Understanding piezoelectric transformers in CCFL backlight applications

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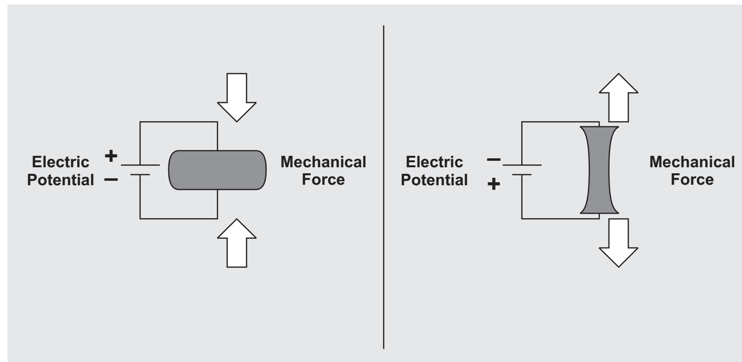
Market forces are reducing both the size and energy consumption requirements of portable devices such as PDAs, Internet appliances, and subnotebook computers. Low-profile cold cathode fluorescent lamp (CCFL) backlight solutions are commonly used in these applications. Traditional topologies have used magnetic transformers to generate the high strike and operating voltages required by CCFL lamps. The latest developments in ceramic piezoelectric transformers (PZTs) make them ideal candidates for low-profile backlight applications. PZTs have higher efficiency, smaller size, lower electromagnetic noise, and higher available strike voltage than magnetic transformers. They are also nonflammable and require only easy-to-generate sinusoidal drive voltages. Ceramic PZT operation is fundamentally different from magnetic transformer operation. A successful design requires an understanding of piezoelectric characteristics and how they relate to driving CCFL lamps.

Figure 1. Piezoelectric effect



PZT theory

Magnetic transformers transfer energy from primary to secondary by coupling two circuit windings together through a magnetic flux path. In contrast, PZTs transfer energy from primary to secondary through the use of mechanical force. C.A. Rosen first proposed PZTs in 1956.[1] The basic principle of piezoelectric operation is shown in Figure 1. When an electrical potential is applied to a piezoelectric material, the electrical energy is converted to mechanical force. This is referred to as the “reverse piezoelectric effect.” When a mechanical force is applied to a piezoelectric material, the material converts the mechanical force to electrical energy. This conversion is referred to as the “direct piezoelectric effect.”

Each manufacturer has a unique, and usually proprietary, “recipe” of materials and structural layering that determines its PZT’s operating characteristics. Common materials used to make PZTs include lead zirconate and lead titanate. A PZT may be single-layer or multilayer. Single-layer PZTs are inexpensive due to easier manufacturing processes but have relatively low voltage gains (typically 5 to 10). Multilayered PZT designs are more expensive due to the manufacturing process but have higher voltage gains (20 to 70). Multilayer PZTs are almost always used in CCFL applications because the higher gain eliminates the need for a step-up transformer and allows the CCFL to be driven with conventional off-the-shelf inductors.

Figure 2. Typical longitudinal-mode PZT for CCFL applications

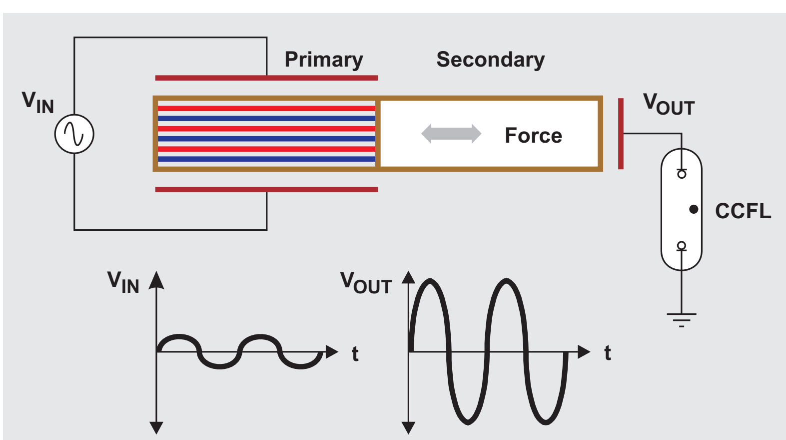


Figure 2 shows a typical multilayer PZT with “longitudinal-mode” geometry. The primary has multiple layers of ceramic material with electrodes on the top and bottom. An ac voltage applied to the primary electrodes generates a mechanical force that causes the material to resonate. When the material is compressed in the vertical direction, it is expanded in the horizontal direction, and its length is increased. When it is expanded in the vertical direction, it is compressed in the horizontal direction, and its length decreases. The horizontal, or longitudinal, displacement of the primary is mechanically coupled into the secondary, which causes the secondary to vibrate. The mechanical energy in the secondary is then converted to electrical energy, which is transferred to the circuit through the secondary electrode.

