Comparing magnetic and piezoelectric transformer approaches in CCFL applications
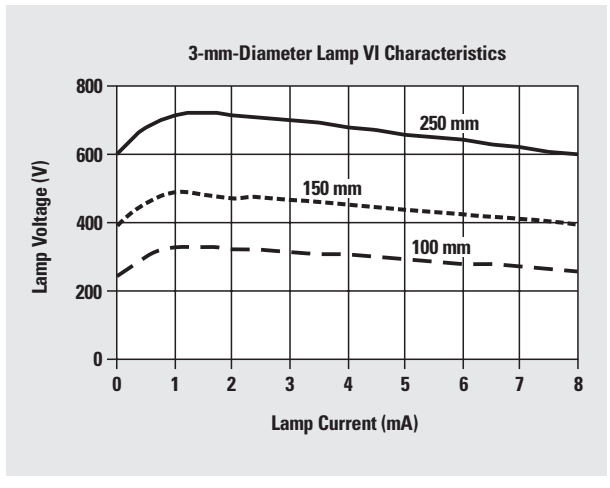
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Cold cathode fluorescent lamps (CCFLs) are commonly used as a backlight source for color liquid crystal displays (LCDs) used in notebook computers and portable electronic devices. These lamps require a high ac voltage for ignition and operation. The required ignition voltage is typically double the operating voltage and increases at cold temperatures. Figure 1 shows the operating voltage of lamps with 3-mm diameters and various lengths (100 mm, 150 mm, and 250 mm). Lamp voltage is primarily dependent on length and is fairly constant with current, giving a non-linear characteristic. Lamp current is roughly proportional to brightness or intensity and is the controlled element of the backlight supply. The lamp requires a sinusoidal voltage to provide the best electrical-to-optical energy conversion.
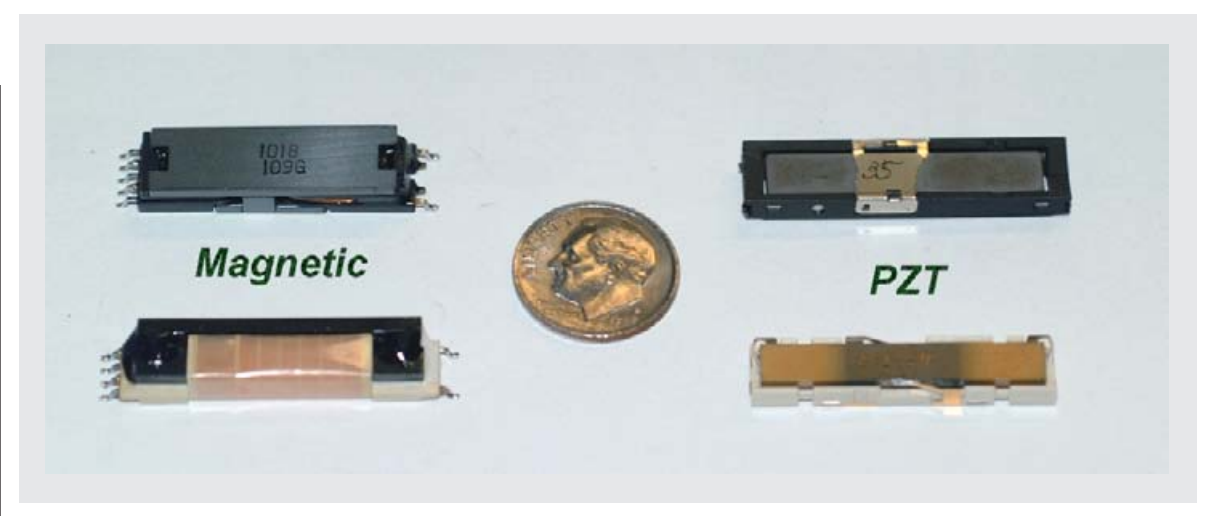
The lamp and display enclosures used for next-generation portable products are becoming increasingly narrow, generating the need for a low-profile CCFL power supply. Advances in both magnetic and ceramic piezoelectric transformers (PZTs) have enabled efficient and smaller backlight converters to be built. The choice of transformer depends on several factors including cost, size, and efficiency. For example, a magnetic transformer may be thicker, heavier, and less efficient than a PZT at a particular power level; but it has the advantages of lower cost and the ability to function over a wider range of load conditions. The PZT transformer has the advantages of inherently sinusoidal operation, high strike voltage (which can

