# A DIMMER CIRCUIT FOR VARIOUS LIGHTING DEVICES

by
Remzi Barış DAİ

Submitted to the Institute of Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science
in
Electrical and Electronics Engineering

Yeditepe University
2013

A DIMMER FOR VARIOUS LIGHTING DEVICES

APPROVED BY:

Prof. Dr. Canbolat Uçak
(Supervisor)

Assist. Prof. Dr. Deniz Yıldırım
(Co-advisor)

Assoc. Prof. Dr. Duygun Erol Barkana

Assist. Prof. Dr. İsmail Aksoy

Assist. Prof. Dr. Levent Ovacık

DATE OF APPROVAL: …./…./….

# ACKNOWLEDGEMENTS

I am heartily thankful to my co-advisor Assist. Prof. Dr. Deniz Yıldırım and supervisor Prof. Dr. Canbolat Uçak for their encouragement, guidance and patience throughout the development of this thesis. It is a pleasure to thank to my thesis committee members Assoc. Prof. Dr. Duygun Erol Barkana, Assist. Prof. Dr. İsmail Aksoy and Assist. Prof. Dr. Levent Ovacık.

I would like to extend my gratitude to Mert Turhan, Furkan Başkurt and Lale Erdem for their help in this thesis and my dear colleagues, research assistants of Yeditepe University Electrical and Electronics Engineering Department, for their great friendship. Also, N. Ceren Aşkın and Fatih Özkul deserve a special mention for their guidance.

Last, but not least, I would like to thank to my family and Tuğçe Hakarar for their patient love and support.

Remzi Barış DAİ

# ABSTRACT


## A DIMMER FOR VARIOUS LIGHTING DEVICES

Incompatibility of compact fluorescent lamps (CFLs) and light-emitting-diode (LED) bulbs with conventional light dimmers is a problem for consumers today. This thesis proposes a dimmer circuit that is suitable for incandescent bulbs, CFLs and LEDs. Different kinds of lighting devices are studied and tested with variable AC and DC sources. The proposed dimmer circuit is designed, simulated, 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 special output voltage ranges. It is observed that incandescent bulbs, CFLs and LED bulbs have different voltage ranges for dimming operation and this creates need for specific output voltage ranges of the dimmer for each kind of lighting device. This can be achieved by using an application-specific PWM generator system that operates the power circuit of the dimmer within a specialized voltage range according to the lamp type.

# ÖZET

## FARKLI TİPTE AYDINLATMA CİHAZLARI İÇİN BİR LOŞLAŞTIRICI

Kompakt flüoresan ve LED lambaların geleneksel loşlaştırıcılarla uyumlu olmaması, bugün tüketiciler için bir problem teşkil etmektedir. Bu tez, akkor telli lambalar, kompakt flüoresan lambalar ve LED lambalara uygun bir loşlaştırıcı devre çözümü sunmaktadır. Farklı tiplerde aydınlatma cihazları çalışılmış ve ayarlanabilir alternatif ve doğru akım kaynaklarıyla test edilmiştir. Loşlaştırıcı devre tasarlanmış, bilgisayar ortamında benzetimi yapılmış, kurulmuş ve farklı tipte lambalarla test edilmiştir. Loşlaştırıcının elektriksel davranışı ve aydınlatma araçlarının optik karakteristiğini gözlemlemek amacıyla deneyler gerçekleştirilmiştir. Deney sonuçları, tasarlanan loşlaştırıcı devrenin özel çalışma aralıklarında bu üç tip aydınlatma cihazıyla kullanılabileceğini göstermiştir. Akkor telli lambalar, kompakt flüoresanlar ve LED lambaların loşlaşma aralığındaki gerilim değerlerinin birbirinden farklı olduğu gözlemlenmiştir ve bu durum her aydınlatma cihazı tipi için, loşlaştırıcının farklı bir çıkış gerilimi aralığında çalışması ihtiyacını doğurmaktadır. Bu durum, lamba tipine uygun özel bir gerilim aralığında loşlaştırıcıyı kontrol edecek, uygulamaya özgü bir PWM üreteciyle sağlanabilir.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## LIST OF SYMBOLS / ABBREVIATIONS

| | |
|---|---|
| $A_1$ | First main terminal of a bidirectional semiconductor device |
| $A_2$ | Second main terminal of a bidirectional semiconductor device |
| $C$ | Capacitance |
| $C_i$ | *i*th capacitor in a circuit |
| $C_f$ | Filter capacitor |
| $C_r$ | Capacitor of the resonant L-C circuit |
| D | Duty cycle |
| deg | Degree |
| E | Illuminance |
| f | Frequency |
| $f_{sw}$ | Switching frequency |
| $i, I$ | Current |
| $i_C, I_C$ | Capacitor current |
| $i_g$ | Gate signal current |
| $i_L$ | Inductor current |
| $I_o$ | Output current |
| K | Parameter of fluorescent tube |
| L | Inductance |
| $L_i$ | *i*th inductor in a circuit |
| $L_f$ | Filter inductor |
| $L_r$ | Inductor of the resonant L-C circuit |
| P | Active power |
| p. f. | Power factor |
| $P_i$ | Input power |
| r | Distance between the light source and illuminated point |
| R | Resistance |
| $R_{arc}$ | Arc resistance of fluorescent tube |
| $R_{bulb}$ | Resistance of an incandescent bulb |
| $R_{DS}$ | Resistance of MOSFET in “on” state |

| | |
|---|---|
| $R_i$ | *i*th resistor in a circuit |
| $t$ | Time |
| $T$ | Period |
| $T_S$ | Switching period |
| $v, V$ | Voltage |
| $V_{BO}$ | Breakover voltage of DIAC |
| $v_{C,} V_C$ | Capacitor voltage |
| $V_D$ | Forward voltage drop of diode |
| $v_{in}, V_{in}$ | Input voltage |
| $v_{L,} V_L$ | Inductor voltage |
| $V_m$ | Magnitude of utility voltage |
| $v_{o,} V_o$ | Output voltage |
| $v_S$ | Source voltage |
| | |
| $\alpha$ | Firing angle |
| $\beta$ | Parameter of fluorescent tube |
| $\Delta i_L$ | Inductor current ripple |
| $\Delta V$ | Voltage ripple |
| $\eta$ | Efficiency |
| $\vartheta$ | Angle between luminous intensity and surface normal |
| $\omega$ | Angular frequency |
| $\mathcal{I}$ | Luminous intensity |
| $\mathcal{I}_\vartheta$ | Luminous intensity in $\vartheta$ direction |
| $\mathcal{I}_0$ | Luminous intensity in 0 direction |
| | |
| AC | Alternating current |
| CCM | Continuous conduction mode |
| CFL | Compact fluorescent lamp |
| DC | Direct current |
| DIAC | Diode for alternating current |
| EMI | Electromagnetic interference |
| ESR | Equivalent series resistance |

| | |
|---|---|
| IC | Integrated circuit |
| LED | Light emitting diode |
| MOSFET | Metal oxide semiconductor field effect transistor |
| N/A | Not available |
| PFC | Power factor correction |
| PWM | Pulse width modulation |
| RMS | Root mean square |
| SCR | Silicon controlled rectifier |
| SMPS | Switched mode power supply |
| SSL | Solid-state lighting |
| THD | Total harmonic distortion |
| TRIAC | Triode for alternating current |
| UV | Ultra-violet |
| VFS | Variable frequency source |
| VVS | Variable voltage source |

# 1. INTRODUCTION

The device that can control the intensity of light is called “light dimmer”. Dimming feature is a necessity where the consumers want to change the ambient light or using an energy efficient lighting system. For instance, auto-dimming lights in the market use a luminescence sensor to detect the light level and automatically dim the lamp to keep the ambient light constant.

## 1.1. LITERATURE REVIEW

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 CFLs and LEDs. LED bulbs 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 power LED provides the best efficiency (lumens per watt) at maximum rated drive current and an efficient brightness control 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,

$$v.i^{\beta} = K \tag{1.1}$$

where $\beta$ and $K$ are constant 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, and V-I characteristic of the lamp is linearized as the frequency of the applied voltage 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.

## 1.2. CONTRIBUTION OF THE THESIS

A new dimmer circuit for various lighting devices is designed and built. The dimmer circuits in the market are usually operated with a single kind of lighting device. Moreover, CFL and LED dimmers in the market are used with "Dimmable CFLs" and "Dimmable LEDs" respectively. Dimmable CFLs and LEDs have special ballasts and drivers for TRIAC-dimming or a different dimmer circuit. The proposed dimmer circuit in this thesis can be used with incandescent lamps, CFLs or LED lamps even if they do not have a "dimmable sign" on the box.

# 2. CHARACTERISTICS OF MAJOR LIGHTING DEVICES

Incandescent bulbs, CFLs and LEDs are three major E27 and E14 screw-in base type light sources of the illumination market today. These lighting devices have different load characteristics. In this section, electrical and optical characteristics of the lighting devices are studied.

## 2.1. INCANDESCENT BULBS

Incandescent bulbs are the conventional and the most well-known lighting device. The research and experiments for light production from electricity has started 1800 by an English scientist, Humphry Davy and it is improved through this century. Modern light bulb is produced when Joseph Swan invented the enclosed incandescent lamp in 1870s [12]. It is becoming unpopular because of the poor efficiency with respect to CFLs or LEDs [13]. A commercial incandescent bulb is depicted in Figure 2.1.

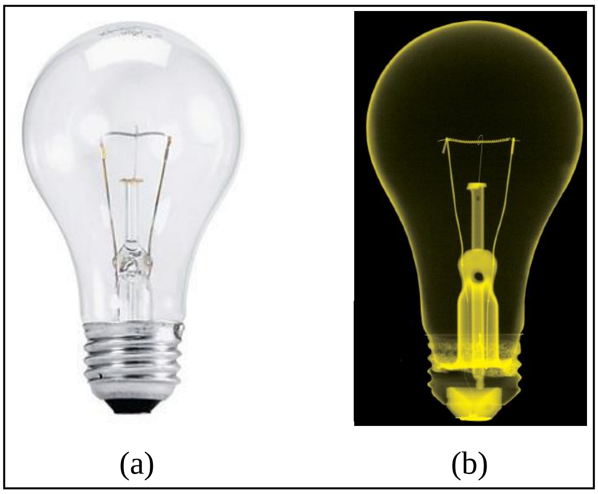



Figure 2.1. (a) Image [14] and (b) X-ray vision [15] of an incandescent bulb

Equivalent circuit of incandescent bulbs consists of the resistance of the filament and an inductance. However, the inductance is negligibly small and incandescent bulbs can be considered as resistance when included in a circuit analysis. Thus, the V-I relation is given in Equation 2.1.

$$v = i \,.\, R_{bulb} \tag{2.1}$$

where $v$ is the voltage across the bulb, $i$ is the current flowing through the bulb and $R_{bulb}$ is the bulb resistance. This resistance is not constant and depends on temperature. Hence, incandescent bulbs draw more current until they heat up. The relationship between light output, current and operating voltage for a typical incandescent lamp is shown in Figure 2.2 [12].

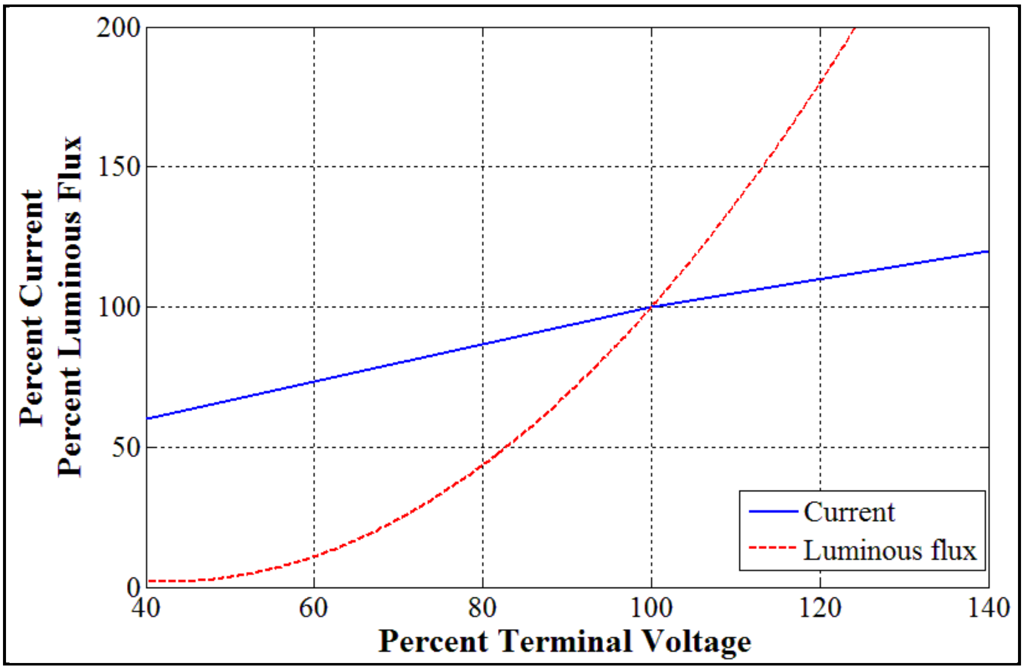



Figure 2.2. Electrical and optical characteristics of a typical incandescent lamp

## 2.2. COMPACT FLUORESCENT LAMPS

The operating principles of the fluorescent and compact fluorescent lamps are similar even though the ballasts and tube forms are different. Briefly, the electric current flowing through the gas tube stimulates the mercury atoms and causes them to release ultraviolet (UV) photons. Then, these photons stimulate phosphor that is used in the coating of the tube. This process results in emitting visible light photons. A CFL is shown in Figure 2.3.

The relationship between light output, current and operating voltage of a fluorescent tube is shown in Figure 2.4 [16].

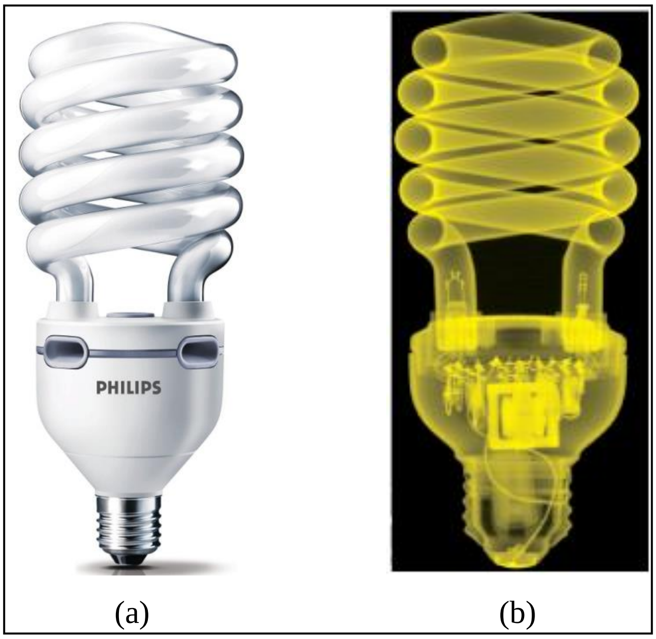



Figure 2.3. (a) Image [17] and (b) X-ray vision [15] of a CFL

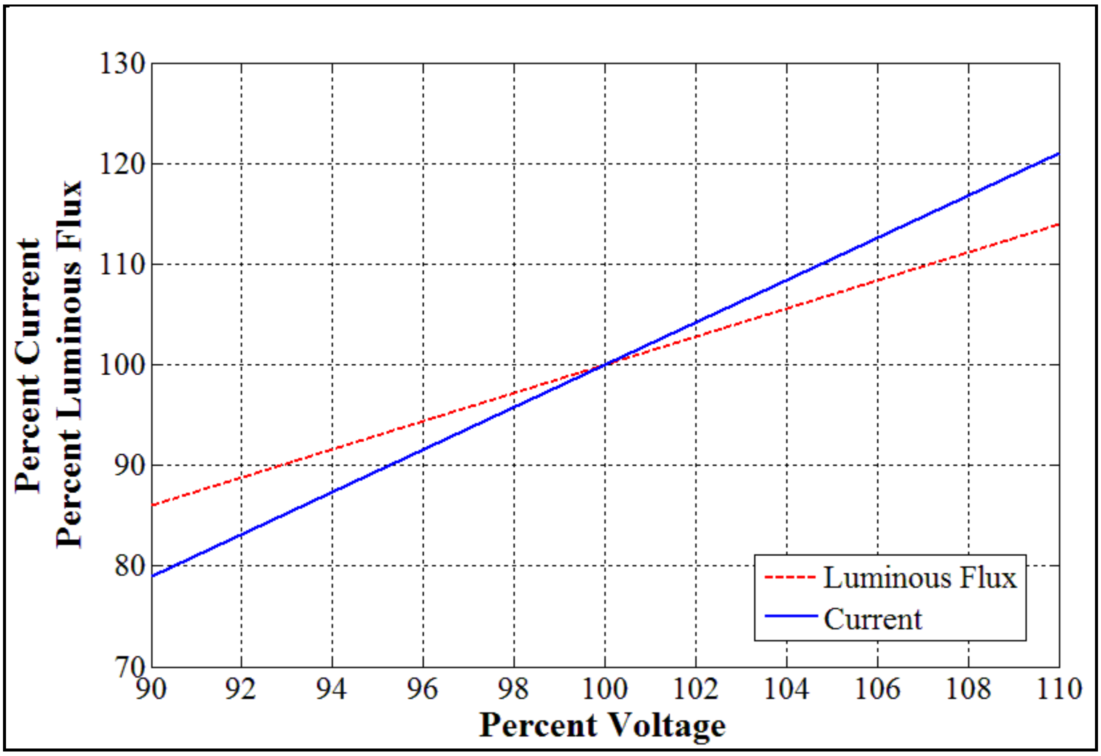



Figure 2.4. Electrical and optical characteristics of a fluorescent tube

Compact fluorescent lamps are fluorescent lamps in a compact form. Conventional fluorescent lamps consist of a tube, starter switch and ballast. The ballast of a conventional fluorescent lamp is an inductor; thus they are called magnetic ballasts. Ballasts are used to limit the current flowing through the tube. The ballast of a CFL is not an inductor but a more complex electronic circuit. A CFL bulb consists of several stages: Power factor correction stage, rectifier stage, oscillator and inverter stage. For simplicity, PFC stage is not included in the thesis. 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 L-C 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 Figure 2.5. The arc resistance of the fluorescent tube is denoted as $R_{arc}$.

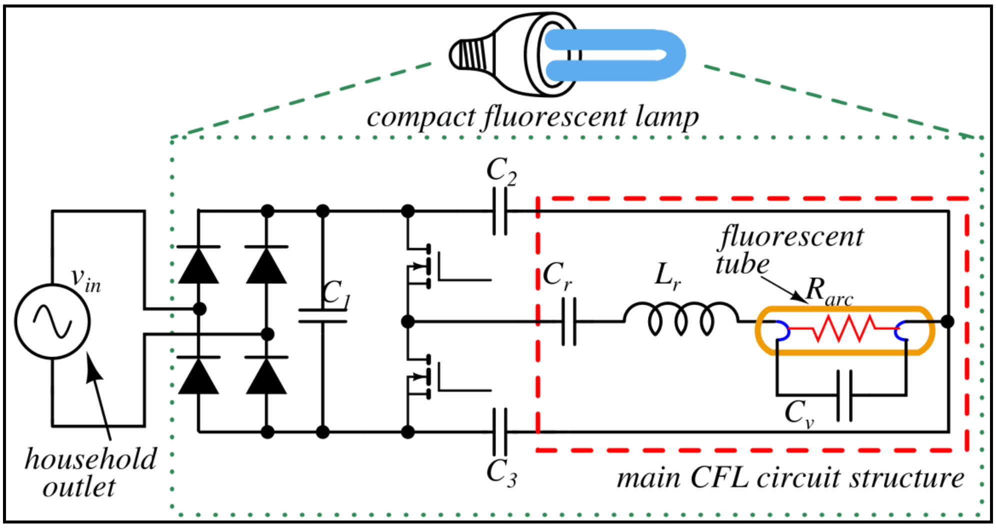



Figure 2.5. Equivalent model of the CFL

## 2.3. LED BULBS

LEDs are used in the industry in many applications for many years. They have been usually using as indicators but LEDs started to be used in TVs, decorative lighting with developing technology and recently, LEDs are used for illumination. LED bulbs consist of several LEDs and a rectifier stage with a current limiting circuitry. An LED bulb is shown in Figure 2.6.


