11. Tripping the Light Fantastic

Introduction

Where do good circuits come from, and what is a good circuit? Do they only arrive as lightning bolts in the minds of a privileged few? Are they synthesized, or derived after careful analysis? Do they simply evolve? What is the role of skill? Of experience? Of luck? I can't answer these weighty questions, but I do know how the best circuit I ever designed came to be.

What is a good circuit, anyway? Again, that's a fairly difficult question, but I can suggest a few guidelines. Its appearance should be fundamentally simple, although it may embody complex and powerful theoretical elements and interactions. That, to me, is the essence of elegance. The circuit should also be widely utilized. An important measure of a circuit's value is if lots of people use it, and are satisfied after they have done so. Finally, the circuit should also generate substantial revenue. The last time I checked, they still charge money at the grocery store. My employer is similarly faithful about paying me, and, in both cases, it's my obligation to hold up my end of the bargain.

So, those are my thoughts on good circuits, but I never addressed the statement at the end of the first paragraph. How did my best circuit come to be? That's a long story. Here it is.

The Postpartum Blues

Towards the end of 1991 I was in a rut. I had finished a large high-speed amplifier project in August. It had required a year of constant, intense, and sometimes ferocious effort right up to its conclusion. Then it was over, and I suddenly had nothing to do. I have found myself abruptly disconnected from an absorbing task before, and the result is always the same. I go into this funky kind of rut, and wonder if I'll ever find anything else interesting to do, and if I'm even capable of doing anything anymore.

Portions of this text have appeared in the January 6, 1994 issue of *EDN* magazine and publications of Linear Technology Corporation. They are used here with permission.

I've been dating me a long time, so this state of mind doesn't promote quite the panic and urgency it used to. The treatment is always the same. Keep busy with mundane chores at work, read, cruise electronic junk stores, fix things and, in general, look available so that some interesting problem might ask me to dance. During this time I can do some of the stuff I completely let go while I was immersed in whatever problem owned me. The treatment always seems to work, and usually takes a period of months. In this case it took exactly three.

What's a Backlight?

Around Christmas my boss, Bob Dobkin, asked me if I ever thought about the liquid crystal display (LCD) backlights used in portable computers. I had to admit I didn't know what a backlight was. He explained that LCD displays require an illumination source to make the display readable, and that this source consumed about half the power in the machine. Additionally, the light source, a form of fluorescent lamp, requires high-voltage, high-frequency AC drive. Bob was wondering how this was done, with what efficiency, and if we couldn't come up with a better way and peddle it. The thing sounded remotely interesting. I enjoy transducer work, and that's what a light bulb is. I thought it might be useful to get my hands on some computers and take a look at the backlights. Then I went off to return some phone calls, attend to other housekeeping type items, and, basically, maintain my funk.

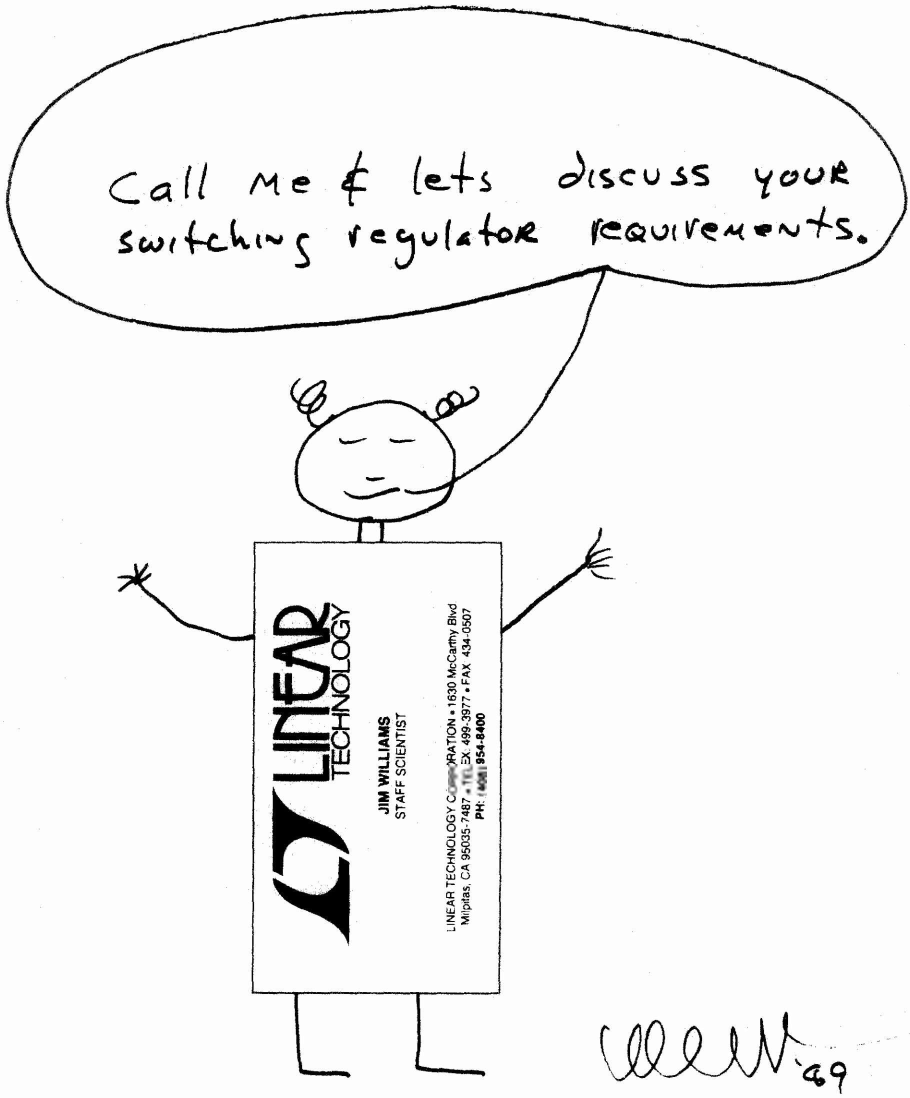
A Call from Some Guy Named Steve

Three days later the phone rang. The caller, a guy named Steve Young from Apple Computer, had seen a cartoon (Figure 11–1) I stuck on the back page of an application note in 1989. Since the cartoon invited calls, he was doing just that. Steve outlined several classes of switching power supply problems he was interested in. The application was portable computers, and a more efficient backlight circuit was a priority. Dobkin's interest in backlights suddenly sounded a lot less academic.

This guy seemed like a fairly senior type, and Apple was obviously a prominent computer company. Also, he was enthusiastic, seemed easy to work with and quite knowledgeable. This potential customer also knew what he wanted, and was willing to put a lot of front end thinking and time in to get it. It was clear he wasn't interested in a quick fix; he wanted true, "end-to-end" system oriented thinking.

What a customer! He knew what he wanted. He was open and anxious to work, had time and money, and was willing to sweat to get better solutions. On top of all that, Apple was a large and successful company with excellent engineering resources. I set up a meeting to introduce him to Dobkin and, hopefully, get something started.

Application Note 35



32 Linear Technology Corporation
1630 McCarthy Blvd., Milpitas, CA 95035-7487 • (408) 432-1900
FAX: (408) 434-0507 • TELEX: 499-3977

IM/GP 989 20K

LINEAR TECHNOLOGY

Figure 11–1.
This invitation appeared in a 1989 application note. Some guy named Steve Young from Apple Computer took me up on it. (Reproduced with permission of Linear Technology Corporation)

The meeting went well, things got defined, and I took the backlight problem. I still wasn't enthralled with backlights, but here was an almost ideal customer falling in through the roof so there really wasn't any choice.

Steve introduced me to Paul Donovan, who would become my primary Apple contact. Donovan outlined the ideal backlight. It should have the highest possible efficiency, that is, the highest possible display luminosity with the lowest possible battery drain. Lamp intensity should be smoothly and continuously variable over a wide range with no hysteresis, or "pop-on," and should not be affected by supply voltage changes. RF emissions should meet FCC and system requirements. Finally, parts count and board space should be minimal. There was a board height requirement of .25".

Getting Started—The Luddite Approach to Learning

I got started by getting a bunch of portable computers and taking them apart. I must admit that the Luddite in me enjoyed throwing away most of the computers while saving only their display sections. One thing I immediately noticed was that almost all of them utilized a purchased, board-level solution to backlight driving. Almost no one actually built the function. The circuits invariably took the form of an adjustable output step-down switching regulator driving a high voltage DC-AC inverter (Figure 11–2). The AC high-voltage output was often about 50kHz, and approximately sinusoidal. The circuits seemed to operate on the assumption that a constant voltage input to the DC-AC inverter would produce a fixed, high voltage output. This fixed output would, in turn, produce constant lamp light emission. The ballast capacitor's function was not entirely clear, but I suspected it was related to lamp characteristics. There was no form of feedback from the lamp to the drive circuitry.

Was there something magic about the 50kHz frequency? To see, I built up a variable-frequency high voltage generator (Figure 11–3) and drove the displays. I varied frequency while comparing electrical drive power

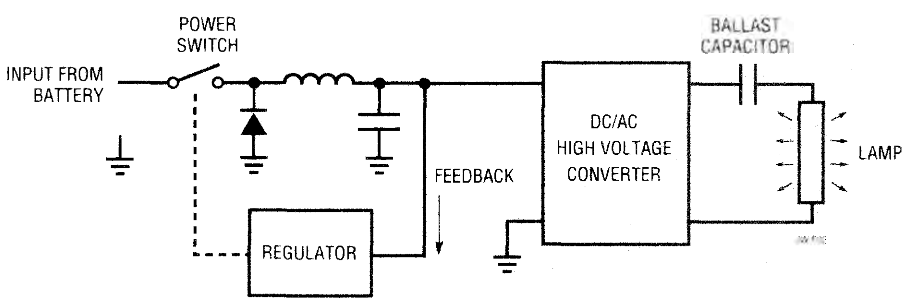


Figure 11–2. Architecture of a typical lamp driver board. There is no form of feedback from the lamp.

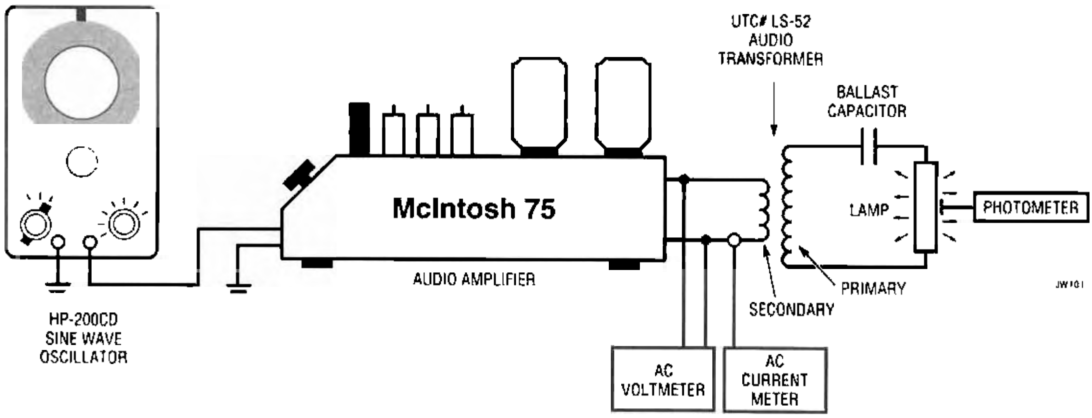


Figure 11-3. Variable frequency high-voltage test setup for evaluating lamp frequency sensitivity.

to optical emission. Lamp conversion efficiency seemed independent of frequency over a fairly wide range. I did, however, notice that higher frequencies tended to introduce losses in the wiring running to the lamp. These losses occurred at all frequencies, but became pronounced above about 100kHz or so. Deliberately introducing parasitic capacitances from the wiring or lamp to ground substantially increased the losses. The lesson was clear. The lamp wiring was an inherent and parasitic part of the circuit, and any stray capacitive path was similarly parasitic.

Armed with this information I returned to the computer displays. I modified things so that the wire length between the inverter board and display was minimized. I also removed the metal display housing in the lamp area. The result was a measurable decrease in inverter drive power for a given display intensity. In two machines the improvement approached 20%! My modifications weren't very practical from a mechanical integrity viewpoint, but that wasn't relevant. Why hadn't these computers been originally designed to take advantage of this "free" efficiency gain?

Playing around with Light Bulbs

I removed lamps from the displays. They all appeared to have been installed by the display vendor, as opposed to being selected and purchased by the computer manufacturer. Even more interesting was that I found identical backlight boards in different computers driving different types of lamps. There didn't seem to be any board changes made to accommodate the various lamps. Now, I turned my attention to the lamps.

The lamps seemed to be pretty complex and wild animals. I noticed that many of them took noticeable time to arrive at maximum intensity. Some types seemed to emit more light than others for a given input power. Still others had a wider dynamic range of intensities than the rest, although all had a seemingly narrow range of intensity control. Most striking was that every lamp's emissivity varied with ambient temperature. Experimenting with a hair dryer, a can of "cold spray" and a photometer, I found that each lamp seemed to have an optimum operating temperature range. Excursions above or below this region caused emittance to fall.

I put a lamp into a reassembled display. With the display warmed up in a 25°C environment I was able to increase light output by slightly ventilating the lamp enclosure. This increased steady-state thermal losses, allowing the lamp to run in its optimum temperature range. I also saw screen illumination shifts due to the distance between the light entry point at the display edge and the lamp. There seemed to be some optimum distance between the lamp and the entry point. Simply coupling the lamp as closely as possible did not provide the best results. Similarly, the metallic reflective foil used to concentrate the lamp's output seemed to be sensitive to placement. Additionally, there was clearly a trade-off between benefits from the foil's optical reflection and its absorption of high voltage field energy. Removing the foil decreased input energy for a given lamp emission level. I could watch input power rise as I slipped the foil back along the lamp's length. In some cases, with the foil fully replaced, I could draw sparks from it with my finger!

I also assembled lamps, displays, and inverter boards in various unoriginal combinations. In some cases I was able to increase light output, at lower input power drain, over the original "as shipped" configuration.

Grandpa Would Have Liked It

I tried a lot of similarly simple experiments and slowly developed a growing suspicion that nobody, at least in my sample of computers, was making any serious attempt at optimizing (or they did not know how to optimize) the backlight. It appeared that most people making lamps were simply filling tubes up with gas and shipping them. Display manufacturers were dropping these lamps into displays and shipping them. Computer vendors bought some "backlight power supply" board, wired it up to the display, took whatever electrical and optical efficiency they got, and shipped the computer.

If I allowed this conclusion, several things became clear. Development of an efficient backlight required an interdisciplinary approach to address a complex problem. There was worthwhile work to be done. I could contribute to the electronic portion, and perhaps the thermal design, but the optical engineering was beyond me. It was not, however, beyond Apple's resources. Apple had some very good optical types. Working together, it seemed we had a chance to build a better backlight with its attendant display quality and battery life advantages. Apple would get a more saleable product and my company would develop a valued customer. And, because the whole thing was beginning to get interesting, I could get out of my rut. The business school types would call this "synergistic" or "win-win." Other people who "do lunch" a lot on company money would call it "strategic partnering." My grandfather would have called it "such a deal."

Goals for the backlight began to emerge. For best overall efficiency, the display enclosure, optical design, lamp, and electronics had to be simultaneously considered. My job was the electronics, although I met regularly with Paul Donovan, who was working on the other issues. In particular, I was actively involved in setting lamp specifications and evaluating lamp vendors.

The electronics should obviously be as efficient as possible. The circuit should be physically compact, have a low parts count, and assemble easily. It should have a wide, continuous dimming range with no hysteresis or "pop-on," and should meet all RF and system emission requirements. Finally, it must regulate lamp intensity against wide power supply shifts, such as when the computer's AC adapter is plugged in.

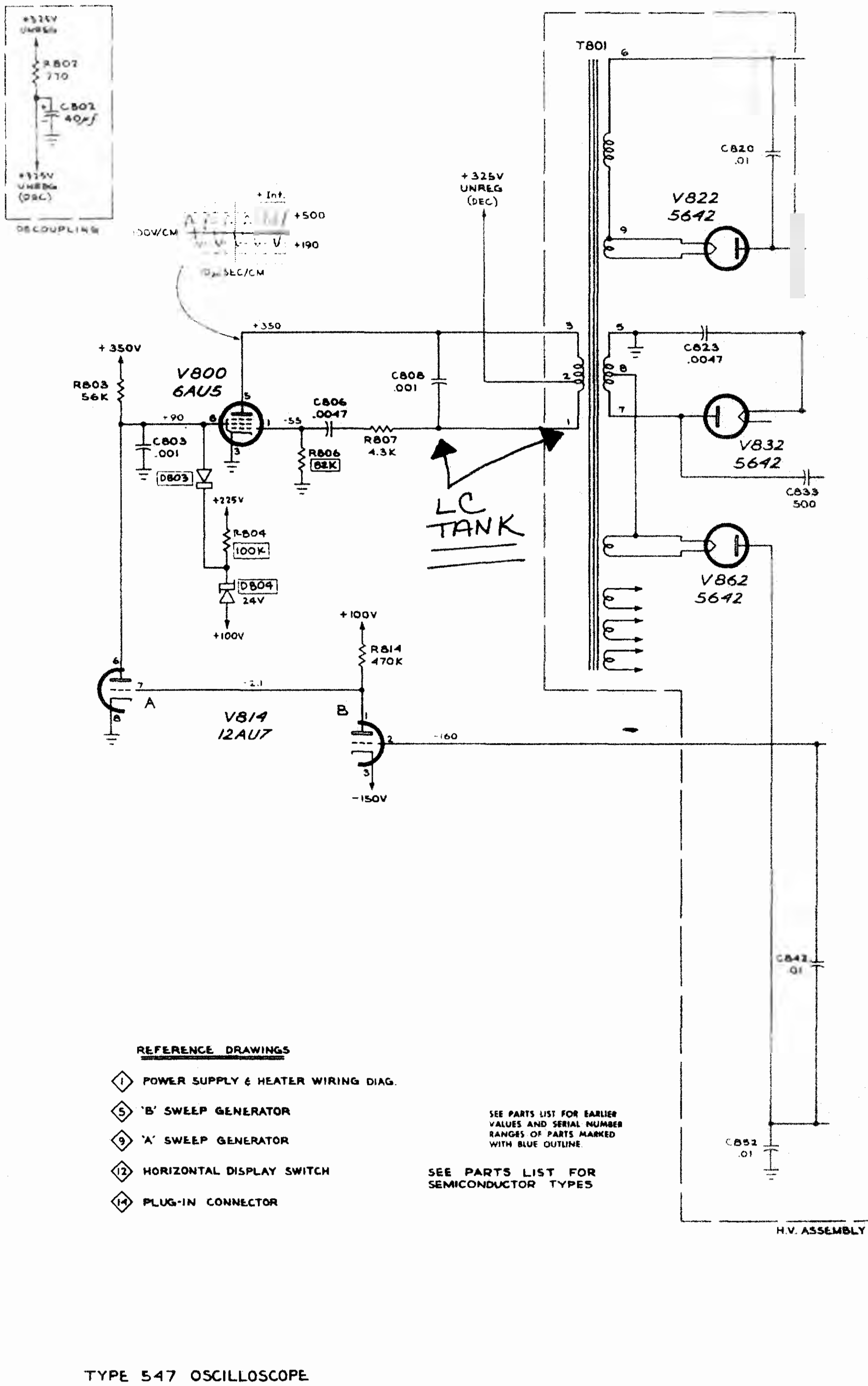
Help from Dusty Circuits

Where, I wondered, had I seen circuitry which contained any or all of these characteristics? Nowhere. But, one place to start looking was oscilloscopes. Although oscilloscope circuits do not accomplish what I needed to do, oscilloscope designers use high frequency sine wave conversion to generate the high voltage CRT supply. This technique minimizes noise and reduces transformer and capacitor size. Additionally, by doing the conversion at the CRT, long high voltage runs from the main power supply are eliminated.

I looked at the schematic of the high voltage converter in a Tektronix 547 (Figure 11–4). The manual's explanation (Figure 11–5) says the capacitor (C808) and transformer primary form a resonant tank circuit. More subtly, the "transformer primary" also includes the complex impedance reflected back from the secondary and its load. But that's a detail for this circuit and for now. A CRT is a relatively linear and benign load. The backlight's loading characteristics would have to be evaluated and matched to the circuit.

