A Discrete Dimming Ballast for Linear Fluorescent Lamps

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A DISCRETE DIMMING BALLAST FOR LINEAR FLUORESCENT LAMPS

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A new discrete dimming ballast for the linear fluorescent lamps is proposed in this paper. The dimming control circuit is combined with a ballast module for multiple lamps to realize three discrete lighting levels control. Compared with conventional step dimming or on/off control methods, the proposed discrete dimming method has following advantages: (1) Digital signal is generated by the dimming control circuit to control the lamps on and off, which makes the system more reliable and integrated. (2) The proposed discrete dimming system replace the relays, which are necessary in conventional lamp on/off control, and decrease the system cost. (3) The proposed dimming ballast can be installed by keeping the original wiring system. This makes the upgrading lighting system more effective and efficient. (4) The dimming control circuit also provides a good isolation for operating the low voltage wall switches by hand safely. Both simulation results and experimental results are in good agreement.
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It has been almost 70 years since fluorescent lamps were first offered to the public. Nowadays fluorescent lamps have become the main lighting source due to their unique features including high color rendering, good light output and energy saving. A fluorescent lamp is a low-pressure mercury vapour discharge lamp containing an inert gas. There is a filament at each end which, when hot, emits electrons to sustain the discharge when lamp is operating. The mercury vapour discharge produces ultraviolet light that is converted to visible light by the phosphors coating the inside of the glass tube. When the lamp is off, it appears as an open circuit, and a very high starting voltage is required to ignite the lamp. When the lamp is on, the ionized gas enclosed inside the lamp turns into plasma.

The fluorescent lamp exhibits a negative impedance characteristic. So it is necessary to place a current limiting device in series with the lamp to prevent its destruction. A ballast is a circuit that meets this requirement. It has two primary functions:

(a) to create a suitable voltage to start the lamp;

(b) to limit the lamp current during the steady state operation.
In addition the ballast has to provide the suitable lamp voltage while maintaining a high input power factor. [1][2].

Most fluorescent lamps are driven with electromagnetic ballasts. Electromagnetic ballasts are mainly composed by a large inductor and operate at 50 or 60 Hz. In recent years, high-frequency electronic ballasts have been widely used to drive the fluorescent lamps. Compared with the traditional electromagnetic ballast, an electronic ballast provides higher efficiency, higher quality light output, longer lamp life and dimming capability [3][7].

An electronic ballast consists mainly of an electromagnetic interference (EMI) filter, a rectifier, a power factor correction (PFC) circuit and a high frequency inverter. The PFC stage and the inverter stage are inter-linked by a DC voltage. Figure 1.1 shows the common electronic ballast topology.

There is a tendency to develop single-stage electronic ballasts, which combines the boost-type PFC stage and the inverter stage [4]-[6].

**Figure 1.1** Basic block diagram of the conventional two-stage electronic ballast
1.1 Resonant Inverter for Electrical Ballast

Typically the inverter stage is a half-bridge series-resonant parallel-loaded inverter [7][8]. It consists of an inductor $L_r$, capacitor $C_s$ and $C_p$, and the lamp. The fluorescent lamp can be modeled as a large resistance before ionization and a small resistance after ionization. Figure 1.2 shows the conventional class D inverter circuit for the electronic ballast.

![Figure 1.2 Basic configuration of SRPL inverter circuit](image)

The inverter converts a DC voltage to a high-frequency AC voltage by controlling the switches to start and operate the lamp. A DC-blocking capacitor $C_s\ (C_s >> C_p)$ prevents the dc current from flowing through the lamp. $C_p$ is used to provide a sufficient high voltage across the lamp cathodes during the starting transient, and then a proper filament current in the steady state.

The following parameters are useful to describe the series-resonant parallel-loaded inverter circuit:
• the natural frequency

\[
\omega_0 = \frac{1}{\sqrt{L_r C_p}}
\]  \hspace{1cm} (1.1)

• the characteristic impedance

\[
Z_0 = \omega_0 L_r = \frac{1}{\omega_0 C_p} = \sqrt{\frac{L_r}{C_p}}
\]  \hspace{1cm} (1.2)

• the loaded quality factor at the natural frequency

\[
Q_p = \omega_0 C_p R_p = \frac{R_p}{\omega_0 L_r} = \frac{R_p}{Z_0}
\]  \hspace{1cm} (1.3)

Electronic ballasts take many forms. According to the way the power switches are driven in the electronic ballast, the resonant half-bridge inverter can be configured as a driven inverter and as a self-oscillating inverter.

1.1.1 Driven inverter

The power switches of the inverter are driven by a separate control circuit, which is shown in Figure 1.3. The control circuit generates two complementary high-frequency square-wave signals. MOSFET can be used as switches. With a 50% duty cycle, switches \( S_1 \) and \( S_2 \) are ON and OFF alternatively. Many integrated circuits have been developed by manufactures to drive the resonant inverter.
1.1.2 Self-oscillating inverter

A typical self-oscillating electronic ballast is shown in Figure 1.4. The behavior of this electronic ballast is based on the feedback of the LC resonant inductor current by means of the current transformer $T_p$. The self-oscillating circuit is composed of $T_p$ and two windings $T_{s1}$ and $T_{s2}$. In electronic ballast applications, the self-oscillating inverter is regarded as one of the simplest and most cost-effective topologies [9][10].
1.2 Dimming Technology

Dimming technology has been considerably developed over the last decade, especially in the arc discharge lamp category. Dimming control is usually employed to align lighting levels with human needs and to save energy. Compared with magnetic ballast, the electronic ballast reduces the energy consumption by 15%-20%. Furthermore, dimming capability is utilized to obtain more than 50% energy saving for the lighting system relative to a non-dimming system.

