

METHODS AND APPARATUS FOR CONTROLLING
THE INTENSITY OF A FLUORESCENT LAMP

5 Background Of The Invention

This invention relates to methods and apparatus for controlling the intensity of a fluorescent lamp. More particularly, this invention relates to methods and apparatus for providing control
10 signals for a fluorescent lamp drive circuit to control the intensity of a fluorescent lamp. This invention also relates to fluorescent lamp circuits that include lamp intensity control circuitry, fluorescent lamp drive circuitry and a fluorescent lamp.

15 Fluorescent lamps increasingly are being used to provide efficient and broad-area visible light. For example, fluorescent lamps are used to back-light or side-light liquid crystal displays used in portable computer displays and flat panel liquid crystal
20 displays. Fluorescent lamps also have been used to illuminate automobile dashboards and may be used with battery-driven, emergency-exit lighting systems.

Fluorescent lamps are useful in these and other low-voltage applications because they are more
25 efficient, and emit light over a broader area, than incandescent lamps. Particularly in applications



requiring long battery life, such as portable computers, the increased efficiency of fluorescent lamps translates into extended battery life, reduced battery weight, or both.

5 Liquid crystal computer displays typically are illuminated using a fluorescent lamp, such as a cold cathode fluorescent lamp (CCFL) that requires a high voltage, low current power source, and requires a much higher voltage to start than it does to maintain
10 illumination. To insure a long lifetime, the lamp must not be operated above a maximum or below a minimum current. If a CCFL is operated at high current, the lamp becomes stressed and the lamp lifetime reduces. If a CCFL is operated at low current, the gaseous
15 components inside the lamp will not fully ionize, and the lamp will slowly poison itself. In addition, at low currents, the lamp illumination tends to become uneven. Indeed, at low currents, the lamp may experience a so-called "thermometer effect," in which
20 one end of the lamp is dark.

Previously known fluorescent lamp drive circuits typically provide a continuous drive signal to illuminate a CCFL. To vary the intensity of a CCFL, the magnitude of the continuous drive current may be
25 varied. Thus, to adjust the brightness of a liquid crystal computer display that includes a CCFL, the magnitude of the continuous drive current may be reduced to dim the display, or increased to brighten the display. Because of the lamp's narrow operating
30 current range, however, a display that uses a CCFL has a narrow dimming range.

One previously known alternative to this continuous technique uses pulse width modulation (PWM) to extend the dimming range of a fluorescent lamp.

That is, rather than varying the magnitude of a continuous drive signal to the lamp, the drive circuitry provides a drive signal that switches the lamp ON and OFF from maximum current to zero current at a fixed frequency. To control the lamp intensity, the drive circuit varies the duty cycle of the drive signal. Thus, a 100% duty cycle provides maximum bulb brightness, whereas a lower duty cycle effectively dims the lamp. PWM techniques extend the dimming range of the lamp without problems associated with uneven illumination at the low end of the dimming range.

To prevent noticeable flicker or interaction with ambient lighting, the PWM frequency must be approximately 100 to 200 Hz. A problem with this PWM technique is that except when the drive circuit operates the lamp at maximum brightness, the drive circuit always switches the lamp ON at maximum current and OFF at zero current at a 100 to 200 Hz rate. Constantly switching the lamp from OFF to ON requires that the drive circuitry repeatedly supply the high voltage necessary to start the lamp, which stresses the lamp and drive circuitry, and limits lamp lifetime.

In view of the foregoing, it would therefore be desirable to provide methods and apparatus for controlling the intensity of a fluorescent lamp without reducing the lamp's lifetime.

It further would be desirable to provide methods and apparatus that combine the advantages of the continuous and PWM techniques for controlling lamp intensity.

Summary Of The Invention

It is an object of this invention to provide methods and apparatus for controlling the intensity of

a fluorescent lamp without reducing the lamp's lifetime.

It further is an object of this invention to provide methods and apparatus that combine the advantages of the continuous and PWM techniques for controlling lamp intensity.

These and other objects are accomplished in accordance with the principles of the present invention by providing control signals for a fluorescent lamp drive circuit. The control signals may be used to cause a fluorescent lamp drive circuit to provide a continuous drive signal over a first (high) range of lamp intensity, and a PWM drive signal over a second (low) range of lamp intensity, with a smooth transition between continuous and PWM drive that is unnoticeable to the user.

In addition, this invention provides fluorescent lamp circuits that include lamp intensity control circuitry, fluorescent lamp drive circuitry, a fluorescent lamp and current feedback circuitry, the lamp intensity control circuitry and current feedback circuitry providing control signals that cause the fluorescent lamp drive circuit to provide a continuous drive signal over a first (high) range of lamp intensity, and a PWM drive signal over a second (low) range of lamp intensity, with a smooth transition between continuous and PWM drive that is unnoticeable to the user.

