Uniform Current Distribution in Driving Cold Cathode Fluorescent Lamps (CCFL) in Parallel

Chang-Gyun Kim1), Kyu-Chan Lee1) and Bo H. Cho2)

1) Interpower Co., Ltd.
1578-51, Silim1-dong, Gwanak-gu
Seoul, Korea 151-869
E-mail: cgkim@e-interpower.com

2) Power Electronics System Lab.
School of Electrical Engineering
Seoul National University
Seoul, Korea, 151-742

Abstract - Cold cathode fluorescent lamps (CCFL) show complex characteristics, which make it difficult to drive them in parallel. In this paper, analysis of the lamp current distribution in parallel operation is presented in detail. The current balancing condition, under which the lamp currents are well balanced in the presence of the lamp voltage variation, is derived. The analysis results are verified from experiments with two 720mm/4mm CCFL’s for 32-inch LCD TVs. Experimental results with eight CCFL’s in parallel are also presented.

1. Introduction

Flat and thin are the current trends in the display industry. The backlight module is a crucial component for driving the light source in flat display panel (FDP) technologies, whose performance will determine the display quality of the FDP. An LCD with a cold cathode fluorescent lamp (CCFL) satisfies the demands regarding display performance, size, and efficiency. In consideration of cost, efficiency and uniformity ratio of illumination, the CCFL is still the best choice [1, 2].

In recent years, there have been increasing interests in large size LCD displays, as required in LCD TV sets and computer monitors, which require higher brightness for proper backlighting. To illuminate the LCD more brightly, the number of CCFL’s should be increased. For example, a 32-inch LCD TV uses 16 CCFL’s. Therefore, a backlight inverter is required to drive multiple CCFL’s.

A number of researches [3-13] have been reported to drive multiple CCFL’s, which can be classified into two categories. One is a series configuration of CCFL’s [3-6]. Connecting CCFL’s in series requires a transformer to deliver a multiple of the striking voltage for each lamp. This is obviously untenable because most transformers are incapable of providing such high voltages, or are prohibitively expensive [3]. Especially in large size LCD displays, the series connection is not adequate because a longer CCFL requires higher striking and sustaining voltages.

The other, which is more feasible, is a parallel configuration of CCFL’s [7-13]. There are several possible ways of configuring CCFL’s in parallel. One method is the direct parallel connection of CCFL’s as shown in Fig. 1. The inverter uses one controller, one transformer and one sensing resistor. The controller can regulate only the sum of the two lamp currents. This configuration has the well-known problem that the two CCFL currents will not be balanced due to the lamp voltage variation and the constant voltage load characteristic of the CCFL [13]. The unbalance of the lamp currents causes a reduced lifetime and non-uniformity of brightness.

Another possible configuration is the parallel connection at the transformer secondary side, as shown in Fig. 2. Each CCFL has its own ballast capacitor (C_b). In this configuration, the performance of current distribution is unsatisfactory because C_b must be impossibly small for uniform current distribution [14]. With a small C_b, the impedance of C_b can reduce the effect of the lamp voltage variation. However, the operating common node voltage (V_cmn) becomes too high to make the two lamp currents well balanced in the presence of the lamp voltage variation and the variation of the resonant components [14]. This makes the backlight inverter expensive and less efficient. With a large C_b, the impedance of C_b becomes much smaller than the CCFL impedance, which makes the effect of C_b negligible.

![Fig.1 Illustration of the direct parallel connection of CCFL’s](image-url)
Thus, one feasible method of parallel configuration is to make the parallel connection at the transformer primary side as shown in Fig. 3(a), which can minimize the effect of the lamp voltage variation on the common node voltage.

In this paper, detailed analysis is performed to derive design equations, which provide balanced current to each lamp with respect to the variations in the lamp voltage and the resonant components. The analysis results are verified from experiments with two 720mm/4mm CCFL’s for 32-inch LCD TV’s. Experimental results with eight CCFL’s in parallel are also presented.