For the linear fluorescent lamp, when it is dimmed over a full range without a reduction in lamp life, its cathode voltage must be maintained while the lamp arc current is reduced. So the rapid start mode is suitable for the fluorescent lamp. In the rapid start mode, the ballast continuously heats the filaments. There are many methods to adjust the light levels of the lamp and realize the dimming function [11]-[20]. Basically they can be divided into two categories: continuous dimming control method and discrete dimming control method.

1.2.1 Continuous Dimming Control

Continuous dimming electronic ballast permits the light output of the lamp to be continuously controlled over a range of approximately 1% to 100% of the full light output. Three methods have been proposed for dimming an electronic ballast of the fluorescent lamp: A) low voltage signal analog dimming; B) phase control analog dimming, and C) digital control dimming. The first two methods are designed for the controllable analog electronic ballast.
A) Low-voltage Signal Analog Dimming

Low voltage signal dimming control system is commonly used today. It is only suitable for the electronic ballast with the driven inverter structure. In addition to the power supply wire, the electronic ballasts have two more wires for a low voltage control circuit, which often rates from 0 to 10 VDC. This low voltage control circuit provides the signal to control the switches of the inverter and realize the dimming control function. This kind of dimmable electronic ballasts is compatible with a wider range of dimming controllers. But the need for additional wiring increases the cost. There are three ways to dim by controlling the power switches of the inverter: a) varying DC link voltage, b) varying switching frequency, and c) varying duty cycle.

a) Varying DC Link Voltage

DC link voltage control refers to adjusting the magnitude of the DC link voltage $V_{dc}$ to control the lamp power while keeping the switching frequency and duty ratio (near 0.5) constant [11][12]. The DC link voltage control is achieved by the rectifier stage and can be adjusted by the PFC stage.

The half-bridge inverter converts the DC link voltage to a high frequency square-wave voltage. High order harmonics of the square wave can be attenuated through the $LC$ network. Thus an approximate analysis can be performed by using the fundamental component of the square wave. The equivalent circuit of SRPL inverter is shown in Figure 1.5.
Figure 1.5 Equivalent circuit of load resonant inverter

The fundamental component of the input voltage is

\[ v_{il} = \frac{2}{\pi} V_{dc} \sin \omega t = v_m \sin \omega t \]  

(1.4)

Then the \textit{rms} value of \( v_{il} \) is

\[ V_{rms} = \frac{V_m}{\sqrt{2}} = \frac{\sqrt{2}}{\pi} V_{dc} \]  

(1.5)

By KVL,

\[
\frac{V_0}{V_{rms}} = \frac{1}{\sqrt{\left(1 + \frac{C_p}{C_s} - \omega^2 L_c C_p\right)^2 + \left(\frac{\omega L_r}{R_p} - \frac{1}{\omega C_s R_p}\right)^2}}
\]

\[
\frac{V_0}{V_{dc}} = \frac{\pi}{\sqrt{2\left[\left(1 + \frac{C_p}{C_s} - \omega^2 L_c C_p\right)^2 + \left(\frac{\omega L_r}{R_p} - \frac{1}{\omega C_s R_p}\right)^2\right]}}
\]  

(1.6)
Equations (1.5) and (1.6) show the linear relationship between the lamp voltage, $V_o$, and the DC link voltage $V_{dc}$ under the assumption that the switching frequency $\omega$ is constant.

**Advantage:**

The half-bridge resonant inverter can easily be designed to operate with zero-voltage-switching (ZVS) under fixed switching frequency and constant duty ratio. The lamp voltage is approximately proportional to the DC link voltage, so dimming control is almost linear with DC link voltage variation.

**Disadvantage:**

The ballast can easily be affected by input voltage fluctuations. The variable dc-link voltage is achieved by using the PFC stage, so there are more requirements for PFC stage design.

**b) Varying Switching Frequency**

This method is to change the lamp power by controlling the switching frequency of the inverter while keeping the duty ratio at 0.5 [13][14]. A regulated constant dc voltage is provided by the PFC stage. By increasing the switching frequency, the impedance of the resonant conductor is increased and the inductor current is reduced. Thus less power is supplied to the lamp. In addition, equation (1.6) shows that the voltage transfer function depends upon the switching frequency.

**Advantage:**

A wider dimming range can be achieved by using a simple control circuit configuration. Actually this is the most popular method for dimming control.
Disadvantage:

The variation of the switching frequency leads to an unpredictable noise spectrum that causes difficulty in the electromagnetic interface control. In addition dimming control is not linear with the frequency variations. Soft switching is not easy to achieve over the whole switching frequency range.

c) Varying Duty Cycle

In this method the duty ratio is adjusted to control the power transferred from the dc source to the lamp while keeping the switching frequency constant. This method is also called as pulse width modulation (PWM) [15][16].

The \( \text{rms} \) value of the voltage delivered to the resonant circuit is controlled by the duty ratio \( D \):

\[
V_{\text{rms}} = \frac{\sqrt{2}}{\pi} V_{\text{dc}} \sin D\pi
\]  

(1.7)

Advantage:

This is the simplest method to vary the load power. It is easier to design the line filter since the switching frequency is constant.

Disadvantage:

The maximal duty ratio is 0.5 and the minimal duty ratio is limited to keep the soft switching, so the dimming range is limited. A small duty ratio causes the resonant inductor current to be discontinuous and the soft switching may not be guaranteed. The switches suffer from severe switching stress.
**B) Phase-control Analog Dimming**

Phase-control dimming ballast is also called high-voltage control dimming ballast. It consists of the high voltage control unit (dimming unit) and the ballast unit. The high voltage control unit includes a manual wall dimmer, which is usually constructed with a Triac triggered by a Diac and an RC timing circuit. This Triac dimmer is adopted to adjust the conduction angle of the main line and the ballast controller will convert the phase information into the frequency information in driving the inverter.

