

# **CAREER: Modeling, Control and Design of Energy-Efficient Lighting Systems**

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*ABSTRACT: Professor Regan Zane and Ph.D. student Ryan Schnell from the University of Colorado traveled to Spain in order participate in a collaborative effort involving high intensity discharge lamps with Professors Francisco Azcondo, University of Cantabria, Spain and J. Marcos Alonso, University of Oviedo, Spain. The effort combined circuitry and design methods provided by the groups in Spain with control algorithms and implementations researched by the travelers. The trip provided a culturally immersive experience for the travelers, while allowing a close interaction between the groups, forging bonds that will drive future collaborations and developments.*

*The broader impact of the program is to enable and catalyze wide-spread development and use of energy-efficient lighting systems by making reliable high quality solutions affordable. Successful transfer of the theoretical and experimental analysis techniques from the international component is essential to developing system design procedures that naturally lead to reliable long life solutions. Large scale commercialization of program technologies could lead to reducing electricity usage in US homes for lighting by over 70%, representing a potential annual savings of 70 billion kWh (based on 2001 DOE RECS report) or over 40 million barrels of oil and associated emissions of green house and poisonous gases and economical impacts. In addition, the long term impact of graduating top quality engineers with a strong basis in energy efficient systems and a global perspective cannot be underestimated.*

## **INTRODUCTION**

The program goal of the current award is to develop innovations in energy-efficient lighting systems through advanced modeling, control algorithm research, and custom integrated circuit (IC) hardware realizations that will bring down technology barriers and enable significant reduction in the environmental and economic impacts of lighting systems. The program has resulted in two innovative (patent pending) approaches for driving high efficiency discharge lamps with up to twice the lifetime using reduced cost circuitry. The first is based around a low cost digital phase controller that provides soft lamp ignition and fast, reliable glow-to-arc transition and warm-up modes for improved lamp life. The second is a new architecture for driving multiple parallel cold cathode fluorescent lamps (CCFLs) at very low frequency based on a key innovation: capacitive ac coupling as a catalyst for reliable, parallel ignition at dc anode to cathode voltages as much as three times lower than rated values, again improving lamp life and also simplifying hardware and reducing electromagnetic interference (EMI). The benefits of both technologies rely significantly on the details of the ignition and discharge behavior within the lamps using the proposed drive circuitry. Current industrial partners are interested in large scale commercialization of the technologies, but design optimization and validation of long term benefits require more detailed theoretical analysis and hardware measurements of lamp ignition behavior, efficacy and system EMI.

Professors Francisco Azcondo, University of Cantabria, Spain and J. Marcos Alonso, University of Oviedo, Spain, lead two of the most internationally recognized and respected research programs in the lighting applications area, with core expertise in theoretical modeling and experimental analysis of electrical arc and discharge behavior in lighting and machining applications. These two programs, only 170 km apart, have a history of close collaboration and have grown over the past decade with significant strategic investments by the Spanish Government, resulting in combined programs with 10 full time faculty in the lighting area and over \$500K in critical laboratory equipment and facilities.

The rationale for the international component is to merge the core expertise of the PI in lighting systems engineering and custom integrated circuit design with those of Drs. Azcondo and Alonso in physical electrical discharge behavior of lamps in order to create new affordable system solutions for long life energy efficient lighting. This cooperation allows an easier transfer of theoretical and experimental techniques between the groups. By visiting the hosts, the researchers hoped to gain insight of the particulars of the design process, testing, and experimentation of the host groups, as well as utilize the existing equipment available at the host laboratories. This involvement is much more than can be obtained by simple long distance communication, in that the daily involvement promotes a closer type of collaboration.

The US travelers were Professor Regan Zane, assistant professor (at the time of travel) at the University of Colorado, and Ryan Schnell, a Ph.D. student at the University of Colorado. Ryan Schnell was in Spain from January 31, 2008, until June 26, 2008. This coincided with a semester at the University of Cantabria, and Ryan was enrolled in courses there. Mr. Schnell was selected due to his extensive experience with resonant switching power converters in lighting applications and his interest in international collaborations and cultural growth. Professor Zane was in Spain from April 5, 2008 through June 30, 2008. An undergraduate student was planned for the travel as well, but had to cancel at the last minute due to unexpected family circumstances.

### RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The primary goal of the program is to research and create solutions for more energy efficient lighting systems. This research includes modeling of lamps and systems, as well as designing controllers for the use of operating lamps. Currently, HID lamps are commercially operated by magnetic or electronic ballasts. Electronic ballasts have a size and weight advantage over existing magnetic ballasts, as well as provide a greater amount of control of operation such as dimming and higher efficiency.