This CRT circuit could not be used to drive a fluorescent backlight tube in a laptop computer. For one reason, this circuit is not very efficient. It does not have to be. A 547 pulls over 500 watts, so efficiency in this circuit was not a big priority. Latter versions of this configuration were transistorized (Figure 11–6, Tektronix 453), but used basically the same architecture. In both circuits the resonating technique is employed, and a feedback loop enforces voltage regulation. For another reason, the CRT requires the high voltage to be rectified to DC. The backlight requires AC, eliminating the rectifier and filter. And, the CRT circuit had no feedback. Some form of feedback for the fluorescent lamp seemed desirable.

The jewel in the CRT circuit, however, was the resonating technique used to create the sine wave. The transformer does double duty. It helps create the sine wave while simultaneously generating the high voltage.


DECOUPLING
R802
C802
40μf
+ Int.
+500
+190
T801
C820
.01
V822
5642
+325V
UNREG
(DEC)
+350
+ 350V
R803
56K
V800
6AU5
C808
.001
C806
.0047
+90
-55
C803
.001
R806
82K
R807
4.3K
D803
+225V
R804
100K
D804
24V
+100V
C823
.0047
V832
5642
C833
500
LC
TANK
V862
5642
+100V
R814
470K
A
B
V814
12AU7
-160
-150V
C842
.01
C852
.01
REFERENCE DRAWINGS
1 POWER SUPPLY & HEATER WIRING DIAG.
5 'B' SWEEP GENERATOR
9 'A' SWEEP GENERATOR
12 HORIZONTAL DISPLAY SWITCH
14 PLUG-IN CONNECTOR
SEE PARTS LIST FOR EARLIER VALUES AND SERIAL NUMBER RANGES OF PARTS MARKED WITH BLUE OUTLINE.
SEE PARTS LIST FOR SEMICONDUCTOR TYPES
H.V. ASSEMBLY
TYPE 547 OSCILLOSCOPE

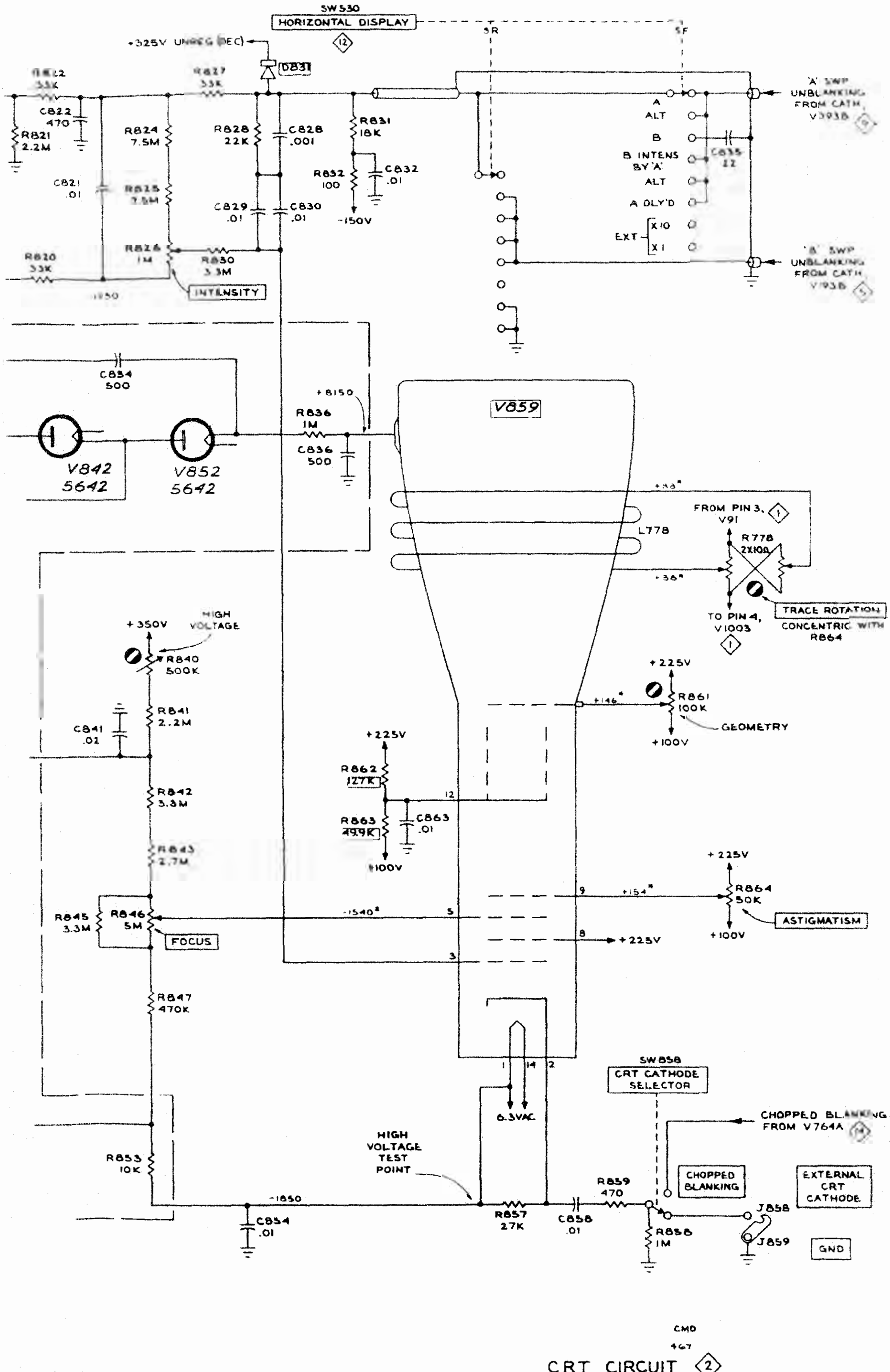


Figure 11–4.
CRT supply used in Tektronix 547. C808 resonates with transformer, creating sine wave drive. (Figure reproduced with permission of Tektronix, Inc.)

Figure 11–5. Tektronix 547 manual explains resonant operation. (Figure reproduced with permission of Tektronix, Inc.)

Crt Circuit

The crt circuit (see Crt schematic) includes the crt, the high-voltage power supply, and the controls necessary to focus and orient the display. The crt (Tektronix Type T5470-31-2) is an aluminized, 5-inch, flat-faced, glass crt with a helical post-accelerator and electrostatic focus and deflection. The crt circuit provides connections for externally modulating the crt cathode. The high-voltage power supply is composed of a dc-to-50-kc power converter, a voltage-regulator circuit, and three high-voltage outputs. Front-panel controls in the crt circuit adjust the trace rotation (screwdriver adjustment), intensity, focus, and astigmatism. Internal controls adjust the geometry and high-voltage output level.

High-Voltage Power Supply. The high-voltage power supply is a dc-to-ac converter operating at approximately 50 kc with the transformer providing three high-voltage outputs. The use of a 50-kc input to the high-voltage transformer permits the size of the transformer and filter components to be kept small. A modified Hartley oscillator converts dc from the +325-volt unregulated supply to the 50-kc input required by high-voltage transformer T801. C808 and the primary of T801 form the oscillator resonant tank circuit. No provisions are made for precise tuning of the oscillator tank since the exact frequency of oscillation is not important.

Voltage Regulation. Voltage regulation of the high-voltage outputs is accomplished by regulating the amplitude of oscillations in the Hartley oscillator. The —1850-volt output is referenced to the +350-volt regulated supply through a voltage divider composed of R841, R842, R843, R845, R846, R847, R853, and variable resistors R840 and R846. Through a tap on the voltage divider, the regulator circuit samples the —1850-volt output of the supply, amplifies any errors and uses the amplified error voltage to adjust the screen voltage of Hartley oscillator V800. If the —1850-volt output changes, the change is detected at the grid of V814B. The detected error is amplified by V814B and V814A. The error signal at the plate of V814A is direct coupled to the screen of V800 by making the plate-load resistor of V814A serve as

How could I combine this circuit's desirable resonating characteristics with other techniques to meet the backlight's requirements? One key was a simple, more efficient transformer drive. I knew just where to find it.

In December 1954 the paper "Transistors as On-Off Switches in Saturable-Core Circuits" appeared in *Electrical Manufacturing*. George H. Royer, one of the authors, described a "d-c to a-c converter" as part of this paper. Using Westinghouse 2N74 transistors, Royer reported 90% efficiency for his circuit. The operation of Royer's circuit is well described in this paper. The Royer converter was widely adopted, and used in designs from watts to kilowatts. It is still the basis for a wide variety of power conversion.

Royer's circuit is not an LC resonant type. The transformer is the sole energy storage element and the output is a square wave. Figure 11–7 is a conceptual schematic of a typical converter. The input is applied to a self-oscillating configuration composed of transistors, a transformer, and a biasing network. The transistors conduct out of phase switching (Figure 11–8: Traces A and C are Q1's collector and base, while Traces B and D are Q2's collector and base) each time the transformer saturates. Transformer saturation causes a quickly rising, high current to flow (Trace E).

This current spike, picked up by the base drive winding, switches the transistors. This phase opposed switching causes the transistors to exchange states. Current abruptly drops in the formerly conducting transistor and then slowly rises in the newly conducting transistor until saturation again forces switching. This alternating operation sets transistor duty cycle at 50%.

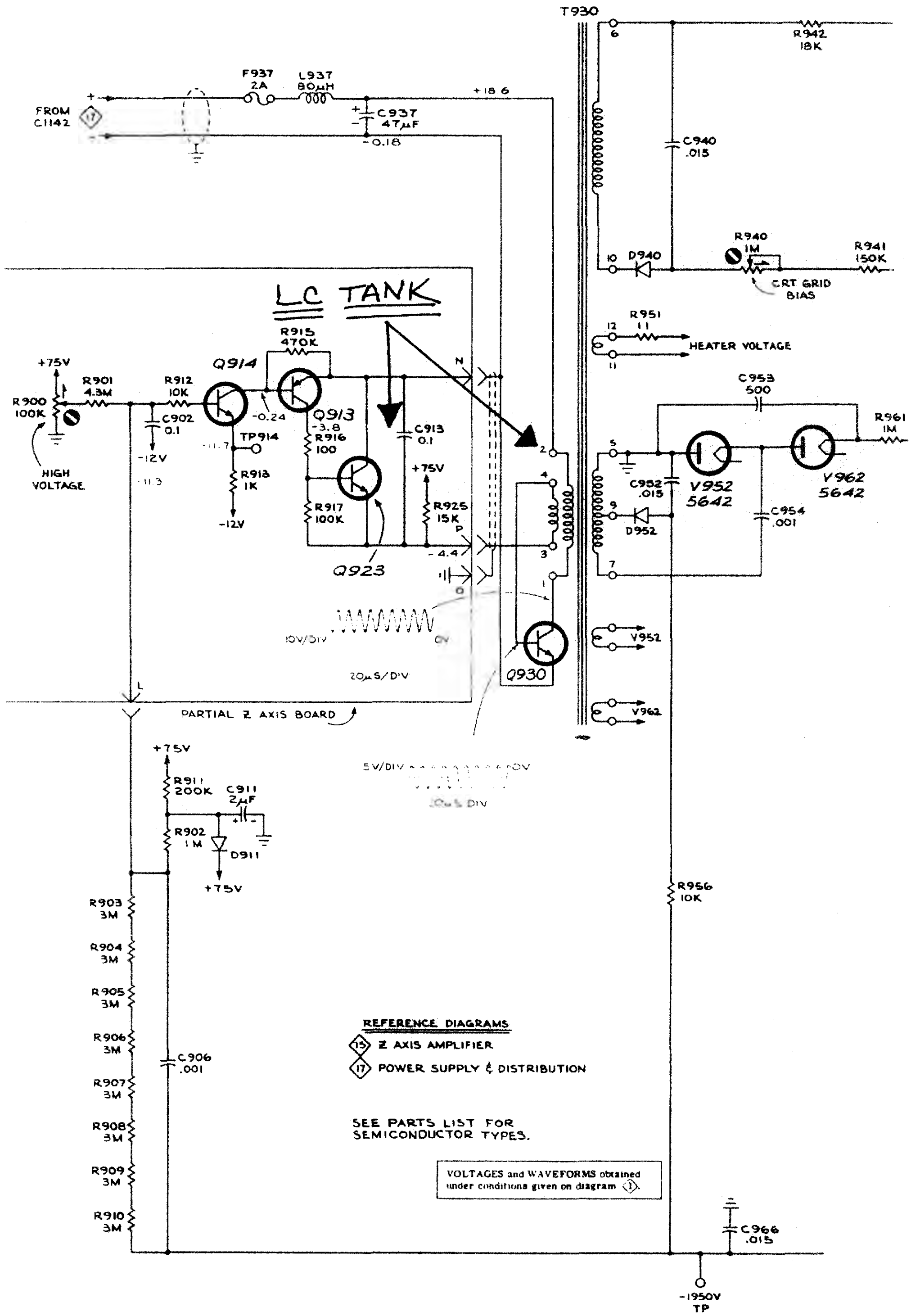
The photograph in Figure 11–9 is a time and amplitude expansion of Figure 11–8's Traces B and E. It clearly shows the relationship between transformer current (Trace B, Figure 11–9) and transistor collector voltage (Trace A, Figure 11–9).[1]

The Royer has many desirable elements which are applicable to backlight driving. Transformer size is small because core utilization is efficient. Parts count is low, the circuit self-oscillates, it is efficient, and output power may be varied over a wide range. The inherent nature of operation produces a square wave output, which is not permissible for backlight driving.

Adding a capacitor to the primary drive (Figure 11–10) should have the same resonating effect as in the Tektronix CRT circuits. The beauty of this configuration is its utter simplicity and high efficiency. As loading (e.g., lamp intensity) is varied the reflected secondary impedance changes, causing some frequency shift, but efficiency remains high.

The Royer's output power is controllable by varying the primary drive current. Figure 11–11 shows a way to investigate this. This circuit works well, except that the transistor current sink operates in its linear region, wasting power. Figure 11–12 converts the current sink to switch mode operation, maintaining high efficiency. This is obviously advantageous to the user, but also a good deal for my employer. I had spent the last six months playing with light bulbs, reminiscing over old oscilloscope circuits, taking arcane thermal measurements, and similar dalliances. All the while faithfully collecting my employer's money. Finally, I had found a place to actually sell something we made. Linear Technology (my employer) builds a switching regulator called the LT1172. Its features include a high power open collector switch, trimmed reference, low quiescent current, and shutdown capability. Additionally, it is available in an 8 pin surface-mount package, a must for board space considerations. It was also an ideal candidate for the circuit's current sink portion.

1 The bottom traces in both photographs are not germane and are not referenced in the discussion.



TYPE 453 OSCILLOSCOPE

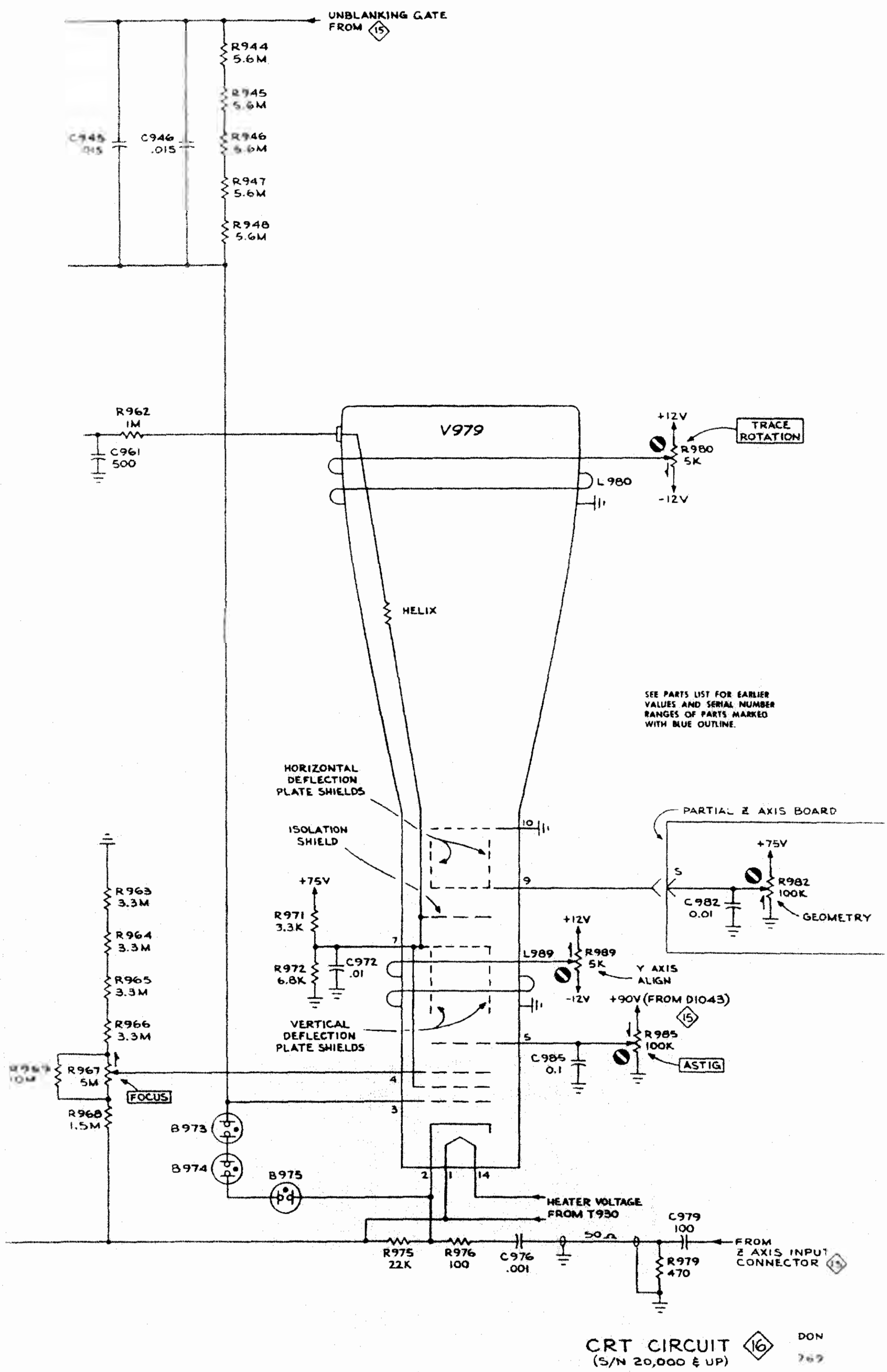


Figure 11–6.
Later model Tektronix 453 is transistorized version of 547's resonant approach. (Figure reproduced with permission of Tektronix, Inc.)

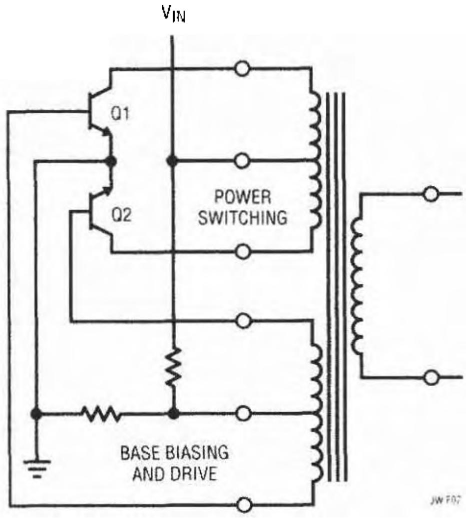


Figure 11–7. Conceptual classic Royer converter. Transformer approaching saturation causes switching.

Of Rafts and Paddles

At about this stage I sat back and stared at the wall. There comes a time in every project where you have to gamble. At some point the analytics and theorizing must stop and you have to commit to an approach and start actually doing something. This is often painful, because you never really have enough information and preparation to be confidently decisive. There are never any answers, only choices. But there comes this time when your gut tells you to put down the pencil and pick up the soldering iron.

Physicist Richard Feynman said, "If you're not confused when you start, you're not doing it right." Somebody else, I think it was an artist, said, "Inspiration comes while working." Wow, are they right. With circuits, as in life, never wait for your ship to come in. Build a raft and start paddling.

