AC 2010-84: COMPACT FLORESCENT LAMP HARMONIC ANALYSIS AND MODEL DEVELOPMENT-AN UNDERGRADUATE RESEARCH EXPERIENCE

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Compact Fluorescent Lamp Harmonic Analysis and Model Development -- An Undergraduate Research Experience

Abstract

Modern electrical devices should operate efficiently to reduce electricity consumption and environmental impacts without introducing undesirable side effects. Incandescent electric illumination is a very inefficient method for producing light. Compact fluorescent lamps have much higher conversion efficiencies but produce non-sinusoidal currents with high harmonic content. These harmonics can cause power quality problems in distribution systems that have significant numbers of compact fluorescent lamps installed. This paper documents the results of an undergraduate research experience in which a student performed harmonic analysis tests on compact fluorescent lamps from three manufacturers. The tests determine the harmonic composition of the lamp currents and their sensitivity to line voltage variation. Measurements using multiple lamps examine how harmonic currents combine. A circuit model derived from test data describes the lamp harmonic performance as voltage varies. An example tests the circuit model and computes voltage harmonic distortion for different levels of lamp load. The research experience utilizes many topics and skills taught in the student's curriculum and gives practical application to theory within a research context. The paper summarizes how this research experience enhanced the student's normal academic performance.

Introduction

Efficient utilization of electricity limits consumer costs, promotes better utility load factors, and reduces environmental impacts. Compact Fluorescent Lamps (CFL's) are much more efficient at producing light than incandescent bulbs. CFL's reduce electricity consumption by seventy-five percent compared to incandescent bulbs. Although CFL's are much more efficient, they require electronic ballasts to operate that can adversely affect power system operations.

Electronic ballasts are non-linear loads that generate harmonic currents of the 60 Hz line frequency.[1,2] Large, non-linear loads produce significant levels of harmonic currents that interact with system impedances. The result is voltage distortion, which can cause mis-operation of sensitive electronic equipment and interfere with communication systems. High levels of harmonic currents in a power system cause transformers and neutral conductors to overheat. The harmonic currents produce corresponding fluxes in transformers that reduce efficiency and contribute to power losses. Harmonic currents find return paths in neutrals, which add to the imbalance load currents in neutral conductors. IEEE Standard 519-1992 sets voltage and current distortion limits to address these issues.[3]

New government policies mandate all incandescent bulbs from 40 to 100 watts be phased out by 2014.[4] This will increase the penetration of CFL's into the distribution system. High penetration of CFL's could introduce sufficient harmonic currents into the power grid to cause widespread violations of voltage distortion limits. Research on CFL harmonic currents began shortly after product introduction and continues today to address possible effects of the large-scale application of these devices on the grid.[5,6,7,8,9]

Examining the harmonic content of CFL's provided an undergraduate research opportunity and enhanced the educational experience of the student. The undergraduate research assistant's work on the project augmented his current educational experiences and provided an application of previously acquired classroom knowledge. During the course of the project, the student engaged in literature reviews, fabricated test circuits, conducted experiments, analyzed data, and prepared results.

Undergraduate research offers several benefits to the student and university community. Previous work shows that student-faculty partnerships positively affect student retention especially in minority populations.[10] Other studies indicate participants in undergraduate research are more likely to pursue advanced degrees.[11,12] Undergraduate researchers are typically high achieving juniors and seniors with a long-standing interest in science and technology. Surveys of undergraduate researchers show that faculty mentors are important to student success. Mentors who combine enthusiasm with superior organizational, interpersonal, and research skills promote positive outcomes.[12] Increased emphasis on undergraduate research is part of the changing university mission to provide knowledge discovery opportunities for undergraduates and enhanced teaching and mentoring for graduate students.[13]

This paper reports the results of an undergraduate research project that measures the harmonic content of CLF's from three manufacturers. It also proposes a voltage-controlled harmonic model for studying the impact of harmonics in the secondary circuits of power distribution systems. In particular, the model focuses on how the number of CFL's affects voltage total harmonic distortion (THD). The paper examines the educational benefits of the research experience through a student report and personal interview. These methods examine how the student researcher applied concepts and skills learned during the research experience to current coursework.

