A Dimmer Circuit for Various Lighting Devices

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Abstract

Incompatibility of compact fluorescent lamps (CFLs) and light-emitting-diodes (LEDs) with conventional light dimmers is a problem for consumers today. This paper proposes a dimmer circuit that is suitable for incandescent bulbs, CFLs and LEDs. Different kinds of lighting devices are studied and tested with AC and DC sources. The proposed dimmer circuit is designed, built and tested with various lighting devices. Experiments are performed in order to observe the electrical characteristic of the dimmer and optical characteristic of the lighting devices when they are used with the dimmer circuit. The experimental results show that the proposed dimmer can be used with these kinds of lighting devices within specific output voltage ranges.

1. Introduction

The device that can control the intensity of light is called "light dimmer". Variable resistors and autotransformers were used as dimmers which can adjust the load current or supply voltage. This situation leads an inefficient, expensive and bulky solution for dimming operation. The modern dimmers are designed and used widely after the advancement in power electronics. The basic dimmer is a device which employs TRIAC in order to chop the sinusoidal voltage. The main disadvantage of the basic dimmer is that can only control purely resistive loads. An inductive load causes the TRIAC extinction angle be larger than zero-crossing of the line voltage for each positive and negative alternating cycle. This causes a limitation on the range of firing angle [1].

The basic dimmer is designed to be used with resistive loads such as incandescent and halogen lamps. However, there are more efficient lighting devices such as LEDs which require a driving circuit that cannot be driven by a basic dimmer. If incompatibility problem of the dimmer and LEDs is solved, LEDs may gain more public acceptance [2]. Drivers of the LEDs can be buck or boost converters depending on the parallel or series connection of the LEDs. A high-brightness LED can be dimmed by driving with less current but this is not an efficient way. Since a power LED provides the best efficiency at rated current, a better efficiency can be obtained by using PWM signal in order to turn the LED on and off while rated current is drawn by the LED when it is "on" [3].

Another widely-used lighting device is fluorescent lamp. Today, fluorescent lamps are in their compact form in general which are called Compact Fluorescent Lamps (CFL). Power-dependent resistance and dynamic response to differences in electrical excitation are two major electrical features of fluorescent lamps [4]. Fluorescent lamp tubes can be modeled as resistors. However, this is a crude approximation according to the real fluorescent characteristics. Fluorescent lamps behave as a resistor at high frequency operation and V-I characteristic of the lamp is linear for the power range from 30% to nominal power. For lower powers, V-I characteristic is non-linear.

There is a strong non-linear relation between voltage and current of a real fluorescent lamp. Modeling the CFL tube as a resistor does not allow analysis of the tube fed by low frequencies, such as utility frequency. Thus, V-I characteristic of the CFL tube can be modeled as,

$$v.i^{\alpha} = K \tag{1}$$

where α and K are parameters of the lamp; v and i are lamp voltage and currents respectively. The simulation of this model shows that the voltage and current have sinusoidal curves as the frequency increases [5].

CFLs are driven by electronic ballasts in general. This ballast includes a rectifier stage, a power factor correction stage (PFC) and an inverter stage. Voltage-sourced half bridge inverters are widely used in CFL ballasts [6]. In a frequency range from 20 kHz to 60 kHz, the lamp voltage shape can be simplified as a square wave with a tilt in falling edge. There are mainly four types of PFC stage topology in the CFL ballasts that can be found in the market: No-power correction, passive power factor control, valley (or improved-valley) fill and active power factor control. The CFLs with no-power correction ballast are categorized as "Poor CFL" with a total harmonic distortion (THD) of 180%-200%. "Excellent CFL" has ballast with active power control filter and it causes a THD of 5%-10% [7].

Commercial CFLs cannot be dimmed by basic TRIAC dimmers. TRIAC dimmer compatibility problem arises when the dimmer is connected to a non-resistive load such as CFL [8]. Dimming a CFL can be achieved by two methods: Constant DC link voltage with variable switching frequency (VFS) and variable DC link voltage with constant switching frequency (VVS). Researches show that VVS is a better method than VFS in respect to a simpler control mechanism, longer life caused by smooth dimming and simple EMI suppression by means of fixed frequency [9]. Moreover, VFS may increase the switching core loss in the ballast circuit.

