Issues, Models and Solutions for Triac Modulated Phase Dimming of LED Lamps

Dustin Rand (Raytheon), Brad Lehman* (Northeastern University), Anatoly Shteynberg (Exclara, Inc.)
*Dept. ECE; Northeastern University; Boston, MA 02115; lehman@ece.neu.edu

Abstract - **This paper discusses the difficulties in dimming Edison socket LED lamps directly from residential phase modulated dimmer switches. In order to explain these difficulties PSpice models for the dimmers are proposed that necessarily include diac characteristics to improve accuracy. A method to dim the LEDs from the residential dimmers is discussed.**

I. Introduction: LED Lighting - the Next Technological Revolution?

Within the last few years, new LED materials and improved production processes have resulted in bright LEDs in colors throughout the visible spectrum with efficacies greater than incandescent lamps [1,2]. In fact, recent technological breakthroughs [3-7] in the high brightness "White Light" LEDs have experts predicting that the "bright white replacement lamp" could trigger a revolution in business and home lighting [8,9,10]. Research laboratories have already built high brightness LEDs that surpass the lumens/watt efficiency of fluorescence lights. Consider the following benefits of LED lighting:

- An incandescent source produces 10 – 20 lumens/watt, while several manufacturers have reported white LEDs that achieved over 120lm/watt in the laboratory.
- LEDs have an incredibly long life, lasting between 50,000 to 100,000 hours.
- According to statistics published by [9,11]: replacement of one 60 watt bulb with an equivalent lumens LED white light bulb for usage of 50,000 hours leads to a cleaner environment due to reduced power plant emissions and will
  - ◊ *Save over 1800 pounds of coal;*
  - ◊ *Reduce carbon dioxide emissions by 3000 pounds;*
  - ◊ *Reduce sulphur dioxide emissions by 12 pounds;*
  - ◊ *Creates no mercury emissions.*

Considering that approximately 20% of US electricity is due to lighting, a simple calculation suggests that for each 3% reduction of US lighting power will result in over $1Billion dollars in annual savings - and this ignores the additional environmental benefits. (These estimates are based on prorated statistics in [12]). In 2002 the U.S. Energy Department estimated that SSL could potentially reduce the U.S. electricity used for illumination up to 50% by 2025. This would cumulatively lead to over *760GW* of power, $2.58x10^8$ metric tons of carbon emission, as well as alleviate the need of more than 40 1000MW power stations [9,10].

<u>Dimmers</u>

Residential dimmers are designed to meet the needs of homeowners and architects in both style and function. Commercial companies offer a complete line of residential dimmers with an amazing array of colors that coordinate with the most popular interior colors and finishes. Commercial dimmers and dimming systems are designed to meet the requirements of architects and specifiers of commercial spaces such as hotels, restaurants, offices and warehouses.

What is a Phase Modulated Dimmer?

Incandescent bulbs primarily utilize phase modulating dimming through triac switches to control the power sent to the bulb. Dimming fluorescent lighting is possible by retrofitting the lighting switches/infrastructure with electronic or other dimming ballasts. Similarly, there are multiple methods to dim HID sources, such as retrofitting constant-wattage autotransformers, variable-reactors, electronic ballasts, etc. [13]. These types of dimming switches that need retrofitting are not being studied in this research.

Most people are unaware of the remarkable benefits that dimmers can have, particularly for commercial lighting (all of which have been well documented with research and case studies): A pilot study by the Lighting Research Center (LRC) at RPI demonstrated individually controlled manual dimming (in cubicles, offices) leads to 6% energy savings [14,15]. According to three separate, independent studies, personal lighting control improved company productivity from 2.8%-7.6% [15]. There was reported up to 15% less absenteeism in the study when advanced dimming strategies are added to the workplace. Daylight harvesting dimming has been shown to generate energy savings of 30%-40% according to the California Energy Commission [15] and the LRC [14] in independent studies.

This paper discusses approaches for off-line Light Emitting Diode (LED) driver systems (ICs and power management devices) for phase modulation dimming of LED lamps directly from the AC-Mains. Specifically, the research contributions of this paper include:

1. *Experimental and simulation explanations that describe the reasons and types of failures that many LED lamps experience when connected to TRiAc Modulated Phase dimmers*. Specifically we show that failures can be caused by one or several factors, including: insufficient current to charge

the capacitor in the dimmer switch, nearly constant voltage in the filter capacitor of a classical rectifier that does not change with phase delay and/or reference control signals to the DC/DC converter driver for the LED lamp that do not change when dimming is wanted.

