
AC 2012-5381: AN UNDERGRADUATE SUMMER RESEARCH EXPERIENCE ON ENERGY EFFICIENT LIGHTING TECHNOLOGIES AND HARMONICS

Dr. Reg Recayi Pecen, University of Northern Iowa

Reg Recayi Pecen holds a B.S. in E.E. and a M.S. in controls and computer engineering from the Istanbul Technical University, an M.S. in E.E. from the University of Colorado, Boulder, and a Ph.D. in electrical engineering from the University of Wyoming (UW, 1997). He has served as Graduate Assistant and faculty at UW and South Dakota State University. He is currently a professor and Program Coordinator of Electrical Engineering Technology program at the University of Northern Iowa. He is also serving as a graduate program coordinator at the Department of Technology. He serves on UNI Energy and Environment Council, CNS Diversity Committee, University Diversity Advisory Board, and Graduate College Diversity Task Force Committees. His research interests, grants, and publications are in the areas of AC/DC Power System Interactions, distributed energy systems, power quality, and grid-connected renewable energy applications including solar and wind power systems. He is a Senior Member of IEEE, and member of ASEE, Tau Beta Pi National Engineering Honor Society, and ATMAE. Pecen was recognized as an Honored Teacher/Researcher in "Who's Who among America's Teachers" in 2004-2009. Pecen is a recipient of 2010 Diversity Matters Award at the University of Northern Iowa for his efforts on promoting diversity and international education at UNI. He is also a recipient of 2011 UNI C.A.R.E Sustainability Award for the recognition of applied research and development of renewable energy applications at UNI and Iowa in general. He was recognized as an Advisor of the Year Award nominee among eight other UNI faculty members in 2010-2011 academic year Leadership Award Ceremony. Pecen received a Milestone Award for outstanding mentoring of graduate students at UNI, and recognition from UNI Graduate College for acknowledging the milestone that has been achieved in successfully chairing 10 or more graduate student culminating projects, theses, or dissertations, in 2011 and 2005. He was also nominated for 2004 UNI Book and Supply Outstanding Teaching Award, March 2004, and nominated for 2006, and 2007 Russ Nielson Service Awards, UNI. Pecen is an Engineering Technology Editor of American Journal of Undergraduate Research (AJUR). He has been serving as a reviewer on the IEEE Transactions on Electronics Packaging Manufacturing since 2001. Pecen has served on ASEE Engineering Technology Division (ETD) in Annual ASEE Conferences as a paper reviewer, session moderator, and co-moderator since 2002. He is currently serving as a Chair-elect on American Society of Engineering Education (ASEE) Energy Conversion and Conservation Division. He served as a Program Chair on ASEE ECCD in 2010. He is also serving on advisory boards of International Sustainable World Project Olympiad (<http://www.isweep.org/>) and International Hydrogen Energy Congress. Pecen received a certificate of appreciation from IEEE Power Electronics Society President Dr. Boroyevich in recognition of valuable contributions to the IEEE Power Electronics Society Solar Splash as 2011 Event Coordinator. Pecen is a board member of Iowa Alliance for Wind Innovation and Novel Development (<http://www.iawind.org/board.php>) and also representing UNI at Iowa Wind Energy Association (IWEA). Pecen has been teaching Building Operator Certificate (BOC) workshops for the Midwest Energy Efficiency Alliance (MEEA) since 2007 at <http://boccentral.org/instructors>. Web: <http://www.uni.edu/~pecen>; <http://www.uni.edu/indtech/eet>.

Mr. Corey Evan Eichelberger

Dr. Faruk Yildiz, Sam Houston State University

An undergraduate summer research experience on energy efficient lighting technologies and harmonics

Abstract

A few qualified undergraduate students at the University of Northern Iowa are given summer research awards that include a competitive stipend and funding for research expenses. The competition is based on an applied research proposal and it requires active collaboration with a summer research faculty from May 15 through July 31 that takes 10-weeks of work. The faculty member is also responsible to monitor student's research progress. The summer research program ends with a project display and presentation day on the last working day of July. A number of BS degree students in the Electrical Engineering Technology program have shown great interest in the summer applied research program. This paper reports an applied engineering technology research project that investigates impacts of artificial lighting induced harmonics on electrical distribution systems. The authors designed and built a unique test bed to investigate harmonic spectrum of the electrical signals when variety of lighting loads are connected in a single phase electrical system. From incandescent light bulbs to a variety of CFLs and state-of-the-art LED light bulbs, a number of commercially available different lighting loads are investigated. The results are very interesting based on the different bulbs available in the market.