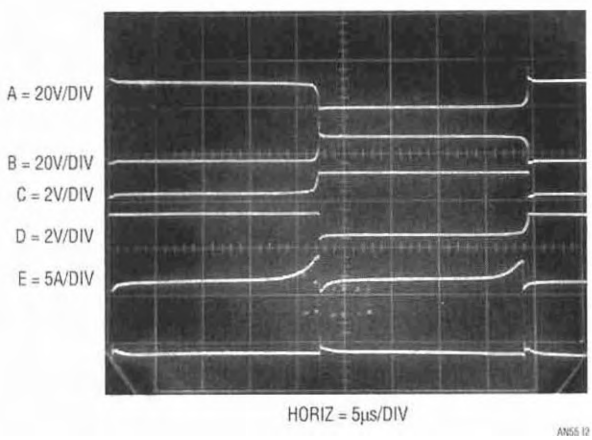


Figure 11–8. Waveforms for the classic Royer circuit.

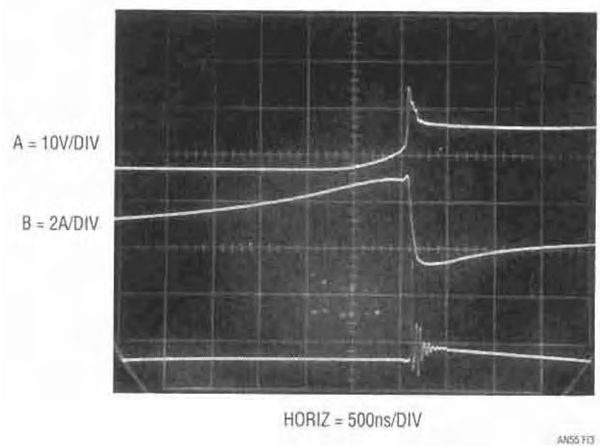


Figure 11–9. Detail of transistor switching. Turn-off (Trace A) occurs just as transformer heads into saturation (Trace B).

Everything was still pretty fuzzy, but I had learned a few things. A practical, highly efficient LCD backlight design is a classic study of compromise in a transduced electronic system. Every aspect of the design is interrelated, and the physical embodiment is an integral part of the electrical circuit. The choice and location of the lamp, wires, display housing, and other items have a major effect on electrical characteristics. The greatest care in every detail is required to achieve a practical, high efficiency LCD backlight. Getting the lamp to light is just the beginning!

A good place to start was to reconsider the lamps. These "Cold Cathode Fluorescent Lamps" (CCFL) provide the highest available efficiency for converting electrical energy to light. Unfortunately, they are optically and electrically highly nonlinear devices.

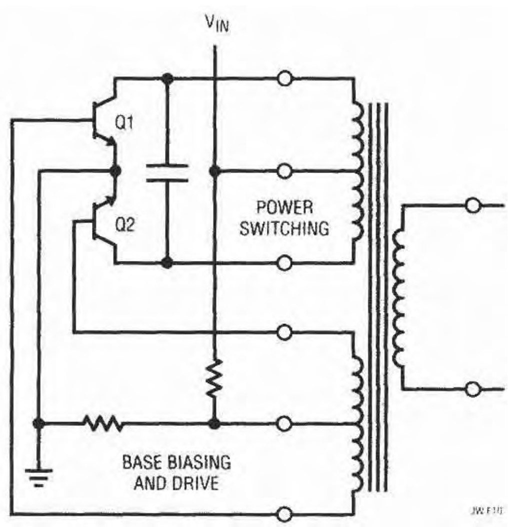


Figure 11–10. Adding the resonating capacitor to the Royer.

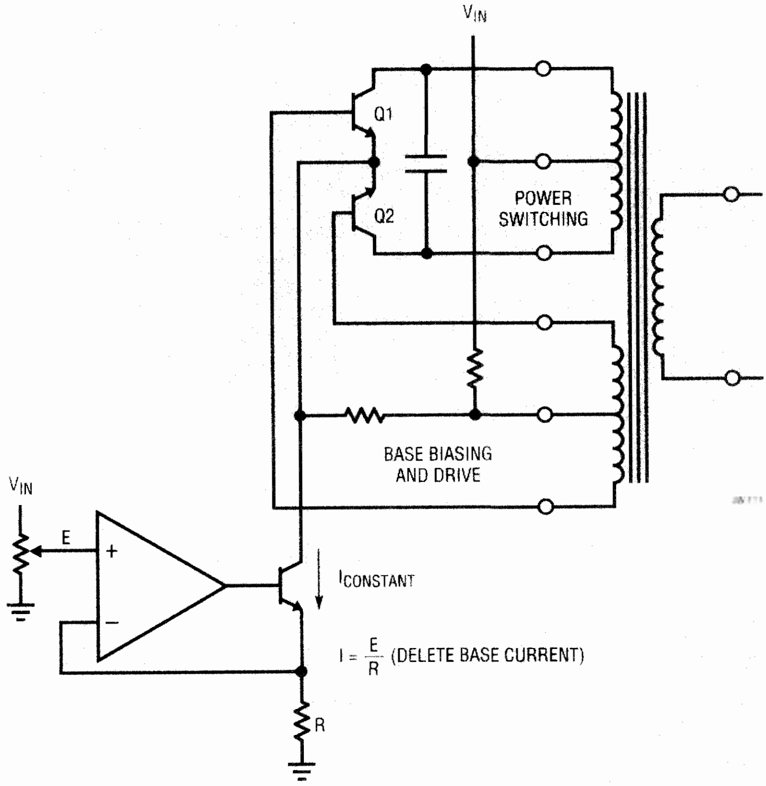


Figure 11–11. Current sink permits controlling Royer power, but is inefficient.

Cold Cathode Fluorescent Lamps (CCFLs)

Any discussion of CCFL power supplies must consider lamp characteristics. These lamps are complex transducers, with many variables affecting their ability to convert electrical current to light. Factors influencing conversion efficiency include the lamp's current, temperature, drive waveform characteristics, length, width, gas constituents, and the proximity to nearby conductors.

These and other factors are interdependent, resulting in a complex overall response. Figures 11–13 through 11–16 show some typical characteristics. A review of these curves hints at the difficulty in predicting lamp behavior as operating conditions vary. The lamp's current and temperature are clearly critical to emission, although electrical efficiency may not necessarily correspond to the best optical efficiency point. Because of this, both electrical and photometric evaluation of a circuit is often required. It is possible, for example, to construct a CCFL circuit with 94% electrical efficiency which produces less light output than an approach with 80% electrical efficiency (see Appendix C, "A Lot of Cut-off Ears and No Van Goghs—Some Not-So-Great Ideas"). Similarly, the performance of a very well matched lamp-circuit combination can be

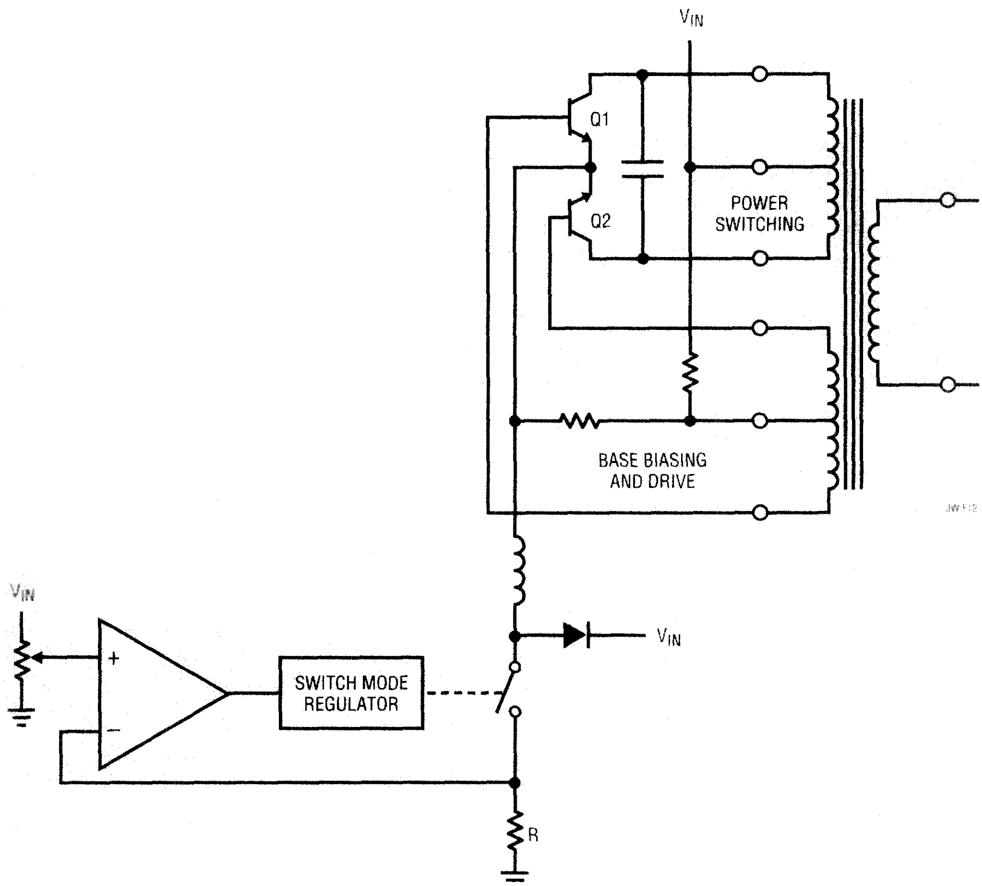


Figure 11–12. Switched mode current sink restores efficiency.

severely degraded by a lossy display enclosure or excessive high voltage wire lengths. Display enclosures with too much conducting material near the lamp have huge losses due to capacitive coupling. A poorly designed display enclosure can easily degrade efficiency by 20%. High voltage wire runs typically cause 1% loss per inch of wire.

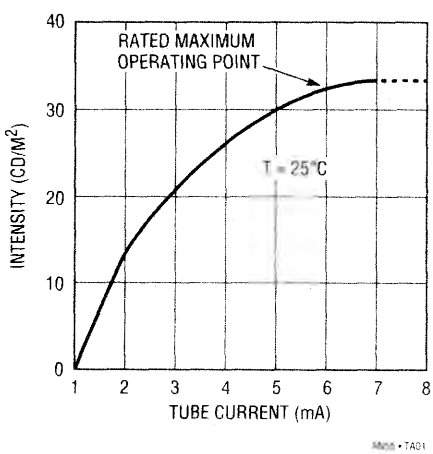


Figure 11–13. Emissivity for a typical 6mA lamp; curve flattens badly above 6mA.

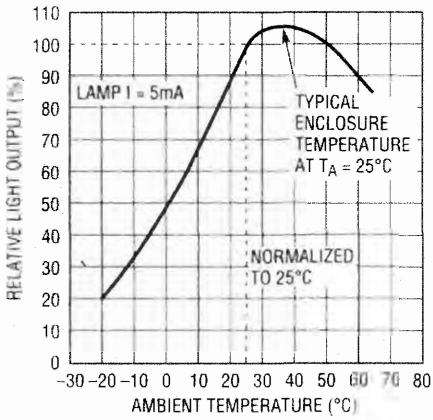


Figure 11–14. Ambient temperature effects on emissivity of a typical 5mA lamp. Lamp and enclosure must come to thermal steady state before measurements are made.

CCFL Load Characteristics

These lamps are a difficult load to drive, particularly for a switching regulator. They have a "negative resistance" characteristic; the starting voltage is significantly higher than the operating voltage. Typically, the start voltage is about 1000V, although higher and lower voltage lamps are common. Operating voltage is usually 300V to 400V, although other lamps may require different potentials. The lamps will operate from DC, but migration effects within the lamp will quickly damage it. As such, the waveform must be AC. No DC content should be present.

Figure 11–17A shows an AC driven lamp's characteristics on a curve tracer. The negative resistance induced "snapback" is apparent. In Figure 11–17B, another lamp, acting against the curve tracer's drive, produces oscillation. These tendencies, combined with the frequency compensation problems associated with switching regulators, can cause severe loop instabilities, particularly on start-up. Once the lamp is in its operating region it assumes a linear load characteristic, easing stability criteria. Lamp operating frequencies are typically 20kHz to 100kHz and a sine-

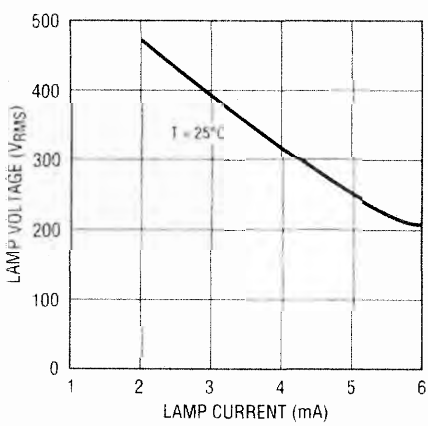


Figure 11–15. Current vs. voltage for a lamp in the operating region.

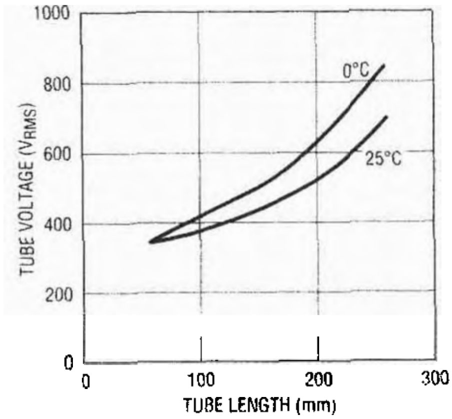


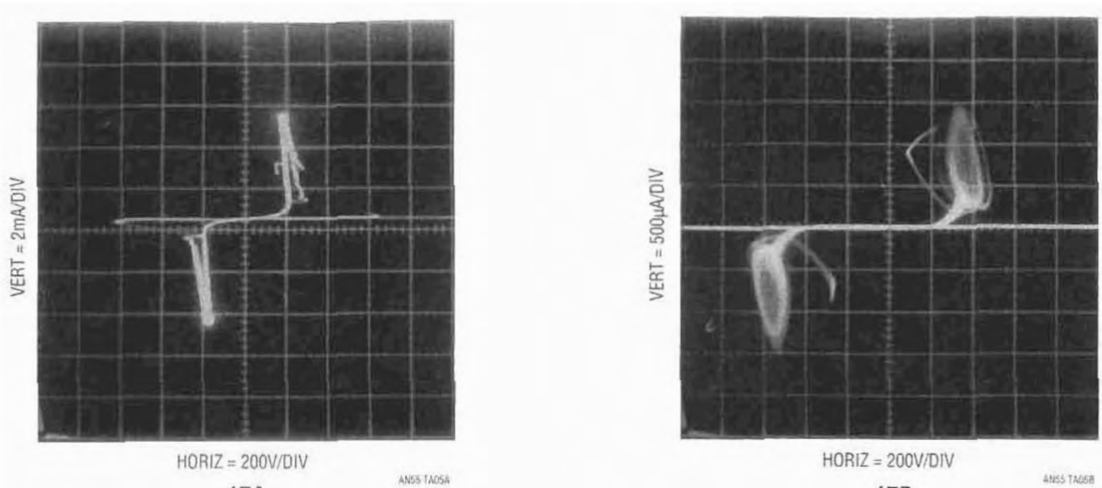
Figure 11-16. Running voltage vs. lamp length at two temperatures. Start-up voltages are usually 50% to 200% higher over temperature.

like waveform is preferred. The sine drive's low harmonic content minimizes RF emissions, which could cause interference and efficiency degradation. A further benefit of the continuous sine drive is its low crest factor and controlled risetimes, which are easily handled by the CCFL. CCFL's RMS current-to-light output efficiency is degraded by high crest factor drive waveforms.[2]

CCFL Power Supply Circuits

Figure 11-18's circuit meets CCFL drive requirements. Efficiency is 88% with an input voltage range of 4.5V to 20V. This efficiency figure will be degraded by about 3% if the LT1172 V_{IN} pin is powered from the same supply as the main circuit V_{IN} terminal. Lamp intensity is continuously and smoothly variable from zero to full intensity. When power is

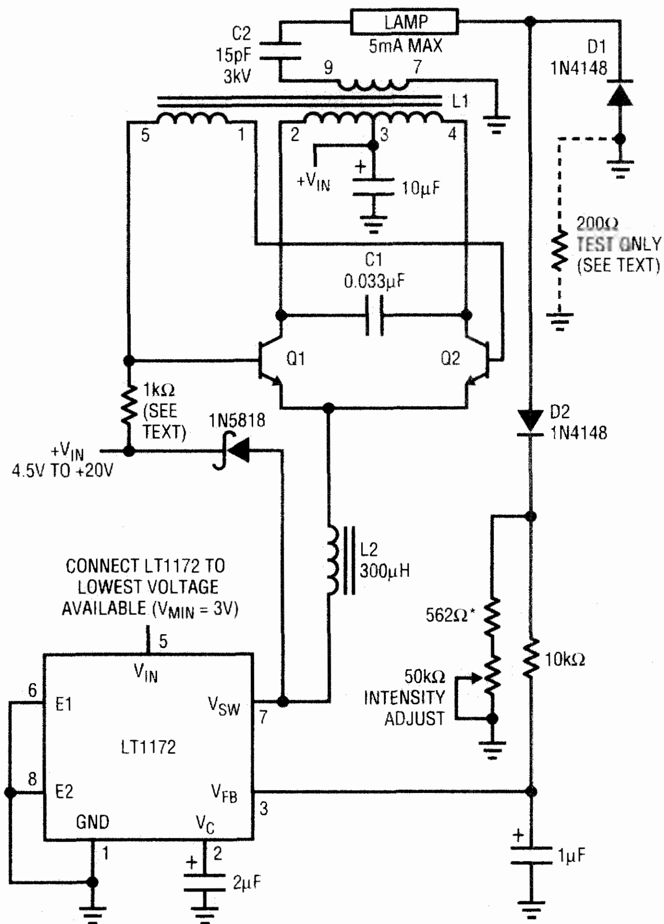
Figure 11-17. Negative resistance characteristic for two CCFL lamps. "Snap-back" is readily apparent, causing oscillation in 11-17B. These characteristics complicate power supply design.



17A 17B

2. See Appendix C, "A Lot of Cut-off Ears and No Van Goghs—Some Not-So-Great Ideas."

Figure 11–18. An 88% efficiency cold cathode fluorescent lamp (CCFL) power supply.



C1 = MUST BE A LOW LOSS CAPACITOR.
METALIZED POLYCARB
WIMA FKP2 OR MKP-20 (GERMAN) RECOMMENDED
L1 = SUMIDA 6345-020 OR COILTRONICS CTX110092-1
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = COILTRONICS CTX300-4
Q1, Q2 = ZETEX ZTX849 OR ROHM 2SC5001
* = 1% FILM RESISTOR
DO NOT SUBSTITUTE COMPONENTS

COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666

applied the LT1172 switching regulator's feedback pin is below the device's internal 1.2V reference, causing full duty cycle modulation at the V_{SW} pin (Trace A, Figure 11–19). L2 conducts current (Trace B) which flows from L1's center tap, through the transistors, into L2. L2's current is deposited in switched fashion to ground by the regulator's action.

L1 and the transistors comprise a current driven Royer class converter which oscillates at a frequency primarily set by L1's characteristics (including its load) and the .033µF capacitor. LT1172 driven L2 sets the magnitude of the Q1-Q2 tail current, and hence L1's drive level. The 1N5818 diode maintains L2's current flow when the LT1172 is off. The LT1172's 100kHz clock rate is asynchronous with respect to the push-pull converter's (60kHz) rate, accounting for Trace B's waveform thickening.