(a) (b)

Figure 2.6. (a) Image [18] and (b) X-ray vision [15] of an LED bulb

Operation principle of an LED is different comparing to incandescent bulbs and fluorescent lamps. Instead of emitting light from a vacuum (as an incandescent bulbs) or a gas (as a CFL), LEDs emits light from a semiconductor solid matter. Thus, LED lighting is also called SSL (Solid-state lighting). A diode consists of a section of N-type material bonded to a section of P-type material, with electrodes on each end. N-type material is a semiconductor with extra electrons and P-type material is a semiconductor with extra holes. The electrons fill the holes when there is not a voltage applied across the electrodes. Thus, there are no free electrons in this state and charge cannot flow. The diode must be connected in the right polarity in order to make the charge move across the diode. When the applied voltage is high enough, the electrons and holes start to move to opposite directions. An electron releases energy when it drops from a higher orbital to a lower one. This energy is released in the form of a photon. The electrons release energy as photons in every kind of diode but not in a visible frequency. This feature is related to the material of the diode. The conductor material of LEDs is usually AlGaAs (aluminum-gallium-arsenide). The color of the LED is also dependent on the material.

Forward voltage – forward current characteristic and the relationship between light output and forward current of Harvatek HT-U7202UWR Series LED are given in Figure 2.7. The rated current of Harvatek HT-U7202UWR Series LED is 200 mA.

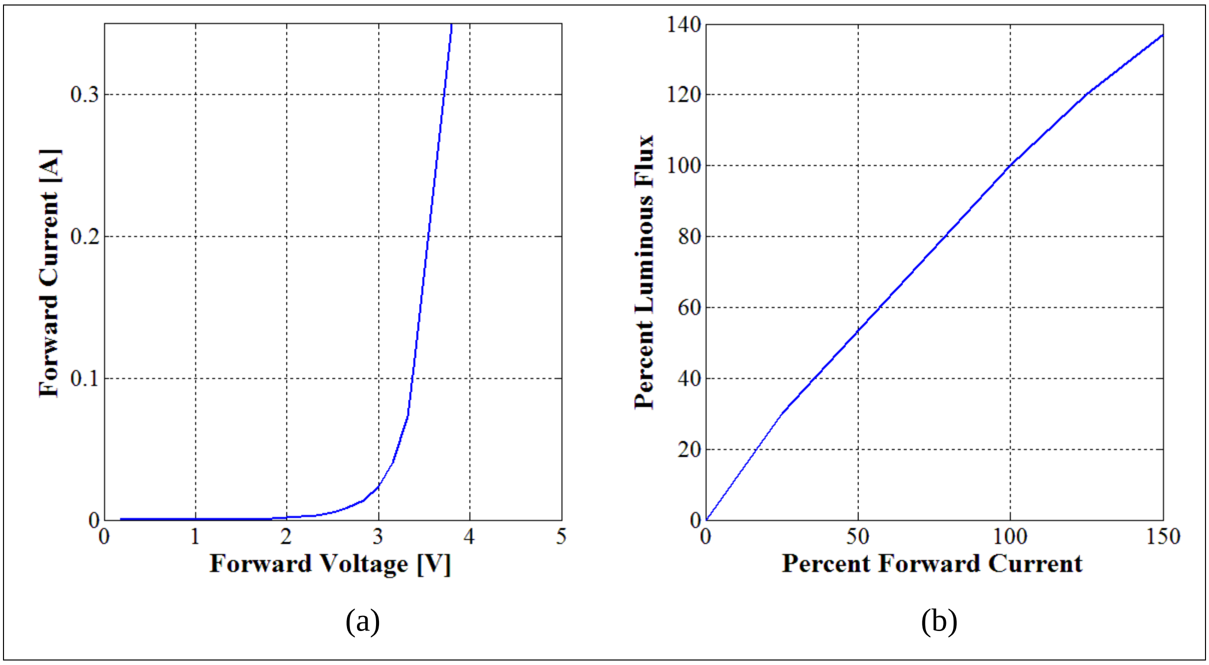



Figure 2.7. (a) V-I and (b) optical characteristics of Harvatek LED

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. Circuit diagram of an LED bulb is given in Figure 2.8.

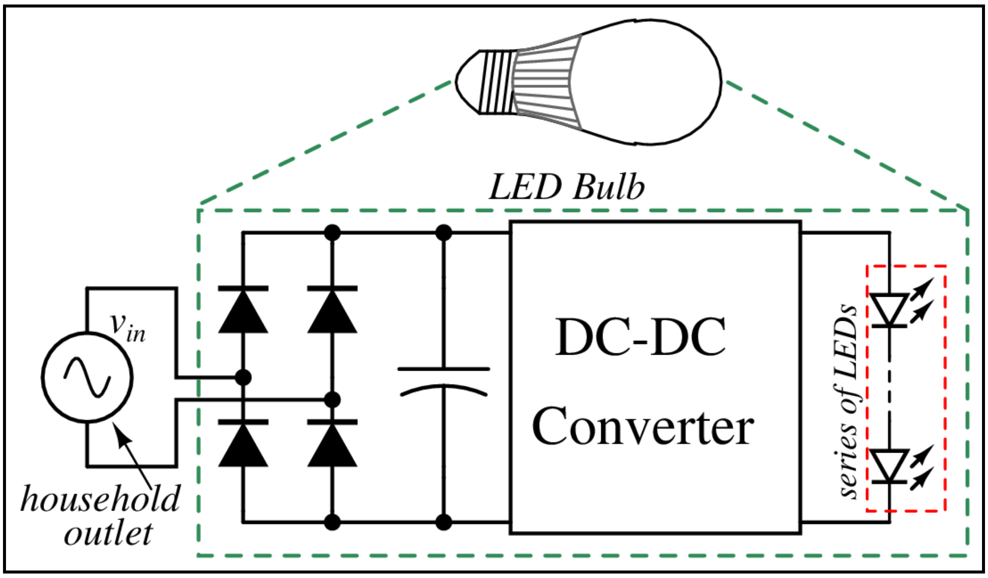



Figure 2.8. Circuit diagram of an LED bulb

There are many different driver circuit topologies inside the bulbs in the market. Buck (step-down) converter is a common LED driver circuit topology. Moreover, isolated DC-DC converters such as flyback or forward converters may be used for driving LEDs.

The dimmer proposed in this thesis might be either an isolated or a non-isolated DC-DC converter. Isolated power converters have an advantage in terms of safety regulations. For instance, isolation prevents input voltage transmit to the output in case of an internal failure. However, a non-isolated converter like buck converter is much easier to built and cheaper. Moreover, the operation of a buck converter will be safe since the dimmer will be mounted onto the wall using an isolated case.

# 3. DIMMER TOPOLOGIES

There are many kinds of systems that can be used as a light dimmer. In this section, only the simple TRIAC dimmer is introduced in detail but other dimmers are also mentioned.

## 3.1. NON-ELECTRONIC DIMMING

The systems that have not an electronic structure are introduced in this section. These are mechanical shutters, resistance dimmers and transformer dimmers. There is another non-electronic dimmer called “Reactor Dimmer” but it is not listed in the thesis due to rare usage of this device.

### 3.1.1. Mechanical Shutters

Mechanical shutters are widely used in studio, stage and entertainment illumination where discharge lamps are chosen for lighting. There are various methods to dim the light mechanically. For instance, a continuously variable filter that consists of a film which is transparent at one end, and has a gradually increasing density along its length can be used as a dimmer [12]. In addition to this, an iris can be used in front of the lamp to reduce the illumination level. The iris “Eclipse” from Wybron Inc. is shown in Figure 3.1.

Figure 3.1. The iris product “Eclipse” from Wybron Inc. [19]

### 3.1.2. Resistance Dimmers

Resistance dimmers are the first lighting control devices and used until 1970s [12]. Resistance dimmers are connected to load in series as shown in Figure 3.2. The operation principle is simply limiting the current flowing through to load by setting the resistance value. The disadvantage of this device is the power dissipation on the dimmer. The current flowing through the resistance dimmer causes a waste energy as heat.

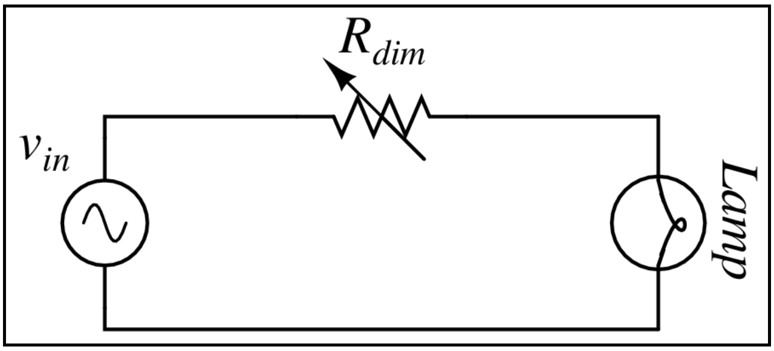



Figure 3.2. Resistance dimmer

### 3.1.2. Transformer Dimmers

Transformers dimmers are simple autotransformers that are used in lighting application as shown in Figure 3.3. The advantages of transformer dimmers are their efficiency comparing to resistance dimmers and sinusoidal output that allows a dimming operation without any harmonic introduction. However, these transformers are heavier, larger and expensive comparing to electronic dimmers.

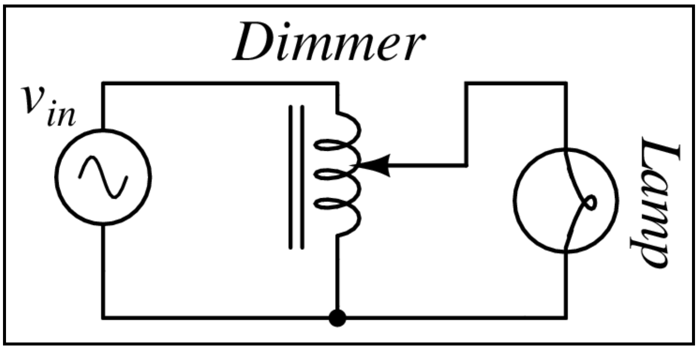



Figure 3.3. Transformer dimmer

### 3.2. THYRISTOR AND TRIAC DIMMERS

Thyristor and TRIAC Dimmers are the most widely used dimmer type in the market and they can be called “conventional dimmer circuits”. These dimmer circuits in the market are basic AC-AC converters that are called “AC chopper”. A basic dimmer circuit is shown in Figure 3.4.

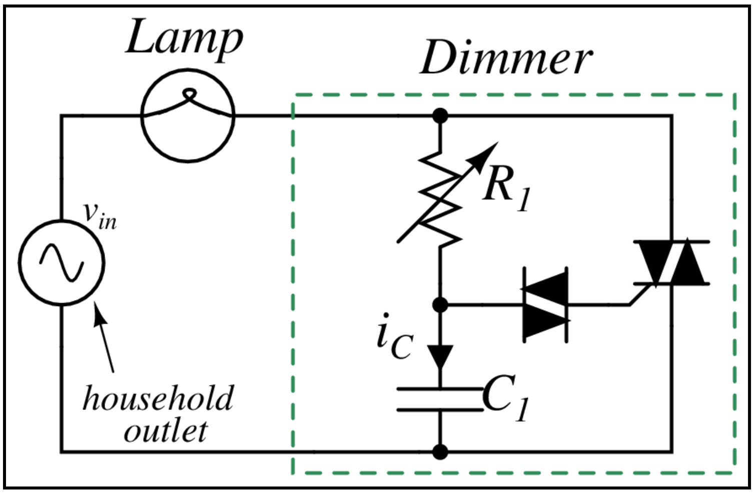



Figure 3.4. Basic TRIAC dimmer circuit

An AC chopper has a switch that periodically turns on and off in order to control the power on the load. The power circuit of an AC chopper generally consists of a TRIAC which is connected in series with the load. TRIAC is operated as a switch to control the current flow, and at the same time, the power on the load.

TRIAC is a semiconductor device from thyristor family and built as a pair of anti-parallel SCRs (Silicon-controlled rectifier) integrated together [20]. SCRs, shown in Figure 3.5 (a), are unidirectional devices that let current flow from anode terminal to cathode terminal when their gate terminal receives a current trigger. They remain “in conduction” until the current flowing through their main terminals drops below their holding current. Since the TRIACs, shown in Figure 3.5 (b), are formed as a two anti-parallel SCR connected together, TRIACs are bidirectional devices and current can flow through them in either direction. Thus, they can be used for AC switching.

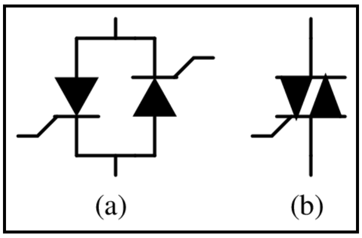



Figure 3.5. Semiconductor devices used in a typical dimmer: (a) SCR, (b) TRIAC

DIAC, shown in Figure 3.6, is a semiconductor device whose name stands for the abbreviation of “Diode for Alternating Current”. Once the breakover voltage of DIAC has been reached momentarily, DIAC conducts current until the current through its terminals drops below its holding current, similar to SCRs. DIACs are widely used as triggering devices for thyristors and TRIACs.

Figure 3.6. Circuit symbol of DIAC

In the circuit given in Figure 3.4, the capacitor $C_1$ is charged through the variable resistor $R_1$. DIAC lets the current flow to the gate of the TRIAC when capacitor voltage reaches the break-over voltage of the DIAC. Resistance of the $R_1$ determines the delay for the capacitor voltage to reach the DIAC break-over voltage. Thus, the firing angle can be set by adjusting the resistance $R_1$. TRIAC is triggered when its gate receives the signal and once it is triggered, it continues to conduct until the current flowing through its terminals A1 and A2 drops below the holding current. Holding current is the cut-off threshold current of a TRIAC. Thyristor and TRIAC dimmers may include a filter circuit for EMC purposes. This circuit is usually a simple L-C filter as shown in Figure 3.7.

The relationship between the resistor, $R_1$ and firing angle, α can be calculated using the equations from Equation 3.1 to Equation 3.4. Considering the input voltage is $v_S = V_m \sin(\omega t)$ ;

$$v_S = R_1 \cdot i_C + v_C \tag{3.1}$$

$$i_C = C_1 \frac{dv_C}{dt} \tag{3.2}$$

where $i_C$ is the current flowing through the capacitor $C_1$, $v_C$ is the capacitor voltage and voltage drop across the lamp is neglected.

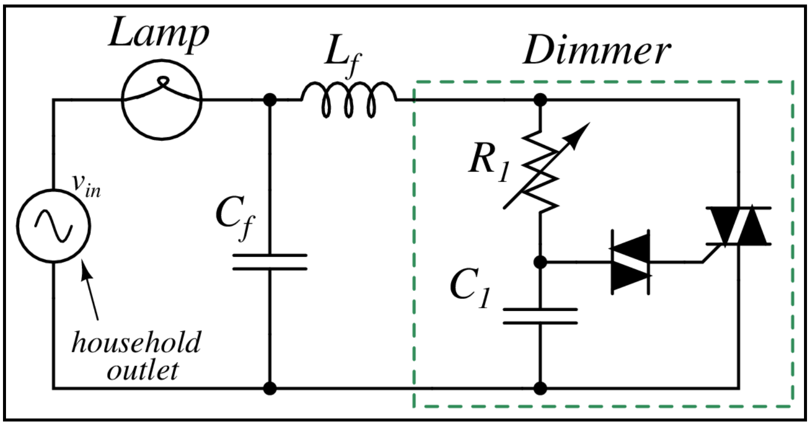



Figure 3.7. Basic TRIAC dimmer circuit with input filter

Combining Equation 3.1 and Equation 3.2,

$$\frac{dv_C}{dt} = -\frac{1}{R_1 \cdot C_1} v_C + \frac{V_m}{R_1 \cdot C_1} \sin(\omega t) \tag{3.3}$$

The firing angle can be calculated by solving Equation 3.3 for $v_C$ where it is equal to breakover voltage of DIAC.

Equation 3.3 is solved for f = 50 Hz, $V_m$ = 325 V, $R_1$ = 250 kΩ and $C_1$ = 0.1 μF where DIAC breakover voltage is 32V. It is calculated that capacitor voltage reaches 32 V at 4.434 ms. Thus, firing angle, α is calculated as $79.81^0$ using Equation 3.4.

$$\alpha = t \cdot f \cdot 360 \tag{3.4}$$

where t is the time, f is frequency of the periodic signal.

Figure 3.8 shows input voltage, capacitor voltage and DIAC breakover voltage for the values given above. Capacitor voltage reaches DIAC breakover voltage at 4.434 ms and TRIAC receives the firing signal to let the current flow to the load.

Firing angle and output power of the AC chopper are calculated for each $R_1$ value from 4 kΩ to 570 kΩ in 2 kΩ increments. Calculated firing angle values are plotted versus resistance values. The relationship between $R_1$, α and output power is shown more clearly in Figure 3.9.

The firing angle of the TRIAC gate is directly related to the amount of the power that will be received by the load. The waveforms of input, output and gate signals of an AC chopper are given in Figure 3.10.

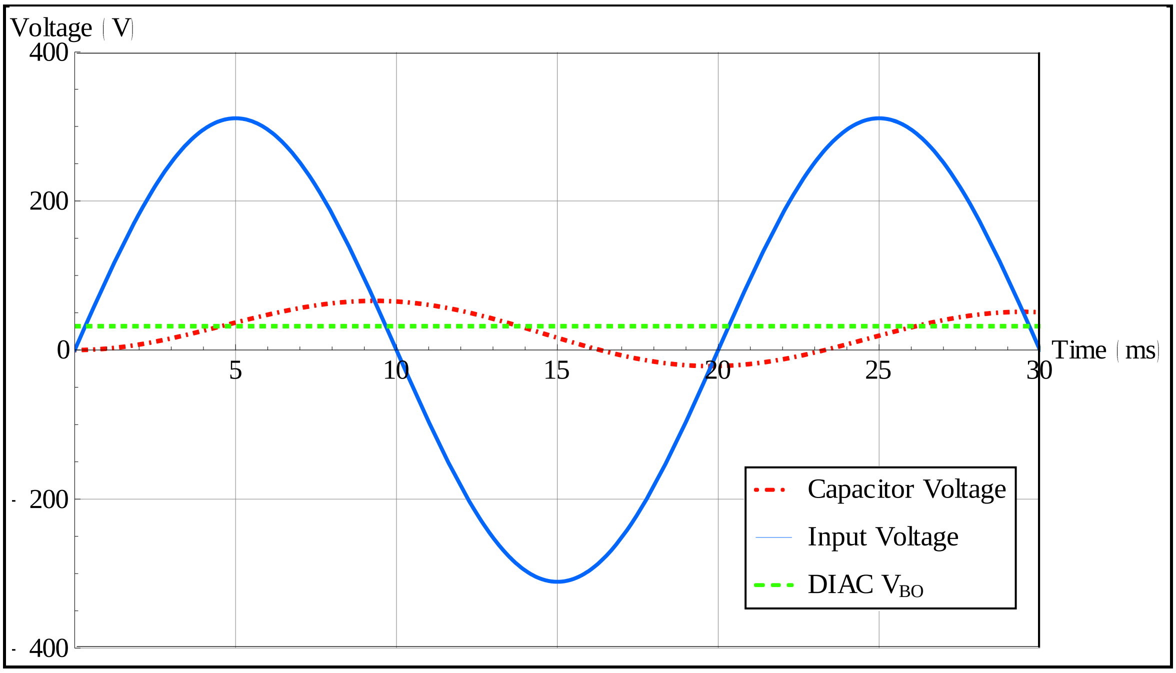



Figure 3.8. Waveforms of the AC chopper depicted in Figure 3.4 when $R_1$=250kΩ

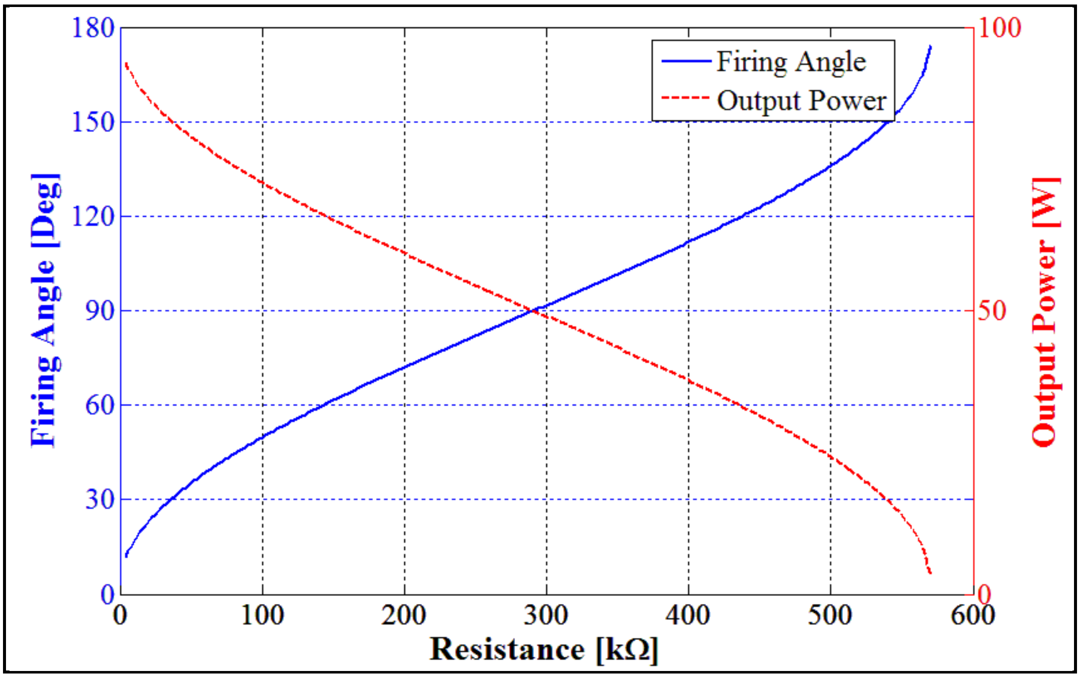



Figure 3.9. The relationship between control resistor, firing angle and output power

