# Design of a Two-Stage Driver for LED MR16 Retrofit Lamps Compatible with Electronic Transformers

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Abstract—Drivers for LED MR16 retrofit lamps need to be compatible with the dimmers and electronic transformers which originally operated with the halogen lamps to be replaced. We present a two-stage MR16 LED driver consisting of a boost converter in the first stage and a buck converter in the second stage. Our design has been analyzed in the frequency domain using simulations to demonstrate that it effectively suppresses the high-frequency components of the AC output of the electronic transformer. Experiment results with a driver prototype verify the simulation results as well as dimmability.

*Index Terms*—LED driver, MR16, retrofit, triac dimmer, electronic transformer

#### **I. INTRODUCTION**

Recent decades have seen a rapid advance in LED technology. The arrival of the blue LEDs in the mid-90s [1], enabled the development of white LEDs [2], which are suitable for lighting applications. Modern LEDs have lifetimes up to 50,000 hours, which greatly surpasses those of incandescent bulbs and fluorescent lamps, and LEDs consume much less power than incandescent bulbs. The efficiency of LEDs expressed in lumens per watt, increases every year, while costs decline. LED drivers can be either AC/DC or DC/DC switched-mode power

<sup>1</sup> Department of Electrical and Computer Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea supplies; and a driver can have a single-stage topology or a two-stage topology, in which the first stage supplies a DC voltage to the second stage, which supplies current to the LED array [3-7].

LED retrofit lamps are now becoming available to replace conventional bulbs as well as fluorescent tubes in existing luminaires, by the advances in triac-dimmable LED drivers, electronic ballasts for the LED lighting, and MR16 LED drivers [8-14]. An MR16 lamp is originally a format for halogen bulbs. MR16 lamps are widely used in directional lighting applications. Since most MR16 lamps operate at 12 V, a step-down transformer is needed for mains operation. Self-oscillating electronic transformers are widely used, and drivers of LED MR16 lamps need to be compatible with them [13] Fig. 1 shows typical configurations for dimming halogen and LED MR16 lamps. One problem is that the electronic transformer generates a high-frequency oscillating voltage. Since it is an unusual input type to the following LED driver, it is necessary to investigate and analyze the effect of these oscillations on the MR16 LED driver. A study deals with a similar problem for the retrofit LED lamp for fluorescent lighting with an electronic ballast [11], yet there is no literature that deals with this topic for MR16 LED application with an electronic transformer.

In this paper we present a dimmable two-stage MR16 LED driver compatible with electronic transformers. The driver consists of a boost converter in the first stage and a buck converter in the second stage. We start by analyzing the operation of an electronic transformer and its oscillating output voltage. Then we examine the operation of the boost converter, with particular focus on its frequency characteristics, so as to predict the response

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Fig. 1. Conventional digital differential transmitter.

of the circuit to an oscillating input. Finally, we validate results of this analysis by means of a PSpice simulation and an evaluation of a prototype driver.

The remainder of the paper is organized as follows. In Section II we review and analyze the operation of an electronic transformer. In Section III we present the design and the analysis of our LED driver. In Section IV we describe the experimental results. Lastly, Section V concludes the paper.

## II. OPERATION OF A TYPICAL ELECTRONIC TRANSFORMER

An electronic transformer supplies an LED driver with an AC voltage that oscillates at a frequency of a few tens of kilohertz, which is unlike the supply to other LED drivers. We will examine how the LED driver responds to this high-frequency supply. Fig. 2 illustrates the operation of a self-oscillating electronic transformer. Switches  $Q_1$  and  $Q_2$  are initially turned off. As the voltage across  $C_t$  exceeds the breakover voltage of the diac (Fig. 2(a)), it briefly conducts a current that turns on  $Q_2$ . The current flowing through  $Q_2$  induces currents through the secondary windings of the feedback transformer  $L_2$ , which turn  $Q_1$  on and  $Q_2$  off (Fig. 2(b)). As the directions of the currents are reversed,  $Q_1$  is turned off, and  $Q_2$  is turned on, and the next oscillation begins (Fig. 2(c)). Oscillation persists until the current through the transformer falls below the holding current, when oscillation stops and the electronic transformer remains off until the next startup.

The oscillation frequency depends mainly on the size and maximum flux density of the core used in the feedback transformer, and the storage time of the



**Fig. 2.** Operation of a self-oscillating electronic transformer (a) startup, (b)  $Q_2$  conducting, (c)  $Q_1$  conducting.



