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High-powered Backlight Inverter for LCD-TVs using Piezoelectric Transformers

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ABSTRACT: In this study, an innovative design of a high-voltage, high-powered, low-cost backlight inverter based on piezoelectric transformer technology for lighting long cold cathode fluorescent lamps (CCFLs) on large size LCD-TVs is presented. Three innovative design thoughts are introduced here. First, the quasi-modal electrode is used as the input electrode of the piezoelectric transformer. It is shown that a full modal filtering effect is achieved. In other words, all unwanted vibration modes of the structure are suppressed, which eliminates all higher harmonics of the input voltage. The second one is an innovative rigid support design which can enhance the modal filtering effect, which can also be used to replace thin input wiring and lead to lower contact resistance. The third innovative design uses direct switching on the rectified voltage from the power line (110/220V). With direct line voltage input, a single layer Rosen-type piezoelectric transformer (PT) can have enough gain to generate a high voltage to light long length CCFLs instead of using high cost multilayered PTs. A piezoelectric transformer-based inverter based on the above design considerations is built and verified in this study.

Key Words: piezoelectric transformer, LCD-TV backlight inverter, quasi-modal electrode.

INTRODUCTION

THERE are many advantages of using piezoelectric transformers (PTs) in LCD-TV backlight inverters. The advantages include possessing a higher energy transfer efficiency, very low temperature rise, compact size, and better safety. However, the high costs of the PT-based inverters prevent it from replacing all conventional coil-based designs in the market. The high cost mainly comes from two factors: one is the expensive proprietary control ICs which are produced in small quantities and the other is the expensive multi-layered PTs adopted in most of the designs (Yamamoto et al., 2001, 2002) for higher voltage step-up ratios. The material cost and the manufacturing cost of the multilayer PT is difficult to reduce. In this study, an innovative design is proposed. The new design employs a single layer PT to drive long length cold cathode fluorescent lamps (CCFLs) efficiently under high voltage and high power while keeping the material and manufacturing cost competitive when compared to conventional coil-based designs.

With the concept of modal sensors and actuators (Lee, 1987; Lee and Moon, 1990), a spatially distributed weighting function can be applied on the surface electrode of the PT to optimize the vibration mode of the PT and to suppress all unwanted vibration modes. According to the modal concept, the quasi-modal PT developed can reduce the input signal noise (Hsu et al., 2003). The input electrode occupies only half the length of the structure on Rosen-type PTs (Rosen, 1958). Thus, full modal electrodes which need to cover the complete length of the whole structure cannot be applied here (Huang, 2004).

However, later it is shown that, when the length of the quasi-modal electrode is equal to half the length of the PT, the third- and fifth-order harmonics of the input driving signal will be completely filtered out. This effect is almost equivalent to that of the full modal filtering effect. The modal filtering effect enables to adopt a square waveform input voltage to drive the PT without exciting a higher-order structural resonance. This in turn corresponds to the harmonics of the driving signal and keeps the efficiency high when compared to ordinary sinusoidal waveform voltage driving conditions. The square waveform input driving signal can be generated with a simple half-bridge circuit topology without the need for additional high-powered inductors in the circuit. The inductorless design completely eliminates electromagnetic interference (EMI) problems, and also lowers the cost of the driving circuitry. However, due to the manufacturing tolerance on the surface electrode

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Figures 2–4 and 6–8 appear in color online: http://jim.sagepub.com

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shape and the dimensions of the PT itself, there would still be a modal spillover energy which goes into the other modes. To further decrease the spillover energy so as to increase the driving efficiency, a rigid support device with its clamping point on the nodal points of the operating vibrating mode is used in the new design. On the basis of the same modal concept, a rigid support on the nodal points of the operating second mode provides a fixed boundary condition on the quarter-length position of the Rosen-type PT. The fixed boundary condition on the quarter-length will suppress all even vibration modes that have a nonzero modal displacement on the quarter-length positions.

Furthermore, thin wires were used to solder on the nodal point of the PT to deliver power into the transformer in a conventional design. For the applications on large-sized LCD-TVs, the driving power will be much higher on the longer length CCFLs. The corresponding high current may cause a high temperature rise due to the high contact resistance associated with the thin wires attached to the input electrodes. The extraordinary temperature rise may lead to permanent damage of the transformer in a poor design. The rigid support device was made of copper slices which significantly reduces the contact resistance when compared to traditional thin input wiring. It can deliver a high power to the transformer with very little wasted energy on the contact resistance and thus can keep the temperature rise low.

To overcome the second factor that prevents the reduction in cost of PT-based inverter design, a single layer quasi-modal PT was used to light the large LCD-TV backlight module in this study. It is to be noted that the driving voltage of the inverter design for long length CCFLs on large sized LCD-TV backlights is much higher than that for the typical LCD monitor. In order to lower the manufacturing cost and to enhance the power efficiency, the power line voltage (110/220 V) can be used to directly drive the single-layer PT after rectification for the long length CCFLs (650 mm, 7 W and 710 mm, 8 W). When driving with the rectified line voltage directly, a Rosen-type single-layer PT can be used to generate sufficiently high voltage to light the long CCFLs. Compared with using expensive and less reliable multilayer PTs, this design provides a feasible solution for lighting long length CCFLs on large sized LCD-TVs using PTs.