Introduction

The most common energy efficiency practice of reducing electrical loading by using energy efficient lighting has resulted in a high level of interest in replacing conventional incandescent lamps with compact fluorescent lamps (CFL). However, CFLs have massive nonlinear voltage and current characteristics; therefore they inject harmonics into the neutral of electrical power system¹⁻⁷. The CFL use electronic ballasts and the design of the ballasts have an enormous impact on both the cost and the electrical performance of the CFL. In the past the harmonics injected into the network by CFLs were ignored since individual CFLs were in the size of 10-20 Watts power ratings. The widespread adoption of CFLs in residential, commercial and industrial lighting systems has caused the combined effect of all these small nonlinear sources to impact the power system as one large disturbance.

The United States Energy Independence and Security Act of 2007 requires all general purpose light bulbs with outputs of between 310-2600 lumens to be 30% more efficient than the modern day incandescent bulbs that are still used at residential and commercial buildings. As import and manufacturing of any 100 W incandescent light bulbs become illegal beginning January 1, 2012 followed by 60 W and 40 W ones respectively in 2013 and 2014, there is a need on cost effective, efficient light bulbs with no or minimum harmonics generation due to current use of electronics ballast in CFLs. This has led to the development of lighting alternatives that are more efficient than their incandescent counterparts but also have caused harmonic problems particularly from inexpensive and imported CFLs that are largely available in the discount stores.

The BS in Electrical Engineering Technology (EET) degree program at the University of Northern Iowa is first and only four-year engineering technology program accredited by ABET-TAC. The EET program teaches the fundamental elements of circuits, conventional and renewable electrical power, analog/digital electronics, microcomputers, telecommunications, instrumentation and data acquisition, control systems, and networking principles. The program begins with a base of introductory classes in math, physics, statistics, and computer programming and continues on into practical applications of the EET in industrial settings. An EET junior student, also a co-author of this paper worked as a summer undergraduate research student involving a number of applied research projects and summer STEM events from May 15 through July 31, 2011. The student's initial role was designing and building a testbed for the harmonic analysis. His tasks were followed with testing and analyzing many different light bulbs for the harmonic contents, power consumption, power factor, and light output values. The student was also involved with many EET related laboratory and project demonstrations for the visiting high school STEM summer camp students on campus.

The purpose of this paper is to describe a summer research project entitled "Impact of Artificial Lighting Induced Harmonics on Electrical Power Distribution Systems" to provide an in depth look at the power characteristics of LED and fluorescent lighting technologies along with issues that may affect the homeowner and power distribution company both physically and economically. The immediate goal of this study is to give an in depth analysis at the power consumption and lighting output that is seen by the consumer along with the reactive power, harmonics, Total Harmonic Distortion (THD) and overall efficiency that is considered by the energy utility company. The current THD is a measurement of the current harmonic distortion present and is defined as the ratio of the square root of the sum of the all current harmonic amplitudes to the current with fundamental frequency as seen in Eq. 1. Similarly, it is also defined for voltage harmonics as seen in Eq. 2.

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_1} \quad (\text{Eq. 1})$$

$$THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots}}{V_1} \quad (\text{Eq. 2})$$

The co-author of this paper, summer research student, was also involved in many community STEM outreach programs during the summer 10-weeks session.

There are a number of studies on investigating harmonics and electrical losses of variety of light bulbs⁵⁻¹¹. Uyaisom investigated the effect of jumbo compact fluorescent lamp on the electrical energy saving and harmonics noise⁸. His work included investigation of harmonics content of different incandescent and fluorescent light bulbs, and verification of the lighting efficiency, electrical performance, and harmonics noise of each lamp. Radakovic et al. investigated voltage distortion in low-voltage networks caused by compact fluorescent lamps with electronic gear⁹.

Procedure

For the testing procedure there was a list of equipment that we used during the tests. The sensors that were used were the Fluke 41B Power Harmonics Analyzer with the included Fluke optical cable and Fluke software. For the measuring of light output the SLM-110 Foot Candela Meter was used with a distance of 3 feet from the apparatus. With the testing apparatus set up, the first step that needs to be done is to check the isolation transformer using the power harmonics analyzer to make sure that harmonics are being isolated from the testing apparatus. The next step is to switch on whichever light is needed to be tested and give it a five-minute warm up time to allow the lamp to be brought up to a stable operating temperature. After this step, you will need to connect the Fluke 41B Power Harmonics Analyzer via the provided optical cable to the personal computer of your choice for data collection within the Fluke Harmonics Analyzer software. After allowing the data collection to run for one singular hour, one will need to average the data and check for any outliers that may be within the data collection. This process was repeated five different times and an average of the results was recorded for the five tests. To test the light output from the various bulbs, the first step was similarly to set up the testbed apparatus and to check the isolation transformer using the power harmonics analyzer to make sure that harmonics are being isolated from the testing apparatus. After the lamp has reached its operating temperature the light output was tested from a mark that is one foot away from the lamp with a direct line of sight. The SLM-110 was used within these tests and a series of 5 tests with an average of light output was used for the final data collection.