**Fig. 3.** Output voltage of an electronic transformer with a resistive load in the time domain.

transistors; it is usually some tens of kilohertz. The envelopes of the oscillating output voltage and current follow the waveform of the line input. The output voltage waveforms obtained by a PSpice simulation of an electronic transformer with a resistive load show this effect (Fig. 3 and 4). The resistive load models a standard MR16 halogen bulb, and the AC input is of 230 V RMS and 50 Hz. The transformer oscillates near 30 kHz. The frequency spectrum of the output voltage shows that the oscillation frequency and its harmonics are the dominant



Fig. 4. A zoomed-in view of the waveform in Fig. 3.



Fig. 5. Output voltage of an electronic transformer with a resistive load in the frequency domain.

components (Fig. 5). Because of rectification by the diode bridge in the electronic transformer, the frequency components associated with the AC input are observed at multiples of twice the line frequency, i.e. 100 Hz, 200 Hz, etc.

Expressions for the electronic transformer will now be formulated. We begin by expressing the input voltage  $v_i(t)$  in terms of the frequency  $\omega_l$  and amplitude  $V_m$  of the line voltage:

$$v_i(t) = V_m \sin \omega_l t. \tag{1}$$

The voltage across the primary winding of the transformer (i.e.  $L_1$  in Fig. 2) can be regarded as the input voltage modulated by a square wave with an amplitude of 1 and a frequency of  $\omega_o = k\omega_l$ . The Fourier representation of the modulating signal is

$$H_o(t) = \sum_{n=\text{odd}}^{\infty} \frac{4}{n\pi} \sin n\omega_o t = \sum_{n=\text{odd}}^{\infty} \frac{4}{n\pi} \sin nk\omega_l t. \quad (2)$$

The voltage  $v_p(t)$  across the primary winding of  $L_1$  is the product of the input voltage  $v_i(t)$  and the modulating signal  $H_o(t)$ :

$$v_{p}(t) = v_{i}(t)H_{o}(t)$$

$$= \frac{2V_{m}}{\pi} \sum_{n=\text{odd}}^{\infty} \frac{1}{n} \Big[ \cos(nk-1)\omega_{i}t - \cos(nk+1)\omega_{i}t \Big].$$
(3)

The waveform of the output voltage developed across the secondary winding of the transformer is that of a scaled version of  $v_p(t)$ . Eq. (3) indicates that a pair of Fourier components occur near a frequency  $nk\omega_l$  for every odd *n* in the spectrum of the output voltage.

## III. DESIGN OF THE DIMMABLE MR16 LED DRIVER

Our MR16 LED driver is designed as a two-stage cascaded switching converter, shown in Fig. 6. The first stage is a boost converter which receives the output voltage from the electronic transformer through a diode bridge. The waveform of the rectified voltage contains harmonics of the oscillation frequency as well as the even harmonics of the line frequency. The boost converter filters out unwanted frequency components, supplies the filtered voltage to the next stage, and widens the dimming range. The second stage is a buck converter which supplies and controls the current through the LED appropriately, and dims the LED with respect to the output voltage of the boost converter.

The boost converter includes a low-cost controller circuit, in which a Schmitt trigger generates a pulsewidth modulated signal to drive the switch  $Q_1$ , by comparing the current  $I_L$  through the inductor with a current induced by a reference voltage (Fig. 6). The reference voltage  $V_{ref}$  is generated from the output voltage. Its DC level is determined by the ratio between  $R_1$  and  $R_2$ . Changes in  $V_1$  are sensed as variations in the leakage currents through the zener diodes  $D_2$  and  $D_3$ . The voltage across  $C_2$  modifies the collector current of  $Q_2$ , and produces a voltage  $V_{ref}$  which opposes changes in  $V_1$ . This also brings about the increased dimming range. If the conduction angle decreases, the power delivered to the driver decreases, hence  $V_1$  drops and  $V_{ref}$  rises, leading to increased  $I_L$  compared with the case without



(4)

Fig. 6. Our LED driver circuit.

the controller. It pulls down the minimum conduction angle at which  $I_L$  is kept above the holding currents of the dimmer and the electronic transformer.

The supply voltage VCC is provided by a low-dropout (LDO) regulator. To provide overvoltage protection, the zener diode  $D_4$  is connected to the negative input of the Schmitt trigger: if  $V_1$  exceeds the breakover voltage of  $D_4$ , the negative input rises quickly to turn off the switch  $Q_1$ .