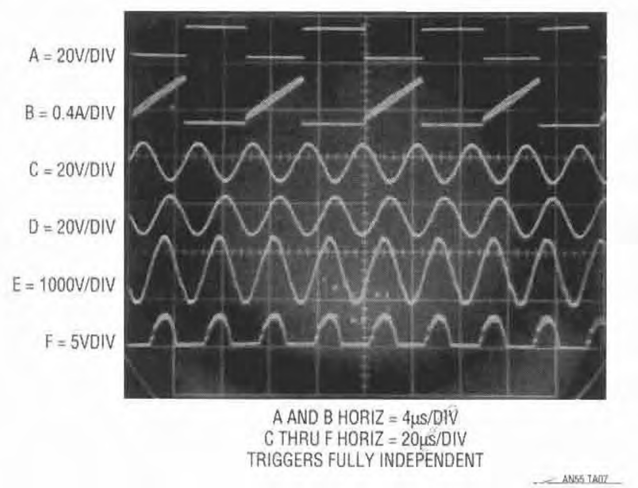


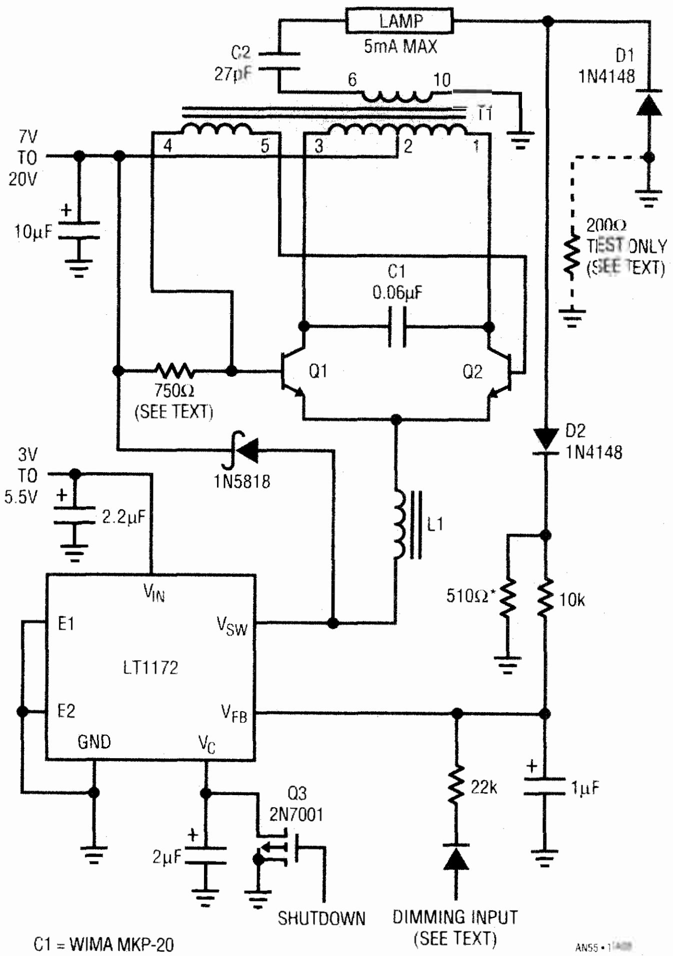
Figure 11–19. Waveforms for the cold cathode fluorescent lamp power supply. Note independent triggering on Traces A and B, and C through F.

The .033μF capacitor combines with L1's characteristics to produce sine wave voltage drive at the Q1 and Q2 collectors (Traces C and D, respectively). L1 furnishes voltage step-up, and about 1400V p-p appears at its secondary (Trace E). Current flows through the 15pF capacitor into the lamp. On negative waveform cycles the lamp's current is steered to ground via D1. Positive waveform cycles are directed, via D2, to the ground referred 562Ω–50k potentiometer chain. The positive half-sine appearing across the resistors (Trace F) represents ½ the lamp current. This signal is filtered by the 10k–1μF pair and presented to the LT1172's feedback pin. This connection closes a control loop which regulates lamp current. The 2μF capacitor at the LT1172's V_C pin provides stable loop compensation. The loop forces the LT1172 to switch-mode modulate L2's average current to whatever value is required to maintain a constant current in the lamp. The constant current's value, and hence lamp intensity, may be varied with the potentiometer. The constant current drive allows full 0%–100% intensity control with no lamp dead zones or "pop-on" at low intensities. Additionally, lamp life is enhanced because current cannot increase as the lamp ages. This constant current feedback approach contrasts with the open loop, voltage type drive used by other approaches. It greatly improves control over the lamp under all conditions.

This circuit's 0.1% line regulation is notably better than some other approaches. This tight regulation prevents lamp intensity variation when abrupt line changes occur. This typically happens when battery powered apparatus is connected to an AC powered charger. The circuit's excellent line regulation derives from the fact that L1's drive waveform never changes shape as input voltage varies. This characteristic permits the simple 10kΩ–1μF RC to produce a consistent response. The RC averaging characteristic has serious error compared to a true RMS conversion, but the error is constant and "disappears" in the 562Ω shunt's value. The base drive resistor's value (nominally 1kΩ) should be selected to provide full V_{CE} saturation without inducing base overdrive or beta starvation. A procedure for doing this is described in the following section, "General Measurement and Optimization Considerations."

Figure 11–20's circuit is similar, but uses a transformer with lower copper and core losses to increase efficiency to 91%. The trade-off is slightly larger transformer size. Value shifts in C1, L2, and the base drive resistor reflect different transformer characteristics. This circuit also features shutdown via Q3 and a DC or pulse width controlled dimming input. Figure 11–21, directly derived from Figure 11–20, produces 10mA output to drive color LCDs at 92% efficiency. The slight efficiency improvement comes from a reduction in LT1172 "housekeeping" current as a percentage

Figure 11–20. A 91% efficient CCFL supply for 5mA loads features shutdown and dimming inputs.



C1 = WIMA MKP-20
L1 = COILTRONICS CTX150-4
Q1, Q2 = ZETEX ZTX849 OR ROHM 2SC5001
T1 = COILTRONICS CTX110600-1 OR SUMIDA EPS-207
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
* = 1% FILM RESISTOR
DO NOT SUBSTITUTE COMPONENTS

COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666 of total current drain. Value changes in components are the result of higher power operation. The most significant change involves driving two tubes. Accommodating two lamps involves separate ballast capacitors but circuit operation is similar. Two lamp designs reflect slightly different loading back through the transformer's primary. C2 usually ends up in the 10pF to 47pF range. Note that C2A and B appear with their lamp loads in parallel across the transformer's secondary. As such, C2's value is often smaller than in a single tube circuit using the same type lamp. Ideally the transformer's secondary current splits evenly between the C2-lamp branches, with the total load current being regulated. In practice, differences between C2A and B and differences in lamps and lamp wiring layout preclude a perfect current split. Practically, these differences are small, and the

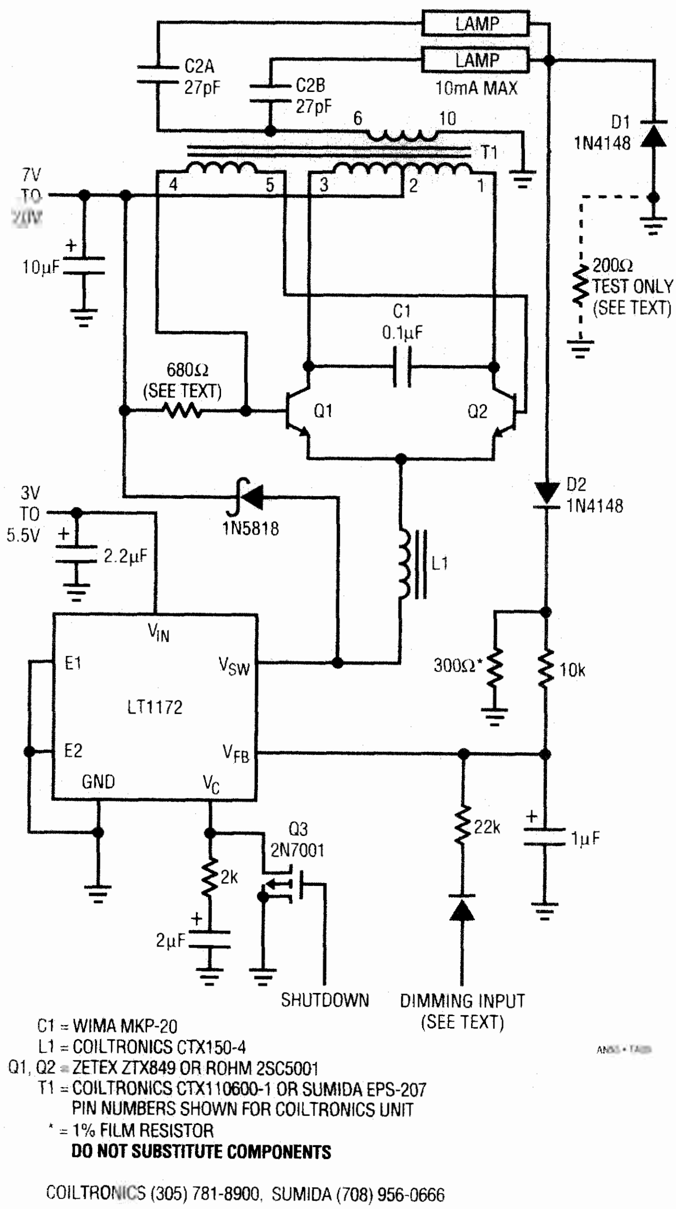


Figure 11–21.
A 92% efficient CCFL supply for 10mA loads features shutdown and dimming inputs. Two lamps are typical of color displays.

lamps appear to emit equal amounts of light. Layout and lamp matching can influence C2's value. Some techniques for dealing with these issues appear in the section "Layout Issues."

General Measurement and Optimization Considerations

Several points should be kept in mind when observing operation of these circuits. L1's high voltage secondary can only be monitored with a wide-band, high voltage probe fully specified for this type of measurement. *The vast majority of oscilloscope probes will break down and fail if used for this measurement.* Tektronix probe types P6007 and P6009 (acceptable) or types P6013A and P6015 (preferred) must be used to read L1's output.

Another consideration involves observing waveforms. The LT1172's switching frequency is completely asynchronous from the Q1-Q2 Royer converter's switching. As such, most oscilloscopes cannot simultaneously trigger and display all the circuit's waveforms. Figure 11–19 was obtained using a dual beam oscilloscope (Tektronix 556). LT1172 related Traces A and B are triggered on one beam, while the remaining traces are triggered on the other beam. Single beam instruments with alternate sweep and trigger switching (e.g., Tektronix 547) can also be used, but are less versatile and restricted to four traces.

Obtaining and verifying high efficiency[3] requires some amount of diligence. The optimum efficiency values given for C1 and C2 are typical, and will vary for specific types of lamps. An important realization is that the term "lamp" includes the total load seen by the transformer's secondary. This load, reflected back to the primary, sets transformer input impedance. The transformer's input impedance forms an integral part of the LC tank that produces the high voltage drive. Because of this, circuit efficiency must be optimized with the wiring, display housing and physical layout arranged exactly the same way they will be built in production. Deviations from this procedure will result in lower efficiency than might otherwise be possible. In practice, a "first cut" efficiency optimization with "best guess" lead lengths and the intended lamp in its display housing usually produces results within 5% of the achievable figure. Final values for C1 and C2 may be established when the physical layout to be used in production has been decided on. C1 sets the circuit's resonance point, which varies to some

3. The term "efficiency" as used here applies to electrical efficiency. In fact, the ultimate concern centers around the efficient conversion of power supply energy into light. Unfortunately, lamp types show considerable deviation in their current-to-light conversion efficiency. Similarly, the emitted light for a given current varies over the life and history of any particular lamp. As such, this publication treats "efficiency" on an electrical basis; the ratio of power removed from the primary supply to the power delivered to the lamp. When a lamp has been selected, the ratio of primary supply power to lamp-emitted light energy may be measured with the aid of a photometer. This is covered in Appendix B, "Photometric Measurements." See also Appendix D, "Perspectives on Efficiency."

extent with the lamp's characteristics. C2 ballasts the lamp, effectively buffering its negative resistance characteristic. Small values of C2 provide the most load isolation, but require relatively large transformer output voltage for loop closure. Large C2 values minimize transformer output voltage, but degrade load buffering. Also, C1's "best" value is somewhat dependent on the lamp type used. Both C1 and C2 must be selected for given lamp types. Some interaction occurs, but generalized guidelines are possible. Typical values for C1 are 0.01µF to .15µF. C2 usually ends up in the 10pF to 47pF range. C1 must be a low-loss capacitor and substitution of the recommended devices is not recommended. A poor quality dielectric for C1 can easily degrade efficiency by 10%. C1 and C2 are selected by trying different values for each and iterating towards best efficiency. During this procedure, ensure that loop closure is maintained by monitoring the LT1172's feedback pin, which should be at 1.23V. Several trials usually produce the optimum C1 and C2 values. Note that the highest efficiencies are not necessarily associated with the most esthetically pleasing waveshapes, particularly at Q1, Q2, and the output.

Other issues influencing efficiency include lamp wire length and energy leakage from the lamp. The high voltage side of the lamp should have the smallest practical lead length. Excessive length results in radiative losses, which can easily reach 3% for a 3 inch wire. Similarly, no metal should contact or be in close proximity to the lamp. This prevents energy leakage, which can exceed 10%.[4]

It is worth noting that a custom designed lamp affords the best possible results. A jointly tailored lamp-circuit combination permits precise optimization of circuit operation, yielding highest efficiency.

Special attention should be given to the layout of the circuit board, since high voltage is generated at the output. The output coupling capacitor must be carefully located to minimize leakage paths on the circuit board. A slot in the board will further minimize leakage. Such leakage can permit current flow outside the feedback loop, wasting power. In the worst case, long term contamination build-up can increase leakage inside the loop, resulting in starved lamp drive or destructive arcing. It is good practice for minimization of leakage to break the silk screen line which outlines transformer T1. This prevents leakage from the high voltage secondary to the primary. Another technique for minimizing leakage is to evaluate and specify the silk screen ink for its ability to withstand high voltages.

4. A very simple experiment quite nicely demonstrates the effects of energy leakage. Grasping the lamp at its low-voltage end (low field intensity) with thumb and forefinger produces almost no change in circuit input current. Sliding the thumb-forefinger combination towards the high-voltage (higher field intensity) lamp end produces progressively greater input currents. Don't touch the high-voltage lead or you may receive an electrical shock. Repeat: Do not touch the high-voltage lead or you may receive an electrical shock.

Efficiency Measurement

Once these procedures have been followed efficiency can be measured. Efficiency may be measured by determining lamp current and voltage. Measuring current involves measuring RMS voltage across a temporarily inserted 200Ω .1% resistor in the ground lead of the negative current steering diode. The lamp current is

$$\text{Ilamp} = \frac{\text{ERMS}}{200} \times 2$$

The ×2 factor is necessitated because the diode steering dumps the current to ground on negative cycles. The 200Ω value allows the RMS meter to read with a scale factor numerically identical to the total current. Once this measurement is complete, the 200Ω resistor may be deleted and the negative current steering diode again returned directly to ground. Lamp RMS voltage is measured at the lamp with a properly compensated high voltage probe. Multiplying these two results gives power in watts, which may be compared to the DC input supply E × I product. In practice, the lamp's current and voltage contain small out of phase components but their error contribution is negligible.

Both the current and voltage measurements require a wideband true RMS voltmeter. The meter must employ a thermal type RMS converter—the more common logarithmic computing type based instruments are inappropriate because their bandwidth is too low.

The previously recommended high voltage probes are designed to see a 1MΩ–10pF–22pF oscilloscope input. The RMS voltmeters have a 10 meg Ω input. This difference necessitates an impedance matching network between the probe and the voltmeter. Details on this and other efficiency measurement issues appear in Appendix A, "Achieving Meaningful Efficiency Measurements."

Layout

The physical layout of the lamp, its leads, the display housing, and other high voltage components, is an integral part of the circuit. Poor layout can easily degrade efficiency by 25%, and higher layout induced losses have been observed. Producing an optimal layout requires attention to how losses occur. Figure 11–22 begins our study by examining potential parasitic paths between the transformer's output and the lamp. Parasitic capacitance to AC ground from any point between the transformer output and the lamp creates a path for undesired current flow. Similarly, stray coupling from any point along the lamp's length to AC ground induces parasitic current flow. All parasitic current flow is wasted, causing the circuit to produce more energy to maintain the desired current flow in D1 and D2. The high-voltage path from the transformer to the display housing should be as short as possible to minimize losses. A good rule of thumb is

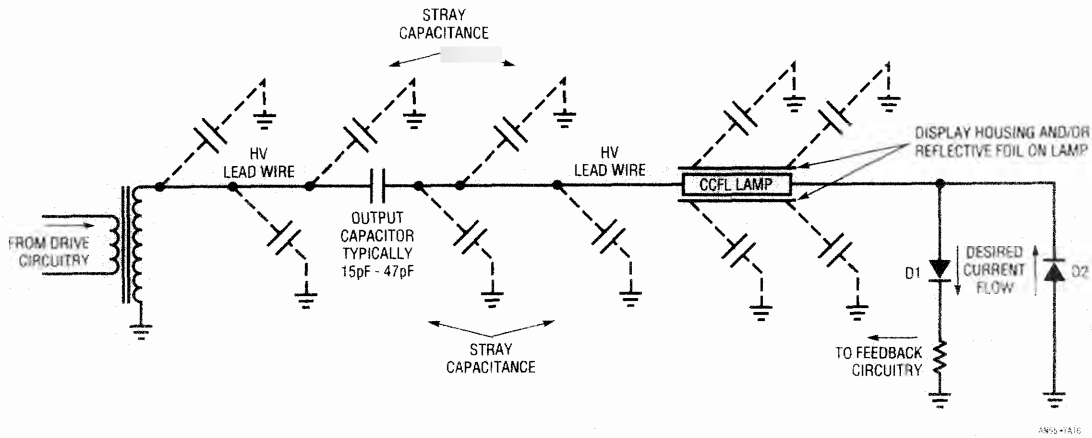


Figure 11–22. Loss paths due to stray capacitance in a practical LCD installation. Minimizing these paths is essential for good efficiency.

to assume 1% efficiency loss per inch of high voltage lead. Any PC board ground or power planes should be relieved by at least ¼" in the high voltage area. This not only prevents losses, but eliminates arcing paths.

Parasitic losses associated with lamp placement within the display housing require attention. High voltage wire length within the housing must be minimized, particularly for displays using metal construction. Ensure that the high voltage is applied to the shortest wire(s) in the display. This may require disassembling the display to verify wire length and layout. Another loss source is the reflective foil commonly used around lamps to direct light into the actual LCD. Some foil materials absorb considerably more field energy than others, creating loss. Finally, displays supplied in metal enclosures tend to be lossy. The metal absorbs significant energy and an AC path to ground is unavoidable. Direct grounding of a metal enclosed display further increases losses. Some display manufacturers have addressed this issue by relieving the metal in the lamp area with other materials.

The highest efficiency "in system" backlights have been produced by careful attention to these issues. In some cases the entire display enclosure was re-engineered for lowest losses.

Layout Considerations for Two-Lamp Designs

Systems using two lamps have some unique layout problems. Almost all two lamp displays are color units. The lower light transmission characteristics of color displays necessitate more light. Therefore, display manufacturers use two tubes to produce more light. The wiring layout of these two tube color displays affects efficiency and illumination balance in the lamps. Figure 11–23 shows an "x-ray" view of a typical display. This symmetrical arrangement presents equal parasitic losses. If C1 and C2 and the lamps are matched, the circuit's current output splits evenly and equal illumination occurs.

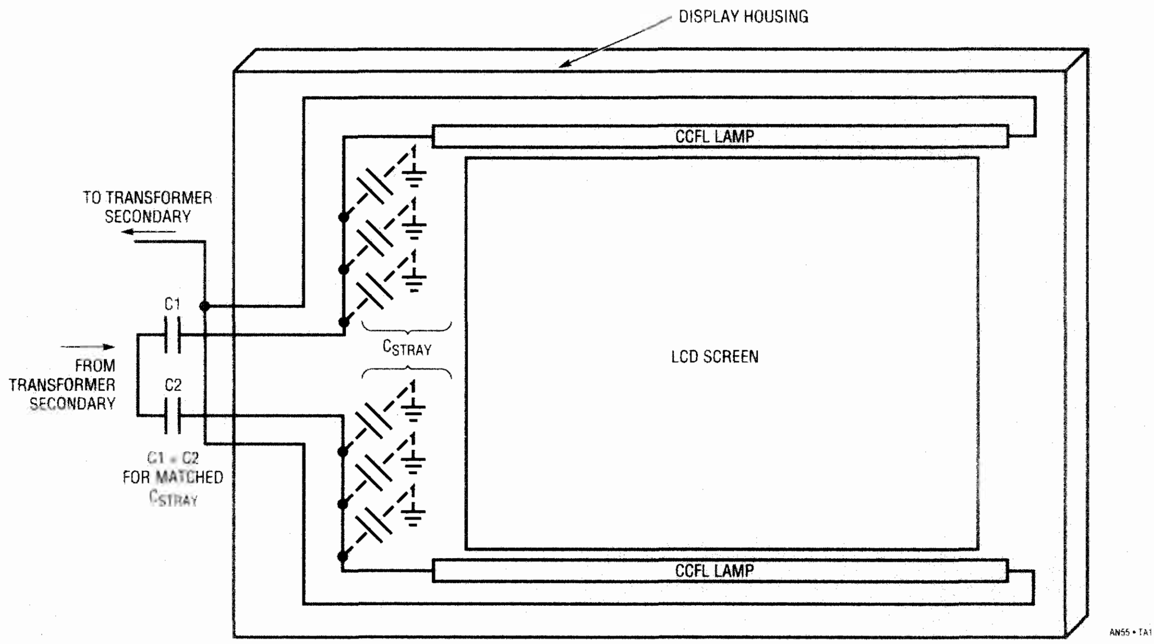


Figure 11–23. Loss paths for a "best case" dual lamp display. Symmetry promotes balanced illumination.