However, VFS and VVS are not simple and do not offer a practical solutions, because internal circuitry of CFL ballasts cannot be accessed externally in general. The brightness of the lamp can be controlled by adjusting the supply voltage. Electric field energy between the two filaments can be changed proportional to supply voltage. Yao designed a special AC chopper to dim CFLs by adjusting the supply voltage at mains frequency [10]. Yao's design shows that it is possible to dim CFLs by an adjustable AC voltage. On the other hand, since CFL ballasts include a rectifier stage, it can be said that CFL ballasts are operated under a DC voltage. As a result, it is possible to drive CFLs with DC power supplies and lamp output can be dimmed by adjusting the DC voltage level [11].

There are various lighting devices in the market today. The type of lamp characteristic should be known in order to design a good dimmer. Three kinds of these devices are considered in this paper: Incandescent bulbs, CFLs and LED bulbs. Incandescent bulbs are nearly pure resistive loads and modeling these devices is not difficult since their behaviors are linear. CFLs have cascaded circuits inside including rectifier, oscillator, inverter and power factor correction stages. LED bulbs include a rectifier stage and current limiting circuitry. Since there are LEDs connected in series inside the bulb, the rectifier converts the mains voltage to the suitable DC voltage.

2. Theoretical Study

Incandescent bulbs, CFLs and LEDs are three major light sources of the illumination market today. These lighting devices have different load characteristics. In this paper, V-P and photometric characteristics are going to be studied.

2.1. Incandescent Bulbs

Incandescent bulbs are the conventional and the most well-known lighting device. It is becoming unpopular because of the poor efficiency with respect to CFLs or LEDs [12]. Incandescent bulbs can be considered as resistance when included in a circuit analysis. Thus, the V-I relation is given in Equation (2).

$$v = i \, . R_{bulb} \tag{2}$$

Where v is the voltage across the bulb, i is the current flowing through the bulb and R_{bulb} is the bulb resistance.

2.2. CFLs

A CFL bulb consists of several stages. For simplicity, power correction stage is not included in the model. Thus, the structure of the CFL consists of a rectifier and a high-frequency inverter connected to the fluorescent tube. The rectifier stage includes a single-phase diode bridge and a filter capacitor in order to obtain a DC voltage with small ripple. The inverter stage is a half-bridge series resonant inverter with an LC tank circuit. In the literature, it can be seen that the fluorescent tubes can be modeled as resistors when used in high-frequency. Since the frequency will be more than 20 kHz, the linear characteristic of the tube can be used for simplicity [4]. The equivalent model of the CFL for high-frequency operation is shown in Fig.1. The arc resistance of the fluorescent tube is denoted as R_{arc}.

2.3. LED Bulbs

LED bulbs consist of several LEDs a rectifier stage with a current limiting circuitry. Since the LEDs should be operated in DC voltage, a diode bridge is used with a filter capacitor in order to have a DC voltage with small ripples. The rectifier stage may include a DC-DC converter in order to obtain a constant DC voltage/current at the terminals of the LED group.

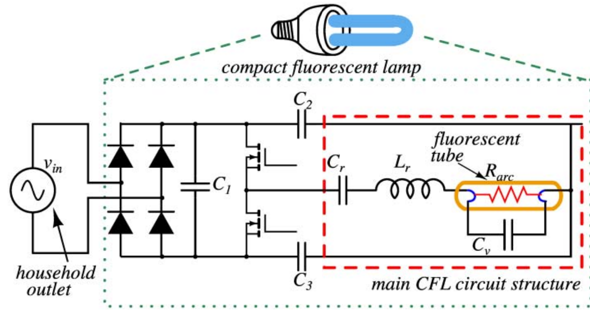

Fig. 1. Equivalent model of the CFL

2.4. Dimmer Circuit

The dimmer circuit consists of a rectifier stage and a buck converter. The rectifier stage does not include a transformer in order to keep the circuit small and light. The proposed dimmer circuit is shown in Fig. 2.

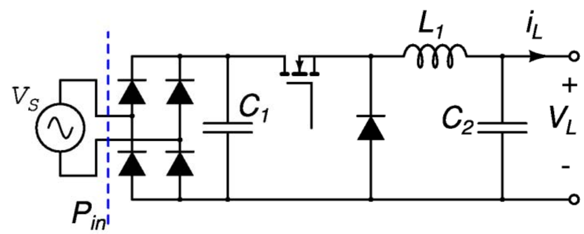

Fig. 2. Equivalent model of the rectifier and buck converter that will be used as the dimmer

Voltage conversion function of the dimmer circuit is given in Equation (3) where all circuit components are assumed ideal and input capacitor C1 is large enough to satisfy a ripple-free voltage. V_L is the output voltage, V_S is the mains voltage and D is the duty cycle of the MOSFET gate signal.

$$V_L = D \, . V_S\sqrt{2} \tag{3}$$

3. Experimental Work

Various light sources are tested with variable AC and variable DC voltage sources. Dimming ranges, electrical and photometric characteristics of the sources are observed under different conditions. The lighting devices used in measurements are given in Table 1.