2. Analysis of Parallel Configuration at the Transformer Primary Side

2.1 Derivation of the current balancing condition

The backlight inverter is composed of a phase-shifted full-bridge switching network, a resonant power stage, a sensing network and a controller as shown in Fig. 3(a). The sensing network is composed of two diodes and one resistor. The lamp current sensing voltage (Vsense) is a half-wave of the lamp current, multiplied by the sensing resistor, R. The controller regulates the lamp current by the phase-shifted duty cycle of the quasi-square wave, which is applied to the resonant circuit. The parallel resonant circuit is composed of L, the transformer, C and C. The blocking capacitor, C, has a relatively large capacitance and does not affect the resonance operation.

Each lamp is driven by its own transformer, parallel resonant capacitor (C), and ballast capacitor (C). The two modules have a common controller and a common sensing resistor, R.

Fig. 3(b) shows the equivalent circuit of the power stage. All of the components are transferred to the transformer secondary side. The DC input voltage and the switching devices are replaced by an ac source. The transformer is simplified as a leakage inductance (L), because the magnetizing inductance is much larger than the leakage inductance. The blocking capacitor (C) is omitted because it has a much lower impedance than the leakage inductance at the switching frequency. The capacitor (C) placed in parallel with the CCFL in the equivalent circuit represents the parasitic capacitance between the CCFL and ground.

For the purpose of analysis, the lamp voltage and current are assumed to be sinewaves at the switching frequency by the fundamental frequency approximation.

The current of the parasitic capacitance, C, is determined by the lamp voltage (VLP) and the impedance of C.

\[
i_{C} = j\omega_{C}C_{v}V_{LP}, \tag{2.1}
\]

where \(\omega_{C}\) is the switching angular frequency and \(V_{LP}\) is the lamp voltage.

The ballast capacitor current is the sum of the lamp current and the C current,

\[
i_{C} = i_{LP} + j\omega_{C}C_{u}V_{LP}, \tag{2.2}
\]

where \(i_{LP}\) is the lamp current.

Then, the ballast capacitor voltage becomes

\[
V_{CB} = \left(i_{LP} + j\omega_{C}C_{u}V_{LP}\right) \frac{1}{j\omega_{C}C_{b}}. \tag{2.3}
\]

The voltage of the parallel resonant capacitor, \(V_{CP}\) is the sum of the lamp voltage and the ballast capacitor voltage. Therefore,

\[
V_{CP} = V_{LP} \left(1 + \frac{C_{u}}{C_{b}}\right) - j\frac{i_{LP}}{\omega_{C}C_{b}}. \tag{2.4}
\]

The current of \(C_{p}\) is
\[ i_{Cp} = \frac{v_{Cp}}{Z_{Cp}} \tag{2.5} \]

where \( Z_{Cp} = \frac{1}{j \omega C_p} \).

From Eq. (2.4) and Eq. (2.5) the current of \( C_p \) becomes

\[ i_{Cp} = j \omega C_p \left( 1 + \frac{C_u}{C_b} \right) i_{lp} + \frac{C_p}{C_b} i_{Cp} \tag{2.6} \]

The current of the leakage inductance, \( i_{lk} \), is the sum of \( i_{Cp} \) and \( i_{Cb} \):

\[ i_{lk} = i_{Cp} + i_{Cb} \tag{2.7} \]

By substitution of Eq. (2.2) and Eq. (2.6) into Eq. (2.7), the leakage inductance current becomes

\[ i_{lk} = j \omega \left( C_p \left( 1 + \frac{C_u}{C_b} \right) v_{lp} + \left( 1 + \frac{C_p}{C_b} \right) i_{lp} \right) \tag{2.8} \]

The terminal voltage, \( v_T \), is the sum of \( v_{Cp} \) and the voltage across the leakage inductance.

\[ v_T = Z_{lk} i_{lk} + v_{Cp} \tag{2.9} \]

where \( Z_{lk} = j \omega L_{lk} \).

By substitution of Eq. (2.4) and Eq. (2.8) into Eq. (2.9), the terminal voltage can be obtained as

\[
v_T = v_{lp} \left( 1 + \frac{C_u}{C_b} \left( 1 - \omega^2 L_{lk} C_{total} \right) \right) + 
\]

\[
\quad j \cdot i_{lp} \cdot \omega L_{lk} \left( 1 + \frac{C_p}{C_b} \left( 1 - \frac{1}{\omega^2 L_{lk} \left( C_b + C_p \right)} \right) \right) \tag{2.10}
\]

where

\[ C_{total} = C_p + \frac{C_b C_u}{C_b + C_u} \tag{2.11} \]

The lamp voltage and current can be assumed to be in the same phase, which is reasonable because the CCFL shows pure resistive characteristics at the switching frequency [15].