![Diagram of Phase-control Dimming Electronic Ballast]

**Figure 1.6** Phase-control dimming electronic ballast

It is possible to use this phase dimming control as a power switch and control information transducer, thereby avoiding the need for additional control wires. The phase dimmer is typically added between the power supply and the electronic ballast. The basic block diagram of the phase-control dimming electronic ballast is shown in Figure 1.6.

Phase-control technology is better suitable for part of an architectural lighting scheme, such as a conference room or an office. But the phase dimmer has some problems
including high EMI due to regenerative turn on, lagging power factor, and degradation of power quality [17][18].

**C) Digital Control Dimming**

Microprocessor-based digital dimming electronic ballast is slowly emerging as a popular means for controlling complete lighting environments in many applications [19][20].

Ballasts respond to digitally encoded pulse signals instead of a variable analog control voltage. Digital control assures the reliability of the control signal and offers a high degree of control flexibility in its applications. The digital ballast usually includes an EMI filter, rectifier, power factor correction, ballast output stage, and a microprocessor controller as shown in Figure 1.7. The microprocessor-controller functions include storing the ballast address, receiving user instruction, setting the dim reference, etc.

Digital dimming systems are expensive. In Europe, they are being applied more broadly. Two systems are often used: a) Digital Addressable Lighting Interface (DALI), and b) Digital Serial Interface (DSI).

![Block diagram of digital control dimming ballast](image-url)
a) Digital Addressable Lighting Interface (DALI)

The DALI-interface is a new standard that is specified as an amendment of the standard IEC 60929. It specifies a simple digital bi-directional interface for electronic devices in lighting applications. In this protocol an address range of 64 addresses and a set of commands are defined to allow lighting installation with medium complexity.

b) Digital Serial Interface (DSI)

The DSI-interface is a manufacturer specific digital interface, which is implemented in digital controlled ballasts. In this protocol no addresses are specified, only the absolute light level is transmitted to the ballasts.

1.2.2 Discrete Dimming Control

As an alternative to the continuous dimming, the discrete dimming method provides a discrete reduction in lighting output. It is advantageous since the dimming can be performed for desired constant brightness in a simpler manner. For example, in a three-lamp fluorescent fixture, two of the lamps may be switched separately from the third, which allows the user to select three different levels of light output.

For the incandescent lamp, the three-way a lamp is perhaps the simplest discrete dimming product currently available. For non-incandescent lighting systems, there are two different ways to step-dim. The first is bi-level switching. The lamps are connected to different switching circuits and relays turn on or turn off the lamps directly. The second method is to specifically design the ballast for this purpose. Discrete dimming ballast based on occupancy sensors or other switching methods can control light level
between low power and full power. Because of the cost of the occupancy sensors, this kind of discrete dimming ballast is not very popular in the market.

In this thesis a new discrete dimming control system for fluorescent lamps is proposed. The proposed discrete dimming ballast consists of a novel dimming control circuit and an electronic ballast module. A linear universal ballast, which drives three fluorescent lamps by three complementary half-bridge inverters, is employed as the ballast module. The dimming control circuit is designed to control the on-off operation of the inverters digitally. Two pairs of momentary low voltage wall switches are employed to achieve three discrete light levels, which are one lamp, two lamps and all three lamps.

Compared with the conventional step dimming or on/off control method, the proposed discrete dimming ballast has the following advantages: (1) The on-off operation of the ballast module inverters is controlled by digital signals that are provided by the built-in dimming control circuit. This makes the control system more integrated and reliable. (2) Usually wall switches turn on or turn off the lamps through relays. The proposed dimming circuit replaces the relays, so the wall switches can control the ballast directly. This makes the overall system cost effective. (3) The proposed discrete dimming ballast can be installed by keeping the original wiring system. There is no need to change the existing wiring. This is a benefit since the existing lighting system can be easily upgraded. (4) The dimming control circuit provides good isolation, so users can operate the wall switches by hand safely.

The proposed discrete dimming ballast has been built in the laboratory. Both the simulation results and the experimental results are in good agreement.
Chapter 2 presents the operational principles of the proposed discrete dimming ballast for multiple fluorescent lamps. Analysis and design of the proposed digital discrete dimming controller are also presented.

Chapter 3 presents the mathematical results, the Pspice simulation results and the experimental results of the proposed discrete dimming ballast.

Chapter 4 summarizes the conclusions of the thesis and suggests the possibilities for future work.
CHAPTER II

DISCRETE DIMMING CONTROL BALLAST

Lighting consumes 25-30% of energy in commercial buildings, and it is a primary source of heat gain and waste. Concerned about energy and budget, many companies are actively upgrading their lighting systems. A comfortable lighting system can also improve the worker's productivity and company's profitability. In recent years, dimming controls are usually employed to align the lighting levels with human needs and to save energy.

Discrete dimming method provides discrete reductions in lighting output. For example, in a system with three lamps, one switch may operate the center lamp while another switch operates the other two outer lamps. This arrangement provides three lighting levels, one lamp, two lamps and all three lamps. As mentioned before, for the fluorescent lighting system, the bi-level switching circuit and the discrete dimming ballast are two ways to realize the discrete dimming. Discrete dimming ballast occupies an intermediate position in the array of energy saving ballast options. It offers more light control and energy savings than the non-dimming ballast, but costs less than the
continuous dimming ballast. Conventional discrete dimming ballast use occupancy sensors to control light level.

It is common to find many commercial buildings equipped with the fluorescent fixtures and the wall-switches with the wiring diagram shown in Figure 2.1. These wall switches turn on or off the lamps through the relays.

![Wiring Diagram](image)

**Figure 2.1** Wiring diagram of a conventional lighting system.

In this thesis a new concept for the discrete dimming control system is proposed. Based on one electronic ballast module, a discrete dimming ballast is developed to provide higher performance and efficiency while keeping the original lighting fixtures. Figure 2.2 shows the wiring diagram of the proposed discrete dimming ballast.