2. *Development of new simulation (Spice) models of triac/phase modulated dimmers that are accurate enough to clearly explain the reasons why triacs, with their associated diacs, fail to properly dim High Brightness (HB) LED lamps.* These models are publicly available at the web site [16] for other researchers to test their own solutions for LED dimming with triacs. The approach proposed is to accurately include in PSpice through Analog Behavioral Modeling (ABM) the influence of the diac on the triac. This improved modeling accuracy enables the residential dimmers to be modeled so that they can qualitatively, and sometimes quantitatively, predict dimmer switch failures.

3. *A driving system for LEDs that is compatible with residential dimmers is proposed and experimentally tested.* In order to allow the residential dimmers to work properly at low currents (in the milli-amps) that dimmed LED lamps require, an additional (active or passive) resistor is added. This has the disadvantage of additional power loss, yet is required to maintain a charging current in the diac required to trigger the triac in the dimmer. Secondly, to make the dimmer switch compatible with Edison socket LED lamps that have simple DC/DC converters in them (e.g. buck converters), we provide a method to convert the modulated triac AC voltage into a separate reference signal that feeds the converter IC. In this way, the current reference of the DC/DC converter changes, and the output load current in the LED lamp can be decreased.

II. LED Lamps Can Fail with Phase Modulation Dimming

A. Motivation

Residential dimmers for incandescent bulbs primarily utilize phase modulating dimming through triac switches to control the power sent to the bulb. These dimmers actually control the RMS voltage applied to the bulb by suppressing part of the AC line voltage using a triac. The effect is a chopped sine wave as shown in the following Figure 1. Thus, as the dimmer switch is manually adjusted, the value of R1 changes, thereby changing the off-time, α (often referred to as the phase delay). As α is increased, less power goes to incandescent bulb and brightness is reduced.

Most LED lamps and their associated drivers within their Edison Socket *do not* perform properly with residential phase modulated dimmers. Often on the LED bulb application notes or on the lamp's manufacturer web sites, there are warnings to the user that their lamps fail with dimmers [17].

Unless advanced driving methods are utilized, one or more of the following will occur when phase dimmers are connected to typical commercially available Edison socket LED lamps (as we tested in the lab):

1) Visible pulsing of LEDs;
2) Audible noise from LED light bulbs;
3) LEDs never fully turn on;
4) LEDs turn on when the dimmer is turned off;
5) Substantial inrush current is possible when a triac turns on, potentially damaging both the triac and LED drivers.

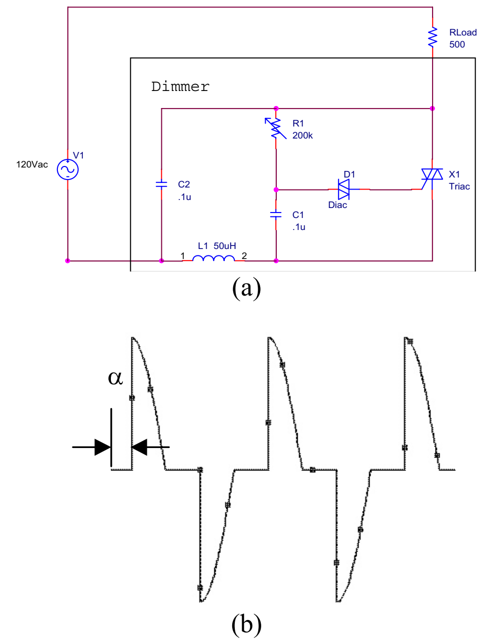

Figure1: (a) Sample Dimmer Schematic and (b) Output Voltage Across RLoad

It is reasonable to ask whether it would be simpler to build entirely new dimmer switches that could be used with HB LED bulbs. Certainly, as the acceptance of HB LEDs evolves, this would be beneficial. However, it is a major investment to ask managers/homeowners to commit to rewiring their lighting infrastructure in order to accommodate a (risky?) emerging lighting technology. We suggest that a more probable dimming/HB LED scenario is

a. *First Transition – As in this paper*
   Using existing wiring and dimmers and placing an LED Driver inside the Edison socket of an LED lamp with a PWM regulator with duty cycle adjusted by position of the dimmer;
b. *Second Transition – After moderate acceptance of LED lamps*
   Rewiring existing dimmer connections such that new LED lamp is powered by a LED driver collocated with a dimmer in the same wall box and connected straight to the AC line, while the dimmer is being used to generate only control voltage/ signal to regulate LED brightness by PWM;
c. *Final Transition – 25 years and beyond*
   Replacing dimmer's circuits by electronic off- line LED driver inside existing dimmers, packages achieving total technical and economical solution of LED lighting.

