26.1: Low-Frequency Square-Wave Drive for Large Screen LCD-TV Backlighting Systems

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Abstract
This paper presents a low-frequency square-wave drive, consisting of a single high voltage converter, an ac lamp ignition circuit, current control devices and a single backlight controller, capable of driving an arbitrary number of parallel cold cathode fluorescent lamps (CCFLs) with independent accurate lamp current regulation. Key to the architecture is a proposed capacitive coupling approach for ac lamp ignition that results in reliable, simultaneous ignition of parallel lamps with a maximum ignition voltage near the normal lamp operating voltage. A brief summary of the lamp model and behavior is presented to explain the findings during the capacitive ignition and low-frequency operation. Experimental results are presented demonstrating parallel lamp ignition and current regulation for four, 250 mm CCFLs.

1. Introduction
Large screen LCD TV backlighting systems, generally consisting of 16 or more cold cathode fluorescent lamps (CCFLs), require a ballast capable of driving all or groups of lamps in parallel with accurate current control and regulation. The most common electronic ballasts, based on high frequency LCC resonant inverters, are capable of driving at most four lamps in parallel and require complex multi-winding transformers and specialized control circuitry. This solution suffers from several disadvantages, the major limitation being the inability to simultaneously maintain high efficiency, proper lamp ignition, and individual lamp current regulation [1, 2].

We present a suitable architecture, capable of driving a large parallel CCFL array with high efficiency, accurate lamp current control and near operating voltage lamp ignition. The system block diagram, shown in Fig. 1, is based on low-frequency square-wave (LFSW) drive and removes many of the drawbacks associated with a high frequency drive, including energy loss through capacitive coupling, the thermometer effect luminance uniformity degradation and electromagnetic interference (EMI). The proposed architecture is capable of driving a large parallel CCFL array with only a single high voltage and high efficiency converter, resulting in reduced size, weight and cost over existing designs. Reduced ignition voltage (at near operating voltage) is achieved by a unique capacitive coupling approach, based on the similar principles to normal operation of electrodeless or external electrode fluorescent lamps. However, the displacement current is only required in our proposed architecture as a short high frequency pulse during cold lamp ignition, which triggers simultaneous lamp ignition of all parallel lamps. High impedance current source circuit (based on MOSFET current mirror) is connected in series with each lamp to ensure individual lamp current regulation and control. In this paper, we discuss a suitable architecture for large CCFL arrays and study new approaches for lamp ignition to enable low frequency drive.

2. Study of Lamp Behavior

2.1 DC Operation of Fluorescent lamps
A steady electric field across the plasma generated in the lamp causes migration of active ions (light emitting specie), mercury in the case of fluorescent lamps, from cathode to anode setting up a gradient along the length of the lamp. The light luminance is directly related to the mercury pressure and hence the axial segregation of mercury under dc drive results in non-uniform axial luminance distribution along the lamp. In order to avoid this effect, sinusoidal ac voltage is conventionally used to drive linear fluorescent lamps and most other discharge lamps.

In a recent investigation, addressing the problem of axial mercury segregation (axial cataphoresis), the measured gradient in the mercury pressure along the length (z) of the lamp ($\frac{\partial p_m}{\partial z}$) was found to be proportional to the local mercury vapor pressure ($p_m$): $\frac{\partial p_m}{\partial z} \propto p_m$ [3, 4]. Further, the study showed that axial segregation under dc drive is predictable and can be quantified based on lamp design parameters. If a limit is set on the allowed luminance variation due to segregation, then bounds can be placed on lamp parameters to meet the specifications. In our study of low-frequency architecture, we observed that the non-uniformity due to the thermometer effect was greater than that due to cataphoresis. Axial luminance degradation is observed with near dc drive, which from our experience and theoretical modeling is within acceptable limits. The theoretical study show that it is also possible to predict the phenomenon of cataphoresis, decrease its effect and achieve a higher efficiency dc drive along with better optical efficiency by redesigning the lamp and selecting optimal parameters.