Experimental Method

The project examined the harmonic current distribution of CFL's produced by three manufacturers. Table 1 lists the ratings and manufacturers tested. The experiments used 26 watt CLF's, which are equivalent in light production to 100 watt incandescent bulbs. The experimental apparatus used lamps installed in standard sockets and mounted in the vertical position with the lamp tube pointing up.

Table 1 - CFL Ratings

Manufacturer	Voltage (V)	Current (A)	Frequency (Hz)	Light Output (lumens)
Bright Effects	120	0.390	60	1750
GE Energy Smart	120	0.390	60	1600
Statco	120	0.430	60	1750

Figure 1 shows the connections used for all testing. An autotransformer provided a variable ac voltage source for the bulb tests. It connected to the local 120 V (nominal) outlet through an isolation transformer. The autotransformer produced a variable voltage output from 0 to 135 Vac. A modified ac line cord connected the autotransformer to the CFL. The line cord had a section of insulation removed and an insulated connector installed to allow current and voltage measurement. The experimental instrumentation consisted of an Agilent 1146 AC/DC current probe and an Agilent 54622D digital storage scope to make voltage and current measurements. Connecting several bulbs to this test setup measured the effects of harmonic current combination for multiple bulb installations.

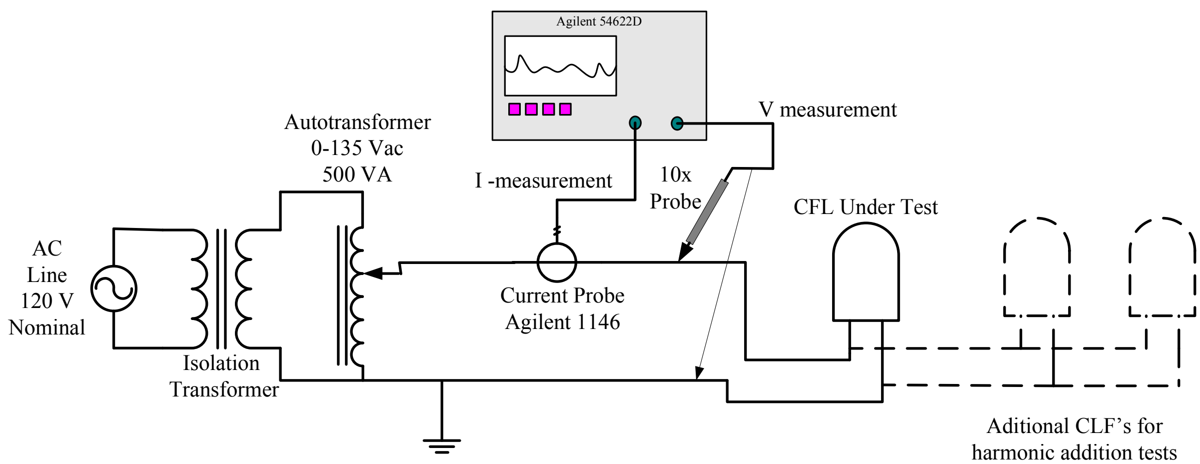


Figure 1. Compact Fluorescent Bulb Harmonic Current Test Apparatus.

The test procedure used the lamp voltage signal as a reference for the lamp harmonic current phase angle measurements. The current probe produces a voltage level proportional to the measured current using a Hall Effect sensor and has a bandwidth of dc-100 kHz. The current phase measurement was made by comparing the waveforms of the lamp voltage and scaled lamp current. The oscilloscope time base setting captured thirteen cycles of the 60 Hz voltage and current waveforms producing a sampling rate of 10,000 samples/second. The oscilloscope was set to average the voltage and current waveforms 64 times and then to record 2000-point current waveform data in CSV file format. Averaging the current waveform signal reduced noise and produced more repeatable measurements.

