The LCC Inverter as a Cold Cathode Fluorescent Lamp Driver

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Abstract - **LCD displays for notebook computers are backlit using Cold Cathode Fluorescent Lamps (CCFLs). An investigation of the LCC (series/parallel) resonant inverter as a potential power supply for these lamps is discussed. The attractiveness of this topology is primarily its simplicity compared to the widely used current-fed Royer oscillator based topologies. Experimental comparisons of LCC resonant inverter and Royer inverter performance are presented.**

I. INTRODUCTION

LCD displays for notebook computers are illuminated from behind using Cold Cathode Fluorescent Lamps (CCFLs). CCFLs typically operate with sinusoidal voltage of 300-400 V_{rms} and current of 5-6 mA_{rms} in the 25-50 kHz frequency range. To start ionization, over 1400V_{peak} needs to be applied to the lamp.

The inverter that drives the lamps is powered by 8-20 Vdc from the computer's batteries or an adapter. The lamp inverter needs to be efficient, small, and low cost. Currently, the de facto standard for notebook computer LCD display backlighting is the current-fed, self-oscillating Royer circuit controlled by a buck pre-regulator, [1]-[6]. Due to their two-stage topology, they suffer from high parts count, limited efficiency, and increased transformer step-up ratio making them less than optimum for backlighting applications.

In this paper, the LCC (series/parallel) resonant inverter was investigated as an alternate resonant topology believed to offer enhanced characteristics as a power supply for CCFL LCD backlighting as compared to the current-fed Royer circuit. This topology was selected due to its simplicity (low parts count), high efficiency, and simple transformer design.

II. CCFL CHARACTERISTICS

Major difficulties in designing CCFL backlight inverters stem from the characteristics of the CCF lamp, Fig. 1. The cold cathode fluorescent lamp is a gas discharge device which is normally driven in the avalanche mode. Being a gas discharge, its characteristics are very temperature dependent. For AC driving frequencies above several kilohertz, the lamp appears like an rms-current modulated resistance after avalanche is begun. To start ionization in a non-ionized lamp, the applied voltage must be increased to the level required for avalanche onset. This voltage is several times the typical forward operating voltage.

The light output of the lamp is roughly proportional to average current, so current loop control is typically used. As the lamp current and/or ambient temperature is varied, the effective impedance changes, thus, no single resistance value can be used to characterize the operation under all conditions, [7].

As shown Fig. 1, the I-V characteristic is multiple valued in the voltage coordinate. The multi-valued V-I characteristic can cause instability whenever the required terminal voltage has two or more current values associated with it. Ballasting (insertion of a series impedance) can be used for stabilization, though this increases the output voltage required and reduces efficiency.

The best method of driving a load with a characteristic such as the CCFL is with a current source. As long as the compliance (open-circuit) voltage is at least as high as the starting voltage, the voltage can rise to the avalanche onset level. As soon as ionization occurs, the voltage will collapse and the desired operating point will be reached immediately and unambiguously. Single frequency component sinusoidal drive is preferred to maximize efficiency and minimize EMI.

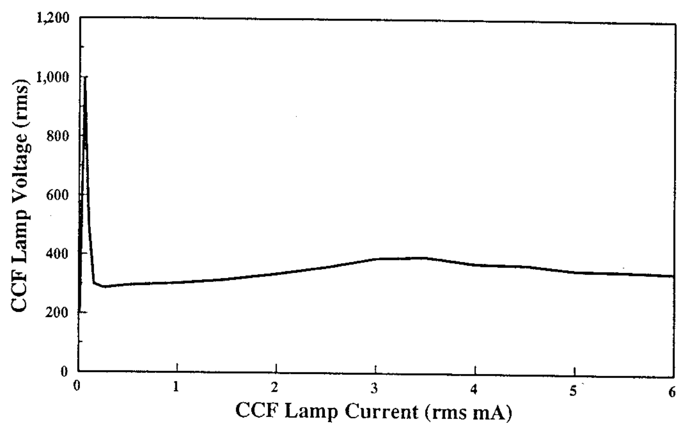

Fig. 1. Cold cathode fluorescent lamp characteristics.

