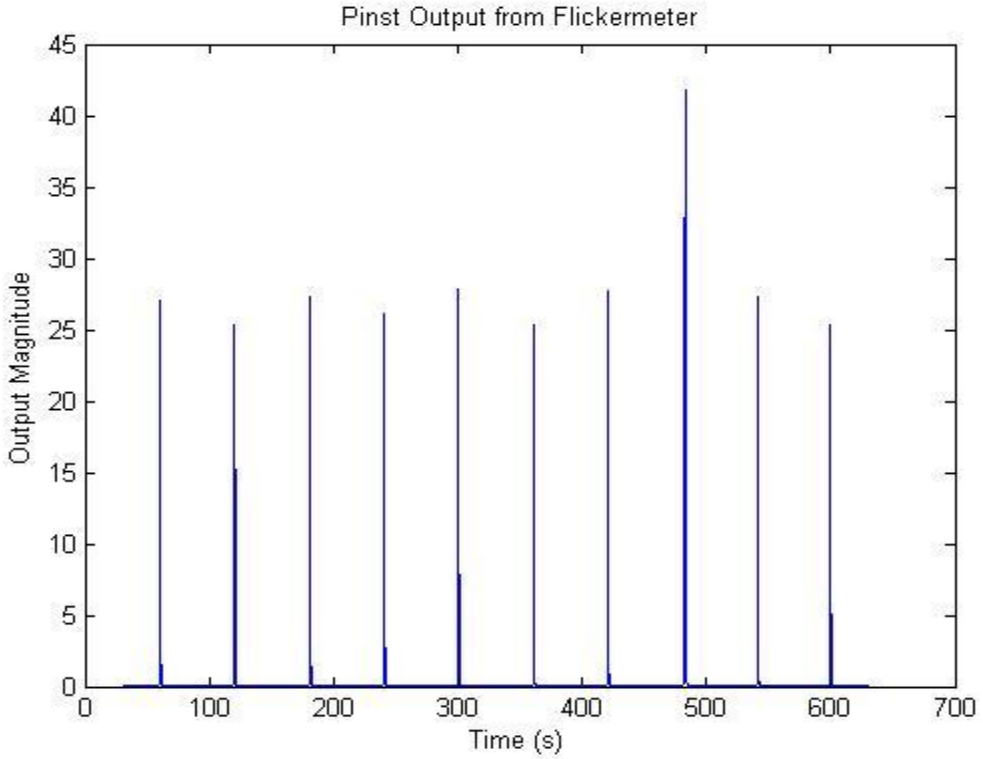

Figure 25: P_{inst} of v_2 with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.057

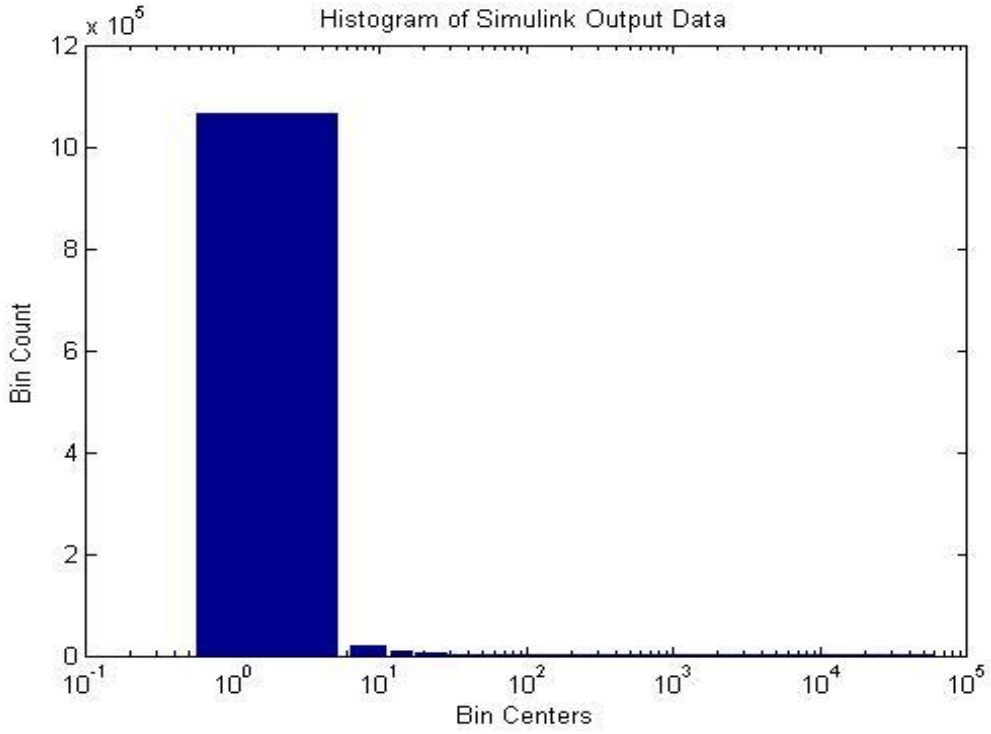

Figure 26: Histogram of P_{inst} of Current with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=33.64

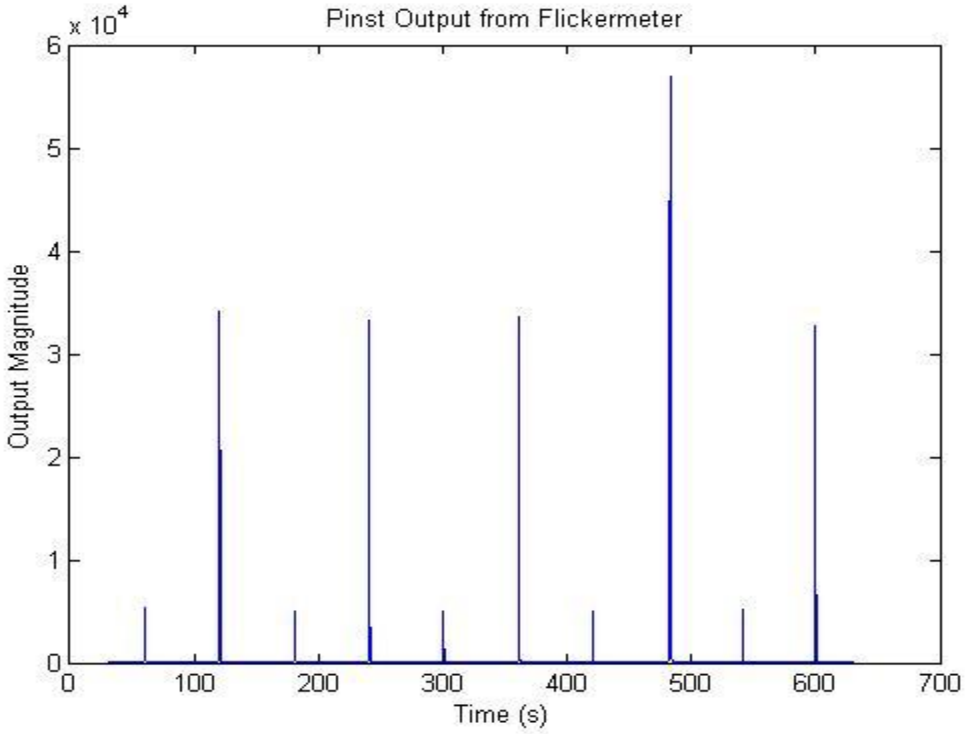

Figure 27: P_{inst} of Current with Source=60Hz Sine & Load=48.8Ω/24.5Ω Every 1min; P_{st}=33.64

Histogram and P_{inst} results from a setup where the source output is a 110CPM flicker test point and the load changes between 24.5Ω and 48.8Ω every 1 minute are given in Figures 28 through 33. Here, as in the 60 Hz variable load results, the load adds on spikes to the test point response. The histograms remain similar in shape but since P_{inst} has several data points larger in magnitude this causes the histogram to be scaled down. The visible correlation between these results and those for the constant load scenario, even with the scaling, supports the prospect of identifying individual contributions to total flicker levels.

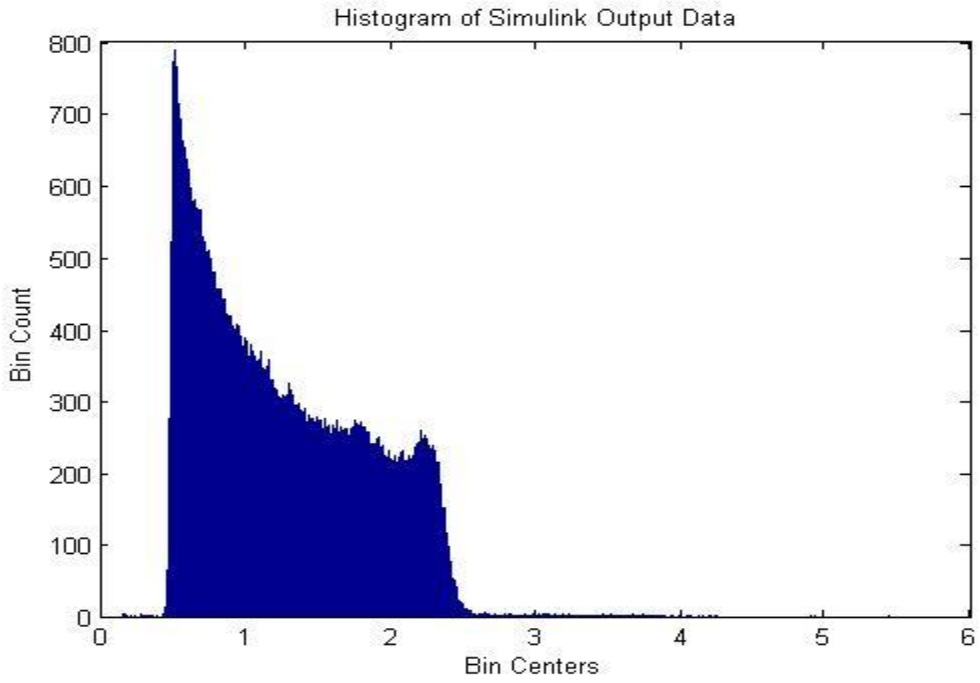

Figure 28: Histogram of P_{inst} of v_1 with Source=110 CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.037

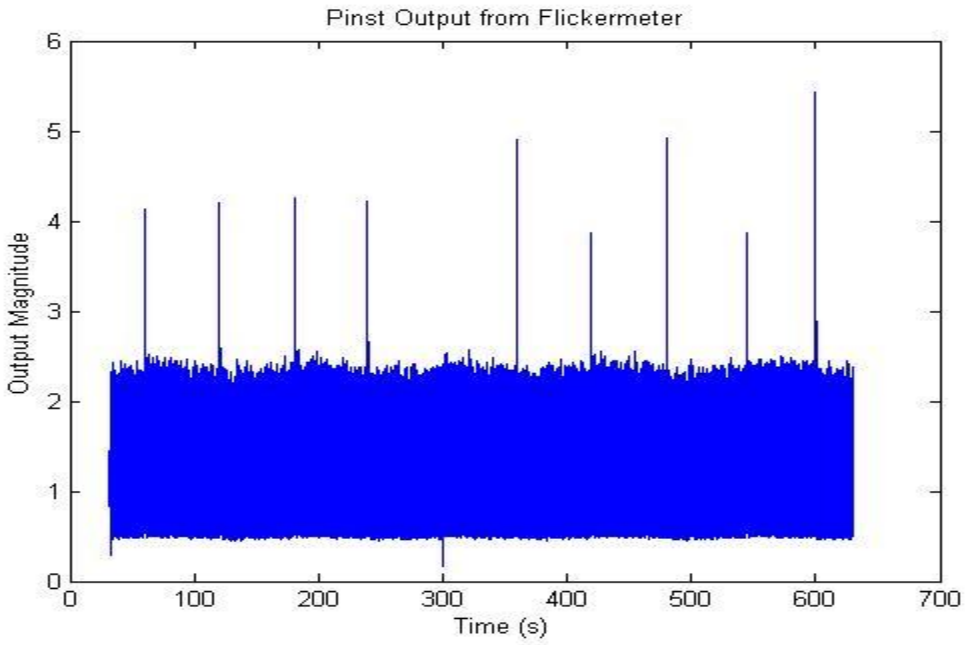

Figure 29: P_{inst} of v_1 with Source=110CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.037

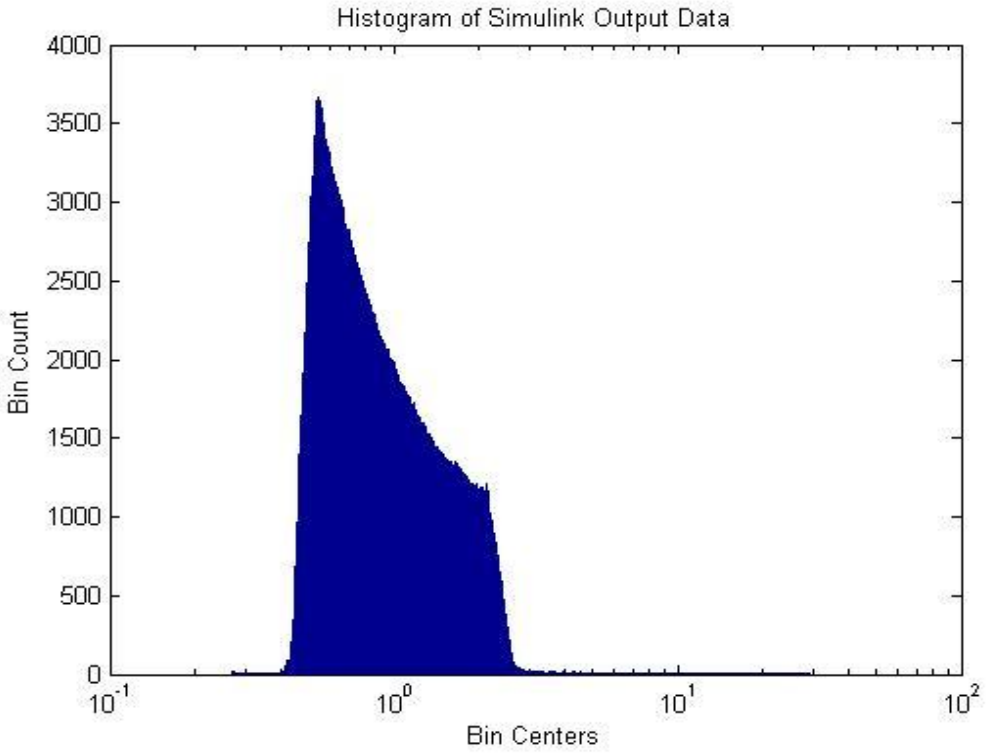

Figure 30: Histogram of P_{inst} of v_2 with Source=110CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.384