An analysis program written in MATLAB processed the current waveform data files to determine the signals' harmonic content. This program read the data files, scaled the data points using the current probe scale factors, plotted the scaled data for visual verification, and computed the Fast Fourier Transform (FFT) of the data. The program identified significant harmonic current components using the results of the FFT and displayed the magnitude and phase angle of these components for further analysis. The program computed the total harmonic distortion percentage for the sampled signal and displayed the value for later analysis.

Each experiment consisted of a series of measurements conducted on sample bulbs from each manufacturer. In these experiments, lamp line voltage was varied from 108 to 132 volts and current waveform data was produced for each voltage level. This is the expected operating voltage range of 120 V secondary distribution systems. A second series of tests consisted of voltage and current measurements over the range of 88 to 132 V. Analyzing these test data established a relationship between lamp harmonic currents and operating voltage.

A third test examined how the currents of CFL's combine when connected to the same voltage source. This test used the same apparatus as the other experiments with a minor modification. Two sockets added to the basic experimental apparatus allowed testing of the additive effects of lamp harmonics connected to the same circuit.

Experimental Results and Model Development

Figures 2, 3, and 4 summarize the first CFL experimental test results. Figure 2 plots CFL harmonic distortion as a function of the lamp voltage. Bright Effects and GE Energy Smart bulbs have similar characteristics, indicating the electronic ballast designs are similar. These devices show a minimum harmonic distortion value of 57%, ±0.5% occurring at approximately 116 V. Statco bulbs produce the highest harmonic distortion levels from 120 to 132 V, but then the levels decline rapidly, and are below other manufacturers' measured values from 116 to 108 V. Statco lamps are the least expensive of the three brands tested.

Figure 3 plots the total lamp current as a function of lamp voltage for the three manufacturers. Again, the Bright Effects and GE Energy Smart bulbs produce nearly identical results within the uncertainty of the experimental measurements.