be used with non-mercury lamps), nonflammability, and no electromagnetic noise. Some examples of transformers used in 3- to 4-W notebook computer applications are shown in Figure 2.

Figure 1. Typical voltage and current behavior in a CCFL

Figure 2. Size comparisons of magnetic and PZT transformers

A quick review of magnetic transformer operation

A high-frequency magnetic transformer consists of multiple wires wrapped around a common ferrite core, as shown in Figure 3. Energy transfer occurs in the core between flux and magnetic fields. This energy transfer can also be equated to volt-seconds and current:

$$\text{Energy} = \int I \times V dt = \int_{\text{volume}} H \times dB.$$

Flux density (B) is proportional to volt-seconds and inversely proportional to the cross-sectional area of the core and number of turns, according to Faraday's law:

$$B \approx \frac{V}{N \times A_{\text{core}} \times \text{Frequency}}.$$

Magnetic field (H) is proportional to amp turns and inversely proportional to path length, as described by Ampere's law:

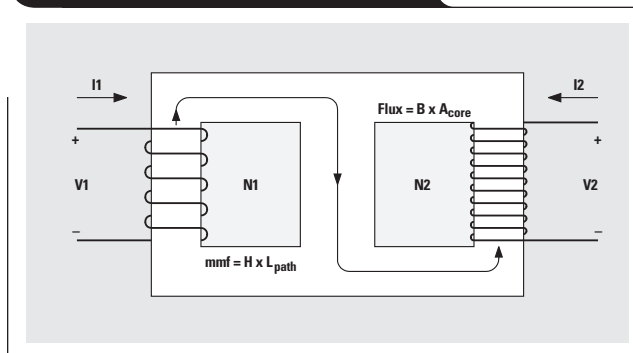$$H \approx \frac{N \times I}{L_{\text{path}}}.$$

The relationship between the flux and magnetic fields is determined by the permeability of the core:

$$\mu = B/H.$$

The voltage gain of the transformer can be easily adjusted by the ratio of secondary to primary turns, N2/N1, where the current gain in the transformer is related by N1/N2.

When a transformer for a CCFL circuit is designed, the number of primary turns is determined by the required inductance of a resonant tank developed between the transformer's primary and an external capacitor. The number of secondary turns should provide sufficient ignition voltage for the lamp. The high number of secondary turns typically requires a large window area in the core. Leakage inductance in CCFL transformers is large due to the high-voltage spacing requirements between primary

Figure 3. Magnetic transformer

and secondary. This leakage inductance reduces the effective turns ratio but does not produce transient switching spikes in the application, as the transformer is operated with sinusoidal waveforms. Other issues with magnetic transformers include stray magnetic fields that may require shielding and the potential of electrical arcing if the secondary voltage is not controlled in a fault situation.

Piezoelectric transformer operation

Unlike magnetic transformers that rely on electromagnetic energy transfer, piezoelectric transformers exchange electric potential with mechanical force. A typical multi-layer PZT with "longitudinal-mode" geometry is shown in Figure 4. An ac voltage is applied to the V_{IN} electrodes, causing mechanical expansion and compression in the thickness direction. This displacement on the primary is transferred as a force in the longitudinal or length direction. Supports at ¼ and ¾ wavelength provide a means for a standing wave to be generated at a resonant frequency, as shown.