Unlike the conventional discrete dimming ballast or on/off control method, the proposed dimming ballast consists of a ballast module for multiple lamps and a discrete dimming control circuit. The discrete dimming control circuit is built in the ballast module to control the on-off operation of the inverters digitally. The dimming control circuit communicates with the wall switches directly without the need to use relays. Compared with the relays, the cost of the proposed dimming control circuit is much
lower. The dimming control circuit also provides good isolation. The proposed discrete dimming ballast is installed by keeping the original wiring system. No new wires are required, thus the installment cost is lower. This would be the most efficient way to upgrade the lighting system.

![Wiring diagram of the discrete dimming ballast](image)

**Figure 2.2** Wiring diagram of the discrete dimming ballast

2.1 Electronic Linear Ballast Module

The GE non-dimming universal electronic linear ballast UltraMAX-F32T8 is used as a ballast module. This electronic ballast module has three complementary self-oscillating half-bridge inverters connected in parallel to drive three fluorescent lamps at the same time. It is mainly composed by the following stages: the EMI stage, the rectifier stage, the high power-factor-correction (PFC) stage [24], and three complementary half-bridge inverters that drive the three lamps respectively. Figure 2.3 shows the block diagram of the linear ballast module.
In the proposed discrete dimming control ballast, a new digital dimming control circuit, which realizes the on or off operation of the lamps, is built in the ballast module board. Its block diagram is shown in Figure 2.4.

**Figure 2.3** Block diagram of the linear ballast module

**Figure 2.4** Block diagram of the proposed ballast with dimming function
The discrete dimming controller provides two digital signals to control the on-off operation of the three inverters. One signal controls lamp#2. Another signal controls lamp#1 and lamp#3. Thus, three lighting levels can be achieved in a fluorescent fixture.

As shown in Figure 2.3, the ballast module inverter stage consists of three identical complementary self-oscillating half-bridge inverters connected in parallel. The schematic diagram of one inverter circuit is shown in Figure 2.5.

![Figure 2.5 Schematic diagram of one ballast module - inverter stage.](image)

The two switches $Q_1$ and $Q_2$ are complementary to each other in the case, for instance, that switch $Q_1$ may be an n-channel enhancement mode device and switch $Q_2$ may be a p-channel enhancement mode device. These are known as MOSFET switches. It can be seen that the source nodes of $Q_1$ and $Q_2$ are connected together at a common node $A_2$ and
the gates of $Q_1$ and $Q_2$ are connected together at a common node $A_I$. The voltage between nodes $A_I$ and $A_2$ controls the conduction states of these two switches.

The gate drive circuit includes a driving inductor $L_D$ that is coupled with to resonant inductor $L_R$, a gate inductor $L_G$ that adjusts the phase angle of the gate-to-source voltage, and a blocking capacitor $C_B$. $L_D$ provides the driving energy for the gate drive circuit. Two zener diodes clamp positive and negative excursions of the gate to source voltage. Capacitor $C_D$ is used to limit the rate of the change of the gate to source voltage (between $A_I$ and $A_2$). It also provides a dead time interval in the switching mode of switches $Q_1$ and $Q_2$. The gate drive circuit is coupled to resistors $R_1$ and $R_2$. $R_1$ is preferably at a high value (greater than 1Mohm) to ensure that the dimming control circuit draws a minimal amount of current when the load is not drawing the current [21][22].

During the starting process, serially connected inductors $L_D$ and $L_G$ act essentially as a short circuit since the capacitor $C_B$ with its equivalent resistance have a long time constant. The START point clamps to around 200V, thus the voltage on node $A_I$ is around 200V. The voltage on node $A_2$ is equal to the bus voltage, which is higher than 200V.

In this manner, the blocking capacitor $C_B$ is initially charged from left to right via resistors $R_1$ and $R_2$. When the blocking capacitor voltage reaches the threshold voltage of the gate-to-source voltage of the lower switch $Q_2$, this switch starts conducting which results in the load current (resonant) flow. This resonant current causes regenerative control of the two switches $Q_1$ and $Q_2$. Then the inverter starts working in the steady state.

During the steady state operation, the voltage of node $A_I$ and $A_2$ are equal, so that $C_B$ cannot be charged again to create another starting pulse.
2.2 Electronic Ballast ON/OFF Operation

The on-off operation of the lamps is realized by the on-off operation of the half-bridge inverters. Normally the analog signals are used to operate the half-bridge inverters. However, digital signal control makes the circuit integrated and more efficient. Electromagnetic relay switches can be used, but they are bulky due to their large size, and they are generally slow. Although solid-state relays are another choice, they are however expensive. Furthermore, the power dissipation occurs when the relay is on, and thus the efficiency of the circuit is decreased.

The proposed discrete dimming control circuit uses a shutdown circuit, which connects to the half-bridge inverter to operate it, and a digital control circuit, which connects to the shutdown circuit to provide a digital signal to operate the shutdown switch. The basic diagram is shown in Figure 2.6. This circuit has a number of advantages. It is more efficient and less expensive than the conventional circuits that utilize the relays.

The proposed discrete dimming control circuit is connected between the common node $A_I$ and the reference ground. The shutdown circuit includes a current limiting resistor $R_s$, a blocking diode and a shutdown switch $Q_3$. The current limiting resistor protects against over current through the shutdown switch and the blocking diode is employed to prevent reverse current through the shutdown switch.