Figure 11–24's display arrangement is less friendly. The asymmetrical wiring forces unequal losses, and the lamps receive imbalanced current. Even with identical lamps, illumination may not be balanced. This condition is correctable by skewing C1's and C2's values. C1, because it drives greater parasitic capacitance, should be larger than C2. This tends to equalize the currents, promoting equal lamp drive. It is important to realize that this compensation does nothing to recapture the lost energy—efficiency is still compromised. There is no substitute for minimizing loss paths.

In general, imbalanced illumination causes fewer problems than might be supposed. The effect is very difficult for the eye to detect at high intensity levels. Unequal illumination is much more noticeable at lower levels. In the worst case, the dimmer lamp may only partially illuminate. This phenomenon is discussed in detail in the section "Thermometering."

Feedback Loop Stability Issues

The circuits shown to this point rely on closed loop feedback to maintain the operating point. All linear closed loop systems require some form of frequency compensation to achieve dynamic stability. Circuits operating with relatively low power lamps may be frequency compensated simply by overdamping the loop. Figures 11–18 and 11–20 use this approach. The higher power operation associated with color displays requires more attention to loop response. The transformer produces much higher output

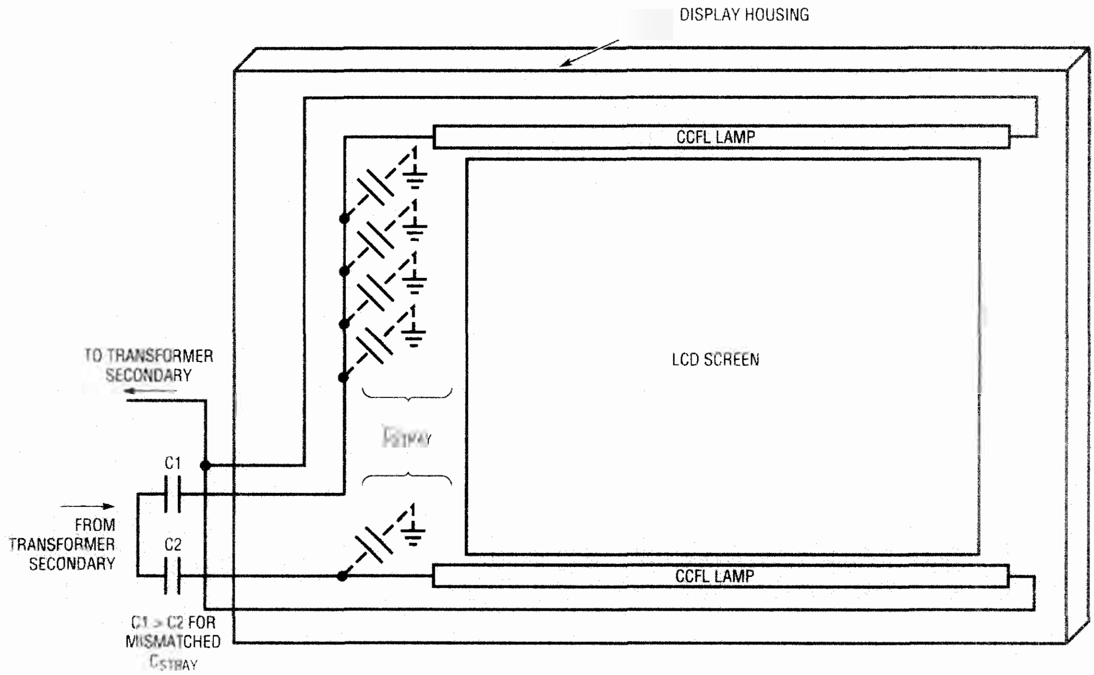


Figure 11–24. Symmetric losses in a dual lamp display. Skewing C1 and C2 values compensates imbalanced loss paths, but not wasted energy.

voltages, particularly at start-up. Poor loop damping can allow transformer voltage ratings to be exceeded, causing arcing and failure. As such, higher power designs may require optimization of transient response characteristics.

Figure 11–25 shows the significant contributors to loop transmission in these circuits. The resonant Royer converter delivers information at

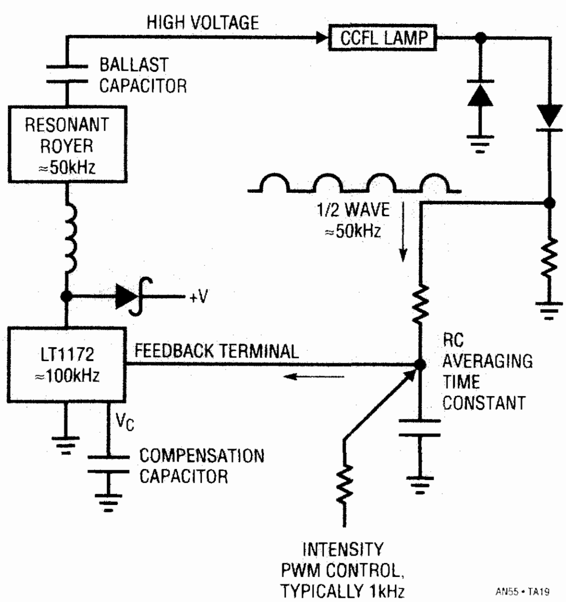


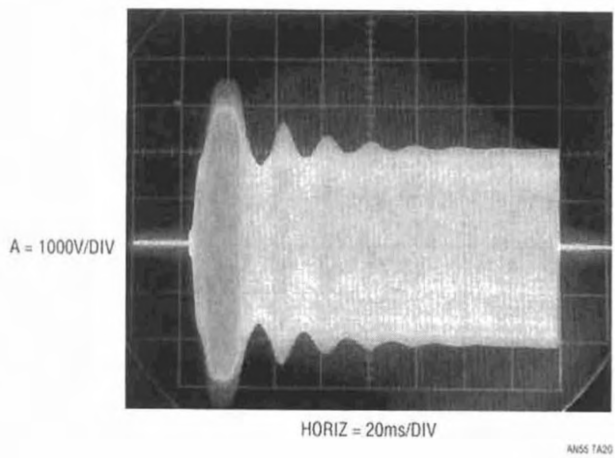
Figure 11–25. Delay terms in the feedback path. The RC time constant dominates loop transmission delay and must be compensated for stable operation.

about 50kHz to the lamp. This information is smoothed by the RC averaging time constant and delivered to the LT1172's feedback terminal as DC. The LT1172 controls the Royer converter at a 100kHz rate, closing the control loop. The capacitor at the LT1172 rolls off gain, nominally stabilizing the loop. This compensation capacitor must roll off the gain bandwidth at a low enough value to prevent the various loop delays from causing oscillation.

Which of these delays is the most significant? From a stability viewpoint, the LT1172's output repetition rate and the Royer's oscillation frequency are sampled data systems. Their information delivery rate is far above the RC averaging time constant's delay and is not significant. The RC time constant is the major contributor to loop delay. This time constant must be large enough to turn the half wave rectified waveform into DC. It also must be large enough to average any intensity control PWM signal to DC. Typically, these PWM intensity control signals come in at a 1kHz rate. The RC's resultant delay dominates loop transmission. It must be compensated by the capacitor at the LT1172. A large enough value for this capacitor rolls off loop gain at low enough frequency to provide stability. The loop simply does not have enough gain to oscillate at a frequency commensurate with the RC delay.

This form of compensation is simple and effective. It ensures stability over a wide range of operating conditions. It does, however, have poorly damped response at system turn-on. At turn-on, the RC lag delays feedback, allowing output excursions well above the normal operating point. When the RC acquires the feedback value, the loop stabilizes properly. This turn-on overshoot is not a concern if it is well within transformer breakdown ratings. Color displays, running at higher power, usually require large initial voltages. If loop damping is poor, the overshoot may be dangerously high. Figure 11–26 shows such a loop responding to turn-on. In this case the RC values are 10kΩ and 4.7µf, with a 2µf compensation capacitor. Turn-on overshoot exceeds 3500 volts for over 10

Figure 11–26. Destructive high voltage overshoot and ring-off due to poor loop compensation. Transformer failure and field recall are nearly certain. Job loss may also occur.



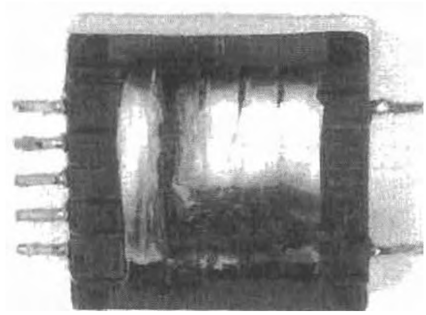


Figure 11–27. Poor loop compensation caused this transformer failure. Arc occurred in high voltage secondary (lower right). Resultant shorted turns caused overheating.

milliseconds! Ring-off takes over 100 milliseconds before settling occurs. Additionally, an inadequate (too small) ballast capacitor and excessively lossy layout force a 2000 volt output once loop settling occurs. This photo was taken with a transformer rated well below this figure. The resultant arcing caused transformer destruction, resulting in field failures. A typical destroyed transformer appears in Figure 11–27.

Figure 11–28 shows the same circuit, with the RC values reduced to 10kΩ and 1µf. The ballast capacitor and layout have also been optimized. Figure 11–28 shows peak voltage reduced to 2.2 kilovolts with duration down to about 2 milliseconds. Ring-off is also much quicker, with lower amplitude excursion. Increased ballast capacitor value and wiring layout optimization reduce running voltage to 1300 volts. Figure 11–29's results are even better. Changing the compensation capacitor to a 3kΩ–2µf network introduces a leading response into the loop, allowing faster acquisition. Now, turn-on excursion is slightly lower, but greatly reduced in duration. The running voltage remains the same.

The photos show that changes in compensation, ballast value, and layout result in dramatic reductions in overshoot amplitude and duration. Figure 11–26's performance almost guarantees field failures, while Figures 11–28 and 11–29 do not overstress the transformer. Even with

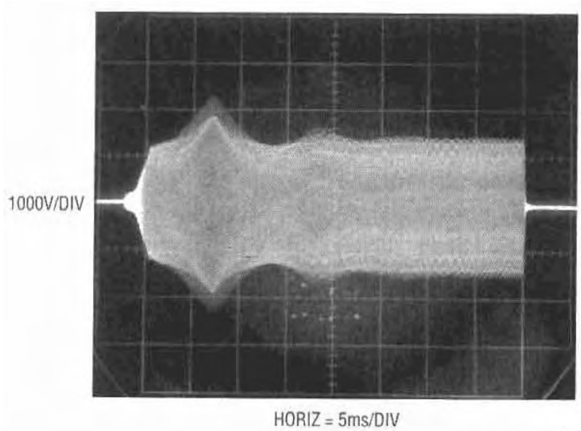


Figure 11–28. Reducing RC time constant improves transient response, although peaking, ring-off, and run voltage are still excessive.

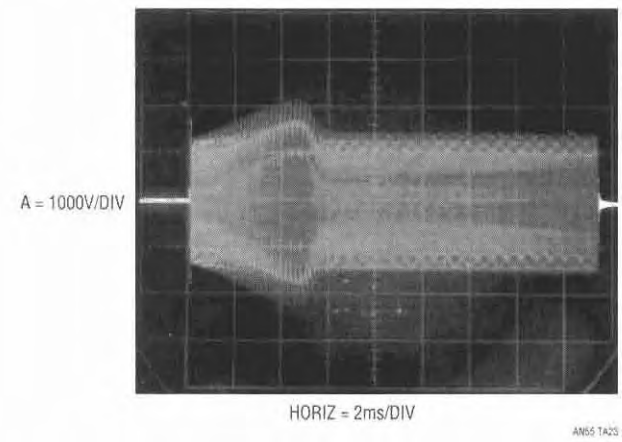


Figure 11–29. Additional optimization of RC time constant and compensation capacitor reduces turn-on transient. Run voltage is large, indicating possible lossy layout and display.

the improvements, more margin is possible if display losses can be controlled. Figures 11–26–11–29 were taken with an exceptionally lossy display. The metal enclosure was very close to the foil wrapped lamps, causing large losses with subsequent high turn-on and running voltages. If the display is selected for lower losses, performance can be greatly improved.

Figure 11–30 shows a low loss display responding to turn-on with a 2µf compensation capacitor and 10kΩ-1µf RC values. Trace A is the transformer's output while Traces B and C are the LT1172's Vcompensation and feedback pins, respectively. The output overshoots and rings badly, peaking to about 3000 volts. This activity is reflected by overshoots at the Vcompensation pin (the LT1172's error amplifier output) and the feedback pin. In Figure 11–31, the RC is reduced to 10kΩ–.1µf. This substantially reduces loop delay. Overshoot goes down to only 800 volts—a reduction of almost a factor of four. Duration is also much shorter. The Vcompensation and feedback pins reflect this tighter control. Damping is much better, with slight overshoot induced at turn-on. Further reduction of the RC to 10kΩ–.01µf (Figure 11–32) results in even faster loop capture, but a new problem appears. In Trace A, lamp turn on is so fast that the overshoot does not register in the photo. The

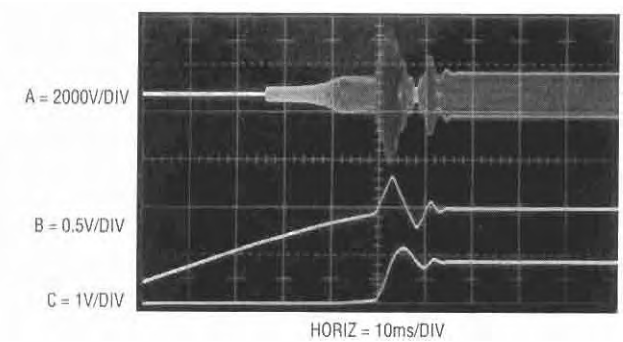


Figure 11–30. Waveforms for a lower loss layout and display. High voltage overshoot (Trace A) is reflected at compensation node (Trace B) and feedback pin (Trace C).

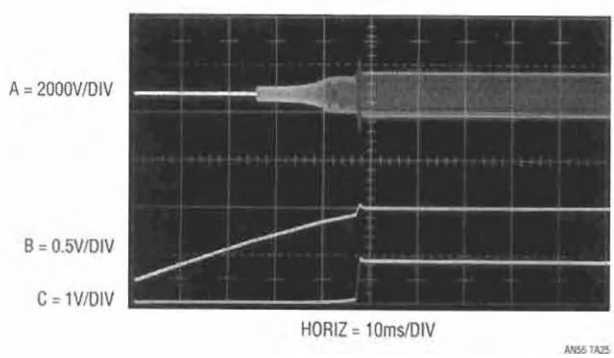


Figure 11–31. Reducing RC time constant produces quick, clean loop behavior. Low loss layout and display result in 650 VRMS running voltage.

Vcompensation (Trace B) and feedback nodes (Trace C) reflect this with exceptionally fast response. Unfortunately, the RC's light filtering causes ripple to appear when the feedback node settles. As such, Figure 11–31's RC values are probably more realistic for this situation.

The lesson from this exercise is clear. The higher voltages involved in color displays mandate attention to transformer outputs. Under running conditions, layout and display losses can cause higher loop compliance voltages, degrading efficiency and stressing the transformer. At turn-on, improper compensation causes huge overshoots, resulting in possible transformer destruction. Isn't a day of loop and layout optimization worth a field recall?

Extending Illumination Range

Lamps operating at relatively low currents may display the "thermometer effect," that is, light intensity may be nonuniformly distributed along lamp length. Figure 11–33 shows that although lamp current density is uniform, the associated field is imbalanced. The field's low intensity, combined with its imbalance, means that there is not enough energy to maintain uniform phosphor glow beyond some point. Lamps displaying the thermometer effect emit most of their light near the positive electrode, with rapid emission fall-off as distance from the electrode increases.

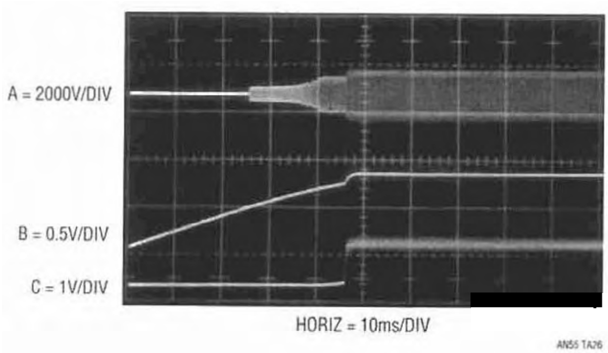


Figure 11–32. Very low RC value provides even faster response, but ripple at feedback pin (Trace C) is too high. Figure 11–31 is the best compromise.

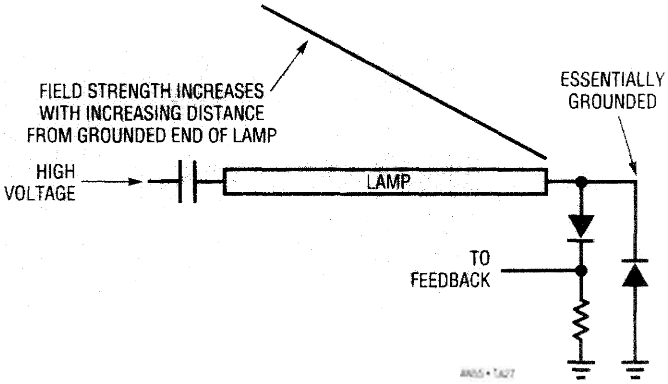
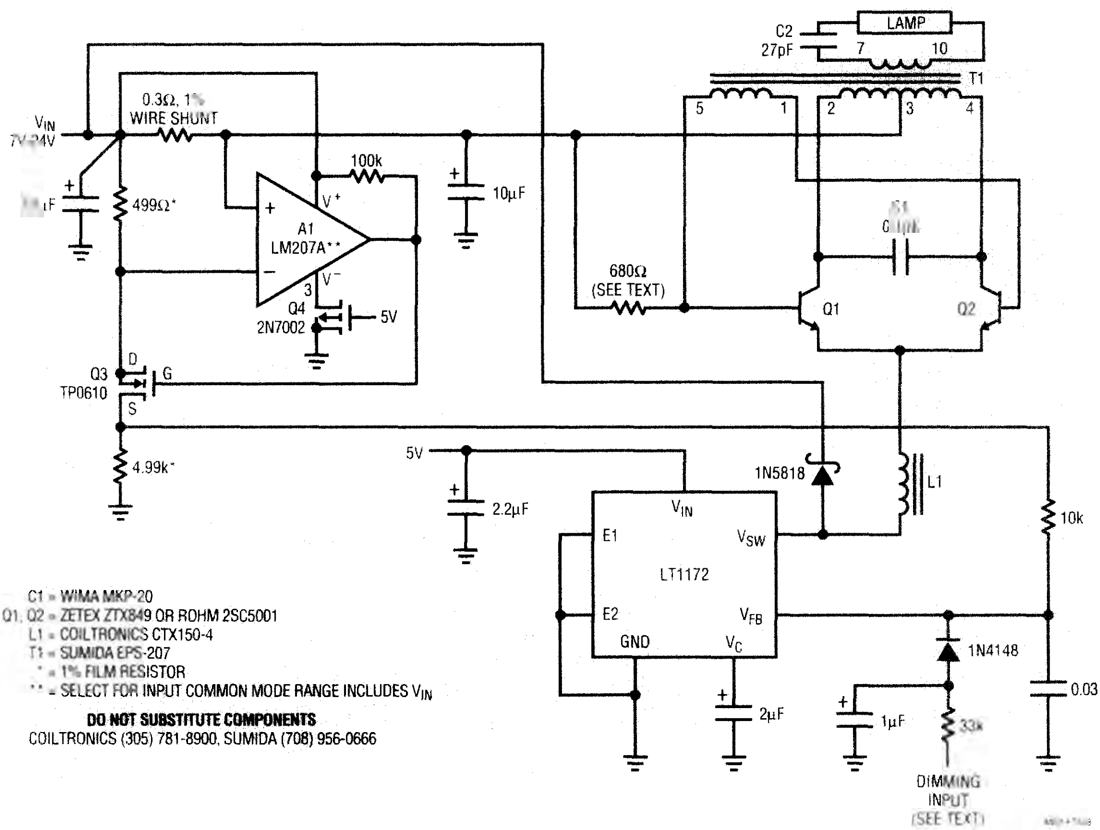


Figure 11–33. Field strength vs. distance for a ground referred lamp. Field imbalance promotes uneven illumination at low drive levels.