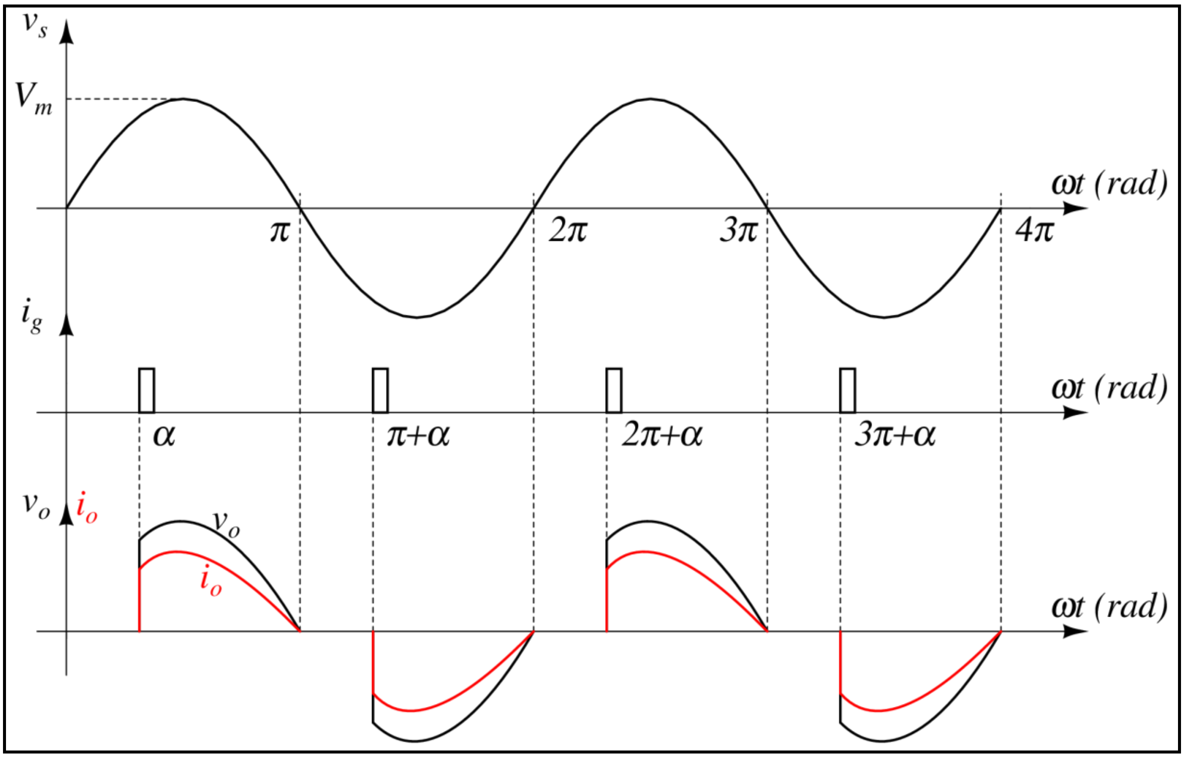



Figure 3.10. Waveforms of input voltage ($v_s$), output voltage ($v_o$), output current ($i_o$) and gate signal ($i_g$) in a conventional dimmer circuit

The TRIAC chops the voltage and current on the load according to the gate signals as seen on Figure 3.10. In other words, angle of the gate signals affects the RMS value of the voltage and current of the load. Equation 3.5 and Equation 3.6 can be used to calculate RMS value of the output voltage as a function of firing angle (α) and input voltage.

$$V_{o,RMS} = \sqrt{\frac{1}{2}\int_{\alpha}^{\pi} [V_m \sin(\omega t)]^2 \, d(\omega t)} \tag{3.5}$$

$$V_{o,RMS} = \frac{V_m}{\sqrt{2}} \cdot \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} = V_{S,RMS} \cdot \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \tag{3.6}$$

where $V_o$ is the output voltage, $V_m$ is magnitude of the input voltage, and $\alpha$ is the firing angle of TRIAC.

There are many options to control an AC chopper. Microcontrollers, variety of analog circuits, ICs are used for AC choppers. The dimmers in the market include very basic analog circuit to control the TRIAC.

Holding current of TRIACs leads to incompatibility problems with the loads that are not purely resistive. For instance, a load with lagging power factor makes the current flow until it falls below the holding current even though the load voltage is zero. Thus, it results a delay for the cut-off. Moreover, CFLs and LEDs may flicker or even break down when they are used with commercial dimmer because of the output voltage and current waveforms.

There are many model and brands of CFLs and LEDs in the market today and some of them are designed especially for dimmers with TRIACs. These products can be used with dimmers but they are more expensive. Moreover, a lot of consumers are complaining about humming and flickering of the products even though they are sold as dimmable. As a result, dimming CFLs and LEDs is a problem in the illumination industry today.

## 3.3. TRANSISTOR DIMMERS

Transistor dimmers are prompted for their quietness. Unlike TRIAC dimmers, they do not include chokes operating at mains frequency. Since they have no chokes and they have a rounded switch-off waveform, transistor dimmers do not produce any audible noise. Contrary to thyristor and TRIAC dimmers, transistor dimmers are suitable for capacitive loads. However, many transistor dimmers cannot be used with inductive loads. A transistor dimmer is depicted in Figure 3.11.

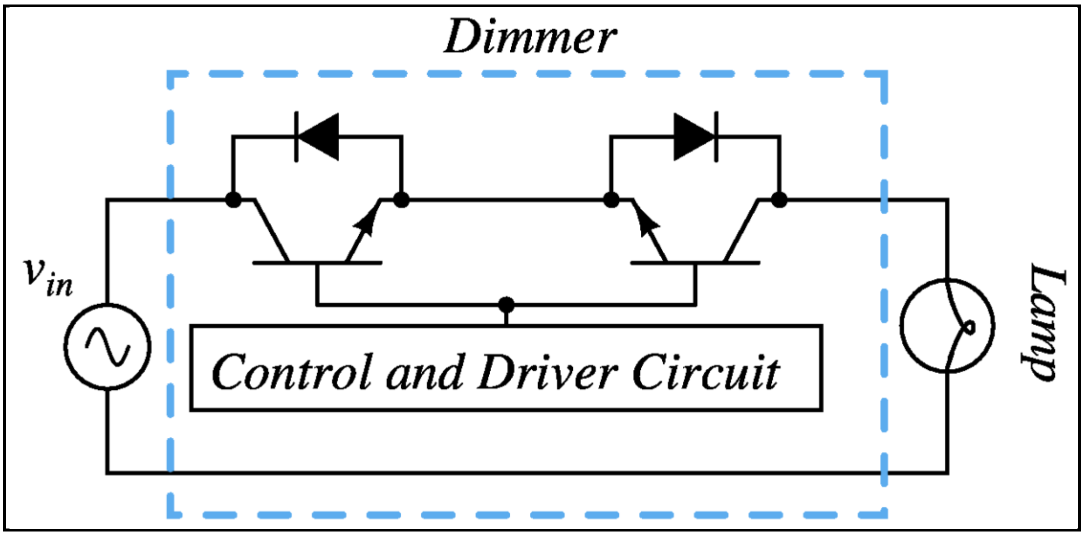



Figure 3.11. Transistor dimmer

Although transistor dimmers are operated in low frequency [12], this circuit topology may also be used in high-frequency applications. This topology is also called PWM AC Chopper [21]. Light output of the CFLs and LED bulbs would be adjusted if the designers added a controller with the bulbs. However, the control signals of CFL ballasts and LED drivers cannot be adjusted externally, usually. Light output of the CFLs can be varied by VFS and VVS techniques as mentioned in the first section of the thesis. Light output of the LEDs can be varied by adjusting the duty cycle of the PWM signal that is controlling the LED driver.

# 4. LIGHTING DEVICES WITH VARIABLE VOLTAGE SOURCES

Incandescent bulbs, CFLs and LEDs are three major light sources of the illumination market today. These lighting devices have different load characteristics. In this section, V-I and V-P characteristics are going to be studied. Since the dimmer circuit proposed in this thesis is a switched-mode DC power supply, the devices are operated with variable AC and DC sources in order to observe if it is possible to operate the devices under DC power and compare their performances. The main goal of the experiments in this section is observing electrical characteristics of the lighting devices but dimming ranges and photometric characteristics of the sources are also observed. The lighting devices used in measurements are given in Table 4.1.

Table 4.1. Lighting devices used in the experiments

| Lamp Type | Rated Voltage [V] | Rated Power [W] | Luminous Flux [lm] |
|---|---|---|---|
| Incandescent Bulb | 230 | 100 | 1320 |
| CFL | 230 | 10 | 660 |
| LED | 100 - 230 | 4 | N/A |

The variable AC source is an auto-transformer and the variable DC source is built with a diode bridge and 115μF capacitor fed by an auto-transformer.

## 4.1. LIGHTING DEVICES WITH VARIABLE AC SOURCE

Firstly, the lighting devices are tested with an autotransformer in order to observe the dimming characteristic of the devices with variable AC power. Terminal voltage, load current, power and power factor values of fundamental frequency are measured. Schematic of the experiment setup is depicted in Figure 4.1.

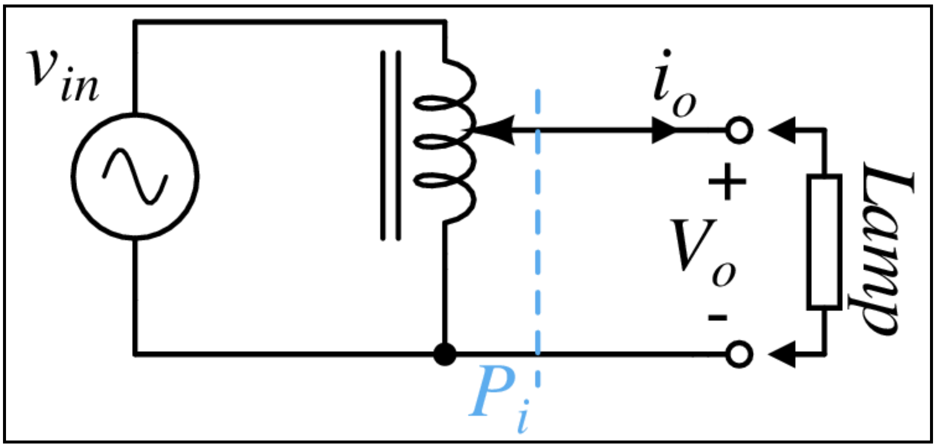



Figure 4.1. Schematic of the AC power experiment setup

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 Figure 4.2. V-I and V-P characteristics of incandescent bulb are shown in Figure 4.3. Reactance of the incandescent bulb is neglected and power factor of the incandescent bulb is assumed “1”.

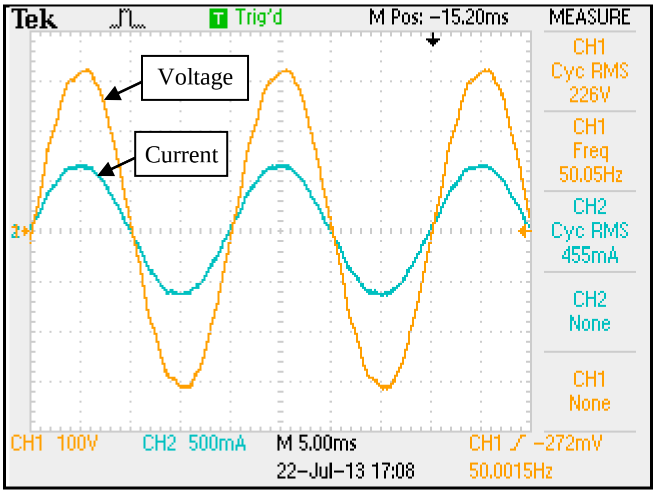



Figure 4.2. Voltage (100 V/div) and current (500 mA/div) waveforms of incandescent bulb operated in rated voltage, time (5 ms/div)

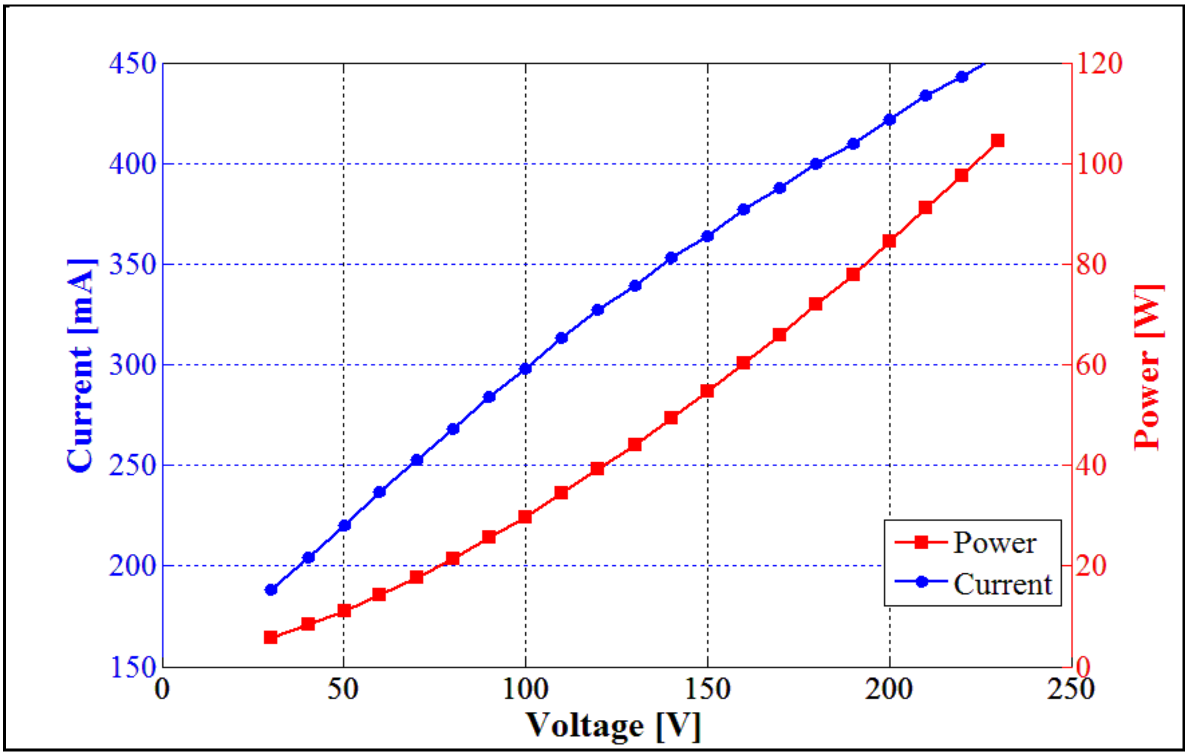



Figure 4.3. V-I and V-P characteristics of incandescent bulb with variable AC source

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 Figure 4.4. Voltage, current, power and power factor of fundamental frequency characteristics of CFL in AC operation are shown in Figure 4.5.

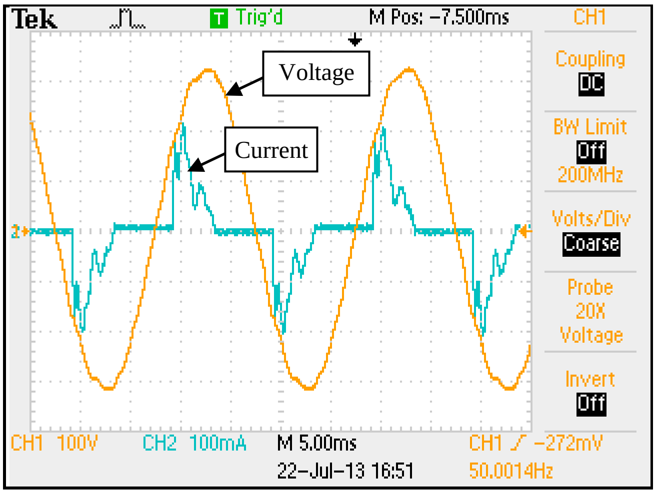



Figure 4.4. Voltage (100 V/div) and current (100 mA/div) waveforms of CFL operated in rated voltage, time (5 ms/div)

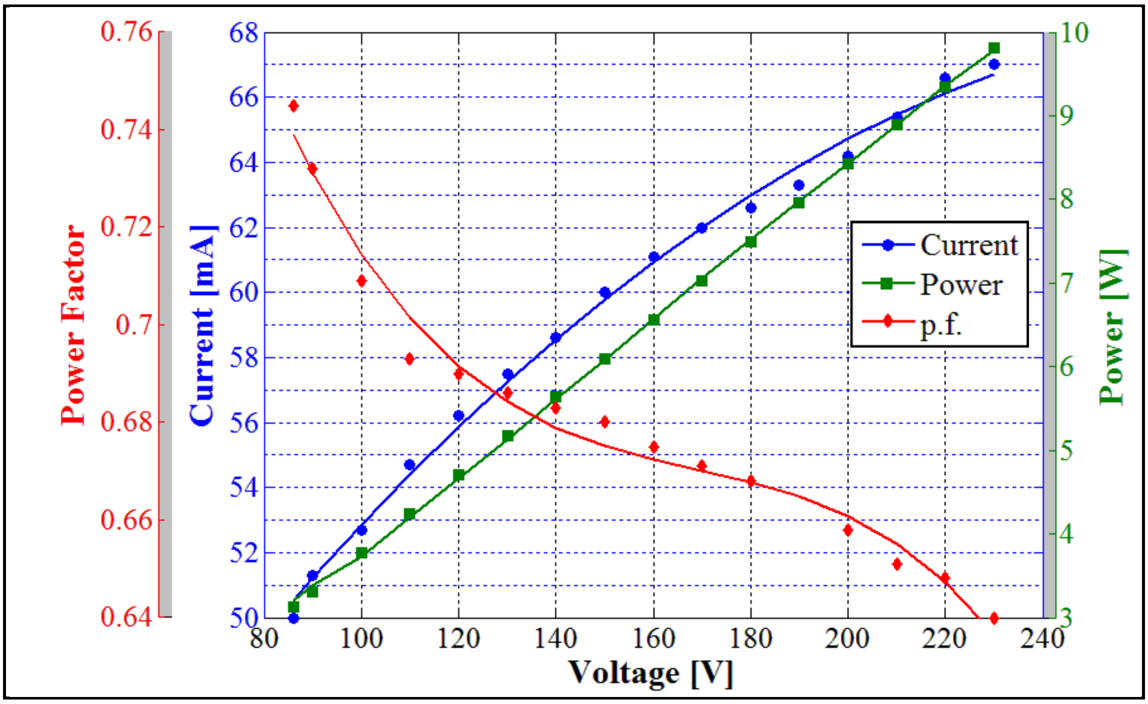



Figure 4.5. V-I, V-P and V-p.f. characteristics of CFL with variable AC source

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 Figure 4.6. Voltage, current, power and power factor of fundamental frequency characteristics are shown in Figure 4.7.