Brief Description Of The Drawings

The above and other objects and advantages of the present invention will be apparent upon consideration of the following detailed description, taken in conjunction with accompanying drawings, in

which like reference characters refer to like parts throughout, and in which:

FIG. 1 is a block diagram of an exemplary lamp intensity control circuit that provides control
5 signals in accordance with principles of the present invention;

FIG. 2 is a schematic diagram of a sawtooth waveform provided by the circuit of FIG. 1;

FIG. 3 is a current versus voltage transfer
10 characteristic of the voltage-controlled current amplifier of FIG. 1;

FIG. 4 is a current versus voltage transfer characteristic of the circuit of FIG. 1;

FIGS. 5A and 5B are pulse width modulated
15 currents of the circuit of FIG. 1;

FIG. 6 is a circuit diagram of an exemplary embodiment of a voltage-controlled current amplifier of the circuit of FIG. 1;

FIG. 7 is circuit diagram of an alternative
20 exemplary embodiment of a voltage-controlled current amplifier of the circuit of FIG. 1;

FIG. 8 is a block diagram of a lamp circuit that includes the lamp intensity control circuit of FIG. 1; and

25 FIG. 9 is a schematic diagram of an exemplary embodiment of the lamp circuit of FIG. 8.

Detailed Description Of The Invention

This detailed description is organized as follows. First, an illustrative embodiment of a lamp
30 intensity control circuit is described that provides control signals in accordance with this invention. Second, a fluorescent lamp circuit is described that includes a lamp intensity control circuit, fluorescent

lamp drive circuit, fluorescent lamp and current feedback circuit in accordance with this invention.

FIG. 1 illustrates an embodiment of a lamp intensity control circuit for providing control signals of this invention. Control circuit 10 includes PWM generator 12, comparator 14, voltage-controlled current amplifier 16, switches 18 and 20, and inverter 22. As described in more detail below, control circuit 10 also may include comparator 23. Control circuit 10 receives input signals V_{PROG} , V_{PWM} , V_{MIN} , I_{EXT} and I_{RMIN} , and provides control signal I_C whose value is a function of V_{PROG} . Control circuit 10 also may receive input signal V_T and may provide control signal $VOFF$ whose value also is a function of V_{PROG} . V_{PROG} , V_{PWM} , I_{EXT} , I_{RMIN} and V_T are direct current (DC) signals. As described in more detail below, as a user adjusts the magnitude of V_{PROG} , I_C varies to control the intensity of a fluorescent lamp.

PWM generator 12 has a first terminal coupled to V_{PWM} and a second terminal coupled to V_{MIN} . As shown in FIG. 2, PWM generator 12 provides sawtooth output VPO that varies between V_{MIN} and V_{PWM} . Alternatively, VPO may have a triangular waveform that varies between V_{MIN} and V_{PWM} . VPO operates at a frequency f_{saw} that is sufficiently high that a controlled lamp has little noticeable flicker, but sufficiently low to permit a lamp drive circuit to settle when the drive circuit operates in PWM mode. Frequency f_{saw} preferably is between 100 to 200 Hz.

Referring again to FIG. 1, comparator 14 has a non-inverting input coupled to VPO, an inverting input coupled to V_{PROG} , and an output VCOU. Inverter 22 has an input coupled to VCOU and provides

output $\overline{\text{VCOUT}}$, which equals the complement of VCOUT. If V_{PROG} is greater than V_{PO} , VCOUT is LOW and $\overline{\text{VCOUT}}$ is HIGH. If V_{PROG} is less than V_{PO} , VCOUT is HIGH and $\overline{\text{VCOUT}}$ is LOW. VCOUT is coupled to switch 20, and
 5 $\overline{\text{VCOUT}}$ is coupled to switch 18.

Voltage-controlled current amplifier 16 has input terminals coupled to I_{EXT} , V_{PROG} and V_{PWM} , and provides output current I_1 that varies as a function of V_{PROG} , as shown in FIG. 3. In particular, if V_{PROG} is
 10 greater than or equal to V_{MAX} , I_1 equals I_{RMAX} (region 24 in FIG. 3). If V_{PROG} is less than V_{MAX} and greater than or equal to V_{PWM} , I_1 varies linearly with V_{PROG} between a maximum value of I_{RMAX} and a clamp value I_{CLAMP} (region 26 in FIG. 3). In this region of operation, I_1 equals:

$$15 \quad I_1 = \left(\frac{I_{\text{RMAX}}}{V_{\text{MAX}} - V_{\text{MIN}}} \right) \times (V_{\text{PROG}} - V_{\text{MIN}}) \quad (1)$$

When $V_{\text{PROG}} = V_{\text{PWM}}$, $I_1 = I_{\text{CLAMP}}$. From equation (1), I_{CLAMP} equals:

$$I_{\text{CLAMP}} = \left(\frac{I_{\text{RMAX}}}{V_{\text{MAX}} - V_{\text{MIN}}} \right) \times (V_{\text{PWM}} - V_{\text{MIN}}) \quad (2)$$

Finally, if V_{PROG} is less than V_{PWM} , I_1 equals I_{CLAMP}
 20 (region 28 in FIG. 3).