Figure 1 shows a custom designed and built testbed for incandescent, CFL, florescent, and LED bulbs for investigating harmonics studies. Summer research student and co-author of this paper designed and built the testbed for the easy and precise light bulb testing. Figure 2 exhibits load current waveform and harmonics measured using a Fluke 41B Power Harmonics Analyzer for a 20 W low quality CFL light bulb. The total harmonics distortion (THD) level for current harmonics is about 79.4% and this is very high compared with IEEE-519 maximum allowable harmonics in the electrical systems. Figure 3 shows the same testing for an LED tube light bulb with very minimum THD level since there is no any electronics ballast used in the bulb. As seen in Figure 5, the LED tube has the lowest THD level of all of the standard 48" tubes and minimal harmonics even out to the 5th order.



Figure 1. A custom designed and built testbed for incandescent, CFL, florescent, and LED sources for investigating harmonics studies.

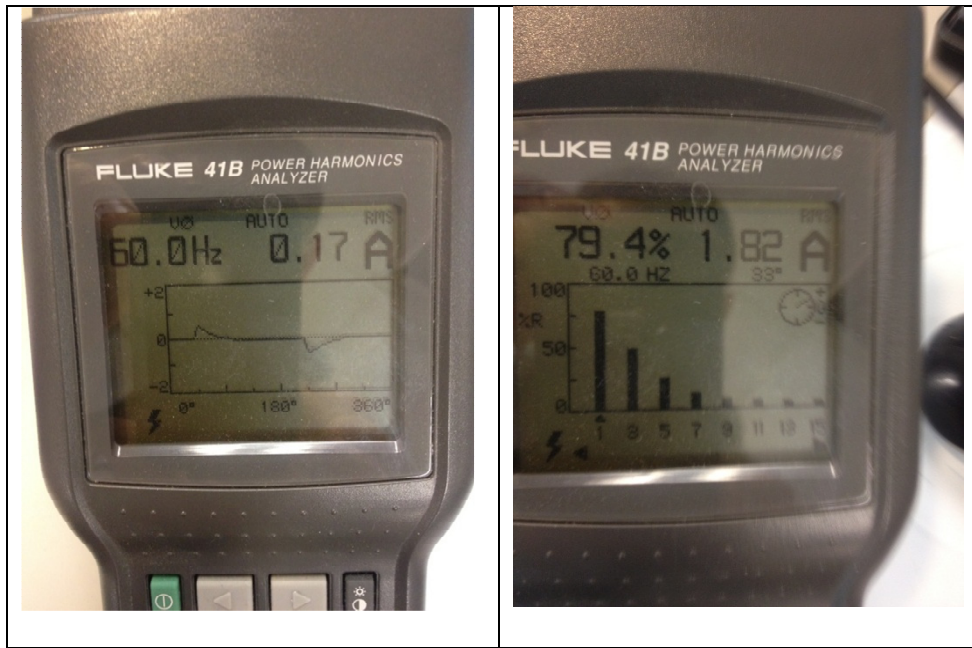


Figure 2. Load current and harmonics measured using a Fluke 41B Power Harmonics Analyzer for a 20 W low quality CFL.



Figure 3. Very low harmonics measured when an LED tube was tested.

Harmonics Testing

Harmonics within power systems are not only known for their negative effects on power quality and sensitive equipment but also for the extra production of heat within the neutral lines of the grid. This extra heat can cause many different failures within the power system but also can be a large source of electrical fires. Harmonics are based upon what would be a fundamental harmonic which depending upon geographical location could either be 50Hz or 60Hz. A second order harmonic would be a doubling of this frequency and so on. The main harmonics that are seen within power systems are the odd harmonics which will produce what can be seen as a symmetrical wave by most instruments but lead to problems within power systems through the production of heat and also can cause sensitive equipment to malfunction or not even work at all. Figure 4 exhibits current harmonic spectrum of tested different light sources of CFL, incandescent, and LED Bulb. The graph is set for harmonics on the X-axis which represents all other integers other than fundamental 60 Hz component.