The shutdown switch is preferably an n-channel MOSFET switch and it is controlled by a digital signal from the digital control circuit. When a digital signal is applied to the shutdown switch $Q_3$ at a high potential, $Q_3$ is turned on. This creates a low impedance conduction path between the common node $A_I$ and the reference ground. This results in
the gate voltages of the switches $Q_1$ and $Q_2$ both clamping at the lower potential. Thus the switches $Q_1$ and $Q_2$ are turned off, and the lamp is shutdown. When the digital single applied to $Q_3$ goes to a low potential, $Q_3$ is turned off and the inverter will operate under the normal condition.

![Schematic diagram of one inverter stage with dimming control](image)

**Figure 2.6** Schematic diagram of one inverter stage with dimming control

2.3 **Digital Controller Strategy**

A digital controller is designed to provide the signals to control the shutdown circuits to operate the on or off of the half-bridge inverters. The electronic ballast has three inverters, so three shutdown circuits are used to control three inverters. Shutdown circuit 1 controls lamp#1, shutdown circuit 2 controls lamp#2 and shutdown circuit 3 controls lamp#3. Since three lighting levels are required, it needs two digital signals for these
three shutdown circuits. One signal controls the shutdown circuit 2 and another signal controls both the shutdown circuit 1 and the shutdown circuit 3.

The proposed digital controller is composed of a high frequency rectangular waveform generator, two pairs of momentary switches, charge-pump circuits, and a dual flip-flop chip. The schematic of the digital dimming controller is shown in Figure 2.7.

The signal generator produces a high frequency rectangular voltage. Four low voltage momentary switches are used to obtain three lighting levels. Once the momentary switch is pressed, the high frequency rectangular voltage will apply to the charge-pump circuit. Then high-level output voltage will be achieved. This high level voltage will set or reset the flip-flop chip. The output signal of flip-flop chip is used to control the switch of the shutdown circuit.

According to the logic control of the dual flip-flop chip, switch SW1 is used to turn off lamp#2, the center lamp, and SW2 can turn it on. For the outer two lamps, lamp#1 and lamp#3, a generated digital signal will control the shutdown circuits 1 and the shutdown circuit 3. Thus switch SW3 will turn off the outer two lamps and SW4 will turn on the outer two lamps at the same time.

The timing diagram of the proposed controller is shown in Figure 2.8.

### 2.4 Rectangular Waveform Generator

The 555 timer is a highly stable controller capable of producing accurate timing pulses. It is used as a rectangular waveform generator in the project.
Figure 2.7 Proposed schematic of a digital dimming controller
Figure 2.8 Timing diagram of proposed digital dimming controller
Usually with the astable operation, two external resistors and one capacitor are needed to control the frequency and duty cycle. In the proposed circuit, 50% duty cycle is required. So only one external resistor and one capacitor are used. This makes the circuit simpler and cost effective.

In astable operation, the trigger terminal and the threshold terminal are connected. When the threshold voltage reaches \( \frac{2}{3}V_{cc} \), the timer output becomes low. When the threshold voltage falls below \( \frac{1}{3}V_{cc} \), the timer output becomes high.

By KVL,

\[
R_1C_1 \frac{dV_{c1}}{dt} + V_{c1} = V_{out}
\]  \hspace{1cm} (2.1)

\[
V_{c1(0^-)} = \frac{V_{cc}}{3}
\]  \hspace{1cm} (2.2)

\[
V_{out} = V_{cc}
\]  \hspace{1cm} (2.3)

From equation (2.1)

\[
\frac{dV_{c1}}{dt} = \frac{V_{out} - V_{c1}}{R_1C_1}
\]

\[-\ln(V_{out} - V_{c1}) = \frac{t}{R_1C_1} + k\]
When \( t = 0 \), according to equations (2.2) and (2.3), we get

\[
k = -\ln\left(\frac{V_{cc} - V_{ce}}{3}\right)
\]

\[
= -\ln\left(\frac{2}{3} V_{ce}\right)
\]

then

\[
V_{cl}(t) = V_{cc} \left(1 - \frac{2}{3} e^{-\frac{t}{R_1C_1}}\right)
\]

(2.4)

If instead the initial condition is \( V_{cl(0^+)} = \frac{2}{3} V_{cc} \), \( V_{out} = 0 \), then

\[
V_{cl}(t) = V_{cc} \frac{2}{3} e^{-\frac{t}{R_1C_1}}
\]

(2.5)

A rectangular waveform has the duty ratio of 0.5 and a duty cycle of \( T \).

From equation (2.4), at \( t = DT \), \( V_{cl(DT)} = V_{cl(0^+)} = \frac{2}{3} V_{cc} \)

\[
V_{cl(DT)} = V_{cc} \left(1 - \frac{2}{3} e^{-\frac{DT}{R_1C_1}}\right)
\]

\[
\frac{2}{3} V_{cc} = V_{cc} \left(1 - \frac{2}{3} e^{-\frac{T}{2R_1C_1}}\right)
\]

\[
R_1C_1 = \frac{2}{\ln\left(\frac{1}{2}\right)} = 0.7213T
\]

(2.6)
This shows that in astable operation, the frequency or the duty cycle of the output waveform can be accurately controlled with the external resistor $R_I$ and capacitor $C_I$.

### 2.5 Charge-pump Circuit

A charge-pump circuit is designed to guarantee the isolation of the system, so that the user can operate the low-voltage wall switch safely. Instead of inductors, two capacitors are used to realize the isolation. This makes the discrete dimming control circuit more cost efficient [23].

The topology of the charge-pump circuit is shown in Figure 2.9. The output voltage $V_o$ will be used to set or reset the flip-flop chip and to drive the MOSFET.

![Figure 2.9 Topology of the charge-pump circuit](image)

When switch $SW$ is on, the pulse voltage source will charge the capacitors and the equivalent circuit is shown in Figure 2.10.
Figure 2.10 Charge-pump equivalent circuit

A small resistor $R_i$ is added to model the switch of the diode and the voltage source, and $C_0 = C_1 + C_2$

Laplace transform is applied to analyze the transient response of this circuit. The Laplace transformed equivalent circuit is shown in Figure 2.11.