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III. CURRENT-FED ROYER OSCILLATOR

The self-oscillating Royer circuit (Fig. 2) is a two transistor push-pull circuit that resonates the magnetizing inductance of the circuit transformer with a discrete high-Q capacitor to generate a quasi-sinusoidal output at the secondary of the transformer. A tertiary winding (W3) is used in the self-oscillating circuits to supply the base drive for the switching transistors.

In current-fed versions, a buck converter is used to regulate the input current to the Royer oscillator. The processed power is dependent on the input current, but the frequency deviation from the LC-tank natural frequency is primarily dependent on the effective load impedance (i.e., the effective damping). The input current is controlled by controlling the duty cycle of the buck pre-regulator switch.

There are several inherent limitations of current-fed Royer circuits. There is an intrinsic limit to their efficiency due to the cascading of two discrete power processing stages. Also, the two stages require significantly more components than would be expected for an equivalent single-stage topology. The use of a parallel resonant circuit means that before the lamp is ionized, there is very little damping and circuitry must be included to prevent an overvoltage condition if the lamp fails to ionize. Additionally, the buck pre-regulator reduces the usable primary voltage to less than the lowest line voltage, driving the step-up ratio of the transformer to be higher than for a single stage unit. This, coupled with the need for a center-tapped primary and a tertiary winding for the self-oscillating versions, makes the transformer relatively complex and expensive.

It was with these limitations in mind, that a simpler, cheaper, more efficient single-stage resonant topology was sought.

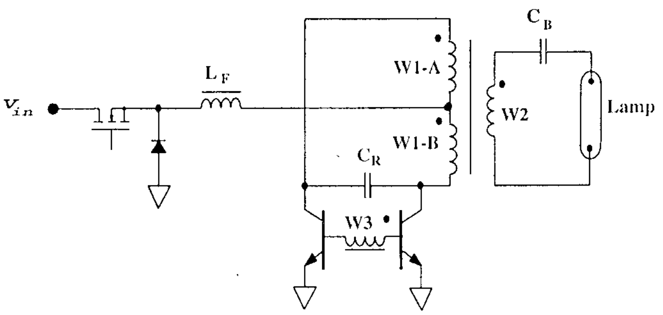

Fig. 2. Current-fed self-oscillating Royer Inverter

IV. LCC BACKLIGHT INVERTER

A. Topology

The half-bridge LCC (Series-Parallel) resonant inverter was chosen because of its simplicity, low cost, and potentially high efficiency. The advantages of this topology are clearly explained in [8] and [9].

Fig. 3 shows the circuit diagram and Fig. 4 shows the key waveforms of the LCC inverter. It is a half-bridge inverter where capacitors C_{S1} and C_{S2} are not only used to split the input voltage, but also used as the series resonant capacitor. The circuit employs only two switches, and these are right across the input dc rail, so they have access to the maximum available voltage. The transformer primary is in series with the resonant inductor and the series resonant capacitance. If the switching frequency is above the series resonant frequency, given by:

$$f_0 = \frac{1}{2\times\pi\times\sqrt{L_R\times(C_{S1}+C_{S2})}} \quad (1)$$

the load appears to be driven by a current source. Because of the current source characteristic, no separate ballast impedance is necessary and the output voltage is equal to the lamp voltage. This results in a relatively low turns ratio, and therefore, a smaller transformer is possible. Since the transformer is paralleled with the parallel resonant capacitance, under pre-ionized conditions, the circuit performs like a parallel-loaded resonant converter and the output tends to behave as a controllable voltage source. As a result of the voltage-boost characteristic of the parallel-loaded converter, the necessary ionization voltage can be generated.