Figure 3 shows the typical construction for a Panasonic PZT (EFTU11R8Mx, EFTU14R0Mxx, and EFTI16R5Mxx series). Notice how the placement of the electrodes corresponds to that shown in Figure 2.

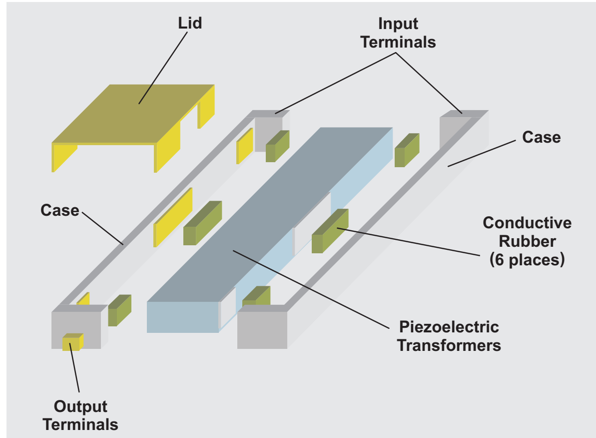
PZT electrical model

To predict PZT performance in a system, it is useful to develop an electrical circuit model. The model shown in Figure 4 is often used to describe the behavior of a longitudinal-mode PZT near the fundamental resonant frequency. Many PZT manufacturers provide component values for the model based on measurements taken at various frequencies and output loads.

The component values depend on the PZT's construction and vary from one PZT part number to another. The input, or primary, capacitance (C_{INPUT}) is formed as a result of the multilayer construction of the primary electrodes and material dielectric constant. This creates a relatively large input capacitance, much like a standard multilayer ceramic capacitor. The output capacitance, C_{OUT}, is much smaller due to the distance between the primary and secondary electrodes. As shown in the following equation, the PZT capacitance is a function of its geometry and material.

$$C_{INPUT} \approx \frac{\text{Length} \times \text{Width} \times \text{Layers} \times \varepsilon}{2 \times \text{Thickness}}$$

Figure 3. Typical construction of PZT (Panasonic's (EFTU11R8Mx, EFTU14R0Mxx, EFTI16R5Mxx series)



The mechanical resonant frequency, ω_0, of the PZT is also dependent upon geometry and material.

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

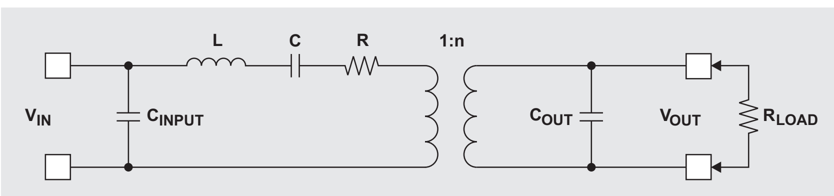
where Y is the material elasticity and ρ is the material density.

The mechanical piezoelectric gain near a single resonant frequency is modeled by the series R, L, and C circuit as depicted in Figure 4.