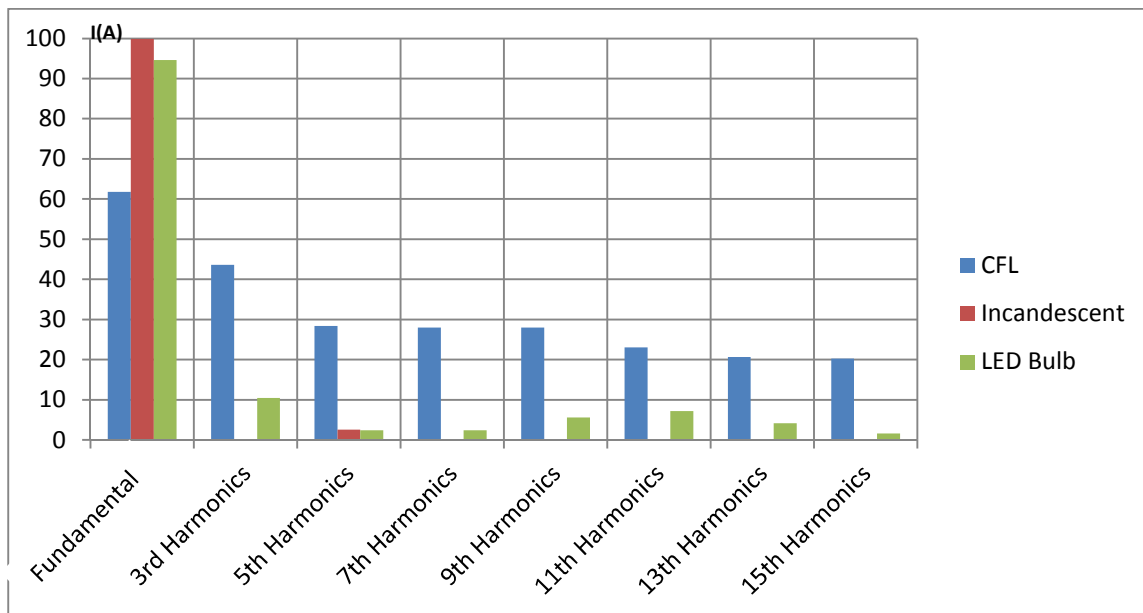


Figure 4. Harmonic spectrum of tested light sources (CFL, Incandescent, and LED Bulb).

Within the testing for harmonics there were two separate comparative tests between the standard size bulbs and the standard 48" tube style banks of lights. As shown in Figure 4, the incandescent light bulb showed no harmonic distortion as it is a pure resistive load. The CFL with its electronic ballast measured high amounts of harmonics all the way out to the 15th order harmonics which poses a problem not only for a single load but also within the standard household or industrial facility which may have multiples of these running at the same time this could pose a serious problem to any sensitive equipment that may be on the same circuit. As seen within the graph there are the results for the LED bulb which has a THD comparable to the standard Incandescent which it replaces but still showed measurable 3rd order harmonics and minimal harmonics out to the 15th order. As for the 48" standard tubes it can be seen that the standard T12 fluorescent tube with the magnetic ballast has a relatively low THD compared to the T8 and T5 tubes which used an electronic ballast which works through the principle of high speed switching to limit current. As seen in Figure 5, the LED tube has the lowest THD of all of

the standard 48" tubes and minimal harmonics even out to the 5th order. This low harmonic distortion is primarily due to the ballast within the LED tube being a resistor based ballast.