Small MOSFETs are used as switches because they can be driven directly with CMOS logic, eliminating separate drive circuits, further improving efficiency. In addition, their body diodes have adequate speed and conduction drop to serve as free-wheeling devices for this soft-switching application.

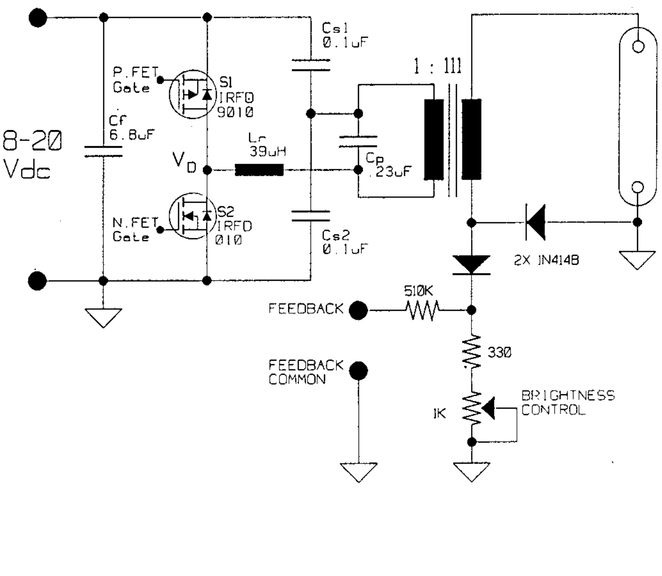

Fig. 3. LCC inverter power stage schematic.

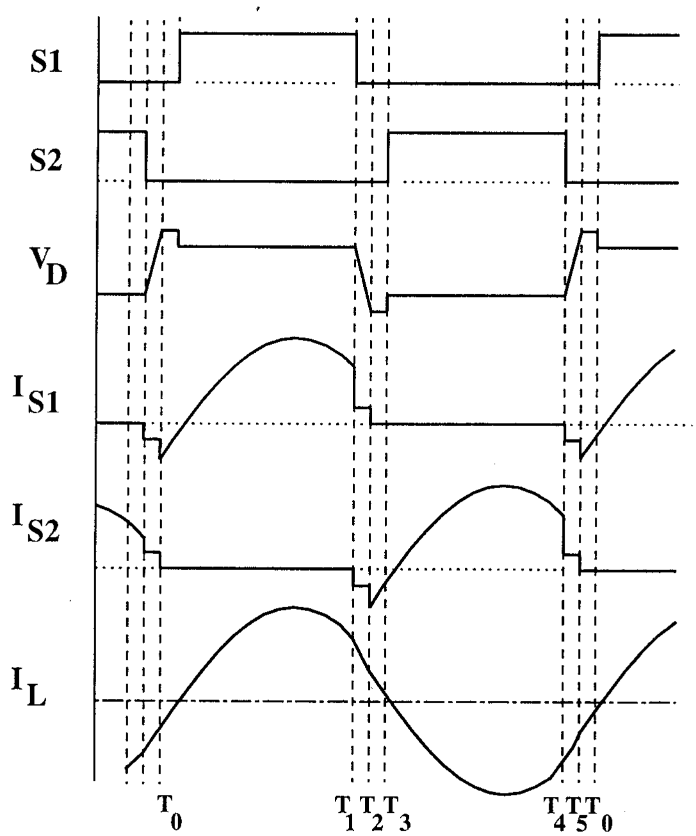

Fig. 4. LCC inverter switching waveforms.

B. Principle of Operation

The operation of the inverter is described using the waveforms of Fig. 4 as follows:

(a) T_0-T_1:
Prior to T_0, the switches are off and the anti-parallel diode of S1 is conducting residual current from the resonant inductor L_R. To achieve ZVS, upper transistor S1 is turned on at T_0 while its body diode is conducting. The current through L_R resonantly increases and charges the series resonant capacitor (C_{S1} in parallel with C_{S2}). Eventually, the voltage across the lower series capacitor, C_{S2}, equals the rail voltage. At this point, the current peaks and starts to decline as the voltage across L_R becomes negative.