Mechanical resonance occurs at multiple standing-wave frequencies (n) based on the transformer's length and material velocity (V):
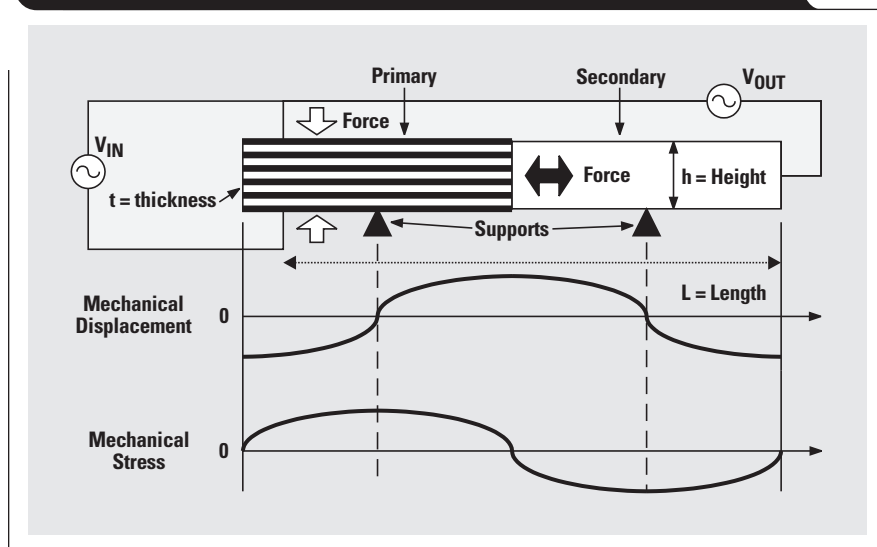
$$f_n = n \frac{\upsilon}{2 \times \text{Length}}.$$

Voltage gain is a function of the PZT material coefficient g(ω), the number of primary layers, the thickness of the material, and the overall length as follows:

$$V(\text{gain}) = \frac{\text{Length} \times \text{Layers}}{\text{Thickness}} \times g(\omega).$$

Figure 4. Typical longitudinal-mode piezoelectric transformer for CCFL applications

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An electrode at V_{OUT} is used to recover the amplified electrical potential at the secondary. To predict PZT performance in a system, it is useful to develop an electrical circuit model. The model shown in Figure 5 is often used to describe the behavior of a PZT near a single resonant frequency. Many PZT manufacturers will provide component values for the model based on measurements taken at various frequencies and output loads.

A large primary capacitance (C_{input}) is formed as a result of the multi-layer construction of the primary electrodes and material dielectric constant. The output capacitance is much smaller due to the distance between the primary and secondary electrodes. The mechanical resonant frequency (ω_0) of the PZT is proportional to the material elasticity (Y), density (ρ), and length:

$$\omega_0 \propto \frac{1}{\text{Length}}\sqrt{\frac{Y}{\rho}} .$$

The mechanical piezoelectric gain near a single resonant frequency can be modeled by a series R, L, and C circuit in the electrical equivalent model of Figure 5; whereas Figure 6 illustrates the gain versus output load and frequency characteristics for a PZT with the following values:

$C_{input} = 0.2\ \mu F$, $C_{OUT} = 30\ pF$, $n = 30$,
Series RLC ($2\ \Omega$, $1\ mH$, $6\ nF$).

As shown in Figure 6, the ceramic transformer provides high Q and gain under light or no-load conditions, producing a high strike potential. Once the lamp strikes, the transformer becomes loaded, causing the transformer gain to decrease and resonant frequency to shift. Because of the unique gain characteristics of the PZT transformer with load, no ballasting element is required between the transformer secondary and the lamp as with the magnetic transformer.

Operating a magnetic transformer with a current-fed, push-pull topology

A current-fed, push-pull topology is commonly used to power a magnetic transformer-based CCFL circuit, as shown in Figure 7. This topology accommodates a wide input voltage and dimming range while retaining sinusoidal operation of the lamp. The converter consists of a resonant push-pull stage, a PWM buck-derived control stage, and a high-voltage secondary stage.