Referring again to FIG. 1, signals VCOUT and $\overline{\text{VCOUT}}$, control switches 20 and 18 to switch currents I_1 and I_{RMIN} to provide control signal I_c . Each of switches 18 and 20 may be any commonly used switch,
 25 such as a bipolar junction transistor (BJT), complementary metal oxide semiconductor (CMOS) transistor, or other suitable switch. As shown in FIG. 1, switch 18 is a BJT having a collector coupled to I_1 , a base coupled to $\overline{\text{VCOUT}}$, and an emitter coupled

to I_C . Switch 20 is a BJT having a collector coupled to I_{RMIN} , a base coupled to V_{COUT} , and an emitter coupled to I_C .

Control circuit 10 operates as follows. I_{RMAX} and I_{RMIN} set the maximum and minimum lamp current values, respectively, and V_{MIN} sets a lower limit for brightness adjustment. V_{PWM} may be selected in the range $V_{MIN} \leq V_{PWM} \leq V_{MAX}$ to set clamp level I_{CLAMP} , as shown in equation (2), above.

As shown in FIG. 4, as a user adjusts the magnitude of V_{PROG} , I_C varies to set a desired lamp intensity. If V_{PROG} is greater than or equal to V_{MAX} , V_{PROG} is greater than V_{PWM} and V_{PO} , I_1 equals I_{RMAX} , V_{COUT} is LOW, V_{COUT} is HIGH, transistor 18 is ON, transistor 20 is OFF, and I_C equals the emitter current of transistor 18, which substantially equals I_{RMAX} (region 30 in FIG. 4).

If V_{PROG} is less than V_{MAX} but greater than or equal to V_{PWM} , V_{PROG} is greater than V_{PO} , I_1 has a value that varies linearly with V_{PROG} between a maximum value of I_{RMAX} and a minimum value I_{CLAMP} , V_{COUT} is LOW, V_{COUT} is HIGH, transistor 18 is ON, transistor 20 is OFF, and I_C equals the emitter current of transistor 18, which substantially equals I_1 (region 32 in FIG. 4). In this region of operation, control current I_C equals:

$$I_C = \left(\frac{I_{RMAX}}{V_{MAX} - V_{MIN}} \right) \times (V_{PROG} - V_{MIN}) \quad (3)$$

If $V_{PROG} = V_{PWM}$, $I_C = I_{CLAMP}$.

If V_{PROG} is less or equal to V_{PWM} but greater than or equal to V_{MIN} , V_{COUT} and V_{COUT} are complementary PWM signals having a clock frequency of f_{saw} (and a

period $T_{sav} = 1/f_{sav}$), transistors 20 and 18 switch ON and OFF as controlled by VCOUT and $\overline{VCOUT}$, and I_C is a PWM signal that switches between a maximum value of I_{CLAMP} and a minimum value of I_{RMIN} , and has an average value shown as dashed region 34 in FIG. 4. That is, I_C is a PWM signal that varies from 100% ON at $V_{PROG} = V_{PWM}$ to 100% OFF at $V_{PROG} = V_{MIN}$, and has an average value $\overline{I_C}$ shown by the dashed line in region 34. Average value $\overline{I_C}$ equals:

$$\overline{I_C} = \left(\frac{I_{CLAMP} - I_{RMIN}}{V_{PWM} - V_{MIN}} \right) \times (V_{PROG} - V_{MIN}) + I_{RMIN} \quad (4)$$

If $V_{PROG} = V_{PWM}$, $(V_{PROG} - V_{MIN})$ equals $(V_{PWM} - V_{MIN})$, and $\overline{I_C} = I_{CLAMP}$. Thus, as V_{PROG} is reduced from just above V_{PWM} to just below V_{PWM} , I_C smoothly transitions from region 32 to region 34 in FIG. 4.

FIG. 5 illustrates I_C versus time for several values of V_{PROG} for $V_{MIN} \leq V_{PROG} < V_{PWM}$. As shown in FIG. 5A, if $V_{PROG} = V_{MIN} + (0.7) \times (V_{PWM} - V_{MIN})$, from equation (4), $\overline{I_C} = (0.7) \times I_{CLAMP} + (0.3) \times I_{RMIN}$. As shown in FIG. 5B, if $V_{PROG} = V_{MIN} + (0.1) \times (V_{PWM} - V_{MIN})$, from equation (4), $\overline{I_C} = (0.1) \times I_{CLAMP} + (0.9) \times I_{RMIN}$.

