A Piezoelectric Cold Cathode Fluorescent Lamp Driver
Operating from a 5 Volt Bus

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Abstract - Cold Cathode Fluorescent Lamps (CCFL) are used as backlight for Liquid Crystal Displays (LCD). To operate the lamps, the driver needs to have an open voltage of above 1000Vrms for igniting the lamp and a nominal output current of about 4mA rms at voltage of about 600Vrms. In this study we investigated CCFL driver that operates from a 5 Volt bus which is common in all digital systems. The driver employs a Rosen type piezoelectric transformer to boost the voltage to the needed levels. The piezoelectric transformer is fed by a 100Vrms voltage obtained at the output of a forward-flyback stage. The theoretical derivations of the study were verified by measurement on an experimental unit. The experimental inverter was found effective for igniting and driving a CCFL. Total efficiency, from 5V to load, was measured to be 70%. It was found that after a slightly modification the ballast can be used to drive two serially connected CCFL.

I. INTRODUCTION

Cold Cathode Fluorescent Lamps (CCFL) are used as backlight for Liquid Crystal Displays (LCD). A typical lamp for this application requires high open circuit voltage for ignition (above 1000Vrms) and about 4mA rms nominal current at an operating voltage of 600Vrms. The conventional method of driving CCFLs is by an inverter that includes a high turns ratio transformer. Considering the high open voltage needed, the required winding isolation of these transformers makes them relatively large and the high turns ratio causes a considerable power loss.

An alternative approach to the design is the application of a Rosen type Piezoelectric Transformer (PT) that has important advantages in the present applications [1-11]. The primary one being the fact that it possesses an inherent high voltage isolation while still having small dimensions. Of particular interest is the fact that practical PTs have a very low profile (a height of 1-2mm) - an attribute which is compatible with the need for low profile units in laptop computers.

II. THE GENERAL CHARACTERISTICS OF THE PT

The general equivalent circuit of a PT when operating around one of its mechanical resonant frequencies is depicted in Fig. 1a. In this figure we replaced the output transformer shown in earlier papers, by two dependent sources: $\frac{V_{Co}}{n}$ and $\frac{I_{Lr}}{n}$. This presentation is valid even when the output is exposed to a DC voltage. The electromagnetic transformer presentation (used by other authors) would be undesirable in such a case, especially when the equivalent circuit is studied by circuit simulation.

From the power transfer point of view the basic equivalent circuit can be simplified to that of Fig. 1b in which the network at the secondary is reflected to the primary. Note that the input capacitance ($C_{in}$ of Fig. 1a) is absent in Fig. 1b since it does not affect the power transfer of the PT. The values of the reflected resistance ($R_{o}'$), reflected capacitance ($C_{o}'$) and reflected output voltage ($V_{out}'$) will be:

$$R_{o} = \frac{R_{o}}{n^2}$$

(1)

$$C_{o} = n^2 C_{o}$$

(2)

$$V_{out} = \frac{V_{out}}{n}$$

(3)

where $R_{o}$ is the load resistance, $C_{o}$ is the output capacitance, $V_{out}$ is the output voltage and $n$ is the mechanical output transfer ratio.

Further simplification can be achieved by converting the parallel network $R_{o}', C_{o}'$ to a series network (Fig. 1c) in which the series resistance $R_{o}''$ and series capacitance $C_{o}''$ are defined as:
\[ R_0'' = \frac{R_0'}{1 + (\omega C_0' R_0')^2} \]  
(4)

\[ C_0'' = C_0' \frac{1 + (\omega C_0' R_0')^2}{(\omega C_0' R_0')^2} \]  
(5)

where \( \omega \) is the operating frequency.

Examination of the dependence of \( R_0'' \) and \( C_0'' \) on \( R_0' \) reveals some interesting and important features. As \( R_0' \) varies from 0 to \( \infty \), \( R_0'' \) varies from zero back to zero with a maximum \( R_{om}'' \) at:

\[ R_{om}' = \frac{1}{\omega C_0} \]  
(6)

On the other hand, over the entire range of \( R_0' \), series capacitance \( C_0'' \) varies from infinity back to the value of \( C_0' \).