$$\omega_0 = \frac{1}{\sqrt{L \times C}}$$

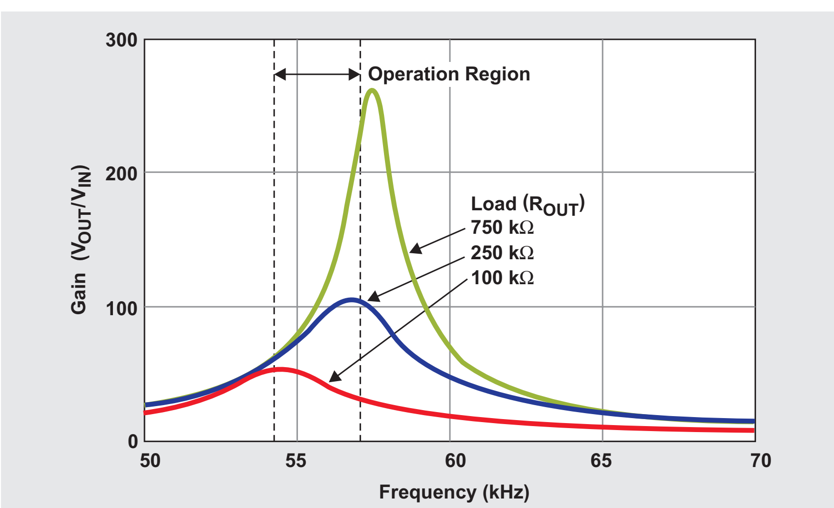
$$Q = \omega_0 \times \frac{L}{R}$$

Figure 4. Equivalent piezoelectric transformer circuit model



Component values for a typical 1.8-W PZT (Panasonic part number EFTU11R8MX50) for Figure 4 are C_{INPUT} = 61.6 nF; C_{OUT} = 11.4 pF; n = 35; and series RLC = 0.66 Ω, 0.94 mH, and 2.79 nF, respectively. The gain and the mechanical resonant frequency of the PZT change with load. These changes directly affect the electrical voltage gain. Figure 5 shows the graph of the electrical voltage gain versus frequency and load for the Panasonic PZT. It also shows that the PZT is capable of providing a large range of voltage gain. The PZT is operated near the 1-MΩ load line to provide the extremely high gain necessary to produce CCFL strike voltages. When loaded, it operates at a much lower gain to provide the lower operating voltages.

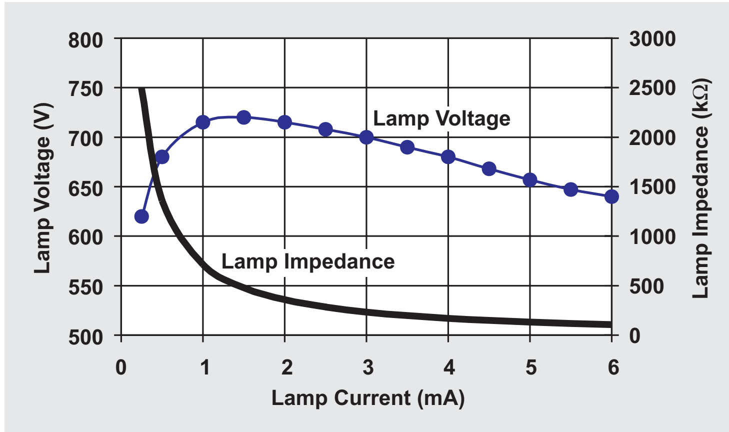
Figure 5. Typical piezoelectric gain characteristics vs. frequency and load



CCFL lamp characteristics

Understanding the electrical operating characteristics of a CCFL is essential to understanding how to control its behavior. Before the lamp is ignited, it has an extremely high resistance and is modeled as an open circuit. The voltage required to ignite the lamp is called the strike voltage. The strike voltage, which is dependent upon lamp length and diameter, is usually in the range of 500 to 2000 V. Strike voltage can be even higher at cold operating temperatures. When the lamp strikes, current begins to flow. The drop in operating voltage and the increase in current reduce the dynamic impedance of the CCFL. Figure 6 shows the nonlinear voltage and current characteristics of a typical CCFL. Although highly nonlinear, the lamp impedance can be modeled as a resistor at any one operating point. Lamp intensity is roughly proportional to lamp current.