In PWM mode (region 34 in FIG. 4), control current I_C may be used to modulate the current of a fluorescent lamp between a maximum value of I_{CLAMP} and a minimum value of I_{RMIN} . Because the lamp is not switched from fully OFF to fully ON, the lamp intensity may be controlled without overstressing the lamp.

Referring again to FIG. 1, if V_{PROG} is less than V_{MIN} , VCOUT is HIGH, $\overline{VCOUT}$ is LOW, transistor 18 is OFF, transistor 20 is ON, and I_C equals the emitter

current of transistor 20, which substantially equals I_{MIN} (region 36 in FIG. 4).

Control circuit 10 also may include circuitry to provide a control signal that may be used to reduce lamp current to zero whenever V_{PROG} is below a predetermined value. For example, control circuit 10 may include comparator 23, which has an inverting input coupled to V_T , a non-inverting input coupled to V_{PROG} , and an open-collector output $VOFF$. V_T is a threshold voltage chosen to set a value at which the lamp current should be reduced to zero, and typically is less than V_{MIN} . If V_{PROG} is greater than V_T , the output of the comparator is an open circuit. If V_{PROG} is less than V_T , the output of the comparator is LOW. Alternatively, comparator 23 may be a conventional comparator having inputs coupled to V_{PROG} and V_T and providing an output signal that may be used to cause fluorescent lamp drive circuitry to shut OFF current to the fluorescent lamp whenever V_{PROG} is reduced below V_T .

Referring to FIG. 6, an illustrative embodiment of voltage-controlled current amplifier 16 is described. Amplifier 16 includes first and second differential gain stages and a current-mirror output stage comprised of NPN transistors 40, 42, 48, 50, 60, 62, 64, 66, 72, 78 and 80, PNP transistors 44 and 46, resistors 52, 54, 88 and 92, and current sources 56, 58, 68, 70, 74 and 76.

The first differential amplifier includes transistors 40, 42, 44, 46, 48 and 50, resistors 52 and 54, and current sources 56 and 58. The first differential amplifier has a first input at a base of transistor 48, a second input at a base of transistor 50, external current source I_{EXT} coupled to

emitters of transistors 40 and 42, and an output at a base of transistor 44. In this exemplary embodiment, I_{EXT} conducts current I_{RMAX} . Diode-connected transistors 44 and 46 and emitter degeneration resistors 52 and 54 serve as loads. Current sources 56 and 58 each conduct current I_{B1} , whose value is chosen to keep emitter-follower transistors 48 and 50 biased ON.

The second differential amplifier includes transistors 60, 62, 64, 66, 72, 78 and 80, resistor 92, and current sources 68, 70, 74 and 76. The second differential amplifier has a first input V_{BIAS} coupled to a base of transistor 72, a second input V_{PROG} coupled to a base of transistor 78, a third input V_{PWM} coupled to a base of transistor 80, a first output at a collector of transistor 64 coupled to the first input of the first differential amplifier, and a second output at a collector of transistor 66 coupled to the second input of the first differential amplifier.

The output stage includes transistor 90 and resistor 88, and has an input at a base of transistor 90 coupled to the output of the first differential amplifier, and an output at terminal I_1 . Transistor 90 and transistor 44 form a current mirror, and emitter degeneration resistors 52, 54 and 88 each have a value R_1 chosen to reduce the effect of any base-emitter voltage (V_{BE}) mismatch between transistors 44, 46 and 90.

Resistor 92 has a value R_2 , current sources 74 and 76 conduct current I_{B1} , and current sources 68 and 70 conduct current I_{B2} . V_{BIAS} is a voltage source having a value of approximately $(V_{MAX} - V_{MIN})/2$ (FIG. 4). Resistance R_2 and bias current

I_{B2} have values selected so that the second differential amplifier has a linear range of operation that extends from approximately V_{MIN} to V_{MAX} (FIG. 4).

Amplifier 16 operates as follows. V_{MAX} has a value approximately equal to $(V_{BIAS} + R_2 \times I_{B2})$. If V_{PROG} is greater than V_{MAX} , transistors 64 and 80 are OFF, transistors 78 and 66 are ON, transistor 42 is OFF, transistors 40 and 48 are ON, and transistors 40 and 44 conduct current I_0 substantially equal to current $I_{EXT} = I_{RMAX}$. Transistors 44 and 90 have substantially the same base-emitter area, and resistors 52 and 88 have substantially the same resistance R_1 . The base-emitter voltage of transistor 44 substantially equals the base-emitter voltage of transistor 90, and therefore, I_1 substantially equals I_{RMAX} . This corresponds to region 24 in FIG. 3.

