Cold Cathod Fluorescent Lamp Power Supply Based on Piezoelectric Transformers

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Abstract **– This paper discusses design and implementation of a switching power supply for low power cold cathod fluorescent lamps (CCFLs), used in high brightness, back-lighted, liquid crystal displays (LCDs). The power supply design is based on piezoelectric transformers. The use of piezoelectric transformers (PZTs), instead of conventional magnetic ones, allows a significant reduction of the converter's size and component count. The particular features of the piezoelectric transformer allow the designer to directly connect the lamp to the secondary side of the device without the need for the typical ballast capacitor. Besides, the start up over-voltage is automatically generated with no need for input voltage amplitude or frequency modulation. On the other hand, the peculiar PZT secondary side arrangement and its high voltage, low current operation, call for particular care in the implementation of the LCD dimming circuit. The paper describes the different power supply components, particularly focusing on the PZT characteristics, outlines the design procedure for the output stage of the power supply (i.e. a resonant half-bridge inverter) and discusses the LCD brightness control strategy. Experimental results coming from a pre-industrialised prototype of the converter are presented.**

KEYWORDS

Cold cathod fluorescent lamps (CCFLs), piezoelectric transformers (PZTs), half bridge resonant inverters.

I. INTRODUCTION

The widespread adoption of liquid crystal displays (LCD's) in several applications like in personal computers, automatic teller machines, measurement instrumentation, has rapidly generated the need for efficient, high intensity light generation. The use of cold cathod fluorescent lamps (CCFLs) represents, at the moment, the state of the art solution for the above applications. Conventional power supplies for these applications employ resonant converters, magnetically coupled to the fluorescent lamp by means of centre-tapped or, more frequently, conventional transformers. These solutions require, as usual with CCFLs, a high voltage capacitor, called the ballast capacitor, to be connected in series with the lamp. This is needed both to compensate for the negative equivalent lamp impedance and to sustain the voltage drop between the lamp's high ignition voltage and its low operating voltage. Common practice is to use an inverter unit for each lamp. Therefore, for large or high intensity panels (like those to be used in full daylight) the number of required converters can be as high as 15. This implies high complexity and cost for the display. Also its reliability is negatively affected (i.e. MTBF is relatively low). As a consequence, most LCD's manufacturers are currently investigating new solutions, aimed at a significant reduction of the component count and complexity of the power supply, offering an improvement in the size, cost and reliability of the display.

This paper presents the development of a new power supply for high intensity LCDs. An interesting feature of the proposed solution is the use of piezoelectric transformers (PZTs) instead of conventional, magnetic ones. This solution provides several advantages such as a significant reduction of the power supply volume, weight and overall cost, especially for large production volumes. In addition to these immediate advantages, with the use of piezoelectric transformers the ballast capacitor is no longer required, since the lamp ignition, which calls for a considerable initial over-voltage, is automatically achieved without the need for voltage amplitude or frequency modulation [1-5].

The organization of the paper is the following: after a short discussion of the power supply organization we describe the basic features of the adopted piezoelectric transformers. We then give some basic design guidelines for the resonant inverter, that is the output stage of our power supply, and discuss some issues related to the active control of the LCD brightness. Finally, we present experimental results from a prototype of the power supply, that is currently being industrialised.

II. POWER SUPPLY ORGANIZATION

The first prototype of the power supply presented in this paper was organized as in Fig. 1a. As can be seen, it is based on two half bridge resonant converters operating at fixed frequency and duty-cycle. A SEPIC dc-dc converter feeds the resonant inverters and is used to regulate the inverter dc link voltage. The SEPIC topology was chosen mainly because of its step-up/step-down capability and boost like input stage (input current is automatically filtered). This converter is completely conventional in its design and no detailed discussion of its operation will be given here: we just say that the converter is designed to operate in continuous conduction mode (CCM) at 200 kHz switching frequency and that we used a typical multi-loop control strategy, where an outer voltage loop provides the reference for an inner peak current mode controller. As is explained in the following, the set-point for the SEPIC voltage controller is provided by the control circuit that regulates the brightness of the display (dimming circuit).