2.2 Lamp Ignition & Capacitive Coupling
From previous studies conducted to model the breakdown phenomenon in long cylindrical tubes, it has become clear that the tube wall and the electrical environment of the lamp play an integral role in the initial phases of the breakdown process [5-7]. In [5], it is shown that starting at the active electrode (cathode), subsequent sections of the wall are negatively charged and this surface charge electrically shields the inside of the tube and extends the cathode potential within the tube until the ionization front reaches the anode. The process was modeled as a distributed RC-line, with resistors representing the discharge gas and capacitors representing the capacitance between the wall and the metal tube at ground potential around the lamps. We now propose our method of capacitive ignition based on our experiments.
3. Low Frequency Architecture

A block diagram for the low frequency architecture is shown in Fig. 1. The system includes a high voltage LFSW source, an ignition circuit that drives the lamps through capacitive coupling after ac operation for long pulse application of ac drive to the metal foil or plate. Our experiments verified successful ignition and operation for long lamps (> 25cm) with sustained operation after removing the ac drive from the metal plate.

3.1 High Voltage LFSW Power Supply

The primary function of the source is to generate a controlled low frequency high voltage square wave to essentially drive the lamps with dc current and equal duty cycles of positive and negative polarity (to equalize electrode degradation). Depending upon the lamp operating voltage, different approaches can be adopted to generate a LFSW in order to achieve maximum drive efficiency. For lamps with operating voltage less than 600 V, a full bridge (H-bridge) employing high voltage switches powered from a single high voltage dc-dc converter can be used. For higher operating voltages, the square-wave voltage can be generated by applying a dc voltage across the electrodes followed by a short pulse application of ac drive to the metal foil or plate. For higher lamp operating voltage, different approaches can be adopted to generate a high output voltage [8, 9].

3.2 Igniter Circuit

The ignition circuit is used to drive the metal plate with a short pulse (or pulses) for ignition of lamps. The applied voltage required depends on many factors, including lamp characteristics, temperature and distance between lamp sidewall and metal plate. As shown in Section 4, we have demonstrated operation with pulses in the few hundred volt range with periods in the ten microseconds range. The key result for our low frequency architecture is that only a single high frequency generator is needed, which is operated for short pulses with a capacitive load. Thus wide ranges of resonant converter or pulse generator approaches are suitable for the ignition circuit.

3.3 Current Control (CC)

The CC circuit is required in series with each lamp to stabilize individual lamp currents following ignition and provide consistent lumen output across the CCFL array. The CC devices must block the maximum lamp-to-lamp voltage variation, which we have measured to be less than 30 V [1], in our experimentation. The low blocking voltage allows active devices to be used for current control while still maintaining high efficiency. Figure 3 gives a block diagram of a discrete unidirectional MOSFET current source circuit, with current set by resistor R_s in series with MOSFET. Note that each string of CC circuits (tied to the same terminal) can be realized using a single integrated circuit (IC).

3.4 Backlight Controller

The backlight controller provides the drive signals for all blocks, including the high voltage dc-dc converters, low frequency switches, S_enable (or bridge network), and the igniter circuit, and may also provide communication with the CC circuits for dimming control. For lamp ignition, high voltage dc is ramped up together with the capacitive coupled ignition current. The controller then monitors the total lamp array current through the current sense feedback and continues ignition current until all lamps are ignited (based on the total current sensed). For concept evaluation purposes, the backlight controller is implemented using a Xilinx Virtex IV FPGA board.
4. Experimental Results

Experiments were conducted to study the lamp ignition characteristics with 4 lamps in parallel as shown in Fig. 4(a). The ac specifications are listed in Table 1.

![Experimental setup diagram](image)

**Table 1: AC lamp specifications [10]**

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Dia. (mm)</th>
<th>White Point (K)</th>
<th>Ignition Voltage (Vrms)</th>
<th>Operating Voltage (Vrms)</th>
<th>Lamp Current (mA rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>3.2</td>
<td>5400</td>
<td>1300</td>
<td>520</td>
<td>5</td>
</tr>
<tr>
<td>250</td>
<td>2.6</td>
<td>8810</td>
<td>1300</td>
<td>525</td>
<td>5</td>
</tr>
</tbody>
</table>

![Graph of experimental results](image)