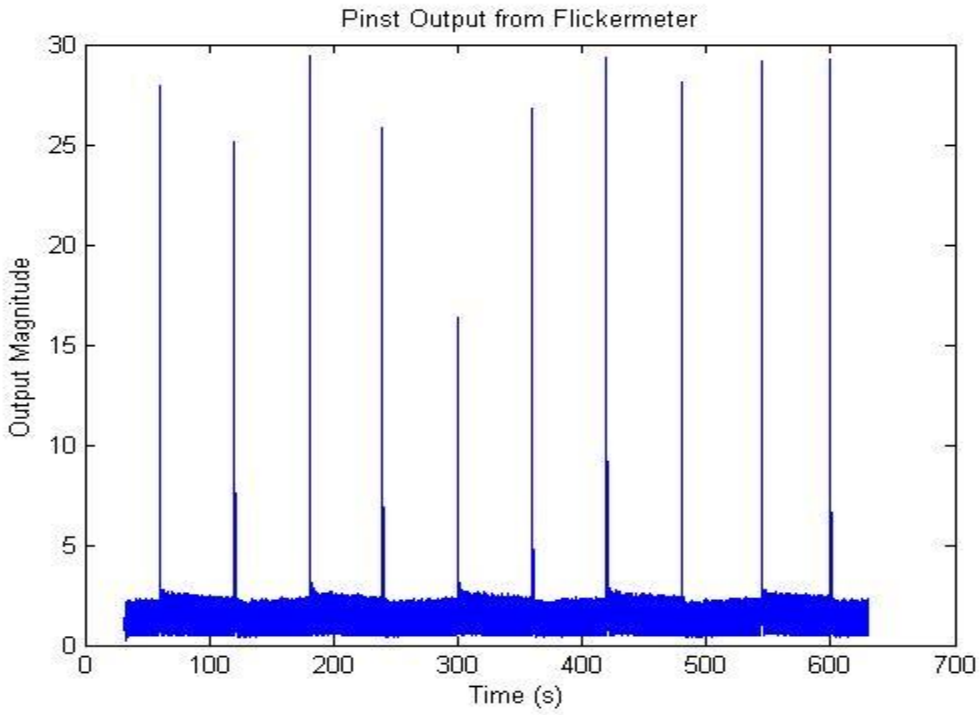

Figure 31: P_{inst} of v_2 with Source=110CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=1.384

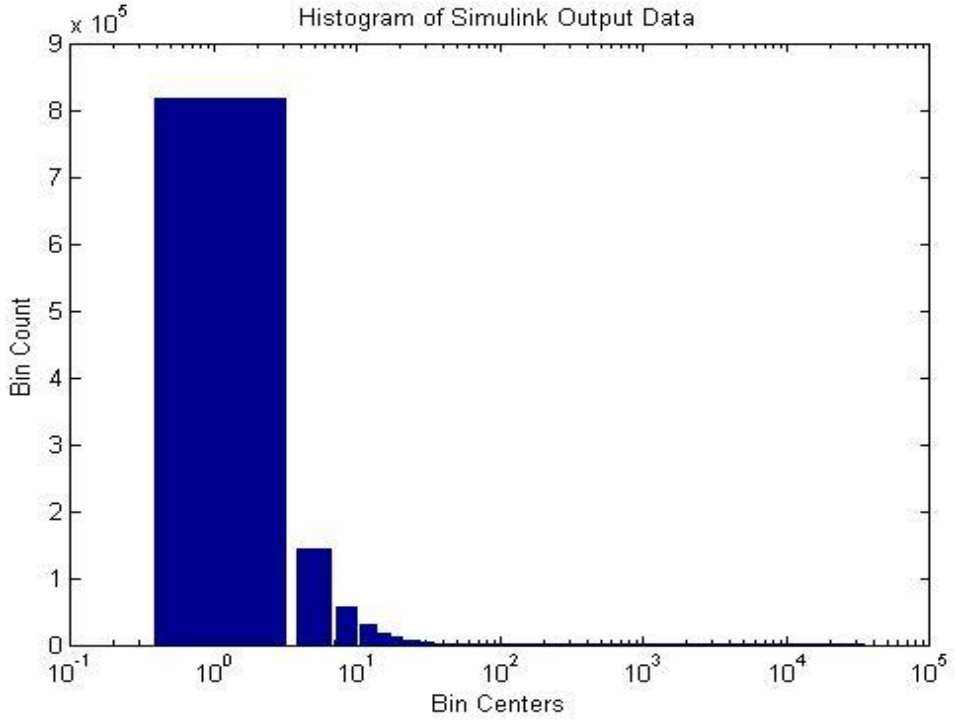

Figure 32: Histogram of P_{inst} of Current with Source=110CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=29.98

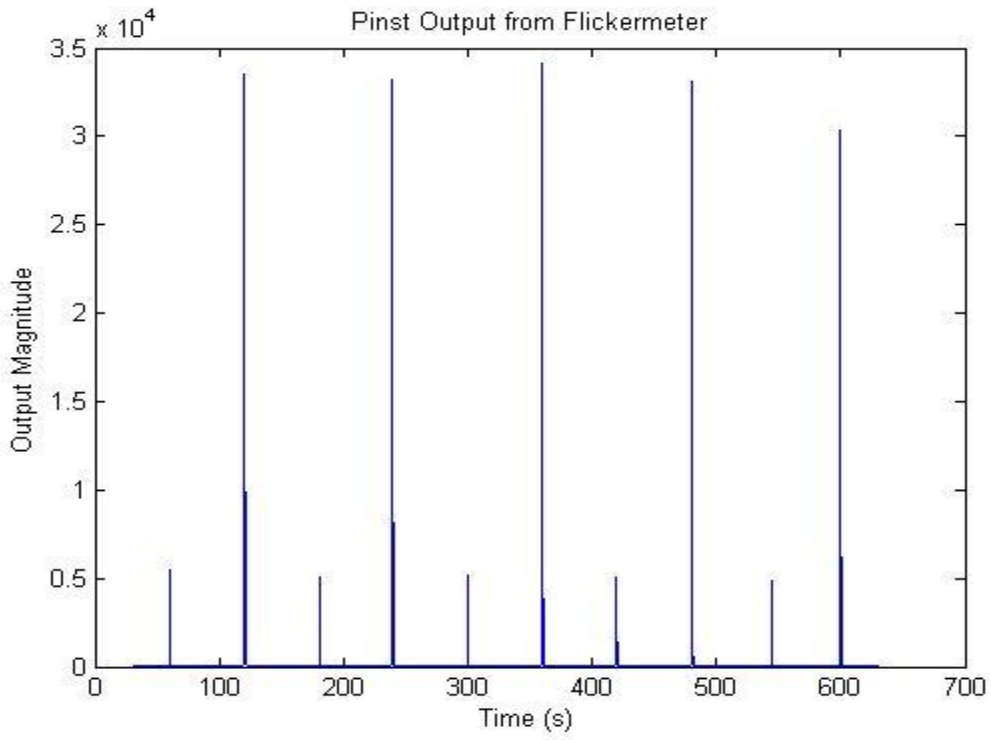

Figure 33: P_{inst} of Current with Source=110CPM & Load=48.8Ω/24.5Ω Every 1min; P_{st}=29.98

Histogram results from a setup where the source output is a 60Hz sine wave and the load changes between 48.8Ω and open every one minute are given in Figures 34, 35, and 36. Instantaneous flicker plots for these cases are not included as they look very similar to the P_{inst} plots in Figures 23, 25, and 27 except with much larger peaks every minute. As the results continue to look similar across the range of test points it becomes clearer that there is correlation between the histograms of various measurement points.

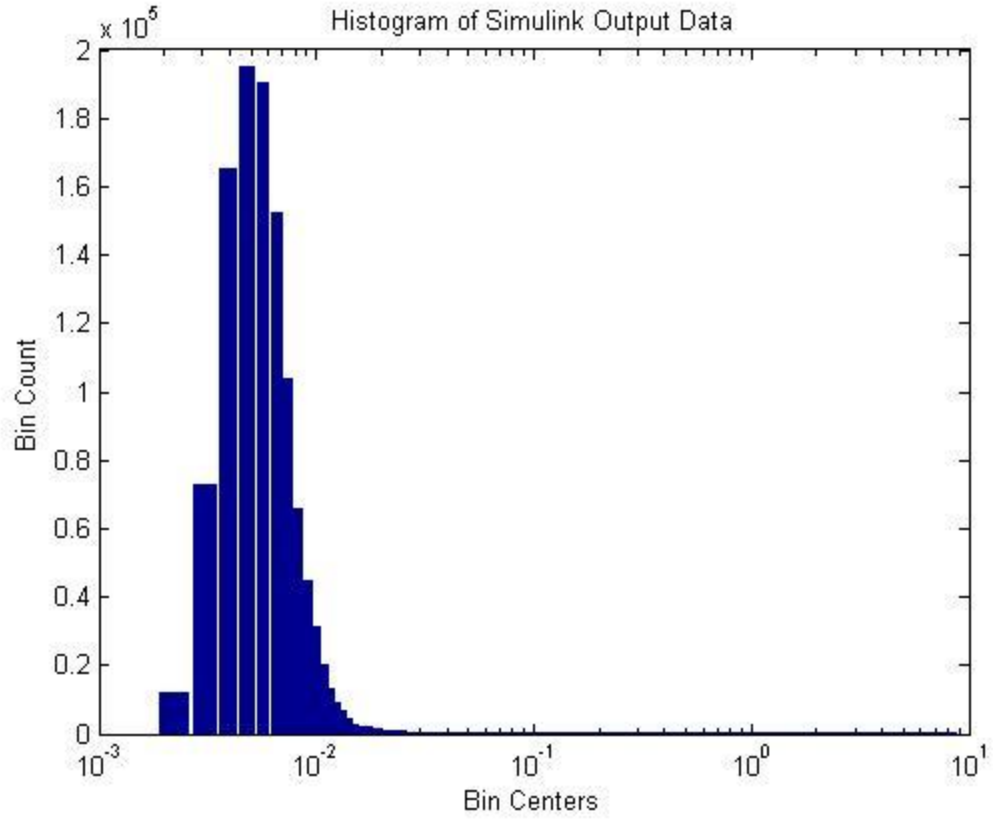

Figure 34: Histogram of P_{inst} of v_1 with Source=60Hz Sine & Load=48.8Ω/Open Every 1min; P_{st}=0.5620

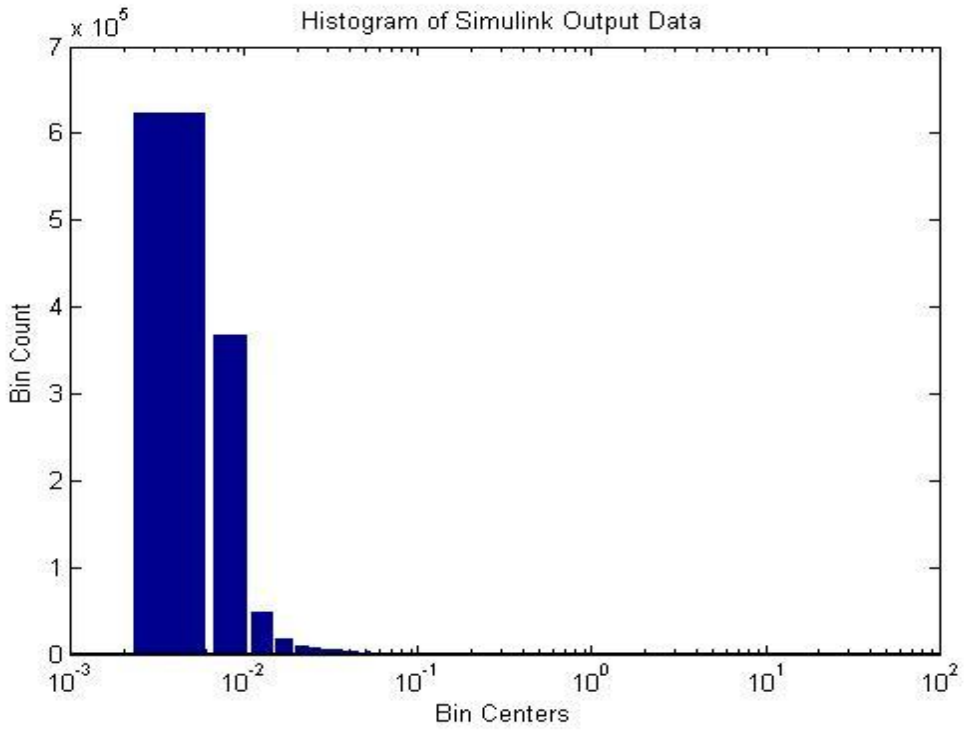

Figure 35: Histogram of P_{inst} of v_2 with Source=60Hz Sine & Load=48.8Ω/open Every 1min; P_{st}=1.228