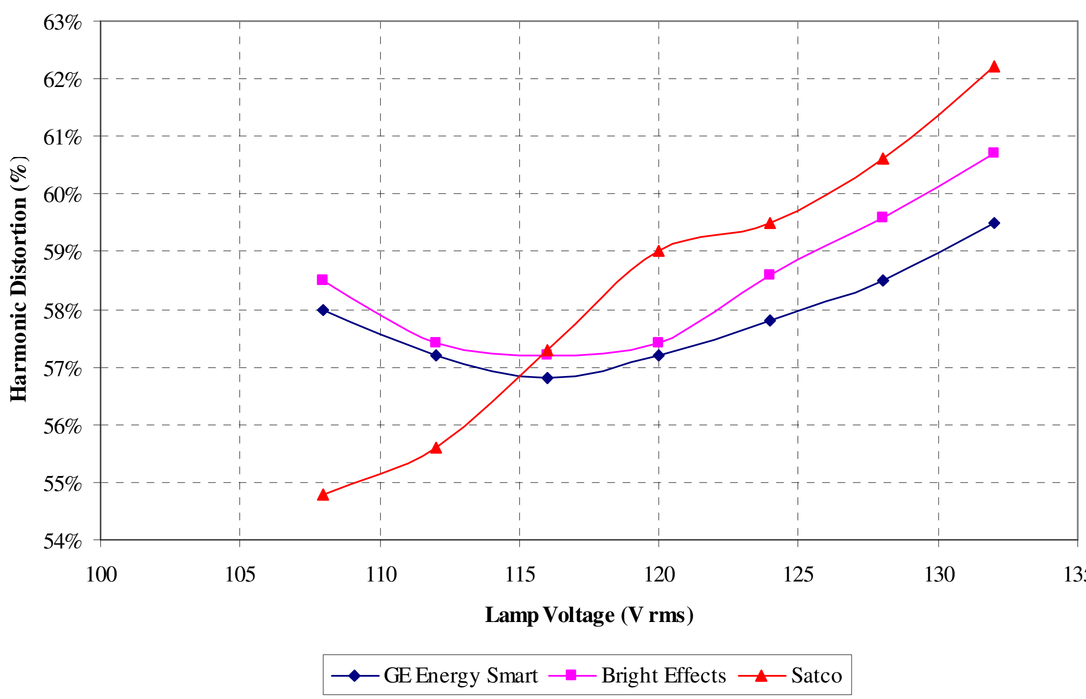


Figure 2. Lamp Total Harmonic Distortion as a Function of the Lamp Line Voltage.
Comparison of Three Manufacturers Lamps over Possible Operating Voltage Range.

Lamp currents rise slightly for these two bulbs as the lamp voltage reaches the lower test point values. The Statco lamp shows a slight decrease in lamp current for reduced lamp voltage.

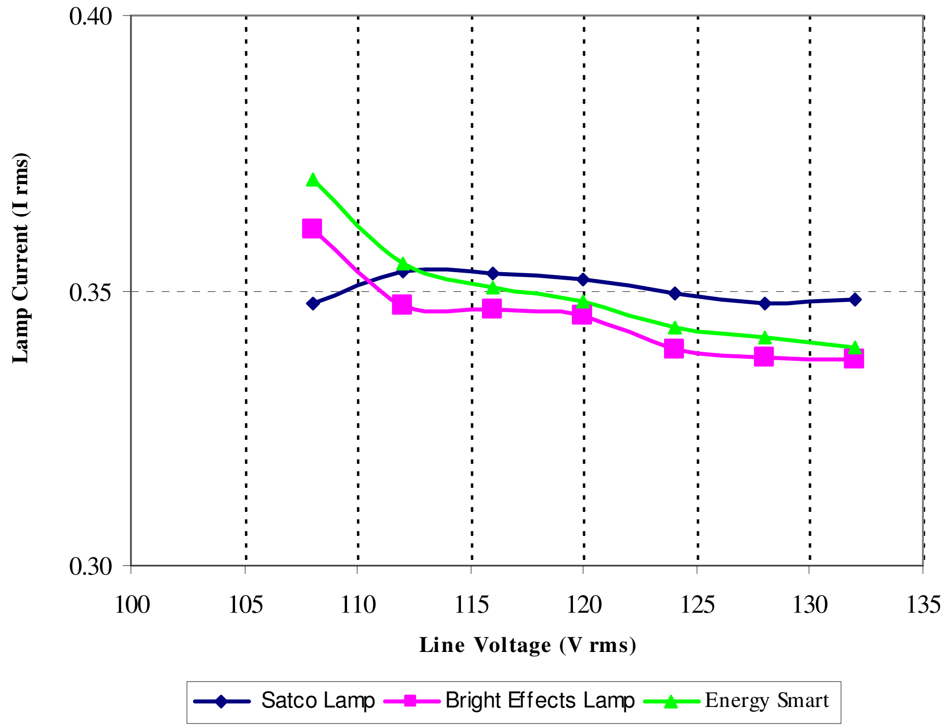


Figure 3. Lamp Current Comparisons Showing the Affect of Lamp Voltage Variation.

Figure 4 summarizes results of the second set of CFL experiments. The plots show how lamp harmonic currents vary with the lamp line voltage for the first nine current harmonics. These harmonics account for the majority of total lamp current. The FFT decomposition found that only odd harmonics of the 60 Hz fundamental frequency are present in the CFL current. Fundamental current decreases as the lamp voltage increases. This corresponds to the active power the bulbs absorb and convert to light. The 3rd harmonic currents are constant, while the 5th and 7th harmonics exhibit linear increases and decreases respectively over the test range. The 9th harmonic also increases as lamp voltage increases, but not in a linear manner.