(b) T_1-T_2:
At T_1, the current in the inductor has started to decay. At T_1, S1 is turned off. The current is commutated to S1's drain to source shunt capacitance. This charges the capacitance, and as a result, the drain voltage of both switches transistors decreases linearly from the upper rail to the lower rail. S1 is soft-switched on turn-off. When the drain voltage begins to go negative with respect to the lower rail at T_2, the anti-parallel diode of S2 starts conducting.

(c) T_2-T_3:
The anti-parallel diode of S2 is conducting. To achieve ZVS, lower transistor S2 is turned on at T_3 while its body diode is conducting.

(d) T_3-T_0:
The process repeats in the complimentary direction using S2 and the body diode of S1 and returning to the original T_0 operational stage.

This is the completion of one full conversion cycle. Note that soft-switching is achieved using the parasitic drain to source capacitance of the MOSFETs.

The current through the resonant circuit and the transformer primary consists of two sinusoidal segments, one when the drain end of the inductor is clamped by S1 and its body diode to the upper rail, and one when the drain end of the inductor is clamped by S2 and its body diode to the lower rail. The intervals when the drain-to-source capacitances are charging and discharging, and the drain voltage ramps between the rails (turn-off ZVS), are insignificant compared to the switching period.

C. Control

1. Output Current Regulation

The normalized rms primary voltage vs. switching frequency curves of the LCC inverter are shown in Fig. 5. (These curves assume parasitic losses account for 10% of the damping resistance.) By varying the switching frequency relative to the natural frequency of the tank, the output level of the inverter can be controlled for both line and load changes.

The CCF lamp used for this work consumes about two watts at full power. This precludes the use of standard IC controllers with their supply current of 10-20 mA. At 20 Vdc input, these controllers reduce maximum efficiencies to 83-91% before the power stage is even considered.

The discrete controller used for the LCC inverter consists of an error amplifier, a VCO and a phase splitting output drive section as shown in Fig. 6. The error amplifier compares the filtered output current to a dc reference voltage. The forward drop of signal diode D1 is used as the reference. The output of the error amplifier is used to modulate the base current of transistor Q1 that is used as a level shifting inverter. Transistor Q1 is used to modulate the base current of transistor Q2. As a result, Q2 acts as a controlled resistor that varies the time constant of the VCO, i.e., its frequency. Fixed resistors are connected across the collector to emitter and in series with the emitter of Q2 to set the minimum and

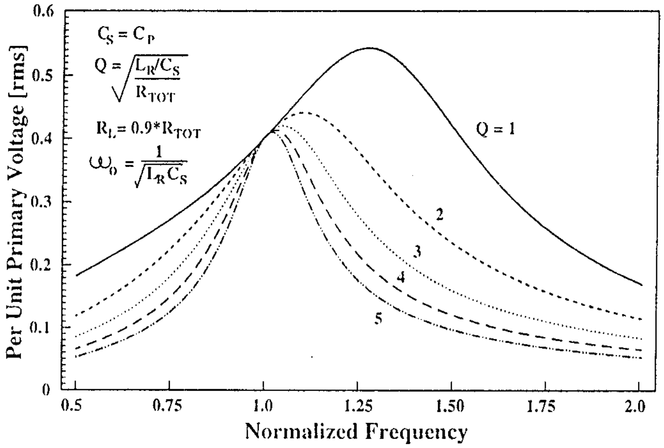

Fig. 5. LCC inverter operating characteristics.

