A Low-Cost High-Efficiency CCFL Inverter With New Capacitive Sensing and Control

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***Abstract*—A new low-cost and efficient cold cathode fluorescent lamp (CCFL) inverter for liquid crystal display (LCD) application is suggested in this paper. The topology of the inverter is derived from modified class E-type resonant electronic ballasts and has a dc-like input current. In addition, a new sensing circuit for lamp current and transformer voltage is proposed. A simple RC-network measures the voltage of a ballasting capacitor in series with the lamp instead of the lamp current itself while the lamp is floated. Utilizing the printed circuit board capacitors for the sensing capacitors and integrating small-valued sensing resistors into a control integrated circuit make the inverter very simple, efficient, and cost-effective. The new sensing circuit can solve many problems that arise when a terminal of the lamp is grounded to sense the lamp current. The control circuits for the prototype experiments are also described in detail. The frequency control scheme with a fixed off-time and a varying on-time was chosen to maintain the operation of zero-voltage switching in the entire dimming range and to reduce the complexity of the control circuits. The control circuits have an analog dimming function using a current control loop, a low frequency pulsewidth modulation dimming, open-lamp protection and voltage regulation, and soft-on/off functions.**

***Index Terms*—Class E, cold-cathode fluorescent lamp (CCFL), current sensing, electronic ballasts, printed circuit board (PCB) capacitance, protection, resonant inverter, voltage sensing.**

I. INTRODUCTION

AS THE digital multimedia industry flourishes, the flat panel display technology that interfaces with human beings develops in parallel. Liquid crystal display (LCD) is one of the strongest candidates in picture quality, brightness, efficiency, and size. LCDs require backlight units because the liquid crystal devices themselves do not inherently emit light.

Although some alternatives have recently been introduced, such as external electrode fluorescent lamps, white light emitting diodes, and surface light sources, a good solution for the light source of a backlight unit in terms of brightness, effectiveness, and cost is the cold cathode fluorescent lamp (CCFL). A kind of discharge tube, the CCFL has voltage-current characteristics which, aside from being severely nonlinear, depend on operating frequency, power, and temperature. Ballasts are therefore indispensable not only for providing a sufficiently high voltage to ignite the CCFL but also for regulating the operating current during normal operation [1], [2]. In principle, almost every ballast topology for general fluorescent lamps or high-intensity discharge lamps can be chosen for a CCFL driving inverter. The most prevalent topology is a current-fed push–pull resonant inverter [3]–[7]. However, resonant inverters of the half-bridge or full-bridge type have also been used recently [2], [8]–[11].

Large monitors and LCD TVs need between four to 20 CCFLs to meet the brightness requirements but one inverter can hardly drive two or more CCFLs in parallel due to the current imbalance [9]. Although inverters which drive two series-connected CCFLs have emerged in the practical field, they are accompanied with the increase of complexity and cost. In addition, in view of the challenge of other light sources, the cost of CCFL inverters must be reduced, and this reduction can be attained by reducing the number of components in the power stage and by integrating as many parts of the inverter as possible into a control integrated circuit (IC).

In CCFL inverters, detecting the lamp current is indispensable for controlling the current or luminance of the lamp to a desired level in spite of variations in the input voltage, temperature, lamp aging, and so on. In addition, some protection or voltage regulation is needed when the lamp is removed from the inverter or when the lamp's life is ended. Otherwise the secondary side of the transformer can be damaged by an excessively high resonant voltage. To measure the lamp current, a terminal connected to the lamp on the transformer's secondary side is usually grounded, and a small resistor is inserted in series with the lamp. The voltage of the resistor is fed back to the controller as information about the lamp current [2], [3], [12], [13]. However, this method also brings forth a leakage path of the lamp current through parasitic capacitances around the lamp, which mainly appears between the grounded coating metal plate over the lamp and the lead wire on the high-voltage side or the lamp body itself. The leakage current disrupts the accurate measurement of the lamp current, diminishes the inverter's effectiveness, initiates the thermometer effect at low current, and shrinks the dimming range. Furthermore, the unpredictable parasitic capacitances around the lamp cause the inverter characteristics to deviate from the design [5], [7], [8].

Since the fundamental cause of these problems is the grounding of the secondary side, researchers have proposed several indirect methods of detecting the primary side's currents while floating the secondary side [5], [7], [8]. However, these methods have not produced accurate values for the lamp current because they inherently represent the primary current instead of the lamp current. Furthermore, they need additional circuits to detect the transformer voltage, thereby making the inverter circuit more complex and inefficient.

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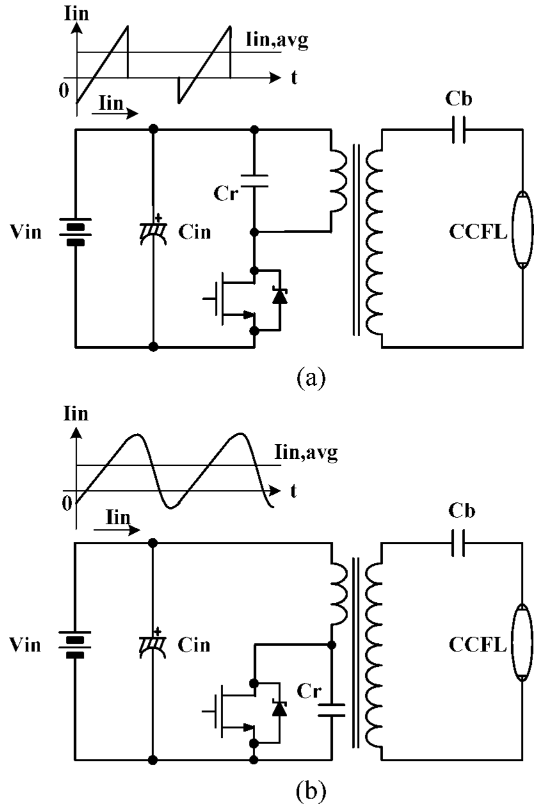


Fig. 1. Low-cost CCFL drivers derived from modified class E-type electronic ballasts.