Figure 2.11 Charge-pump Laplace transformed equivalent circuit

Because the voltage source is a pulse voltage source, the circuit has two operating modes:
**Mode I: the pulse voltage source at low level**

$D_1$ is off and $D_2$ conducts. The equivalent circuit is shown in Figure 2.12.

![Laplace transformed equivalent circuit in Mode I](image)

**Figure 2.12** Laplace transformed equivalent circuit in Mode I

By using the KCL

$$C_3 \frac{dv_{o1}}{dt} = \frac{v_{o1}}{R_2}$$

For initial condition, when $t = 0$, $v_{o1}(0^-) = v_{o1}(0^+) = v_{o2}$

The following solution is obtained and given by

$$v_{o1} = v_{o2} \cdot e^{-\frac{t}{R_2C_3}} \quad (2.7)$$

**Mode II: the pulse voltage source at high level**

Diode $D_1$ conducts and $D_2$ is off. The equivalent circuit is shown in Figure 2.13.
At the transition from Mode I to Mode II, $C_0$ is charged to a potential $V_{c0}$ and $C_3$ is charged to the potential $V_{c3}$, where,

$$V_{c0}(0) = \frac{V_{g1}(s)}{s}, \quad V_{c3}(0) = \frac{V_{o1}(s)}{s}$$

By KCL, we have

$$I(s) = \frac{V_{o2}(s)}{R_2} + \frac{V_{o2}(s) - V_{o1}(s)}{s} \frac{1}{sC_3}$$

By KVL,

$$\frac{V_{g2}(s)}{s} - (R_1 + \frac{1}{sC_0})I(s) + \frac{V_{c0}}{s} - V_{o2}(s) = 0$$

Upon substitution,
By assuming that $R_1$ approaches zero, 

$$
\lim_{R_1 \to 0} V_{o2}(s) = \lim_{R_1 \to 0} \left[ \frac{C_0 R_2 (V_{g1}(s) + V_{g2}(s)) + (sC_0 C_3 R_1 R_2 + C_3 R_2) V_{o1}(s)}{s^2 C_0 C_3 R_1 R_2 + sC_0 R_1 + sC_0 R_2 + sC_3 R_2} \right]
$$

(2.11)

The following equation is obtained and given by,

$$
V_{o2}(s) = \frac{V_{o1}(s) \cdot C_3 + \left( V_{g1}(s) + V_{g2}(s) \right) \cdot C_0}{1 + s \cdot R_2 \cdot (C_0 + C_3)} \cdot R_2
$$

(2.12)

Since $V_g(s) = V_{g1}(s) + V_{g2}(s)$, above equation can be written as,

$$
V_{o2}(s) = \frac{\left( V_{o1}(s) \cdot C_3 + V_g(s) \cdot C_0 \right) \cdot R_2}{1 + s \cdot R_2 \cdot (C_0 + C_3)}
$$

(2.13)

By using inverse Laplace transform, the following equation is obtained,

$$
v_{o2}(t) = \left( \frac{V_{o1}(s) \cdot C_3 + V_g(s) \cdot C_0}{C_0 + C_3} \right) e^{-\frac{t}{R_2(C_0 + C_3)}}
$$

(2.14)

$v_g$ is a high frequency rectangular voltage source, with duty cycle $T$ and duty ratio is $D$. Let $k$ be the $k^{th}$ cycle. The time interval within the cycle is $0 \leq t \leq T$, and the same
time interval applies to the next cycle \( k+1 \). This definition is also explained by Figure 2.14.

\[
\begin{align*}
\text{Figure 2.14} & \quad \text{Time sequence diagram of the charge-pump output voltage} \\
\end{align*}
\]

From equation (2.7), by continuously, the voltage at the end of cycle \( k \) is related to the voltage at the beginning of the next cycle by

\[
v_{o1}(0, k + 1) = v_{o2}(T, k) \cdot e^{-\frac{T}{R_2C_3}}
\]  
(2.15)

From equation (2.14)

\[
v_{o2}(T, k) = \frac{v_{o1}(DT, k) \cdot C_3 + v_g \cdot C_0}{C_0 + C_3} \cdot e^{-\frac{T(1-D)}{R_2(C_0+C_3)}}
\]  
(2.16)

Then

\[
v_{o1}(DT, k + 1) = v_{o2}(T, k) \cdot e^{-\frac{DT}{R_2C_3}}
\]  
\[
= \left( \frac{v_{o1}(DT, k) \cdot C_3 + v_g \cdot C_0}{C_0 + C_3} \right) \cdot e^{-\frac{T(1-D)}{R_2(C_0+C_3)}} \cdot \frac{DT}{R_2C_3}
\]  
\]  
(2.17)

Assuming the voltage is constant in each cycle, then \( v_{o1}(DT, k) \) can be expressed as \( v_{o1}(k) \). Let \( \tau_1 = R_2C_3, \tau_2 = R_2(C_0 + C_3) \), equation (2.17) can be written as
\[ v_{ol}(k+1) = \left( v_{ol}(k) \cdot \frac{C_3}{C_0 + C_3} + v_g \cdot \frac{C_0}{C_0 + C_3} \right) \cdot e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)} \]  

(2.18)

Let \( v_{ol} = v_{oc} + v_{op} \), where \( v_{oc} \) is the homogeneous solution and \( v_{op} \) is the particular solution

\[ v_{op} = \xi \cdot \left( \frac{C_3}{C_0 + C_3} \right)^k \cdot e^{-kT \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)} \]  

(2.19)

where \( \xi \) is a constant of proportionality.

\[ v_{oc} = \left( v_{oc} \cdot \frac{C_3}{C_0 + C_3} + v_g \cdot \frac{C_0}{C_0 + C_3} \right) \cdot e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)} \]  