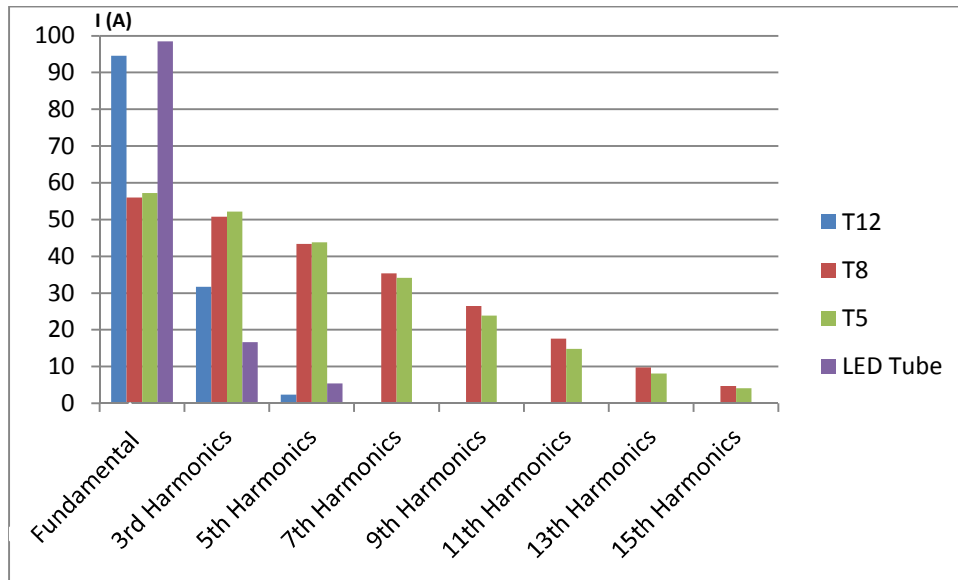


Figure 5. Harmonic spectrum of fluorescent and LED Tube lights.

Power Consumption and Reactive Power Testing

Power consumption as seen by the average consumer is seen as a Volt-Amp rating or the wattage that an object consumes. What the consumer does not see is the reactive power which is wasted power that is put back into the power grid. Reactive power is measured in VAR which is shown as the bar on top of the real power as seen in Figure 6. By taking the complex sum of the real power and reactive power, we get the apparent power which is the true load that is put on the power companies and distribution lines. The compact fluorescent bulb showed a large amount of reactive power relative to the given real power due to the ballast that is used for starting and current limiting of the bulb. The LED bulb that was tested showed low amounts of reactive power but still much more than was expected especially compared to the incandescent bulb with its purely resistive load. As for the 48" standard tubes the fluorescent tubes across the board showed significant amounts of reactive power regardless of the use of the magnetic ballast with a large inductive load or the electronic ballast which is known as the more efficient choice but as can be seen with the large amounts of reactive power it clearly is not nearly as efficient as it has been portrayed. The final round of tests was with the LED tube which not only showed a minimal amount of reactive power but also a low power consumption overall.

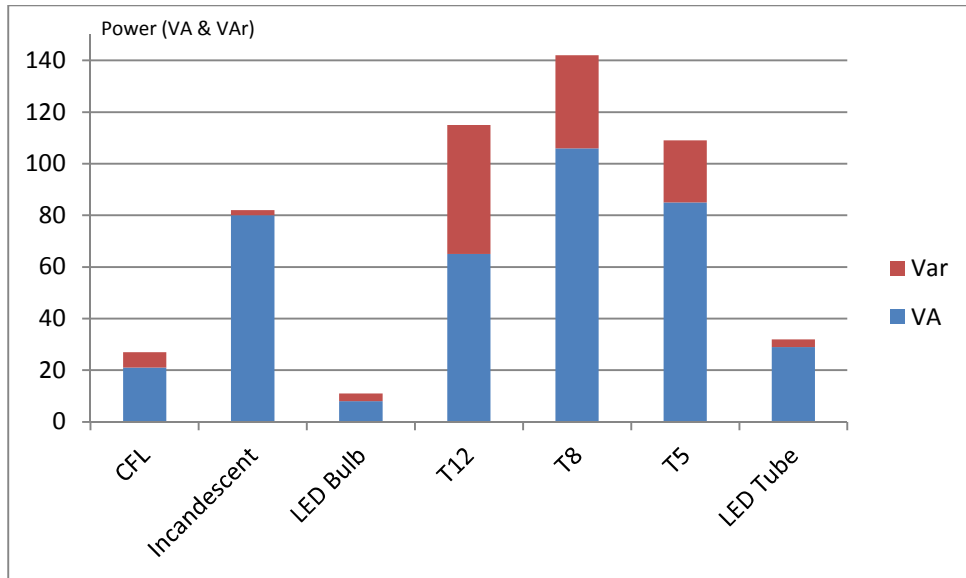


Figure 6. Apparent power (VA) and reactive power (VAr) components of different light sources.