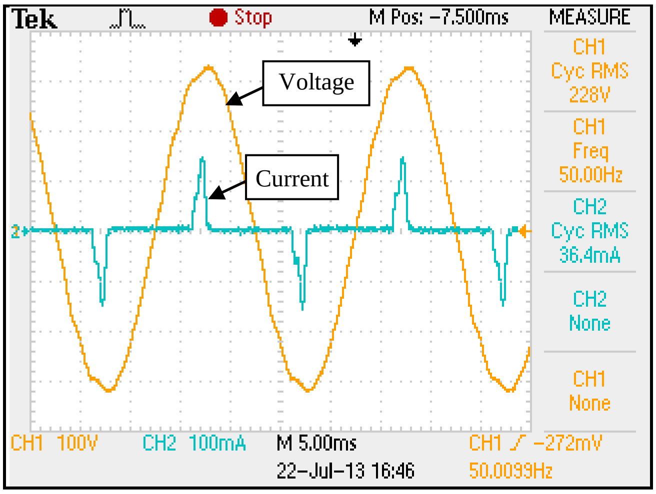



Figure 4.6. Voltage (100 V/div) and current (100 mA/div) waveforms of LED bulb operated in rated voltage, time (5 ms/div)

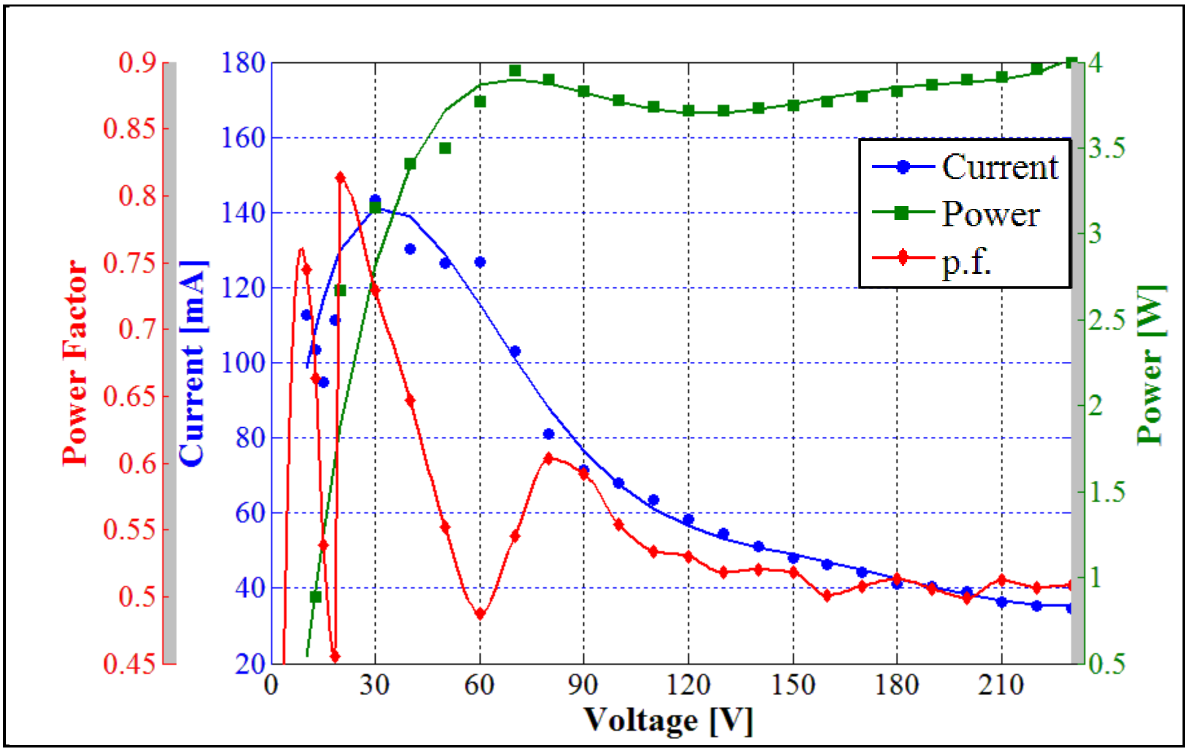



Figure 4.7. V-I, V-P and V-p.f. characteristics of LED bulb with variable AC source

Marked points appearing in figures are indicating the data from measurements. Tabulated list of measurement values are given in Appendix A. CFLs and LEDs have a leading power factor.

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.

## 4.2. LIGHTING DEVICES WITH VARIABLE DC SOURCE

Since the planned dimmer is a DC SMPS, the characteristics of the devices under DC power should be observed. The schematic of the DC source that is built can be seen in Figure 4.8. $C_1$ is 115µF electrolytic capacitor in order to have a terminal voltage with a ripple less than 10%.

V-I and V-P characteristics of DC-supplied incandescent bulb are similar to when it is supplied by an AC source. Voltage and current waveforms of incandescent bulb when supplied with 230 $V_{DC}$ are shown in Figure 4.9. V-I and V-P characteristics of incandescent bulb are shown in Figure 4.10.

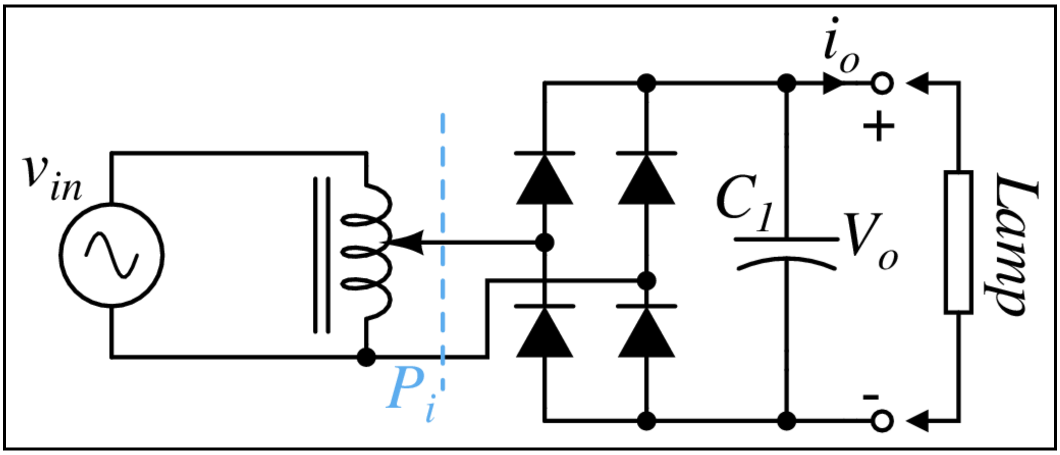



Figure 4.8. Schematic of the DC-power experiment setup

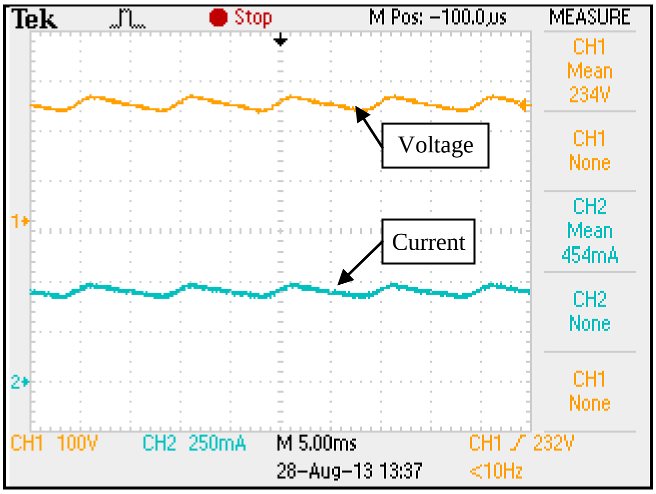



Figure 4.9. Voltage (100 V/div) and current (250 mA/div) waveforms of incandescent bulb when 230 $V_{DC}$ applied, time (5 ms/div)

Since CFL ballasts include a rectifier stage, the CFL can be supplied by a DC source. The voltage and current waveforms of the CFL supplied with 230 $V_{DC}$ are shown in Figure 4.11. Voltage, current, power and power factor of fundamental frequency characteristics are given in Figure 4.12. It is observed that flickering starts below 65 Volts and the lamp turns off below 40 Volts.

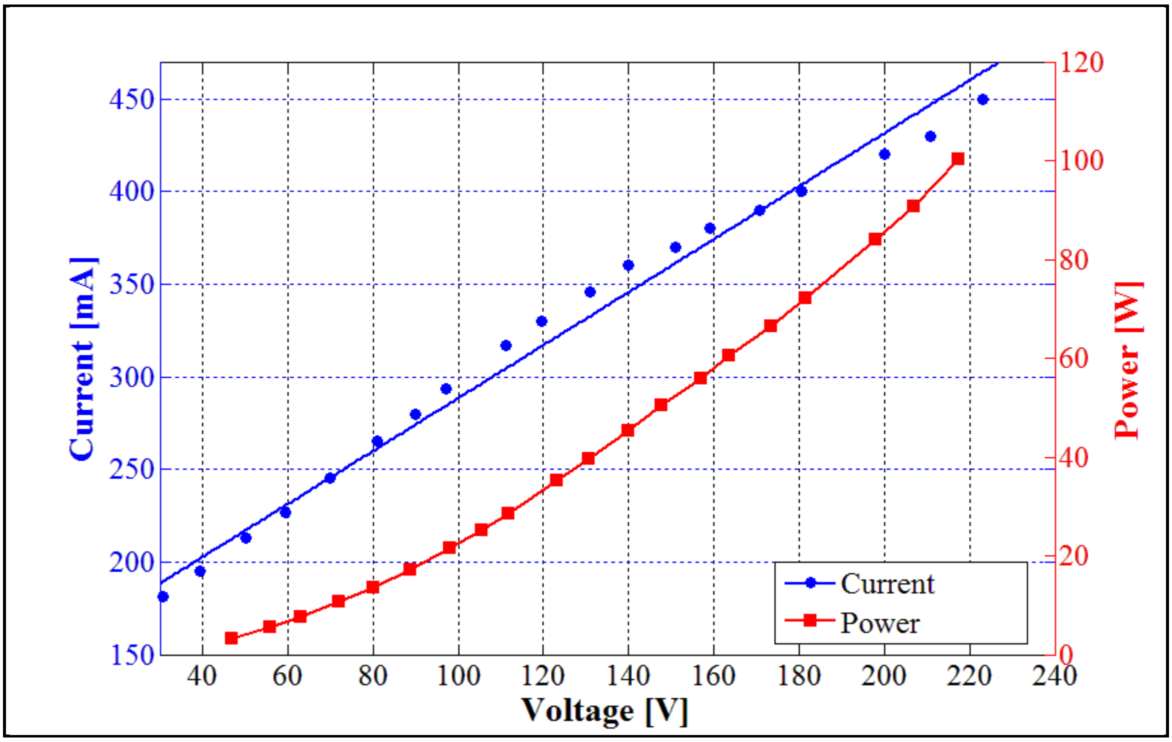



Figure 4.10. V-I and V-P characteristics of incandescent bulb with variable DC source

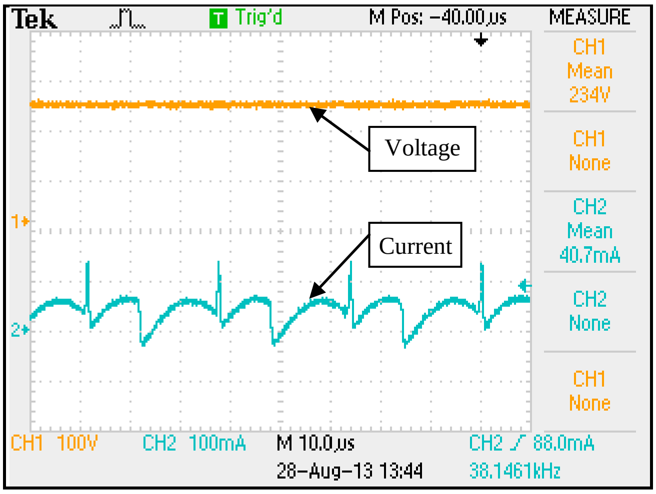



Figure 4.11. Voltage (100 V/div) and current (100 mA/div) waveforms of CFL when 230 $V_{DC}$ applied, time (10 µs/div)

LED drivers include a rectifier stage like CFL ballasts. Thus, DC voltage can be applied on LED bulbs. The current voltage and current waveforms of the LED when supplied with 230 $V_{DC}$ is shown in Figure 4.13. Voltage, current, power and power factor of fundamental frequency characteristics are given in Figure 4.14.

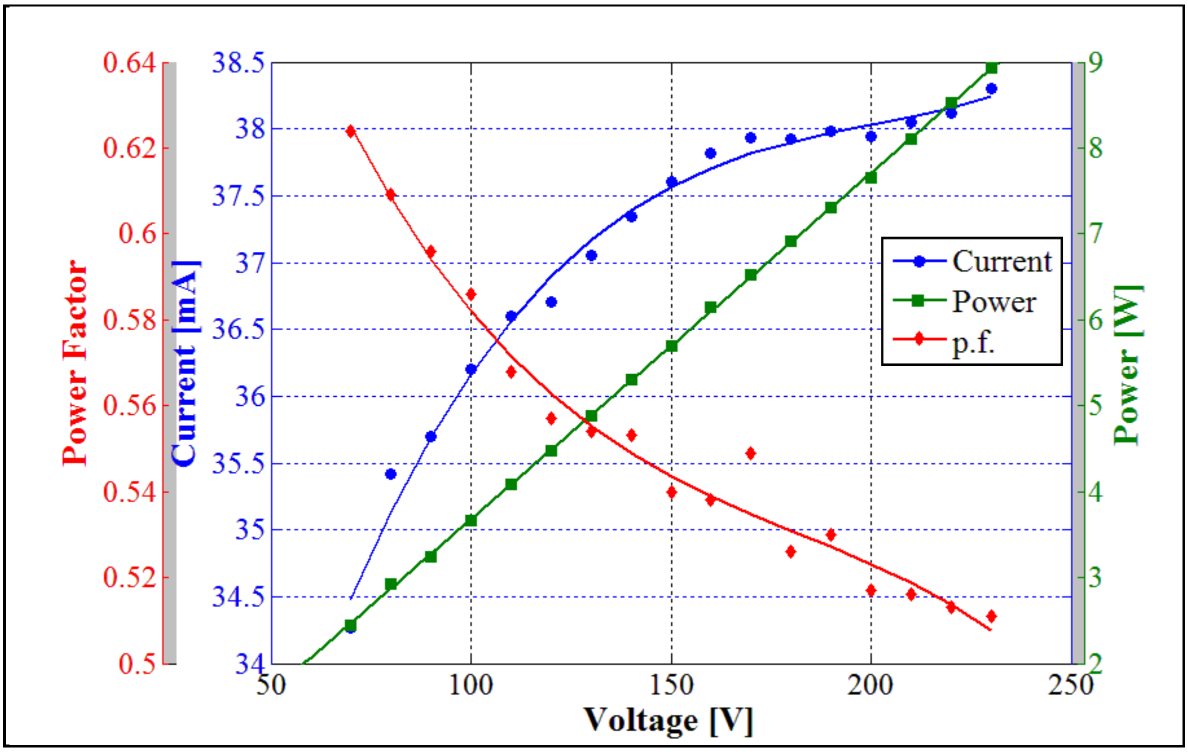



Figure 4.12. V-I, V-P and V-p.f. characteristics of CFL with variable DC source

Power consumption of the device is constant when the applied voltage is between 100-230 Volts. The reason is the terminal voltage range of the lamp. The DC-DC converter inside stabilizes the power. The lamp starts to flicker below 18 Volts and turns of below 10 Volts. The LED turns on when 50 Volts applied again.

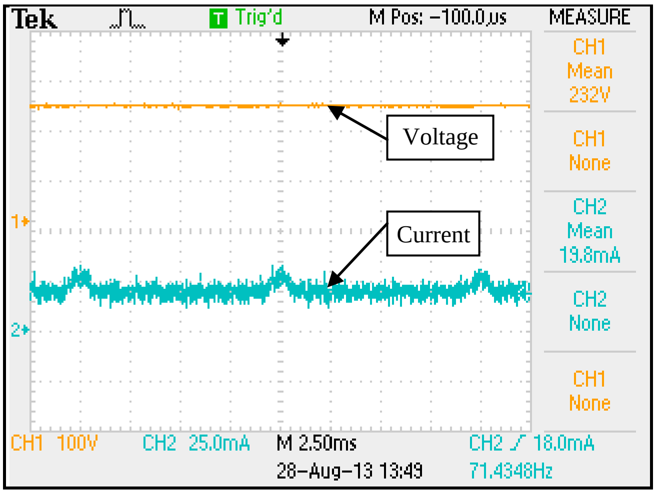



Figure 4.13. Voltage (100 V/div) and current (25 mA/div) waveforms of LED bulb when 230 $V_{DC}$ applied, time (2.5 ms/div)

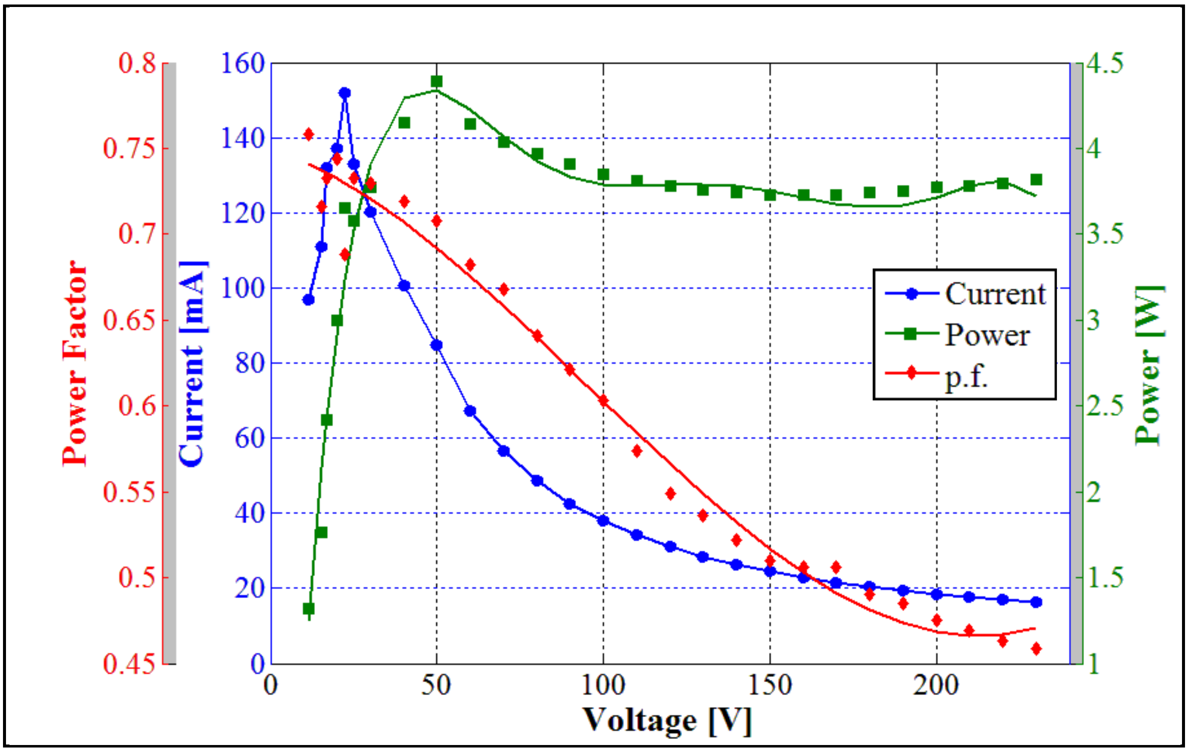



Figure 4.14. V-I, V-P and V-p.f. characteristics of LED bulb with variable DC source

Marked points appearing in figures are indicating the data from measurements. Marked points appearing in figures are indicating the data from measurements. Tabulated list of measurement values are given in Appendix B. CFLs and LEDs have a leading power factor.

It is observed that incandescent bulbs, CFLs and LED lamps can be operated with AC or DC sources. Since it is seen that dimming operation can be done by changing average DC voltage value, the dimmer can be a buck converter. Incandescent bulbs can be fully dimmed, CFL dimming range is limited by a low-voltage limit and LED dimming range is limited from upper and lower voltage limits. Low-voltage limit of the CFL is caused by heat of the filaments which is not enough to stimulate the mercury atoms.

# 5. DESIGN OF THE DIMMER

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 Figure 5.1.

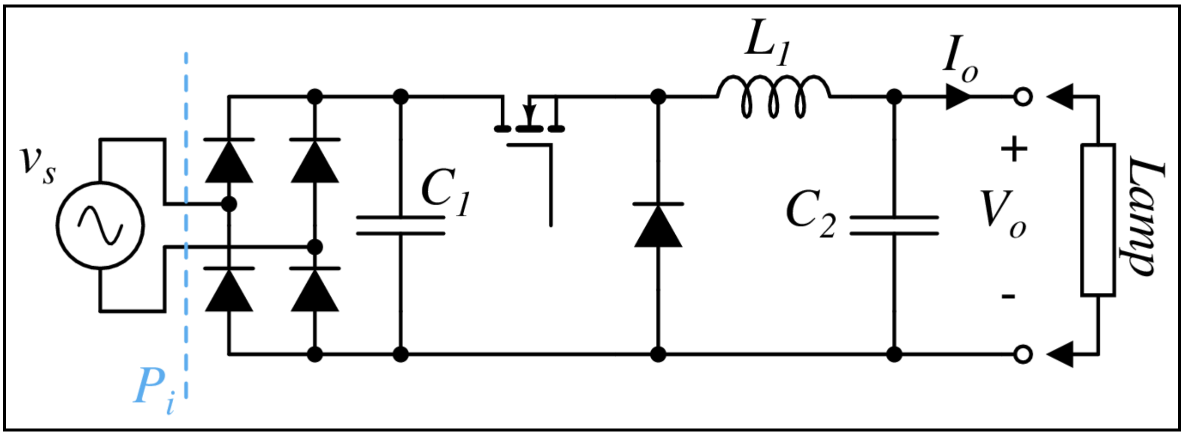



Figure 5.1. Equivalent model of the rectifier and buck converter that will be used as the dimmer

## 5.1. STEADY-STATE ANALYSIS

Buck converter can be analyzed in two subintervals for continuous conduction mode. $v_S$ is equal to $V_m \cdot \sin(\omega t)$ where $V_m$ is the magnitude of the utility voltage (325 V) and $\omega$ is 314 rad/s for 50 Hz utility. For simplicity, the dimmer will be analyzed assuming the input voltage is constant 325 $V_{DC}$ instead of an AC source and a rectifier. Subinterval 1, when MOSFET is on, diode is off and subinterval 2, when MOSFET is off, diode is on. Non-idealities of MOSFET, diode and the inductor are taken into account but ESR of the capacitor is neglected.