Table 1. Lighting devices used in the experiments

Lamp Type	Rated Voltage [V]	Rated Power [W]
Incandescent Bulb	230	100
CFL	230	10
LED	100 - 230	4

Firstly, the lighting devices are tested with an autotransformer in order to observe the dimming characteristic of the devices with variable AC power. Terminal voltages and power are measured.

Incandescent bulb experiment showed what is expected from a resistor. The light output was barely visible when the applied voltage is less than 50V. Voltage and current waveforms of the bulb at the rated voltage are shown in Fig. 3.

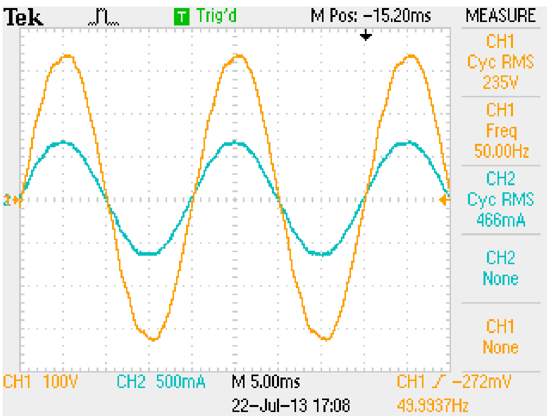

Fig. 3. Voltage and current waveforms of incandescent bulb operated in rated voltage

It is observed that CFL turns off below 80 Volts when supplied by an autotransformer. Low voltage avoids the tube becoming hot enough. Voltage and current waveforms of the CFL at the rated voltage are shown in Fig. 4.

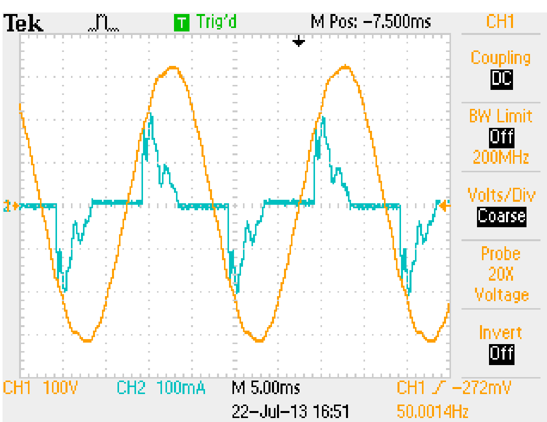

Fig. 4. Voltage (Sinusoidal shape) and current waveforms of CFL operated in rated voltage

The experiment made with LED bulb shows that the light level does not significantly change over 90 Volts. Moreover lamp turns off below 10 Volts and does not turn on again until the terminal voltage rises up to 30 Volts. The voltage and current waveforms of the LED bulb operated in rated voltage are shown in Fig. 5.

Dimming characteristics of incandescent bulb, CFL and LED are observed when they are supplied by an autotransformer. Experiments show that a variable AC voltage source can dim these kinds of lighting devices in specific ranges.

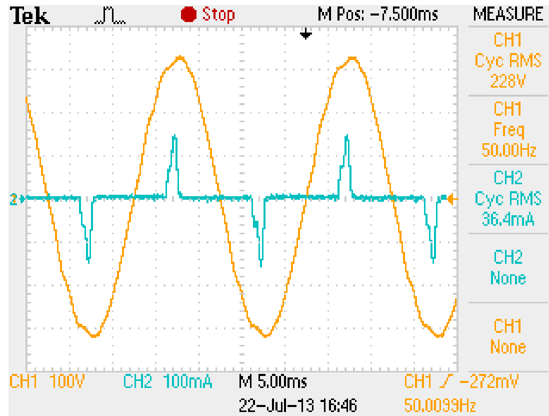

Fig. 5. Voltage and current waveforms of LED operated in rated voltage

The rectifier stage of the dimmer does not include a transformer in order to keep the circuit as small as possible and avoid any conversion losses at the input stage as shown in the dimmer circuit depicted in Fig 2. Thus, the rectifier consists of a diode bridge and 115μF capacitor.