As V_{PROG} is reduced below V_{MAX} , the voltages at the emitters of transistors 66 and 78 reduce, transistor 80 remains OFF, transistor 64 begins to conduct, and the second differential amplifier enters its linear range of operation. As a result, transistor 42 begins to conduct, and steers a portion of I_{EXT} away from transistors 40 and 44. As a result, I_0 and I_1 reduce linearly with V_{PROG} . This corresponds to region 26 in FIG. 3.

As V_{PROG} is further reduced, the voltage at the base of transistor 78 approaches V_{PWM} and transistors 78 and 80 both conduct current. I_0 and I_1 continue to reduce with reductions in V_{PROG} , until V_{PROG} is slightly less than V_{PWM} . At that point, transistor 78 is OFF, and any further reductions in V_{PROG} produce no further reductions in I_0 or I_1 . V_{PWM}

thus sets clamp level I_{CLAMP} for amplifier 16. This corresponds to region 28 in FIG. 3.

In this embodiment, resistor 88 and transistor 90 are ratioed to resistor 52 and transistor 44 so that $I_1 = I_0$. By modifying the ratios, I_1 may be made substantially equal to a multiple of I_{RMAX} .

FIG. 7 shows an alternative embodiment of a voltage-controlled current amplifier in accordance with this invention that consumes less power than amplifier 16, and provides a more accurate output current at maximum current levels. In particular, amplifier 16' is similar to amplifier 16, but resistor 88' and transistor 90' are ratioed so that $I_1 = 5 \times I_0$. That is, transistor 90' has a base-emitter junction area five times the size of the base-emitter junction area of transistors 44 and 46, and resistor 88' has a resistance R_3 that is one-fifth the size of resistance R_1 (i.e., $R_3 = R_1/5$). Further, to provide a maximum current $I_1 = I_{RMAX}$, $I_{EXT} = I_{RMAX}/5$. Thus, the differential pair comprising transistors 40, 42, 44 and 46, and resistors 52 and 54 operate at a lower current than in amplifier 16.

Because transistor 40 operates at a lower current than in amplifier 16, the collector current of transistor 40 may not by itself be sufficient to drive the base of transistor 90'. Thus, an amplifier including resistor 82, transistor 84 and capacitor 86 is included to supply additional base drive for transistor 90'. Resistor 82 biases transistor 84 at a small current, and has a resistance R_4 that is much larger than R_1 and R_3 (e.g., $R_4 = 25 \times R_1$). Capacitor 84

has a capacitance C to compensate the base-drive amplifier.

FIG. 8 illustrates an exemplary embodiment of a fluorescent lamp circuit that includes a lamp
5 intensity control circuit in accordance with this invention. Circuit 100 includes control circuit 10, low voltage DC source 110, regulator 112, high voltage inverter 114, lamp 116, current feedback circuit 118, summing node 120, and current-to-voltage converter 122.

10 Low-voltage DC source 110 provides power for circuit 100, and may be any source of DC power. For example, in the case of a portable computer such as a lap-top or notebook computer, DC source 110 may be one or more nickel-cadmium or nickel-hydride batteries
15 providing 3-20 volts. Alternatively, if lamp circuit 100 is used with an automobile dashboard, DC source 110 may be a 12-14 volt automobile battery and power supply.

DC source 110 supplies low-voltage DC to
20 regulator 112 and may provide low-voltage DC to inverter 114. Regulator 112 may include any of a number of commercially available linear or switching regulators. As shown in FIG. 8, voltage regulator 112 includes switching regulator 124 and inductor 126.
25 Switching regulator 124 may be, for example, the LT-1072 switching regulator manufactured by Linear Technology Corporation, Milpitas, CA, or other suitable switching regulator. When implemented using the LT-1072, switching regulator 124 includes feedback
30 terminal FB adapted to receive a feedback signal by which the output of voltage regulator 112 can be controlled, and control terminal V_C , by which the switching regulator may be placed in shutdown mode.

Voltage regulator 112 provides regulated low-voltage DC output I_{dc} to inverter 114. Inverter 114 converts I_{dc} to a high-voltage, high-frequency AC output V_{AC} of sufficient magnitude to drive fluorescent lamp 116. Fluorescent lamp 116 may be any type of fluorescent lamp. For example, in the case of lighting a display in a portable computer, fluorescent lamp 116 may be a cold- or hot-cathode fluorescent lamp.

Current feedback circuit 118 generates a feedback current I_{FB} that is proportional to fluorescent lamp current I_L . Summing node 120 provides an error signal I_E proportional to the difference between control current I_C and feedback current I_{FB} . Current-to-voltage converter 122 converts error signal I_E to voltage V_{FB} , which is coupled to terminal FB of switching regulator 124. This feedback loop causes the magnitude of lamp current I_L to be proportional to the control current I_C , so that I_E is substantially zero.