Based on this simple observation some general conclusions can already be drawn:

1. For a given reflected load \( R_0' \), maximum output voltage will be obtained at the resonant frequency \( \omega_m \) (Fig. 1):

\[ \omega_m = \frac{1}{\sqrt{L_r C_{eq}}} \]  
(7)

where \( C_{eq} \) is the series value of \( C_r \) and \( C_0'' \):

\[ C_{eq} = \frac{C_r C_0''}{C_r + C_0''} \]  
(8)

2. The range of the series resonant frequency is dictated by the range of \( C_0'' \):

\[ \omega_{rs} < \omega_m < \omega_{r0} \]  
(9)

where \( \omega_{rs} \) is the resonant frequency at short circuit (\( R_0 = 0 \)):

\[ \omega_{rs} = \frac{1}{\sqrt{L_r C_r}} \]  
(10)

and \( \omega_{r0} \) is the series resonant frequency at open circuit (\( R_0 = \infty \)):

\[ \omega_{r0} = \frac{1}{{\sqrt {L_r \frac {C_r C_0'}{C_r + C_0'}}}} \]  
(11)

3. For any given load \( R_0 \), power can be controlled by shifting the frequency above or below \( \omega_{pm} \). This is, in fact, the method used in inverters and converters operating in frequency-shift control mode.

4. For any given load \( (R_0) \) the fraction of power transferred to the load will depend on the ratio of \( R_0'' \) to \( R_m \) (Fig. 1c).

5. Maximum power will be delivered to the load when \( R_0'' = R_m \). Since \( R_0'' \) is convex, two \( R_0'' \) (and hence two \( R_0' \)) satisfy the maximum power condition.

6. At maximum output power \( (R_0'' = R_m) \) the PT efficiency will be 0.5.

7. Maximum efficiency is obtained at the peak of \( R_0'' \).

8. Since maximum efficiency point corresponds to the maximum \( R_0'' \), it also corresponds to a local minimum of output power (per a given input voltage).

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**Fig. 1. Equivalent circuits of a piezoelectric transformer (PT):**

(a) - general model; (b) - after reflecting the output capacitance and load resistance to the primary; (c) - after parallel to series transformation.
Results of a rigorous analysis support the intuitive reasoning given above. Further, the generic PT behavior can be described by:

\[ \frac{V_{out}}{V_{in}} = \frac{n}{\sqrt{Y}} \]  

(12)

where

\[ Y = 1 + \left( \frac{\omega}{\omega_{rs}} \right)^2 \left( \frac{R_m}{R_0} \right)^2 \]

(13)

\[ \omega_{rs} \leq \omega_0 \]

(14)

\[ Q = \omega_{rs} C_0 R_0 \]

(15)

\[ Q_m = \frac{1}{\omega_{rs} C_0 R_m} \]

(16)

Q is the electrical quality factor and \( Q_m \) is the mechanical quality factor.

\( k_{21} \) has a maximum value \( (k_{21m}) \) at a frequency ratio \( \omega_{m} \) corresponding to the minimal value of \( Y \).

The output power \( P_0 \) can be calculated from the following expression:

\[ P_0 = \left( k_{21m} V_{in} \right)^2 \]

(17)

Efficiency is found to be:

\[ \eta = \frac{R_0^{-''}}{R_0^{-''} + R_m} \]

(18)

where \( R_0^{-''} \) is the reflected load resistance in the equivalent series circuit \( R_0^{-''} C_0 \) (Fig. 1c).

III. THE CCFL

The VA characteristics of the experimental lamp were measured and are given in Fig. 2. The data reveal that the lamp requires an ignition voltage in the neighborhood of 1000Vrms. At the operating point, the required voltage is about 600Vrms. Prior to ignition the lamp represents a very high impedance. At the operating point the equivalent resistance is about 150kOhm.