Regression equations define the relationships between lamp harmonic currents and voltage. Figure 4 shows equations on the plot along with the correlation coefficient for each relationship. Linear models provide goods fits for the 1st, 5th and 7th harmonic data. The 3rd harmonic is considered constant. A quadratic function provides a good fit for the 9th harmonic data. Test data show that the 1st harmonic (60 Hz) current component leads lamp voltage implying a resistive-capacitive circuit model. Dependent current sources use the regression equations to represent the remaining harmonic currents in the circuit model.

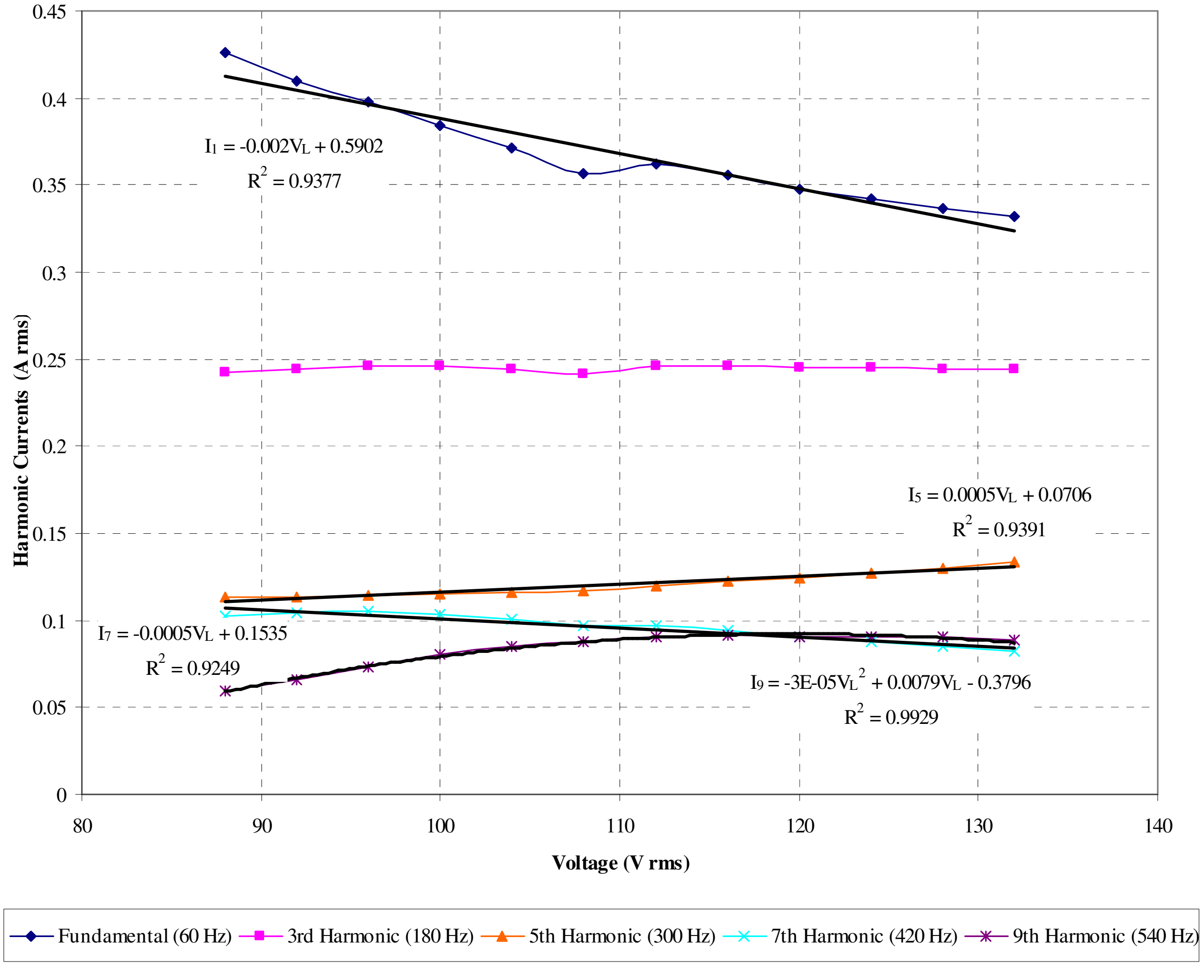
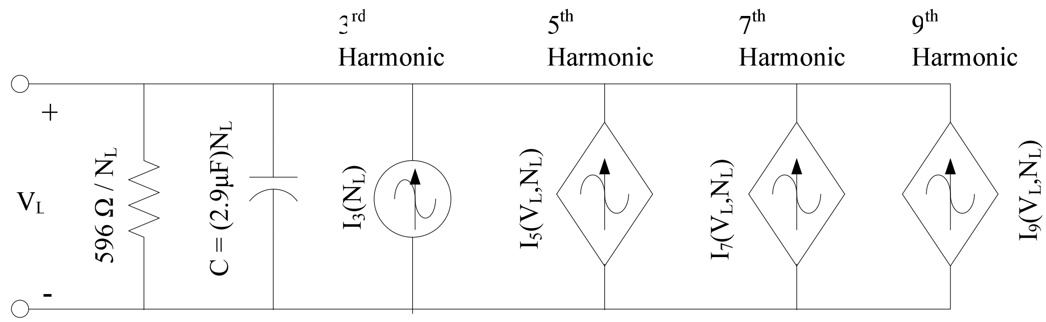