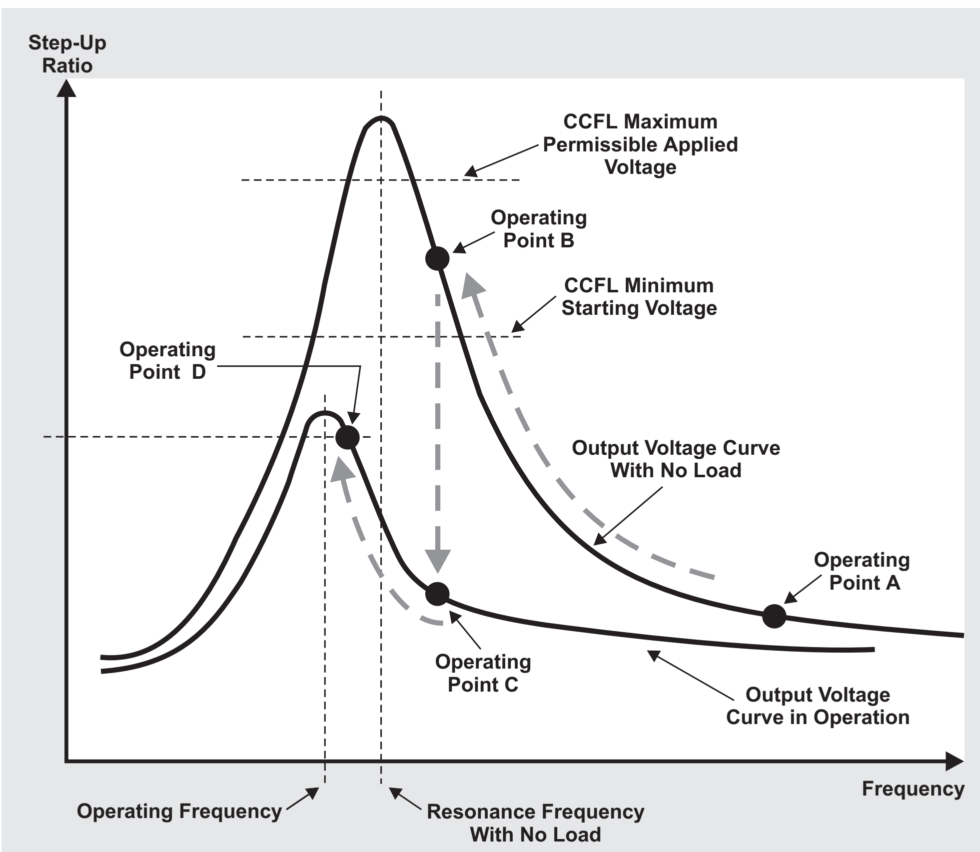
Figure 6. CCFL characteristics



CCFL/PZT interaction

Figure 7 shows the operational interaction between the CCFL and the PZT. Figure 7 is a combination of Figure 5 (PZT gain versus frequency and load) with Figure 6 (CCFL impedance versus current). Integrating Figures 5 and 6 and examining the result gives insight into the basic operating principle of the CCFL backlight power-supply controller. At turn-on, the lamp is an open circuit, so the PZT operates on the high-gain, high-impedance load line shown in Figure 7. Since the exact strike voltage and operating frequency are not known, the controller applies

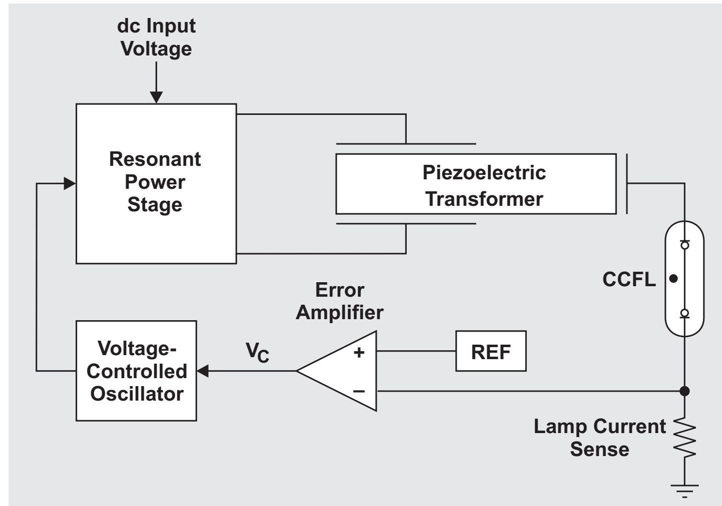
Figure 7. PZT with CCFL load operating points



a relatively low voltage to the lamp by operating at the maximum-programmed operational frequency. This is shown as Point A. As the operating frequency is decreased, the PZT gain moves up the no-load line until the CCFL strike voltage is reached. This is shown as operating Point B. At Point B, the CCFL strike voltage is reached and the lamp impedance begins to decrease. The operating frequency continues to decrease as the lamp impedance drops until the correct operating point is reached, somewhere between Points C and D. Varying the operating point between Points C and D controls the lamp intensity. This is accomplished by varying the operating frequency of the converter.