Thus, the need to create LED driving systems compatible with residential phase modulated dimming has become an emerging area of research [18-21]. Therefore, it is important to have PSpice models for the residential dimmers that can indicate when there are problems, such as those listed above. Below we present a model for a typical phase modulated dimmer. We remark that although dimmer switches precise characteristics vary from manufacturer to manufacturer, almost all follow the qualitative representation given below.

B. PSpice

As shown in Fig. 1, time constant of R1 and C1 controls the firing angle of the triac. The diac is used to maximize symmetry between the firing angle for the positive and negative half cycles, as discussed later. C2 and L1 is a simple low pass filter to help reduce noise generated by the dimmer switch. Despite the extensive modeling literature on triacs [22,23], the triac/diac combination for residential dimmers could not be found.

1. Triac operation

Triacs are well known to have different turn on thresholds for positive and negative conduction. This difference is usually minimized by using a diac, which have well defined positive and negative breakover voltage to control the turn on of the triac. Triacs also have minimum latching and holding currents. The latching current is the minimum current required to turn the triac on when given a sufficient gate pulse. The holding current is the minimum current required to hold the triac on once conducting. When the current drops below this holding current, the triac will turn off. The latching current is typically higher than the holding current. For dimmer switches that use triacs capable of switching 3A - 8A, the holding and latching currents are on the order of 10mA to about 70mA. We remark that LED currents during dimming often may drop below the latching and holding current, making it difficult to trigger the dimmer.

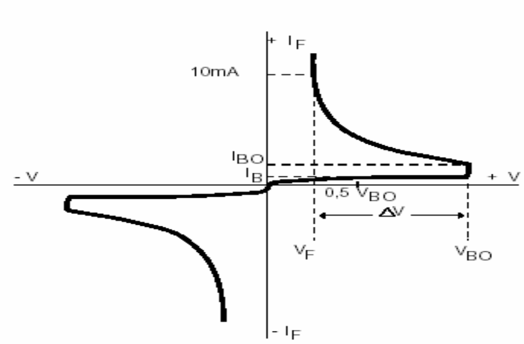

Figure 2: Diac V-I Characteristics

A diac is sometimes referred to as a bi-directional trigger diode. The diac will block current until the voltage exceeds a well defined breakover voltage, Vbo. Once Vbo is exceeded, the current increases exponentially and the voltage drops, as seen in Fig. 2. The diac is typically connected to a capacitor, which will discharge rapidly through the diac and supply a large current pulse to the gate of the triac.

The firing angle α is limited between 0° and 180° and is determined by the RC time constant of C1 and R1 + Zload, see Fig. 1. In typical dimming applications, Zload will be orders of magnitude lower than R1 and resistive, thus will not affect the firing angle appreciably. However, when the load is comparable to R1 or is not resistive, the firing angle and behavior of the dimmer switch can change dramatically.

2. Dimmer PSpice Model

The following model was developed to simulate the behavior of the dimmer switch. The triac model used is the MAC15A6 supplied by PSpice. This model was tested with various voltages and resistances to verify the expected functionality. The holding and latching current are 6mA.

The diac is modeled with two ETABLEs and one voltage controlled switch. To understand the behavioral model of the diac, one needs to first understand behavior of the diac in the dimmer switch. The primary function of the diac is turn the triac on when the voltage across C1 exceeds it breakdown voltage, about 14V. This is accomplished with E1 (see Fig. 3). E1 turns the triac on by applying 30V through a 100 Ohm resistor to the gate of the triac whenever the voltage across C1 exceeds a predefined breakdown voltage.

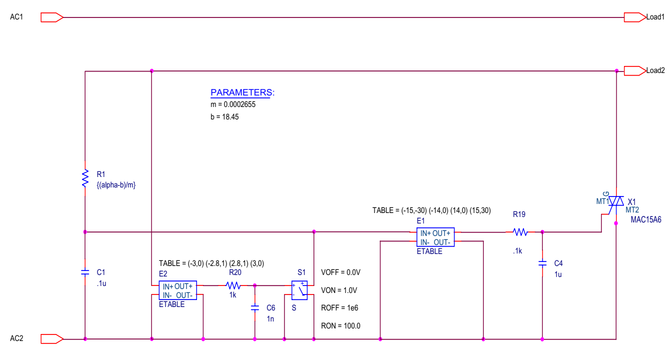

Figure 3: Dimmer Switch Model

We also know that the energy used to turn the triac on is sourced by the filter capacitor, and the voltage applied to the gate of the triac is a pulse. This implies that during each attempted firing of the triac the capacitor C1 should be discharged to approximately Vf (about 1V) to reset the capacitor and to remove the gate drive to the triac. This behavior is accomplished by using E2 to monitor the voltage across the triac and discharge C1 through S1 whenever the triac is on (when voltage is between –3V and 3V). The discharge of the capacitor is done through S1, a voltage controlled switch, which has an output resistance of 1 MΩ when open circuit and 100 Ω when closed circuit. In addition, the behavior needs to be valid for both positive and negative portions of the AC line voltage. The filter resistors (R19, 20) and capacitors (C4,6) are used to slow down the edges of the switches.