If the lamp current is set as a phase reference, then

\[ i_{lp} = I_{lp} \leq 0 \quad v_{lp} = V_{lp} \leq 0 \tag{2.12} \]

From Eq. (2.10) and Eq. (2.12), the terminal voltage becomes

\[
v_T = v_{lp} \left( 1 + \frac{C_u}{C_b} \left( 1 - \omega^2 L_{lk} C_{total} \right) \right) + 
\]

\[
\quad j \cdot I_{lp} \cdot \omega L_{lk} \left( 1 + \frac{C_p}{C_b} \left( 1 - \frac{1}{\omega^2 L_{lk} \left( C_b + C_p \right)} \right) \right) \tag{2.13}
\]

From Eq. (2.13), the coefficient of \( v_{lp} \) can be reduced to zero, which eliminates the effect of the lamp voltage variation. The condition is

\[ \omega^2 = \frac{1}{L_{lk} \cdot C_{total}} \tag{2.14} \]

If the condition of Eq. (2.14) is satisfied, the coefficient of the lamp voltage \( v_{lp} \) becomes zero and the terminal voltage \( v_T \) becomes independent of the lamp voltage. That is, the difference between the two lamp voltages does not affect the current distribution. The condition of Eq. (2.14) is defined as the current balancing condition in this paper.

The effect of the current balancing condition can be explained from the terminal voltage illustrations as shown in Fig. 4. The two figures represent the current balancing condition as it is satisfied for different \( L_0 \) values. The current balancing condition has the effect of making the difference of the two terminal voltages \( (V_{T1}, V_{T2}) \) very small in the presence of a large lamp voltage difference (the two lamp voltages \( (V_{lp1}, V_{lp2}) \) have a deviation of ±7% from the typical lamp voltage).

2.2 Analysis of current distribution for two CCFL’s in parallel

In this section, the difference between the two CCFL currents is derived using the terminal voltage equation obtained in the previous section.

From Eq. (2.10), the two terminal voltages \( (v_{T1}, v_{T2}) \) can be expressed as

\[ v_{Tn} = v_{lpn} K_{Tn} + j \cdot I_{lpn} \cdot K_{In} \tag{2.15} \]

where
\[ K_{1n} = \left(1 + \frac{C_{pn}}{C_{bn}} \right) \left[1 - \omega_n^2 L_{kn} C_{\text{totaln}} \right], \]
\[ K_{2n} = \omega_n L_{kn} \left(1 + \frac{C_{pm}}{C_{bn}} \right) \left[1 - \frac{1}{\omega_n^2 L_{kn} \left( C_{bn} + C_{pm} \right)} \right]. \] 

(2.16)

\[ n = 1, 2 \]

The phases of the two lamp currents are also defined as Eq. (2.17), considering that the two lamp currents may not be in the same phase.

\[ i_{Lp1} = I_{Lp1} \angle \theta, \quad i_{Lp2} = I_{Lp2} \angle (-\theta). \] 

(2.17)

Under the assumption that the lamp voltage and current are in the same phase [15], as in Eq. (2.12), the two lamp voltages can be expressed as

\[ v_{Lp1} = V_{Lp1} \angle \theta, \quad v_{Lp2} = V_{Lp2} \angle (-\theta). \] 

(2.18)

The coefficients \( K_{1}, K_{2}, K_{11}, K_{12} \) depend on the resonant components and the switching frequency. In this stage, the variation of the resonant components is assumed to be zero, that is

\[ K_{1} = K_{2} = K_{11} = K_{12} = K_{1}. \] 

(2.19)