QUASI-MODAL ELECTRODES AND RIGID SUPPORT DEVICES

The layout of the PT with a quasi-modal input electrode is shown in Figure 1. To examine the modal filtering effect of the quasi-modal electrode, the theoretical modeling is first detailed here.

The governing equation and the boundary conditions of a Rosen-type PT are

$$c_{11}^{E}\frac{\partial^2 u}{\partial x^2}-\rho\frac{\partial^2 u}{\partial t^2}=E_3^{\mathrm{in}}e_{31}\frac{\partial A(x)}{\partial x}, \quad (1)$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=0}=\left.\frac{e_{31}E_3^{\mathrm{in}}(t)}{c_{11}^{E}}\right|_{x=0}, \quad \text{and} \quad \left.\frac{\partial u}{\partial x}\right|_{x=l}=\frac{h_{33}D_3^{\mathrm{out}}(l,t)}{c_{33}^{D}}, \quad (2)$$

where $u(x, t)$ is the displacement along the x-direction (1-direction). By using the eigen-function expansion, the displacement field of the PT along the x-direction can be represented as

$$u(x,t)=\sum_{i=1}^{\infty}A_i(t)\varphi_i(x), \quad (3)$$

$$\frac{\mathrm{d}^2\varphi_i}{\mathrm{d}x^2}+\lambda_i\varphi_i=0, \quad \frac{\mathrm{d}\varphi_i}{\mathrm{d}x}(0)=0\frac{\mathrm{d}\varphi_i}{\mathrm{d}x}(l)=0, \quad (4)$$

where $\varphi_i(x)$ is the ith vibration mode shape function, $A(x)$ is the shape function of the input electrode, and $\varphi_i(x)$ forms the orthogonal modal coordinates that is used as the expansion basis. By using Equations (3) and (4), the governing equation of a traditional Rosen-type PT can be written as

$$\frac{\mathrm{d}^2A_i(t)}{\mathrm{d}t^2}+\frac{c_{11}^{E}}{\rho}\lambda_iA_i(t)$$
$$=q_i(t)+\frac{c_{11}^{E}}{\rho}\sqrt{\frac{2}{l}}\left[(-1)^{i+1}\frac{h_{33}D_3^{\mathrm{out}}(l,t)}{c_{33}^{D}}-\left.\frac{e_{31}E_3^{\mathrm{in}}(t)}{c_{11}^{E}}\right|_{x=0}\right],$$

and

$$q_i(t)=\int_0^l\left(-\frac{e_{31}E_3^{\mathrm{in}}(t)}{\rho}\frac{\partial A(x)}{\partial x}\right)\varphi_i\,\mathrm{d}x;$$

$$\varphi_i(x)=\sqrt{\frac{2}{l}}\cos\left(\frac{i\pi x}{l}\right), \quad (5)$$

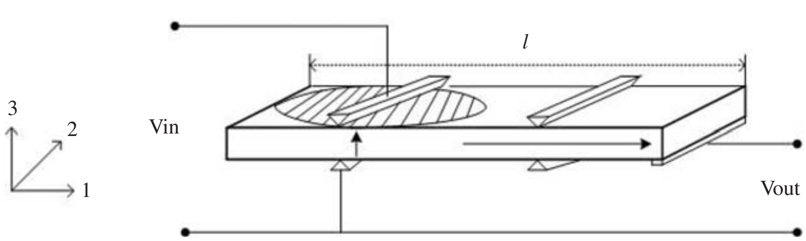

Figure 1. *Quasi-modal PT with rigid support.*

where $q_i(t)$ is the distributed forced term induced by the input electric field E_3^{in}, and the last two terms are obtained from the boundary conditions. In order to simplify the influence of the boundary condition, it can be considered that the PT operates under an open output condition. The output current of the PT under an open condition is zero, and thus the output electric displacement $D_3^{\text{out}}(l,t)$ is also zero. As the input electric field acts as a distributed force exerted through the surface electrode to the PT, the last term of Equation (5) on the right-hand side will be zero in the boundary. Equation (5) can then be rewritten as

$$\frac{\mathrm{d}^2 A_i(t)}{\mathrm{d}t^2} + \frac{c_{11}^E}{\rho}\lambda_i A_i(t) = q_i(t),$$
$$q_i(t) = \int_0^l \left(-\frac{e_{31}E_3^{\text{in}}(t)}{\rho}\frac{\partial A(x)}{\partial x}\right)\varphi_i\,\mathrm{d}x, \tag{6}$$

where the PT is driven by using a sinusoidal input voltage, the input electric field E_3^{in} can be represented in sinusoidal form as

$$E_3^{\text{in}}(t) = \left|E_3^{\text{in}}\right|\cos\omega t, \tag{7}$$

where ω stands for the angular frequency of the input electric field. By using Equations (6) and (7), the governing equation can again be rewritten as

$$\frac{\mathrm{d}^2 A_i(t)}{\mathrm{d}t^2} + \frac{c_{11}^E}{\rho}\lambda_i A_i(t) = r_i\cos\omega t, \tag{8}$$

and

$$r_i = -\frac{e_{31}\left|E_3^{\text{in}}\right|}{\rho}\sqrt{\frac{2}{l}}\left[\int_0^l \frac{\partial A(x)}{\partial x}\cos\left(\frac{i\pi x}{l}\right)\mathrm{d}x\right]. \tag{9}$$