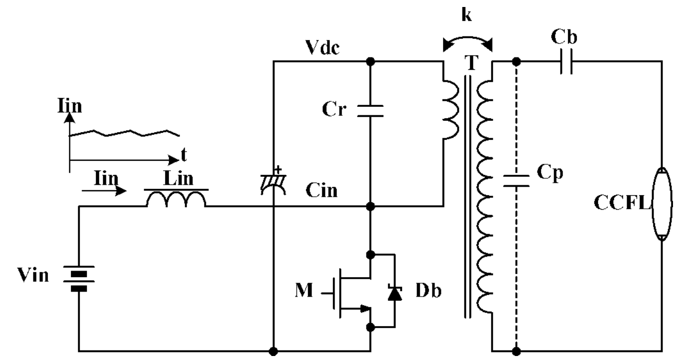


Fig. 2. Proposed low-cost CCFL inverter featuring a low input current ripple.

We therefore propose a new low-cost CCFL inverter, for which we adopted and improved the modified class E-type electronic ballast. We also propose a new simple, low-cost, and effective circuit that detects the lamp current and the transformer's voltage. The control circuits that use the proposed detecting circuit are followed. To maintain zero voltage switching in the entire dimming range, we chose a frequency control scheme with a fixed off-time and a variable on-time. Soft-on/off actions during low frequency pulsewidth modulation (PWM) dimming as well as open-lamp protection and transformer voltage regulation were implemented in the prototype.

II. Low-Cost CCFL Inverter With a Low Input Current Ripple

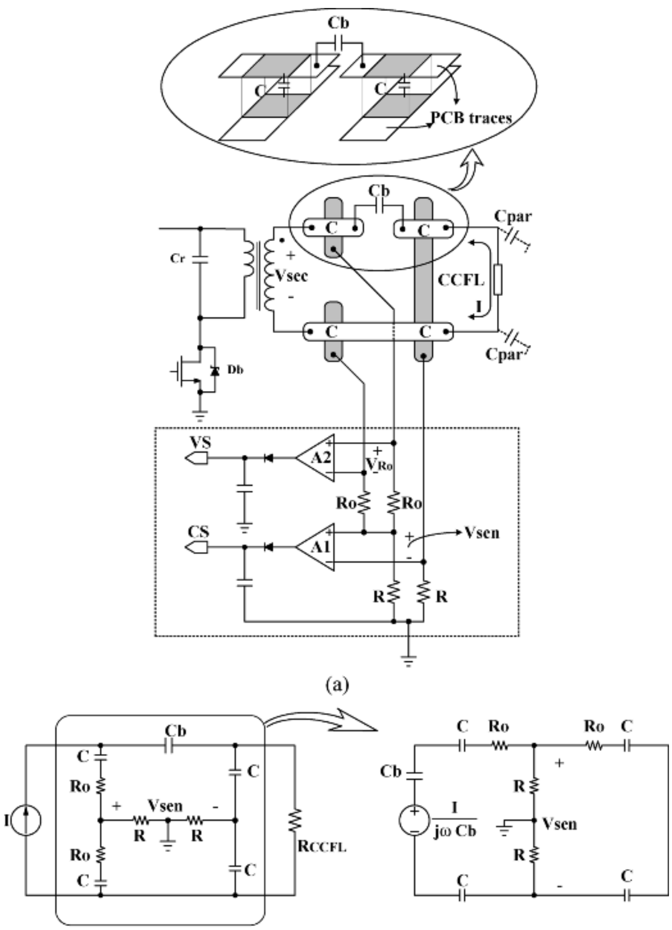
Fig. 1 shows CCFL inverters with a minimum of switches and components. The inverters are modified from the electronic ballast applied first to high intensity discharge (HID) lamps [14], [15], and they can be regarded as modified class E-type resonant inverters [1], [13]–[18]. By increasing the leakage of the transformer, we can simply use the leakage inductance of the transformer as a substitute for the input choke coil of the generic class E inverter to reduce the number of components.

Given that the operation and design procedure has been fully described in [14] and [15], we merely present an outline of the operation. When the switch is turned on, the input current flows through the primary side of the transformer and the switch. When the switch is turned off, the primary current resonates through the resonant capacitor C_r. In both the on and off cases, the energy is delivered to the load. At the secondary side, the voltage gain is obtained in the resonant network, which is composed of the equivalent inductance, the capacitance and the lamp's resistance. Because the resonant network of the secondary side has an appropriate quality factor, the lamp current resembles the sine wave. In addition, because the off time voltage of the switch is similar to the half-wave sine, the switch softly turns off. Furthermore, after the resonant current turns on the freewheeling diode, the switch turns on at zero voltage. The inverter is then implemented with high efficiency and low cost due to the soft switching operation and the minimum number of components.

Although the main drawback of the class E-type ballast is the high switch voltage, it is inconsequential when the input voltage is low. Nonetheless, the inverters in Fig. 1 have other problems. In the case of Fig. 1(a), the input current is discontinuous with much higher peak value than the average value. The inverter can therefore adversely affect the other units that comprise the display system. Fig. 1(b) shows high input reactive power, which may cause high loss. In addition, applying these inverters to the CCFL drivers causes a proprietary issue [19].