The drive requirements are compatible with the PT which is basically a resonant circuit that can develop very high open circuit voltage as required for ignition. However, to meet the operating point requirements the gain of the PT needs to be very high if a 5V supply is used at the primary side. In such a case the loaded PT gain needs to be 400. Since no commercial PT will meet this requirement, we designed the ballast of this study as a two stage system.

![Fig. 2. CCFL characteristics.](image)

IV. THE CCFL DRIVER

The proposed CCFL driver (Fig. 3) is built around a forward-flyback inverter that feeds the PT. \( T_1 \) is an integrated-magnetic element that functions as a transformer and inductor (\( L_m \) is the magnetization inductance and \( L_{kg2} \) is the leakage inductance reflected to the secondary). This topology is similar to the power stage is given in [12]. The function of the first inverter stage is to boost the 5V voltage to about 100Vrms. The PT provides an additional voltage gain to ignite the lamp and then run it under nominal conditions. In this case, the open circuit gain required of the PT is only around 10.

Under loaded condition, and assuming operation at resonant, the PT can be represented by a simplified RC circuit including \( C_{in}, R_m, R_0^{-''} \) (Fig. 4). SPICE simulation was used to optimize the parameters of the circuit to ensure sufficient gain and soft switching (Fig. 5).

![Fig. 3. CCFL driver.](image)
Fig. 3. Basic circuit configuration of proposed CCFL driver with Rosen-type PT.

Fig. 4. The equivalent circuit of the CCFL at the operating point of the lamp when run at the resonant frequency of the PT.

V. EXPERIMENTAL

The parameters of the experimental Rosen type PT (PXE43 48x8x2.2mm) were as follows (Fig. 1a):

\[ C_{in} = 735 \text{ pF}; \quad C_{o} = 5.5 \text{ pF}; \quad C_{p} = 24.5 \text{ pF} \]
\[ L_{r} = 201 \text{ mH}; \quad R_{m} = 63 \text{ Ohm}; \quad n = 5.6 \]

The voltage gain of the PT for various load resistors was found to match the simulation results based on the models presented above (Fig. 5). It was found that the gain at 150kOhm load (the CCFL resistance at the nominal operating point) was around 10. The inverter section was thus designed to complement the gain such that the nominal lamp voltage will be reached with a input bus voltage of 5V.

General description of the experimental driver is given in Fig. 6. The driver was based on a self oscillation circuit that locked into the resonant frequency of the PT. The transistor used was 2SK1792 (R_{ds(on)} = 15 \text{ mOhm}; V_{ds} = 60V). The magnetic element was wound on pot core (PI4/8).

The open voltage of the experimental driver was measured to be about 2.5kV, more than ample for igniting the experimental lamp. Good match was achieved between the output characteristic of the driver and the V-A characteristic of the lamp (Fig. 7). The crossing between the two operating curves insures a steady state condition despite the negative incremental resistance of the lamp.

A cursory experiment was carried out to check the possibility of operating two serially connected CCFL by a single driver. It was found that the open circuit voltage was sufficient to strike the two lamps. The operating point was about 3mA, below the 4mA considered as the nominal current of the lamps. It is plausible that the nominal current can be reached by redesign of the magnetic element. This was not tested in this study.

The performance of the driver is shown in Fig. 8. Over all efficiency (5V to electrical drive of the lamp) was found to reach 70% at the nominal voltage. This is a very good result considering the fact that such a low input voltage is used and that the drive includes, in fact, two power stages.

Fig. 5. PT output voltage (SPICE simulation and experimental, \( V_{in}=30V \))

Fig. 6. The experimental driver.

Fig. 7. Output of experimental driver and lamps VA characteristics.
VI. CONCLUSIONS

The proposed topology is unique in its ability to drive a CCFL from a 5V bus. The small size of the PT (48x8x2.2mm) and of the magnetic element (P14/8 or equivalent) makes possible the construction of a low profile inverter for portable equipment. Since the winding of the magnetic element do not carry high voltages, isolation is not a problem and smaller size magnetic can probably be achieved.

REFERENCES