Reactive power is not a concern for the average consumer but any commercial building is subject to penalties due to poor power factor. Power factor is found by taking the cosine of the phase difference of the voltage and current that is flowing through a point. A power factor of 1.0 is perfect power factor and could be thought of a purely resistive load. This can also be attained through power factor correction which can be costly to implement but due to the cost savings that can be realized through the reduction of power factor penalties the power factor correction system will often pay for itself within a few years. The standard incandescent bulb had a power factor of 1 which was to be expected with being a purely resistive load. Due to the large amounts of reactive power that were shown with the 48" standard fluorescent tubes and the compact fluorescent bulb the resulting power factor for these bulbs and tubes were generally poor with only the T12 tube with the magnetic ballast being the only set that had a power factor of above .5. The LED Tube that was used during testing due to its low power consumption and minimal amounts of reactive power showed a power factor of .96 which in comparison to the standard fluorescent tubes that are used in commercial buildings this would show a large rise in power factor across the building. Figure 7 shows power factor testing of different light sources. It is really interesting that ultimate lighting sources of the future, LED tube, performs an excellent power factor of 0.96.

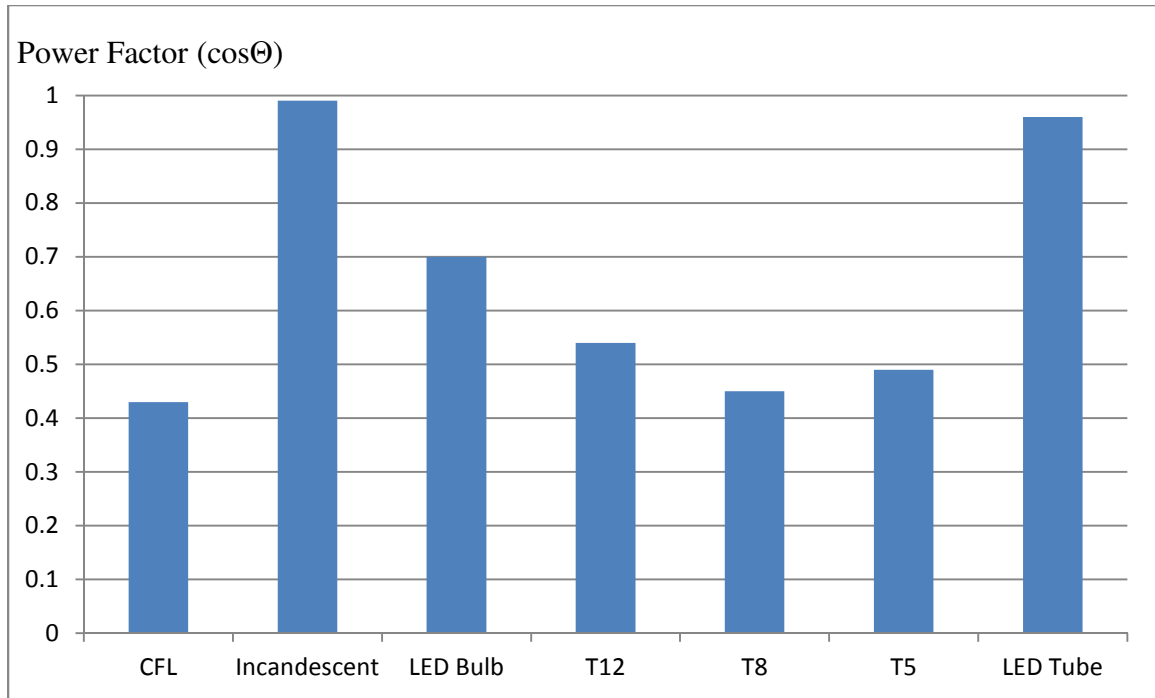


Figure 7. Power factor testing of different light sources.

Light Output Testing

The last test that needed to be made was a comparison of the light output of each of the standard bulbs from the test set as seen in Figure 8. Each of the bulbs were switched on and once they reached stable operating conditions an average of the light output over the 5 minute period was recorded. For the standard household bulbs the standard 100W incandescent bulb had the highest output in the category with an output of 171 Lux. This was closely followed by the LED Bulb which had an output of 155 Lux which is a close follower to the incandescent bulb while only having 10% of the power consumption. The compact fluorescent bulb did not fare nearly as well however coming in at 67 Lux.