**Table 2: Experimental DC lamp operating conditions**

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Dia. (mm)</th>
<th>Ignition Pulse (Vpk)</th>
<th>Lamp Ignition Voltage (VDC)</th>
<th>Typical Operating Voltage (VDC)</th>
<th>Lamp Current (mA DC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>3.2</td>
<td>500</td>
<td>670</td>
<td>610</td>
<td>5</td>
</tr>
<tr>
<td>250</td>
<td>2.6</td>
<td>500</td>
<td>670</td>
<td>600</td>
<td>5</td>
</tr>
</tbody>
</table>

The experimental setup consisted of two CCM Flyback converters (Fig. 2), a CC circuit built using discrete MOSFET current source circuit (Fig. 3) and an ignition circuit with series resonant LC circuit that generated damped sinusoidal ignition pulses. The individual lamp current was measured across the sense resistor Rs in series with the MOSFET current source and the total current was measured using a dc current probe at the output of LFSW power supply (Terminal 1). The lamp ignition was achieved at a dc drive of 670 V with a capacitive ignition pulse voltage of 500 Vpk (Table 2). The steady state voltage drop across the lamp was observed to be in range of 590 V to 620 V (lamp-to-lamp variation of 30 V) and the current was regulated at a dc value of 5 mA by the current control circuit.

Figure 4(b) illustrates the operation of the low frequency architecture. The polarity across the lamps was changed after 30 s corresponding to LFSW of frequency = 0.016 Hz. The individual lamp current and total lamp current is shown to be regulated at 5 mA (corresponding to 5 V across 1 kΩ resistor) and 20 mA, respectively. The lamp current changes polarity from positive to negative according to the lamp voltage transition. The LFSW period is controlled thorough the FPGA and made to vary between 200 ms to 120 s (5 Hz to 0.008 Hz) to study the lamp behavior.
We varied the LFSW frequency through the complete range and found no notable change in the output waveform characteristics.

Figure 5 illustrates the transient behavior of the low frequency architecture during both positive and negative transitions of the square wave. The ignition circuit is set to generate a pulse output with a peak voltage of 500 Vpk at each LFSW transition. By observing the total current, we see that simultaneous ignition of the parallel lamps is achieved during both positive and negative transitions. The control is provided such that the energy stored in the lamp since the required blocking voltage is low and the lamp operating voltage in each case. Further investigations on dimming without giving rise to lamp flicker.

Continuous dimming can also be achieved by controlling the command reference for the CC circuit. Again, the fast lamp and circuit dynamics lead to smooth and continuous dimming without giving rise to lamp flicker.

From the waveforms in Fig. 5 we can also see that the lamp current drops to zero in less than 100 μs with a small decrease in the applied voltage (e.g. < 50 V). This allows use of the CC circuits to perform pulse-width-modulation (PWM) dimming of the lamp since the required blocking voltage is low and the lamp dynamics are sufficiently fast. Dimming is achieved through on/off control of the CC circuit or by controlling the dead-time in the LFSW transition. Continuous dimming can also be achieved by controlling the command reference for the CC circuit. Again, the fast lamp and circuit dynamics lead to smooth and continuous dimming without giving rise to lamp flicker.

We have tested multiple lamp lengths with voltages from 200 V to greater than 800 V to verify that ignition is achieved at nominal operating voltage in each case. Further investigations on dimming ranges and the lamp-to-lamp voltage variation were also carried out, with results presented in [1].

5. Conclusion
The proposed low frequency architecture results in a high efficiency and low cost drive for parallel CCFL arrays used in large screen backlighting applications. The system provides the benefit of a single power converter capable of driving parallel CCFL arrays for significant size, weight and cost reduction in large screen LCD TVs. The low frequency drive results in improved efficiency through the elimination of sensitivities to parasitic capacitances associated with packaging and significantly reduced EMI. We found no notable change in the output waveform characteristics.

6. Acknowledgements
The authors thank Dick McCartney of National Semiconductor Corporation (NSC) for his conversations and input related to this work. The work is co-sponsored by NSC through the Colorado Power Electronics Center, the National Science Foundation (under Grant No. 0348772) and Spanish Government through the project CICYT TEC 2004-02607/MIC. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

7. References