Fig. 2 shows the proposed low-cost CCFL inverter with a low input ripple current. The input current is close to a dc current with a low ripple because the input current always flows through a choke coil (L_{in}). When the switch M is on, the input current flows through the choke coil and the switch, and inverter current is delivered from C_{in}. When the switch M is off, the input current flows into C_{in} via the resonant capacitor (C_r). In a steady state, the energy fed from input voltage source via L_{in} to C_{in} equals the energy that C_{in} delivers to the resonant circuits.

In addition, because the average voltage across the input inductance and the transformer should be zero, the voltage of $C_{\text{in}}(V_{\text{dc}})$ equals the input voltage (V_{in}). Furthermore, the steady-state value of V_{dc} is always the same despite the varying load power under the dimming control. Therefore, by choosing sufficiently large value of L_{in} and C_{in}, and by assuming the voltage of $C_{\text{in}}(V_{\text{dc}})$ is a constant voltage source, the inverter in Fig. 2 can be regarded as inverters in Fig. 1 and can be analyzed and designed similarly as in [14] and [15]. The main difference between inverters in Figs. 1 or 2 and inverters in [14] or [15] is that the resonant network in the secondary side should be considered in the design. Moreover, the resonant network includes the winding capacitance C_p of the transformer.



(b)

Fig. 3. Proposed sensing circuits for the lamp current and the transformer's secondary voltage. (a) Simplified circuits and implementation of sensing capacitors. (b) Equivalent circuits of the secondary side, which explain the current sensing principle.

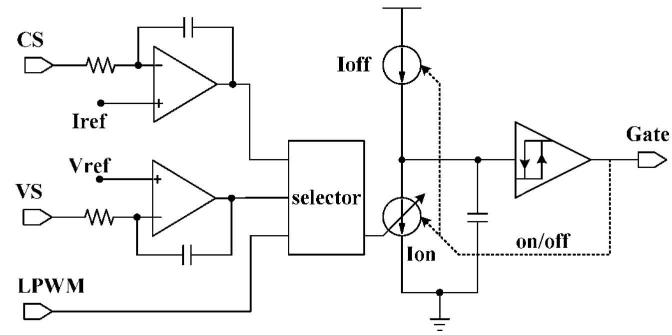


Fig. 4. Simplified block diagram of the control circuits.

III. New Current-Voltage Sensing Circuits

Fig. 3(a) shows the proposed new current-voltage sensing circuits. A simple resistor-capacitor network measures the voltage of the ballasting capacitor in series with the lamp while the lamp is floated.

The principle for detecting the lamp current is as follows: If there is no leakage of the lamp current to the ground when the lamp is floating, the lamp current is the same as the current that flows through the ballasting capacitor, C_b. The lamp current can therefore be measured from the voltage across C_b. To measure the voltage of C_b, we used four small-valued capacitors and one pair of resistors connected as shown in Fig. 3. By assuming that the current in the secondary side is sinusoidal and by referring to the equivalent circuit in Fig. 3(b), it can be shown that the voltage across the resistor pair is straightforwardly proportional to the lamp current, as in the following equation:

$$V_{sen} \cong \frac{I}{j\omega C_b} \cdot \frac{2R//\frac{2}{j\omega C}}{\left(2R//\frac{2}{j\omega C}\right) + \frac{2}{j\omega C}} \cong \frac{CR}{C_b} \cdot I \qquad (1)$$

where I, the lamp current, is almost the same as the current that flows through C_b as long as the lamp is floated. The sensing capacitors and resistors were assumed to be $C \ll C_b$ and $R \ll 1/\mathrm{j}\Omega C$, respectively. Note that this result is independent of the operating frequency and the sensed voltage is in phase with the lamp current. The voltage $V_{\rm sen}$ was amplified by a differential amplifier and fed back to the controller after the peak value was detected.

The transformer's secondary voltage, which is divided by the two capacitors C, and two R_o, can be expressed as

$$V_{R_o} \cong V_{\rm sec} \cdot j\omega C \cdot R_o \qquad (2)$$

under the assumption of $\mathrm{Ro} \ll 1/\mathrm{j}\Omega C$.

This voltage is processed in a similar way to the current sensing signal and is used to regulate the transformer's secondary voltage under a fault condition such as an open lamp.

Because the secondary side is floated, the common-mode noise can corrupt the sensed signals. We therefore processed the sensed signals with the differential amplifiers because accurate sense signals are required for precise regulation of the lamp current and the transformer's voltage.

Four sensing capacitors (C) should have a high voltage rating of several kilovolts with a small value of 1 pF $\sim$ 2 pF each. Then, by using the parasitic capacitance of the printed circuit board (PCB) traces for these capacitors, as illustrated in Fig. 3(a), we can make a very simple and cost-effective sensing circuit. Moreover, by integrating the PWM controllers, the amplifiers, and the sensing resistors into a single chip, we can drastically simplify the secondary side of the CCFL inverter so that the chip requires only three input terminals.

The sensing circuit enables us to solve the problems caused by the grounding of one side of the lamp. That is, by preventing leakage of the lamp current, we can increase the effectiveness of the inverter as well as the dimming range; and the characteristics of the inverter are not affected by the unpredictable parasitic capacitances around the lamp. In addition, we can also monitor the transformer's voltage with few additional components.