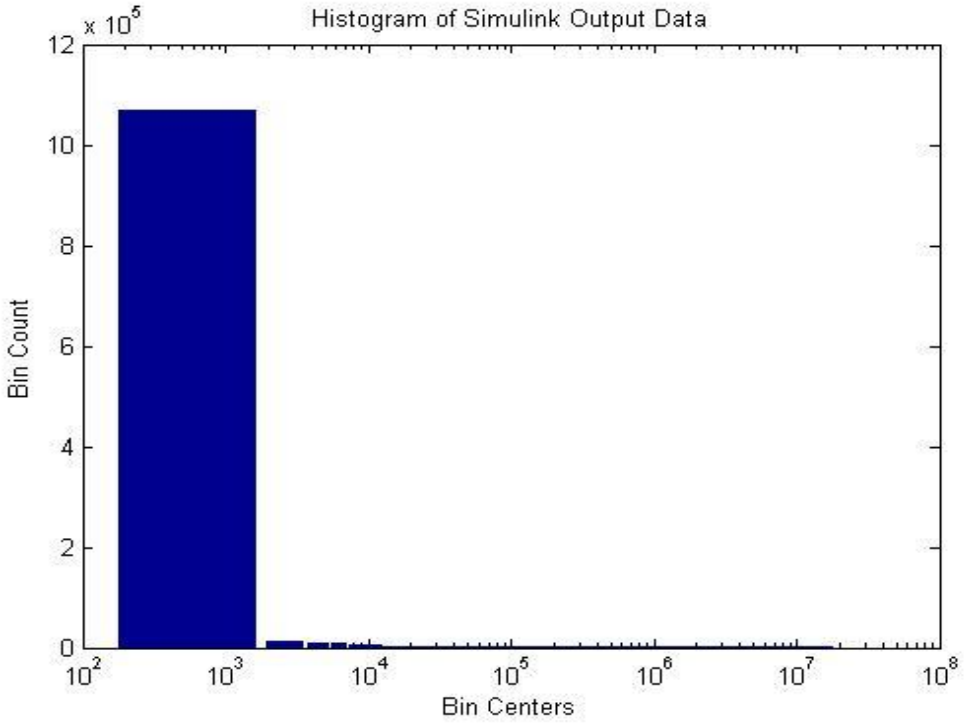

Figure 36: Histogram of P_{inst} of Current with Source=60Hz Sine & Load=48.8Ω/open Every 1min; P_{st}=560.3

Histogram results from a setup where the source output is a 110 CPM flicker test point and the load changes between 48.8Ω and open every 1 minute are given in Figures 37, 38, and 39. Instantaneous flicker plots for these cases are not included as they look very similar to the P_{inst} plots in Figures 29, 31, and 33 except with much larger peaks every minute.

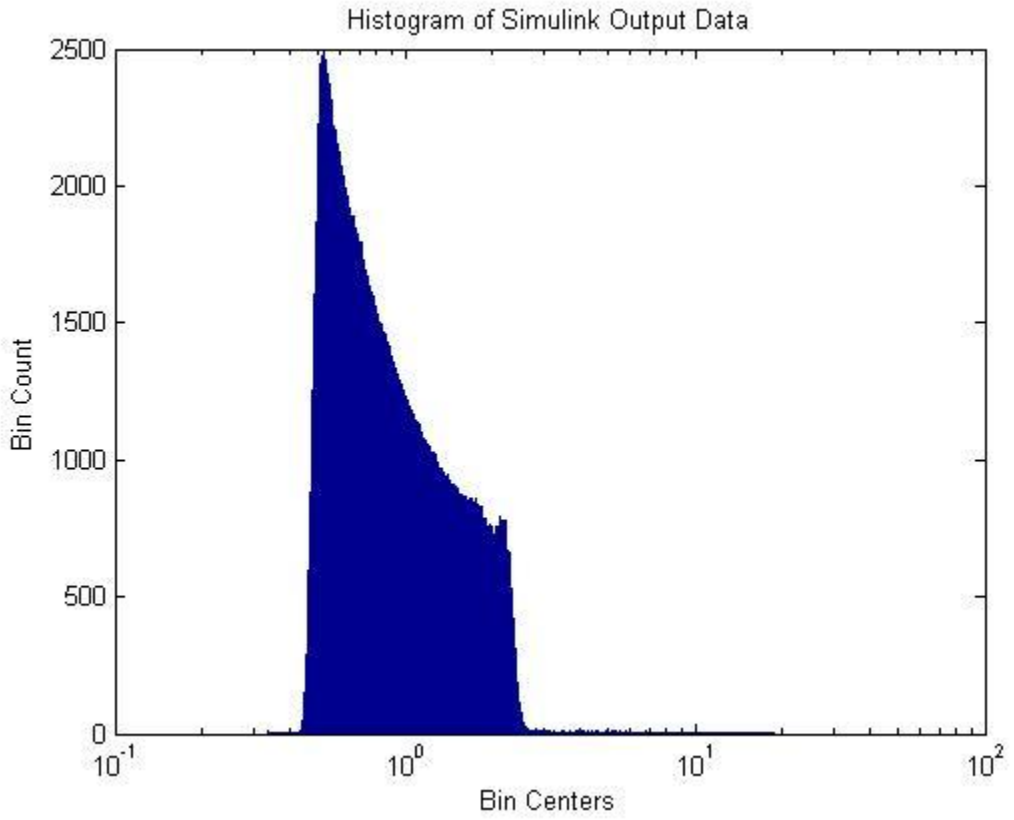

Figure 37: Histogram of P_{inst} of v_1 with Source=110CPM & Load=48.8Ω/open Every 1min; P_{st}=1.148

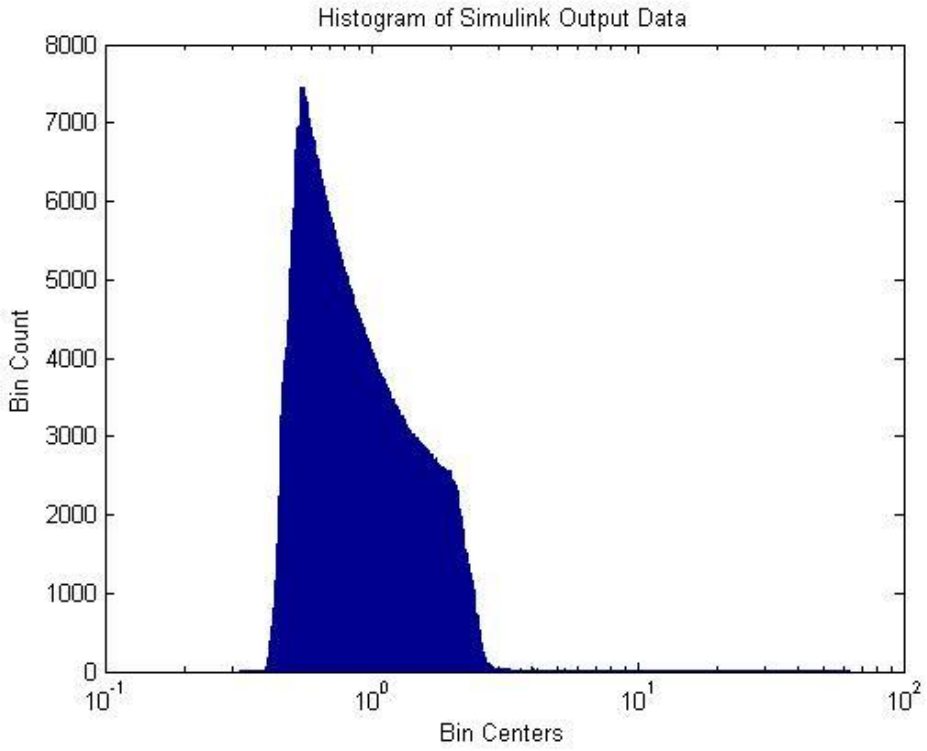

Figure 38: Histogram of P_{inst} of v_2 with Source=110CPM & Load=48.8Ω/open Every 1min; P_{st}=1.593

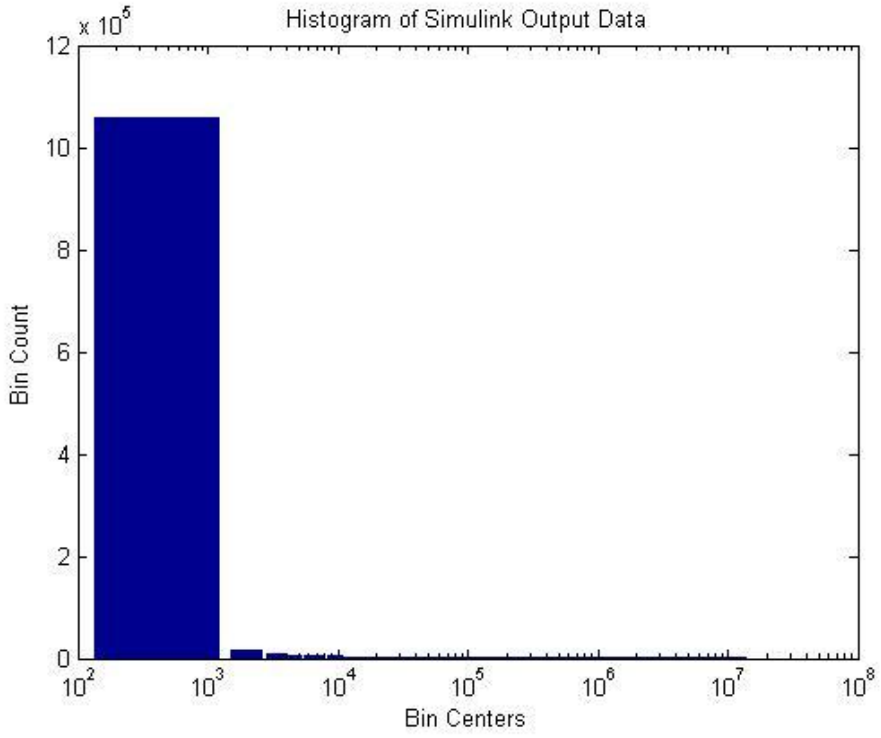

Figure 39: Histogram of P_{inst} of Current with Source=110CPM & Load=48.8Ω/open Every 1min; P_{st}=525.9

One of the most important inferences from the various results is that over a very systematic method of testing the results retain similarities. The nature of the histograms coupled with the instantaneous flicker severity plots from each measurement point implies that there is significant statistical correlation. These results provide reasoning for using both voltage and current measurements in flicker severity analysis.

4.2 v_1-v_2 Results & Analysis

In this section, results are presented for the input waveform, P_{inst}, histogram, and P_{st} from the flickermeter after running data for v_1-v_2 in each setup. This notation refers again to Figure 2 in the Introduction: v_1 being the source voltage and v_2 as the load voltage. The testing scenarios explored here are the same as those in the previous section of analysis to provide for easy reference. Due to the nature of the flickermeter and input signals, the results are not dependent on the order of subtraction. The process can be interpreted in several ways but ultimately it provides a voltage directly proportional to the load current. Passing the resulting waveform through the flickermeter should give insight as to the flicker resulting from the load's fluctuating current.

An example current input waveform is given in Figure 40. Note that the input magnitude is lower than the actual value due to a 10:1 current transformer used for measurement purposes. It can easily be seen from the calculated voltage input waveform plots in Figures 47, 50, 53, and 56 that the resulting

voltage signal closely resembles that of the current. Again, these values are lower than actual due to a 100:1 voltage divider in the signal conditioning box used for measurement purposes. The P_{inst} plots also mimic those of the previous section. Spikes due to the voltage change caused by the switching load resistance are stacked on top of the source response. This results in histograms of similar construction to those in the previous section. Again, this shows evidence of statistical correlation between the various histograms across methodologies and test scenarios. In Table 6 the testing scenarios and P_{st} values are given along with their corresponding figure number.