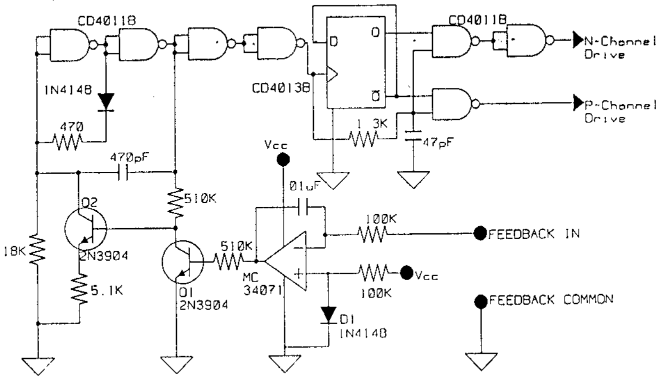

Fig. 6. LCC exerimental control circuit.

maximum VCO frequency, respectively.

The controller is set up so that if the lamp current is less than the current reference, the VCO frequency is decreased. With an open circuit, the frequency will decrease to its minimum value. With a short-circuited output, the Q of the series circuit increases substantially. This immediately decreases the voltage gain at the operating frequency mitigating the current increase. Subsequently, the controller will control the current to its reference value by increasing the frequency substantially higher than normal, where the voltage gain is very low. Thus, the circuit is intrinsically self-protected against short-circuit damage.

2. Control of Starting Voltage

The lamp ionization voltage is independent of the input voltage level, but the applied load voltage is proportional to the input voltage level for a given frequency. If a specific operating frequency is used whenever the lamp is to be ionized, the peak stress would be proportional to the input voltage. In the present case, where the input varies from 8-20 Vdc, the high line output would be 2.5 times the low line output.

In the LCC circuit, the input fundamental to primary voltage gain can only be greater than unity when the converter has a light enough load so that it is operating like a parallel-loaded resonant converter. This makes it very easy to obtain a relatively line independent open circuit voltage limit. If the transformer is designed to saturate just above the maximum required initiating voltage, the output voltage will rise to this level and then the transformer will incrementally appear as a very low impedance. This will lower the parallel resonant gain, and keep the output voltage from rising further. Since the lamp running voltage is several times less than the initiating voltage, the transformer flux will be well below the saturation level during normal operation.

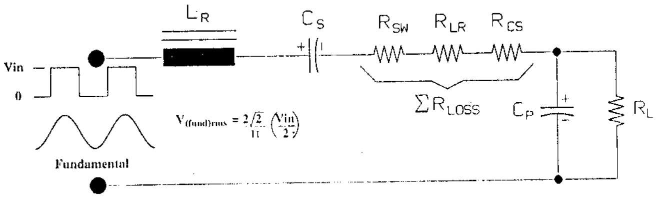

Fig. 7. LCC equivalent circuit at series resonance.

V. DESIGN METHOD

A basic analysis method, useful for specifying circuit parameters, is described in [9]. As shown in Fig. 7, the half-bridge LCC inverter can be represented as a square-wave source, generated by the action of the switches, driving a passive LCC filter including parasitic resistances. The input square wave can be represented by a Fourier series with the fundamental at the switching frequency. The series contains only odd harmonics so that the next non-zero harmonic is the third harmonic. For switching frequencies above the series resonance frequency of the LC tank, all the harmonics above the fundamental will be effectively attenuated so the fundamental component is the only one that needs to be considered for a first order analysis. The value of this fundamental is given by:

$$V_{pk(fund)} = \frac{2 * V_{in}}{\pi} . \qquad (2)$$

A. Operating Point and transformer ratio

The pure series-resonant converter has the current source characteristic desired in this application. The parallel mode is needed only to generate the starting voltage. Figure 7 shows that under normal load, the parallel capacitor and the equivalent load resistor form an RC pole. For reasonable values of load resistance, the frequency of this pole will be much higher than the natural frequency of the series resonant circuit alone. Therefore, all load based performance parameters can be normalized to the parameters of the series-resonant part of the LCC converter. Thus Q is defined as:

$$Q = \frac{\sqrt{L_R/C_S}}{R_{TOT}} . \tag{3}$$

If the switching frequency is the natural frequency of the series L and C, their impedances cancel, leaving the parasitic resistances and the load resistance in series. Because the power passed in this configuration is:

$$P = \frac{V^2_{rms(fund)}}{R_{TOT}} , \tag{4}$$

R_{TOT} must be small enough to achieve the rated power at the minimum V_{in}. Since R_{TOT} is the sum of the parasitic resistances and the load resistance, the constraint on R_{TOT} puts an upper limit on R_L given a certain level of parasitics.