C. Failures with Residential Dimmers

Using the improved residential PSpice dimmer model, it is possible to explain and simulate the failures of residential dimmers when applied to typical LED Edison Socket Lamps:

Dimmer with Full Wave Rectifier and Capacitive Filter

One of the most common methods to drive LED lamps is to take AC-Mains and send it to a full wave rectifier and capacitor filter. This approach is used within many LED lamps on the market. A full wave rectifier with capacitive filter allows current to flow to the filter capacitor, Cfilt (Fig.4), when the input voltage is greater than the voltage across the capacitor. This circuit will continuously peak charge the capacitor to the peak voltage of the input waveform, 169Vdc for standard 120Vac line voltage. This high level DC voltage may then be fed into a large string of LEDs in series. For example, typical lamps may have parallel strings of 50 or more (perhaps Red, Green and Blue, averaging 2.6V at 90mA) LEDs in series attached through a current limiting resistor to the high level DC voltage.

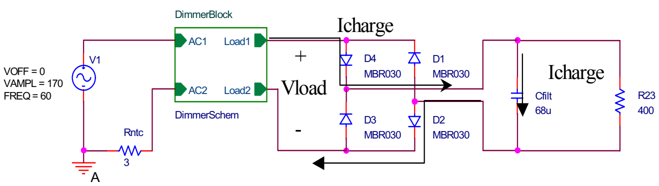

Figure 4: Full wave rectifier with capacitor filter

A typical PSpice simulation of a capacitor rectified load is presented in Fig.4. The dimmer block in the figure is represented by the detailed dimmer switch model in Fig. 3.When used with a dimmer switch, the charging current of the filter capacitor is limited by the dimming resistance R1 (inside the dimmer, see Fig. 2**)** and is Icharge = (Vin – Vload – Vc1)/R1. The voltage across the filter capacitor can be approximated to a DC voltage source due to the large difference between C1(internal to the dimmer) and Cfilt. The charging current of the filter capacitor is also the charging current for C1, which controls the firing angle of the dimmer. The charging current for C1 will be decreased from normal dimmer operation due to the large voltage drop across the filter capacitor. For large values of Vcap, the current into C1 will be small and thus slowly charge. The small charging current may not be enough to charge C1 to the diac breakover voltage during one half cycle.

Fig. 5 represents a simulation for alpha of 90 degrees when the load is considered as either LEDs or a resistor. Notice that for this simulation, the diac voltage peaks at around 10V and never reaches its breakover voltage. In this time window, the triac will not fire, causing the LED lamp to stay off. After many more cycles, the voltage on the filter capacitor is small enough to allow C1 to charge to the breakover voltage. Thus, it may take many cycles for the triac to trigger, and the LED lamp will flicker on and off or pulse between low and high intensity at frequencies at or below 60Hz. This is noticeable to the human eye.

Fig. 6 shows experimental data of the voltage across the triac with a full wave rectifier and capacitor filter when used with a common LED lamp. The phase angle is set to around 90 degrees, and the experimental data reflects the simulation outcomes.

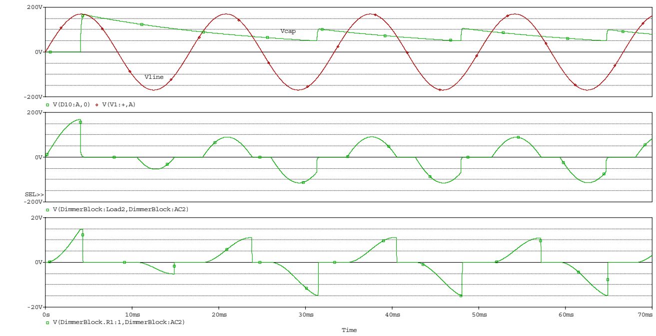

Figure 5: Dimmer with full wave rectifier and filter capacitor, Top: Line Voltage and Vcfilt, Middle: Voltage across triac , Bottom: Voltage on diac

Notice that triac/dimmer voltage does not operate periodically every half-line cycle. It takes four complete line cycles to reach steady state, i.e. the signal is periodic at 15 Hz. This is how long it takes for the diac to reach its breakover voltage. (The simulations predict a longer time to charge the capacitor, but still reflect the reasons for the failure). As expected, the experiments demonstrated that the dimmer switch causes the LED bulb to have a noticeable low frequency flicker that caused the lamp to pulse light.