The power supply is designed to feed all the lamps needed by the application through a sinusoidal bus, delivering the input voltage to all the transformer primary sides, that are connected in parallel.

The typical characteristics of the lamps considered for this design are reported in Table I. As can be seen, the typical lamp input power is close to 5.5 W. However, the LCD manufacturer wanted the power supply to be able to operate also with higher power lamps. For our design we therefore set the maximum lamp input power to 7 W.

In the early phases of the design process, the more common and readily available piezoelectric transformers presented a typical power rating lower than 5 W and single ended output; bigger transformers or transformers with custom output arrangements were more expensive and could only allow a limited volume reduction.

Table I - CCFL Specifications

Lamp Voltage (V_{RMS}) 25°C		910
Starting Voltage (V)	0°C	1850
	25°C	1475
Lamp Current (mA_{RMS})		6.0
Ambient operating range (°C)		-10 to 70

This explains why the lamp power supply employs two half-bridge inverters, 180° phase shifted with respect to each other, and two PZTs for each lamp: a single PZT could not handle the required power. Moreover, even if it could, it was observed that single ended lamp driving always results in a non-optimal light emission, especially at low current levels, because of stray capacitances, which draw increasing amounts of lamp current along the lamp length (maximum light intensity is achieved close to the high voltage terminal, decreasing towards the grounded terminal). These considerations naturally led to the idea of using two transformers for each lamp, thus achieving symmetrical lamp driving, with homogenous light emission, and guaranteeing the possibility of driving higher power lamps with the same power supply.

Later on, the piezoelectric transformer manufacturer released a new type of device, optimised for this application.

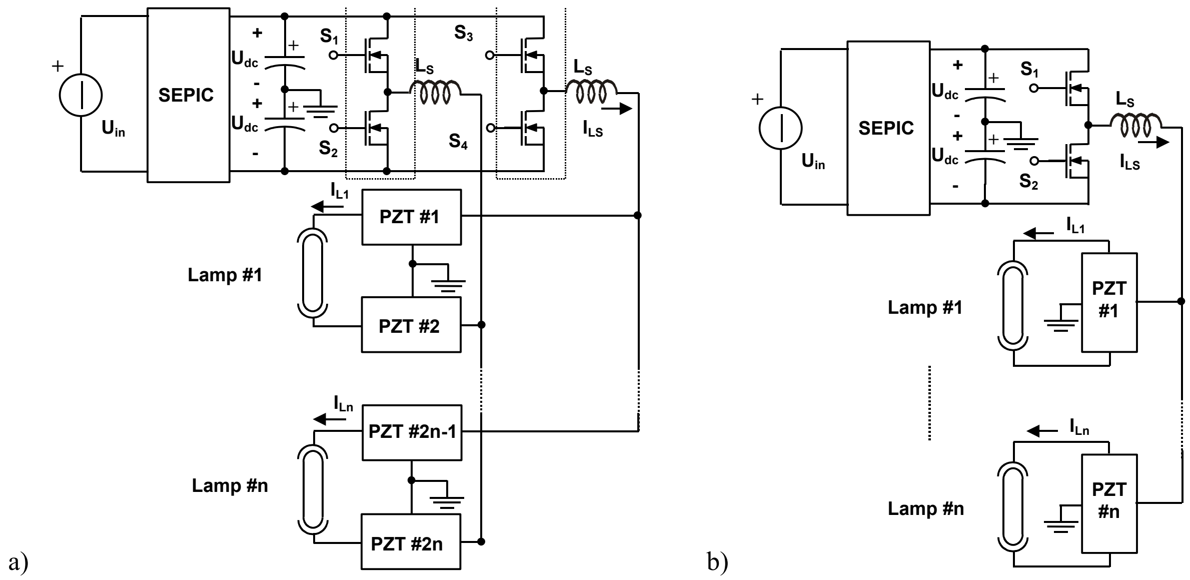

Fig. 1 –Schematic of the proposed power supply: a) single ended transformers; b) balanced output transformers.