### 5.1.1. Subinterval 1

MOSFET is on and diode is off in first subinterval. The equivalent circuit including the non-ideality of the MOSFET is depicted in Figure 5.2.

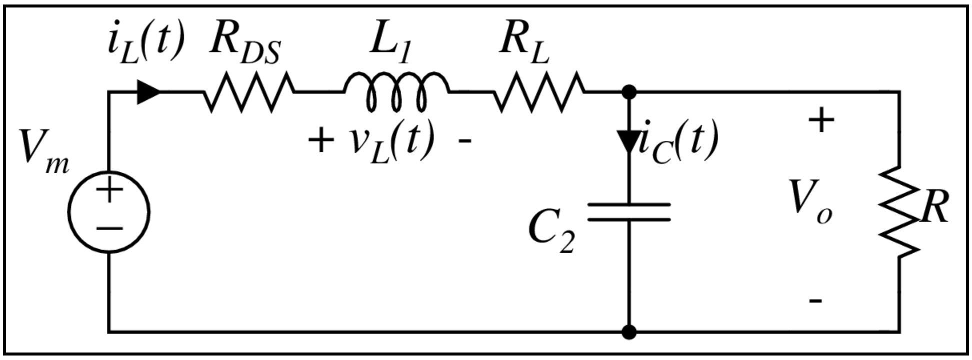



Figure 5.2. Subinterval 1

$V_m = 325\ V$ and $V_o = 230\ V$. Voltage and current waveforms of inductor and capacitor is to be observed for analysis.

Inductor voltage can be calculated using Equation 5.1.

$$v_L(t) = V_m - v_o(t) - R_{DS} \cdot i_L(t) - R_L \cdot i_L(t) \tag{5.1}$$

with small ripple approximation,

$$V_L = V_m - V_o - R_{DS} \cdot I - R_L \cdot I \tag{5.2}$$

where $I$ is the average value of inductor current. Inductor current can be calculated using the inductance formula.

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} \approx \frac{V_m - V_o - R_{DS} \cdot I - R_L \cdot I}{L} \tag{5.3}$$

Capacitor current can be calculated using Equation 5.4.

$$i_C(t) = i_L(t) - \frac{v_o(t)}{R} \tag{5.4}$$

with small ripple approximation,

$$< i_C > = 0 = I - \frac{V_o}{R} \tag{5.5}$$

### 5.1.2. Subinterval 2

MOSFET is off and diode is on in the second subinterval. The equivalent circuit including the non-ideality of the diode is depicted in Figure 5.3,

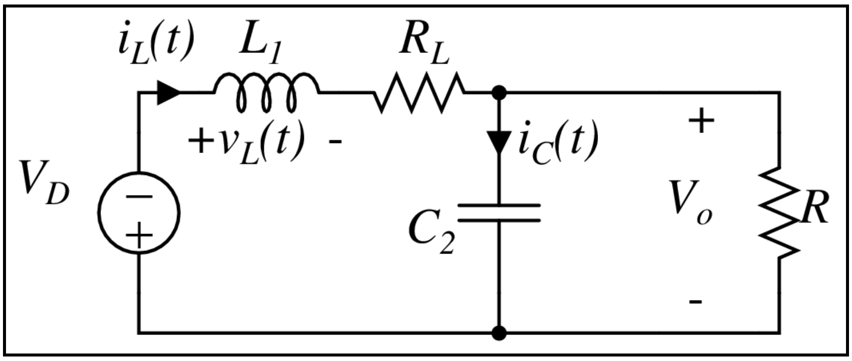



Figure 5.3. Subinterval 2

where $V_D$ is diode forward voltage drop and equal to 0.7 Volts. Inductor voltage can be calculated using Equation 5.6.

$$v_L(t) = -v_o(t) - V_D - R_L \cdot i_L(t) \tag{5.6}$$

with small ripple approximation,

$$V_L = -V_o - V_D - R_L \cdot I \tag{5.7}$$

Inductor current can be calculated using the inductance formula.

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} \approx \frac{-V_o - V_D - R_L \cdot I}{L} \tag{5.8}$$

Capacitor current can be calculated using Equation 5.9.

$$i_C(t) = i_L(t) - \frac{v_o(t)}{R} \tag{5.9}$$

with small ripple approximation,

$$< i_C > = 0 = I - \frac{V_o}{R} \tag{5.10}$$

The waveforms of inductor voltage $v_L(t)$ and current $i(t)$ are given in Figure 5.4.

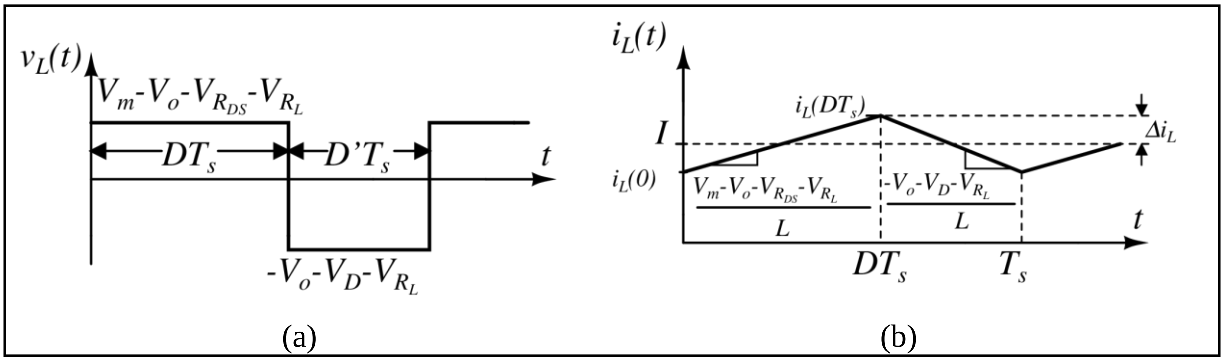



Figure 5.4. (a) Inductor voltage and (b) current waveforms

If the change in inductor current is equal to slope times length of the subinterval,

$$2\Delta i_L = \frac{V_m - V_o - R_{DS} \cdot I - R_L \cdot I}{L} \cdot DT_S \tag{5.11}$$

$$\Delta i_L = \frac{V_m - V_o - R_{DS} \cdot I - R_L \cdot I}{2L} \cdot DT_S \tag{5.12}$$

where $T_S$ is switching period, $V_{R_{DS}} = R_{DS} \cdot I$ and $V_{R_L} = R_L \cdot I$.

The net change in inductor current is zero in periodic steady state. Thus, the total area under the inductor waveform is zero in steady state operation.

$$\frac{1}{T_S}\int_0^{T_S} v_L(t)d = 0 \quad (5.13)$$

$$DT_S \cdot (V_m - V_o - R_{DS} \cdot I - R_L \cdot I) + D'T_S(-V_o - V_D - R_L \cdot I) = 0 \quad (5.14)$$

$$V_o = D \cdot (V_m - R_{DS} \cdot I) - D'V_D - R_L \cdot I \quad (5.15)$$

If the circuit components were assumed ideal, Equation 5.15 would become,

$$V_o = D \cdot V_m \quad (5.16)$$

## 5.2. TYPICAL DESIGN OF 100 W BUCK CONVERTER

Since the rectified mains voltage is 325 $V_{DC}$ and rated voltages of the lamps are 230 Volts, converter topology is selected to be a buck converter, which is a step-down DC-DC 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 greater than 70%.

It is desired to design a buck converter which converts 325 V input voltage to a variable output voltage that has a maximum value of 230 Volts. The rated power of the converter is 100W since the load with the highest power rating is a 100 W incandescent bulb for this design. Switching frequency is chosen as 20 kHz. The output voltage ripple is 1% and the current ripple is 10%.

Inductor and capacitor values for the desired buck converter will be calculated according to the design criteria. Then, diode and MOSFET are going to be chosen. Assume,

$V_m = 325V \pm 32.5V$

$V_o = 230V$

$P = 100W$

$I \cong 17.3\ mA - 450\ mA$

$f_{sw} = 20\ kHz$

$D = \frac{V_{out}}{V_{in}} = 0.7077 = 70.77\%$ (for an ideal buck converter)

Since the current ripple is defined as 10% and voltage ripple is 0.1%,

$$\Delta i_L = 0.1 \times I = 45\ mA \tag{5.17}$$

$$\Delta v_o = 0.001 \times V_o = 0.23\ V \tag{5.18}$$

Inductance that can satisfies the current ripple less than or equal to 45mA, can be calculated by rearranging Equation 5.12. Assuming the inductor is ideal,

$$L \geq \frac{V_m - V_o - I \cdot R_{DS}}{2\Delta i_L \cdot f_{sw}} \cdot D \tag{5.19}$$

$$L \geq \frac{325 - 230 - (0.48 \cdot 0.45)}{2 \cdot 0.045 \cdot 20000} \cdot 0.7088 = 37.32\ \text{mH} \tag{5.20}$$

where $R_{DS}$ is on-state resistance of the MOSFET. The calculated value of inductance is the inductance value for CCM (continuous conduction mode) with less than or equal to 10% current ripple. Thus, the minimum value in order to operate the converter in with 10% current ripple is 37.32 mH. The inductance value is chosen as 50 mH. There must be an upper limit when choosing inductance value. Inductor would affect the dynamic response of the system if it is too large. Resistance of the inductor is 1.4 **Ω**. The inductor value is chosen for the incandescent bulb since the other lamp types has their own power conditioning circuits inside.

Output capacitor current, $i_C(t)$ is alternating between positive and negative values in a switching period. $i_C(t)$ is positive for one half of the period and negative for the other half as seen in Figure 5.5. When the capacitor current is positive, capacitor voltage starts to increase from its minimum value to maximum value. Capacitor deposits charge in this interval. Since the change in voltage is $2\Delta v$,

$$q = C(2\Delta v) \tag{5.21}$$

where q is the change in charge and $\Delta v$ is change in capacitor voltage that is equal to the output voltage ripple.

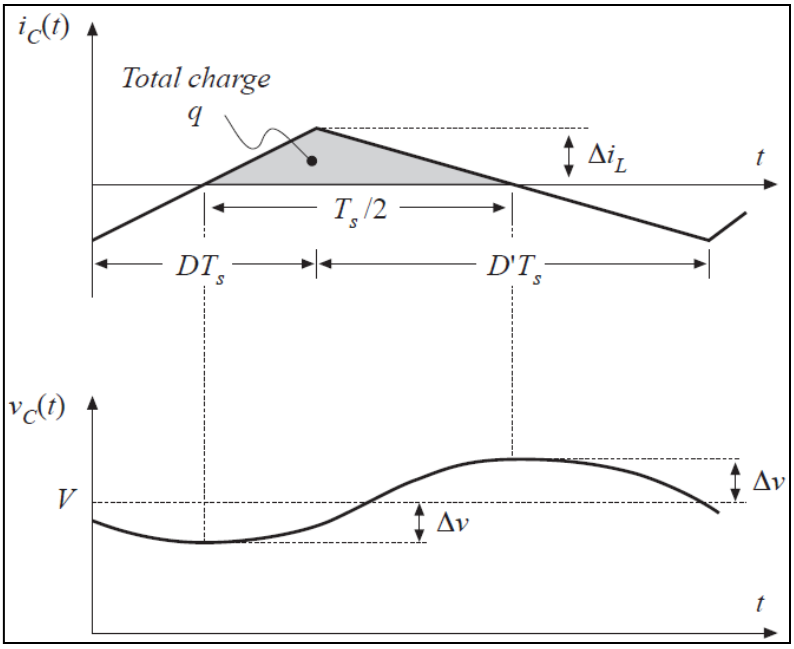



Figure 5.5. Current and voltage waveforms of the output capacitor [22]

Since the total charge q is equal to the area of the triangle shown in Figure 5.5,

$$q = \frac{1}{2}\Delta i_L \frac{T_s}{2} \tag{5.22}$$

Combining Equation 5.21 and 5.22 and solve for capacitor value;

$$C \geq \frac{\Delta i_L \cdot T_s}{8\Delta v} = 1.22\ \mu F \tag{5.23}$$

This is the minimum value in order to operate the converter for the maximum ripple criteria. Considering the non-idealities in the circuit and a safety factor, the capacitance value is chosen as 4.7 μF. There must be an upper limit when choosing capacitor value. Capacitor would affect the dynamic response of the system if it is too large. Settling time of the system will increase and this affects the dimming operation. The capacitor is assumed ideal.

Replacing the values of the Equation 5.14 for semiconductor and inductor losses,

$$230 = D \cdot (325 - 0.048 \cdot 0.45) - D' \cdot 0.7 - (1.4 \cdot 0.45) \tag{5.24}$$

$$D \cong 0.71 \tag{5.25}$$

If the non-idealities of the components were neglected,

$$D = \frac{V_o}{V_m} = \frac{230}{325} = 0.7077 \tag{5.26}$$

## 5.3. DESIGN OF RECTIFIER STAGE

Rectifier circuit consists of a diode bridge and a filtering capacitor. Bridge rectifier is chosen according to Maximum repetitive peak reverse voltage and maximum forward current. The diode bridge will be operated under 230 $V_{RMS}$, in other words it must be capable of operating with maximum repetitive voltage of 325 Volts. The diode bridge is chosen as 2KBP04M which has maximum repetitive peak reverse voltage rating of 400 Volts.

Filter capacitor value is determined according to maximum ripple limits for rated powers of different lighting devices with a voltage rating of at least 325 V. The voltage across a capacitor in an RC circuit is calculated by Equation 5.27.

$$v_{C_f}(t) = V_m e^{-t/R_o C_f} \tag{5.27}$$

where $v_{C_f}$ is the voltage across the filter capacitor, $R_o$ is the equivalent load resistance of the rectifier and $t$ is the time after output has reached its peak value. Using Equation 5.27 to calculate lowest output voltage;

$$V_{min} = V_m e^{-T_d/R_oC_f} \tag{5.28}$$

where $T_d$ is the discharge time of the capacitor. Thus, peak-to-peak voltage, $\Delta V_r$ can be calculated by Equation 5.29.

$$\Delta V_r = V_m - V_{min} = V_m(1 - e^{-T_d/R_oC_f}) \tag{5.29}$$

Taylor expansion of $e^{-T_d/R_oC_f}$ is given in Equation 5.30.

$$e^{-T_d/R_oC_f} = 1 - \frac{T_d}{R_oC_f} + \frac{\left(\frac{-T_r}{R_oC_f}\right)^2}{2} + \frac{\left(\frac{-T_r}{R_oC_f}\right)^3}{3} + \frac{\left(\frac{-T_r}{R_oC_f}\right)^4}{4} + \cdots \tag{5.30}$$

Assuming discharge time is much shorter than the time constant of the circuit ($T_d << R_oC_f$), high-order terms are negligible. Thus,

$$e^{-T_d/R_oC_f} \cong 1 - \frac{T_d}{R_oC_f} \cong 1 - \frac{T_r}{R_oC_f} \tag{5.31}$$

where discharge time is assumed to be equal to ripple period, $T_r$ . Since $T_r = 2f$ for a full wave rectifier, rearranging Equation 5.29 using Equation 5.31 gives,

$$\Delta V_r \cong V_m \frac{T_r}{R_oC_f} = \frac{V_m}{2f \cdot R_oC_f} \tag{5.32}$$

where $f$ is the frequency of the utility voltage $v_S$. $R_o$, the equivalent resistance that is seen by $C_f$, consists of the buck converter impedance and resistance of the lamp. The impedance of the buck converter can be obtained by using steady-state equivalent circuit of the buck converter [23]. DC state equations are used to derive the steady-state equivalent circuit of the buck converter operating in CCM. Equation 5.33 and 5.34 shows DC state equations of the buck converter.

$$\begin{bmatrix}0\\0\end{bmatrix} = \begin{bmatrix}-R_L - D\cdot R_{DS} & 1\\ 1 & -\frac{1}{R}\end{bmatrix}\begin{bmatrix}I\\V_o\end{bmatrix} + \begin{bmatrix}D & -D'\\0 & 0\end{bmatrix}\begin{bmatrix}V_m\\V_D\end{bmatrix} \tag{5.33}$$

$$[I_i] = [1 \quad 0]\begin{bmatrix}I\\V_m\end{bmatrix} + [0 \quad 0]\begin{bmatrix}V_m\\V_D\end{bmatrix} \tag{5.34}$$

where $I_i$ is the input current. Using Equations 5.33 and 5.34, steady-state equivalent circuit of the buck converter is depicted in Figure 5.6. Using steady-state equivalent circuit of the buck converter, $R_o$ is equal to,

$$R_o = \frac{R_{DS} + D\cdot R_L + D\cdot R}{D^2} = 748\ \Omega \tag{5.35}$$

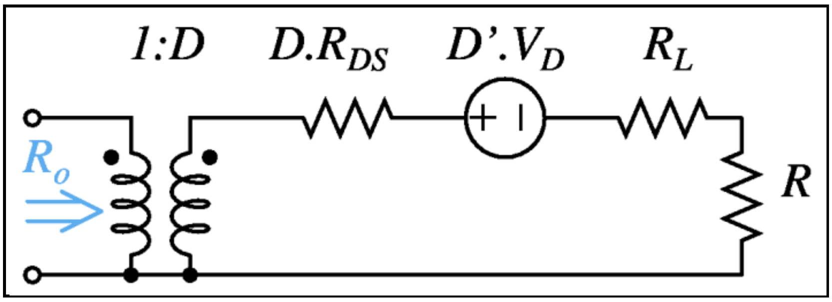



Figure 5.6. Steady-state equivalent circuit of the buck converter

for 100 W incandescent bulb which is the load that has the highest power rating. Rearranging Equation 5.31 for 100W load with %10 ripple constraint and assuming that forward voltage drop of the diode is in series with input voltage for simplicity,

$$C_f \geq \frac{V_m - D'V_D}{2f\cdot R_o \Delta V_r} = 133.6\ \mu\text{F} \tag{5.36}$$

The result is the minimum value for the ripple constraint. However, voltage ripple does not have great importance for incandescent bulbs as long as they are in a frequency that is faster than visual perception of human eye. Thus, a capacitor with lower value would work for incandescent bulbs and low-power loads such as CFL and LED bulb will have much less ripple. The input capacitor is chosen 115μF.

Table 5.1. Circuit components of the dimmer

| Circuit Component / Parameter | Model / Value |
|---|---|
| Diode Bridge | 2KBP04M |
| Input Capacitor $C_1$ | 115 μF |
| Inductor $L_1$ | 50 mH |
| MOSFET | STP11NK50ZFP |
| Diode | MUR840 |
| Output Capacitor $C_2$ | 4.7 μF |
| Switching Frequency | 20 kHz |

Circuit component values of the dimmer circuit are given in Table 5.1. Using these components and parameters, voltage and current ripple is small enough to perform a stable operation.

## 5.4. DESIGN OF THE CONTROL CIRCUIT

In this thesis, control circuit of the dimmer is a PWM generator which is producing the gate signals of the MOSFET. A PWM generator consists of a saw-tooth wave generator and a comparator. The duty cycle of the PWM signal is adjusted by changing the amplitude of a DC signal which is connected to the comparator with the saw-tooth signal. The frequency of the PWM signal frequency is determined by and equal to the frequency of saw-tooth signal. Schematic of a basic PWM generator is depicted in Figure 5.7. SG3525A is used for PWM generation. Dimmer is controlled by the variable resistor $R_C$. The light output level of the dimmer is proportional to the value of $R_C$. The dimmer is operated with open loop control. TC4427 is used for driving the MOSFET gate. Moreover, Zener diodes are connected between gate and source terminals of the MOSFET in order to protect the MOSFET in case of excessive gate voltages that may be caused by transient voltages. Control circuit is supplied by an AC-DC converter including a linear regulator and a transformer in order to isolate the control and power stages of the dimmer. An isolated power supply IC or a flyback converter might be used for the power supply of the control circuit. The disadvantage of the current system is the size because of low operating frequency transformer. The size of the dimmer would be smaller if an SMPS was used in the control system. Moreover, overall efficiency would be improved since lossy linear regulator is removed from the circuit. However, the power supply with linear regulator is much easier to build and cheaper. The complete connection diagram of the circuit is given in Figure 5.8.