IV. Control Circuits

A. Frequency Control With a Fixed Off-Time

As stated in Section II, the switch voltage in the off-time is close to the half sine wave and the width of the waveform is almost constant as expressed in the following equations [13]–[15]:

$$T_{\rm off} \cong \pi\sqrt{C_r \cdot L_{\rm eq}} \qquad (3)$$

$$L_{\rm eq} \cong (1-k^2) \cdot L_1 \qquad (4)$$

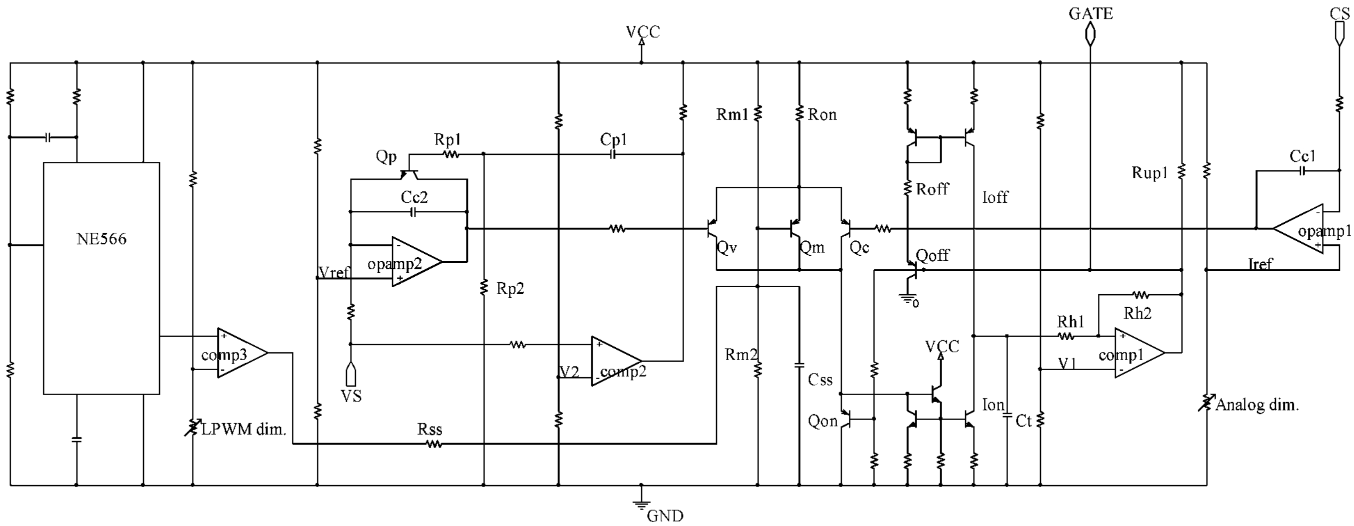


Fig. 5. Control circuits implemented with discrete components for the prototype.

where L_1 is the self-inductance of the primary side of the transformer.

To simplify the control circuit without losing the zero voltage switching operation, we fixed $T_{\rm off}$ to (3) but controlled $T_{\rm on}$ to regulate the lamp current. As a result, we put the inverter under the frequency control scheme.

As shown in Fig. 4, the gate driving signal is generated from a hysteresis comparator and current sources that charge or discharge the capacitor connected at the input of the comparator. Whereas the current source $I_{\rm off}$, which is related to the off-time, is fixed, the current source $I_{\rm on}$, which corresponds to the on-time, is controlled by the current or voltage regulation command or by the low-frequency PWM dimming signal.

Fig. 5 shows the implemented prototype control circuits. As in a preliminary stage of designing the control IC, we designed and tested these circuits using discrete components.

With R_{h1} and R_{h2}, the input hysteresis of the comparator comp1 is given by

$$V_{hys} \cong 2 \cdot V_1 \cdot \frac{R_{h2}}{R_{h1}}. \tag{5}$$

The transistors $Q_{\rm on}$ and $Q_{\rm off}$ switch the two current sources according to the output of comparator comp1. The current source $I_{\rm on}$ mirrors the current of one transistor that has the minimum base voltage among three transistors Q_m, Q_c, and Q_v, which is shown by

$$I_{\rm on} \cong \frac{V_{cc} - V_{b,\min} - V_{BE}}{R_{\rm on}} \tag{6}$$

where $V_{b,\min}$ is the minimum base voltage of the three transistors.

As $V_{b,\min}$ is lowered, the current $I_{\rm on}$ increases, the on-time decreases and, eventually, the operating frequency increases. In addition, from the frequency characteristics of the inverter, the lamp current decreases as the operating frequency increases. The base voltage of Q_m indicates the rating current—that is, the maximum current of the lamp. Moreover, the base voltage of Q_c is controlled by the control loop of the lamp current, whereas that of Q_v is controlled by the transformer's voltage control loop. Especially, by adjusting the voltage of $I_{\rm ref}$ node, lamp current or brightness is controlled; therefore the analog dimming function is achieved.

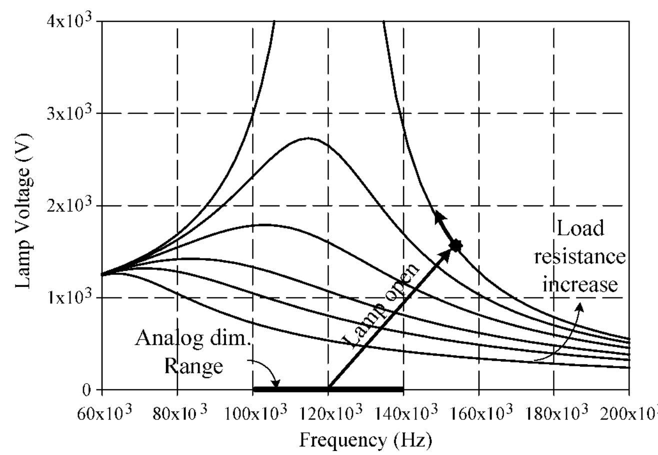


Fig. 6. Simulated frequency characteristics of the lamp's voltage.