The push-pull stage consists of transistors Q2 and Q3, which drive the center-tapped transformer T1. The transistors are driven 180° out of phase at 50% duty cycle with an auxiliary winding on the transformer. A resonant tank is formed between the primary inductance of T1 and a low-loss, external resonant capacitor (C4). The resonant tank provides a sinusoidal voltage to the transformer's primary and sets the operating frequency of the system.

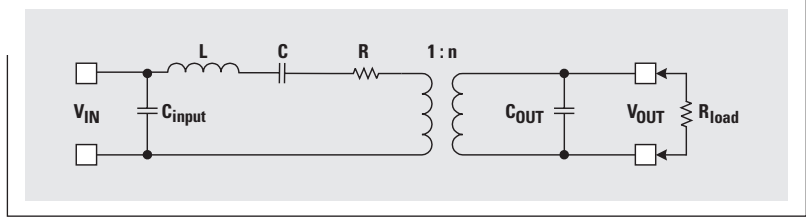Figure 5. Equivalent piezoelectric transformer circuit model

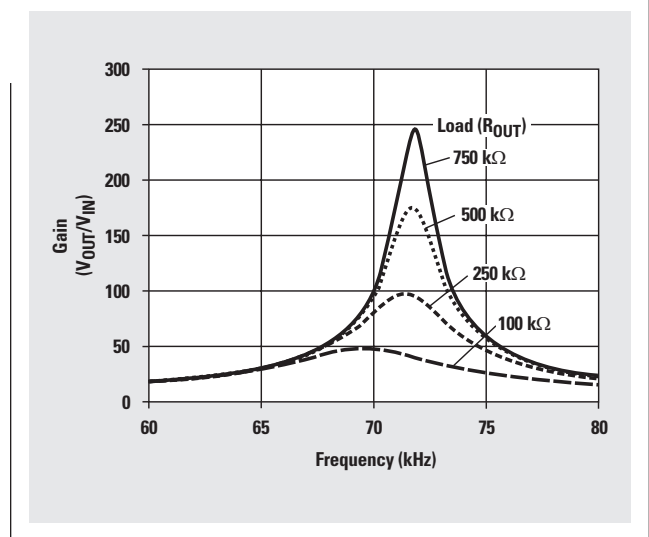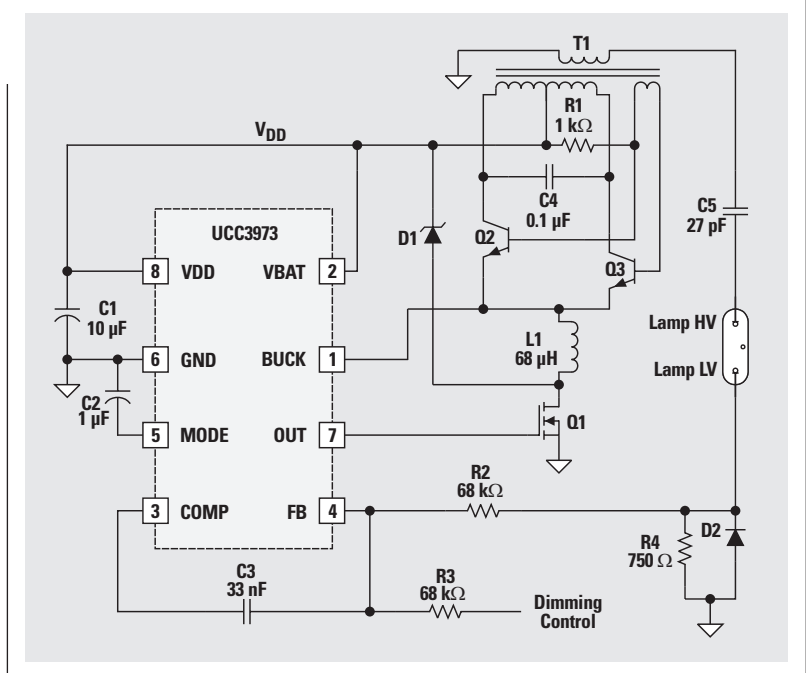Figure 6. Typical piezoelectric gain characteristics vs. frequency and load