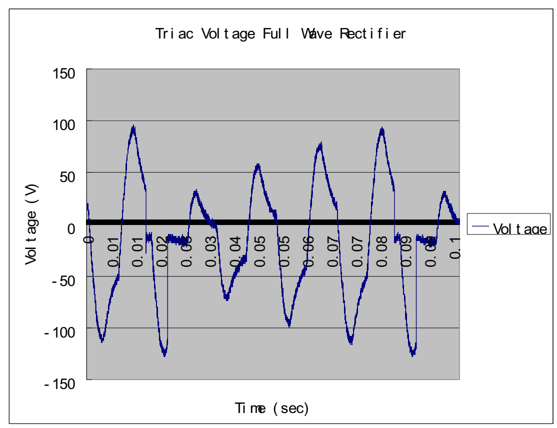

Figure 6. Experimental verification: full wave rectifier and capacitor filter inside the bulb causes noticeable flicker

Problems with Light Load

In a strange paradigm, a major benefit of the LEDs is also a reason why LED lamps have difficulty working with residential dimmers, i.e. they operate at low power with low current. LED currents of the order of 10s to 100s of milli-Amps are often desired when dimming (depending on the dimming level, type and quantity of LED's). This causes for the lamp to ask the dimmer to source power at levels sometimes as low as a fractional watt. Under light load conditions, though, Iload may be less than the holding current for all values of the AC input. When the capacitor (C1) voltage exceeds Vbo the diac will discharge the capacitor into the gate of the triac. This will momentarily turn the triac on. However, because the load current is too low, the triac will turn off. When the triac turns off, the timing capacitor C1 begins charging again through R1 and Rload. If there is enough time remaining in the half cycle, the triac will fire again. This process repeats itself through each half cycle. Fig. 7 simulates the dimmer with light load.. The behavior is as expected as seen in the top plot.

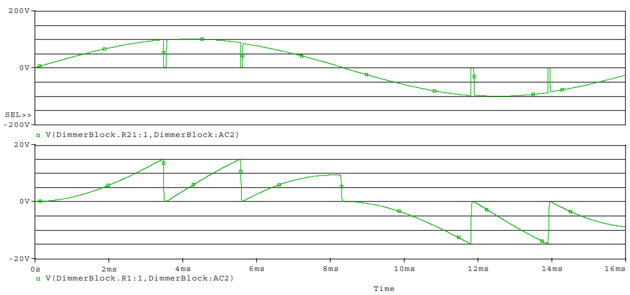

Figure 7: Dimmer with light load (Top - triac voltage, Bottom – C1 voltage)

Fig. 8 shows the actual voltage across the triac of the dimmer switch controlling at light load. The measurements were taken with a differential isolation probe. Notice the triac turns on twice during one half cycle and attempts a third, but runs out of time, as predicted in simulation

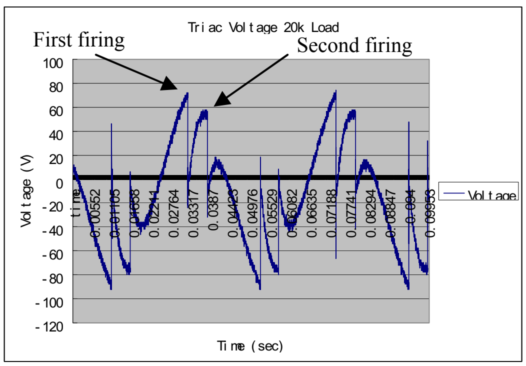

Figure 8: Dimmer with Light Load

If the impedance of the LED light is too large, the modified time will be so long that the timing capacitor (C1) voltage never reaches the diac breakover voltage, the diac will never turn on.

DC/DC Converters for LED Drivers with Residential Dimmers

Often, LED lamps utilize DC/DC converters after the full wave rectification and capacitive filter. These LED Edison socket bulbs rarely utilize power factor correction, since their wattage is so small and there are no regulations forcing them to be implemented. Thus, simple buck derived, low cost, systems are primarily utilized after the rectifications. There are numerous IC drivers with dimming capabilities on the market, yet these systems typically have difficulty with phase modulated dimmers. For example, even when the triac dimmer is off, it has finite leakage current. This sometimes results in enough voltage across the input of the driver IC to turn the LED lamp briefly on and then off again. Hence, the LED lamp flickers and never fully turns off.