The r_i is referred to as the driving factor here and represents the amplitude of the forced term which drives the vibration of the transformer associated with the input electric field. The driving factor can be used to examine the modal effect. If higher vibration modes are filtered out by the modal effect, the associated driving factors will be zero, which then means no vibration was excited in these modes. To further simulate the nature of higher attenuation on higher vibration modes, a normalized driving factor r_{ib} is obtained by dividing i^2. The normalized driving factor can be represented as

$$r_{ib} = -\frac{1}{i^2}\frac{r_i}{\left(e_{31}\left|E_3^{\text{in}}\right|/\rho\right)\sqrt{(2/l)}}. \tag{10}$$

The normalized driving factor can then be compared on different modes to verify the modal filtering effect on the PTs with a quasi-modal and uniformly distributed electrodes. The electrode shape functions for the quasi-modal and for the uniformly distributed PT are

$$A(x)_{\text{quasi-modal}} = \sin\left(\frac{2\pi x}{l}\right)\{H[x] - H[x-al]\}; \tag{11}$$

$$A(x)_{\text{distributed}} = H[x] - H[x-al], \tag{12}$$

where $H[x]$ is the Heaviside step function. By substituting Equations (11) and (12) into Equation (10), the normalized driving factors for the quasi-modal and distributed electrode PTs are obtained as

$$r_{ib} = \frac{1}{i^2}\left(\frac{2\pi}{l}\right)\int_0^{(1/2)l}\cos\left(\frac{2\pi x}{l}\right)\cos\left(\frac{i\pi x}{l}\right)\mathrm{d}x$$
$$i = 1,2,3,\ldots \text{ for quasi-modal electrode}; \tag{13}$$

$$r_{ib} = \frac{1}{i^2}\left[1-\cos\left(\frac{i\pi}{2}\right)\right]$$
$$i = 1,2,3,\ldots \text{ for distributed electrode}. \tag{14}$$

The simulated results of the driving factor r_{ib} for the case where the length of the input electrode is equal to 1/2 is shown in Figure 2. It is clear from Figure 2 that the sixth and the tenth driving factor of the PT with a quasi-modal electrode is zero. It also indicates that the high-frequency noise will be filtered out in quasi-modal PTs, which means that a square waveform can be used to drive the transformer without exciting a higher structural resonance. Despite the filtering effect associated with the PTs designed to have quasi-modal electrode shape, some modal spillover noises still remain. In addition to manufacturing tolerances and induced noise, the transverse vibration noise is not modeled in the one-dimensional governing equation, i.e., Equation (1), used to design the quasi-modal PT. In order to reduce the modal spillover noise, a rigid support device is designed and developed to suppress the spillover vibration noise. The design thought of the rigid support is shown in Figure 1.

The quasi-modal PT has two nodal points at the operating second transverse vibration mode along the x-direction, and the rigid support device is designed to physically attach to the two nodal points on this mode. The rigid support device consists of copper slices to hold the PT at the nodal points. The main function of the strong rigid copper slice is to limit the PT vibration on the fixed supporting nodal points, and thus

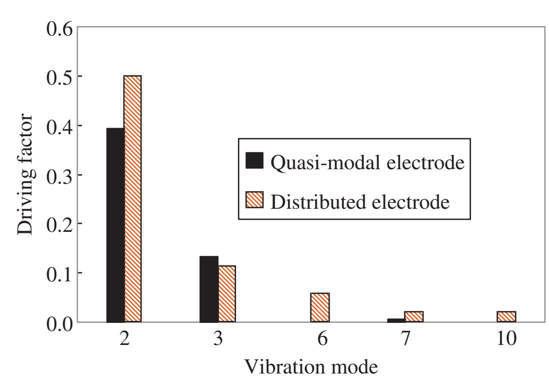

***Figure 2.** Theoretical result of driving factor for two different types of piezoelectric transformers.*

eliminate the vibration noise induced by even transverse vibration modes, and also all thickness vibration modes in the z-direction (the 3-direction in Figure 1). The rigid copper support device can improve the modal-filtering performance and also the overall driving efficiency. To verify the modal filter effect of the right support device, the step-up ratios of three different samples with and without the rigid supports and the quasi-modal electrode were measured and the results are shown in Figure 3. The measurement samples were Rosen-type PTs manufactured by the Eleceram Technology Co. Ltd, Taiwan. The dimensions of all the three transformer samples were 53 mm long $\times$7.5 mm wide $\times$2.6 mm high. An Agilent 4395 network analyzer was used to measure the step-up ratio of the three transformers. The first transverse vibration mode frequency was about 30 kHz, and the second transverse vibration resonance was used to design the Rosen-type PT. If the square waveform has to be used to drive the PT, the third and the fifth harmonics of the square waveform that matches the sixth and tenth resonance frequency of the structure in a transverse direction need to be considered.