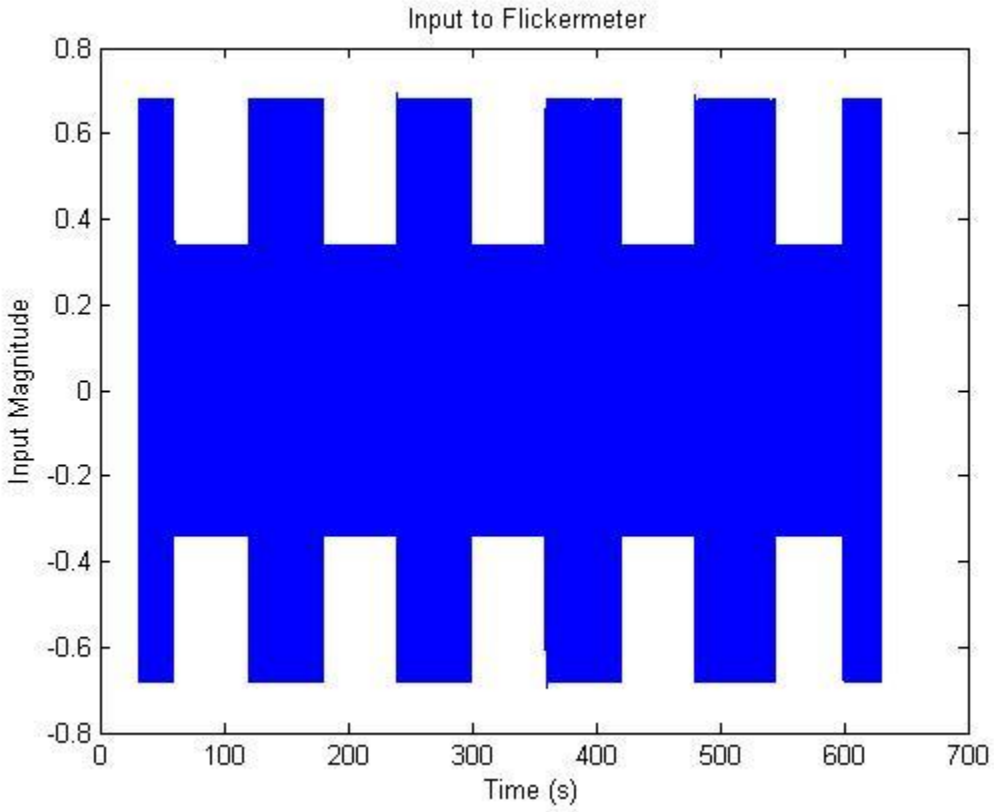

Figure 40: Current Input at 110CPM Source Flicker with 48.8Ω/24.5Ω Load Switching Every 1min

LABEL	SOURCE	LOAD	P_{st} (V_1-V_2)
Figure 41	110 CPM	48.8Ω Constant	2.020
Figure 42			
Figure 43			
Figure 45	60Hz Sine		1.808
Figure 46			
Figure 47			
Figure 48	110 CPM	48.8 Ω/Open Switch Every 1min	56.50
Figure 49			
Figure 50			
Figure 51	60Hz Sine		59.04
Figure 52			
Figure 53			
Figure 54	110 CPM	24.5 Ω/48.8 Ω Switch Every 1min	38.31
Figure 55			
Figure 56			
Figure 57	60Hz Sine		43.12
Figure 58			
Figure 59			

Table 6: Figure List for Obtained Testing Results

These P_{st} results suggest possible anomalies. The summations laws that exist for mathematically combining multiple flicker sources would suggest that P_{st} for two sources of flicker should be greater than when only one source of flicker is present. Two possible reasons this isn't the case are that error may be magnified due to the low signal levels and that depending on when the fluctuations of each flicker source occur in time, they could partially cancel instead of add. This could also be why the P_{st} level isn't zero when everything is constant. But the point is that the value of these tests isn't contained within these P_{st} numbers but within the resulting histograms of P_{inst} that follow and any noticeable trends therein.

Flickermeter input, histogram, and P_{inst} results from a setup where the source output is a 110CPM flicker test point and the load is a constant 48.8Ω

resistance are given in Figures 41, 42, and 43. The histogram results more closely resemble those of a sine wave source from the previous section. This is due to the fact that the only source of flicker is at the source.

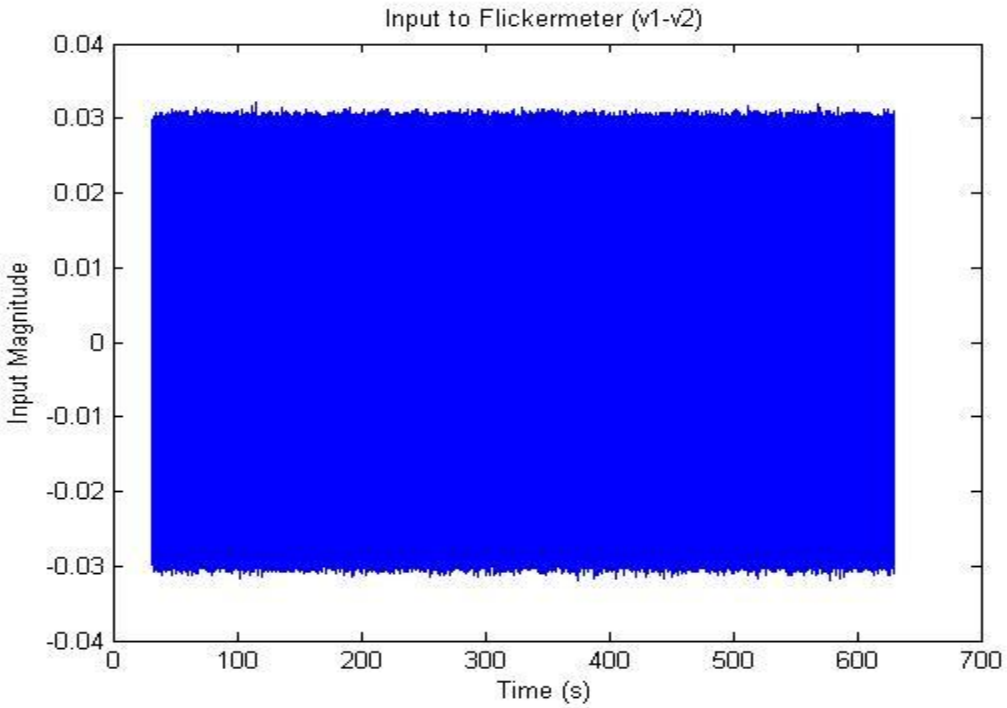

Figure 41: Input (v_1-v_2) at 110CPM Source Flicker with 48.8Ω Load Resistance;P_{st}=2.0202

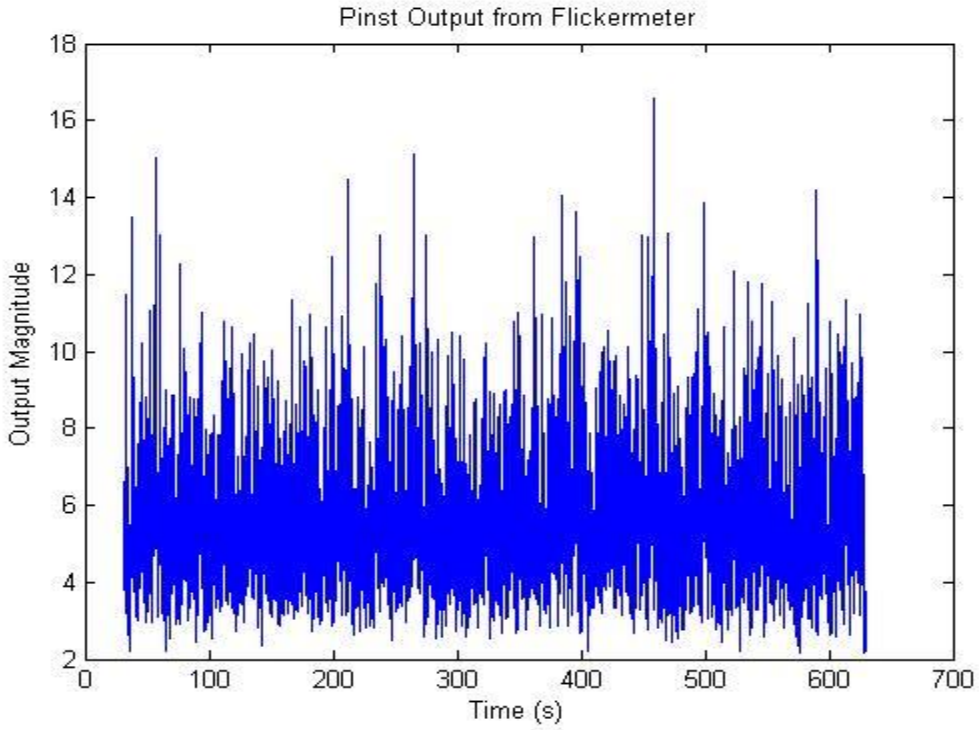

Figure 42: P_{inst} of v_1-v_2 at 110CPM Source Flicker with 48.8Ω Load Resistance; P_{st}=2.0202

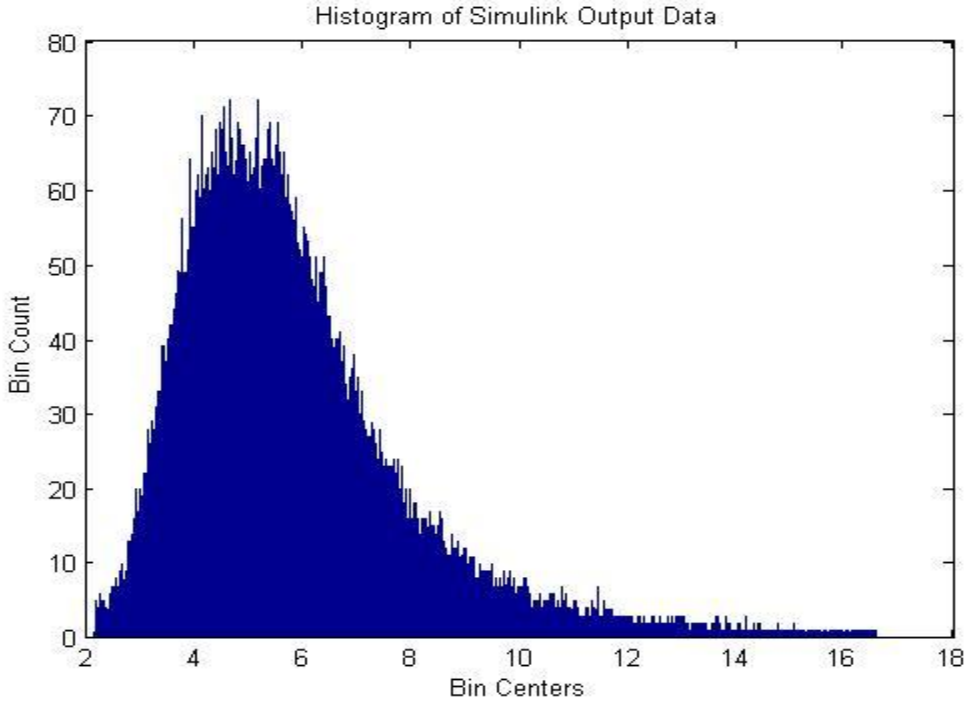

Figure 43: Histogram of P_{inst} of v_1-v_2 at 110CPM Source Flicker with 48.8Ω Load Resistance; P_{st}=2.0202

Evidence of some measurement error or small signal noise can be seen in Figures 42, 43, 46, and 47. In these cases the resulting P_{inst} of the v_1-v_2 waveform is expected to be effectively zero. With measurement error in the larger signals (v_1 and v_2) this error is magnified when subtracting and is larger relative to the smaller v_1-v_2 signal. A P_{inst} result of v_1 from a setup where the source output is a 60Hz sine wave from the amplifier while the load is a constant 48.8Ω is given in Figure 44. This shows the noise occurring at a much lower level relative to the large signal, nearly zero, which is as expected.

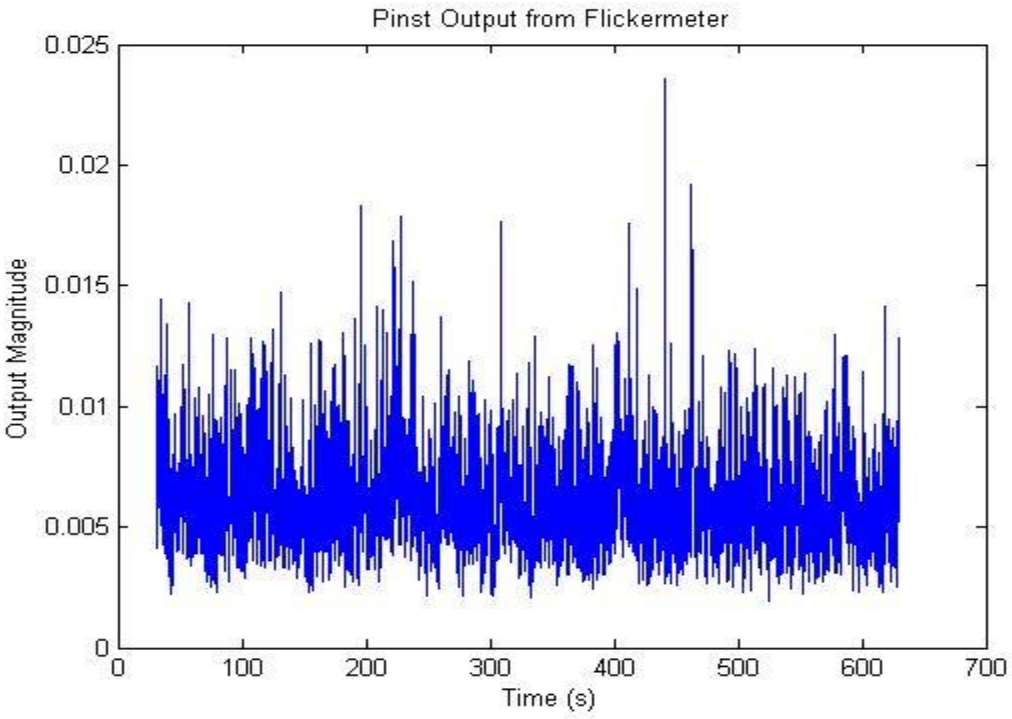

Figure 44: P_{inst} of v_1 with 60Hz Sine Source and 48.8Ω Load Resistance

Flickermeter input, histogram, and P_{inst} results from a setup where the source output is a 60Hz sine wave from the amplifier while the load is a constant 48.8Ω resistance are given in Figures 45, 46, and 47. It can be seen that Figure

47 closely resembles Figure 18 of the previous section. This is a good sign as it was expected to resemble the histogram from the P_{inst} of the current for the same testing scenario.