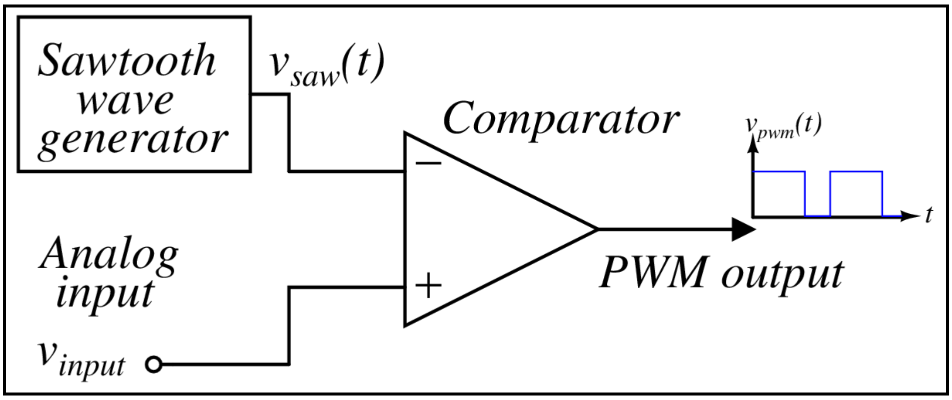



Figure 5.7. Diagram of a basic PWM generator

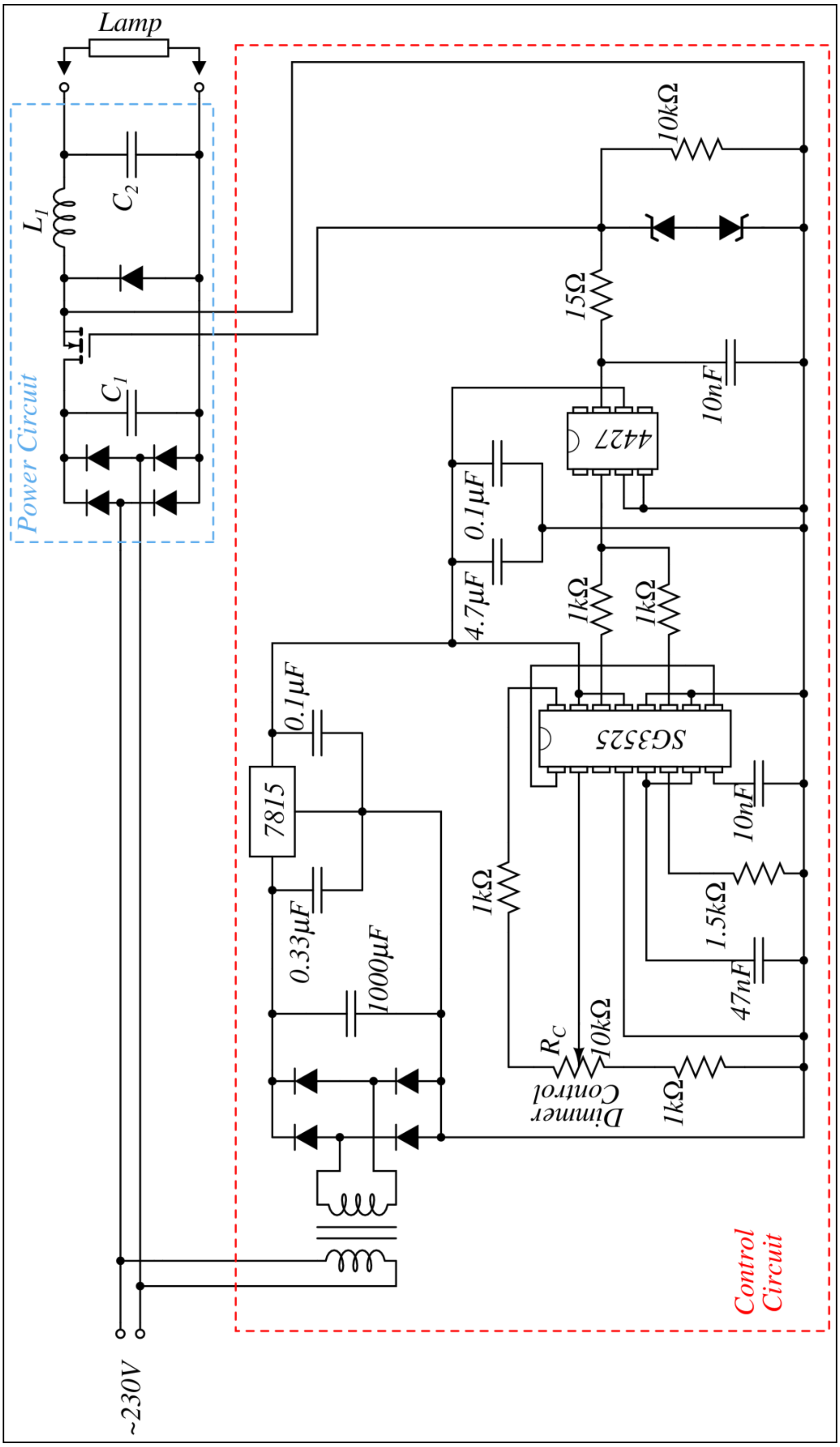



Figure 5.8. Complete schematic of the dimmer circuit

# 6. SIMULATION AND EXPERIMENTAL RESULTS

A simulation is performed using the values obtained in the design section before building the circuit. It is observed that the circuit component values are suitable for the dimmer. Then, the designed circuit is built and tested. The results of the simulation and the experiments are given in this section.

## 6.1. SIMULATION

The circuit is simulated in PSIM, including non-idealities of inductor, MOSFET and diode. MOSFET on-resistance and inductor resistance are included into the circuit as *Rds* (0.48Ω) and Rl (1.4Ω), respectively. Diode forward voltage drop is added to the schematic as *Vd* which is a 0.7 V DC voltage source. The lamps are included in the simulation as resistors for simplicity. Simulated circuit is shown in Figure 6.1.

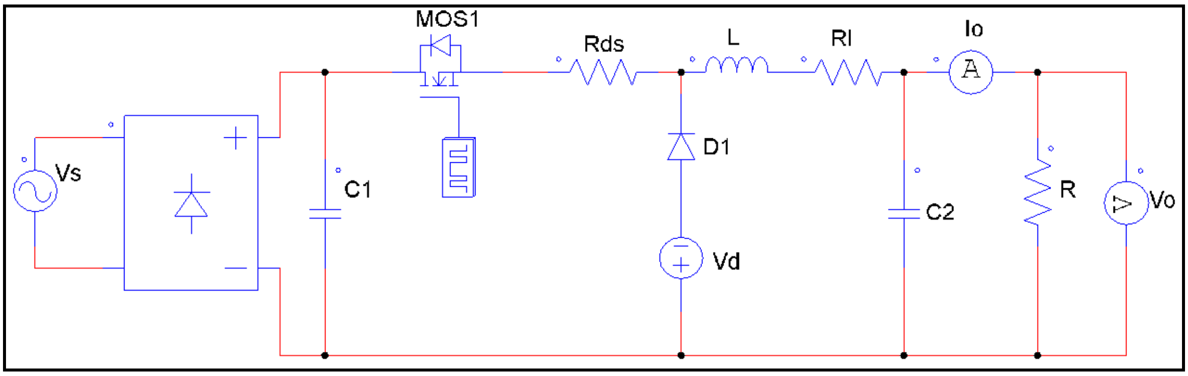



Figure 6.1. Simulated circuit in PSIM

Simulation is performed for 50 milliseconds with 3.1746 μs time step. Initial conditions are set to zero for all parameters. Netlist of the simulation is given in Appendix C. The simulation results are shown in Figure 6.2.

The simulation results show that the selected values for the circuit parameters are suitable for building circuit. Settling time of the system is approximately 16 ms for 1% voltage ripple that is considered as the error band. Overshoot of the voltage and current does not exceed the absolute maximum ratings of the components. There is 0.065% steady-state error at the output voltage.

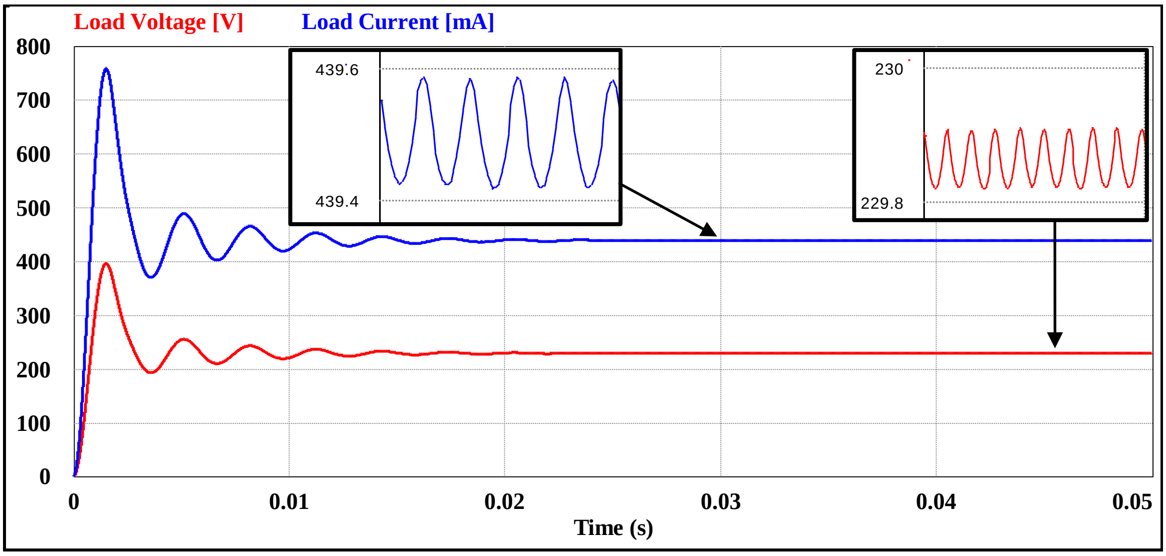



Figure 6.2. Simulation results

## 6.2. EXPERIMENTAL RESULTS

The dimmer circuit has built and tested with various lighting devices. Experiments were performed in Power Electronics Laboratory and darkroom of Lighting and Interior Wiring Laboratory in Istanbul Technical University.

Input power, output voltage and output current were measured in order to obtain electrical characteristics of the dimmer. Moreover, photometric measurements were taken to observe the dimming operation. A panoramic view of the experiment setup in darkroom is shown in Figure 6.3.


Figure 6.3. Panoramic view of the darkroom

Illuminance ( E ) was chosen as the photometric quantity to be measured. Luminous intensities ( ʆ ) at of the lighting sources are obtained by measured illuminance values. Illuminance was measured using a lux meter. The relationship between illuminance and luminous intensity is given in Equation 6.1.

$$E = \frac{ʆ_\vartheta}{r^2}\cos\vartheta \qquad (6.1)$$

where $\vartheta$ is the angle between direction of luminous intensity and surface normal, and *r* is the distance between lighting source and surface. The lux meter was placed perpendicular to the luminous intensity direction and the experiment was performed in a darkroom. Thus, $ʆ_0$, luminous intensity at 0 degrees is obtained. The distance between the lux meter and light source is 5 meters. Rearranging Equation 6.1 for luminous intensity at $0^o$,

$$ʆ_0 = E \cdot 5^2 \cdot \cos 0 = 25 \cdot E \qquad (6.2)$$

Figure 6.4, Figure 6.5 and Figure 6.6 show voltage, current, power, efficiency and luminous intensity characteristics of incandescent bulb, CFL and LED bulb respectively.

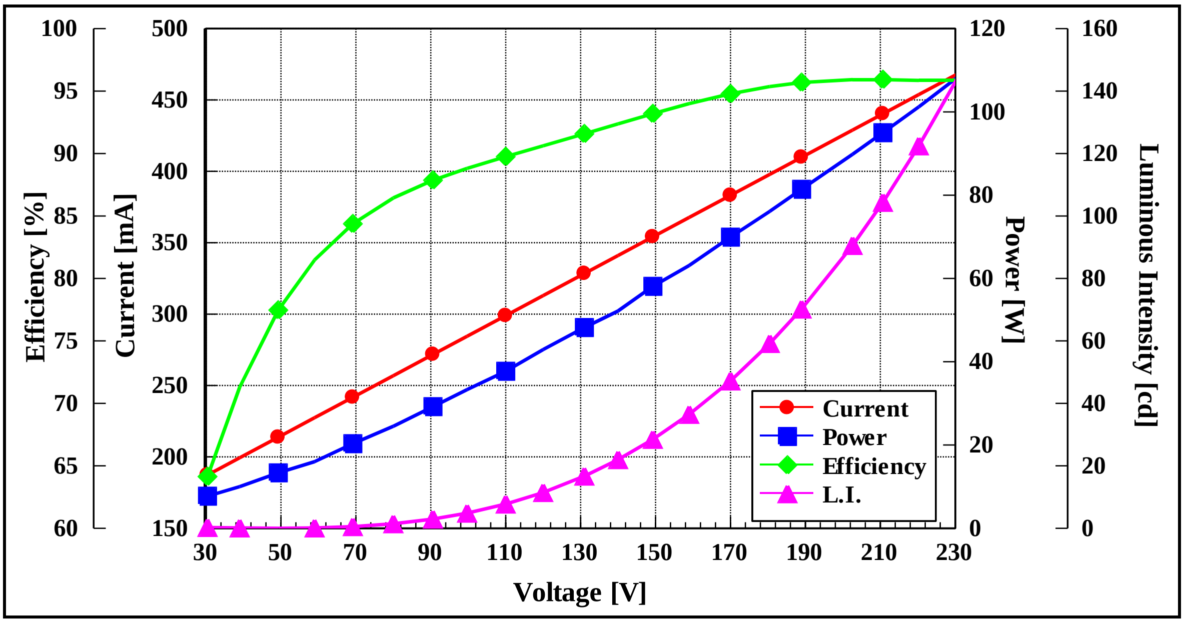



Figure 6.4. V – I , V – P, V – η, V – $ʆ_0$ characteristics of 100 W incandescent bulb

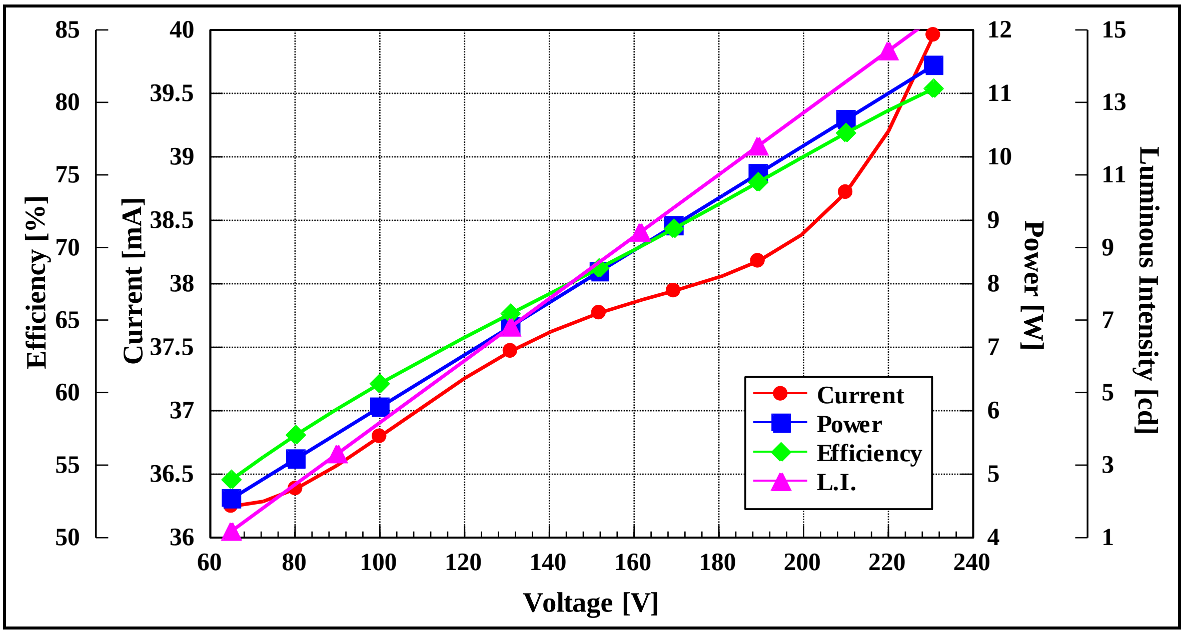



Figure 6.5. V – I , V – P, V – η, V – $\int_0$ characteristics of 10 W CFL

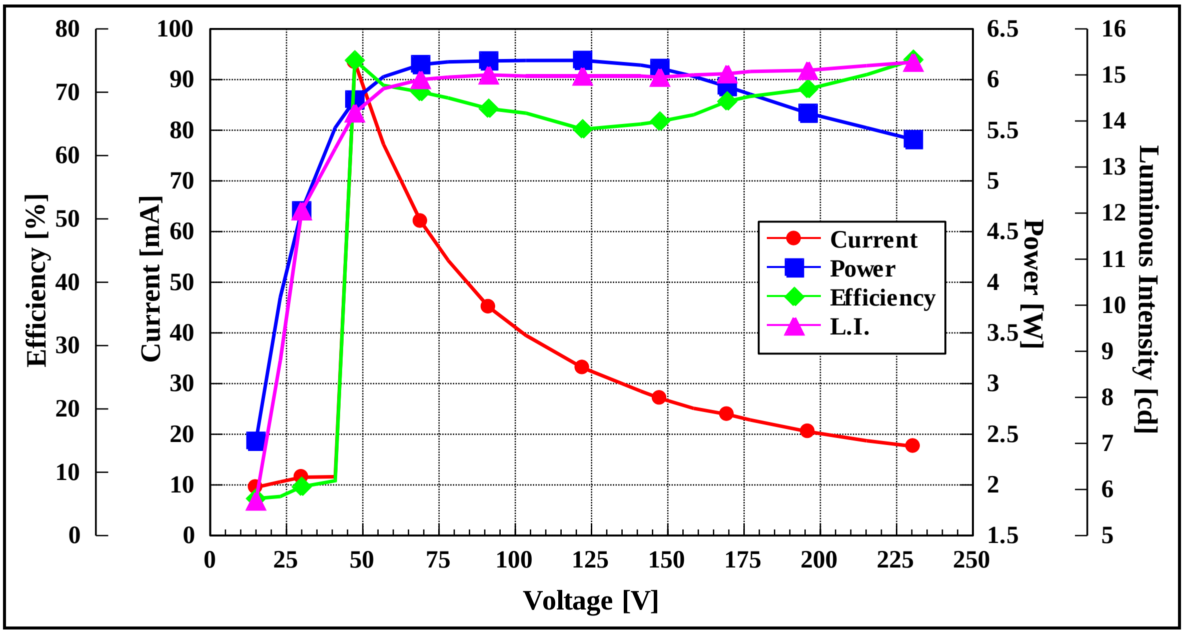



Figure 6.6. V – I , V – P, V – η, V – $\int_0$ characteristics of 4 W LED bulb

Marked points appearing in figures are indicating the data from measurements. Tabulated list of measurement values are given in Appendix D.

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 Figure 6.7, Figure 6.8 and Figure 6.9, respectively. Additionally, experiment setup diagram is depicted in Figure 6.10.