This new PZT presents balanced output and 7 W output power capability. It also turns out to be significantly smaller and only slightly more expensive than two single ended devices. It was then adopted for the second power supply implementation. This allowed the modification of the converter topology as in Fig. 1b, where one of the two half-bridge converters has been removed. This solution has been patented by the manufacturer co-authoring this paper and has already undergone the final testing and pre-industrialisation phases of its development.

III. PIEZOELECTRIC TRANSFORMERS

As previously explained, the first implementation of the proposed power supply employed commercially available single-ended Rosen-type piezoelectric transformers. In the early stages of the design a careful evaluation of available devices has been done, considering different manufacturers. The FUJI T2508A transformers were finally chosen. These are characterized by high voltage gain, with a maximum value of about 32 dB (nominal load conditions) and 4 W maximum output power. The maximum gain frequency of these devices lays in a range between 62 and 65 kHz and must be precisely matched by the input voltage to get a reasonable voltage gain and conversion efficiency.

The equivalent electrical model for these Rosen-type transformers has been identified [6-9]. The model schematic is shown in Fig. 2, average parameter values for the above transformers are instead given in Table II. These values imply the capability for the piezoelectric transformer to directly drive the lamp, without ballast capacitor.

As it will be shown in the following, based on this model, it is possible to devise a design procedure to select a proper value for the coupling inductor L_S, so as to guarantee soft-switching operation.

Similar characteristics were measured also for the balanced output PZTs, that were later adopted (FUJI NA3208_7W). The voltage gain measured between the input and the differential output, in particular, turned out to be quite similar (about 35 dB), while the maximum gain frequency a little lower (about 51 kHz). However, a single balanced output PZT has now to supply the lamp instead of two single ended ones (with 180° phase-shifted drive). This implies a reduction of nearly 50% of the gain between the PZT input voltage and lamp voltage. The lower gain of these devices was dealt with by suitably increasing the SEPIC converter output voltage.

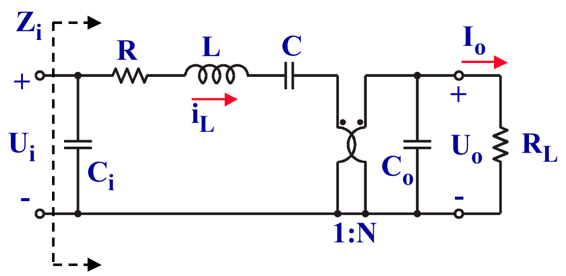

Fig. 2 – Equivalent electrical model of the Rosen type piezoelectric transformer.

IV. BASIC DESIGN OF THE RESONANT INVERTER

Both our designs (Fig. 1) adopt a coupling inductor, L_S, to interface the voltage source inverter and the PZTs [10, 11]. The inductor, interacting with the PZT input impedance allowed us to get an almost sinusoidal voltage across the power bus that connects the PZT primary sides. This solution not only represents the optimal driving strategy for the PZTs (according to the manufacturer indications) but also provides minimum EMI generation and avoids auto-compatibility problems. Moreover, a careful design of the inductor allows the inverter to operate in soft switching mode, at least at the nominal output power. The design procedure is outlined in the following.

Table II – FUJI single-ended piezoelectric transformer: parameters of the Rosen type model

R	5.37	Ω
C_i	150.4	nF
L	0.7	mH
C	10.22	nF
C_o	15.5	pF
N	50.75	

Given the transformer input impedance, the inductor L_S needs to be large enough to allow the inverter output current to be phase lagging the inverter voltage, so as to get zero voltage switching (ZVS). Predictably, the required L_S value depends on the number of driven transformers and on their load. As an example, Fig. 3 shows magnitude and phase of the input impedance of four parallel connected single-ended transformers (Z_{iTOT}) and the load impedance seen at the inverter output, including also the series inductance (Z_g). In this case, a value of about 50 µH (on each inverter phase) is used for L_S, considering one half of the nominal lamp impedance (150kΩ) as the load of each transformer.