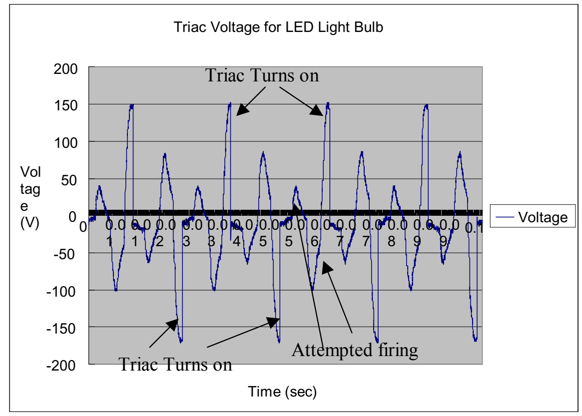

Figure 9: DC/DC converter does allow triac to recharge input capacitor each cycle, resulting low input voltage and noticeable flicker.

In actuality, there are three separate regions of performance for functionality: small alpha, large alpha and dimmer switch off. For small alpha, the average dc voltage across the filter capacitor of the converter only decreases a little, since the capacitor is continuously charged to a constant voltage. This feeds the DC/DC converter and thus, the converter attempts to maintain current regulation through the load to be constant. Thus, in this mode, the bulbs will not dim. In multiple experiments, a hum was noticed in the LED lamps even at low alpha, probably a result of the inrush current making the choke vibrate. However, for larger alpha, Cfilt may have deep discharge such that the voltage across the input capacitor of the converter drops below the minimum operating threshold turning the converter off. The deep capacitor discharge will result in higher inrush current when the triac does turn on. This increased current will shorten dimmer lifetime and create an audible hum within the dimmer or LED light.

Experiments indicated that with a large alpha, light flickers are very noticeable (see Fig. 9), the effective brightness decreased and the LED light bulb hummed considerably. With a large alpha, the triac does not fire during each half cycle. This allows the voltage across the filter capacitor to decrease. The filter capacitor voltage actually reaches zero, as can be inferred from the triac voltage in Fig. 9. During the negative half cycles the triac voltage is about 170V, which is the same voltage as the input, thus the voltage across the filter capacitor is actually zero. This indicates the converter has actually turned off and the LEDs are off.

III. DIMMING LED LAMPS WITH PHASE MODULATION

As previously mentioned, there is an emerging area of research on how to make LED lamps behave properly with residential dimmers [18-21]. The previous contribution, above, focused on the fundamental reasons why conventional LED Edison socket bulbs have failed to properly dim when connected to residential dimmers. To deal with the failures, some have proposed to add power factor correction circuits along with additional bleeder loads to maintain proper firing and also sufficient current to charge the diac [18,21]. In this section, we show how it is possible to create simple approaches to dim LED lamps when buck derived converters are used to drive the bulb (not two-stage or advanced single stage pfc circuits with higher part count and BOM).

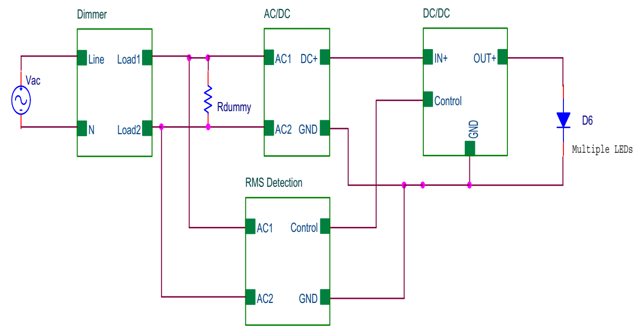

Figure 10: Proposed Block Diagram to Dim LED Lamp from AC Mains

Specifically, a proposed LED dimming system is illustrated in Fig. 10. The basic principals of operation is as follows:

- The AC mains feeds the residential dimmer. This is the first block in Fig. 10. We assume that the dimmer is a standard residential dimmer that is not specialized for LED bulbs. In fact, it is possible to dim both the LED lamps and incandescent lamps on the same phase modulated dimmer switch.
- The system will compute the RMS value of the phase modulated, chopped, AC line voltage and compare this with nominal RMS when there is no dimming. Thus, in Fig. 10, the RMS detection block is in the bottom part of the system diagram and is an input to the dc/dc converter. Similarly, the output of the rectifier is also an input to the converter. Alternatively, a power detector or similar circuit could be used instead of the RMS detector. The purpose of this circuit is to obtain a signal that indicates an amount of dimming desired.
- The comparison between the RMS detector and the rectifier output current is used to determine the duty ratio of dc-dc converter for brightness control of the LED bulb. PWM dimming could also be applied.
- An active or passive resistor load is placed across the capacitor rectifier to guarantee that the triac dimmer has adequate firing and holding currents to properly operate. The advantage of an active filter is that for small alpha the power dissipation across the load is made to be nearly zero.