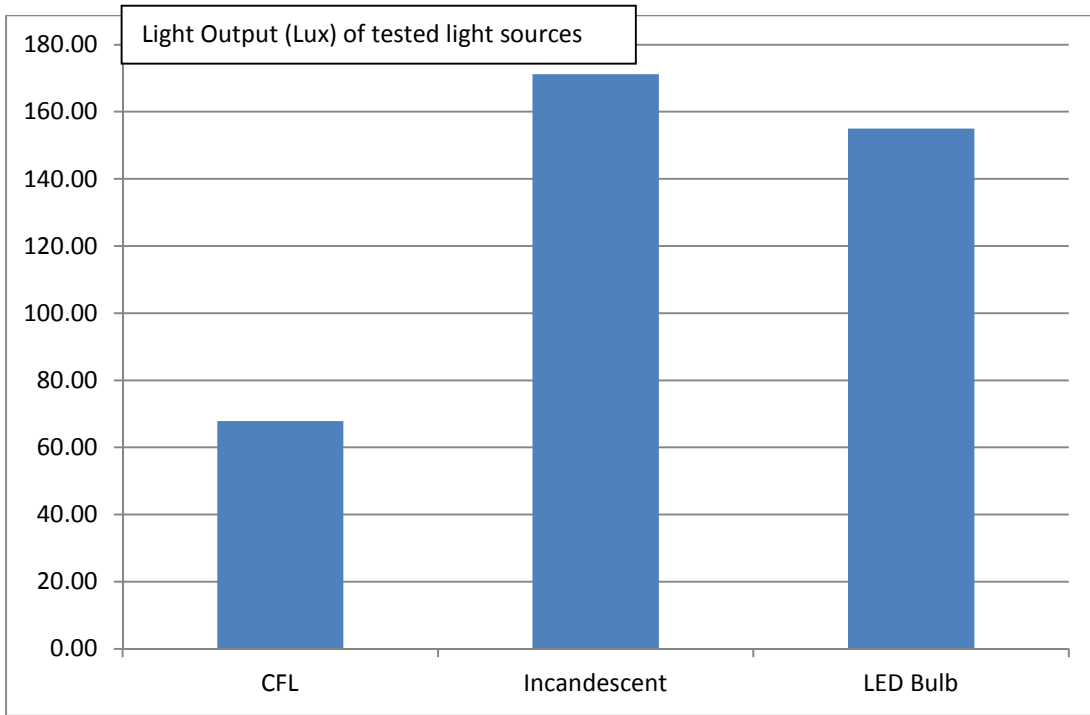


Figure 8. Light Output (Lux) of tested light sources of CFL, Incandescent, and LED bulb.

For the testing of the standard 48" tubes each of the lights were switched on and once they reached stable operating conditions an average of the light output over the 5 minute period was recorded. The T12 with the magnetic ballast and the T5 with the electronic ballast had similar outputs of 503.7 and 561.8 Lux respectively. As seen in Figure 9, the T8 tube had the highest output of the fluorescent tubes within the tests with an output of 917 Lux. This of course trailed behind the LED Tube which had a light output of 1204.9 Lux.

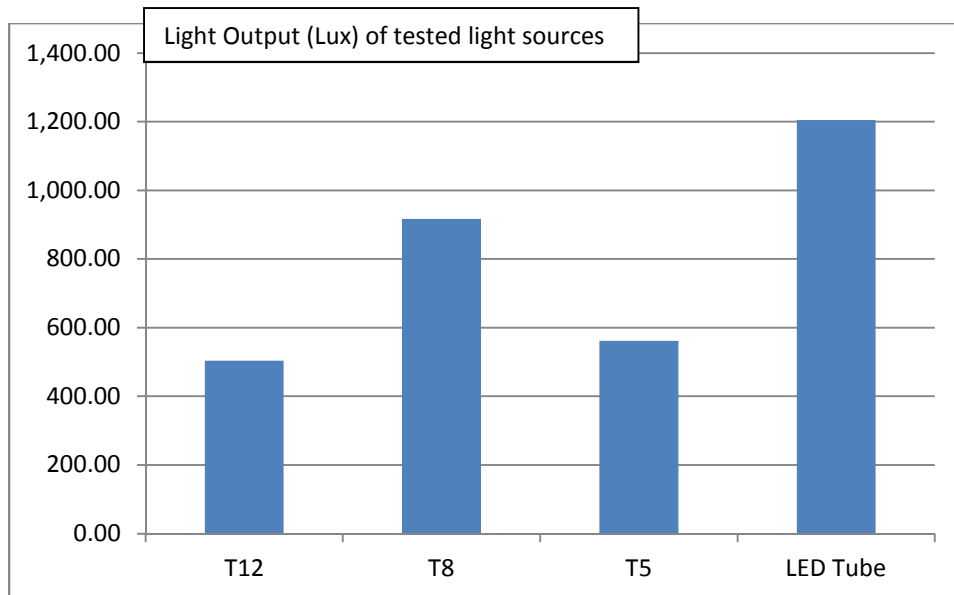


Figure 9. Light Output (Lux) of tested light sources of T12, T8, T5, and LED tube.