As can be seen, the inverter load impedance, Z_g, has positive phase in the interval between frequencies ω_1 and ω_2, that includes the series resonant frequency $\omega_s = 1/\sqrt{LC}$ (that is also the normalizing factor of the frequency axis). This implies that, if the nominal operating frequency is kept inside this interval and the load is at its nominal value, the inverter will achieve soft switching (ZVS), provided that enough energy is stored in the coupling inductor L_S to discharge the switches' output capacitance. This, of course, depends on the inverter output current. In our design, soft-switching is obtained from nominal output power down to the minimum LCD brightness. In fact, when the LCD is dimmed, the inverter peak output current does not decrease much, while its waveform and phase shift, with respect to the inverter output voltage, change in a way that allows the inverter to maintain soft-switching (Fig. 8).

To complete the analysis, in Fig. 4 we plotted the different voltage gains of interest for system design. All of them refer to ideal sinusoidal excitation signals and are valid only for the fundamental components of the converter waveforms, at frequencies close to the maximum gain frequency of the PZT. Gain M_{PZT} represents the voltage gain of the piezoelectric transformer, calculated according to the model represented in Fig. 2. Gain M_i represents instead the gain from the inverter output to the transformer input. Finally, gain M_g represents the overall gain from the converter output to the transformer output. It is important to note that, because of the resonance between the coupling inductors L_S and the transformer input impedance, gain M_i exhibits significant voltage amplification. This must be carefully considered, because the piezoelectric transformer is very sensitive to input over-voltage, that may cause performance degradation and, in the worst case, transformer failure.

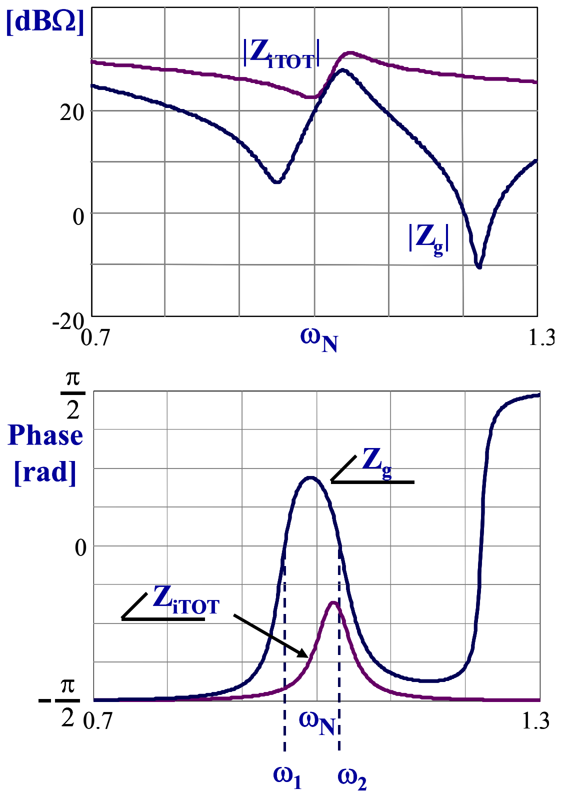

Fig. 3 – Magnitude and phase of the inverter load impedance (Z_g) and of four parallel connected transformer input impedance (Z_{iTOT}). The frequency axis is normalized to the series resonance frequency ($1/\sqrt{LC}$) of the model in Fig. 2. Soft switching is guaranteed between ω_1 and ω_2.