Figure 7. UCC3973-based CCFL power supply using a resonant half-bridge topology

The primary resonant tank is fed with a dc current from the buck stage consisting of Q1, D1, and L1. The UCC3973 synchronizes the buck frequency to the push-pull stage to prevent a beat frequency from occurring. The dc current in L1 is controlled by the duty cycle of Q1. The buck stage duty cycle is determined by the feedback network (at FB and COMP), which is used to regulate lamp current (sensed across R4).

The high voltage at the secondary of T1 is used to ignite and operate the lamp. Since the ignition or strike voltage is higher than the operating voltage, a high voltage capacitor (C5) is required to allow a voltage difference between the transformer secondary and lamp. This capacitor is also used as a ballasting element for the circuit to deal with the nonlinear nature of the lamp as it is dimmed. The transformer secondary can be designed with a high leakage inductance, allowing the ballast capacitor to be eliminated.

Waveforms for the buck, push-pull, and lamp circuits are shown in Figures 8 and 9. The square wave in Figure 8 is the common node of the buck stage where D1, Q1, and L1 connect. The rectified sinusoid of the push-pull resonant tank (Figures 8 and 9, top trace) is measured where L1 and the emitters of Q2 and Q3 connect. Lamp voltage is shown in Figure 9. The sinusoidal shape of the waveform provides good electrical-to-optical efficiency. Finally, Figure 10 shows system efficiency performance from V_{IN} to V_{lamp} over a wide range of input voltage and lamp current.

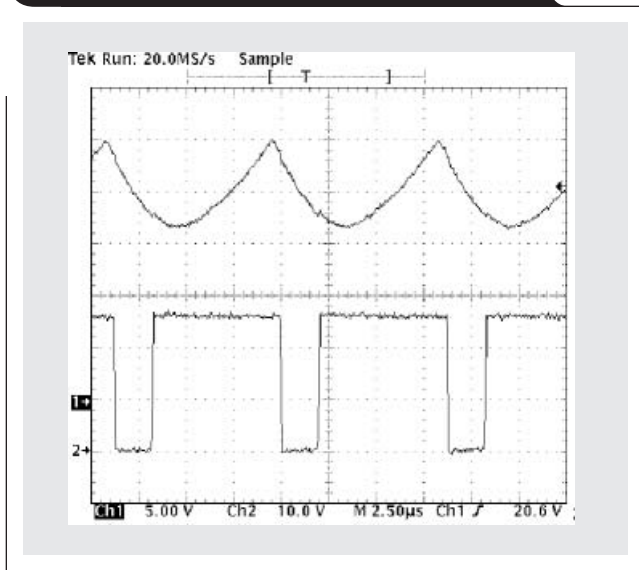### Figure 8. Buck and push-pull waveforms