During the trip carried out under IREE, a focus on the ignition of high-intensity discharge (HID) lamps was performed. A collaborative effort was to augment a current electronic ballast design created by Professor Francisco Azcondo's group that operated with frequency control into one that was phase controlled, as developed by the PI. By moving towards a phase controlled resonant ignition as compared to a frequency control, many component variations and variations caused by different types of lamps could be mitigated, resulting in a more robust ignition of HID lamps. A block diagram of the basic system is given in Fig. 1.a. Another benefit of phase control over frequency control was that the ballast system could use a soft saturation core, instead of a standard hard saturation ferrite core, resulting in a dramatic size and weight reduction. The previous and current inductors are shown in Fig. 1.b.

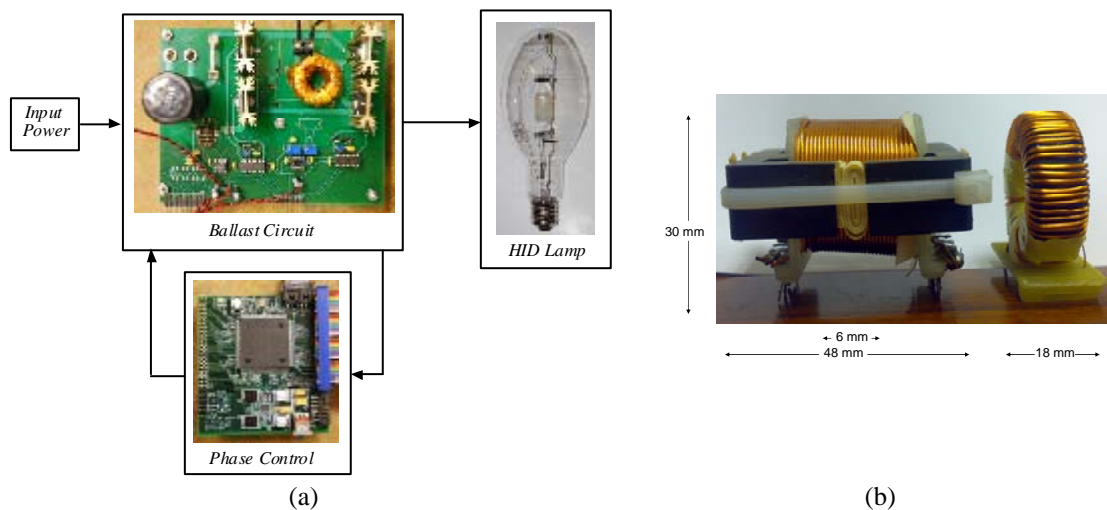


Figure 1: (a) Block diagram of system. (b) Size comparison of hard saturation core (left) and reduced size soft saturation core used in IREE research (right).

The travelers were given on campus office space at the University of Cantabria, as well as access to laboratory space during normal Spanish business hours. There was daily involvement from Professor Azcondo with overseeing the student. Professor Azcondo also incorporated a team of undergraduate international students that were visiting the University of Cantabria into the project. Weekly group meetings provided a backdrop for exposure to other projects going on in the group, as well as insight from other group members into progress of the project. On campus fabrication of circuit boards was possible from interaction with other groups in the electrical engineering department at the University of Cantabria.

Interaction with Professor J. Marcos Alonso was long distance communication, as well as periodic visits to the Oviedo campus for presentations. The student on the trip also participated in an intensive three week introductory course for energy efficient lighting systems Ph.D. students at the University of Oviedo. The course provided an expansive overview of the past and current research efforts at the university, as well as expanded the exposure of the student to the Spanish language.

The host groups provided detailed insight on the inner workings of the lamps that comes from years of working with the lamps. Professor Azcondo's group provided a lot of information about the lamp behavior, aging, and ignition that was instrumental in understanding possible issues with operating HID lamps. The group also provided the researchers with circuit analysis techniques catered to HID lamps.

During the trip, the student constructed a resonant ballast designed using research and design methods previously carried out by the group at the University of Cantabria. This circuit later served as the experimental portion of a class taught by Professor Azcondo. The class taught VHDL coding and design methods, and was composed of international students visiting the University of Cantabria, as well as the student sent on trip through IREE. In this class, the student was exposed to the design process of the host, as well as accomplishing goals of the project. At the end of the class, the student had learned the core design process for a modular project written in VHDL. The end of the class culminated with the programming of an FPGA capable of operating the resonant ballast converter for operation in either frequency or phase control, resulting in resonant HID lamp ignition and resonant operation.

Research continued after the completion of the class, with phase control being implementing on an existing full-bridge converter provided by the group at the University of Cantabria. An IEEE conference paper will be presented in the upcoming Applied Power Electronics Conference and Exposition (APEC) in February, 2009 [1], and later submitted to the journal for review. Figure 2 shows the PI and student together with the developed full-bridge electric HID ballast system.