Using the phase relations of Eq. (2.17) and Eq. (2.18), the two terminal voltages of Eq. (2.15) becomes

\[ v_{T1} = \left( K_{1} V_{Lp1} \cos \theta - K_{1} I_{Lp1} \sin \theta \right) + j \left( K_{1} V_{Lp1} \sin \theta + K_{1} I_{Lp1} \cos \theta \right), \]
\[ v_{T2} = \left( K_{1} V_{Lp2} \cos \theta + K_{1} I_{Lp2} \sin \theta \right) + j \left( -K_{1} V_{Lp2} \sin \theta + K_{1} I_{Lp2} \cos \theta \right). \] 

(2.20)

The two terminal voltages should be equal because the two terminals are connected at the same node. By equating the two terminal voltages of Eq. (2.20),

\[ \tan \theta = \frac{V_{Lp1} - V_{Lp2}}{I_{Lp1} + I_{Lp2}} \frac{K_{1}}{K_{1}}. \] 

(2.21)

By substitution of Eq. (2.21) into Eq. (2.20),

\[ I_{Lp2} - I_{Lp1} = \frac{V_{Lp1}^2 - V_{Lp2}^2}{I_{Lp1} + I_{Lp2}} \frac{K_{1}^2}{K_{1}}. \] 

(2.22)

The difference between the two lamp currents \( (\Delta I_{Lp}) \) is defined as

\[ \Delta I_{Lp} = I_{Lp1} - I_{Lp2} = \frac{V_{Lp1}^2 - V_{Lp2}^2}{I_{ref}} \frac{K_{1}^2}{K_{1}}. \] 

(2.23)

where

\[ I_{ref} = I_{Lp1} + I_{Lp2}. \] 

(2.24)

The percent error in the current balancing is defined as

\[ \% Err = \frac{\Delta I_{Lp}}{I_{ref}} \times 100 \% \] 

(2.25)

Fig. 5 shows the percent error as a function of the parallel resonant capacitor \( C_{p} \) for two \( L_{s} \) values, with \( C_{s} \) as a running parameter. The CCFL is assumed to be a constant voltage load with ±17% deviation. The ±7% deviation represents the variation between the CCFL’s, and the ±10% deviation is added to represent the lamp voltage change according to the lamp current. In the case that the current balancing condition is satisfied, the percent error is almost zero, as shown in Fig. 5. As \( C_{p} \) deviates from the condition, the percent error becomes larger. It is better to make \( C_{s} \) larger in case the condition is not satisfied.

2.3 Experimental results of driving two CCFL’s

Table 1 summarizes the example specifications of the CCFL’s used for 32-inch LCD TVs. It is noticeable that the lamp voltage variation is ±7%, which should be considered in the inverter design.

<table>
<thead>
<tr>
<th>Length</th>
<th>Outer Diameter</th>
<th>Typ. Current (rms)</th>
<th>Typ. Voltage (rms)</th>
<th>Luminance</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>720mm</td>
<td>4mm</td>
<td>6.2mA</td>
<td>1065 ± 7% [V]</td>
<td>15700 ± 13% [cd/m²]</td>
<td>40kHz - 60kHz</td>
</tr>
</tbody>
</table>

(a) \( L_{s} = 0.4H \)

(b) \( L_{s} = 0.14H \)

![Fig. 5 The percent error as a function of the parallel resonant capacitor](image)

(The lamp voltage deviation is ±17%)
The measured sensing voltages \(v_{sense}\) of two CCFL currents for six operating points (Table 2) are presented in Fig. 6. Operating points (1a) and (1b) satisfy the current balancing condition for different \(L_a\) values. The effects of \(C_p\) (operating points (2a) and (2b)) and the effect of \(C_b\) (operating points (3a) and (3b)) are also tested when the current balancing condition is not satisfied. It is verified from the experimental waveforms of Fig. 6(a) and 6(b), that the two currents are well balanced when the current balancing condition is satisfied, as discussed in the previous section. Fig. 6(c) and 6(d) show that the current unbalance becomes severe when \(C_p\) deviates more from the balancing condition. Fig. 6(e) and 6(f) show that it is better to make \(C_b\) larger when the balancing condition is not satisfied.