We analyzed the frequency response of the boost converter through a PSpice simulation. An analytic approach using transient simulation was employed instead of AC sweep simulation because the operation of the boost converter depends on nonlinear and secondorder effects. A voltage of

 $v_{s}(t) = 12 + \sin 2\pi ft$ 

where,

$$f = [100 \text{ Hz}, 1 \text{ kHz}, 10 \text{ kHz}, 100 \text{ kHz}],$$
 (5)

was applied to the boost converter driving a resistive load, as shown in Fig. 7. The values of f were chosen to cover both line and oscillation harmonics. The frequency-domain representation of the output voltage at each frequency is shown in Fig. 8, which demonstrates a low-pass filtering characteristic of the boost converter.

In the frequency domain, the response to a sinusoidal input appears as a spike at the same frequency of the input, on a curve rolling off along the frequency axis. The response has a lower magnitude for a higher f, as shown in Fig. 8. It is thus reasonable to predict the boost converter will attenuate oscillation harmonics in the tens



Fig. 7. Test circuit to analyze the boost converter without an electronic transformer.

of kilohertz more significantly than line harmonics in the hundreds of hertz. By choosing the switching frequency to be sufficiently higher than the oscillation harmonics, the frequency and its harmonics are also attenuated, and the oscillation of the electronic transformer does not interfere with the operation of the boost converter. The switching frequency components can be found on the curve near 140 kHz and higher.

To validate the result of the analysis just described, we performed another PSpice simulation of a circuit composed of both the electronic transformer and the boost converter (Fig. 9). This circuit is supplied with a standard line voltage of 230 V and 50 Hz. Fig. 10 shows the simulated waveforms of the input and output voltages of the boost converter. The oscillation components are attenuated more than the ripple at twice the line frequency. Fig. 11 shows the frequency-domain representation of the simulated waveforms above. The



Fig. 8. Simulated frequency response of the boost converter to the sinusoidal input voltage with a frequency of (a) 100 Hz, (b) 1 kHz, (c) 10 kHz, (d) 100 kHz.



Fig. 9. Test circuit for analysis of the boost converter with an electronic transformer.

oscillation harmonics are the dominant components in the spectrum of the input voltage, but in the output voltage spectrum, the high-frequency components are greatly attenuated, and the line harmonics are the dominant components. The buck converter circuit is a step-down LED driver employing Maxim's MAX16832 for LED current regulation and dimming. The internal blocks of MAX16832 involved in dimming control are shown in Fig. 12. MAX16832 senses the current through the



Fig. 10. Simulated waveforms of the input voltage  $V_{in}$  to the boost converter and the output voltage  $V_{out}$  from the boost converter in the time domain.



Fig. 11. Simulated waveforms of the input voltage  $V_{in}$  to the boost converter and the output voltage  $V_{out}$  from the boost converter in the frequency domain.



**Fig. 12.** Buck converter configuration employing MAX16832, obtaining the dimming information from the input voltage.

sensing resistor ( $R_s$  in Fig. 12) and regulates the LED current to be a linear function of the voltage on TEMP\_I pin, as presented in the datasheet. This linear relationship is used for analog dimming. If the input voltage is low-pass filtered and applied on TEMP\_I node, it indicates



Fig. 13. Experimental setup and prototype.

the average power delivered to the buck converter, which can be used as a dimming control signal (Fig. 12). In our design, the output voltage of the boost converter,  $V_1$  is the input voltage to the buck converter. If the conduction angle of the dimmer is decreased, the power transferred from the line through the dimmer is decreased, hence  $V_1$ drops. The boost converter controller tries to oppose the change but is not effective because it can manage only small variations in  $V_1$ . Dropped  $V_1$  is low-pass filtered and then applied on TEMP\_I pin. Then MAX16832 senses the voltage and regulates the LED current with respect to the value, hence the LED current is reduced. The less the conduction angle is set in the dimmer, the less current flows through the LED. On the other hand, if the conduction angle is increased, a more amount of current flows through the LED.

### **IV. EXPERIMENTAL RESULTS**

We constructed a prototype board which is sufficiently small to fit in an MR16 fixture. A leading-edge triac dimmer and a Tridonic Possum electronic transformer, together with the prototype board, were installed in the experimental setup shown in Fig. 13. An AC source was employed to generate and supply the line voltage of 230 V RMS and 50 Hz. The measured data are summarized and compared with those of [10] and [11] (Table 1). The dimming range was determined from the range of the output current as the ratio of the minimum

	[10]	[11]	This Work	
Input Voltage(V)	110	230	230	
Input Current (mA)	_	270	52.2	
Input Power (W)		63	12.0	
Power Factor	_	0.959	0.926	
Vout (V)	24.16	27.1	11.86	
Iout (mA)	298	745	655	
Iout Range (mA)	13-298	398-745	37-627.37	
Pout (W)	7.2	20.19	7.768	
Efficiency (%)	80	74*/84.5†	64.7*/70.54†	
Dimming Range (%)	13-100	53.4-100	5.9-100	

Table 1. Performance Comparison

\* Efficiency of the whole system.