B. Open Lamp Protection

Fig. 6 shows how the frequency characteristics of the lamp's voltage in the designed inverter vary with load resistance. These characteristics are determined by the equivalent inductance of the transformer's secondary side, C_b, C_p, and the lamp's impedance. Resonant circuit components are listed in Table I, and the equivalent load resistance are 100 kΩ, 150 kΩ, 200 kΩ, 300 kΩ, 500 kΩ, and 10 kΩ, respectively, from the bottom. As shown in the figure, if the open lamp situation occurs in the operating range—that is, in the analog dimming range, the excessive voltage would damage the transformer. Therefore, when the lamp is opened, we must protect it with a higher operating frequency because the voltage control loop is slow. The second comparator comp2, Q_p, C_{p1}, R_{p1}, and R_{p2} accomplish this function. The voltage sensing signal VS, is low during normal operation. As the transformer's voltage becomes high in the open-lamp situation, the output of comp2 surges up.

TABLE I
PARAMETERS OF COMPONENTS IN THE EXPERIMENT

Inverter Part		
Transformer	turn ratio	1:70
	primary self-inductance	100 uH
	coupling coefficient	0.7
C_r	22 nF	
C_b	22 pF	
C_p	~ 5pF	
Sensing Part		
Capacitor	value	~ 1.8 pF
	area	5 mm × 5 mm
	ε_r	4.5
R, R_o	1 kΩ	
A1 gain	10	
A2 gain	5	

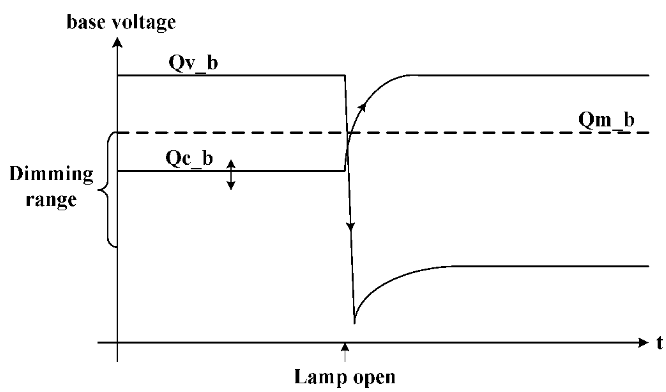


Fig. 7. Representative base voltages for lamp open.

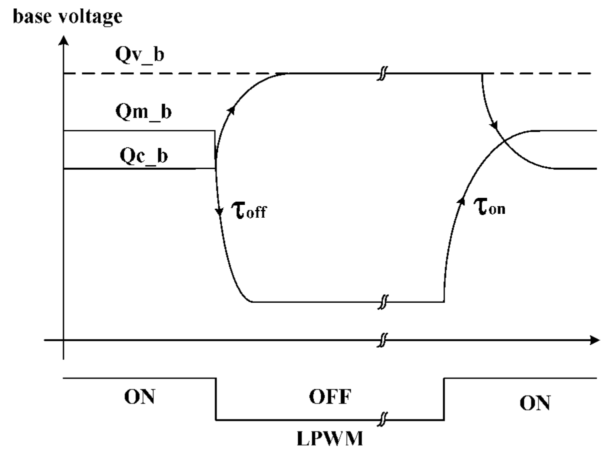


Fig. 8. Representative base voltages during the LPWM dimming.

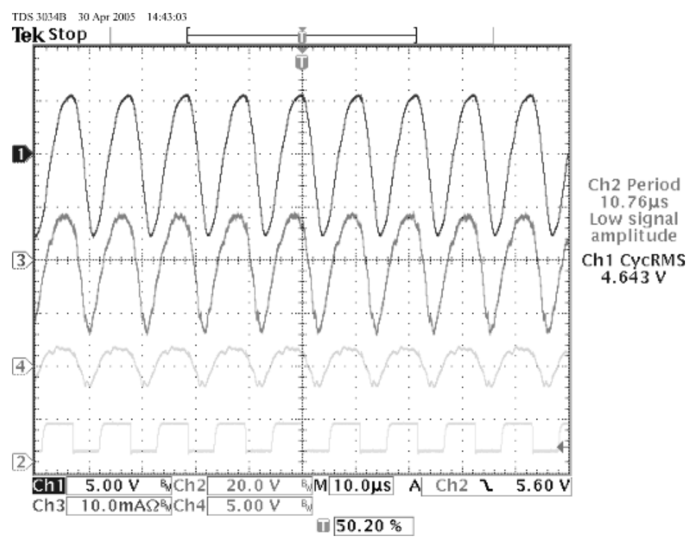


Fig. 9. Key waveforms during the rated current operation: sensed lamp current (channel 1), secondary current measured using a current probe (channel 3), sensed transformer secondary voltage (channel 4), and the gate signal of the switch (channel 2).