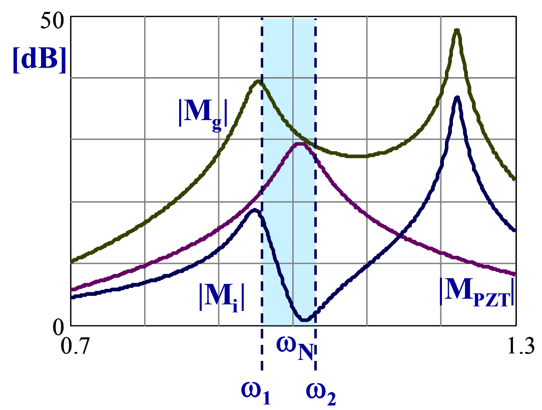

Fig. 4 – Magnitude of piezoelectric transformer voltage gain (M_{PZT}), of the voltage gain from inverter output to transformer input (M_i) and of the overall voltage gain from inverter output to transformer output (M_g). The frequency axis is normalized to the series resonance frequency ($1/\sqrt{LC}$) of the model in Fig. 2.

From Fig. 4, we can conclude that the nominal operating frequency of the inverter should be set slightly above the PZT maximum gain frequency. This guarantees ZVS for the inverter and an almost unity voltage amplification between inverter output and transformer input voltage. Besides, this choice also keeps the piezoelectric transformer in an operating point that is very close to its maximum voltage gain. According to the manufacturer's indications and also to simple temperature measurements, this implies the maximum operating efficiency for the transformer. Finally, as can be seen from Fig. 4, this choice guarantees an overall voltage gain close to 30 dB. Similar considerations are possible if balanced output PZTs are taken into account and if the number of parallel connected transformers is varied.

V. Control of LCD Brightness (Dimming)

The LCD panel dimming is implemented by means of U_{dc} voltage control. As shown in Fig. 1, this voltage is generated by a conventional SEPIC converter. The feedback signal that drives the controller of the SEPIC converter, providing the set-point to its voltage loop, is optical in nature. An array of photo-resistors was used to measure the intensity of the light emission of each lamp. The signals from each photo-resistor are processed by a suitable circuit, whose output is proportional to the average light intensity of the display. This is the regulated variable. The adopted regulator is a simple proportional-integral (PI) controller. The design of its gains is simple, because the lamps behave very closely to a first order system with a slow time constant.

The choice of an optical feedback is related to the particular lamp connection. Being both lamp terminals floating, the conventional lamp current measurement is hard to implement, because of the unavoidable high common mode noise. Only the use of photodiodes and optical fibre links allowed us to get a reliable current measurement, getting rid of common mode noise. In conventional solutions, either one of the lamp terminals is grounded or a centre-tapped magnetic transformer is used, which allows to measure the lamp current by means of a simple shunt resistor.

However, it is worth noting that the lamp current is non-linearly related to the lamp light intensity. Therefore, the current feedback does not guarantee accurate control of the light emitted by the lamps. Temperature drifts, ageing effects are indeed likely to be encountered in conventional implementations. With an optical feedback instead, all these problems can be overcome. In addition, a significant auto-diagnostic capability is achieved, which allows to identify malfunctioning lamps within the panel. This feature is also extremely interesting for LCD manufacturers.

As far as the dimming ratio is concerned, we found that a reduction of the lamp current of about 60%, with respect to nominal, is enough to reduce the LCD brightness to a negligible level. To get that reduction, a 50% decrease of the SEPIC output voltage is required, that can be easily achieved.

Another crucial aspect concerning the control of the LCD is the inrush current. The luminous efficiency (in lm/W) of the lamps, which expresses the ratio between the luminous flux (i.e. the visual perception of the emitted light) and electrical input power, is indeed a strong function of temperature. When they are relatively cold, e.g. at the start-up, the lamps require a large amount of current to produce the expected light intensity; the current then slowly decreases as they gradually get warm. The warm-up requires several seconds to take place. Therefore, early after the start-up, the optical feedback forces the inverter output current to grow, by increasing the SEPIC output voltage. If this was not taken care of, it could cause strong inverter overload and, eventually, PZT failure (overvoltage stress at the input). To prevent that, we implemented a saturation mechanism for the optical feedback, by limiting the maximum U_{dc} voltage. After some time, the initially saturated optical feedback gets in the linear operating mode and reduces the SEPIC output voltage value, so as to regulate the display brightness to the desired value. Moreover, the correct start-up procedure should be taking advantage of the dimming capability of the power supply, always turning the display on at the minimum brightness level. Dimming should then be reduced with a slow time constant (some seconds) by the external controller supervising the LCD operation. This prevents any occurrence of overloading and the triggering of the SEPIC over-current protection.