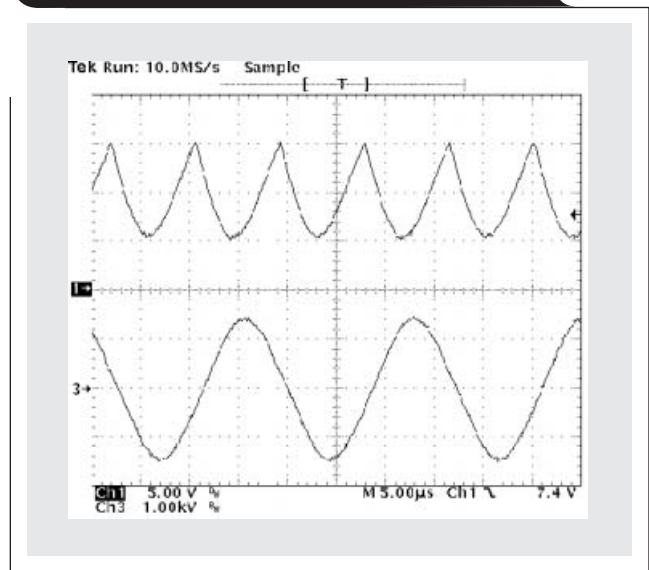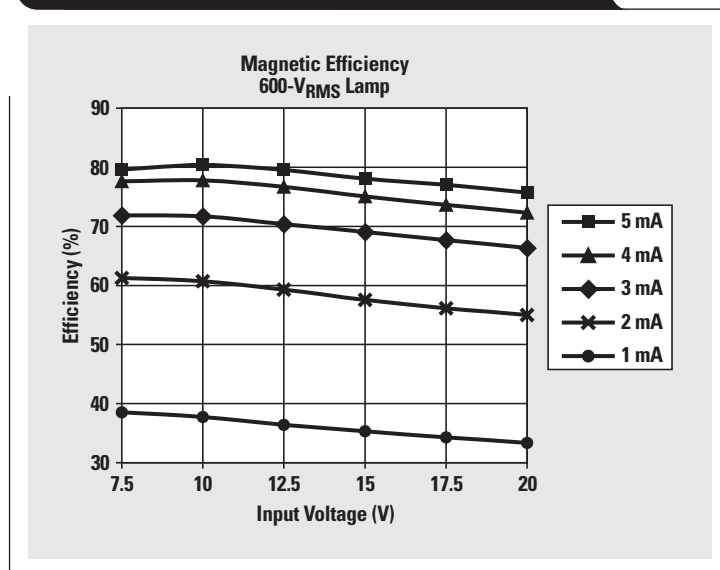### Figure 9. Push-pull and lamp waveforms

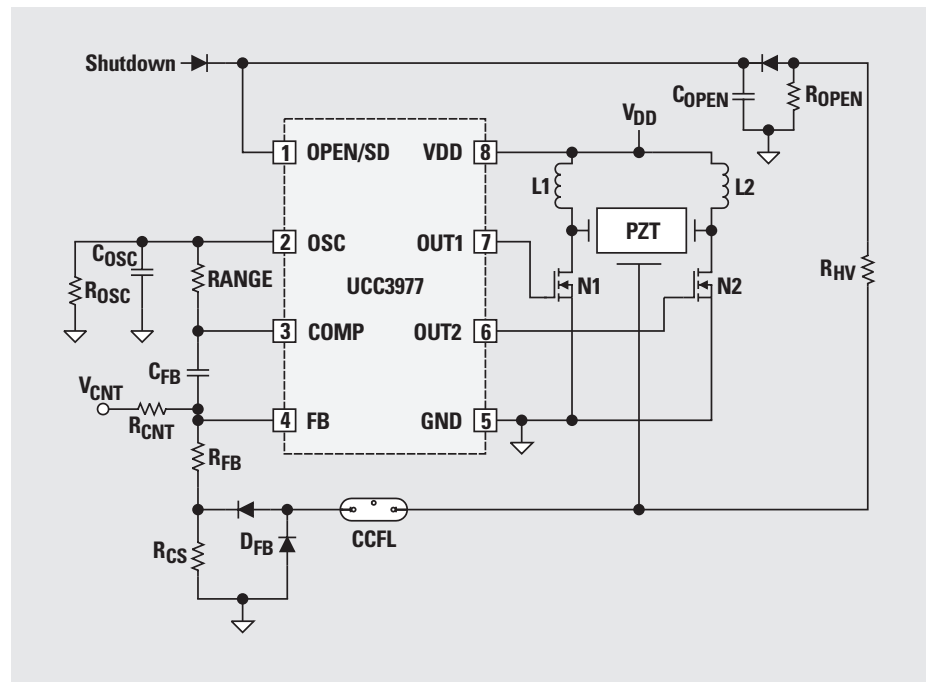### Figure 10. Electrical efficiency for magnetic-based backlight

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Operating a PZT with a voltage-fed, push-pull topology

A circuit used to control a piezo-electric transformer in a resonant push-pull topology is shown in Figure 11. This topology uses two standard inductors (L1 and L2) that are driven 180° out of phase at 50% duty cycle with the UCC3977 controller and MOSFETs N1 and N2. The push-pull circuit has the advantage of providing voltage gain from the dc input voltage to the piezo-electric transformer primary. Resonant operation is achieved with the LC relationship between the inductors and primary capacitance of the PZT.