The output of comp2 turns on Q_p to discharge C_{c2} after being differentiated by R_{p1}, R_{p2}, and C_{p1}. The base voltage of Q_v then drops to around V_{ref}, and the operating frequency of the inverter rapidly increases. After C_{c2} is discharged, Q_p turns off via R_{p2} and the voltage control loop is reactivated. Fig. 7 shows the base voltages around the open lamp.

C. LPWM and Soft On/Off

Low-frequency PWM (LPWM) dimming is necessary to widen the dimming range in a high-performance CCFL inverter [10], [11]. We therefore applied a low-frequency dimming signal, the output of comparator comp3, to the base of Q_m. When the OFF command was given, the operating frequency shifted to a frequency that was higher than the analog dimming range shown in Fig. 6. When the ON command was given, as comp3 releases the base of Q_m, the inverter returns to the operating frequency that is determined by the analog dimming loop.

When operated with LPWM, the lamp must be turned on softly; otherwise the lamp's lifespan decreases due to excessively high periodic voltage. In Fig. 5, the time constant determined by C_{ss}, R_{ss}, R_{m1}, and R_{m2} performs this function. The base voltage of Q_m decreases with the time constant τ_{off} in (7) when the lamp turns off, and it increases with the time constant τ_{on} in (8) when the lamp turns on. Therefore, the operating frequency gradually changes. Fig. 8 shows a diagram of the base voltages during the LPWM operation

$$\tau_{\text{off}} = C_{ss} \cdot (R_{ss}//R_{m1}//R_{m2}) \quad (7)$$

$$\tau_{\text{on}} = C_{ss} \cdot (R_{m1}//R_{m2}). \quad (8)$$

V. EXPERIMENTAL RESULTS

Table I summarizes the components used in the prototype experiments. We measured several voltage-current operating points of a lamp of which length is 22 cm using the existing Royer-type inverter and modeled the lamp as a resistor according to the rating value of the voltage and current. The rating current and voltage of the lamp was 6 mA(rms) and about 520 V(rms), respectively. Then, we chose the ballasting capacitor C_b to have the reactance approximately equal to the lamp resistance. The desired input voltage was 12 V(dc), and the operating frequency was chosen to be 100 kHz. Coupling

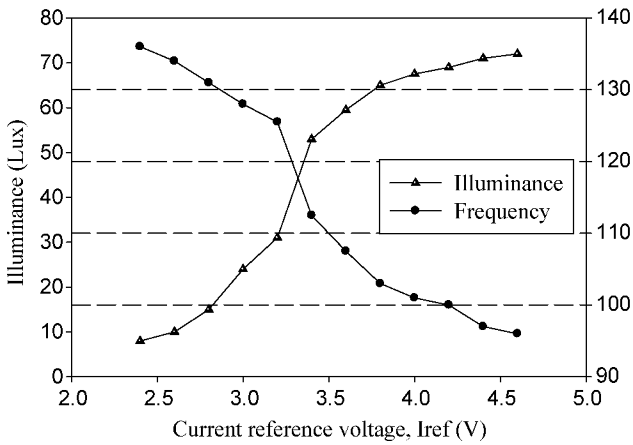


Fig. 10. Analog dimming characteristics.

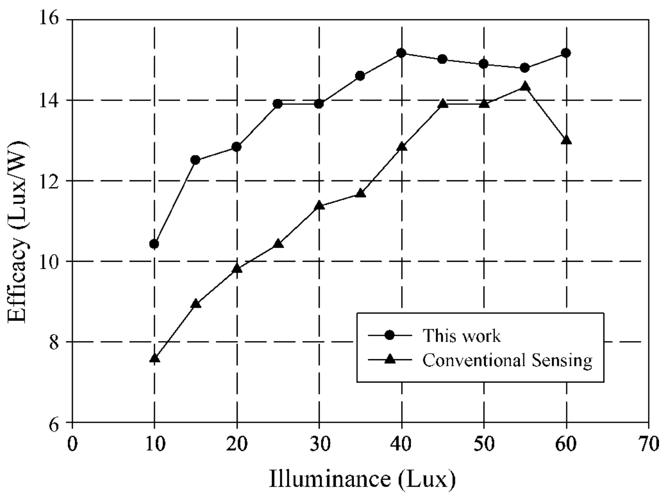


Fig. 11. Efficacy comparison.