Since the rectified mains voltage is 325 VDC and rated voltages of the lamps are 230 Volts, converter topology is selected to be a buck converter. The light level can be adjusted by changing duty cycle of the gate signal of the MOSFET. Since the rated voltage of the load can be obtained with a duty cycle of 70%, the duty cycle should not be more than 70%.

Circuit component values of the dimmer circuit are given in Table 2. The inductance value is selected such that continuous conduction mode operation is possible for all operating conditions. Using these parameters, voltage and current ripple is small enough to perform a stable operation.

Table 2. Circuit component values of the dimmer

Circuit Component / Parameter	Model / Value
Diode Bridge	2KBP04M
Input Capacitor C1	115 μF
Inductor L1	50 mH
MOSFET	STP11NK50ZFP
Diode	MUR840
Output Capacitor C2	4.7 μF
Switching Frequency	20 kHz

Output voltage and output current waveforms with MOSFET gate signals of the dimmer that is connected to incandescent bulb, CFL and LED are given in Fig. 6, Fig. 7 and Fig. 8, respectively.

Fig. 9, Fig. 10 and Fig. 11 show voltage – input power and voltage – luminous intensity characteristics of incandescent bulb, CFL and LED bulb respectively. Luminous intensity values are measured when the lighting devices are connected to the dimmer. Each figure shows the V-P characteristics of the lighting devices when they are used with autotransformer and the dimmer.

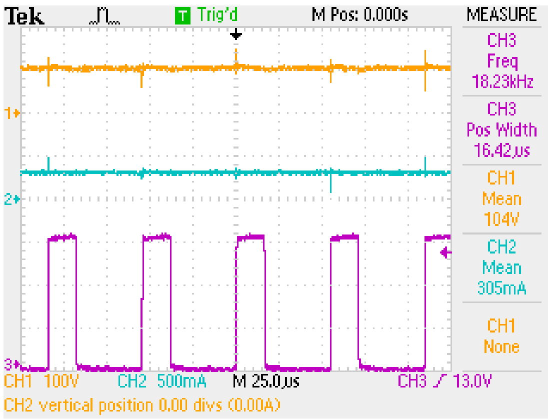

Fig. 6. Voltage and current waveforms of incandescent bulb and MOSFET gate signal