Figure 8 shows a simplified block diagram of a PZT-based backlight converter. The PZT is driven by a resonant power stage whose amplitude is proportional to input voltage. The PZT provides the voltage gain necessary to drive the lamp. A control loop is formed around the error amplifier that compares average lamp current to a reference signal, REF, allowing the intensity of the lamp to be regulated. The resulting control voltage, V_C, drives a voltage-controlled oscillator (VCO) that determines the operating frequency of the resonant power stage. The frequency range of the VCO must include the strike and operating frequencies of the PZT. For example, a frequency range of 51 to 71 kHz is required for proper operation of the lamp characteristics shown in Figure 5. The designer must guarantee that the PZT gain is sufficient to provide the required lamp voltage at minimum input voltage to keep the operating point on the right side of resonance. If the operating point crosses from the right side to the left side of resonance, the supply loses control of the lamp current and the lamp turns off.

Figure 8. Control system for variable-frequency PZT backlight circuit

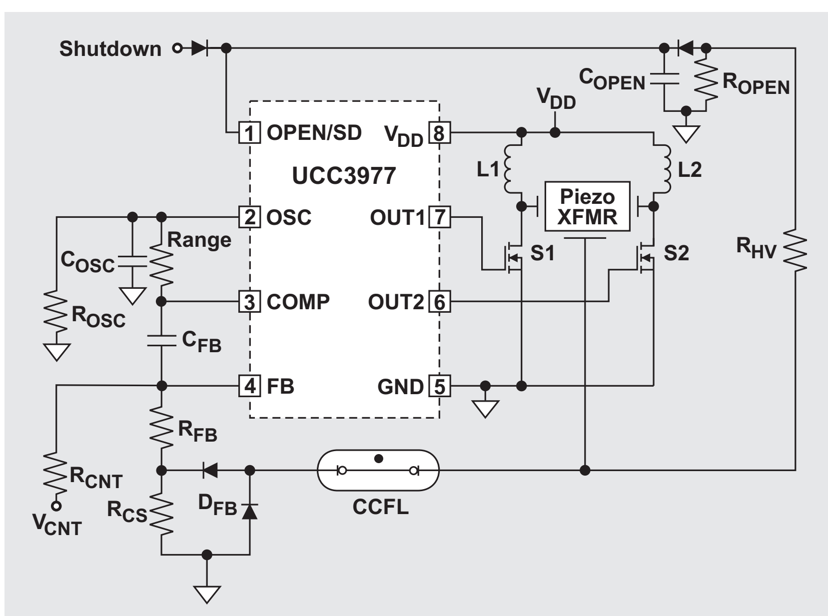


Power topologies

Several topologies exist for the resonant power stage shown in Figure 8. Input voltage range, lamp characteristics, and PZT characteristics determine the correct resonant power stage topology. Some of the more popular choices are the push-pull, half bridge, and full bridge.

Figure 9 shows a basic resonant push-pull topology. The push-pull topology requires two external inductors but has the advantage of providing increased voltage across the PZT primary. This allows a lamp to be operated from a lower input voltage.

Figure 9. Resonant push-pull topology



The explanation of circuit operation is fairly simple. For the push-pull circuit, MOSFETs S1 and S2 are driven out of phase with 50% duty cycle at variable frequency (see Figure 10, trace 2). Inductors L1 and L2 resonate with the PZT primary capacitance, forming half sinusoids at the drain of S1 (trace 1) and S2 (trace 4). The resulting voltage across the PZT primary is a near sinusoid (trace M1). Due to the high Q of the ceramic transformer, the lamp voltage, which is approximately 600 V in this particular application, is sinusoidal (trace 3).

To achieve 0-V switching, each drain voltage must return to 0 V 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

$$L < \frac{1}{4\pi^2 f^2 C_{INPUT}},$$

where C_{INPUT} is the input capacitance of the transformer primary.

PZT performance

High efficiency can be achieved by selecting the best power topology while matching the lamp, input voltage, and PZT characteristics. Figure 11 shows the performance of a 4-W-rated multilayer PZT operating a 600-V lamp with the push-pull topology at various input-voltage and lamp-current conditions. Electrical efficiency is greater than 85% at lower input voltages, decreasing at higher input voltages as the PZT gain is reduced. This circuit and lamp can operate from 2 Li-Ion cells (5 to 8.2 V). The same PZT and lamp would require 3 Li-Ion cells for a half-bridge topology but would yield similar efficiency.

Dimming by linearly reducing lamp current causes the efficiency to degrade, since the PZT is operated at less than optimal gain (see the 1.5-mA curve in Figure 11). Improved efficiency can be achieved by using burst-mode dimming. This dimming method involves running the lamp at full power but controlling average lamp current by modulating the on/off duty cycle at a frequency higher than the eye can detect (100 Hz, for example).