(2.20)

By solving the above equation (2.20),

\[ v_{oc} = v_g \cdot C_0 \cdot \frac{e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)}}{C_0 + C_3 - C_3 \cdot e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)}} \]  

(2.21)

When \( k = 1 \), \( v_{ol}(t) = v_{ol}(DT) \) (initial condition). \( \xi \) can be obtained by using equations (2.18), (2.19) and (2.21)

\[ \xi = v_{ol}(DT) \cdot \frac{(C_0 + C_3)}{C_3} \cdot e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)} - v_g \cdot \frac{C_0(C_0 + C_3)}{C_3(C_0 + C_3 - C_3 \cdot e^{-T \left( \frac{D + 1-D}{\tau_1 + \tau_2} \right)}} \]
Finally the output voltage of the charge–pump circuit

\[
    v_{o1}(k) = \left( \frac{C_3}{C_0 + C_3} \right)^{k-1} \cdot \left[ v_{o1}(DT) \cdot e^{-\frac{(k-1)T}{\tau_1}} \left( \frac{D + \frac{1-D}{\tau_2}}{\tau_1} \right) - v_g \cdot C_0 \cdot e^{-\frac{kT}{\tau_1}} \left( \frac{D + \frac{1-D}{\tau_2}}{\tau_1} \right) \right] + v_g \cdot C_0 \cdot e^{-\frac{T}{\tau_1}} \left( \frac{D + \frac{1-D}{\tau_2}}{\tau_1} \right) \left( \frac{C_0 + C_3 - C_3 \cdot e^{-\frac{T}{\tau_1}} \left( \frac{D + \frac{1-D}{\tau_2}}{\tau_1} \right)}{C_0 + C_3 - C_3 \cdot e^{-\frac{T}{\tau_1}} \left( \frac{D + \frac{1-D}{\tau_2}}{\tau_1} \right)} \right)
\]

(2.22)
Chapter III

Experimental, Simulation and Mathematical Results

3.1 Introduction

In this chapter, the mathematical, simulation, and experimental results of the proposed discrete dimming control ballast are presented. The GE non-dimming linear universal ballast UltraMAX-F32T8 is used as a ballast module. The discrete dimming controller is built to control the ballast module. The power supply is 120V, 50Hz. Three 32W T8 lamps are controlled to obtain three discrete lighting levels.

3.2 Discrete Dimming Controller

As discussed in Chapter 2, the discrete dimming controller is composed of a rectangular generator stage, charge-pump stage, flip-flop stage and shutdown circuit
stage. The LMC 555CN Timer is used as a rectangular generator and the CD4013B is used for the flip-flop stage.

Consider the rectangular signal generator, which is shown in Figure 2.7, with the following parameters:

\[ R_1 = 68 \, K\Omega \]
\[ C_1 = 100 \, pF \]

According to equation (2.6), the duty cycle of the generated rectangular waveform is,

\[ T = \frac{R_1 C_1}{0.7213} = \left( \frac{68 \cdot 10^3}{0.7213} \right) \left( \frac{100 \cdot 10^{-12}}{0.7213} \right) \approx 9.43 \, \mu s \]

\[ f = \frac{1}{T} = \frac{1}{9.43 \times 10^{-6}} \approx 106 \, KHz \]

Figure 3.1 shows the experimental result of the rectangular generator output voltage.

![Figure 3.1 Experimental result of the rectangular waveform](image-url)
Consider the charge-pump circuit, which is shown in Figure 2.10, with the following parameters:

\[ R_i = 2.4 \, \text{M}\Omega \]

\[ C_0 = 50 \, \text{pF} \]

\[ C_3 = 0.1 \, \text{\mu F} \]

The voltage of the source \( V_g \) is equal to 15V with a duty cycle of \( T = 10\mu s \) and a duty ratio of \( D = 0.5 \)

According to equation (2.22), a MathCAD program has been used to plot the output waveform, which is shown in Figure 3.2. The output voltage is about 11.996 volts at the steady state and the setting time is about 200ms.

Figure 3.3 shows the PSPICE simulation result of the charge-pump circuit. The output voltage is 11.729 volts at the steady state and the setting time is about 100ms.

Figure 3.4 shows the experimental result of the charge-pump circuit. The output voltage is 10.16 volts at the steady state and the setting time is about 110ms.

It can be seen that the steady state output voltages of all three results are in agreement, although there are small errors. About the setting time, the PSPICE simulation result agrees with the experimental results. But the setting time of the MathCAD result is longer. This is because that we did not consider the diode conduct voltage in the calculation. And the capacitors and voltage source are assumed to be ideal in the MathCAD calculation.

When the output voltage of the charge-pump circuit is high enough, it will provide a set or reset signal to the dual flip-flop IC to change the \( \bar{Q} \) status.
Figure 3.2 Charge-pump output voltage waveform (MathCAD result)
Figure 3.3 Charge-pump output voltage waveform (simulation results).
Figure 3.4 Charge-pump output voltage waveform (experimental result).
3.3 Simulation Results for Proposed Discrete Dimming Ballast

The PSPICE model of the proposed discrete dimming ballast is shown in Figure 3.5. It consists of two sections. One is the discrete dimming controller unit and another is the half-bridge inverter stage of the linear ballast module. Only one lamp is employed in the simulation to show the realization of the ON and OFF operation. The three lamps system will be presented later. In PSPICE simulation, the lamp is modeled as a pure resistor. During the preheating and ignition, it appears as a large resistor of about 100 KΩ. In the steady state, the resistance of the fluorescent lamp is around 800 Ω.