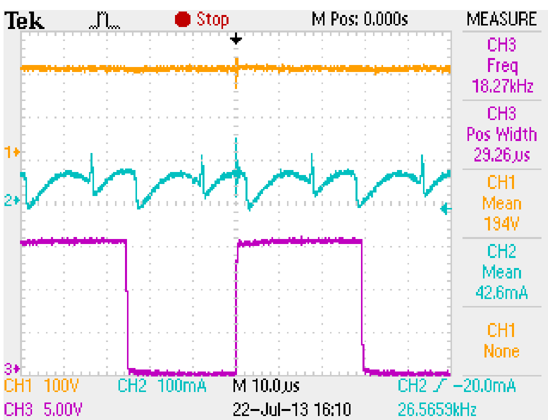

Fig. 7. Voltage and current waveforms of CFL and MOSFET gate signal

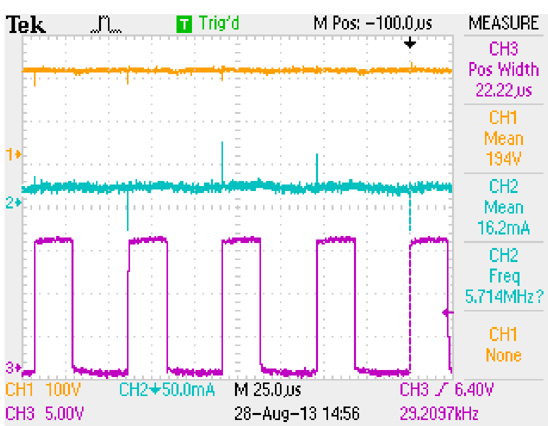

Fig. 8. Voltage and current waveforms of LED and MOSFET gate signal

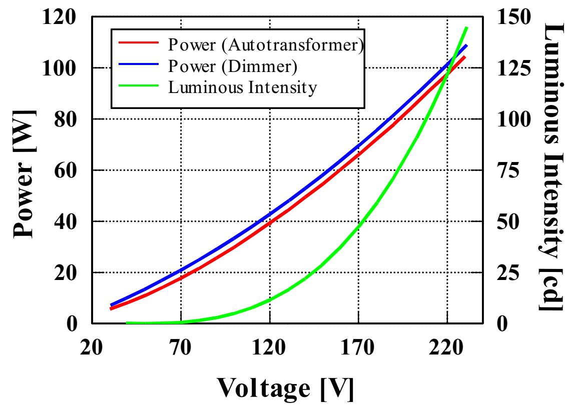

Fig. 9. V-P characteristics of 100W incandescent bulb

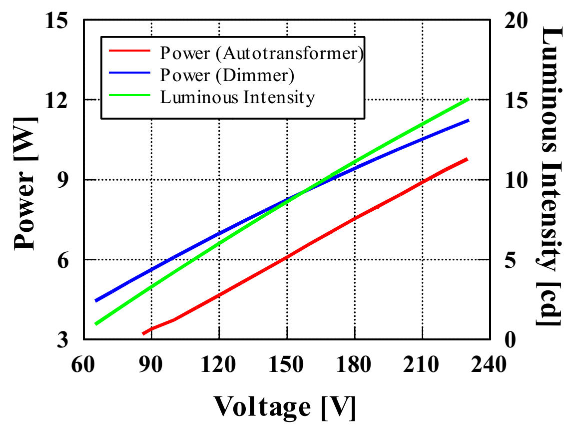

Fig. 10. V-P characteristics of 10W CFL

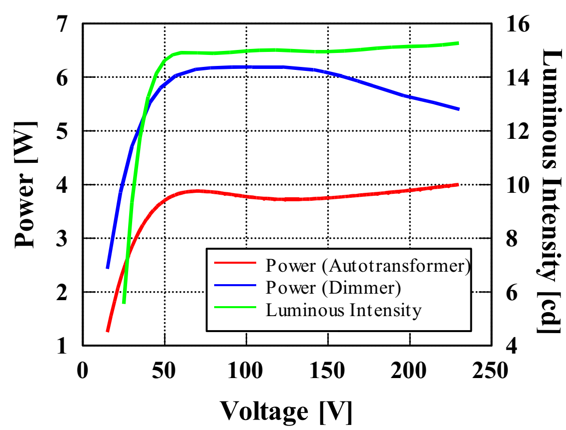

Fig. 11. V-P characteristics of 4W LED

The dimming operation of the incandescent bulb is performed without any problem or constraint. However, some problems are encountered with CFL and LED.

CFLs and LEDs do not start to operate easily with a stepped-down voltage. For instance, when the terminal voltage of the CFL is increased step by step from zero volts, the lamp gives a visible output at 100 Volts and until this step, lamp is cold and flickering. Nevertheless, if the supply voltage is decreased step by step from the rated voltage, lamp stops illuminating at 65 Volts instead of 100 Volts. Moreover, dimming range of some LED bulbs is restricted because of their driver with feedback.

Input power of the LED is constant after the value which is at the input range of the driver of the LED lamp. It is observed that the luminous intensity does not significantly change because of the LED driver. Thus, dimming range should be limited and made more sensitive for given range in order to perform a proper dimming. The duty cycle of the buck converter dimmer is limited between 5% and 30% when LED bulb is connected, because the lamp does not start with a duty cycle value less than 5% and not sensitive with duty cycle value that is greater than 30%.

Experiment results show that the buck converter can be used as a dimmer for incandescent bulbs, CFLs and LED lamps for specific terminal voltage ranges. It is observed that incandescent bulbs and CFLs can be used within same output voltage range. However, LED bulbs need a different operation range for dimming as mentioned above.

4. Conclusion

It is observed that incandescent bulbs, CFLs and LED lamps can be operated with AC or DC sources. Incandescent bulbs can be considered as resistors while CFLs and LEDs have more sophisticated transfer functions. Since it is seen that dimming operation can be done by changing average DC voltage value, the dimmer is designed as two-stage power converter that consists of a rectifier and a buck converter. The dimmer is built according to ripple constraints and used as a dimmer for three different kinds of lighting devices. It is observed that the dimmer performs a better dimming performance than the autotransformer. Incandescent bulbs, CFLs and LED bulbs have specific dimming ranges because of their internal structure.

5. References

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