In Figure 3, the UN line shows the step-up ratio of the PT sample with an uniform input electrode and without rigid supports. There is no modal filtering effect at all and thus this configuration can be used as the baseline for the comparison. The QMN line shows the

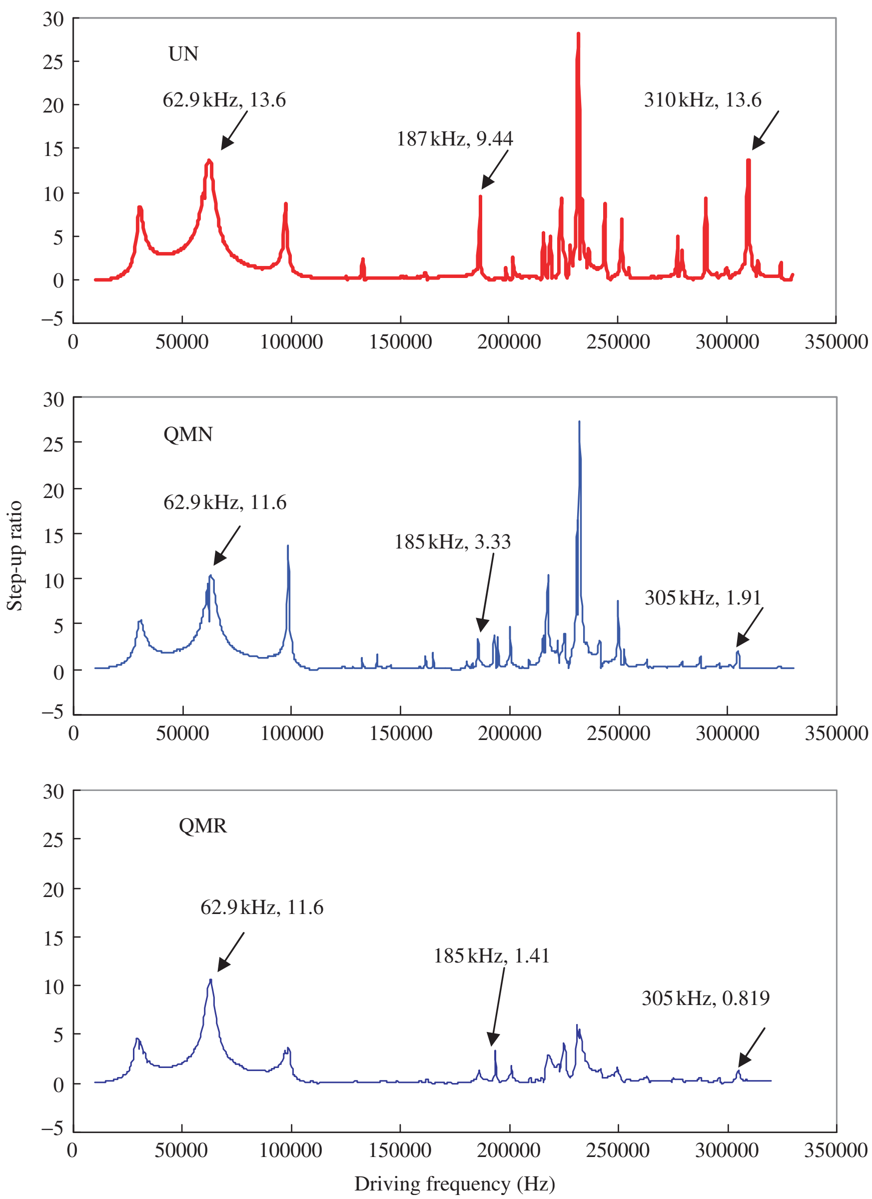

Figure 3. The transfer functions of three transformers with and without the quasi-modal electrode and the rigid supports, where QMN is with the quasi-modal electrode without rigid supports; QMR is with the quasi-modal electrode and the rigid supports, and UN is with uniform electrode without rigid supports.

transformer with a quasi-modal input electrode shape but without rigid supports, and the gain of the sixth and the tenth mode are 3.33 and 1.91 respectively when compared to 9.44 and 13.66 in the UN case. These data clearly demonstrate the modal filtering effect which suppresses the gains of the sixth and the tenth transverse vibration when compared to the UN case. The QMR line shows the transformer with the quasi-modal electrode and rigid supports, which indicates that the gain of the sixth and the tenth modes are 1.41 and 0.819 respectively when compared to 3.33 and 1.91 discovered in the QMN case. This data demonstrate that the gains of the sixth and the tenth transverse vibration modes are further reduced by the rigid support device when compared with the QMN case.

In order to further verify the modal filtering effect more clearly, another measurement was conducted. An Agilent 4294 impedance analyzer was used to measure the input impedance of the PTs with and without the quasi-modal electrode. Figure 4(a) shows the magnitude of the input impedance, and Figure 4(b) shows the phase difference of the input impedance. Again, the authors focused on the sixth and the tenth resonance peaks of the transformer that matches the third and the fifth harmonics of the square driving waveform. It can be seen clearly that the sixth and the tenth resonance and anti-resonance peaks of the transformer with a quasi-modal electrode disappear from both the impedance magnitude and phase plot. Except for the frequencies close to the resonance