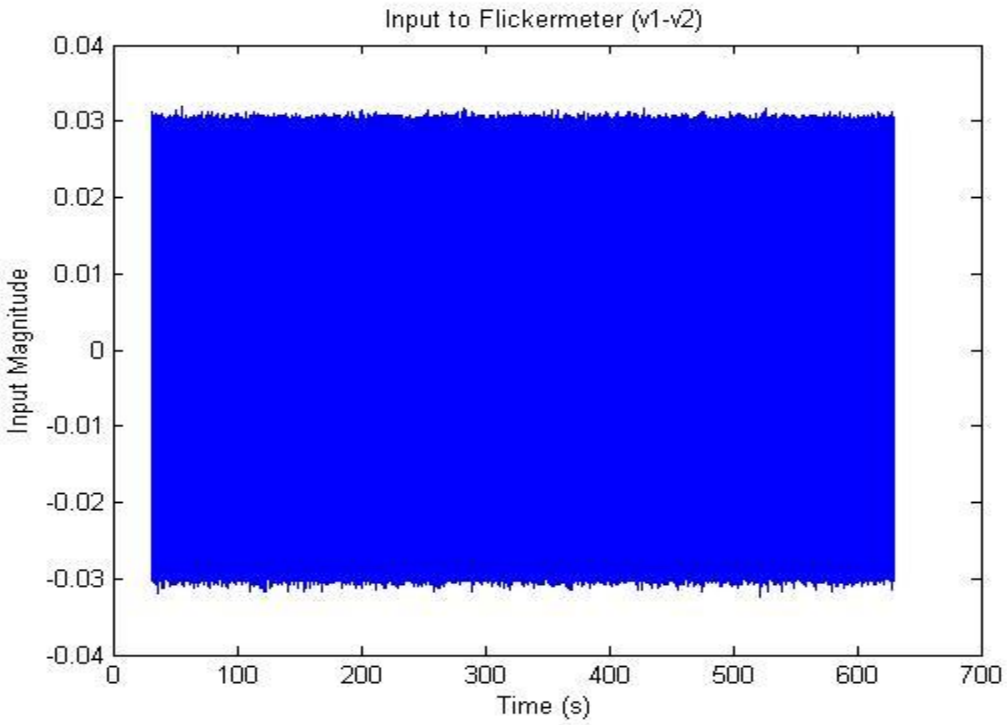

Figure 45: Input (v_1-v_2) at 60Hz Sine Source with 48.8Ω Load Resistance; P_{st}=1.8079

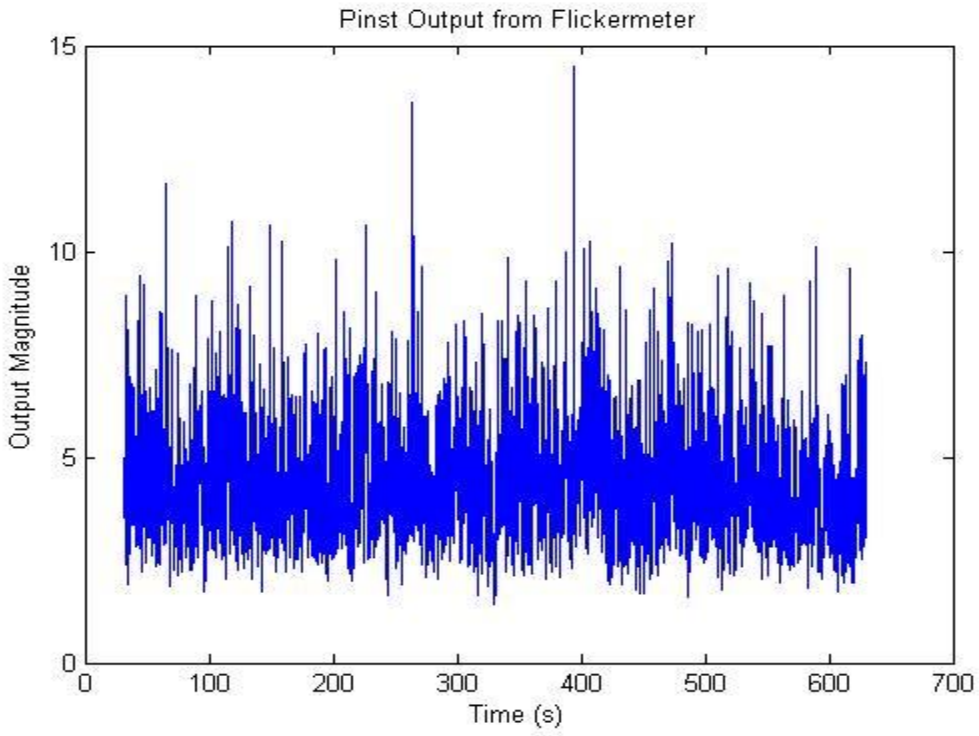

Figure 46: P_{inst} of v_1-v_2 at 60Hz Sine Source with 48.8Ω Load Resistance; P_{st}=1.8079

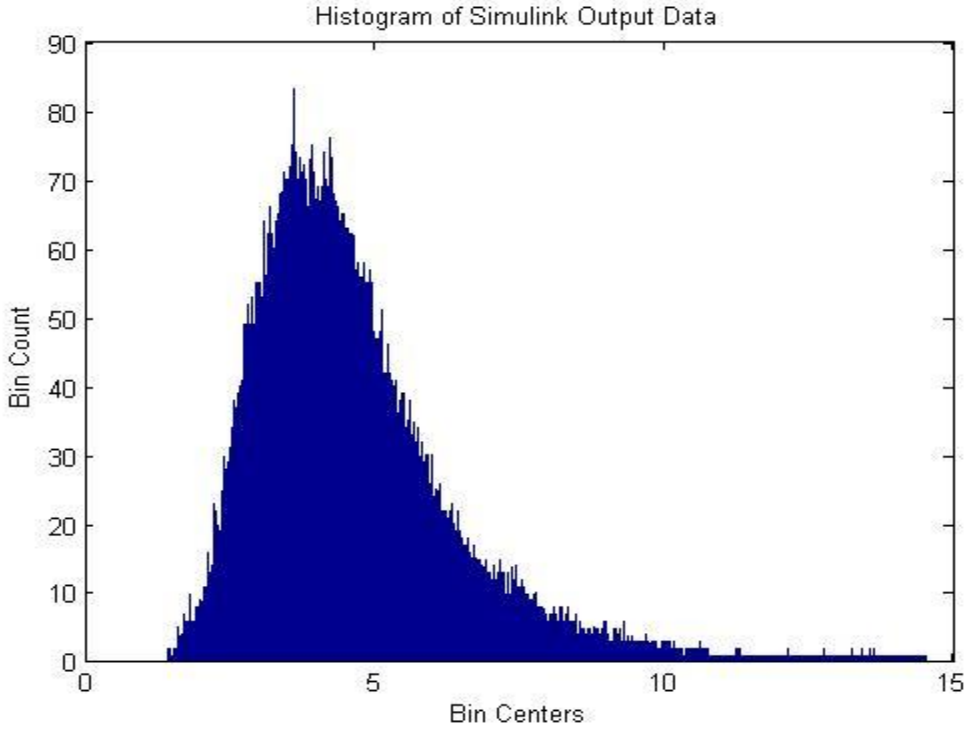

Figure 47: Histogram of P_{inst} of v_1-v_2 at 60Hz Sine Source with 48.8Ω Load Resistance; P_{st}=1.8079

Flickermeter input, histogram, and P_{inst} results from a setup where the source output is a 110 CPM flicker test point and the load changes between 48.8Ω and open every 1 minute are given in Figures 48, 49, and 50. It can be seen that Figure 50 closely resembles Figure 39 of the previous section. As expected, the histogram from the P_{inst} of the current resembles that of v_1-v_2 for the same testing scenario. In this case it can be seen that the large P_{inst} spikes are driving all the data into the first few bins of the histogram. This becomes a pattern for all testing scenarios that flicker at the load has introduced. It should also be noted that small signal noise is likely increasing the value around which P_{inst} is centered. This causes the lower bin centers to be higher than expected.

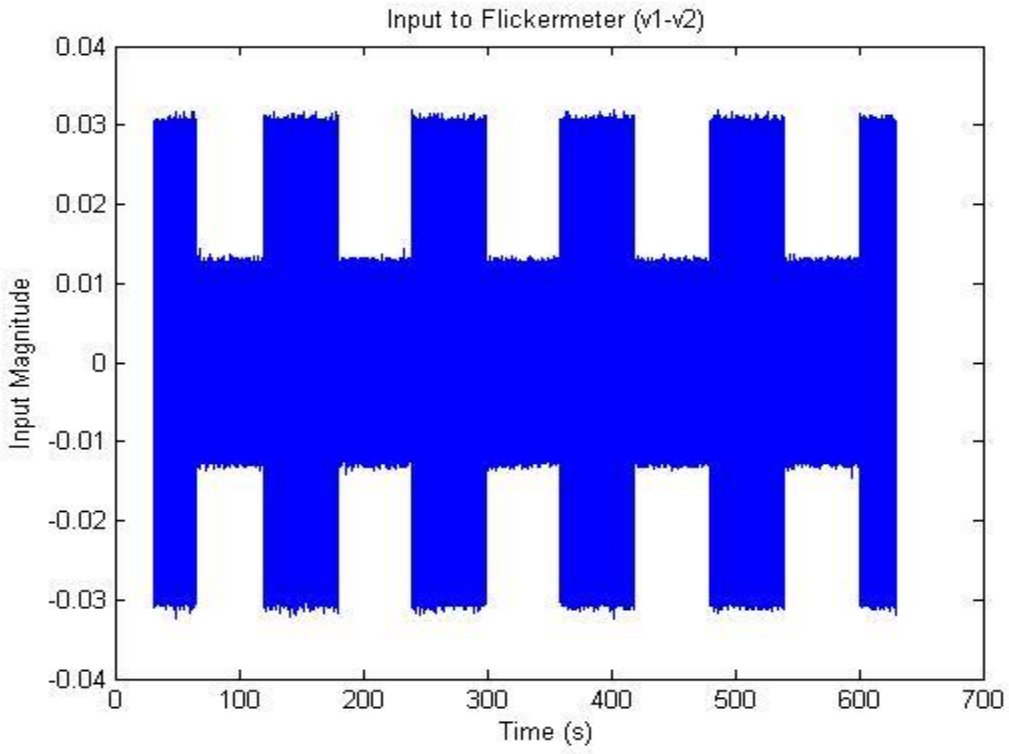

Figure 48: Input (v_1-v_2) at 110CPM Source Flicker with 48.8Ω/Open Load Switching Every 1min; P_{st}=56.4052

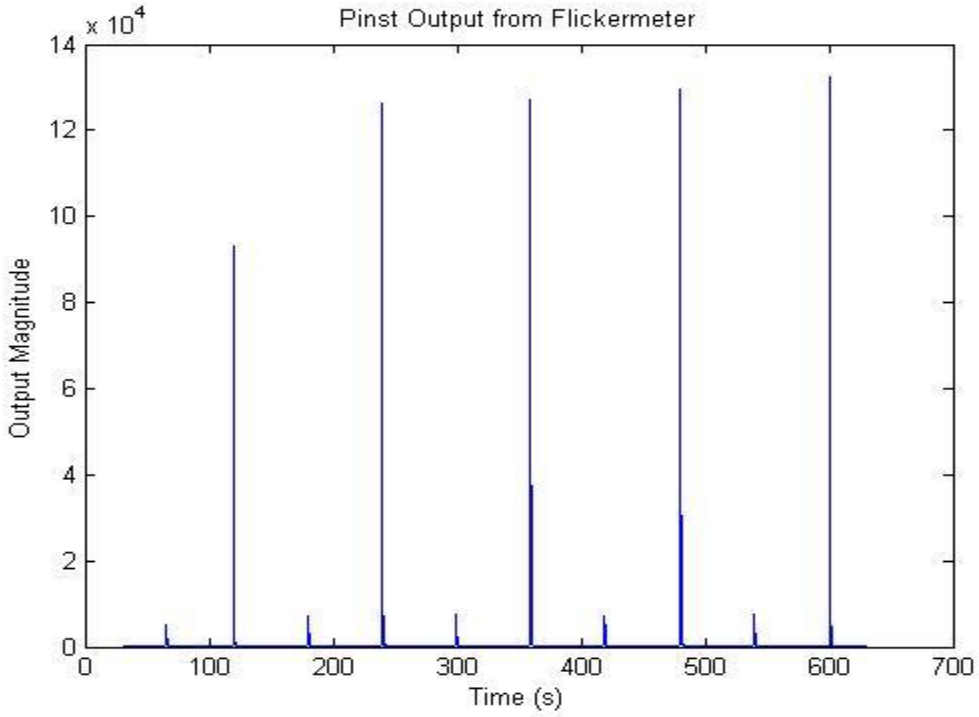

Figure 49: P_{inst} of v_1-v_2 at 110CPM Source Flicker with 48.8Ω/Open Load Switching Every 1min; P_{st}=56.4052

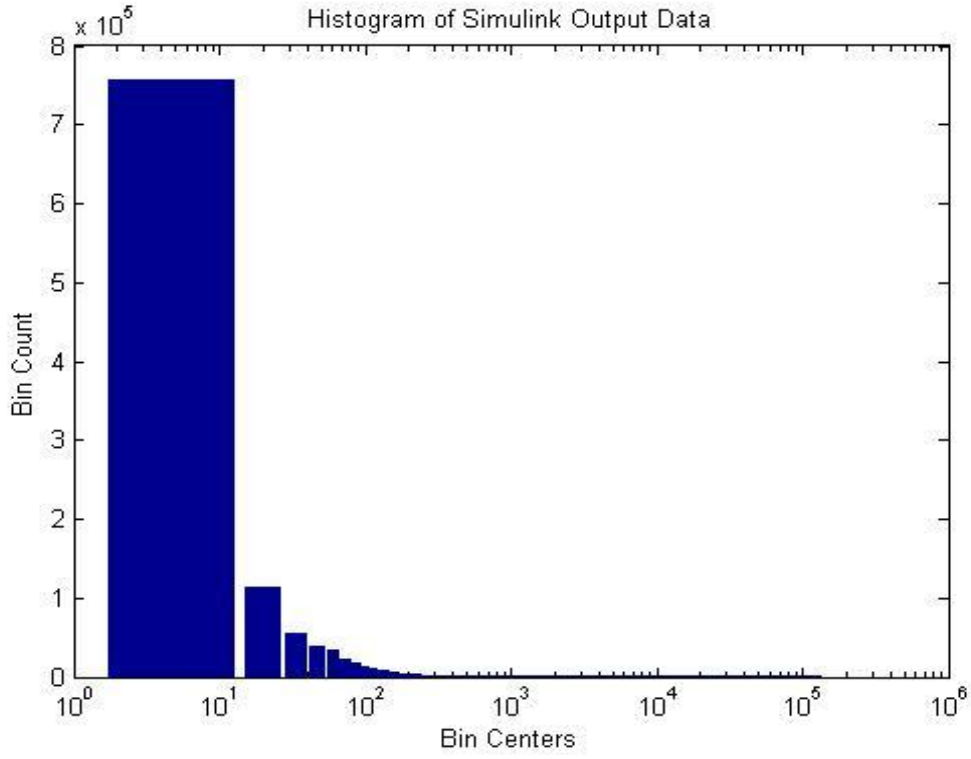

Figure 50: Histogram of P_{inst} of v_1-v_2 at 110CPM Source Flicker with 48.8Ω/Open Load Switching Every 1min; P_{st}=56.50

Flickermeter input, histogram, and P_{inst} results from a setup where the source output is a 60Hz sine wave and the load changes between 48.8Ω and open every one minute are given in Figures 51, 52, and 53. It can be seen that Figure 53 closely resembles Figure 36 of the previous section. As expected, the histogram from the P_{inst} of the current resembles that of v_1-v_2 for the same testing scenario. Again, in this case it can be seen that the large P_{inst} spikes are driving all the data into the first few bins of the histogram.