Conclusion

This paper reported an applied engineering technology research project that investigated impacts of artificial lighting induced harmonics on electrical distribution systems. An undergraduate EET major student, a co-author of this paper, was selected for the project and he worked on the project in summer 2011. The authors designed and built a unique test bed to investigate harmonic spectrum of the electrical signals when variety of lighting sources and loads are connected in a single phase electrical system. From incandescent light bulbs to a variety of CFLs and state-of-the-art LED light bulbs, a number of commercially available different lighting loads are investigated. The results are very interesting based on the different bulbs available in the market.

The student experience on working with faculty and helping summer STEM activities was very valuable. Many high school students visiting the UNI campus for STEM summer camps found the project demonstrations by a junior EET student very useful. It was very interesting for many high school students to find conceptual similarities between the “clean electrical signal” and “clean air” as they observe pure sinusoidal signal and the signal waveforms with many harmonics on the oscilloscope in the light bulb testing bed.

The clear choice for the standard household bulb given all factors of power consumption is the LED bulb. Not only did it have a light output that was only marginally less than the 100W incandescent but also only consumed 8W while having low harmonic distortion. As for the 48” standard tubes the best choice out of the test bed would be the LED Tube with not only having the highest light output but also while having the lowest power consumption by a wide margin. All of this with a low amount of harmonic distortion and a power factor of .96. This would be a large improvement not only in power consumption but also help with the power factor of any commercial office or industrial space and thus the cost savings would allow for the tubes to pay back for themselves many times over.

Acknowledgements

The authors greatly appreciate to Mr. Les Chewing from ThyssenKrupp Crankshaft Company in Illinois for providing LED light bulbs for this study. The authors also acknowledge the summer undergraduate research funding from College of Humanities, Arts, and Sciences (CHAS) at the University of Northern Iowa.

References

1. D. T. Bradshaw, “Our Electric System of the Future, and its Unintended Consequences,” *The Electricity Journal*, Elsevier Ltd, Volume 21, Issue 4, May 2008, Pages 76-80.
2. N.G. Chondrakis, F.V. Topalis, “Starting characteristics of fluorescent tubes and compact fluorescent lamps operating with electronic ballasts,” Elsevier, *The Measurement Journal*, 42 (2009) pp. 78-86.
3. N. Hamza, D. Greenwood, “Energy Conserv. Regulations: Impacts on design & procurement of low energy buildings,” *Building and Environment, Elsevier Ltd, Sci. Direct*, Vol. 44, Issue 5, May 2009, pp 929-936.
4. Y. Ji, R. Davis, C. O’Rourke, E.W.M. Chui, “Compatibility testing of fluorescent lamp and ballast systems,” *IEEE Transactions on Industry Applications* 35 (6) (1999), pp. 1271–1276.
5. P.F. Keebler, R. Gilleskie, “In-rush currents of electronic ballasts and compact fluorescent lamps affect lighting controls,” *Industry Applications Conference, 1996. Thirty-First IAS Annual Meeting, IAS apos;96.*, Conference Record of the 1996 IEEE Volume 4, Issue , 6-10 Oct 1996, pp. 2201 – 2208.
6. L. Tang, *Technology Recommendations from the T&D Sector*, Grid Week, April 23–26, 2007.

7. A. Nassara and M. Mednik, "Introductory physics of harmonic distortion in fluorescent lamps," 2003 *American Association of Physics Teachers*, <http://ojps.aip.org/ajp/> Am. J. Phys. 71 (6), June 2003, DOI: 10.1119/1.1544505.
8. C. Uvaisom, "Effect of Jumbo Compact Fluorescent Lamp on the Electrical Energy Saving and Harmonics Noise" School of Electrical Engineering and EEE for Sustainable Development, published by Elsevier Ltd., December 2010, 1877–7058, Published by Elsevier Ltd. DOI:10.1016/j.proeng.2011.03.027
9. Z. Radakovic, F. V. Topalis, M. Kostic, "The voltage distortion in low-voltage networks caused by compact fluorescent lamps with electronic gear," Elsevier Ltd. DOI:10.1016/j.epsr.2004.06.008.
10. <http://www.osha.gov/SLTC/healthguidelines/mercuryvapor/recognition.html> retrieved 05 January 2012.
11. http://www.energystar.gov/ia/partners/promotions/change_light/downloads/Fact_Sheet_Mercury.pdf retrieved 05 January 2012