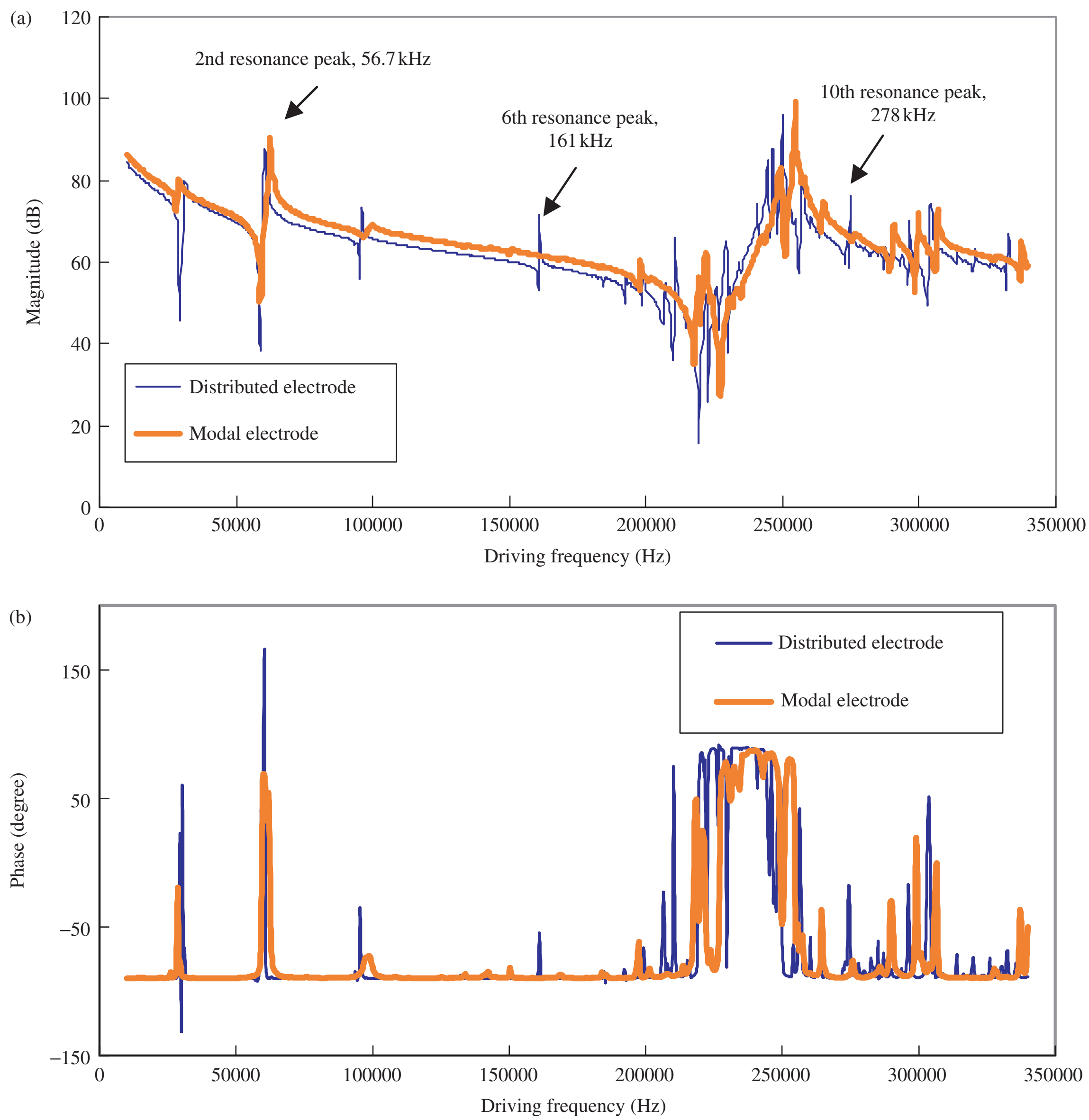

Figure 4. *The input impedance of piezoelectric transformer with distributed and modal electrodes. (a) Magnitude (kΩ) and (b) Phase (degree).*

of the PT, the input impedance of the transformer is dominated by the static capacitance formed by parallel input electrodes. When the transformer is driven to the second mode with the square waveform, the third and the fifth harmonics of the driving waveform will be excited about the sixth and the tenth resonance of the transformer. The effect is that the overall efficiency is thus lowered due to the poor driving efficiency at the higher modes. Transformers with quasi-modal electrodes do not have the sixth and the tenth resonance peaks, and thus at the frequencies of the third and the fifth harmonics of the driving waveform, no resonance will be excited and only the capacitance effect will dominate these frequencies.

DRIVING CIRCUIT FOR LARGE SIZED LCD-TV BACKLIGHTS

In order to lower the total cost of the PT-based inverter, a single layer Rosen-type PT was chosen in this design. The single layer PT has a poor step-up ratio, as the driving circuit must provide a higher input voltage for generating a sufficiently high voltage on lighting the long length CCFLs. As the panel size of LCD-TVs keeps getting larger, the length of the CCFLs has also extended correspondingly. For example, the length of the CCFL on a 30 in. LCD-TV is 652 mm, and the length of the CCFL on a 32 in. LCD-TV is 710 mm. Longer CCFLs require a higher voltage to light up. With a direct rectified line voltage from a power outlet (110/220V), an inverter can provide an adequate voltage level to light up these long length CCFLs even for the case that only a single layer Rosen-type PT was used. Driven by using the directly rectified line voltage also eliminates the step-down DC converters in front of the inverters, which again increases the overall driving efficiency. The schematic of the driving circuit is shown in Figure 5. The integrated circuit UCC3976 made by Texas Instruments was used to track the optimal driving frequency close to the second resonance of the PT. Another integrated circuit IR2104 was used to drive the N-type MOSFET IRF840 to the high side of the half-bridge block in the circuit. The resistor RCS is used to adjust the constant feedback current level and ROSC, COSC, and RRANGE are used to tune the sweep frequency range to light the long CCFL. Voltage VB is used to adjust the brightness of the CCFL. The rectified power line voltage (110/220V) is supplied to the half-bridge directly and the square waveform generated from the half bridge can be fed into the PT to light up the CCFLs.