In the PSPICE model, the lamp is started. The ignition time is about 2.5ms. After 0.5ms, the switch U4 is closed. The turn-off signal is generated to set the common node at low potential. After 11.5ms, the lamp is turned off. At 15 ms, the switch U5 is closed. The turn-off signal is replaced by the turn-on signal and the lamp is restarted again at 23 ms.

Figure 3.6 shows simulation result of the lamp voltage. It matches the design very well. First, the lamp is ignited with a high voltage and then it works in the steady state. At about 14.5 ms, it turns off completely, so the voltage is zero. At 23 ms, the lamp is restarted.

Figure 3.7 shows the lamp voltage and current waveforms in the steady state. The lamp current on the graph is enlarged (multiplied) by 200.
Figure 3.5 The PSPICE model of the discrete dimming ballast
Figure 3.6 Lamp voltage under discrete dimming control (simulation results).
Figure 3.7 Lamp voltage and current in the steady state (simulation results).
3.4 Experimental Results for Proposed Discrete Dimming Ballast

Discrete dimming control circuit has been built in the lab and used with the GE UltraMAX-F32T8 non-dimming linear universal ballast module. Its schematic has been shown in Figure 2.7. The proposed discrete dimming ballast has been tested in the laboratory and compared with the simulation results.

Figure 3.8 shows the lamp voltage waveform when the discrete dimming ballast starts normally. First the lamp is ignited at a high voltage, about 600V. Then it works in the steady state. The amplitude of the voltage is about 200V.

Figure 3.9 shows the lamp voltage and current during the steady state operation.

When the OFF switch SW1 is pressed by hand, the charge-pump circuit resets the flip-flop and causes it to provide a high level signal to the shutdown circuit. Then inverter #2 is shutdown and the center lamp #2 is turned off.

Figure 3.10 shows the lamp voltage, control signal and charge-pump output. Ch1 is the voltage waveform of lamp #2, Ch2 is the digital output signal of discrete dimming controller and Ch4 is the output voltage of the charge-pump circuit. As it has been shown, when the output voltage of the charge-pump circuit increases from zero to a certain value, it will trigger the flip-flop chip to generate a high level signal, 15V. This digital signal turns on the transistor of the shut down circuit to turn off the inverter, and then the lamp gets turned off.

When ON switch SW2 is pressed, the charge-pump circuit sets the flip-flop and makes it provide a low level to the shutdown circuit to turn on inverter #2. The center lamp #2 is turned on again.
Figure 3.11 also shows the center lamp #2 voltage, the output signal of the discrete dimming controller and output signal of the charge-pump circuit. The output voltage that is generated by the charge-pump circuit triggers the flip-flop chip to generate a low level signal. The signal turns off the transistor of the shut down circuit to operate the inverter and turn on the lamp.

During the same operation, OFF switch SW3 turns off the lamp. The difference is that the output of the flip-flop controls inverter #1 and inverter #3 together. So lamp #1 and lamp #3 are turned off at the same time. Figure 3.12 shows the lamp #1 voltage, the lamp #2 voltage, and the output voltage of the charge-pump circuit.

Switch SW4, turns on lamp #1 and lamp #2 simultaneously. Figure 3.13 shows the lamp #1 voltage, the lamp #2 voltage, and the output voltage of the charge-pump circuit IV.
Figure 3.8 Lamp voltage of the discrete dimming ballast (experimental results)
**Figure 3.9** Lamp voltage and current of the discrete dimming ballast (experimental results)
Figure 3.10 Lamp #2 voltage when OFF signal is generated (experimental results)
Figure 3.11 Lamp #2 voltage when ON signal is generated (experimental results)
Figure 3.12 Lamp #1 and lamp #3 voltage when OFF signal is generated (experimental results).
Figure 3.13 Lamp #1 and lamp #3 voltage when ON signal is generated (experimental results)
CHAPTER IV

CONCLUSION

This thesis presents the analysis and design of a novel discrete dimming control ballast for linear fluorescent lamps. Three discrete lighting levels, full light, 66% light and 33% light are obtained by using the proposed dimming ballast to control three fluorescent lamps. The proposed discrete dimming control circuit is built in the electronic ballast module and provides digital signals to realize the on/off operation of the inverters. Compared with the conventional step dimming or on/off control methods, the proposed dimming ballast has the following advantages:

(1) Digital control makes the system more reliable and integrated.

(2) The proposed discrete dimming system replaces the expensive relays, which are used in conventional lamp on/off control. This makes the overall system cost effective. The cost estimation for the discrete dimming circuit can be seen in APPENDIX A.

(3) The proposed discrete dimming ballast can be installed by keeping the original wiring system. This makes the upgrading of the lighting system more effective and efficient.
(4) The proposed dimming control circuit also provides a good isolation for operating
the low voltage wall switches by hand safely.

The proposed discrete dimming ballast has been built and tested in the laboratory. The experimental results are in excellent agreement with the results obtained from the mathematic model and PSPICE simulation.

Discrete dimming systems provide discrete reductions in light output at a lower cost than continuous dimming systems. In addition, this method can also be applied for other lamps, especially for HID fixtures. Therefore, the proposed discrete dimming concept might have a wider application.

The disadvantage of the proposed discrete dimming control system is that the lamps are turned on or off to realize the dimming. This increases the cycling of the lamp, so the lamp life might be shorter.

The charge-pump circuit provides the isolation for the proposed discrete dimming system. Now this system is used to drive three lamps. Furthermore, when we increase the number of the lamps, the isolation needs to be tested. And it also needs to explore how to choose the suitable charge-pump capacitors to guarantee the system isolation according to the number of lamps.
BIBLIOGRAPHY


APPENDIX A

Cost estimation for the proposed discrete dimming control circuit:

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<th>Component</th>
<th>Description</th>
<th>Value</th>
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<th>Cost</th>
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<td>0.01uF, X7R, 50v, 10%</td>
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Total cost $1.057