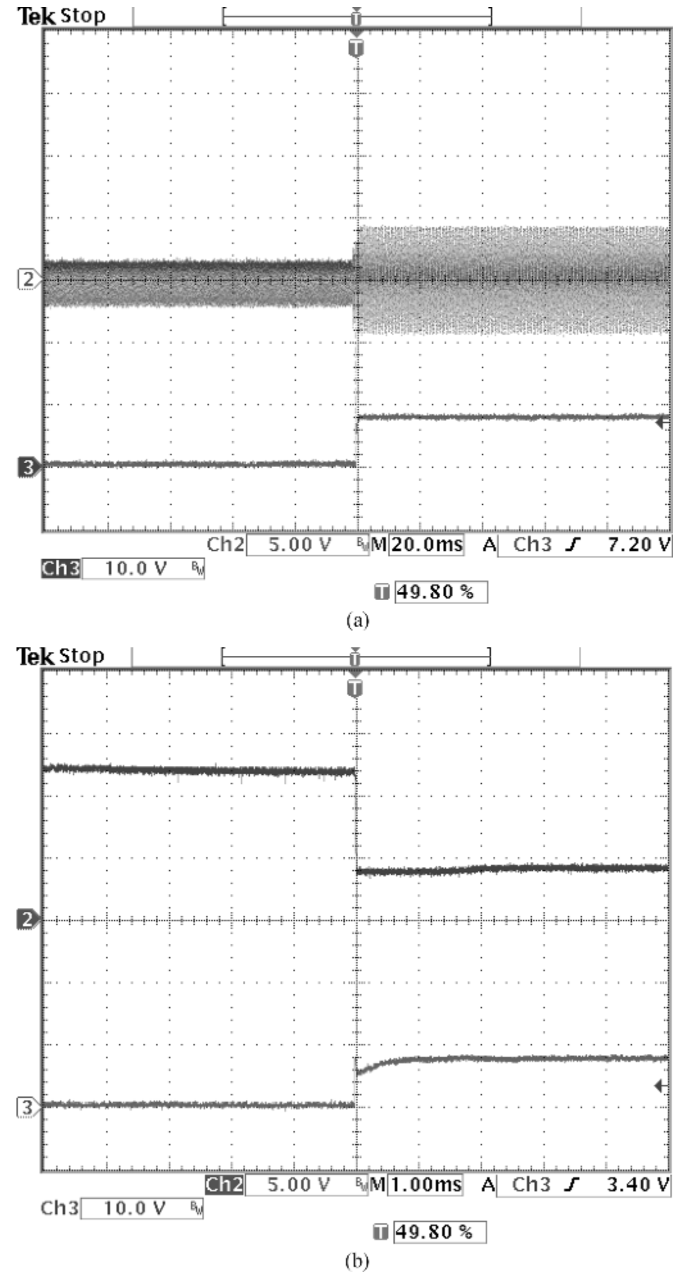


Fig. 12. Open lamp protection: (a) the sensed transformer voltage (upper) and output of comp2 (lower) and (b) the base voltage of $Q_{?}$ (upper) and the output of comp2 (lower).

coefficient of the transformer was set by adjusting the air gap. The number of turns of the secondary winding was calculated so that the resonant network at the secondary side has the resonant frequency somewhat lower than the rating frequency. Using Pspice simulation, the turn ratio can be obtained so that the secondary side of the transformer has the rating voltage at the rated operating frequency. The primary-side resonant capacitor was chosen according to (3). The small values of R and R_o and the gain of amplifiers A1 and A2 can be arbitrarily chosen so that the outputs of amplifiers have appropriate amplitudes to be handled.

Fig. 9 shows the waveforms of the lamp current and transformer's voltage that are sensed by the proposed sensing circuits during the rating operation along with the lamp current waveform measured by a current probe. The outputs of the differential amplifiers, A1 and A2 in Fig. 3 are shown as the sensed signals. Equation (1) with the actual current value measured by a current probe corresponded to the measured current sensing voltage with little error. The lamp current waveform contained a little even harmonics due to the asymmetrical driving of class-E type inverter. Since the asymmetry was not too high and the inverter generally operates at room temperature or higher [20], however, we ignored the effects of the asymmetrical waveform in this prototype experiments. A tiny phase difference between the actual current and the sensed waveform was caused by the deviation from the assumptions for (1), and can be neglected since only the amplitude of the current was used in the current regulation.

In Fig. 10, which shows the characteristics of the analog dimming control loop, we see the operating frequency of the inverter and the illuminance of the LCD panel that uses one CCFL as a backlight. The dependence of the lamp's impedance on the lamp current causes the nonlinearity of the control characteristics. As the lamp current decreases, its impedance increases and changes the resonant network at the secondary side. This nonlinear property is unavoidable in the frequency controlled CCFL inverter. However, using the current control loop for the analog dimming is still possible and useful for practical backlight units.

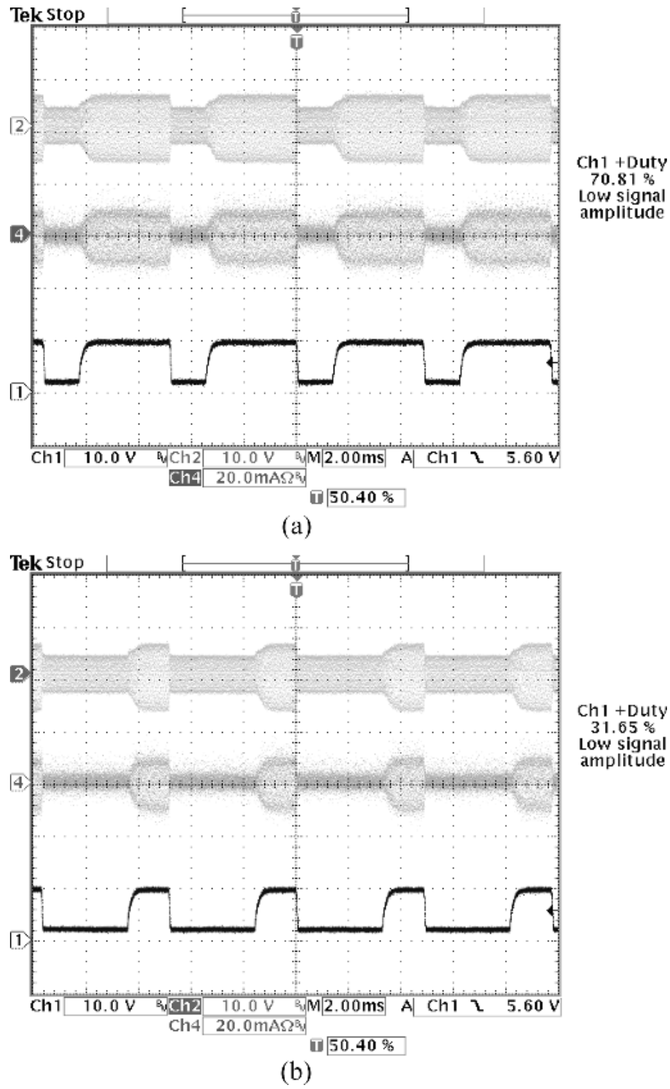


Fig. 13. LPWM dimming: the sensed lamp current (upper), lamp current measured with current probe (middle), and the base voltage of Q_m (lower): (a) duty $= 70\%$ and (b) duty $= 30\%$.