Figure 4. CFL Harmonic Current Relationship as a Function of Lamp Voltage.

The current addition experiments, performed with up to three lamps, determine that CFL harmonics increase proportionally as the number of bulbs increased. The test uses short interconnections between the lamps. This approximates conditions in residential locations. Based on this test, it may be assumed that multiple lamps installed within close proximity produce harmonic currents that add.

Figure 5 shows the model derived from the CFL harmonic test results. A parallel resistor-capacitor combination represents the fundamental (60 Hz) CFL load current. The model represents multiple installations of the bulbs by the scaling factor N_L. This model assumes that CFL's draw 60 Hz currents and are a harmonic current source. An independent current source with a constant value represents the 3rd harmonic current injections. Dependent current sources represent the remaining harmonic injections. The dependent sources use the regression equations shown in Figure 4 to relate terminal voltage to the 5th, 7th, and 9th harmonic currents. The constants in the relationship reflect scaling to produce peak current values.



$$I_3(N_L)=(0.348)N_L$$
$$I_5(V_L,N_L)=(0.000707\times V_L + 0.0998)N_L$$
$$I_7(V_L,N_L)=(-0.00707\times V_L + 0.217)N_L$$
$$I_9(V_L,N_L)=[(-3\times 10^{-5}\times V^2_L) + (0.0079\times V_L) - (0.3796)]\ N_L$$

Figure 5. CFL Harmonic Model Derived from Test Data.

High saturation of CFL's in distribution secondary circuits due to the phase out of incandescent bulbs will introduce many CFL harmonic sources. These sources can interact with system impedances to cause high levels of voltage distortion that can adversely affect power system operation even on a small scale, such as a residential distribution transformer. A MATLAB Simulink system implements the CFL circuit model in Figure 5 to test the impact of multiple CFL installations in a 120/240 volt secondary circuit.