Conversely, to increase the efficiency, as much of the input voltage as possible should be dropped across the load resistance. This goal drives the load resistance to be as high as possible. (Note the maximum *power* transfer for a given amount of parasitics would occur if the load resistance was set equal to the parasitic resistance. However, under this condition the efficiency would be only 50%.)

The two constraints above are incorporated in the following quadratic equation:

$$R_L^2 - \left[\frac{V^2_{rms(fund)(\min)}}{P_{o(\max)}} - 2\sum R_{LOSS}\right] R_L + \left(\sum R_{LOSS}\right)^2 = 0. \tag{5}$$

This relation gives the value of R_L for which the design output power can be achieved while maximizing efficiency, given the minimum design input voltage, the maximum output power required, and the actual parasitic losses. The transformer ratio is then designed to reflect this impedance at full load.

B. Resonant Tank

To have the LCC circuit run efficiently, it is important to minimize the circulating current, [10]. The Q of the resonant network at full load should be designed to be in the range of 4 to 5. If the Q is lower than this, excessive current will be forced through the parallel resonant capacitor, and the circulating reactive current will be relatively high, [10]. If Q is beyond this range, the crossover from series resonant characteristics to parallel resonant characteristics will occur at too light a load, [9]. The desired Q and resonant frequency uniquely determine the values of L_R and C_S needed.

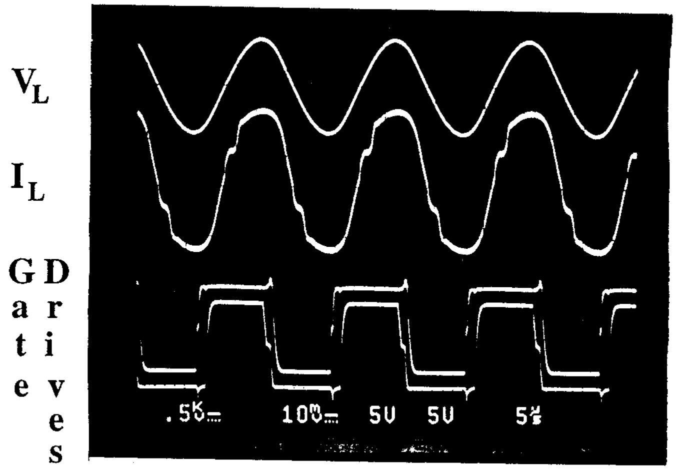

Fig. 8. LCC exerimental waveforms, V_{in} = 8 V.

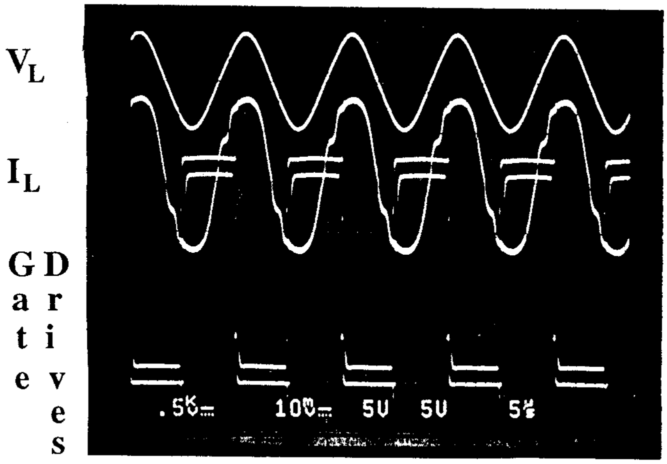

Fig. 9. LCC exerimental waveforms, V_{in} = 20 V.