Figure 10. Push-pull waveforms

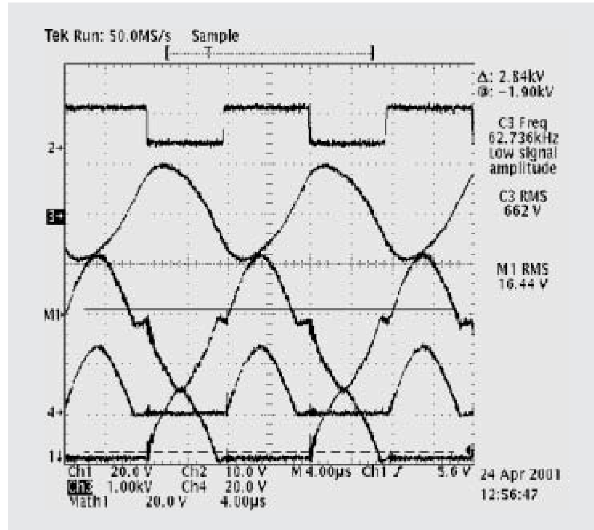


Figure 11. Typical PZT efficiency with input voltage and loading

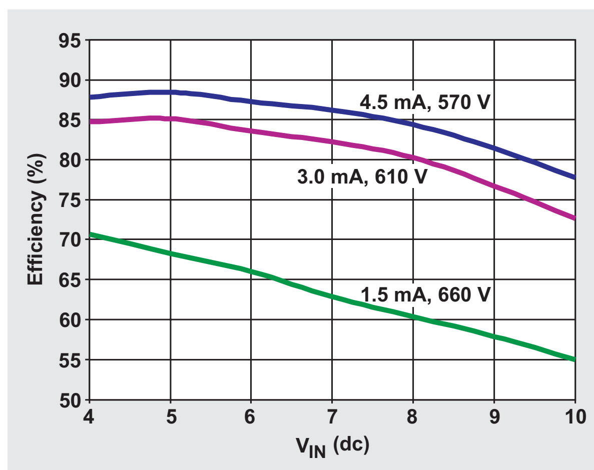


Figure 12 shows plots of PZT operating frequency over the same lamp conditions as Figure 11. As expected, frequency decreases at higher lamp currents as the PZT characteristics shift to a lower operating frequency when loaded (see Figure 5). Frequency increases linearly with input voltage, since the required V_{OUT}/V_{IN} gain to operate the lamp is decreased.

Summary

Piezoelectric transformers offer several advantages for size-constrained, high-performance portable applications. Designing a backlight supply with PZT technology requires a basic understanding of PZT characteristics and performance. A push-pull power topology, along with its various merits for driving a PZT, has been presented. The operation of longitudinal-mode PZTs in a variable-frequency control system has also been reviewed. A successful design will require matching the ceramic transformer to the application to attain high efficiency and stable performance. More information about the control ICs presented in this article can be obtained by contacting the author.

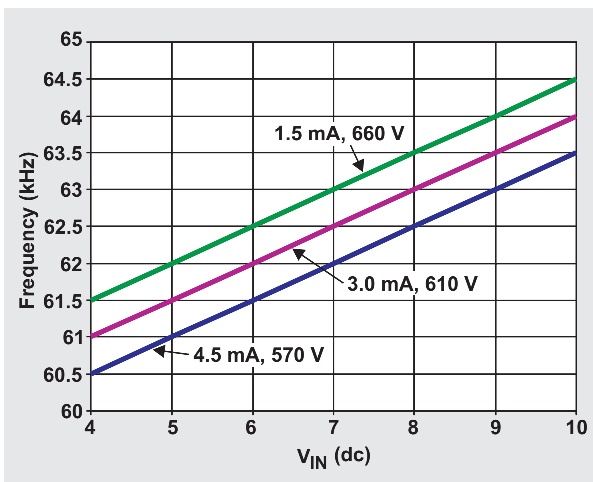
Reference

1. C.A. Rosen, "Ceramic Transformers and Filters," *Proceedings of the Electronic Components Symposium* (1956), p. 205.

Related Web sites

analog.ti.com
www.ti.com/sc/device/UCC3977

Figure 12. PZT operating frequency vs. input voltage and lamp load



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