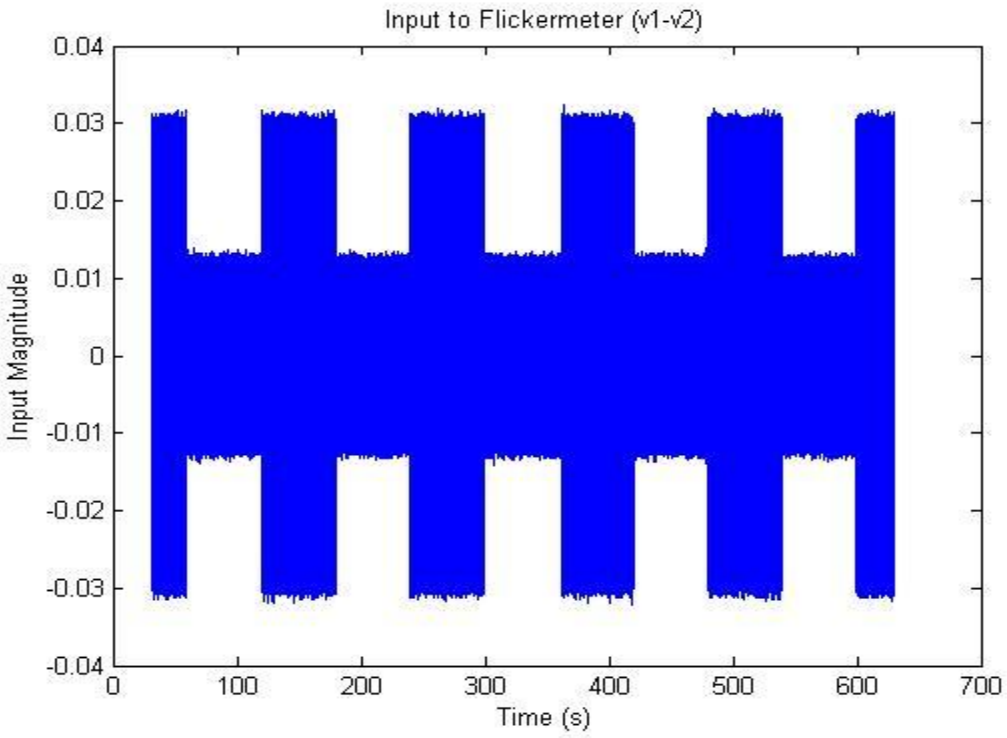

Figure 51: Input (v_1-v_2) at 60Hz Sine Source with 48.8Ω/Open Load Switching Every 1min; P_{st}=58.9633

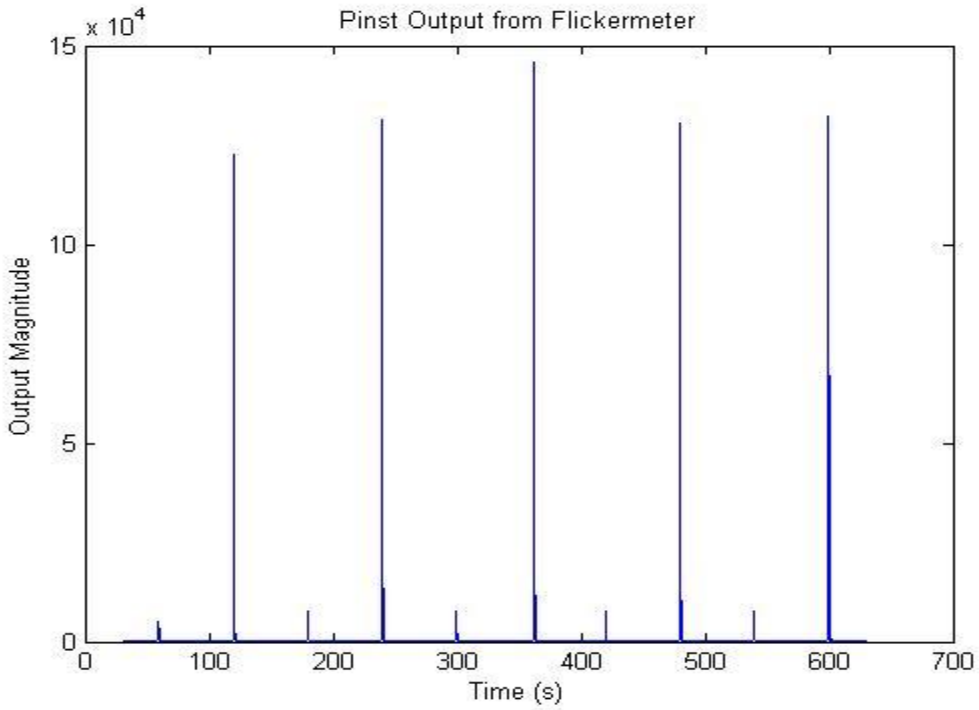

Figure 52: P_{inst} of v_1-v_2 at 60Hz Sine Source with 48.8Ω/Open Load Switching Every 1min; P_{st}=58.9633

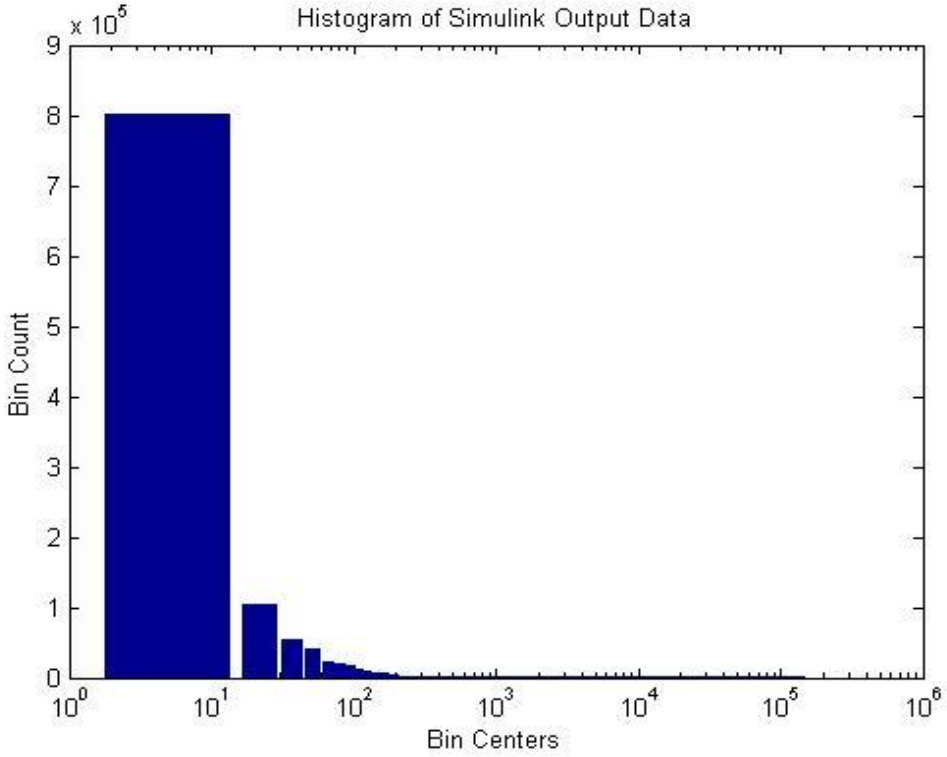

Figure 53: Histogram of P_{inst} of v_1-v_2 at 60Hz Sine Source with 48.8Ω/Open Load Switching Every 1min; P_{st}=59.04

Flickermeter input, histogram, and P_{inst} results from a setup where the source output is a 110CPM flicker test point and the load changes between 24.5Ω and 48.8Ω every 1 minute are given in Figures 54, 55, and 56. It can be seen that Figures 55 and 56 closely resemble the corresponding histogram and P_{inst} results from the previous section, seen in Figures 32 and 33.

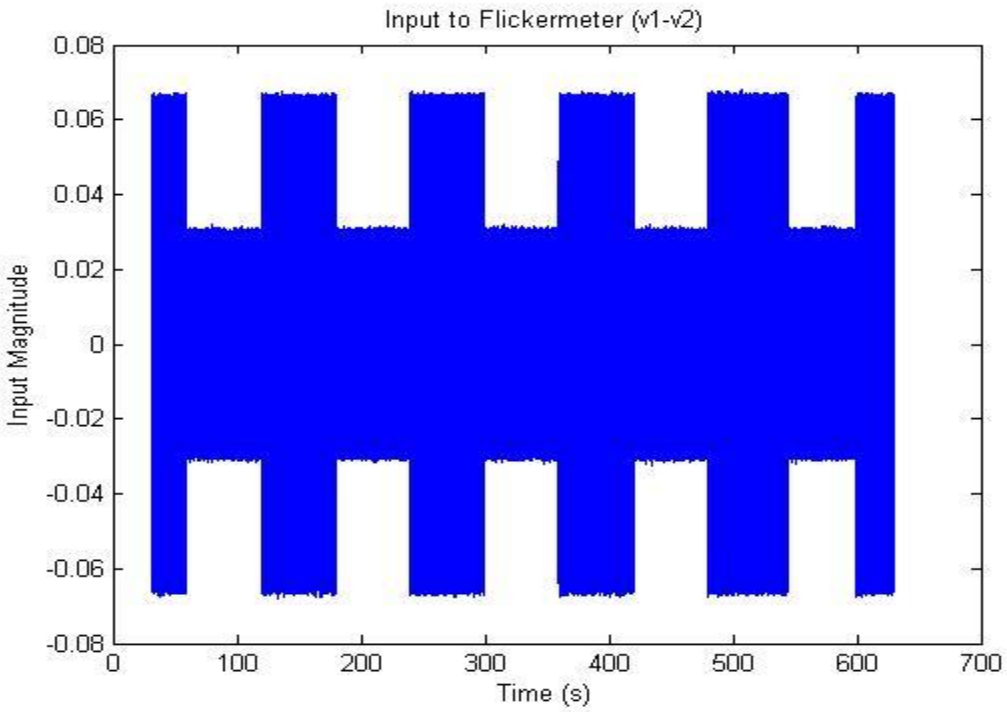

Figure 54: Input (v_1-v_2) at 110CPM Source Flicker with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=38.2787

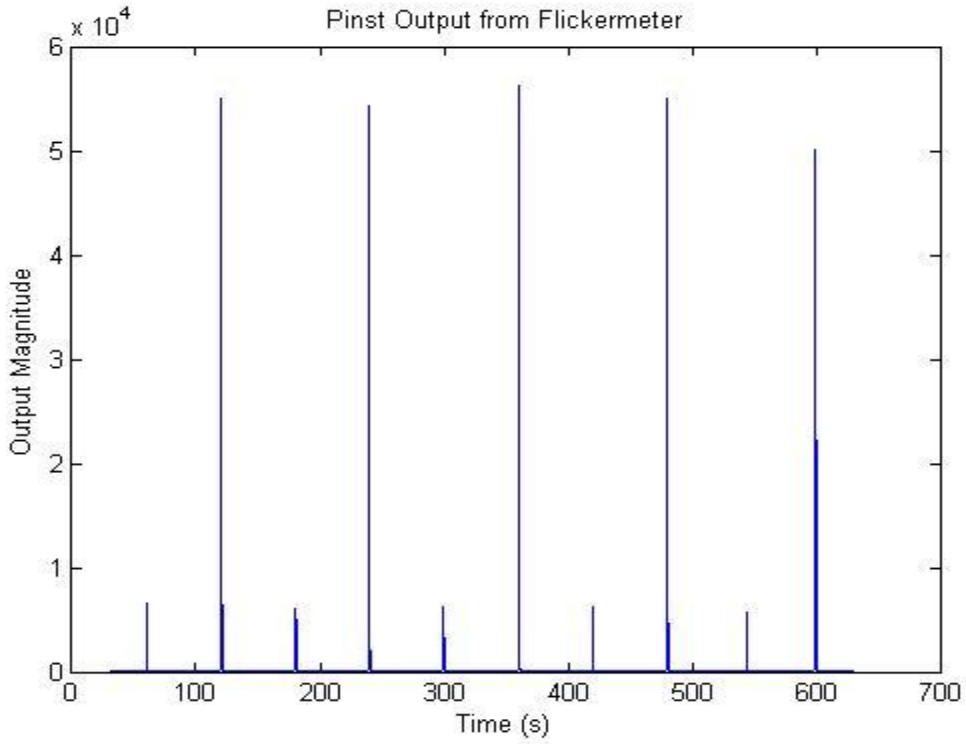

Figure 55: P_{inst} of v_1-v_2 at 110CPM Source Flicker with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=38.2787