† Efficiency of the LED driver except the dimmer/electronic transformer/electronic ballast.



**Fig. 14.** Measured input voltage to the boost converter and output voltage from the boost converter in the time domain.

value to maximum value possible [14]. Although our design has low efficiency compared to other designs, it can be dimmed down to 5.9% of the maximum, which is the widest dimming range among the designs.

Fig. 14 shows the measured waveforms of the input and the output voltages of the boost converter, with the maximum conduction angle. They are comparable to the simulated waveforms in Fig. 10. The boost converter of the prototype has the buck converter as the load while the simulated boost converter drove a resistor. Also the prototype is powered through a dimmer unlike the simulated circuit. Nonetheless, both cases share the tendency that the high-frequency oscillating components of the input voltage are greatly attenuated in the output voltage. Instead the DC component and the ripple of twice the line frequency is prominent.

Fig. 15 shows the measured waveforms of the input



**Fig. 15.** Measured waveforms of the input voltage  $V_{in}$  (top) and current  $I_{in}$  (bottom) to the driver.



**Fig. 16.** Measured waveforms of the output current through the LED current  $I_{out}$  (top) and the output voltage from the boost converter  $V_{out}$  (bottom), not dimmed (maximum  $I_{out}$ ).



Fig. 17. Measured waveforms of the output voltage from the boost converter  $V_{out}$  (top) and the LED current  $I_{out}$  (bottom), dimmed (50% of the maximum  $I_{out}$ ).

voltage and current to the LED driver with the maximum conduction angle. The waveforms of the LED current and the boost output voltage are shown in Fig. 16. The input voltage and current to the driver oscillate at high frequencies, and the waveform of the output voltage from the boost converter mainly consists of DC and 100 Hz components, with the high-frequency components of the input significantly diminished, as predicted by the



**Fig. 18.** Measured waveforms of the output voltage from the boost converter  $V_{out}$  (top) and the LED current  $I_{out}$  (bottom), dimmed (15% of the maximum  $I_{out}$ ).



Fig. 19. Measured waveforms of the output voltage from the boost converter  $V_{out}$  (top) and the LED current  $I_{out}$  (bottom), dimmed (10% of the maximum  $I_{out}$ ).

	 	 2	/.1:	 	 
		2ms			
		$V_{out}$ (1)	0V/div)		
Luis Ballyting			lealest P		
	 	 $I_{out}$ (0.	1A/div)	 	 

**Fig. 20.** Measured waveforms of the output voltage from the boost converter  $V_{out}$  (top) and the LED current  $I_{out}$  (bottom), dimmed (3.5% of the maximum  $I_{out}$ ).

simulations, and a fairly stable current flows through the LED.

Fig. 16-20 show the boost output voltage waveform and the LED current declining by the reduced conduction angle of the dimmer for the cases of 100%, 50%, 15%, 10%, and 3.5% of the maximum output current  $I_{out}$ , respectively.  $I_{out}$  drops down to 37 mA, which is the lowest value of the LED current while the LED remains lit.

## **V. CONCLUSIONS**

We have presented a new design of an MR16 LED

driver in the form of a two-stage cascaded switching converter. In the first stage, a boost converter is combined with a low-cost controller, and the second stage is a commercial buck converter. We analyzed the operation of an electronic transformer, in order to characterize the output oscillating voltage. We found that the dominant components of the spectrum of the electronic transformer output were largely the harmonics of its oscillation. We also examined the operation of the boost converter, with emphasis on its frequency characteristics, and found that it acts as a low-pass filter. We combined the electronic transformer and the boost converter and carried out a PSpice simulation, and confirmed that the boost converter attenuates the oscillation harmonics to a significant degree. We also produced a prototype dimmable MR16 LED driver. The results of both simulation and experiment showed that the high-frequency components of the boost output voltage, including oscillation harmonics, were significantly filtered, leaving the DC and the component at double the line frequency. Also, the dimming function was tested to show the LED current can be reduced to 5.9% of the maximum.

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