VI. EXPERIMENTAL RESULTS

Several prototype LCC CCFL inverters were built in the 1.5-2 watt range operating at resonant frequencies from 30 kHz to 85kHz. The oscilligrams of Figs. 8 and 9 show typical drive and output waveforms for 8 V line and 20 V line, respectively.

Efficiencies of the LCC and Royer backlight inverters were compared. It is difficult to measure absolute backlight inverter efficiencies accurately due to the low power, high voltage level, phase shift, and inverter dependent distortion of the ac output. Since the ultimate goal of the backlight system is to produce light from the CCFL as efficiently as possible, a light output monitor was designed so that comparisons could be made of the dc input power required by various circuits producing the same light output with the same lamp. In this way, accurate relative comparisons can be made between circuits with widely different topologies and controllers.

The light monitor consists of a box with eight photodiodes mounted on the inner surfaces. The eight sensors are used in the photovoltaic mode and their output currents are summed with an operational amplifier to give an output voltage proportional to the average light output of the lamp. The photodiodes are arranged in pairs along the length of the tube to account for any axial non-homogeneity in the light output. The light box is enclosed in an overall metal box which helps control differences between various power supply circuits by stabilizing the local capacitance associated with driving the lamp.

The relative efficiency curves shown in figs. 10-12 are a comparison, using the light monitor described above, between a currently produced SMD-based current-fed Royer circuit and a discrete prototype LCC CCFL inverter designed for the same frequency range. IRFD010 FETs were used for the N-channel device and IRFD9020 FETs were used for the P-channel device. An MPP toroid core was used to construct a 124μH resonant inductor. Relative efficiency was normalized to the Royer circuit at full load with 8 V input.

The operating frequency of the Royer circuit was 36.24-36.74 kHz for input voltages of 8-20 volts at full load and increased to 44.5 kHz at one-quarter light output at all inputs. In comparison, the LCC circuit's full-load operating frequency varied from 36.5 kHz at 8V to 44.5 kHz at 20V. At one-quarter light output, the LCC operating frequency varied from 45 kHz at 8V to 54 kHz at 20V.

The relative efficiency of the LCC circuit is higher than the Royer circuit in the critical low voltage region where the inverter would be running directly from the batteries. (These measurements include the controller.) At the higher voltages, where the inverter is likely to be running off wall power from the adapter, the efficiency of the LCC inverter rolls off substantially due to the amount of circulating current generated when the voltage gain is reduced by moving the switching frequency far above the natural frequency of the series tank circuit, [10]. For the LCC inverter, a two-winding transformer with a turns ratio of 1:111 was used. 0.1μF disc ceramic capacitors were used for the series resonant capacitors. No discrete parallel resonant capacitor was used because the transformer winding capacitance was about 250nF, referenced to the primary, and the secondary stray capacitance reflected back another 100-200nF to the primary. This is actually more parallel capacitance than desired. Improving the winding technique to minimize capacitance could reduce the circulating current and improve the efficiency somewhat.

Further, it should be noted that the LCC inverter's controller still dissipated extra power at high inputs because it was built from discrete IC's with unused elements. Optimizing the controller could be expected to improve the LCC efficiency at least 1% at high line.

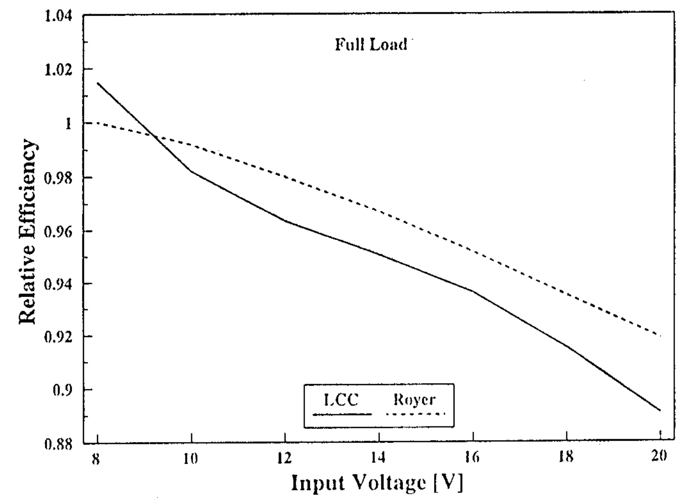

Fig. 10 Relative efficiency at full load as a function of input voltage.