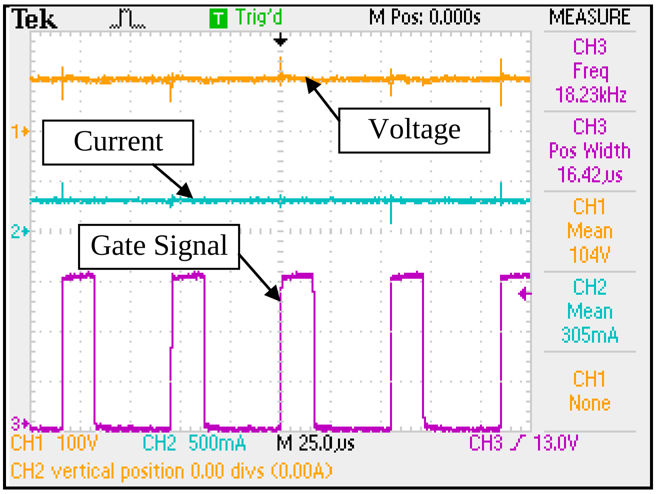



Figure 6.7. Voltage (100 V/div) and current (500 mA/div) waveforms of incandescent bulb with MOSFET gate signal (5 V/div), time (25 µs/div)

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

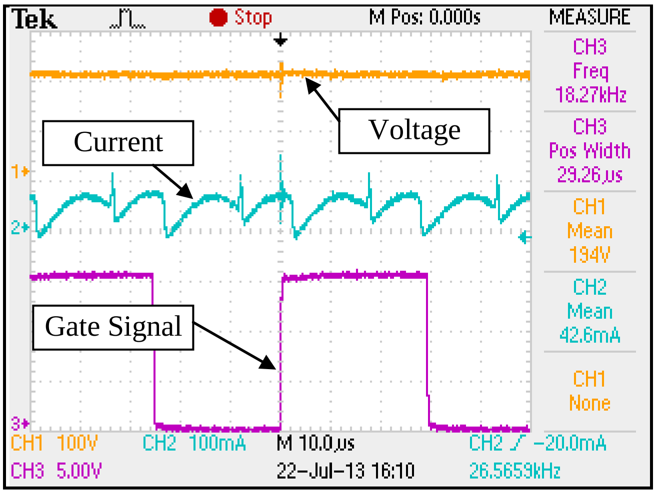



Figure 6.8. Voltage (100 V/div) and current (100 mA/div) waveforms of CFL with MOSFET gate signal (5 V/div), time (10 µs/div)

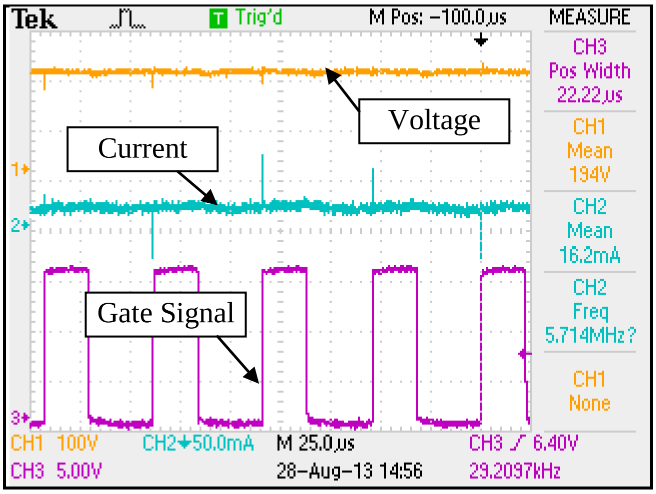



Figure 6.9. Voltage (100 V/div) and current (50 mA/div) waveforms of LED bulb with MOSFET gate signal (5 V/div), time (25 µs/div)

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.

Input power of the LED is constant after the value which is at the input range of the feedback driver of the LED bulb. 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 to give light output with a duty cycle of less than 5% and not sensitive with duty cycle of more 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. It is clearly seen that light output level of the LED bulb should be controlled between 15 Volts and 70

Volts. Dimming ranges of the lighting devices used in the experiments are given in Table 6.1.

Table 6.1. Voltage and luminous intensity ranges of lamps for dimming operation

| **Lamp Type** | **Voltage Range [V]** | **Luminous Intensity Range [cd]** | **Rated Luminous Intensity [cd]** |
|---|---|---|---|
| Incandescent Bulb | 30 – 230 | 0 – 145 | 145 |
| CFL | 65 – 230 | 0 – 15 | 15 |
| LED bulb | 15 – 70 | 0 – 15 | 15 |

Position range of the potentiometer in the dimmer is different for LED bulbs than the other types of lighting devices. For instance, incandescent bulbs and CFLs can be controlled when the position of the control knob is between 0-270 degrees while the lowest position of the knob gives the maximum input voltage for the LED bulbs if it is planned to turn the dimmer off below 65 Volts for incandescent bulbs and CFLs. However, this problem has a solution as long as there is a special PWM generator that generates the gate signal within specific ranges. A microcontroller based system can be used in this process in order to generate special duty cycle ranges for different kinds of lighting devices. If the microcontroller knows that an incandescent bulb or CFL is connected, the dimmer outputs 65 Volts when the knob is in lowest position and 230 Volts for highest position. Similarly, if the microcontroller knows that an LED bulb is connected, the dimmer output 15 Volts when the knob is in the lowest position and 70 Volts for highest position. This can be applied both on open-loop or closed-loop systems.

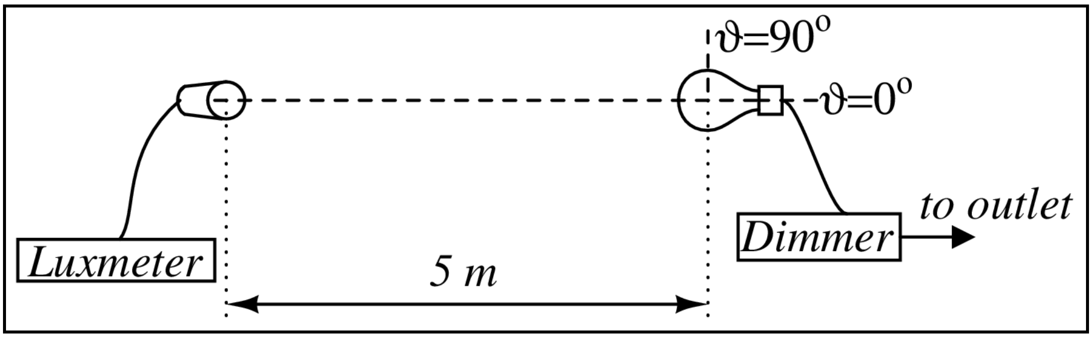



Figure 6.10. Diagram of the experiment setup

# 7. CONCLUSION

In this thesis a new dimmer circuit that can be used for different lighting devices has been developed. The dimmer can be operated with incandescent bulbs, halogen lamps, LED lamps and CFLs.

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 do not require a special current and voltage waveform unless the voltage or current have ripples in visible frequency. Compact fluorescent bulbs need to transfer enough energy to electrodes connected to the gas tube in order to heat the gas properly. Flicker occurs if the filaments are not heated enough. LEDs usually can be operated in a voltage range of 100-230 $V_{ac}$. Thus, the LED driver inside the bulb converts the electrical energy in order to keep the power constant when the input voltage is greater than 100 Volts.

Incandescent bulbs, CFLs and LED bulbs have different dimming ranges because of their internal structures. Incandescent bulbs can easily be driven by the dimmer in the range of 0-230 Volts. CFLs can cause flickering when supplied with low voltage depending on tube geometry. Moreover, CFLs should be dimmed starting from voltage that is close to the rated voltage. This is caused by the low energy that is transferred to the filaments is not enough to heat the gas to generate light. The dimming range of the LEDs can be chosen as 0-100 Volts.

The dimmer circuit is designed, built and tested with various lighting devices. The new dimmer is suitable for a wide range of lighting devices in the market, including incandescent bulbs, halogen lamps, CFLs and LED bulbs for specific output voltage ranges. This system will provide a more economical solution when used with high-power illumination applications such as LED projector lights. An application-specific PWM generator system should be used which generates PWM signals in specific duty cycle ranges for different cases.

As a future work, closed-loop controller can be employed in order to identify the lamp type. The dimmer will adjust the voltage range for dimming operation automatically by a feedback circuitry detecting the load type by the current waveform.

## REFERENCES


1. Smith, J., Speaks, J. and Rashid, M. H. , "An Overview of the Modern Light Dimmer: Design, Operation, and Application", *Proceedings of the 37th Annual North American Power Symposium*, pp. 299 – 303, Ames, Iowa, USA, 2005.

2. Qu, X., Wong, S. C. and Tse, C. K., "Resonance-Assisted Buck Converter for Offline Driving of Power LED Replacement Lamps", *IEEE Trans. Power Electron.*, Vol. 26, No. 2, pp. 532 – 540, 2011.

3. Ching, T.W., "Modular Dimmable Light-Emitting-Diode Driver For General Illumination Applications", *23rd Canadian Conference on Electrical and Computer Engineering*, p. 1 – 4, Calgary, Alberta, Canada, 2010.

4. Yaakov, S.B., Shvartsas, M. and Glozman, S., "Statics and Dynamics of Fluorescent Lamps Operating at High Frequency: Modeling and Simulation", *IEEE Trans. on Ind. Applications*, Vol. 38, No. 6, pp. 1486 – 1492, 2002.

5. Siqueria, G. P. and Junior, Y. B., "Static and Dynamic Electric Behavior of Compact Fluorescent Lamps", *Power Electronics and Motion Control Conference*, pp. 1268 – 1270, Portoroz, Slovenia, 2006.

6. Sun, Y., "PSpice Modeling of Electronically Ballasted Compact Fluorescent Lamp Systems", *Industry Applications Society Annual Meeting*, pp. 2311 – 2316, Toronto, Canada, 1993.

7. Wei, Z., Watson, N. R. and Frater, L. P., "Modelling of Compact Fluorescent Lamps", *Harmonics and Quality of Power*, pp. 1 – 6, Wollongong, New South Wales, Australia, 2008.

8. Tam, P. W., Hui, S. Y. R., and Chung, S. H., "An Analysis and Practical Implementation of a Dimmable Compact Fluorescent Lamp Ballast Circuit without Integrated Circuit Control", *Power Electronics Specialists Conference*, pp. 1 – 8, Jeju, South Korea, 2006.

9. Ho, Y. K. E., Lee, S. T. S., Chung, H. S. H. and Hui, S. Y., "A Comparative Study on Dimming Control Methods for Electronic Ballasts", *IEEE Trans. Power Electron.*, Vol. 16, No. 16, pp. 828 – 836, 2001.

10. Yao, X. L., "Dimmer for Energy Saving Lamp", *U.S. Patent Application*, 0222604 A1, Dec. 4, 2003.

11. Wong, T. P., Chow, H. L. and Li, C. K., "A DC-DC Converter Used as a Light Dimmer For Compact Fluorescent Lamps", *Power Electronics Systems and Applications*, pp. 1 – 7, Hong Kong, China, 2009.

12. Simpson, R. S., *Lighting Control: Technology and Applications*, Focal Press, Oxford, 2003.

13. Bowers, B., "Lights Out", *IEEE Spectr.*, Vol. 48, No. 4, pp. 44 – 52, 2011.

14. "DuraMax Incandescent Household, 40W", Philips North America Corporation, *http://www.usa.philips.com*, < http://www.usa.philips.com/c/other-light-bulbs/duramax-40w-a19-clear-medium-base-046677167974/prd/en/>, September 18, 2013.

15. Wier, B., "Driving the 21st Century's Lights", *IEEE Spectr.*, Vol. 49, No. 3, pp. 42 – 47, 2012.

16. Inman, G. E., "Characteristics of Fluorescent Lamps", *Transactions of the Illuminating Engineers Society*, Vol. 34, No. 1, pp. 65 – 86, 1939.

17. "Ecotone High Lumen Spiral Energy Saving Bulb, 65W", Philips India Limited, *http://www.philips.co.in*, <http://www.philips.co.in/c/energy-saving-light-

bulbs/ecotone-high-lumen-65-w-200-w-e27-cool-white-929676001204/prd/>, September 22, 2013.

18. “LED A Shape, 11W”, Philips North America Corporation, *http://www.usa.philips.com*, <http://www.usa.philips.com/c/led-light-bulbs/led-11w-60w-medium-base-e26-dimmable-a19-dimmable-046677424381/prd/en/;jsessionid =A550D697C82A67421D39324C74213685.app121-drp1>, September 22,2013.

19. “Wybron 812020 Eclipse IT Iris 2K Dowser”, Wybron, Inc., http://www.wybron.com/, <http://www.wybron.com/stage-lighting-accessories/mechanical-dowsers/Eclipse-IT-iris/2K/images/812020_large.png>, September 18, 2013.

20. Hudgins, J., et al., “Thyristors”, in Rashid, M. H. (ed.), *Power Electronics Handbook*, pp. 27 – 55, Academic Press, San Diego, USA, 2001.

21. Yıldırım, D., Bilgic, M., “PWM AC chopper control of single-phase induction motor for variable-speed fan application”, *IECON 2013*, pp. 1337 - 1342, Orlando, FL, US, 2008.

22. Erickson, R., Maksimovic, D., *Fundamentals of Power Electronics*, Secaucus, pp. 221-226, Kluwer Academic Publishers, NJ, USA, 2000.

23. Turhan, M., Dai, R. B., Yıldırım, D., “Analytical MPPT Solution Using Thevenin Approach for Solar Panels”, *EuroCon 2013*, pp. 803 – 808, Zagreb, Croatia, 2013.

# APPENDIX A: ELECTRICAL CHARACTERISTICS OF LIGHTING DEVICES WITH VARIABLE AC SOURCE

Various lighting devices are tested with variable AC source. Voltage, current, power and power factor measurements of incandescent bulb, CFL and LED bulb are given in Table A.1, Table A.2 and Table A.3, respectively. Reactance of the incandescent bulb is neglected and power factor of the incandescent bulb is assumed “1”.

Table A.1. Voltage, current, power values of incandescent bulb in AC operation

| Voltage [V] | Current [mA] | Power [W] |
|---|---|---|
| 30 | 188 | 5.64 |
| 40.5 | 204 | 8.262 |
| 50.2 | 22 | 11.044 |
| 60 | 237 | 14.22 |
| 70 | 253 | 17.71 |
| 80 | 268 | 21.44 |
| 90 | 284 | 25.56 |
| 100 | 2978 | 29.78 |
| 110 | 313 | 34.43 |
| 120 | 327 | 39.24 |
| 130 | 339 | 44.07 |
| 140 | 353 | 49.42 |
| 150 | 364 | 54.6 |
| 160 | 377 | 60.32 |
| 170 | 388 | 65.96 |
| 180 | 400 | 72 |
| 190 | 410 | 77.9 |
| 200 | 422 | 84.4 |
| 210 | 434 | 91.14 |
| 220 | 443 | 97.46 |
| 230 | 454 | 104.42 |

Table A.2. Voltage, current, power and p.f. values of CFL in AC operation

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Power Factor** |
|---|---|---|---|
| 86 | 50 | 3.2 | 0.745 |
| 90 | 51.3 | 3.39 | 0.732 |
| 100 | 52.7 | 3.73 | 0.709 |
| 110 | 54.7 | 4.19 | 0.693 |
| 120 | 56.2 | 4.66 | 0.69 |
| 130 | 57.5 | 5.13 | 0.686 |
| 140 | 58.6 | 5.61 | 0.683 |
| 150 | 60 | 6.08 | 0.68 |
| 160 | 61.1 | 6.58 | 0.675 |
| 170 | 62 | 7.06 | 0.671 |
| 180 | 62.6 | 7.53 | 0.668 |
| 190 | 6.3 | 7.98 | 0.662 |
| 200 | 64.2 | 8.43 | 0.658 |
| 210 | 65.4 | 8.9 | 0.651 |
| 220 | 66.6 | 9.36 | 0.648 |
| 230 | 67 | 9.78 | 0.64 |

Table A.3. Voltage, current, power and p.f. values of LED bulb in AC operation

| Voltage [V] | Current [mA] | Power [W] | Power Factor |
|---|---|---|---|
| 10.3 | 112.7 | 0.86 | 0.745 |
| 12.78 | 103.5 | 0.89 | 0.663 |
| 15 | 94.7 | 0.774 | 0.539 |
| 18.33 | 11.4 | 0.93 | 0.455 |
| 20 | 160.5 | 2.67 | 0.813 |
| 30 | 143.5 | 3.15 | 0.729 |
| 40 | 130.4 | 3.408 | 0.647 |
| 50 | 126.6 | 3.5 | 0.552 |
| 60 | 127 | 3.77 | 0.487 |
| 70 | 103 | 3.95 | 0.545 |
| 80 | 81 | 3.9 | 0.603 |
| 90 | 71.5 | 3.83 | 0.592 |
| 100 | 68.1 | 3.78 | 0.554 |
| 110 | 63.4 | 3.74 | 0.534 |
| 120 | 58.4 | 3.72 | 0.530 |
| 130 | 54.7 | 3.72 | 0.518 |
| 140 | 51.3 | 3.73 | 0.520 |
| 150 | 48 | 3.75 | 0.518 |
| 160 | 46.2 | 3.77 | 0.501 |
| 170 | 44.2 | 3.8 | 0.508 |
| 180 | 41.2 | 3.83 | 0.513 |
| 190 | 40.4 | 3.87 | 0.506 |
| 200 | 39 | 3.9 | 0.499 |
| 210 | 36.5 | 3.91 | 0.512 |
| 220 | 35.3 | 3.96 | 0.507 |
| 230 | 34.5 | 4 | 0.509 |

# APPENDIX B: ELECTRICAL CHARACTERISTICS OF LIGHTING DEVICES WITH VARIABLE DC SOURCE

Various lighting devices are tested with variable DC source. Voltage, current, power and power factor measurements of incandescent bulb, CFL and LED bulb are given in Table B.1, Table B.2 and Table B.3, respectively.

Table B.1. Voltage, current, power values of incandescent bulb in DC operation

| Voltage [V] | Current [mA] | Power [W] |
|---|---|---|
| 20 | 155 | 3.1 |
| 30.8 | 181 | 5.5748 |
| 39.3 | 195 | 7.6635 |
| 50.1 | 213 | 10.6713 |
| 59.6 | 227 | 13.5292 |
| 70 | 245 | 17.15 |
| 81 | 265 | 21.465 |
| 90 | 280 | 25.2 |
| 97.3 | 293.8 | 28.58674 |
| 111.1 | 317 | 35.2187 |
| 119.7 | 330 | 39.501 |
| 131 | 346 | 45.326 |
| 140 | 360 | 50.4 |
| 151 | 370 | 55.87 |
| 159 | 380 | 60.42 |
| 170.6 | 390 | 66.534 |
| 180.5 | 400 | 72.2 |
| 200 | 420 | 84 |
| 210.7 | 430 | 90.601 |
| 223 | 450 | 100.35 |

Table B.2. Voltage, current, power values of CFL in DC operation

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Power Factor** |
|---|---|---|---|
| 70 | 34.27 | 2.45 | 0.624 |
| 80 | 35.42 | 2.92 | 0.609 |
| 90 | 35.7 | 3.24 | 0.596 |
| 100 | 36.2 | 3.66 | 0.586 |
| 110 | 36.6 | 4.09 | 0.568 |
| 120 | 36.7 | 4.48 | 0.557 |
| 130 | 37.05 | 4.89 | 0.554 |
| 140 | 37.34 | 5.31 | 0.553 |
| 150 | 37.6 | 5.7 | 0.54 |
| 160 | 37.82 | 6.14 | 0.538 |
| 170 | 37.93 | 6.52 | 0.549 |
| 180 | 37.92 | 6.91 | 0.526 |
| 190 | 37.98 | 7.3 | 0.53 |
| 200 | 37.94 | 7.66 | 0.517 |
| 210 | 38.05 | 8.1 | 0.516 |
| 220 | 38.12 | 8.52 | 0.513 |
| 230 | 38.3 | 8.93 | 0.511 |

Table B.3. Voltage, current, power values of LED bulb in DC operation

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Power Factor** |
|---|---|---|---|
| 11.3 | 96.89 | 1.32 | 0.758 |
| 15.4 | 111 | 1.767 | 0.716 |
| 17 | 132 | 2.417 | 0.733 |
| 20 | 137 | 3 | 0.744 |
| 22.5 | 152 | 3.65 | 0.688 |
| 25.22 | 133 | 3.58 | 0.733 |
| 30 | 120.25 | 3.77 | 0.73 |
| 40 | 100.68 | 4.15 | 0.719 |
| 50 | 84.85 | 4.39 | 0.708 |
| 60 | 67.29 | 4.14 | 0.682 |
| 70 | 56.55 | 4.04 | 0.668 |
| 80 | 48.62 | 3.97 | 0.641 |
| 90 | 42.53 | 3.91 | 0.621 |
| 100 | 37.96 | 3.85 | 0.603 |
| 110 | 34.21 | 3.81 | 0.574 |
| 120 | 31.01 | 3.78 | 0.549 |
| 130 | 28.49 | 3.76 | 0.536 |
| 140 | 26.43 | 3.74 | 0.522 |
| 150 | 24.45 | 3.73 | 0.510 |
| 160 | 22.96 | 3.73 | 0.506 |
| 170 | 21.64 | 3.73 | 0.506 |
| 180 | 20.486 | 3.74 | 0.49 |
| 190 | 19.44 | 3.75 | 0.485 |
| 200 | 18.542 | 3.77 | 0.475 |
| 210 | 17.758 | 3.78 | 0.469 |
| 220 | 17 | 3.8 | 0.463 |
| 230 | 16.37 | 3.82 | 0.459 |

# APPENDIX C: NETLIST OF THE DIMMER SIMULATION PERFORMED IN PSIM

```
.TIME 3.1746E-006 0.05 0 1 0 0 0 0 0
MOSFET MOS1 1 2 3 0 0 0 0 0
L L 5 11 50m 0 0
DIODE D1 4 5 0 0 0 0
C C2 6 7 4.7u 0 0
GATING G1 3 20000 2  0 255.
VP2 Vo 8 7
IP Io 6 8
R R 8 7 523 0
VDC Vd 7 4 0.7
R Rds 2 5 0.48 0
BDIODE1 BD11 9 10 1 7 0 0 0 0 0 0 0 0 0
C C1 1 7 115U 0 0
VSIN Vs 9 10 325 50 0 0 0
R Rl 11 6 1.4 0
```

# APPENDIX D: ELECTRICAL AND OPTICAL CHARACTERISTICS OF LIGHTING DEVICES

Various lighting devices are tested with the proposed dimmer. Voltage, current, power, efficiency and illuminance measurements of lighting devices are given with calculated luminous intensity values at $0^0$. Experiment results of incandescent bulb, CFL and LED bulb are given in Table D.1, Table D.2 and Table D.3, respectively.