Figure 11–34. The "low thermometer" configuration. "Topside sensed" primary derived feedback balances lamp drive, extending dimming range.

Placing a conductor along the lamp's length largely alleviates "thermometering." The trade-off is decreased efficiency due to energy leakage (see Note 4 and associated text). It is worth noting that various lamp types have different degrees of susceptibility to the thermometer effect.

Some displays require an extended illumination range. "Thermometering" usually limits the lowest practical illumination level. One acceptable way to minimize "thermometering" is to eliminate the large



field imbalance. Figure 11–34's circuit does this. This circuit's most significant aspect is that the lamp is fully floating—there is no galvanic connection to ground as in the previous designs. This allows T1 to deliver symmetric, differential drive to the lamp. Such balanced drive eliminates field imbalance, reducing thermometering at low lamp currents. This approach precludes any feedback connection to the now floating output. Maintaining closed loop control necessitates deriving a feedback signal from some other point. In theory, lamp current proportions to T1's or L1's drive level, and some form of sensing this can be used to provide feedback. In practice, parasitics make a practical implementation difficult.[5]

Figure 11–34 derives the feedback signal by measuring Royer converter current and feeding this information back to the LT1172. The Royer's drive requirement closely proportions to lamp current under all conditions. A1 senses this current across the .3Ω shunt and biases Q3, closing a local feedback loop. Q3's drain voltage presents an amplified, single ended version of the shunt voltage to the feedback point, closing the main loop. The lamp current is not as tightly controlled as before, but .5% regulation over wide supply ranges is possible. The dimming in this circuit is controlled by a 1kHz PWM signal. Note the heavy filtering (33kΩ–2µf) outside the feedback loop. This allows a fast time constant, minimizing turn-on overshoot.[6]

In all other respects, operation is similar to the previous circuits. This circuit typically permits the lamp to operate over a 40:1 intensity range without "thermometering." The normal feedback connection is usually limited to a 10:1 range.

The losses introduced by the current shunt and A1 degrade overall efficiency by about 2%. As such, circuit efficiency is limited to about 90%. Most of the loss can be recovered at moderate cost in complexity. Figure 11–35's modifications reduce shunt and A1 losses. A1, a precision micropower type, cuts power drain and permits a smaller shunt value without performance degradation. Unfortunately, A1 does not function when its inputs reside at the V+ rail. Because the circuit's operation requires this, some accommodation must be made.[7]

At circuit start-up, A1's input is pulled to its supply pin potential (actually, slightly above it). Under these conditions, A1's input stage is shut off. Normally, A1's output state would be indeterminate but, for the amplifier specified, it will always be high. This turns off Q3, permitting the LT1172 to drive the Royer stage. The Royer's operation causes Q1's collector swing to exceed the supply rail. This turns on the 1N4148, the BAT-85 goes off, and A1's supply pin rises above the supply rail. This "bootstrapping" action results in A1's inputs being biased within the am-

5. See Appendix C, "A Lot of Cut-Off-Ears and No Van Goghs—Some Not-So-Great Ideas," for details.
6. See section "Feedback Loop Stability Issues."
7. In other words, we need a hack.

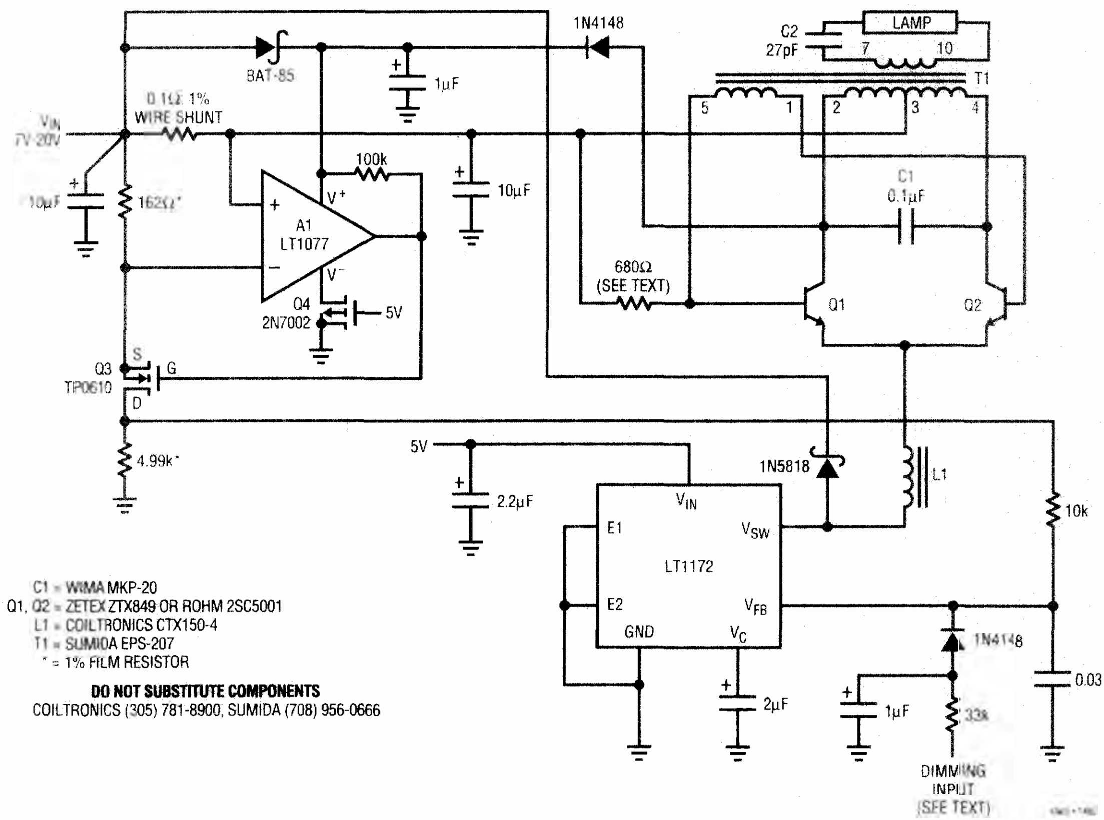


Figure 11–35. The "low thermometer" circuit using a micropower, precision topside sensing amplifier. Supply bootstrapping eliminates input common mode requirement, permitting a 1.6% efficiency gain.

plifier's common mode range, and normal circuit operation commences. The result of all this is a 1.6% efficiency gain, permitting an overall circuit efficiency of just below 92%.

Epilogue

Our understanding with Apple Computer gave them six months sole use of everything I learned while working with them. After that, we were free to disclose the circuit and most attendant details to anyone else, which we did. It found immediate use in other computers and applications, ranging from medical equipment to automobiles, gas pumps, retail terminals and anywhere else LCD displays are used. The development work consumed about 20 months, ending in August, 1993. Upon its completion I immediately fell into a rut, certain I would never do anything worthwhile again.

References

1. Blake, James W. *The Sidewalks of New York.* (1894).
2. Bright, Pittman, and Royer. "Transistors As On-Off Switches in Saturable Core Circuits." *Electrical Manufacturing* (December 1954): Available from Technomic Publishing, Lancaster, PA.
3. Sharp Corporation. *Flat Panel Displays.* (1991).
4. Kitchen, C., and L. Counts. *RMS-to-DC Conversion Guide.* Analog Devices, Inc. (1986).
5. Williams, Jim. "A Monolithic IC for 100MHz RMS-DC Conversion." Linear Technology Corporation, *Application Note 22* (September 1987).
6. Hewlett-Packard. "1968 Instrumentation. Electronic Analytical-Medical." *AC Voltage Measurement* (1968): 197–198.
7. Hewlett-Packard. *Model 3400RMS Voltmeter Operating and Service Manual.* (1965).
8. Hewlett-Packard. *Model 3403C True RMS Voltmeter Operating and Service Manual.* (1973).
9. Ott, W.E. "A New Technique of Thermal RMS Measurement." *IEEE Journal of Solid State Circuits* (December 1974).
10. Williams, J.M., and T.L. Longman. "A 25MHz Thermally Based RMS-DC Converter." *IEEE ISSCC Digest of Technical Papers* (1986).
11. O'Neill, P.M. "A Monolithic Thermal Converter." *H.P. Journal* (May 1980).
12. Williams, J. "Thermal Technique in Measurement and Control Circuitry," "50MHz Thermal RMS-DC Converter." Linear Technology Corporation, *Application Note 5* (December 1984).
13. Williams, J., and B. Huffman. "Some Thoughts on DC-DC Converters": Appendix A, "The +5 to 10 ±15V Converter—A Special Case." Linear Technology Corporation, *Application Note 29* (October 1988).
14. Baxendall, P.J. "Transistor Sine-Wave LC Oscillators." *British Journal of IEEE* (February 1960): Paper No. 2978E.
15. Williams, J. "Temperature Controlling to Microdegrees." Massachusetts Institute of Technology, Education Research Center (1971): out of print.
16. Fulton, S.P. "The Thermal Enzyme Probe." Thesis, Massachusetts Institute of Technology (1975).
17. Williams, J. "Designer's Guide to Temperature Measurement." *EDN* part II (May 20, 1977).
18. Williams. J. "Illumination Circuitry for Liquid Crystal Displays." Linear Technology Corporation, *Application Note 49* (August 1992).
19. Olsen, J.V. "A High Stability Temperature Controlled Oven." Thesis, Massachusetts Institute of Technology (1974).
20. MIT Reports on Research. *The Ultimate Oven.* (March 1972).
21. McDermott, James. "Test System at MIT Controls Temperature of Microdegrees." *Electronic Design* (January 6, 1972).
22. Williams, Jim. "Techniques for 92% Efficient LCD Illumination." Linear Technology Corporation, *Application Note 55* (August 1993).

Appendix A

Achieving Meaningful Efficiency Measurements

Obtaining reliable efficiency data for the CCFL circuits presents a high order difficulty measurement problem. Establishing and maintaining accurate AC measurements is a textbook example of attention to measurement technique. The combination of high frequency, harmonic laden waveforms and high voltage makes meaningful results difficult to obtain. The choice, understanding, and use of test instrumentation is crucial. Clear thinking is needed to avoid unpleasant surprises![1]

Probes

The probes employed must faithfully respond over a variety of conditions. Measuring across the resistor in series with the CCFL is the most favorable circumstance. This low voltage, low impedance measurement allows use of a standard 1X probe. The probe's relatively high input capacitance does not introduce significant error. A 10X probe may also be used, but frequency compensation issues (discussion to follow) must be attended to.

The high voltage measurement across the lamp is considerably more demanding on the probe. The waveform fundamental is at 20kHz to 100kHz, with harmonics into the MHz region. This activity occurs at peak voltages in the kilovolt range. The probe must have a high fidelity response under these conditions. Additionally, the probe should have low input capacitance to avoid loading effects which would corrupt the measurement. The design and construction of such a probe requires significant attention. Figure 11–A1 lists some recommended probes along with their characteristics. As stated in the text, almost all standard oscilloscope probes will fail[2] if used for this measurement. Attempting to circumvent the probe requirement by resistively dividing the lamp voltage also creates problems. Large value resistors often have significant voltage coefficients and their shunt capacitance is high and uncertain. As such, simple voltage dividing is not recommended. Similarly, common high voltage probes intended for DC measurement will have large errors because of AC effects. The P6013A and P6015 are the favored probes; their 100MΩ input and small capacitance introduces low loading error. The penalty for their 1000X attenuation is reduced output, but the recommended voltmeters (discussion to follow) can accommodate this.

All of the recommended probes are designed to work into an oscilloscope input. Such inputs are almost always 1MΩ paralleled by (typically)

1. It is worth considering that various constructors of Figure 11–18 have reported efficiencies ranging from 8% to 115%.
2. That's twice I've warned you nicely.

10pF–22pF. The recommended voltmeters, which will be discussed, have significantly different input characteristics. Figure 11–A2's table shows higher input resistances and a range of capacitances. Because of this the probe must be compensated for the voltmeter's input characteristics. Normally, the optimum compensation point is easily determined and adjusted by observing probe output on an oscilloscope. A known-amplitude square wave is fed in (usually from the oscilloscope calibrator) and the probe adjusted for correct response. Using the probe with the voltmeter presents an unknown impedance mismatch and raises the problem of determining when compensation is correct.

The impedance mismatch occurs at low and high frequency. The low frequency term is corrected by placing an appropriate value resistor in shunt with the probe's output. For a 10MΩ voltmeter input, a 1.1MΩ resistor is suitable. This resistor should be built into the smallest possible BNC equipped enclosure to maintain a coaxial environment. No cable connections should be employed; the enclosure should be placed directly between the probe output and the voltmeter input to minimize stray capacitance. This arrangement compensates the low frequency impedance mismatch. Figure 11–A4 shows the impedance-matching box attached to the high voltage probe.

Correcting the high frequency mismatch term is more involved. The wide range of voltmeter input capacitances combined with the added shunt resistor's effects presents problems. How is the experimenter to know where to set the high frequency probe compensation adjustment? One solution is to feed a known value RMS signal to the probe-voltmeter combination and adjust compensation for a proper reading. Figure 11–A3 shows a way to generate a known RMS voltage. This scheme is simply a standard backlight circuit reconfigured for a constant voltage output. The op amp permits low RC loading of the 5.6K feedback termination without introducing bias current error. The 5.6kΩ value may be series or parallel trimmed for a 300V output. Stray parasitic capacitance in the feedback network affects output voltage. Because of this, all feedback associated nodes and components should be rigidly fixed and the entire circuit built into a small metal box. This prevents any significant change in the parasitic terms. The result is a known $300V_{RMS}$ output.

Now, the probe's compensation is adjusted for a 300V voltmeter indication, using the shortest possible connection (e.g., BNC-to-probe adapter) to the calibrator box. This procedure, combined with the added resistor, completes the probe-to-voltmeter impedance match. If the probe compensation is altered (e.g., for proper response on an oscilloscope) the voltmeter's reading will be erroneous.[3] It is good practice to verify the

3. The translation of this statement is to hide the probe when you are not using it. If anyone wants to borrow it, look straight at them, shrug your shoulders, and say you don't know where it is. This is decidedly dishonest, but eminently practical. Those finding this morally questionable may wish to reexamine their attitude after producing a day's worth of worthless data with a probe that was unknowingly readjusted.

Figure 11–A1. Characteristics of some wideband high voltage probes. Output impedances are designed for oscilloscope inputs.

TEKTRONIX PROBE TYPE	ATTENUATION FACTOR	ACCURACY	INPUT RESISTANCE	INPUT CAPACITANCE	RISE TIME	BAND-WIDTH	MAXIMUM VOLTAGE	DERATED ABOVE	DERATED TO AT FREQUENCY	COMPENSATION RANGE	ASSUMED TERMINATION RESISTANCE
P6007	100X	3%	10MΩ	2.2pF	14ns	25MHz	1.5kV	200kHz	$700V_{RMS}$ at 10MHz	15-55pF	1M
P6009	100X	3%	10MΩ	2.5pF	2.9ns	120MHz	1.5kV	200kHz	$450V_{RMS}$ at 40MHz	15-47pF	1M
P6013A	1000X	Adjustable	100MΩ	3pF	7ns	50MHz	12kV	100kHz	$800V_{RMS}$ at 20MHz	12-60pF	1M
P6015	1000X	Adjustable	100MΩ	3pF	1.4ns	250MHz	20kV	100kHz	$2000V_{RMS}$ at 20MHz	12-47pF	1M

Figure 11–A2. Pertinent characteristics of some thermally based RMS voltmeters. Input impedances necessitate matching network and compensation for high voltage probes.

MANUFACTURER AND MODEL	FULL SCALE RANGES	ACCURACY AT 1MHz	ACCURACY AT 100kHz	INPUT RESISTANCE AND CAPACITANCE	MAXIMUM BANDWIDTH	CREST FACTOR
Hewlett-Packard 3400 Meter Display	1mV to 300V, 12 Ranges	1%	1%	0.001V to 0.3V Range = 10M and < 50pF, 1V to 300V Range = 10M and < 20pF	10MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Hewlett-Packard 3403C Digital Display	10mV to 1000V, 6 Ranges	0.5%	0.2%	10mV and 100mV Range = 20M and 20pF ±10%, 1V to 1000V Range = 10M and 24pF ±10%	100MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Fluke 8920A Digital Display	2mV to 700V, 7 Ranges	0.7%	0.5%	10M and < 30pF	20MHz	7:1 At Full Scale, 70:1 At 0.1 Scale

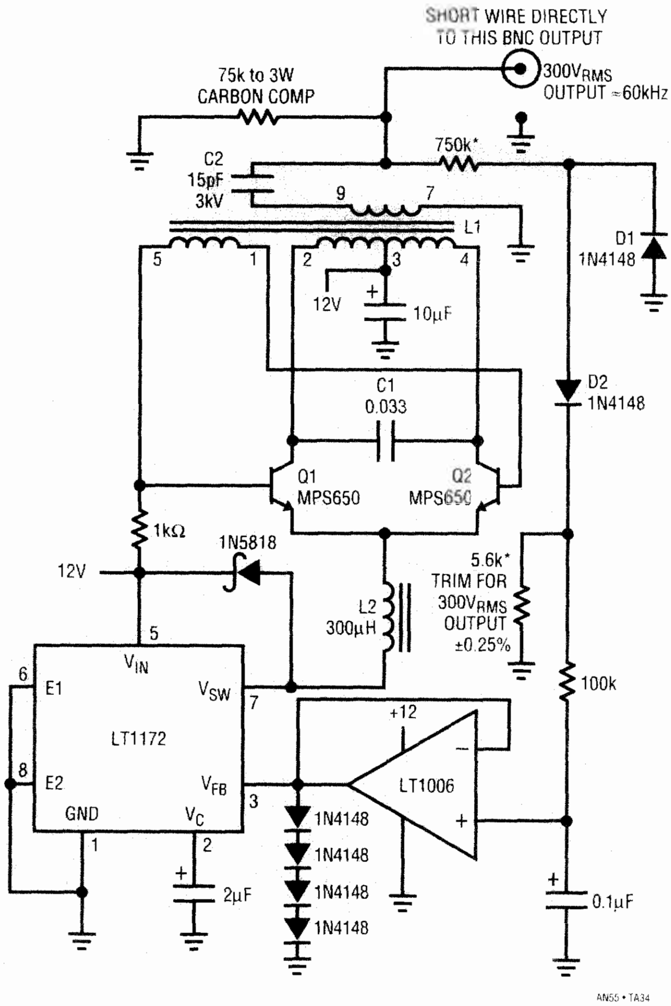


Figure 11–A3. High voltage RMS calibrator is voltage output version of CCFL circuit.

C1 = MUST BE A LOW LOSS CAPACITOR.
METALIZED POLYCARB
WIMA FKP2 OR MKP-20 (GERMAN) RECOMMENDED
L1 = SUMIDA 6345-020 OR COILTRONICS CTX110092-1
PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = COILTRONICS CTX300-4
Q1, Q2 = AS SHOWN OR BCP 56 (PHILLIPS SO PACKAGE)
* = 1% FILM RESISTOR (10kΩ TO 75kΩ RESISTORS IN SERIES)
DO NOT SUBSTITUTE COMPONENTS

COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666

calibrator box output before and after every set of efficiency measurements. This is done by directly connecting, via BNC adapters, the calibrator box to the RMS voltmeter on the 1000V range.

RMS Voltmeters

The efficiency measurements require an RMS responding voltmeter. This instrument must respond accurately at high frequency to irregular and harmonically loaded waveforms. These considerations eliminate almost all AC voltmeters, including DVMs with AC ranges.