The above approach works well with alternate power electronic drivers other than the buck derived converters (quadratic converters, two stage pfc's etc.) .

RMS Detection

Inside the LED driver system we use an RMS voltage sensor which measures RMS voltage modulated by the dimmer. There are different ways to sense RMS voltage: One approach is to utilize an RMS converter of phased modulated signal of the dimmer. A typical circuit that does this is given by Fig. 11. In this circuit, collector current is Ic = CTR * Id, where CTR is the current transfer ratio of the phototransistor.

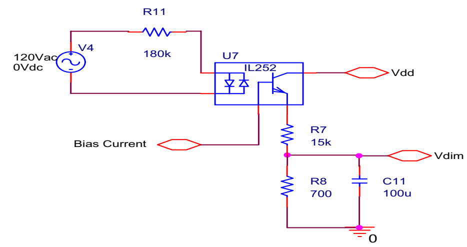

Figure 11: RMS Detection Circuit

The collector current is used to generate a low voltage AC voltage across the resistor divider R7 and R8. The voltage across R8 is capacitor filtered to extract the RMS voltage and determined by the ratio of the resistors.

A second approach is to measure the delay time, α, and this can be digitally converted to give an indication of the signal's RMS value. This is possible, since the LED driver IC may have a digital core and can compute these delays through a simple counter and timer.

Dummy Load

As previously described, residential dimmers require sufficient load current to adequately fire their triacs through the diac. One simple, yet inefficient method, to create this current is to add load resistor, R, across the dimmer (in front of the capacitor rectifier). Then there would always be a load current of at least V_{Triac}/R when the triac is firing. By setting the resistor values small enough, the current can be made sufficiently high to assure that it is above the threshold current (typically in the vicinity of 50mA ~ 100mA) needed to turn the triac on, even at the minimum allowable phase delay angle of the dimming switch. However, the power dissipation across the resistor would be extremely high, i.e. $120^2/R$ when there 0^o phase angle. Alternatively, an active resistor can be added to the circuit to supplement the necessary current to fire the triac and to hold it on, but to do so only when necessary. Thus, it is more power efficient because it reduces the supplemented current (and therefore power loss =V x I) when there are other loads providing load currents or when the phase angle is high.

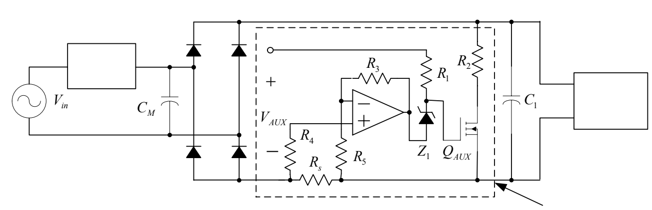

Figure 12: Circuit maintains suitable threshold currents to fire triac

Fig. 12 suggests an active load solution that can be implemented. The circuit has smaller power loss when the load is light. The auxiliary part can draw an extra current to fire the Phase Dimmer when the load current is not enough. The voltage on the zener (Z_1) is used as a reference. When the load current, which goes through sensing resistor R_s, is unable to fire the triac in the dimmer because it is too small, the auxiliary part operates as a linear regulator to insert needed extra current. Also, a small resistance value is chosen for R_s in order to reduce the conduction loss of the sensing resistor. The sensed small voltage signal is amplified by using an operational amplifier, which is shown in Fig. 12. So the impedance of the auxiliary part is regulated based on the load condition, and extra power loss is reduced. At that time, the gate voltage of the auxiliary switch (Q_{AUX}) is equal to the MOSFET threshold voltage. The resistance of R_2 limits the maximum current that Q_{AUX} can produce. Q_{AUX} is turned off when load current can create enough voltage on R_s. Capacitor Cm of the EMI filter should be also added, which is typically 0.47uF (impedance 5-6 kΩ) will provide extra 20mA current pass and further reduce loses.