FIG. 9 shows a schematic diagram of an exemplary embodiment of lamp circuit 100 of FIG. 8. Switching regulator 124 is implemented using an LT-1072 switching regulator, although any other suitable switching regulator may be used. As shown in FIG. 9, switching regulator 124 includes pin V_{IN} coupled to low voltage DC source 110, terminals E1, E2 and GND coupled to GROUND, control terminal V_C coupled to open-collector output $VOFF$ from lamp intensity control circuit 10 and coupled through capacitor 156 to GROUND, switched output pin V_{SW} coupled to inductor 126 and Schottky diode 154, and feedback pin FB coupled to terminal I_C of lamp intensity control circuit 10 and capacitor 152.

Inverter circuit 114 is a current-driven, high-voltage, push-pull inverter which converts DC power from low voltage DC source 110 to high-voltage, sinusoidal AC. Inverter circuit 114 is a self-oscillating circuit, and includes transistors 132 and 134, capacitors 136 and 138, and transformer 140. Transistors 132 and 134 conduct out of phase and switch each time transformer 140 saturates. During a complete cycle, the magnetic flux density in the core of transformer 140 varies between a saturation value in one direction and a saturation value in the opposite direction. During the cycle time when the magnetic flux density varies from negative minimum to positive maximum, one of transistors 132 and 134 is ON. During the rest of the cycle time (i.e., when the magnetic flux density varies from positive maximum to negative minimum), the other transistor is ON.

Switching of transistors 132 and 134 is initiated when the magnetic flux density in transformer 140 begins to saturate. At that time, the inductance of transformer 140 decreases rapidly toward zero, with the result that a quickly rising high collector current flows in the transistor that is ON. This current spike is picked up by transformer bias winding 140b of transformer 140. Because the base terminals of transistors 132 and 134 are coupled to bias winding 140b of transformer 140, the current spike is fed back into the base of the transistor that produced the spike. As a result, that transistor drops out of saturation and into cutoff, and the transistor is turned OFF. Accordingly, the current in transformer 140 abruptly drops, and the transformer winding voltages then reverse polarity resulting in the turning ON of the other transistor that previously had

been OFF. The switching operation is then repeated for this second transistor.

Transistors 132 and 134 alternately switch ON and OFF at a duty cycle of approximately 50 percent.

5 Capacitor 136, coupled between the collectors of transistors 132 and 134, causes what would otherwise be square-wave-like voltage oscillation at the collectors of transistors 132 and 134 to be substantially sinusoidal. Capacitor 136, therefore, operates to
10 reduce radio-frequency (RF) emissions from the circuit. The characteristics of transformer 140, capacitor 136, fluorescent lamp 116, and ballast capacitor 146 coupled to secondary winding 140d of transformer 140 primarily determine the frequency of oscillation. Capacitor 138
15 reduces the high frequency impedance so that transformer center tap 140a sees zero impedance at all frequencies.

Transformer 140 steps-up the sinusoidal voltage at the collectors of transistors 132 and 134 to
20 produce at secondary winding 140d an AC waveform of sufficiently high voltage to drive fluorescent lamp 116 (shown coupled to secondary winding 140d through ballast capacitor 146). Ballast capacitor 146 inserts a controlled impedance in series with lamp 116 to
25 minimize sensitivity of the circuit to lamp characteristics and to minimize exposure of fluorescent lamp 116 to DC components.

Inverter 114 and current-mode switching regulator circuit 124 thus operate to deliver a
30 controlled AC current at high voltage to fluorescent lamp 116. Inductor 126, coupled between V_{SW} of regulator 124 and the emitters of transistors 132 and 134, is an energy storage element for switching regulator circuit 124. Inductor 126 also sets the

magnitude of the collector currents of transistors 132 and 134 and, hence, the energy through primary winding 140c of transformer 140 that is delivered to lamp 116 via secondary winding 140d. Schottky diode 154, coupled between low voltage DC power source 110 and switched output pin V_{SW} , maintains current flow through inductor 126 during the OFF cycles of switching regulator circuit 124. Resistor 130 DC-biases the respective bases of transistors 132 and 134.

Inverter 114 may be implemented using circuitry other than that illustrated in FIG. 9. For example, inverter 114 may be implemented using ceramic step-up transformer technologies.

Current feedback circuit 118 may be implemented in integrated circuit technology, and includes diode-connected transistor 148, transistor 150 and diode-connected transistor 158. Transistor 148 has its base and collector coupled to GROUND, and has its emitter coupled to lamp 116. Transistor 150 has its collector coupled to summing node 120, its base coupled to the base of transistor 148, and its emitter coupled to lamp 116 and the emitter of transistor 148. Transistor 158 has its base and collector coupled together and to lamp 116, and its emitter coupled to GROUND.