VI. Improved Converter Organization

As previously discussed, we modified the original power supply design to take advantage of the new balanced output PZTs provided by the manufacturer. The design procedure we outlined for the single ended PZTs can be applied also to the balanced output ones. As previously mentioned, since the balanced output PZTs present a maximum voltage gain of about 35 dB, which is roughly equivalent to a half of that offered by a couple of single ended transformers feeding the same lamp, it was necessary to re-design the SEPIC converter to provide twice the U_{dc} voltage provided by the first implementation. This also improved the overall converter efficiency, because the conduction losses were positively affected by the output current reduction.

Moreover, given the U_i input voltage range specifications, it appeared that the step-down capability could be no longer needed in the large majority of the possible applications. Therefore, a third power supply implementation is currently being developed, where the SEPIC converter is replaced by a simple boost converter, with further reduction of the component count and circuit complexity.

VII. Experimental Results

We present here experimental results taken from the second implementation of the power supply (Fig. 1b). The power supply was implemented using surface mounted devices (SMD) on a single side aluminium PCB (i.e. applying the Insulated Metallic Substrate, IMS, technology). This solution allowed us to exploit the PCB itself as the circuit heat-sink, greatly reducing the vertical size of the board. In the final applications, the circuit will be mounted on the LCD chassis itself.

Fig. 5 shows how the pre-industrialised power supply prototype looks like. The PCB area is rather large (11 cm x 9.5 cm), but this is not a problem at all, since any LCD chassis offers plenty of room in the horizontal plane. What is really important is the vertical size of the supply, that is lower than 1.5 cm. Fig. 6 instead shows the PZT board arrangement. As can be seen, the shape of the PZTs allowed us to locate them very close to the lamps, exploiting an hollow volume in the bottom of the LCD chassis. This limits to the minimum the length of the connecting cables delivering the high voltage, high frequency power supply to the lamps. On the opposite side of the display we mounted the array of photo-resistors. The basic power supply specifications, for a 7 lamp LCD, are summed-up in Table III.

Table III – Power supply ratings (n=7)

Input voltage (U_i)	12÷24	V
SEPIC output voltage	32	V
Maximum input power*	44	W
Maximum output power	36	W
Efficiency at nominal load	82	%
Coupling inductor	12	μH

* measured at minimum input voltage.

An example of inverter waveforms, measured at nominal output power i.e. maximum display brightness, is shown in Fig. 7. As can be seen, the inverter current and voltage waveforms are correctly phase shifted, which guarantees soft-switching operation of the resonant inverter. The peak input current is slightly higher than 4 A and phase leading the PZT input voltage.

Fig. 5 - PCB of the power supply.

Fig. 6 - Piezoelectric transformers PCB. The board is located at the bottom of the LCD display.

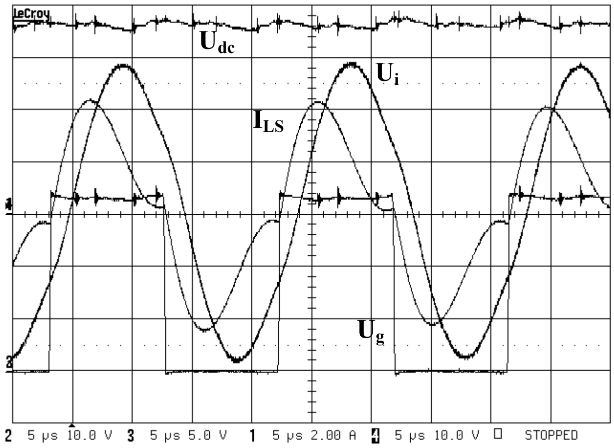

Fig. 7 - Typical converter waveforms at nominal output power for a seven lamp LCD. From top to bottom: SEPIC output voltage U_{dc} (5 V/div), PZT input voltage U_i (5 V/div, almost sinusoidal), inverter output current I_{LS} (2 A/div), inverter output voltage U_g (10 V/div). Timebase is 5 µs/div.