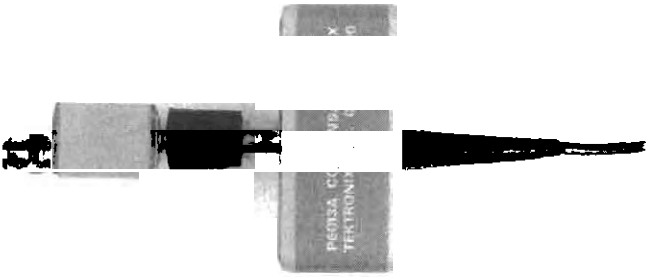


Figure 11–A4. The impedance matching box (extreme left) mated to the high voltage probe. Note direct connection. No cable is used.

There are a number of ways to measure RMS AC voltage. Three of the most common include average, logarithmic, and thermally responding. Averaging instruments are calibrated to respond to the average value of the input waveform, which is almost always assumed to be a sine wave. Deviation from an ideal sine wave input produces errors. Logarithmically based voltmeters attempt to overcome this limitation by continuously computing the input's true RMS value. Although these instruments are "real time" analog computers, their 1% error bandwidth is well below 300kHz and crest factor capability is limited. Almost all general purpose DVMs use such a logarithmically based approach and, as such, are not suitable for CCFL efficiency measurements. Thermally based RMS voltmeters are direct acting thermo-electronic analog computers. They respond to the input's RMS heating value. This technique is explicit, relying on the very definition of RMS (e.g., the heating power of the waveform). By turning the input into heat, thermally based instruments achieve vastly higher bandwidth than other techniques.[4] Additionally, they are insensitive to waveform shape and easily accommodate large crest factors. These characteristics are necessary for the CCFL efficiency measurements.

Figure 11–A5 shows a conceptual thermal RMS-DC converter. The input waveform warms a heater, resulting in increased output from its associated temperature sensor. A DC amplifier forces a second, identical, heater-sensor pair to the same thermal conditions as the input driven pair. This differentially sensed, feedback enforced loop makes ambient temperature shifts a common mode term, eliminating their effect. Also, although the voltage and thermal interaction is non-linear, the input-output RMS voltage relationship is linear with unity gain.

The ability of this arrangement to reject ambient temperature shifts depends on the heater-sensor pairs being isothermal. This is achievable by thermally insulating them with a time constant well below that of ambient shifts. If the time constants to the heater-sensor pairs are matched, ambient temperature terms will affect the pairs equally in phase and amplitude.

4. Those finding these descriptions intolerably brief are commended to references 4, 5, and 6

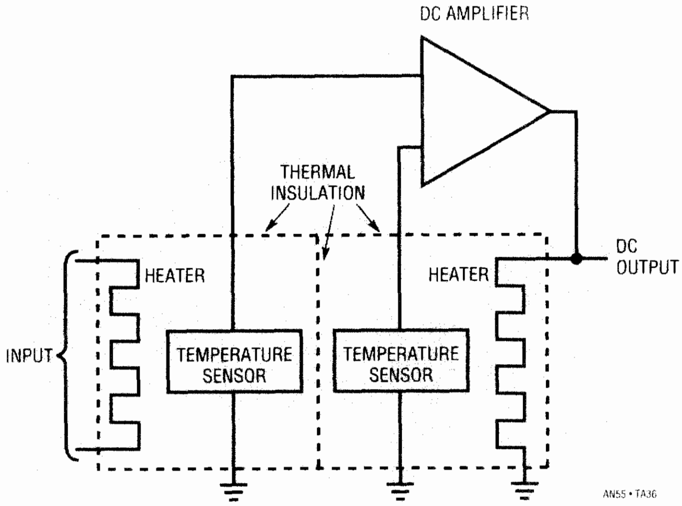


Figure 11–A5. Conceptual thermal RMS-DC converter.

The DC amplifier rejects this common mode term. Note that, although the pairs are isothermal, they are insulated from each other. Any thermal interaction between the pairs reduces the system's thermally based gain terms. This would cause unfavorable signal-to-noise performance, limiting dynamic operating range.

Figure 11–A5's output is linear because the matched thermal pair's nonlinear voltage-temperature relationships cancel each other.

The advantages of this approach have made its use popular in thermally based RMS-DC measurements.

The instruments listed in Figure 11–A2, while considerably more expensive than other options, are typical of what is required for meaningful results. The HP3400A and the Fluke 8920A are currently available from their manufacturers. The HP3403C, an exotic and highly desirable instrument, is no longer produced but readily available on the secondary market.

Figure 11–A6 shows equipment in a typical efficiency test setup. The RMS voltmeters (photo center and left) read output voltage and current via high voltage (left) and standard 1X probes (lower left). Input voltage is read on a DVM (upper right). A low loss clip-on ammeter (lower right) determines input current. The CCFL circuit and LCD display are in the foreground. Efficiency, the ratio of input to output power, is computed with a hand held calculator (lower right).

Calorimetric Correlation of Electrical Efficiency Measurements

Careful measurement technique permits a high degree of confidence in the accuracy of the efficiency measurements. It is, however, a good idea to check the method's integrity by measuring in a completely different domain. Figure 11–A7 does this by calorimetric techniques. This arrangement, identical to the thermal RMS voltmeter's operation (Figure 11–A5),

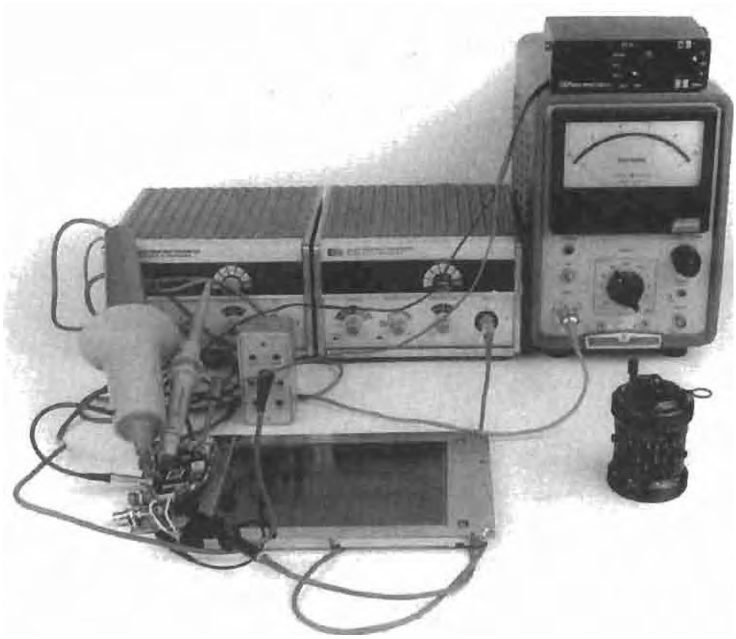


Figure 11–A6. Typical efficiency measurement instrumentation. RMS voltmeters (center left) measure output voltage and current via appropriate probes. Clip-on ammeter (right) gives low loss input current readings. DVM (upper right) measures input voltage. Hand calculator (lower right) is used to compute efficiency.

determines power delivered by the CCFL circuit by measuring its load temperature rise. As in the thermal RMS voltmeter, a differential approach eliminates ambient temperature as an error term. The differential amplifier's output, assuming a high degree of matching in the two thermal enclosures, proportions to load power. The ratio of the two cells' E × I products yields efficiency information. In a 100% efficient system, the amplifier's output energy would equal the power supplies' output. Practically it is always less, as the CCFL circuit has losses. This term represents the desired efficiency information.

Figure 11–A8 is similar except that the CCFL circuit board is placed within the calorimeter. This arrangement nominally yields the same information, but is a much more demanding measurement because far less heat is generated. The signal-to-noise (heat rise above ambient) ratio is unfavorable, requiring almost fanatical attention to thermal and instru-

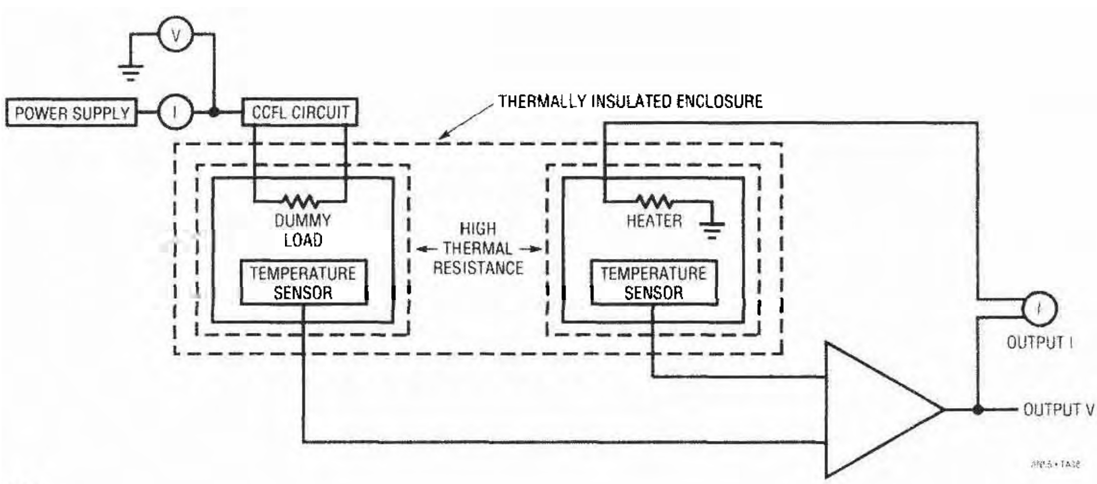


Figure 11–A7. Efficiency determination via calorimetric measurement. Ratio of power supply to output energy gives efficiency information.

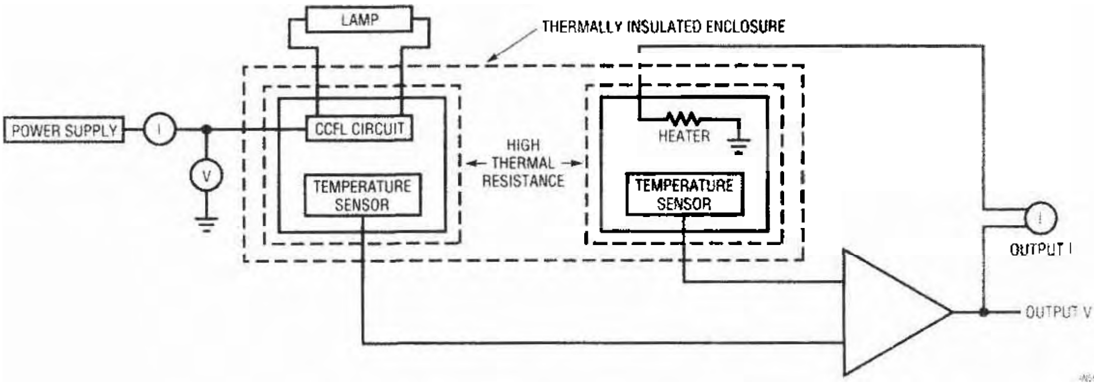


Figure 11–A8. The calorimeter measures efficiency by determining circuit heating losses

mentation considerations.[5] It is significant that the total uncertainty between electrical and both calorimetric efficiency determinations was 3.3%. The two thermal approaches differed by about 2%. Figure 11–A9 shows the calorimeter and its electronic instrumentation. Descriptions of this instrumentation and thermal measurements can be found in the References section following the main text.

5. Calorimetric measurements are not recommended for readers who are short on time or sanity.

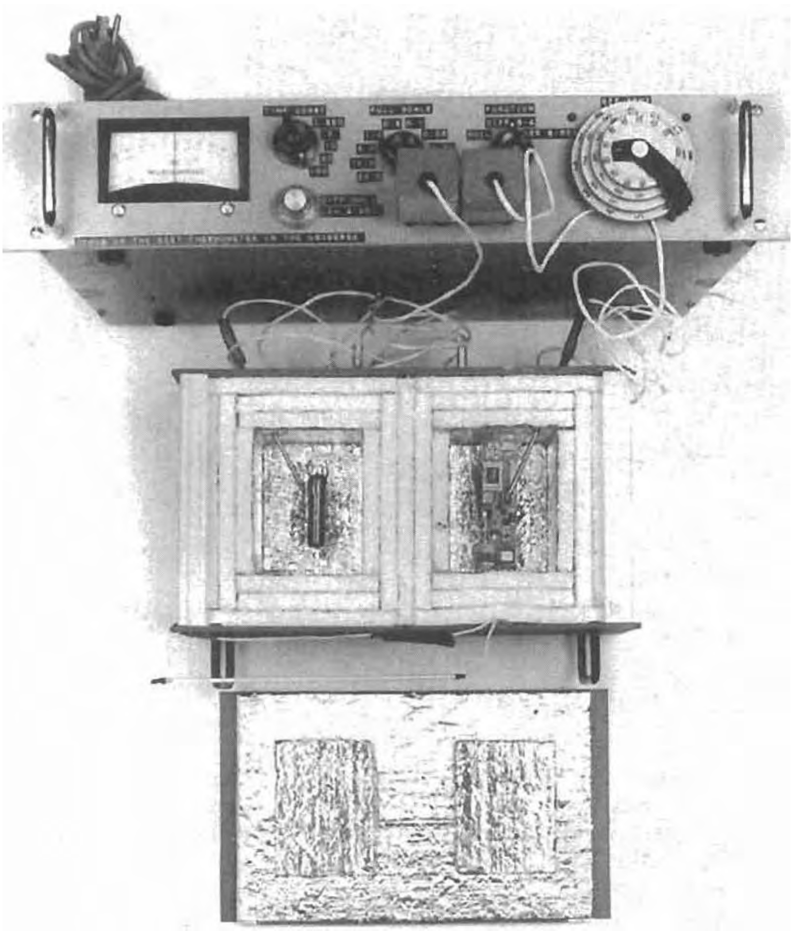


Figure 11–A9. The calorimeter (center) and its instrumentation (top). Calorimeter's high degree of thermal symmetry combined with sensitive servo instrumentation produces accurate efficiency measurements. Lower portion of photo is calorimeter's top cover.

Appendix B

Photometric Measurements

In the final analysis the ultimate concern centers around the efficient conversion of power supply energy to light. Emitted light varies monotonically with power supply energy,[1] but certainly not linearly. In particular, bulb luminosity may be highly nonlinear, particularly at high power, vs. drive power. There are complex trade-offs involving the amount of emitted light vs. power consumption and battery life. Evaluating these trade-offs requires some form of photometer. The relative luminosity of lamps may be evaluated by placing the lamp in a light tight tube and sampling its output with photodiodes. The photodiodes are placed along the lamp's length and their outputs electrically summed. This sampling technique is an uncalibrated measurement, providing relative data only. It is, however, quite useful in determining relative bulb emittance under various drive conditions. Figure 11–B1 shows this "glometer," with its uncalibrated output appropriately scaled in "brights." The switches allow various sampling diodes along the lamp's length to be disabled. The photodiode signal conditioning electronics are mounted behind the switch panel.

Calibrated light measurements call for a true photometer. The Tektronix J-17/J1803 photometer is such an instrument. It has been found

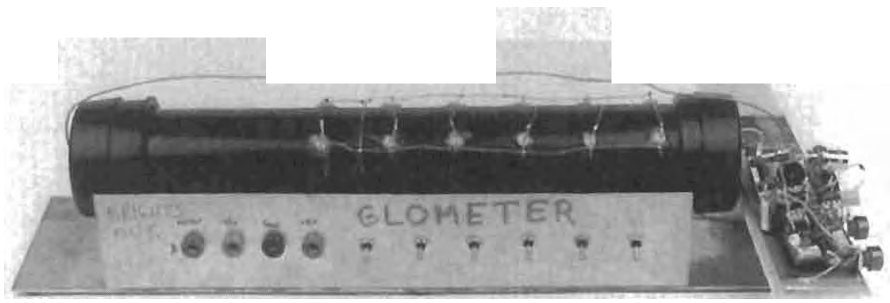


Figure 11–B1.
The "glometer" measures relative lamp emissivity. CCFL circuit mounts to the right. Lamp is inside cylindrical housing. Photodiodes (center) convert light to electrical output (lower left) via amplifiers (not visible in photo).

1. But not always! It is possible to build highly electrically efficient circuits that emit less light than "less efficient" designs. See Appendix C. "A Lot of Cut-Off Ears and No Van Goghs—Some Not-So-Great Ideas."

particularly useful in evaluating display (as opposed to simply the lamp) luminosity under various drive conditions. The calibrated output permits reliable correlation with customer results.[2] The light tight measuring head allows evaluation of emittance evenness at various display locations. This capability is invaluable when optimizing lamp location and/or ballast capacitor values in dual lamp displays.

Figure 11–B2 shows the photometer in use evaluating a display.

2. It is unlikely that customers would be enthusiastic about correlating the "brights" units produced by the aforementioned glometer.

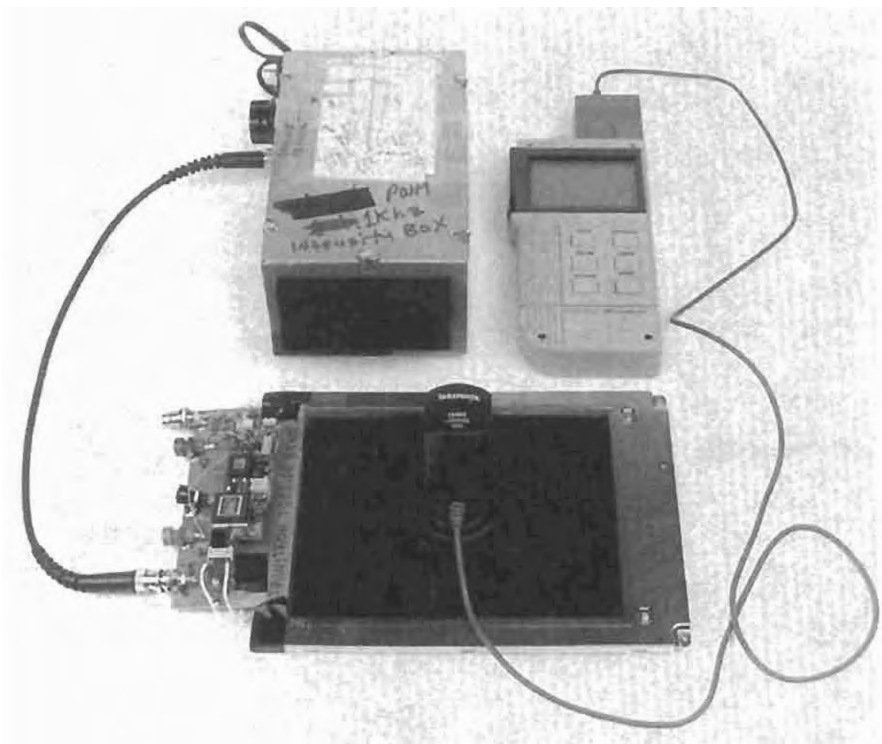


Figure 11–B2.
Apparatus for calibrated photometric display evaluation. Photometer (upper right) indicates display luminosity via sensing head (center). CCFL circuit (left) intensity is controlled by a calibrated pulse width generator (upper left).

Appendix C

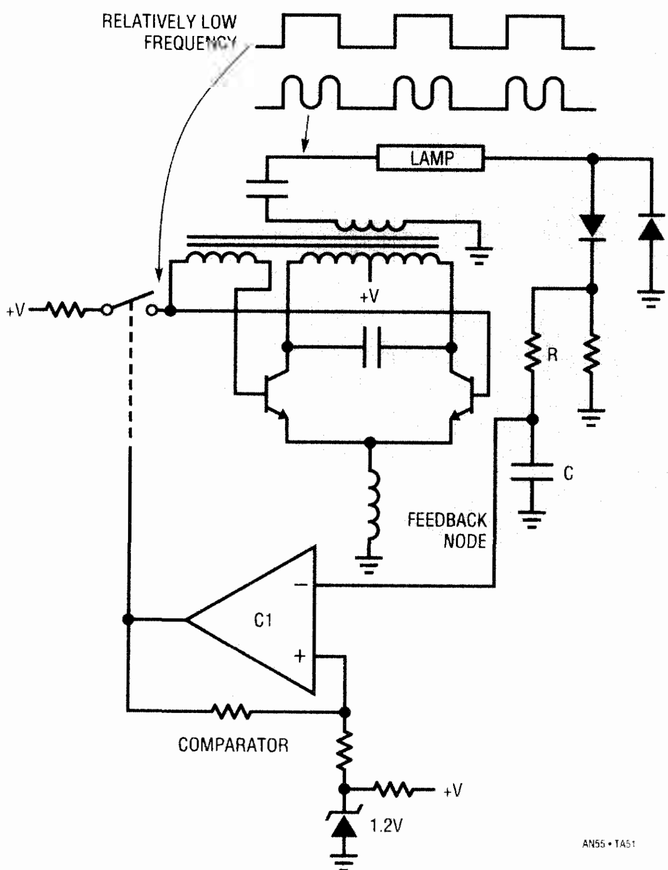
A Lot of Cut-Off Ears and No Van Goghs—Some Not-So-Great Ideas

The hunt for a practical CCFL power supply covered (and is still covering) a lot of territory. The wide range of conflicting requirements combined with ill-defined lamp characteristics produces plenty of unpleasant surprises. This section presents a selection of ideas that turned into disappointing breadboards. Backlight circuits are one of the deadliest places for theoretically interesting circuits the author has ever encountered.