Table D.1. Electrical and photometric data of incandescent bulb with dimmer

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Efficiency [%]** | **E [lx]** | **$I_0$ [cd]** |
|---|---|---|---|---|---|
| 30.4 | 163 | 7.7 | 64.35 | 0.002 | 0.05 |
| 39 | 180 | 10 | 70.20 | 0.003 | 0.075 |
| 49.3 | 210 | 13.3 | 77.84 | 0.005 | 0.125 |
| 59 | 227 | 16 | 83.71 | 0.013 | 0.325 |
| 69.2 | 245 | 20.3 | 83.52 | 0.028 | 0.7 |
| 80 | 262.5 | 24.5 | 85.71 | 0.059 | 1.475 |
| 90.6 | 280 | 29.2 | 86.88 | 0.12 | 3 |
| 99.7 | 295 | 33.3 | 88.32 | 0.18 | 4.5 |
| 110 | 309 | 37.7 | 90.16 | 0.3 | 7.5 |
| 120 | 325 | 42.9 | 90.91 | 0.45 | 11.25 |
| 131 | 340 | 48.2 | 92.41 | 0.63 | 15.75 |
| 140 | 350 | 52.17 | 93.92 | 0.88 | 22 |
| 149.3 | 360 | 58.1 | 92.51 | 1.18 | 29.5 |
| 159 | 370 | 63.1 | 93.23 | 1.48 | 37 |
| 170 | 387.5 | 69.9 | 94.24 | 1.87 | 46.75 |
| 180.5 | 400.8 | 76.1 | 95.06 | 2.36 | 59 |
| 189 | 410.8 | 81.4 | 95.38 | 2.9 | 72.5 |
| 202.6 | 427 | 89.8 | 96.34 | 3.49 | 87.25 |
| 210.7 | 437 | 95 | 96.92 | 4.15 | 103.75 |
| 220.3 | 438 | 101.2 | 95.35 | 4.98 | 124.5 |
| 231 | 450 | 108.6 | 95.72 | 5.78 | 144.5 |

Table D.2. Electrical and photometric data of CFL with dimmer

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Efficiency [%]** | **E [lx]** | **$I_0$ [cd]** |
|---|---|---|---|---|---|
| 65 | 36 | 4.35 | 53.79 | 0.018 | 0.45 |
| 72.5 | 37.54 | 4.89 | 55.66 | 0.053 | 1.325 |
| 80.2 | 37.18 | 5.23 | 57.01 | 0.112 | 2.8 |
| 90 | 36.23 | 5.45 | 59.83 | 0.149 | 3.725 |
| 100 | 36.6 | 6.1 | 60.00 | 0.194 | 4.85 |
| 120 | 37.19 | 7.05 | 63.30 | 0.234 | 5.85 |
| 130.9 | 37.42 | 7.5 | 65.31 | 0.268 | 6.7 |
| 140.3 | 37.55 | 7.87 | 66.94 | 0.305 | 7.625 |
| 151.8 | 37.8 | 8.35 | 68.72 | 0.341 | 8.525 |
| 161.5 | 37.96 | 8.72 | 70.30 | 0.376 | 9.4 |
| 169.4 | 38.05 | 9 | 71.62 | 0.414 | 10.35 |
| 181 | 38.14 | 9.42 | 73.28 | 0.447 | 11.175 |
| 189.3 | 38.23 | 9.72 | 74.45 | 0.476 | 11.9 |
| 199.5 | 38.27 | 10.06 | 75.89 | 0.511 | 12.775 |
| 210 | 38.5 | 10.48 | 77.15 | 0.543 | 13.575 |
| 220 | 39.3 | 10.8 | 80.06 | 0.571 | 14.275 |
| 230.7 | 40 | 11.4 | 80.95 | 0.6 | 15 |

Table D.3. Electrical and photometric data of LED bulb with dimmer

| **Voltage [V]** | **Current [mA]** | **Power [W]** | **Efficiency [%]** | **E [lx]** | **$I_0$ [cd]** |
|---|---|---|---|---|---|
| 15 | 9.5 | 2.44 | 5.84 | 0.23 | 5.75 |
| 23 | 10.6 | 3.96 | 6.16 | 0.352 | 8.8 |
| 30 | 11.5 | 4.48 | 7.70 | 0.482 | 12.05 |
| 41 | 11.6 | 5.5 | 8.65 | 0.536 | 13.4 |
| 47.4 | 93.4 | 5.9 | 75.04 | 0.567 | 14.175 |
| 56.8 | 77.2 | 6.17 | 71.07 | 0.588 | 14.7 |
| 69 | 62 | 6.11 | 70.02 | 0.596 | 14.9 |
| 78 | 54.3 | 6.13 | 69.09 | 0.598 | 14.95 |
| 91.3 | 45.1 | 6.11 | 67.39 | 0.6 | 15 |
| 103.5 | 39.5 | 6.13 | 66.69 | 0.599 | 14.975 |
| 122.1 | 33.1 | 6.3 | 64.15 | 0.599 | 14.975 |
| 141.1 | 28.5 | 6.19 | 64.97 | 0.599 | 14.975 |
| 147.4 | 27.1 | 6.11 | 65.38 | 0.598 | 14.95 |
| 158.5 | 25.1 | 5.99 | 66.42 | 0.6 | 15 |
| 169.5 | 23.9 | 5.91 | 68.55 | 0.601 | 15.025 |
| 177 | 22.8 | 5.82 | 69.34 | 0.603 | 15.075 |
| 196 | 20.5 | 5.7 | 70.49 | 0.604 | 15.1 |
| 215.2 | 18.7 | 5.53 | 72.77 | 0.608 | 15.2 |
| 230.5 | 17.6 | 5.4 | 75.13 | 0.611 | 15.275 |

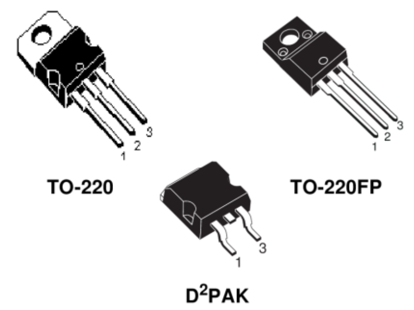
# APPENDIX E: DATASHEET OF MOSFET STP11NK50ZFP

## STP11NK50Z - STP11NK50ZFP
## STB11NK50Z

N-CHANNEL 500V - 0.48Ω - 10A TO-220/TO-220FP/$D^2$PAK
Zener-Protected SuperMESH™Power MOSFET

| TYPE | $V_{DSS}$ | $R_{DS(on)}$ | $I_D$ | Pw |
|---|---|---|---|---|
| STB11NK50Z | 500 V | < 0.52 Ω | 10 A | 125 W |
| STP11NK50Z | 500 V | < 0.52 Ω | 10 A | 125 W |
| STP11NK50ZFP | 500 V | < 0.52 Ω | 10 A | 30 W |

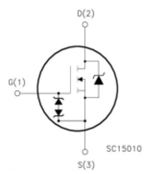
- TYPICAL $R_{DS}$(on) = 0.48 Ω
- EXTREMELY HIGH dv/dt CAPABILITY
- 100% AVALANCHE TESTED
- GATE CHARGE MINIMIZED
- VERY LOW INTRINSIC CAPACITANCES
- VERY GOOD MANUFACTURING REPEATIBILITY
- ADD SUFFIX "T4" FOR ORDERING IN TAPE & REEL ($D^2$PAK VERSION)




### DESCRIPTION

The SuperMESH™ series is obtained through an extreme optimization of ST's well established strip-based PowerMESH™ layout. In addition to pushing on-resistance significantly down, special care is taken to ensure a very good dv/dt capability for the most demanding applications. Such series complements ST full range of high voltage MOSFETs including revolutionary MDmesh™ products.

### INTERNAL SCHEMATIC DIAGRAM




### APPLICATIONS

- HIGH CURRENT, HIGH SPEED SWITCHING
- IDEAL FOR OFF-LINE POWER SUPPLIES, ADAPTORS AND PFC
- LIGHTING

### ORDERING INFORMATION

| SALES TYPE | MARKING | PACKAGE | PACKAGING |
|---|---|---|---|
| STB11NK50ZT4 | B11NK50Z | $D^2$PAK | TAPE & REEL |
| STP11NK50Z | P11NK50Z | TO-220 | TUBE |
| STP11NK50ZFP | P11NK50ZFP | TO-220FP | TUBE |

# APPENDIX F: DATASHEET OF DIODE MUR840

FAIRCHILD SEMICONDUCTOR®

## MUR840, MUR860, RURP840, RURP860

**Data Sheet** **March 2001**

## 8 A, 400 V - 600 V, Ultrafast Diodes

The MUR840, MUR860, RURP840, RURP860 is an ultrafast diode with low forward voltage drop. This device is intended for use as freewheeling and clamping diodes in a variety of switching power supplies and other power switching applications. It is specially suited for use in switching power supplies and industrial application.

### Features

- Ultrafast Recovery $t_{rr}$ = 70 ns (@ $I_F$ = 8 A)
- Max Forward Voltage, $V_F$ = 1.5 V (@ $T_C$ = 25°C)
- 400 V, 600 V Reverse Voltage and High Reliability
- Avalanche Energy Rated
- RoHS Compliant

### Applications

- Switching Power Supplies
- Power Switching Circuits
- General Purpose

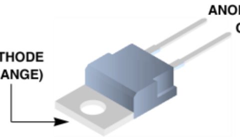
### Ordering Information

| PART NUMBER | PACKAGE | BRAND |
|---|---|---|
| MUR840 | TO-220AC | MUR840 |
| RURP840 | TO-220AC | RURP840 |
| MUR860 | TO-220AC | MUR860 |
| RURP860 | TO-220AC | RURP860 |

NOTE: When ordering, use the entire part number.

### Packaging

JEDEC TO-220AC




### Symbol


**Absolute Maximum Ratings** $T_C$ = 25°C, Unless Otherwise Specified

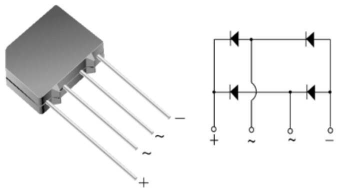
| | | MUR840 RURP840 | MUR860 RURP860 | UNIT |
|---|---|---|---|---|
| Peak Repetitive Reverse Voltage | $V_{RRM}$ | 400 | 600 | V |
| Working Peak Reverse Voltage | $V_{RWM}$ | 400 | 600 | V |
| DC Blocking Voltage | $V_R$ | 400 | 600 | V |
| Average Rectified Forward Current ($T_C$ = 155°C) | $I_{F(AV)}$ | 8 | 8 | A |
| Repetitive Peak Surge Current (Square Wave, 20kHz) | $I_{FRM}$ | 16 | 16 | A |
| Nonrepetitive Peak Surge Current (Halfwave, 1 Phase, 60Hz) | $I_{FSM}$ | 100 | 100 | A |
| Maximum Power Dissipation | $P_D$ | 75 | 75 | W |
| Avalanche Energy (See Figures 10 and 11) | $E_{AVL}$ | 20 | 20 | mJ |
| Operating and Storage Temperature | $T_{STG}$, $T_J$ | -65 to 175 | -65 to 175 | °C |
| Maximum Lead Temperature for Soldering | | | | |
| Leads at 0.063 in. (1.6mm) from case for 10s | $T_L$ | 300 | 300 | °C |
| Package Body for 10s, see Tech Brief 334 | $T_{PKG}$ | 260 | 260 | °C |

# APPENDIX G: DATASHEET OF DIODE BRIDGE 2KBP04M

## 2KBP005M thru 2KBP10M, 3N253 thru 3N259

Vishay General Semiconductor

## Glass Passivated Single-Phase Bridge Rectifier




Case Style KBPM

### FEATURES

- UL Recognition file number E54214
- Ideal for printed circuit board
- High surge current capability
- High case dielectric strength
- Solder Dip 260 °C, 40 seconds
- Component in accordance to RoHS 2002/95/EC and WEEE 2002/96/EC

### TYPICAL APPLICATIONS

General purpose use in ac-to-dc bridge full wave rectification for Switching Power Supply, Home Appliances, Office Equipment, and Telecommunication applications.

| MAJOR RATINGS AND CHARACTERISTICS | |
|---|---|
| $I_{F(AV)}$ | 2 A |
| $V_{RRM}$ | 50 V to 1000 V |
| $I_{FSM}$ | 60 A |
| $I_R$ | 5 µA |
| $V_F$ | 1.1 V |
| $T_j$ max. | 150 °C |

### MECHANICAL DATA

**Case:** KBPM

Epoxy meets UL 94V-0 flammability rating

**Terminals:** Silver plated leads, solderable per J-STD-002B and JESD22-B102D

E4 suffix for commercial grade

**Polarity:** As marked on body

**MAXIMUM RATINGS** ($T_A$ = 25 °C unless otherwise noted)

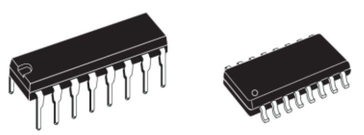
| PARAMETER | SYMBOL | 2KBP 005M | 2KBP 01M | 2KBP 02M | 2KBP 04M | 2KBP 06M | 2KBP 08M | 2KBP 10M | UNIT |
|---|---|---|---|---|---|---|---|---|---|
| | | 3N253 | 3N254 | 3N255 | 3N256 | 3N257 | 3N258 | 3N259 | |
| Maximum repetitive peak reverse voltage | $V_{RRM}$ | 50 | 100 | 200 | 400 | 600 | 800 | 1000 | V |
| Maximum RMS voltage | $V_{RMS}$ | 35 | 70 | 140 | 280 | 420 | 560 | 700 | V |
| Maximum DC blocking voltage | $V_{DC}$ | 50 | 100 | 200 | 400 | 600 | 800 | 1000 | V |
| Max. average forward output rectified current at $T_A$ = 55 °C | $I_{F(AV)}$ | 2.0 | | | | | | | A |
| Peak forward surge current single half sine-wave superimposed on rated load | $I_{FSM}$ | 60 | | | | | | | A |
| Rating for fusing (t < 8.3 ms) | $I^2t$ | 15 | | | | | | | $A^2$sec |
| Operating junction and storage temperature range | $T_J$, $T_{STG}$ | - 55 to + 165 | | | | | | | °C |

# APPENDIX H: DATASHEET OF PWM GENERATOR SG3525A

## SG2525A
## SG3525A

## REGULATING PULSE WIDTH MODULATORS

- 8 TO 35 V OPERATION
- 5.1 V REFERENCE TRIMMED TO ± 1 %
- 100 Hz TO 500 KHz OSCILLATOR RANGE
- SEPARATE OSCILLATOR SYNC TERMINAL
- ADJUSTABLE DEADTIME CONTROL
- INTERNAL SOFT-START
- PULSE-BY-PULSE SHUTDOWN
- INPUT UNDERVOLTAGE LOCKOUT WITH HYSTERESIS
- LATCHING PWM TO PREVENT MULTIPLE PULSES
- DUAL SOURCE/SINK OUTPUT DRIVERS

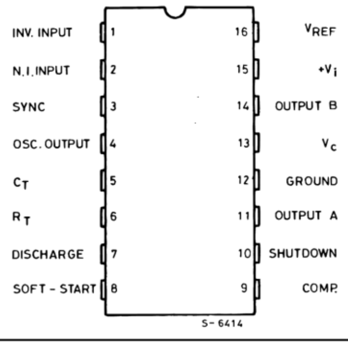


**DIP16** **16(Narrow)**

### DESCRIPTION

The SG3525A series of pulse width modulator integrated circuits are designed to offer improved performance and lowered external parts count when used in designing all types of switching power supplies. The on-chip + 5.1 V reference is trimmed to ± 1 % and the input common-mode range of the error amplifier includes the reference voltage eliminating external resistors. A sync input to the oscillator allows multiple units to be slaved or a single unit to be synchronized to an external system clock. A single resistor between the $C_T$ and the discharge terminals provide a wide range of dead time ad- justment. These devices also feature built-in soft-start circuitry with only an external timing capacitor required. A shutdown terminal controls both the soft-start circuity and the output stages, providing instantaneous turn off through the PWM latch with pulsed shutdown, as well as soft-start recycle with longer shutdown commands. These functions are also controlled by an undervoltage lockout which keeps the outputs off and the soft-start capacitor discharged for sub-normal input voltages. This lockout circuitry includes approximately 500 mV of hysteresis for jitter-free operation. Another feature of these PWM circuits is a latch following the comparator. Once a PWM pulses has been terminated for any reason, the outputs will remain off for the duration of the period. The latch is reset with each clock pulse. The output stages are totem-pole designs capable of sourcing or sinking in excess of 200 mA. The SG3525A output stage features NOR logic, giving a LOW output for an OFF state.

### PIN CONNECTIONS AND ORDERING NUMBERS (top view)




| Type | Plastic DIP | SO16 |
|---|---|---|
| SG2525A | SG2525AN | SG2525AP |
| SG3525A | SG3525AN | SG3525AP |

# APPENDIX I: DATASHEET OF MOSFET DRIVER TC4427

MICROCHIP **TC4426/TC4427/TC4428**

## 1.5A Dual High-Speed Power MOSFET Drivers

### Features:

- High Peak Output Current – 1.5A
- Wide Input Supply Voltage Operating Range:
  - 4.5V to 18V
- High Capacitive Load Drive Capability – 1000 pF in 25 ns (typ.)
- Short Delay Times – 40 ns (typ.)
- Matched Rise and Fall Times
- Low Supply Current:
  - With Logic '1' Input – 4 mA
  - With Logic '0' Input – 400 µA
- Low Output Impedance – 7Ω
- Latch-Up Protected: Will Withstand 0.5A Reverse Current
- Input Will Withstand Negative Inputs Up to 5V
- ESD Protected – 4 kV
- Pin-compatible with the TC426/TC427/TC428
- Space-saving 8-Pin MSOP and 8-Pin 6x5 DFN Packages

### Applications:

- Switch Mode Power Supplies
- Line Drivers
- Pulse Transformer Drive

### General Description:

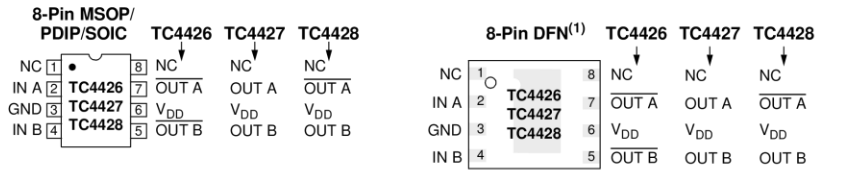
The TC4426/TC4427/TC4428 are improved versions of the earlier TC426/TC427/TC428 family of MOSFET drivers. The TC4426/TC4427/TC4428 devices have matched rise and fall times when charging and discharging the gate of a MOSFET.

These devices are highly latch-up resistant under any conditions within their power and voltage ratings. They are not subject to damage when up to 5V of noise spiking (of either polarity) occurs on the ground pin. They can accept, without damage or logic upset, up to 500 mA of reverse current (of either polarity) being forced back into their outputs. All terminals are fully protected against Electrostatic Discharge (ESD) up to 4 kV.

The TC4426/TC4427/TC4428 MOSFET drivers can easily charge/discharge 1000 pF gate capacitances in under 30 ns. These devices provide low enough impedances in both the on and off states to ensure the MOSFET's intended state will not be affected, even by large transients.

Other compatible drivers are the TC4426A/TC4427A/TC4428A family of devices. The TC4426A/TC4427A/TC4428A devices have matched leading and falling edge input-to-output delay times, in addition to the matched rise and fall times of the TC4426/TC4427/TC4428 devices.

### Package Types




**Note 1:** Exposed pad of the DFN package is electrically isolated.