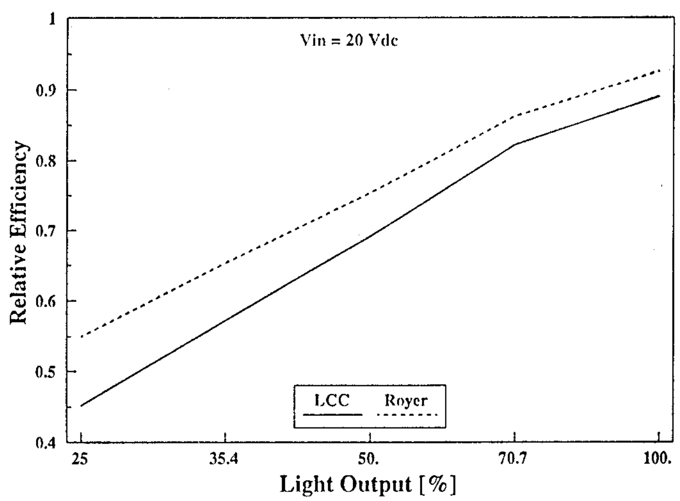

Fig. 11 Relative efficiency at high input as a function of light output level.

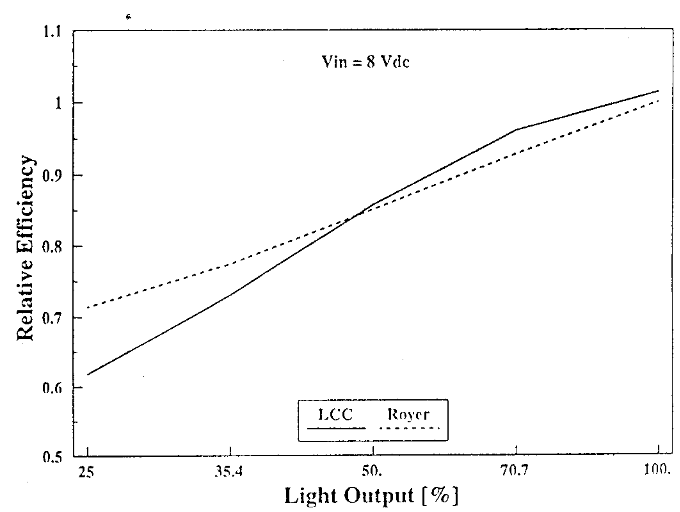

Fig. 12 Relative efficiency at low input as a function of light output level.

Gate switching losses at high line are a problem as well. Replacing the FETs with the small BJTs used by the Royer circuit for its push-pull switches, could reduce these losses and increase the efficiency another 1%.

The LCC transformer was designed to saturate just above starting voltage and this controlled the open-circuit output as anticipated. The inverters were run continuously into a short circuit without electrical and thermal stresses becoming excessive. Parasitic losses in the switches, inductor, and capacitors typically equal 11% of the effective load resistance at full load.

VII. SUMMARY

LCC inverters were shown to be very simple drivers for cold cathode fluorescent lamps used for backlighting LCD displays in notebook computers. These inverters have efficiencies that compare favorably with currently used current-fed self-oscillating Royer circuits. At low line, LCC prototypes exceed the efficiency of Royer circuits. With further work it is expected that improved efficiency can be achieved at all input voltages. These circuits handle lamp starting and short circuit situations in a straightforward manner.

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