Figure 2. PI, Prof. Zane (front) and Ph.D. student Ryan Schnell (back) with the long life, reduced size and weight HID ballast developed on the IREE program.

## **BROADER IMPACTS OF THE INTERNATIONAL COOPERATION**

The trip has created a greater bond between the host and visiting group. The groups are currently writing papers about the on-site research performed while on the trip, as well as extended research that is currently being performed. Communication between the groups is currently mainly through email, but joint attendance to conferences are also planned. Currently, a grant from the Spanish government is planned which will allow members from one of the host groups to visit the US laboratory of the PI for an extended period of time, similar to that which the researchers had with this IREE trip.

A broader cultural experience was gained for both US travelers. Prior to the travel, the PI and student studied the Spanish language through software tools and discussions with friends and other students. However, Spanish speaking skills were not sufficient at the beginning of the trip. By the end of the travel, the student was able to operate alone in the city of Santander, Spain, without assistance. The student participated in an intensive Spanish course, and was often quizzed by the host group at any chance they had. The student was also exposed to other European people as he was housed with international students, and took classes with students from around Europe. Communication with some of those students is ongoing today.

In addition to the networking, dealing with the different surroundings with respect to technologies was also enriching. A greater understanding of what is required in a system to operate and be certified in multiple continents due to the difference in 110V and 220V wall supplies was gained.

Daily interaction with the surrounding people also enhanced the cultural experience. Periodic luncheons provided time to converse with the group in Spain and learn about specific aspects about life in Spain. Professor Azcondo would mention weekly happenings and suggest good things to attend. These included events such as the Semana Santa parades performed during the Easter week, Spanish independence day celebrations, and synchronized air show displays performed by the Spanish air force. There was no escape from the experience when football games would occur in town. Many discussions were held related to the ongoing US Presidential campaigns and related politics and public developments and concerns local to Spain and the Cantabria region. Discussions were also held related to European and Spanish history and their impacts on present day conflicts and debates in Spain.

### DISCUSSION AND SUMMARY

The trip provided the backdrop for major interaction between the involved groups, both producing progress towards better lighting systems, as well as forging bonds that will continue. The bonds between the groups will capitalize on the strengths of both groups, generating and accelerating research results and technology developments. The host groups are two of the most internationally renowned research groups in the area of lighting. The visiting group can help with a strong history of digital implementation of control systems.

Accomplishments of the trip include a phase controlled resonant ignition of a HID lamp. This will lead into HID lamps with a longer lifetime than current ballasts. This result was the culmination of a collaborative effort from multiple groups, and is research that is being continued. The next steps will take the project closer to a full lighting system that will eventually be able to operate in either Europe or the Americas.

Learning the language beforehand would have aided in the travelers' comfort level. Group meetings proved to be instrumental in obtaining input from all members of the groups, as well as sharing ideas and insights of all group members.

### ACKNOWLEDGEMENTS

National Science Foundation Grant No. 0348772, Program officer: Dr. Dagmar Niebur.

### REFERENCES

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### BRIEF BIOGRAPHIES OF RESEARCHERS

**Ryan Schnell** received the combined BS/MS in Electrical Engineering from the University of Colorado in 2007. He is currently a Ph.D. candidate at the University of Colorado. Research interests include electronic ballast systems for high intensity discharge lamps, envelope modelling, and power factor correction.

**Regan Zane** received the Ph.D. in Electrical Engineering from the University of Colorado, Boulder, in 1999. He then joined GE Global Research in Niskayuna, NY, where he developed custom integrated circuit controllers for power management in electronic ballasts and lighting systems. Since 2001 he has been an Assistant (2001-2007) and Associate (2008-present) Professor of Electrical and Computer Engineering at the University of Colorado at Boulder, where he has ongoing research programs in energy-efficient lighting systems, adaptive and robust power management systems, and low power energy harvesting for wireless sensors. He teaches

undergraduate and graduate courses in analog and mixed-signal integrated circuits and power electronics.

Dr. Zane received the NSF Career Award in 2004 for his work in energy efficient lighting systems, the 2005 IEEE Microwave Best Paper Prize for his work on recycling microwave energy, the 2007 IEEE Power Electronics Society Transactions Prize Letter Award for his work on modeling of digital power converters and the 2008 IEEE Power Electronics Society Richard M. Bass Outstanding Young Power Electronics Engineer Award for "outstanding achievement in the field of power electronics" before the age of 35. He also received the 2006 University of Colorado Inventor of the Year award, 2006 Provost Faculty Achievement award, and 2008 John and Mercedes Peebles Innovation in Teaching Award. He currently serves as Associate Editor for the IEEE Transactions on Power Electronics, Letters, and as a member-at-large of the IEEE Power Electronics Society Administrative Committee.