Unlike the magnetic transformer circuit previously discussed, the PZT-based circuit uses frequency rather than duty cycle to control lamp current. The UCC3977 contains a programmable voltage-controlled oscillator (VCO) formed at the COMP and OSC pins. The VCO is used to set the system's operational frequency range, which must include the strike and operating frequencies of the PZT. Lamp current, sensed at the FB pin,

Figure 11. UCC3977-based CCFL power supply using a resonant push-pull topology

is controlled by the gain-to-frequency characteristics of the PZT (see Figure 6). The gain of the PZT must provide sufficient lamp voltage at minimum input voltage to ensure that the control loop will always operate on the right side of resonance.

Operating waveforms for the push-pull circuit are shown in Figure 12. MOSFETs N1 and N2 are driven out of phase at 50% duty cycle (see Figure 12, trace 2). Inductors L1 and L2 resonate with the PZT primary capacitance, forming half sinusoids at the drain of N1 (trace 1) and S2 (trace 4). The resulting voltage across the PZT primary is a near sinusoid (trace M1). The lamp voltage, which is approximately 600 V in this application, is sinusoidal (trace 3) due to the high Q of the ceramic transformer.

To achieve zero-voltage switching, the drain voltage must return to zero before the next switching cycle. This dictates that the LC resonant frequency be greater than the switching frequency. The maximum inductance to meet these conditions can be found from:

$$L < \frac{1}{4 \times \pi^2 \times f^2 \times Cp}.$$

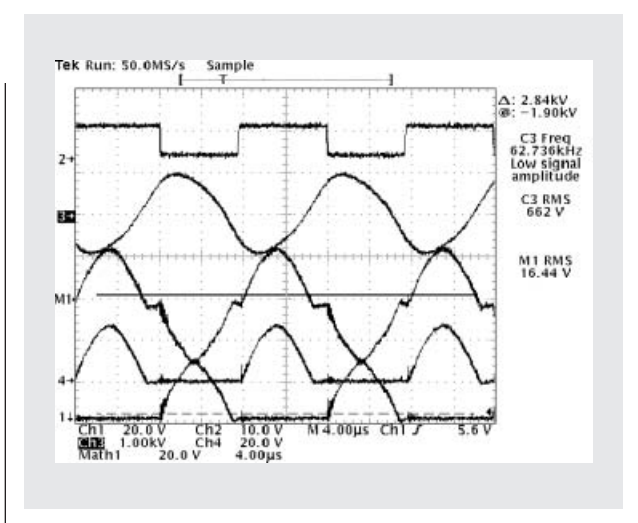**Figure 12. UCC3977 push-pull waveforms with V_{IN} 7-Vdc and 600-V lamp**

Figure 13 shows the efficiency performance of a 3-W-rated, multi-layer PZT configured with push-pull topology when operating a 600-V lamp. Electrical efficiency is greater than 85% at lower input voltages, decreasing at higher input voltages as the PZT gain is reduced.

Figure 14 shows plots of PZT operating frequency over the same lamp conditions as those shown in Figure 13. As expected, frequency decreases at higher lamp currents as the PZT characteristics shift to a lower operating frequency when loaded (see Figure 6). Frequency increases linearly with input voltage, since the required V_{OUT}/V_{IN} gain to operate the lamp is decreased.