EXPERIMENTAL RESULTS

There are three important parameters normally used to evaluate the performance of the PT-based inverter designs. They are the step-up ratio, energy transfer efficiency, and driving frequency. In order to use PTs to light CCFLs under an optimal working frequency, first the characteristics of the PTs and the CCFLs are to be obtained. A constant input voltage of 80 Vrms with different frequencies is used to drive the PT. The step-up ratio and the energy transfer efficiency on different loading impedance conditions are shown in Figure 6(a) and (b). A Tektronix high voltage probe was used to measure the input and output voltage, a small resistance of 100 Ω was serially connected with the load impedances to measure the output current. The input current was measured using a Tektronix current probe A6302 and a current amplifier AM503B. The experimental result shown in Figure 6 indicates

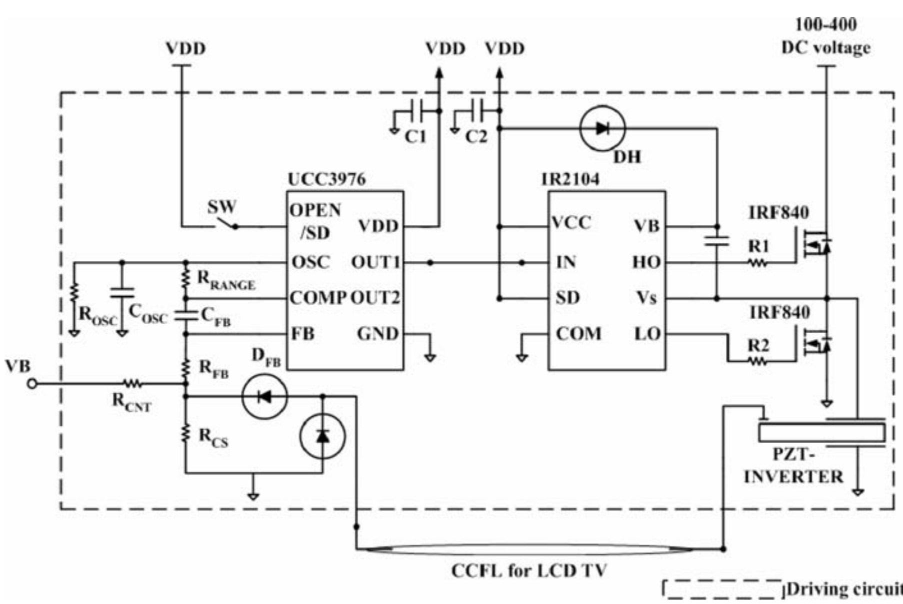

Figure 5. The driving circuit schematic for the PT.

that the optimal working frequency is located between the frequencies for the maximum step-up ratio and the maximum energy transfer efficiency (Lin, 1997). However, if the PT has to be made to work around the optimal driving frequency, the PT must be designed according to the load impedance. Figure 7 shows the relationship between the maximum energy transfer efficiency and load impedance. The efficiency of the PT is greater than 90% when the load impedance is around 200 kΩ.

The impedance of a 650 mm CCFL was measured and shown in Figure 8(a). The result shows that the impedance of the 650 mm CCFL is about 200 kΩ, which can vary from 150 kΩ to 300 kΩ. The impedance of the