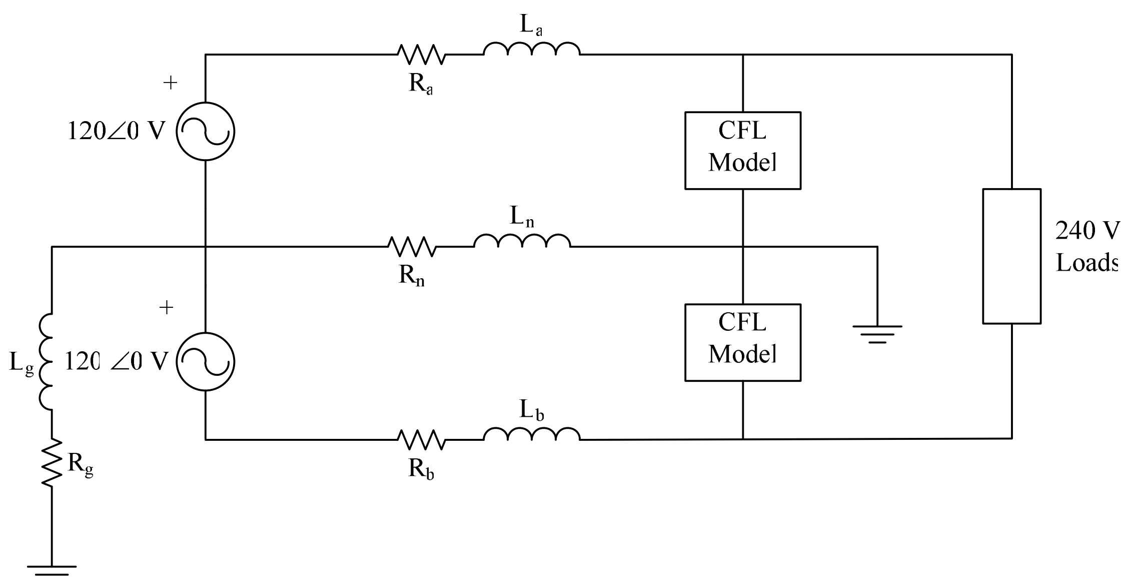


Figure 6. Distribution Secondary Model used For Harmonic Distortion Analysis.

Figure 6 shows the system used for harmonic distortion simulations. Table 2 gives values of secondary resistance and inductance for each secondary conductor and values for the ground path. The secondary conductor resistances and inductances include impedances for 200 feet of No. 4 aluminum triplex overhead service conductor, a 25 kVA 12.47-120/240 V transformer, and 5 miles of 1/0 ACSR primary conductor built to12.47 kV spacing. All impedances values are referred to the secondary side of the transformer. A lumped resistance value represents 5,000 watts of 240 V load operating at rated voltage.

Table 2- Simulation Impedance Values

	Resistance (ohms)	Inductance (μH)
a-phase	0.1067	41
b-phase	0.1067	41
neutral	0.1500	41
ground	3.5000	1,000

Figure 7 plots the results of a series of MATLAB Simulink simulations with an increasing number of CFL's installed. Increasing the number of bulbs cause the voltage THD to increase proportionally. High levels of voltage THD require large numbers of coincidently energized bulbs. This is not likely to occur in a single residence but may be possible in multiple residences served from a single distribution transformer. Fifty bulbs divided among five homes served by the same transformer gives a reasonable average of ten bulbs per residence. Voltage harmonic distortion produced by CFL's may also add to voltage distortion generated by other electronic devices connected to transformer secondary circuits mitigating part of the voltage THD.