Diode-connected transistor 148 and diode-connected transistor 158 half-wave rectify lamp current I_L . Transistor 158 shunts positive portions of each cycle of I_L to GROUND, and transistor 148 shunts a fraction of negative portions of I_L to GROUND. In particular, transistor 148 and 150 form a current mirror, with the collector of transistor 150 conducting

a fraction of the current conducted by the collector of transistor 148. As shown in FIG. 9, the base-emitter area of transistor 148 is ten times the size of the base-emitter area of transistor 150, and therefore the collector current of transistor 150 is approximately one-tenth the collector current of transistor 148. As a result, feedback current I_{FB} equals the negative portions of I_L , reduced in magnitude by approximately one-eleventh.

10 Error current I_E equals the difference between control current I_C and feedback current I_{FB} . Current-to-voltage converter 122 comprises capacitor 152, which provides voltage V_{FB} equal to the integral of error current I_E . V_{FB} therefore is
15 proportional to error current I_E , and is coupled to feedback pin FB of switching regulator 125. The above connections close the feedback control loop that regulates lamp current I_L to control the intensity of lamp 116.

20 Upon start-up of circuit 100 of FIG. 9, voltage V_{FB} on feedback pin FB generally is below the internal reference voltage of regulator circuit 124 (i.e., 1.23 volts for the LT-1072 discussed above). Thus, full duty cycle modulation at the switched output
25 pin V_{SW} of regulator circuit 124 occurs. As a result, transistors 132 and 134 and inductor 126 conduct current from center tap 140a of transformer 140. This current is conducted in switched fashion to GROUND by the action of switching regulator 124. This switching
30 action controls lamp current I_L , which is set by the magnitude of the feedback signal V_{FB} at the feedback terminal FB of switching regulator 124. The feedback loop forces switching regulator 124 to modulate the

output of inverter 114 to whatever value is required so that error current I_E is substantially zero.

The circuit of FIG. 9 may be implemented using commercially available components. For example, the circuit can be constructed and operated using the components and values set forth below:

	Component	Source or Value
	Regulator 124	LT-1072
	Inductor 126	300 μ H(COILTRONICS CTX300-4)
10	Resistor 130	1 K Ω
	Transistors 132 & 134	MPS650
	Capacitor 136	low loss 0.02 microfarad (Metalized polycarb WIMA-FKP2 (Germany) preferred)
	Capacitor 138	10 μ F
	Transformer 140	SUMIDA-6345-020 (available from SUMIDA ELECTRIC (USA) CO., LTD., of Arlington Heights, Illinois) or COILTRONICS CTX110092-1 (available from Coiltronics Incorporated, of Pompano Beach, Florida)
15	Capacitor 146	33 pF, rated up to 3 KV
	Transistor 148	10X
	Transistor 150	1X
	Schottky diode 154	1N5818
	Capacitor 156	0.1 μ F
20	Transistor 158	1X

The above circuit components and values are merely illustrative. Other circuit components and values also may be used.

Persons of ordinary skill in the art will recognize that lamp intensity control circuits of this invention may be implemented using integrated circuit technology along with other circuitry. For example, a
5 lamp intensity control circuit may be combined along with a regulator circuit, such as a current-mode switching regulator circuit, and a current feedback circuit on a single integrated circuit to provide a fluorescent lamp controller.

10 In addition, persons of ordinary skill in the art will recognize that lamp intensity control circuits and lamp circuits of the present invention can be implemented using circuit configurations other than those shown and discussed above. All such
15 modifications are within the scope of the present invention, which is limited only by the claims that follow.

I claim:

1. A method for controlling the intensity of a fluorescent lamp based on a magnitude of a first control signal, the lamp coupled to a fluorescent lamp drive circuit and conducting a lamp current, the method comprising:

providing a lamp current control signal to the drive circuit, the lamp current control signal comprising a direct current (DC) signal if the magnitude of the first control signal is greater than a first predetermined threshold, and comprising a pulse-width modulated (PWM) signal if the magnitude of the first control signal is less than the first predetermined threshold.

2. The method of claim 1, wherein the DC signal has a magnitude that varies based on the magnitude of the first control signal.

3. The method of claim 1, wherein the PWM signal comprises pulses having a duty cycle that varies based on the magnitude of the first control signal.

4. The method of claim 1, wherein the first predetermined threshold is adjustable.

5. The method of claim 1, wherein the DC signal has a magnitude that varies linearly with the magnitude of the first control signal.

6. The method of claim 1, wherein the PWM signal comprises pulses having a duty cycle that varies linearly with the magnitude of the first control signal.



7. The method of claim 1, wherein the lamp current control signal comprises a first substantially constant value if the magnitude of the first control signal is greater than a second predetermined threshold.

8. The method of claim 7, wherein the first substantially constant value comprises a maximum desired lamp current.

9. The method of claim 1, wherein the lamp current control signal comprises a second substantially constant value if the magnitude of the first control signal is less than a third predetermined threshold.