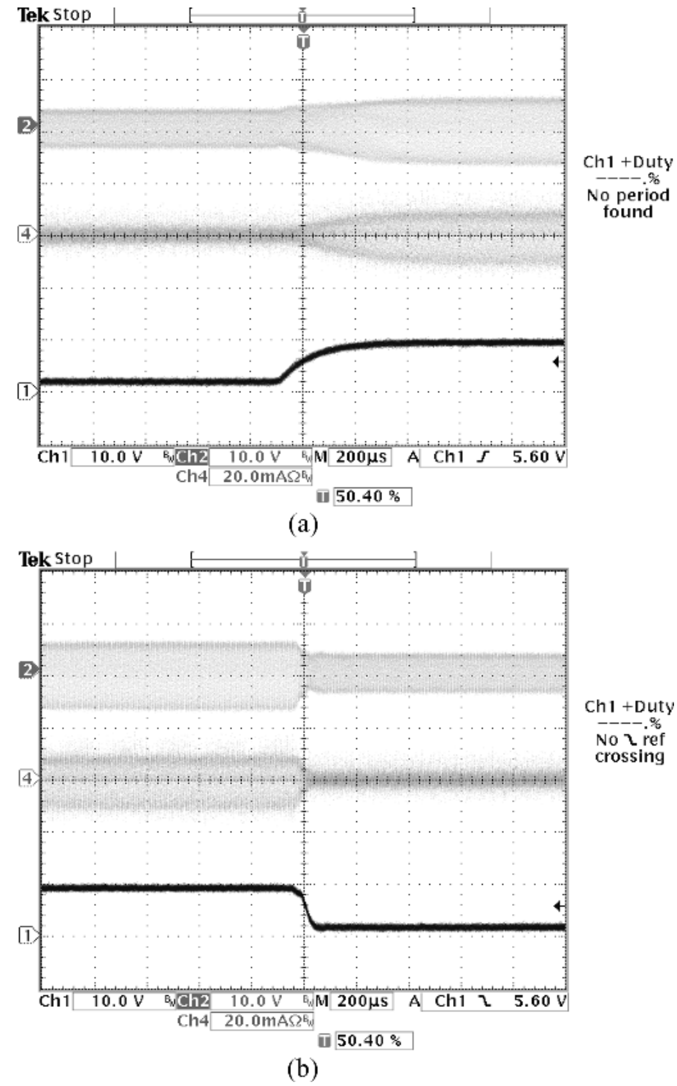


Fig. 14. Soft on/off for LPWM dimming: the sensed lamp current (upper), lamp current measured with current probe (middle), and the base voltage of Q_m (lower): (a) soft on and (b) soft off.

Furthermore, the dimming range can be widened extensively by combining the LPWM dimming with the analog dimming.

Fig. 11 shows the efficacy of the inverter of this work when the inverter uses the proposed sensing circuit and when the inverter uses the conventional sensing scheme [2], [3], [5], [8], [10]–[13]. The efficacy is defined here as the ratio of the illuminance of the lamp measured by a lux meter attached to the LCD panel and the input power. Because the secondary side is floated, the lamp current leakage is reduced and the efficacy is increased over the entire dimming range.

Fig. 12 shows the key waveforms for the open-lamp protection and voltage regulation process. Prior to the slow voltage regulation loop, a fast protection circuit which was explained in Section IV suppressed the excessive voltage spikes from the transformer.

Fig. 13 shows the waveforms that occurred during the LPWM dimming operations. When the dimming command was ON, the lamp operated with its rating current. When the dimming command was OFF, the inverter operated at about 150 kHz which is well above the analog dimming range shown in Fig. 6. At this frequency, although the lamp current and brightness were almost zero, the current sensing signal still appeared because, as explained in Section III, the sensing circuit detected the voltage of C_b. This characteristic, however, did not cause any error within the analog dimming range of Fig. 6. Note that $L_{\rm in}$ and $C_{\rm in}$ should be properly chosen not so as to cause the ringing in the current waveform at the LPWM transient region.

Fig. 14 shows the soft on/off operations for the LPWM dimming.

VI. Conclusion

We propose a new low-cost, efficient CCFL inverter for the backlight units of wide LCD monitors and TVs. By using a modified class E-type resonant inverter, we obtained the features of low cost and a low ripple input current. The new sensing circuit can accurately measure the lamp current and the transformer's voltage with the floating condition of the secondary side, thereby significantly increasing the efficacy of the lamp. As we suggested, by utilizing PCB patterns for the sensing capacitors and by integrating small-valued sensing resistors into the control IC, we can implement a very simple, efficient, and cost-effective inverter. Using the new sensing circuits, we designed the control circuits including functions such as analog dimming through the current control loop, low frequency PWM dimming, open lamp protection and voltage regulation, and soft on/off functions.

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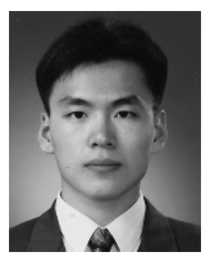

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