Using a burst dimming technique

Dimming by linearly reducing lamp current causes the efficiency to degrade for both magnetic and PZT transformers. Light load efficiency decreases in the magnetic transformer circuit due to the circulating currents in the resonant tank, which are a constant loss regardless of lamp current. Efficiency degrades in the PZT circuit at light load because the system is operated at less than optimal gain. Efficiency can be improved with either circuit by using a burst dimming technique. This method involves running the lamp at full current and controlling the average lamp current by modulating the on/off duty cycle at a frequency higher than the eye can detect (>100 Hz).

Figure 15 shows burst-dimming waveforms of the PZT-based backlight circuit. Burst-dimming waveforms for the magnetic-transformer-based circuit would be similar. An external drive signal (trace 2) is used to command the duty cycle and frequency of the burst (125 Hz at 50% duty cycle in this case). Trace 1 is the gate of one of the MOSFETs; whereas trace 3 shows the COMP pin of the feedback network used to set the operating frequency. Lamp voltage is shown on trace 4. These pictures were taken with a digital oscilloscope, so aliasing is present. Strike voltage for the lamp is barely detectible, since the lamp is warm and operating from the previous burst cycles.

Summary

Characteristics of cold cathode fluorescent lamps used as backlight sources for portable applications have been presented. The operating principles of two transformer types (magnetic and piezoelectric) that address the high voltage requirements of these lamps have been discussed. The choice of transformer for a particular application depends on several factors including efficiency, size, and cost. Resonant power circuits that provide sinusoidal operation to increase optical efficiency were presented for both transformer types. Lamp brightness can be controlled by either a linear or burst dimming technique. Efficiency of greater than 80% can be achieved with either transformer type, increasing the run time of a battery-powered system.

Related Web sites

www.ti.com/sc/docs/products/analog/ucc3973.html
www.ti.com/sc/docs/products/analog/ucc3977.html

Figure 13. Typical PZT efficiency with input voltage and loading
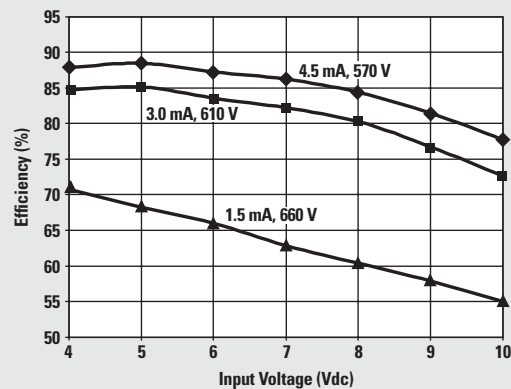

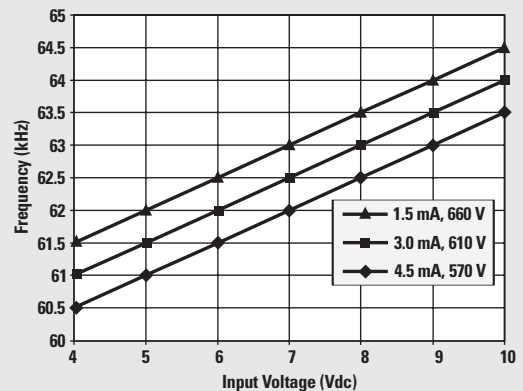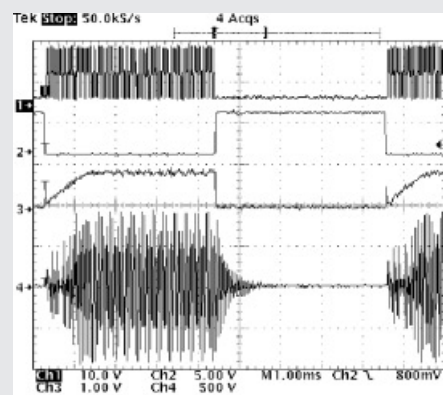### Figure 14. PZT operating frequency vs. input voltage and lamp load

Figure 15. Burst dimming for a PZT-based backlight circuit

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