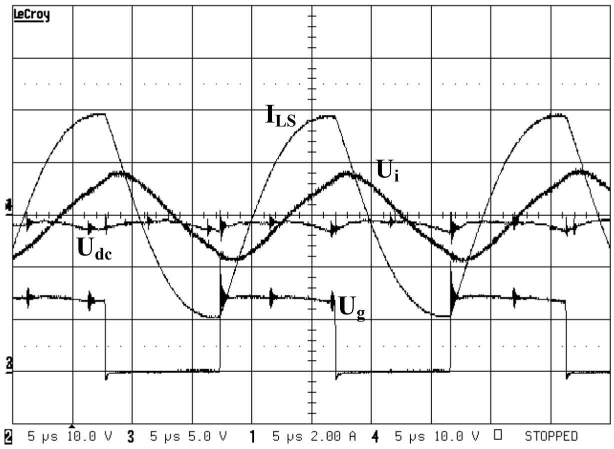

Fig. 8 - Typical converter waveforms at reduced output power (maximum dimming) for a seven lamp LCD. From top to bottom: inverter output current I_{LS} (2 A/div), PZT input voltage U_i (5 V/div), SEPIC output voltage U_{dc} (5 V/div), inverter output voltage U_g (10 V/div). Timebase is 5 µs/div.

Fig. 8 shows the same waveforms at the maximum dimming level. In this condition the LCD presents the minimum appreciable brightness. As can be seen, the peak inverter current does not decrease much, and, thanks to the waveform and phase-shift improvements, soft-switching can be maintained.

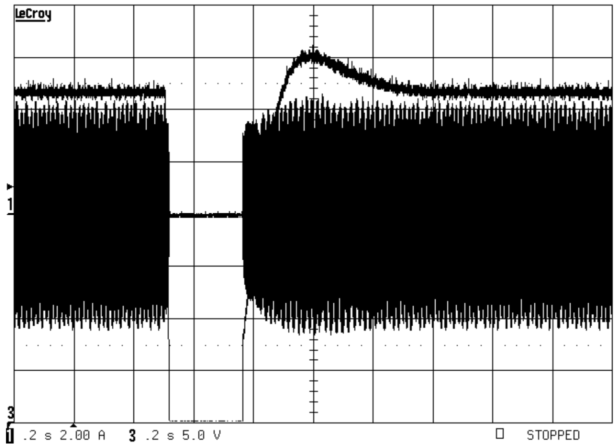

Fig. 9 - Typical start-up waveforms. From top to bottom: SEPIC output voltage U_{dc} (5 V/div), inverter output current (2 A/div). Timebase is 200 ms/div.

The converter operation at the start-up is shown in Fig. 9. A control signal causes the shutdown and re-start of the LCD. As can be seen, the SEPIC output voltage exhibits a small overshoot, but gets smoothly to the steady state value in 0.7 s. The inverter output current also presents a small overshoot, but is well controlled and limited to acceptable values.

If a longer turn-off interval is applied, the response of the supply gets a little worse, because the lamps are allowed to get cooler. Anyway, thanks to the saturation of the inverter input voltage, the current is always kept within the limits.

VIII. CONCLUSIONS

The implementation of the power supply for a CCFL based, high intensity, LCD using piezoelectric transformers is described. The use of piezoelectric transformers is shown to offer significant advantages with respect to conventional magnetic solutions. The characteristic of the Rosen type devices adopted for this design are illustrated and their equivalent electrical model is identified. The motivations for the different design choices are described and the operation of the implemented converter is illustrated by experimental results.

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