Not-So-Great Backlight Circuits

Figure 11–C1 seeks to boost efficiency by eliminating the LT1172's saturation loss. Comparator C1 controls a free running loop around the Royer by on-off modulation of the transistor base drive. The circuit delivers bursts of high voltage sine drive to the lamp to maintain the feedback

Figure 11–C1. A first attempt at improving the basic circuit. Irregular Royer drive promotes losses and poor regulation.



node. The scheme worked, but had poor line rejection, due to the varying waveform vs. supply seen by the RC averaging pair. Also, the "burst" modulation forces the loop to constantly re-start the bulb at the burst rate, wasting energy. Finally, bulb power is delivered by a high crest factor waveform, causing inefficient current-to-light conversion in the bulb.

Figure 11–C2 attempts to deal with some of these issues. It converts the previous circuit to an amplifier-controlled current mode regulator. Also, the Royer base drive is controlled by a clocked, high frequency pulse width modulator. This arrangement provides a more regular waveform to the averaging RC, improving line rejection. Unfortunately the improvement was not adequate. 1% line rejection is required to avoid annoying flicker when the line moves abruptly, such as when a charger is activated. Another difficulty is that, although reduced by the higher frequency PWM, crest factor is still non-optimal. Finally, the lamp is still forced to restart at each PWM cycle, wasting power.

Figure 11–C3 adds a "keep alive" function to prevent the Royer from turning off. This aspect worked well. When the PWM goes low, the Royer is kept running, maintaining low level lamp conduction. This eliminates the continuous lamp restarting, saving power. The "supply correc-

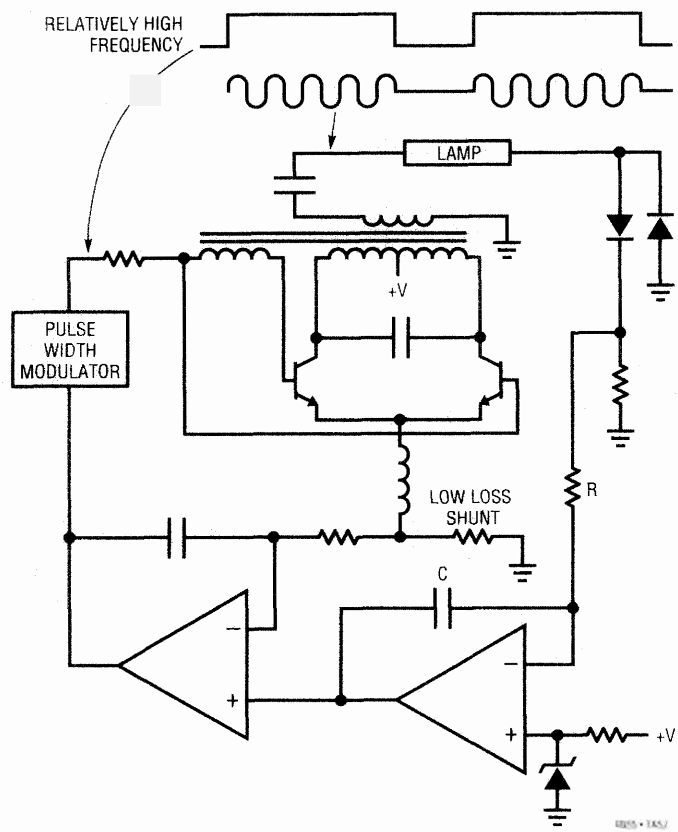


Figure 11–C2. A more sophisticated failure still has losses and poor line regulation.

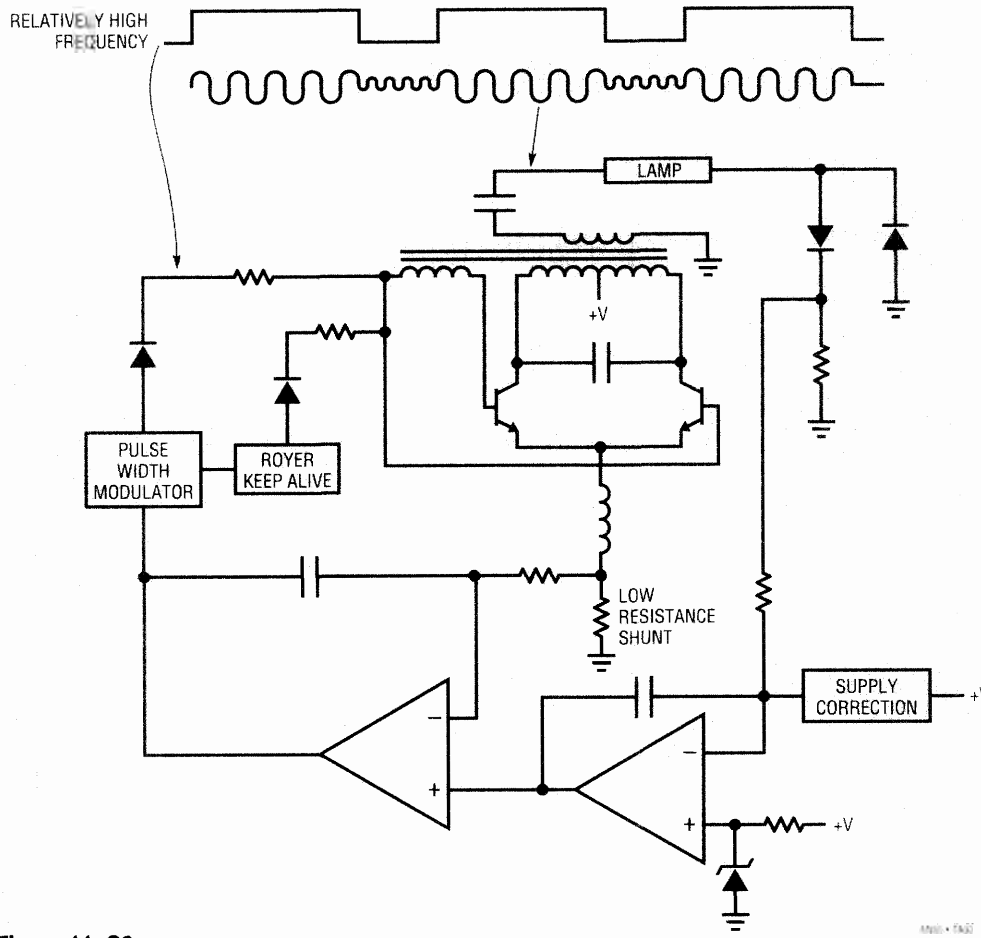


Figure 11–C3. "Keep alive" circuit eliminates turn-on losses and has 94% efficiency. Light emission is lower than "less efficient" circuits.

tion" block feeds a portion of the supply into the RC averager, improving line rejection to acceptable levels.

This circuit, after considerable fiddling, achieved almost 94% efficiency but produced less output light than a "less efficient" version of Figure 11–18! The villain is lamp waveform crest factor. The keep alive circuit helps, but the lamp still cannot handle even moderate crest factors.

Figure 11–C4 is a very different approach. This circuit is a driven square wave converter. The resonating capacitor is eliminated. The base drive generator shapes the edges, minimizing harmonics for low noise operation. This circuit works well, but relatively low operating frequencies are required to get good efficiency. This is so because the sloped drive must be a small percentage of the fundamental to maintain low losses. This mandates relatively large magnetics—a crucial disadvantage. Also, square waves have a different crest factor and rise time than sines, forcing inefficient lamp transduction.

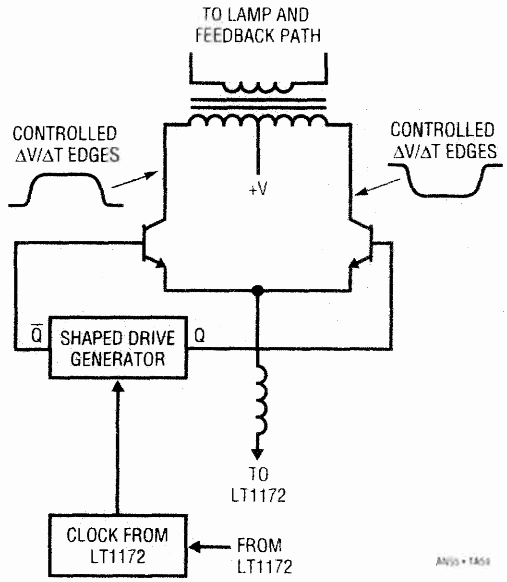


Figure 11–C4. A non-resonant approach. Slew retarded edges minimize harmonics, but transformer size goes up. Output waveform is also non-optimal, causing lamp losses.

Not-So-Great Primary Side Sensing Ideas

Figures 11–34 and 11–35 use primary side current sensing to control bulb intensity. This permits the bulb to fully float, extending its dynamic operating range. A number of primary side sensing approaches were tried before the "topside sense" won the contest.

Figure 11–C5's ground referred current sensing is the most obvious way to detect Royer current. It offers the advantage of simple signal conditioning—there is no common mode voltage. The assumption that essentially all Royer current derives from the LT1172 emitter pin path is true. Also true, however, is that the waveshape of this path's current

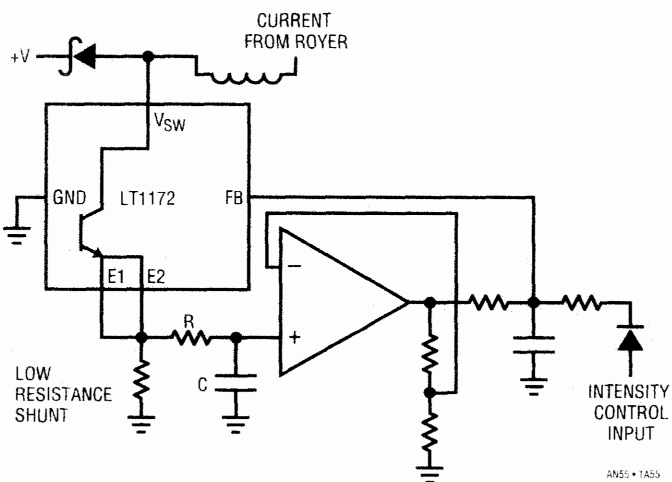


Figure 11–C5. "Bottom side" current sensing has poor line regulation due to RC averaging characteristics.

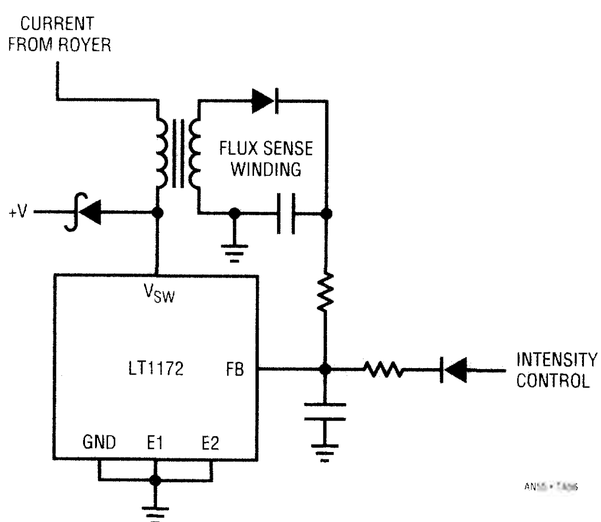
varies widely with input voltage and lamp operating current. The RMS voltage across the shunt (e.g., the Royer current) is unaffected by this, but the simple RC averager produces different outputs for the various waveforms. This causes this approach to have very poor line rejection, rendering it impractical. Figure 11–C6 senses inductor flux, which should correlate with Royer current. This approach promises attractive simplicity. It gives better line regulation but still has some trouble giving reliable feedback as waveshape changes. It also, in keeping with most flux sampling schemes, regulates poorly under low current conditions.

Figure 11–C7 senses flux in the transformer. This takes advantage of the transformer's more regular waveform. Line regulation is reasonably good because of this, but low current regulation is still poor. Figure 11–C8 samples Royer collector voltage capacitively, but the feedback signal does not accurately represent start-up, transient, and low current conditions.

Figure 11–C9 uses optical feedback to eliminate all feedback integrity problems. The photodiode-amplifier combination provides a DC feedback signal which is a function of actual lamp emission. It forces the lamp to constant emissivity, regardless of environmental or aging factors.

This approach works quite nicely, but introduces some evil problems. The lamp comes up to constant emission immediately at turn-on. There is no warm-up time required because the loop forces emission, instead of current. Unfortunately, it does this by driving huge overcurrents through the lamp, stressing it and shortening life. Typically, 2 to 5 times rated current flows for many seconds before lamp temperature rises, allowing the loop to back down drive. A subtle result of this effect occurs with lamp aging. When lamp emissivity begins to fall off, the loop increases current to correct the condition. This increase in current accelerates lamp aging, causing further emissivity degradation. The resultant downward spiral continues, resulting in dramatically shortened lamp life.

Figure 11–C6. Flux sensing has irregular outputs, particularly at low currents.



Other problems involve increased component count, photodiode mounting, and the requirement for photodiodes with predictable response or some form of trim.

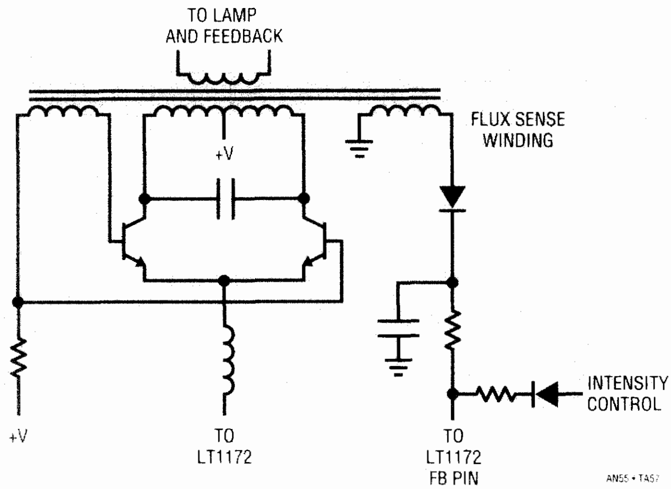


Figure 11–C7. Transformer flux sensing gives more regular feedback, but not at low currents.

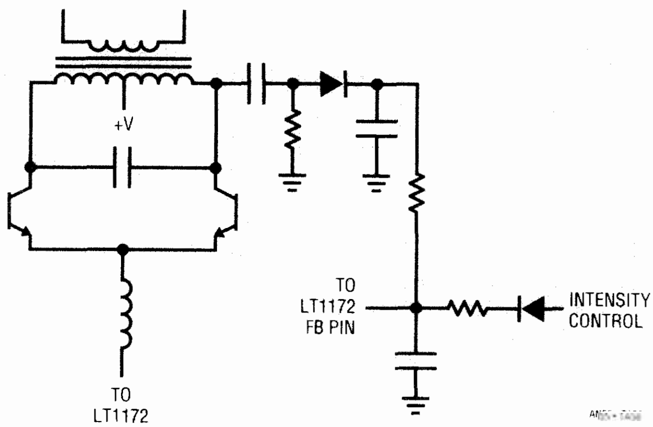


Figure 11–C8. AC couples drive waveform feedback is not reliable at low currents.

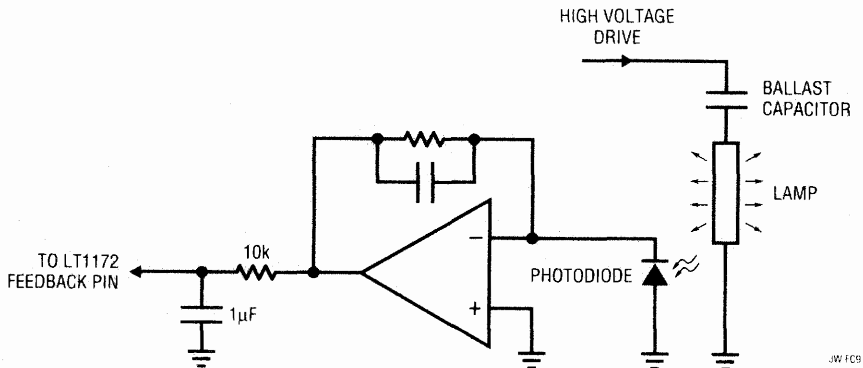


Figure 11–C9. Optically sensed feedback eliminates feedback irregularities, but introduces other problems.

Appendix D

Perspectives on Efficiency

The LCD displays currently available require two power sources, a backlight supply and a contrast supply. The display backlight is the single largest power consumer in a typical portable apparatus, accounting for almost 50% of the battery drain when the display intensity control is at maximum. Therefore, every effort must be expended to maximize backlight efficiency.

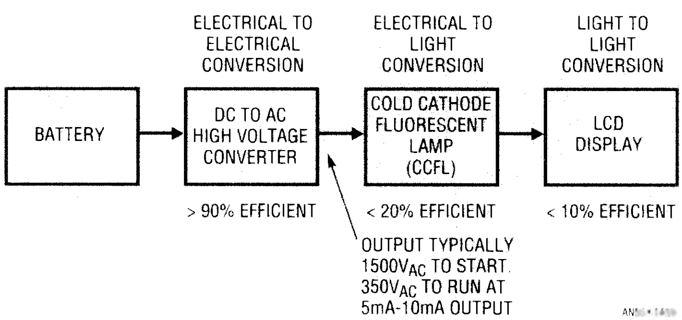
The backlight presents a cascaded energy attenuator to the battery (Figure 11–D1). Battery energy is lost in the electrical-to-electrical conversion to high voltage AC to drive the cold cathode fluorescent lamp (CCFL). This section of the energy attenuator is the most efficient; conversion efficiencies exceeding 90% are possible. The CCFL, although the most efficient electrical-to-light converter available today, has losses exceeding 80%. Additionally, the light transmission efficiency of present displays is about 10% for monochrome, with color types even lower. Clearly, overall backlight efficiency improvements must come from bulb and display improvements.

Higher CCFL circuit efficiency does, however, directly translate into increased operating time. For comparison purposes Figure 11–20's circuit was installed in a computer running 5mA lamp current. The result was a 19 minute increase in operating time.

Relatively small reductions in backlight intensity can greatly extend battery life. A 20% reduction in screen intensity results in nearly 30 minutes of additional running time. This assumes that efficiency remains reasonably flat as power is reduced. Figure 11–D2 shows that the circuits presented do reasonably well in this regard, as opposed to other approaches.

The contrast supply, operating at greatly reduced power, is not a major source of loss.

Figure 11–D1. The backlit LCD display presents a cascaded energy attenuator to the battery. DC to AC conversion is significantly more efficient than energy conversions in lamp and display.



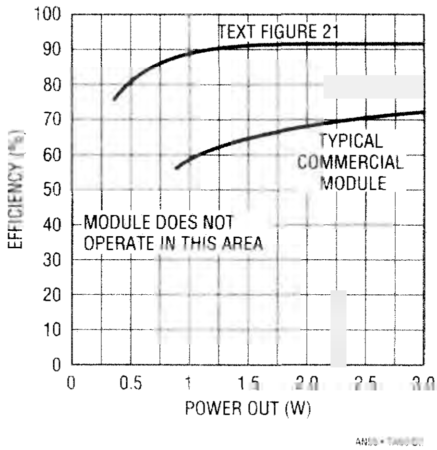


Figure 11–D2. Efficiency comparison between Figure 11–21 and a typical modular converter.