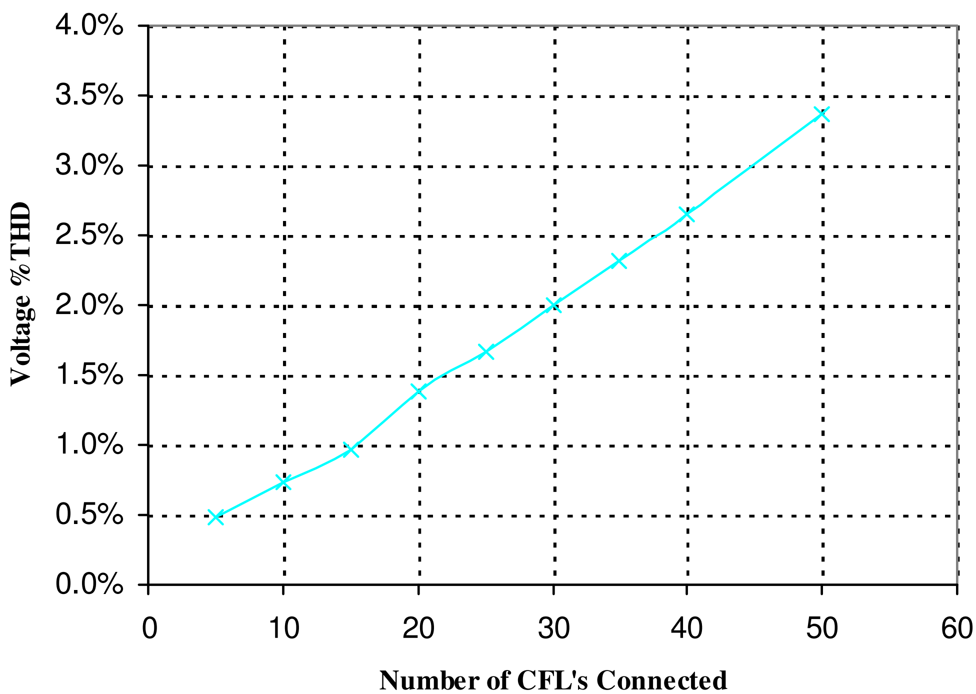


Figure 7. Plot of Secondary Voltage Total Harmonic Distortion as a Function of the Number of CFL's Connected to a Distribution Transformer Secondary.

Undergraduate Researcher Educational Benefits

A student report and personal interview with the supervising professor was used to assess the educational benefits provided by this research project. The research question was how the experience affected performance in courses the student was taking.

The undergraduate researcher had previous work experience as a technician in the military and an electrician in the coal mining industry. He had earned an AAS degree in electronics technology and came to the project with skills in circuit fabrication, repair, and troubleshooting. He had senior standing in an EET program and took courses in electronics design, communications, and control systems while he worked on this project. His report identified the following benefits from the experience.

- The project demonstrated theories experimentally, particularly Fourier analysis. This related to content in the communication classes.
- The student improved his knowledge and skills in testing procedures using the digital scope and other test instruments. This related to all course laboratories.
- The student improved his design skills by demonstrating the use of component data sheets and software design tools. His testing, calibration and troubleshooting skills were enhanced. The undergraduate researcher prototyped a current sensor circuit for future use using a Hall Effect current sensor and OP AMPs. All courses use OP AMPs for design projects.
- The student gained programming experience with software used in classes. The control system course uses MATLAB to solve control problems.
- The student broadened his view of higher education and improved his ability to help other students.
- The student was better able to utilize course concepts to solve problems.
- The personal interaction with the professor identified options in his career path.
- The student improved his interpersonal communications skills.
- The student gained an appreciation of the value of teamwork in achieving a common goal.

Other students acquainted with the undergraduate researcher took interest in the project and came to the lab to observe its progress. This gave the researcher a chance to explain to his classmates theories and results used in the project. These students may choose to take part in future research projects or independent studies based on their own observations and the student researchers experiences.

Conclusions

This paper presents the results of an undergraduate research project that tests the harmonic content and system effects of currents drawn by modern CFL's. Tests determine the relationship between CFLs current total harmonic distortion and lamp voltage for three manufacturers' bulbs. Results indicate that the CFL's THD percentages vary with the lamp voltage and the electronic ballast construction. Analysis of lamp current test samples produces a harmonic model that is a function of the lamp voltage. Simulations using this model show there is a proportional relationship between the numbers of CFL's installed on distribution secondary circuits and the voltage total harmonic distortion produced from the current injections. The paper documented the educational benefits the project provided to the undergraduate researcher. These benefits included enhanced laboratory, problem solving, and communication skills. This project also found that having a member of a class take part in an undergraduate research project could engage other members of classes and attract future students to research projects.

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