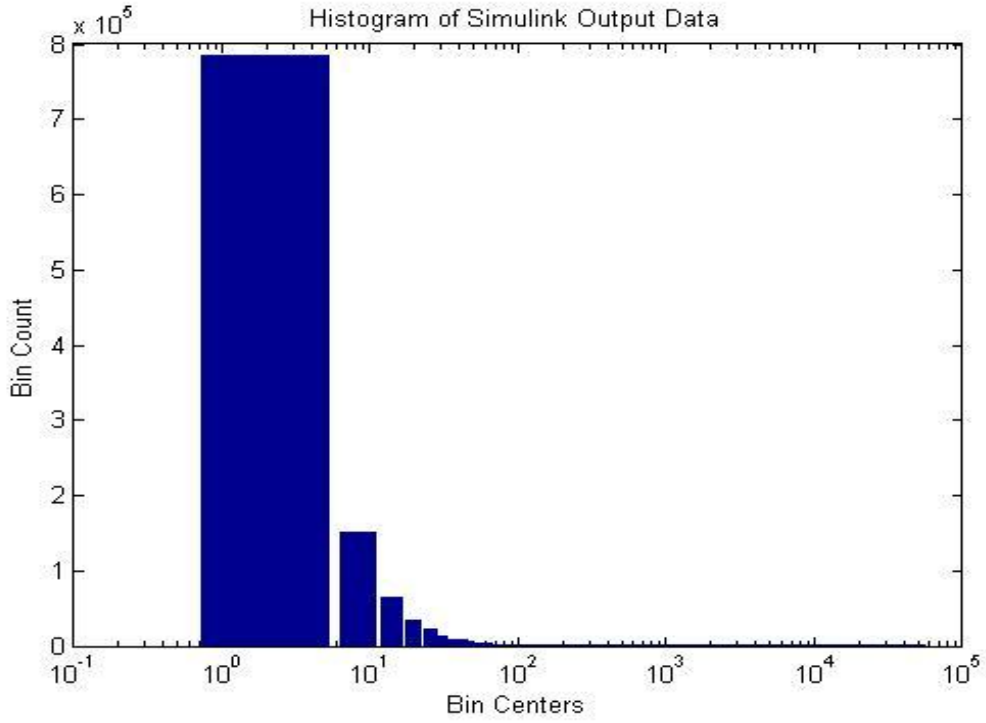

Figure 56: Histogram of P_{inst} of v_1-v_2 at 110CPM Source Flicker with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=38.31

Flickermeter input, histogram, and P_{inst} results from a setup where the source is a 60 Hz sine wave and the load changes between 24.5Ω and 48.8Ω every one minute are given in Figures 57, 58, and 59. It can be seen that Figures 58 and 59 closely resemble the corresponding histogram and P_{inst} results from the previous section, seen in Figures 26 and 27.

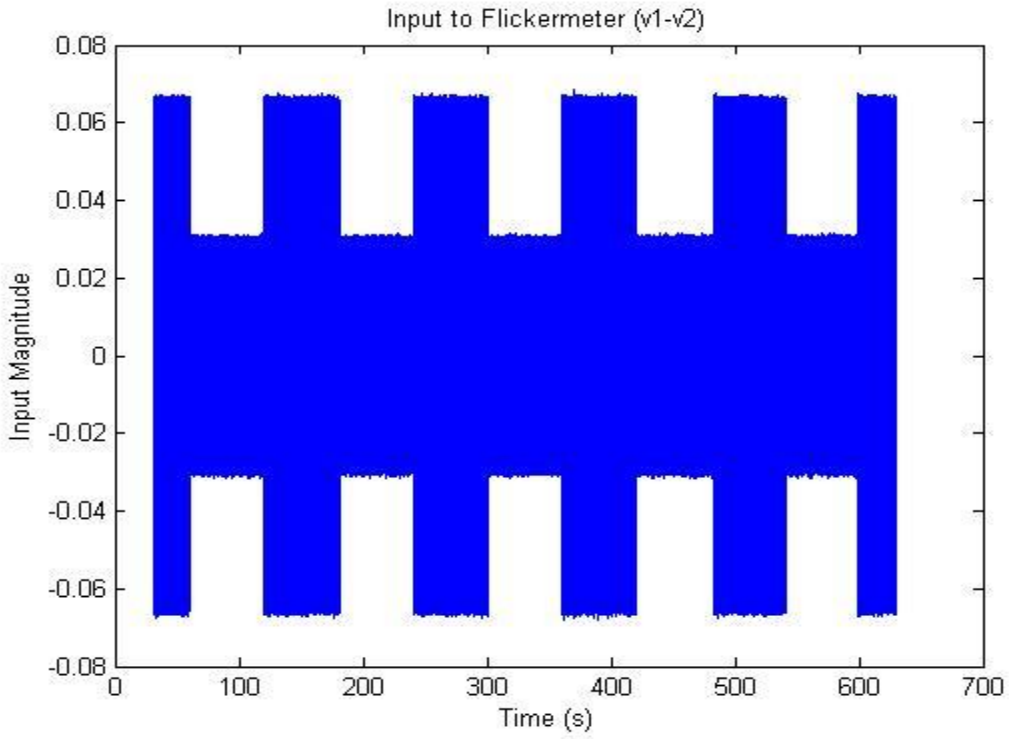

Figure 57: Input (v_1-v_2) at 60Hz Sine Source with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=43.0900

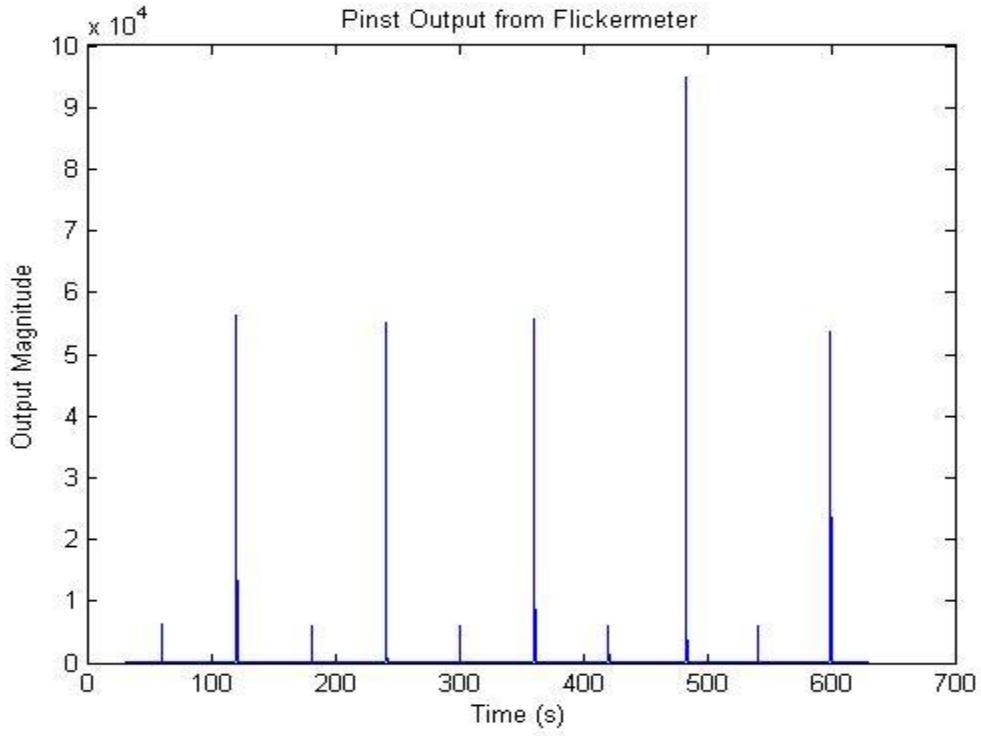

Figure 58: P_{inst} of v_1-v_2 at 60Hz Sine Source with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=42.0900

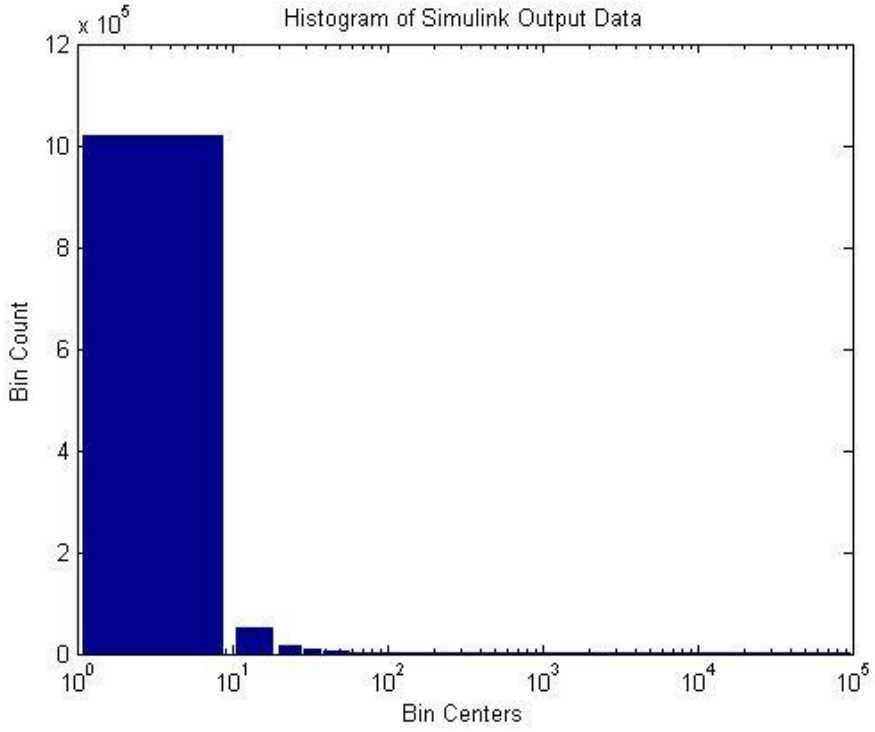

Figure 59: Histogram of P_{inst} of v_1-v_2 at 60Hz Sine Source with 24.5Ω/48.8Ω Load Switching Every 1min; P_{st}=43.12

A few conclusions can be drawn from the results of the v_1-v_2 test scenarios. As was expected, with purely resistive line impedance, the voltage v_1-v_2 closely resembles the corresponding current waveforms from the previous section. This naturally leads to the same trends in the P_{inst} and histogram results and their behavior between test cases. Some small signal noise is likely causing minor anomalies but doesn't greatly impact the general behavior or trends seen between test cases. It is clear that there is some correlation between the histograms of the current and v_1-v_2. Though, it should also be noted that these results may not be indicative of those in a practical scenario due to the nature of the line impedance. These results also provide insight for analysis and serve as a base for comparison with results from test scenarios using an RL line impedance model. Simulations of such scenarios are presented in the following section. It should be noted that these computer simulations are not affected by the previously discussed measurement error.

4.3 RL Line Impedance Results & Analysis

To examine a more practical situation, simulations of a model with RL line impedance were analyzed. Test scenarios will focus on differing X/R ratios as opposed to various source and load flicker scenarios. Histograms of the P_{inst} results for the current and v_1-v_2 waveforms are presented along with the corresponding P_{st} results. Analysis of the results from v_1 and v_2 was also

performed and remains consistent with the corresponding results from section 4.1.

Effects from the RL line impedance are expected to cause the v_1-v_2 methodology to become unreliable due in part to a phase shift between the node voltages. Histogram results from the v_1-v_2 P_{inst} results would consequently show no signs of visible correlation with the histograms of the current P_{inst} results. The model was implemented within Simulink using the SimPowerSystems Blockset and can be seen in Figure 60. Note that these results can't be compared exactly with those from the previous sections as there is no source output impedance present in this model.

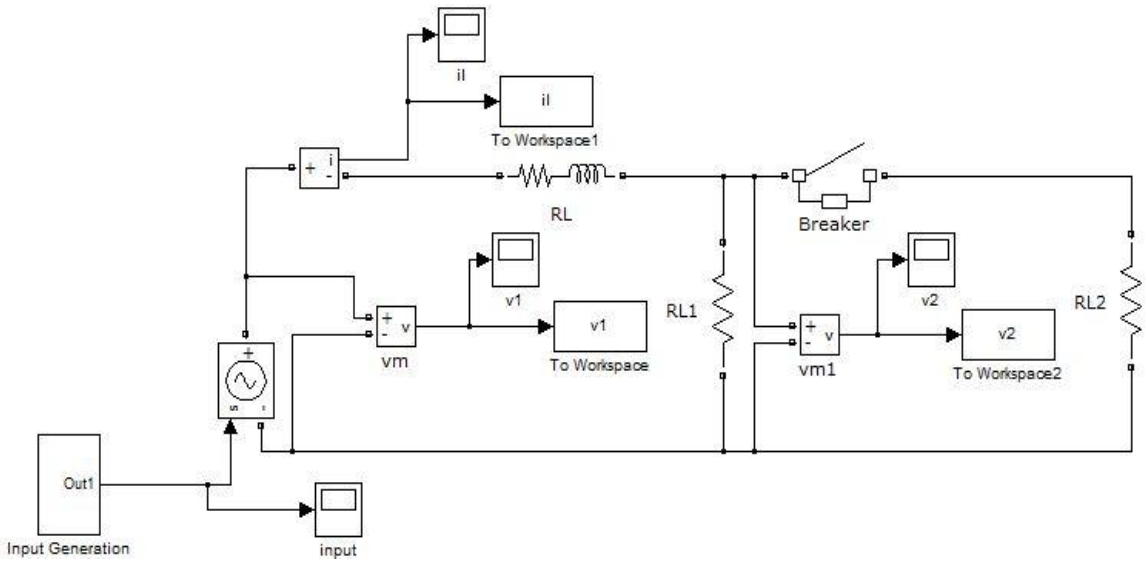

Figure 60: Simulink Model for Testing with RL Line Impedance

The source flicker in all cases is 110 CPM while the load switching for all cases is 24.4Ω↔48.8Ω every 1 minute. In Table 7 the testing scenarios and P_{st}

values are given along with their corresponding figure number. Note that the x-axis has a log scaling to aid analysis.