<table>
<thead>
<tr>
<th>Operating points</th>
<th>(L_a)</th>
<th>(C_p)</th>
<th>(C_b)</th>
<th>(C_v)</th>
<th>(f_e)</th>
<th>Satisfactory of the condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP. 1a</td>
<td>0.4H</td>
<td>10pF</td>
<td>100pF</td>
<td>20pF</td>
<td>50kHz</td>
<td>o</td>
</tr>
<tr>
<td>OP. 1b</td>
<td>0.14H</td>
<td>50pF</td>
<td>100pF</td>
<td>20pF</td>
<td>50kHz</td>
<td>o</td>
</tr>
<tr>
<td>OP. 2a</td>
<td>0.14H</td>
<td>15pF</td>
<td>(\infty)</td>
<td>20pF</td>
<td>50kHz</td>
<td>x</td>
</tr>
<tr>
<td>OP. 2b</td>
<td>0.14H</td>
<td>15pF</td>
<td>(\infty)</td>
<td>20pF</td>
<td>50kHz</td>
<td>x</td>
</tr>
<tr>
<td>OP. 3a</td>
<td>0.14H</td>
<td>15pF</td>
<td>100pF</td>
<td>20pF</td>
<td>50kHz</td>
<td>x</td>
</tr>
<tr>
<td>OP. 3b</td>
<td>0.14H</td>
<td>15pF</td>
<td>(\infty)</td>
<td>20pF</td>
<td>50kHz</td>
<td>x</td>
</tr>
</tbody>
</table>

In order to test the worst-case lamp voltage deviation between the CCFL’s, two 150V (14% deviation from the typical lamp voltage) zener diodes are connected in series with one of the two CCFL’s as shown in Fig. 7. It is verified from the experiments, as shown in Fig. 8, that the two currents are well balanced in the presence of the 14% error of the lamp voltage, when the current balancing condition is satisfied.

Fig. 7 Series connection of 150V zener diodes with CCFL to test the lamp voltage deviation

(a) when 150V zener diodes are connected in series with CCFL

(b) when 150V zener diodes are connected in series with CCFL

Fig. 8 The experimental waveforms of \(v_{sense}\) when the current balancing condition is satisfied

\(L_a=0.22H, \ C_p=27pF, \ C_v=\text{short}, \ C_b=20pF, \ f_e=50kHz\)
3. Experimental results of driving of 8 CCFL’s

The parallel connection of 8 CCFL’s is tested and the experimental waveforms are presented in this section. The current balancing condition was derived from the terminal voltage (Eq. (2.13)). It is noticeable that the terminal voltage was derived from only each branch (composed of $L_{	ext{iks}}$, $C_p$, $C_b$ and CCFL). That is, the current balancing condition can be extended to a parallel connection of more than three CCFL’s without modification.

Figure 9 shows the sensing voltage waveforms when 8 CCFL’s are connected in parallel at the transformer primary side. The parameters satisfy the current balancing condition such that

$$1 \sqrt{L_{	ext{iks}} C_{\text{total}}} = 304[\text{krad/sec}] \approx \omega_h.$$

The currents are well balanced, although 150V zener diodes are connected in series with CCFL1 to test the effect of the lamp voltage variation. Figure 9 verifies that the lamp voltage difference does not affect the current balance when the condition is satisfied. In the test, the controller uses only the information of the sensing voltage of $I_{Lp1}$ and $I_{Lp2}$ for the current regulation. The other sensing voltages are measured only to show each lamp current.

Figure 10 shows the sensing voltage waveforms when CCFL1 has 150V zener diodes in series, along with a 10% deviation of $L_p$ and a 10% deviation of $C_{\text{total}}$. Figure 10(a) shows the case of full brightness and Fig. 10(b) shows the case of analog dimming (60% of the rated current). In both cases, the percent error of $I_{Lp1}$ is within 10% percent.

4. Conclusion

Cold cathode fluorescent lamps (CCFL) have complex characteristics, which make them difficult to drive in parallel. In this paper, the analysis of current distribution for the parallel configuration at the transformer primary side is presented in detail. Design guides are also presented for uniform current distribution. The current balancing condition, which can minimize the effect of the lamp voltage variation, is derived. The analysis results are verified from experiments with two 720mm/4mm (for 32-inch LCD TV) CCFL’s and also with eight CCFL’s in parallel. The experiments verify well balanced lamp currents in the presence of a ±7% lamp voltage variation and 10% resonant inductor and capacitor variations.

Reference