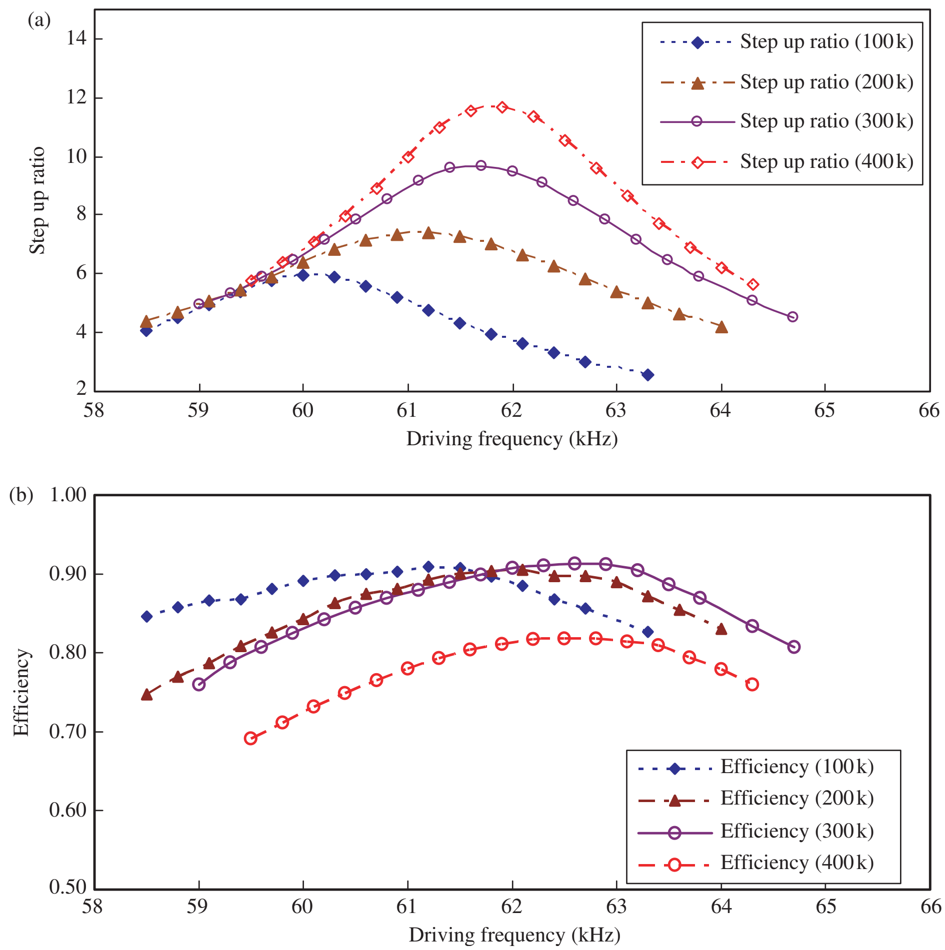

Figure 6. *Step-up ratio and energy transfer efficiency of the quasi-modal PT. (a) Step-up ratio and (b) efficiency.*

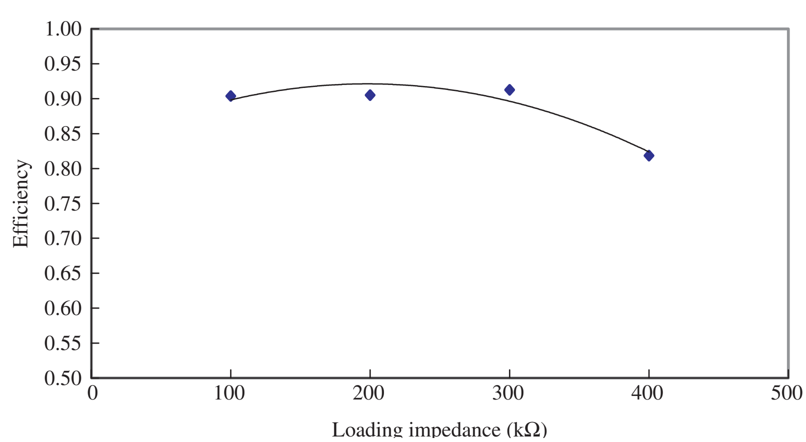

Figure 7. *The energy transfer efficiency of the PT operated under different loading impedance.*

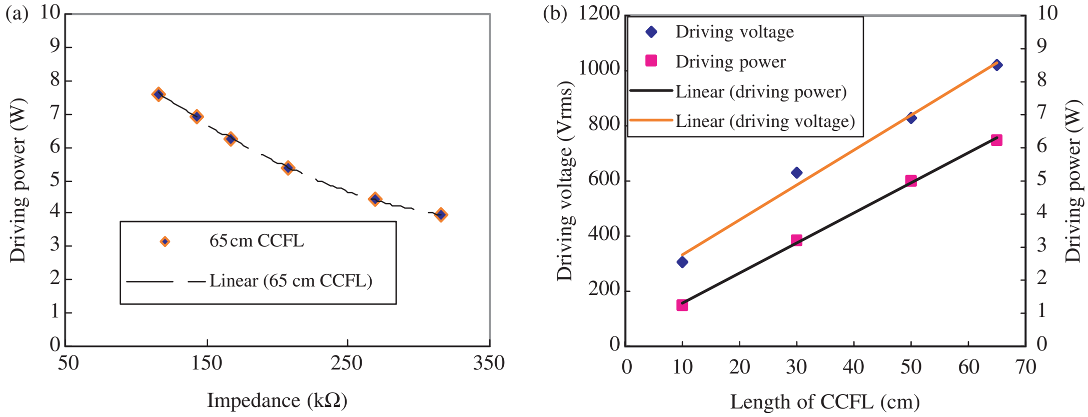

Figure 8. *(a) The impedance of CCFL under different driving powers and (b) driving voltage and driving power of different length CCFLs.*