LABEL	LINE IMPEDANCE	MEASUREMENT	P_{st}
Figure 61	X/R=1 R=0.7071 Ω L=1.876 mH	i	30.07
Figure 62		v_1-v_2	18.75
Figure 63	X/R=4 R=0.2425 Ω L=2.573 mH	i	30.67
Figure 64		v_1-v_2	6.140

Table 7: Figure List for RL Line Impedance Test Results: Source = 110 CPM; Load = 24.4Ω↔48.8Ω Every 1 min

The histogram of P_{inst} of the current from a setup where the line impedance X/R=1 is given in Figure 61. The histogram of the P_{inst} result of v_1-v_2 from a setup where the line impedance X/R=1 is given in Figure 62. It starts to become evident that the histograms aren't visibly correlated. This is due to the fact that with the introduction of inductance into the line impedance the v_1-v_2 voltage fluctuations are slightly less pronounced than those of the current.

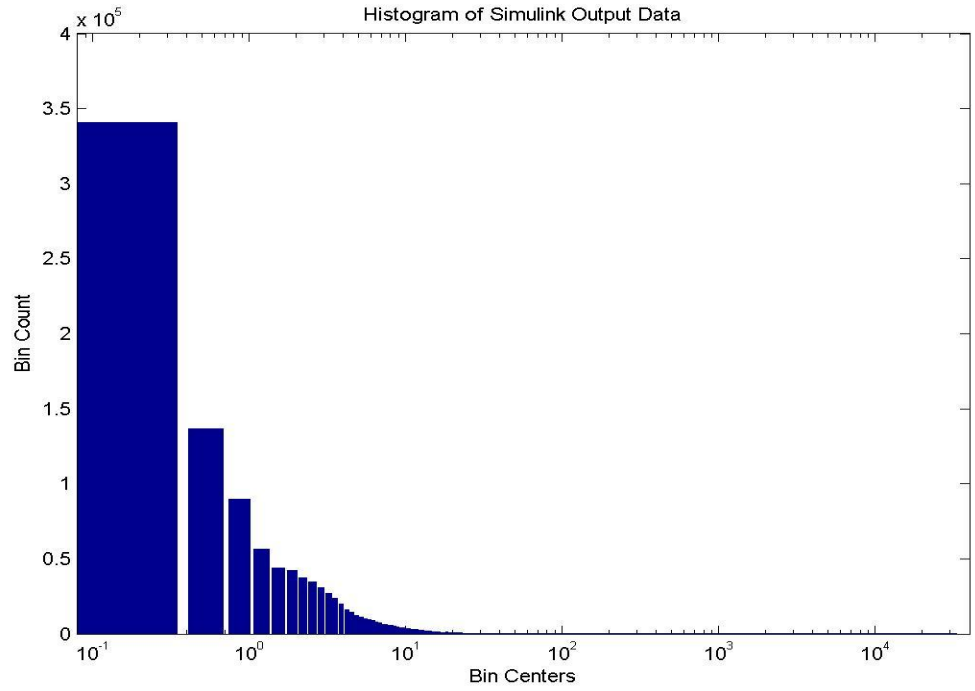

Figure 61: Histogram of P_{inst} of Current with Line X/R=1; P_{st}=30.07

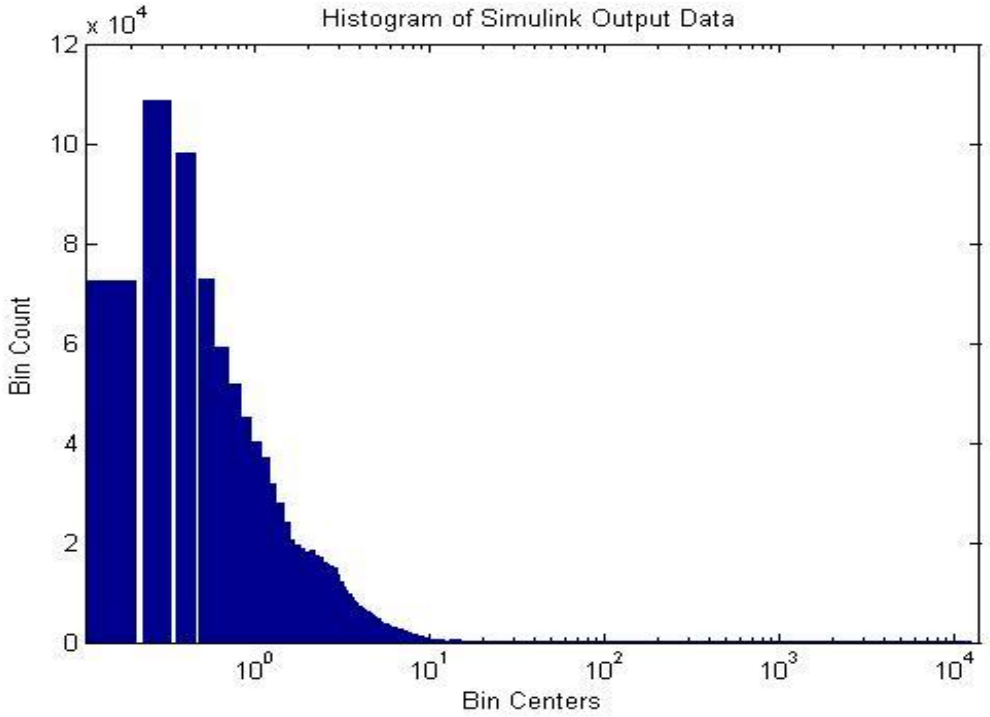

Figure 62: Histogram of P_{inst} of v_1-v_2 with X/R=1; P_{st}=18.74

The histogram of P_{inst} of the current from a setup where the line impedance X/R=4 is given in Figure 63. The histogram of the P_{inst} result of v_1-v_2 from a setup where the line impedance X/R=4 is given in Figure 64. It is clearer here that the histograms are no longer visibly correlated, as in the previous sections. With the RL line impedance X/R increasing, the voltage fluctuations of v_1-v_2 continue to scale down breaking consistency with the current fluctuations.

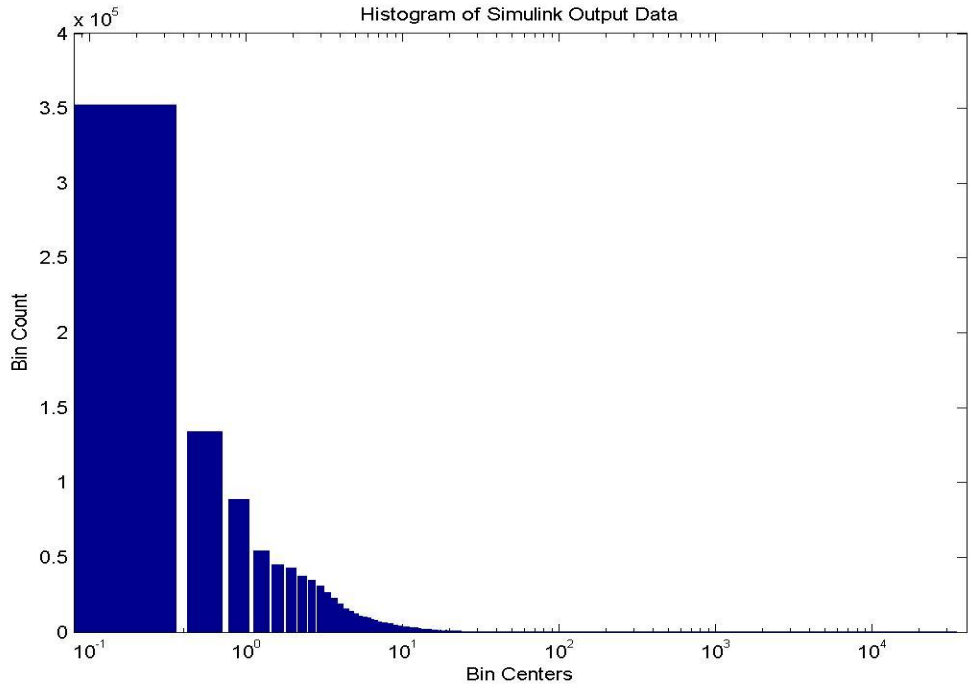

Figure 63: Histogram of P_{inst} of Current with Line X/R=4; P_{st}=30.67

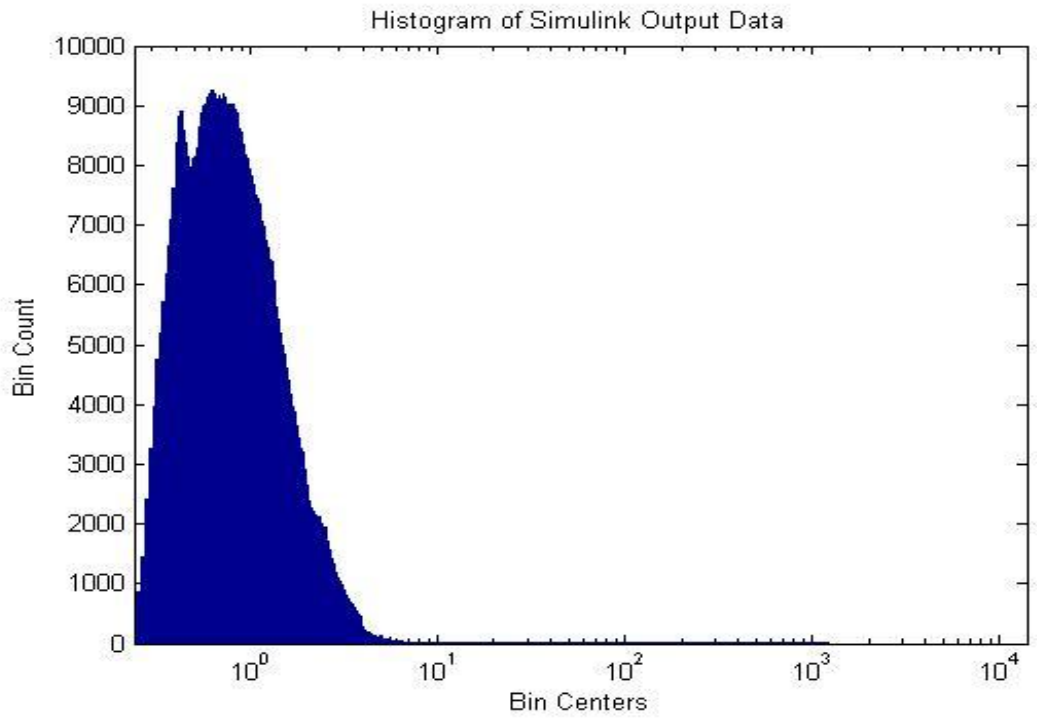

Figure 64: Histogram of P_{inst} of v1-v2 with Line X/R=4; P_{st}=6.140

After examining these histograms it is clear that RL line impedance has a huge impact on visible correlation between the current and v_1-v_2 results. As the line impedance X/R increases the v_1-v_2 voltage fluctuations decrease in magnitude and in response the histograms of the P_{inst} results no longer resemble those of the current. This implies that there wouldn't be any statistical correlation between the results and as such the v_1-v_2 methodology may not be feasible in practical situations. These results are based on computer simulations and should be examined in lab and field situations.

Chapter 5

Conclusions & Future Work

Flicker is a low frequency visual phenomenon that can disturb many customers on utility power systems. Flicker severity levels generated at one node must be kept below certain levels. These levels are monitored with a measurement device known as a flickermeter. A digital implementation of this device via MATLAB has been presented. The key points of this device are cyclic r.m.s. signal normalization, lamp-eye-brain chain response, and statistical evaluation. To use this implementation there are programs and processes needed for flicker waveform generation, data gathering, and data storage.

As there are typically multiple sources of flicker in a power system, methodologies for determining how much of the total flicker level an individual load is responsible for have been proposed, tested, and analyzed. A sufficient and systematic testing approach has been employed to determine the possibility of statistical correlation between various measurement and test scenarios. With a purely resistive line impedance there is evidence of visible correlation between current and v_1-v_2 analysis. There isn't such evidence for a more practical situation involving RL line impedance. For these various situations there has been discussion and analysis of flicker waveform generation, instantaneous flicker levels, and the calculation of short-term flicker severity.

This development and testing process has provided a strong foundation for much further research in this area of study. Employing the designed flickermeter implementation and testing processes will allow for easy examination of other proposed methodologies of flicker analysis. It will be important to examine a larger range of X/R line impedance ratios in both computer simulation and a lab setting. It would also be valuable to provide for better control over the variable load so as to allow for easy implementation of other testing scenarios, particularly using a less exaggerated flicker level at the load node. Most importantly the similarities between histogram results should be explored mathematically to determine if any statistical correlation exists. The ultimate goal is to perform field testing to validate the results from a lab setting.

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