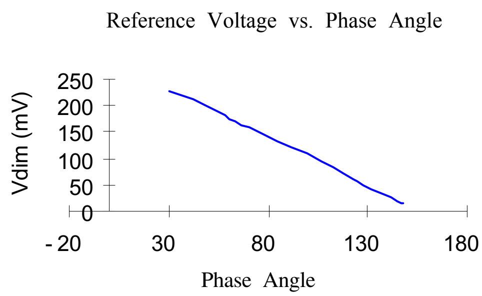

Figure 13: Experimental Reference Voltage vs. Phase Angle

Experimental Results

The LEDs using the RMS detection circuit and the structure in Fig. 11 dim linearly, as indicated in the experimental measurements in Fig. 13. Measurements were taken to compare the reference voltage from the phototransistor with the phase angle of the triac. The measurements show the results to be approximately linear, as in Fig. 13. None of the previously reported LED lamp dimming issues exists with this approach: no light pulsing, no audible noise, no turn on/turn off problems, etc.

IV. Conclusion

This paper focuses on the simulation of residential phase modulated dimmers, and then applies these PSpice simulation models to LED Edison socket lamps. The new models help explain difficulties of dimming these lamps with the triac dimmers. From these models, new approaches to dimming can be tested. We show that it is possible to sample the AC line and extract RMS voltage information to use as a control signal for LED brightness. An experimental system with a capacitor rectifier feeding a Buck converter to drive an LED lamp is presented. It provides a simple method for controlling the brightness of the LEDs without complicated control algorithms and with a minimum of parts. However, a dummy load was needed to maintain the necessary current through the dimmer.

Acknowledgments

The authors would like to acknowledge Mr. Ting Qian for his experimental help in testing the proposed dimming system.

References

[1]. Roland Haitz et al. “Another semiconductor revolution: this time it’s lighting” *Compound Semiconductor Magazine,* March 2002, pp.1-4.
[2]. *LED Magazine*, 8/2/01, p.75.
[3]. Klaus Streubel et al, “High Brightness AlGaInP Light-Emitting Diodes,” *IEEE Journal on Selected Types in Quantum Electronics*, March/April 2002.
[4]. D. Huo, et al, “Mirror adhesion technique boosts LED chip brightness,” *Compound Semiconductor*, Dec. 2003.
[5]. J. Mason, “Quantum control holds the key to a shining LED lighting market,” *Small Times*, Jan. 27, 2004.
[6]. J. Freyssinier, et al, “Evaluation of light-emitting diodes for signage applications,” *Proc. SPIE Int. Conf. Solid State Lighting*, 2004.
[7]. N. Narendran, et al, “Performance characteristics of high-power light emitting diodes,” *Proc. SPIE Int. Conf. Solid State Lighting*, 2004.
[8]. R. Haitz, “Another semiconductor revolution. This time it’s Lighting,” *Advances in Solid State Physics*, Volume 43/2003.
[9]. OIDA, Optoelectronics Industry Development Association. *Light Emitting Diodes for General Illumination. An OIDA Technology Roadmap Update*. September 2002.
[10]. www.netl.doe.gov/ssl/whyinvest.html
[11]. http://www.lightingscience.com/benefits_of_led_lighting.php
[12]. E. Mills, “The $230-billion global lighting energy bill,” 2002 Proc. Int. Conf. Energy-Efficient Lighting, eetd.lbl.gov/emills/PUBS/PDF/Global_Lighting_Energy.pdf
[13]. C. DiLouie, “Dimming HID lamps,” Lighting Controls Association, Oct. 2004: www.aboutlightingcontrols.org/education/papers/hiddimming.shtml,
[14]. C. DiLouie, “Personal control: boosting productivity, energy savings,” *Lighting Controls Assoc.*, Sept. 2004: www.aboutlightingcontrols.org/education/papers/personalcontrol.shtml,
[15]. R. Leslie, R. Raghavan, O. Howlett, and C. Eaton, “The potential of simplified concepts for daylight harvesting,” *Lighting Research and Technology* 37 (1), 2005, pp. 21-40.
[16]. http://www.ece.neu.edu/groups/power/lehman/index.html
[17]. http://www.superbrightleds.com/MR16_specs.htm
[18]. D. Rand, *Off Line Dimming for High Brightness LEDs.* MS Project, Northeastern University, Boston, MA, 2005.
[19]. www.permlight.com
[20]. Color Kinetics, Inc, “Dimmable LED-based MR16 lighting apparatus methods” USPTO No. 20050253533, Nov. 2005 .
[21]. Supertex, “HV9931 unity power factor LED lamp driver,” Applic. Note H52.
[22]. L. Giacoletto, “Simpple SCR and TRIAC PSPICE Computer Models*,” IEEE Trans. Ind. Electr*., Aug. 1989, pp. 451-455.
[23]. G. Arsov, “Triac model for computer aided analysis and design*,” IEE Proceedings-G*, , June 1991, pp. 430-431.