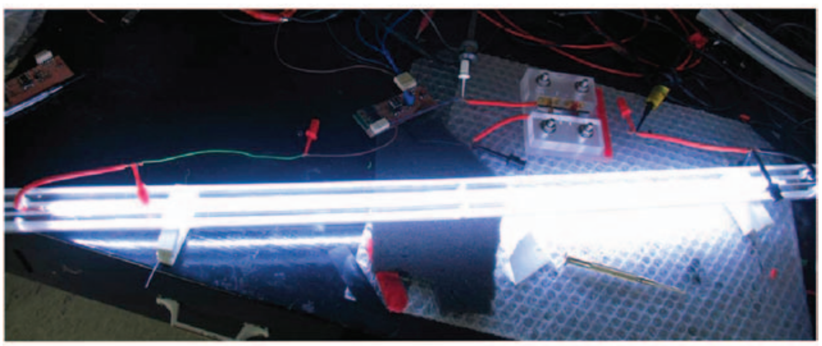

Figure 9. *The PT based inverter lit a 650 mm long CCFL.*

CCFL changes according to the driving power applied. Figure 8(b) shows the required driving voltage and power for different lengths of CCFLs. The driving voltage and power is almost linearly proportional to the length of CCFLs. The driving voltage and power of 650 mm long CCFLs can reach almost 1000 Vrms and 8 W. This requirement poses a grand challenge in terms of an efficient inverter design. Furthermore, from Figure 6, it can be seen that the energy transfer efficiency of this PT is over 90% when the load impedance is in the range between 100 and 300 kΩ. The impedance of the 650 mm CCFL fits perfectly in this range, i.e., the impedance of the 650 mm CCFL matches the impedance of the PT. In order to track the optimal operating frequency near the resonance, a UCC3976 was used to control the driving frequency which automatically tracks the driving frequency to reach the preset tube current. From the experimental results obtained when using the PT to drive the 650 mm CCFL mentioned earlier, the optimal working frequency was found to be between 61 and 62 kHz. Figure 9 shows an inverter, which incorporates all the design thoughts mentioned, that can successfully light up a 650 mm long CCFL. The temperature rise of the PT in the inverter was found to be within 10°C after more than 2 h running. Figure 10(a) shows the waveforms of the input and output voltages taken with an oscilloscope, where Channel 1 shows the rectified input voltage and Channel 3 shows the output voltage of the quasi-modal PT. Figure 10(b) shows the FFT spectrum of the input/output voltage, where Channel A is the FFT spectrum of the output voltage and Channel B is the FFT spectrum of the input voltage from the PT. It can be clearly seen from the FFT spectrum that high frequency noise in the input voltage was filtered out by the quasi-modal electrode and the rigid supports. From the spectrum of the output current it can be seen that only the single frequency of the operating second mode is delivered by the PT.

CONCLUSIONS

In this study, a PT-based LCD-TV backlight inverter was designed and verified. This newly developed design can be used to light 650 mm long CCFLs for LCD-TVs successfully for a long period of time with very low temperature rises. An innovative half-bridge driving circuit driven by a direct rectified power line voltage (110/220 V) to drive the PTs was shown to eliminate the need to use expensive multilayer PTs. The overall driving efficiency is thus much higher without the use of DC converters within the backlight modules. The quasi-modal electrode and the rigid support

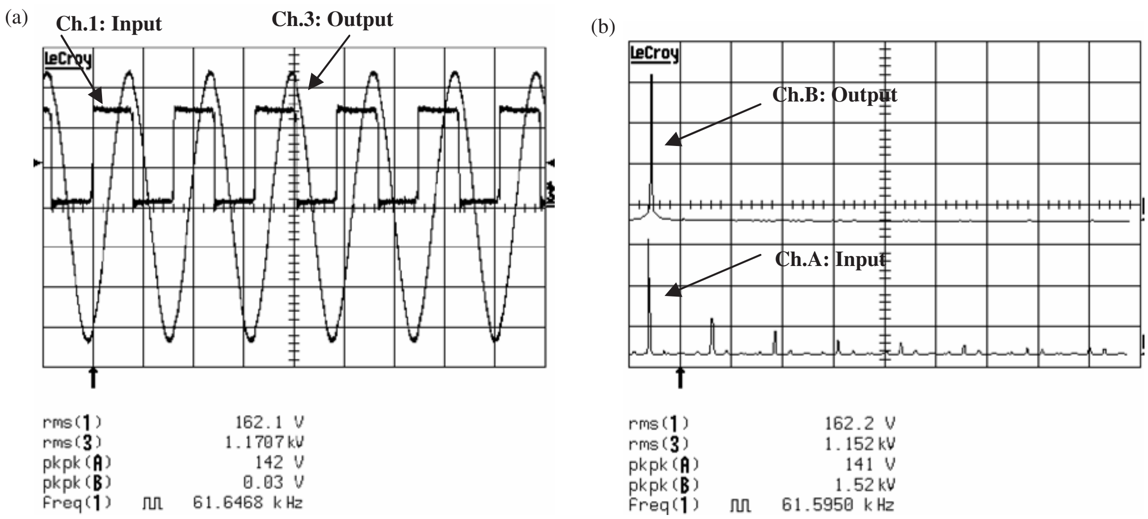

Figure 10. *(a) Rectified input voltage and output voltage of the quasi-modal PT and (b) Channel A shows the FFT spectrum of the rectified input voltage, Channel B shows the FFT spectrum of the input voltage and Channel C means the FFT (output current 1 mA/10 mV).*

device were shown to have the ability to filter out undesirable vibration modes, which in effect improves the driving efficiency when operating under a square waveform input condition. The PT-based design proposed in this study possesses a very high driving efficiency and a very low temperature rise. Most importantly, this newly designed configuration is shown to be low cost and thus more cost-effective when compared to conventional coil-based inverters. Thus, this new configuration can be a commercially viable solution towards the use of PTs for LCD-TV backlight applications.

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