10. The method of claim 9, wherein the second substantially constant value comprises a minimum desired lamp current.

11. A method for controlling the intensity of a fluorescent lamp based on a magnitude of a first control signal, the lamp conducting a current, the method comprising:

providing a fluorescent lamp drive circuit coupled to the fluorescent lamp, the drive circuit comprising a control terminal for controlling the lamp current;

providing a lamp current control signal comprising a direct current (DC) signal if the magnitude of the first control signal is greater than a first predetermined threshold, and comprising a pulse-width modulated (PWM) signal if the magnitude of the first control signal is less than the first predetermined threshold;



providing a feedback signal proportional to the lamp current;

providing an error signal proportional to a sum of the lamp current control signal and the feedback signal; and

coupling the error signal to the control terminal.

12. The method of claim 11, wherein the DC signal has a magnitude that varies based on the magnitude of the first control signal.

13. The method of claim 11, wherein the PWM signal comprises pulses having a duty cycle that varies based on the magnitude of the first control signal

14. The method of claim 11, wherein the first predetermined threshold is adjustable.

15. The method of claim 11, wherein the DC signal has a magnitude that varies linearly with the magnitude of the first control signal.

16. The method of claim 11, wherein the PWM signal comprises pulses having a duty cycle that varies linearly with the magnitude of the first control signal.

17. The method of claim 11, wherein the lamp current control signal comprises a first substantially constant value if the magnitude of the first control signal is greater than a second predetermined threshold.



18. The method of claim 17, wherein the first substantially constant value comprises a maximum desired lamp current.

19. The method of claim 11, wherein the lamp current control signal comprises a second substantially constant value if the magnitude of the first control signal is less than a third predetermined threshold.

20. The method of claim 19, wherein the second substantially constant value comprises a minimum desired lamp current.

21. A fluorescent lamp intensity control circuit that receives a control signal at a control signal terminal, a first predetermined threshold at a first input terminal, a second predetermined threshold at a second input terminal, a first current at a first current terminal, a second current at a second current terminal, and that generates an intensity control signal at an intensity control signal terminal, the control circuit comprising:

a voltage-controlled current amplifier comprising a first terminal coupled to the control signal terminal, a second terminal coupled to the first input terminal, a third terminal coupled to the first current terminal, and an output terminal, the current amplifier generating a direct current (DC) output signal at the output terminal, wherein the DC output signal has a magnitude that (a) has a first substantially constant value that is proportional to the first current if a magnitude of the first control signal is greater than a third predetermined threshold, (b) varies linearly with the magnitude of the first



control signal if the magnitude of the first control signal is less than the third predetermined threshold and greater than the first predetermined threshold, and (c) has a second substantially constant value if the magnitude of the first control signal is less than the first predetermined threshold;

a pulse width modulator comprising a first modulator input terminal coupled to the first input terminal and a second modulator input terminal coupled to the second input terminal, and providing a sawtooth signal at an output terminal, the sawtooth signal having a peak amplitude substantially equal to the first predetermined threshold and a minimum amplitude substantially equal to the second predetermined threshold;

a first comparator comprising an inverting input coupled to the control signal terminal, a non-inverting input coupled to the output terminal of the pulse width modulator, and an output terminal;

an inverter having an input terminal coupled to the output terminal of the comparator, and an output terminal;

a first switch comprising a first terminal coupled to the output terminal of the voltage controlled current amplifier, a second terminal coupled to the output terminal of the inverter, and a third terminal coupled to the intensity control signal terminal; and

a second switch comprising a first terminal coupled to the second current terminal, a second terminal coupled to the output terminal of the comparator, and a third terminal coupled to the intensity control signal terminal.



22. The intensity control circuit of claim 21, further receiving a fourth predetermined threshold signal at a third input terminal, and further comprising a second comparator comprising input terminals coupled to the third input terminal and the control signal terminal, and providing an output at an output terminal.

23. A fluorescent lamp circuit for use with a direct current (DC) power source and a fluorescent lamp, the lamp conducting a lamp current, the circuit comprising:

a regulator circuit comprising an input terminal coupled to the DC power source, a feedback terminal, and an output terminal;

an inverter circuit comprising an input terminal coupled to the output of the regulator, and an output terminal coupled to the lamp;

a current feedback circuit comprising an input terminal coupled to the lamp, and an output terminal;

a lamp intensity control circuit that provides a lamp current control signal at a control signal terminal, the lamp current control signal comprising a direct current (DC) signal if the magnitude of the first control signal is greater than a first predetermined threshold, and comprising a pulse-width modulated (PWM) signal if the magnitude of the first control signal is less than the first predetermined threshold;

a current-to-voltage converter comprising an input terminal coupled to the control signal terminal and to the output terminal of the



current feedback circuit, and an output terminal coupled to the feedback terminal of the regulator.

