Transistor Considerations for LCD Backlighting

High Efficiency DC to AC Conversion

Neil Chadderton

Introduction

LCD Backlighting has generated widespread interest from many diverse disciplines within the engineering industry. This has no doubt been fueled by the trend to portability and particularly to the enormous growth of the computing market. Products such as notebook, laptop, and palmtop personal computers, portable televisions, viewcams, point of sale terminals, automotive dashboards, avionics displays, metering and instrumentation usually employ an LCD screen, and as such require a means of backlighting. To date the most prevalent method has been to use a small cold cathode fluorescent (CCFL) tube that is usually integrated with a reflector/diffuser into the display unit. The CCFL power consumption can account for a significant portion (up to 50%) of the total system requirement. Therefore to achieve marketable advantages in battery life and re-charge frequency, much attention must be applied to the CCFL power supply, so as to attain the highest possible conversion efficiency.

This problem has been the focus of many electronic component vendors: much research and design effort being invested in order to offer system designers the most attractive components/solutions in terms of efficiency, cost, weight, and size. Many of the analog IC companies have published application specific reports, and characterised or developed specifically, integrated circuits for the application.

This note acknowledges this work, and will draw upon such sources and reproduce these vendors' circuits where appropriate (a list of references is included in Appendix A) but it is focused primarily on the transistor requirements – their mode of operation within the backlighting circuit, important parameters, and their impact on the system efficiency.

CCFL Lamp Characteristics

An understanding of the requirements for the backlighting power supply should begin with a description of the load involved. The fluorescent tube presents a serious challenge to the circuit designer. Around 1kV is required to strike the tube (initiate conduction), at which event the tube's gaseous contents ionise and it begins to conduct at a lower sustaining voltage – thus a negative resistance characteristic is evident. Other power supply constraints include an intolerance of DC current, a sensitivity to waveform crest factor, and RFI criteria.

The curve tracer plots shown in Figures 1 and 2 show the negative resistance region for two typical CCFL units: – the first for a 150mm linear, 10mm diameter backlight tube for a laptop display, and the other a "U" tube as produced for a car dashboard display. Referring to figure 1, the high striking voltage can be seen at 560V and the negative resistance excursion to 240V is self evident. Similarly, these values for Figure 2 are 1240V and 900V. Note should also be made of the slope impedance in the conducting state. The power supply must accommodate this, and in some cases provision made to regulate the lamp current to ensure a long tube life.

For drive waveforms at low frequencies, a fluorescent tube has time to react to the changing waveform potential, and effectively re-strikes on each reversal of the waveform polarity, (perceived as flicker on line frequency units). At high drive waveform frequencies, this effect is not apparent, and the lamp can be approximated to a resistive load. Usual operating frequencies range from 25 to 120kHz, this being dictated by consideration of inaudibility requirements, converter inductor size, and at the extreme, parasitic and HV-lead-to-ground coupling capacitance.

Basic Operation Of Converter

The drive requirements dictated by the CCFL tube's behaviour and preferred operating conditions can be achieved by the resonant push-pull converter shown in Figure 3. This is also referred to as the Royer Converter, after G.H. Royer who proposed the topology in 1954 as a power converter. (Note: Strictly speaking the backlighting converter uses a modified version of the Royer converter – the original used a saturating transformer to define the operating frequency, and therefore produced a squarewave drive

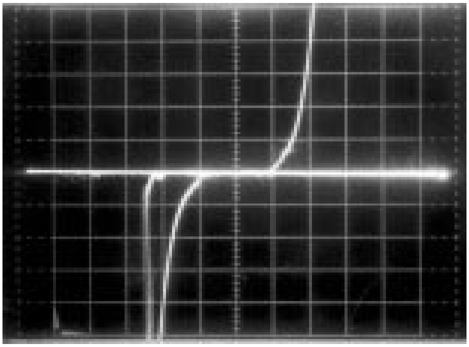

Figure 1.
CCFL Characteristics - 150mm linear; 100V/div horizontal, 200μA/div vertical.

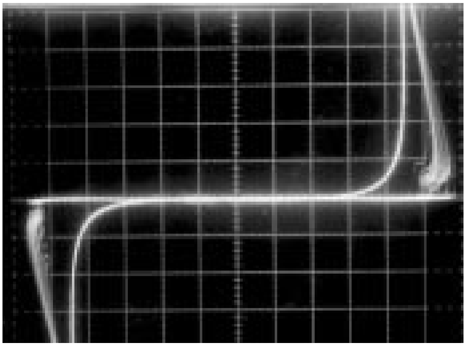

Figure 2.
CCFL Characteristics - "U" tube; 200V/div horizontal, 1mA/div vertical.

ZETEX

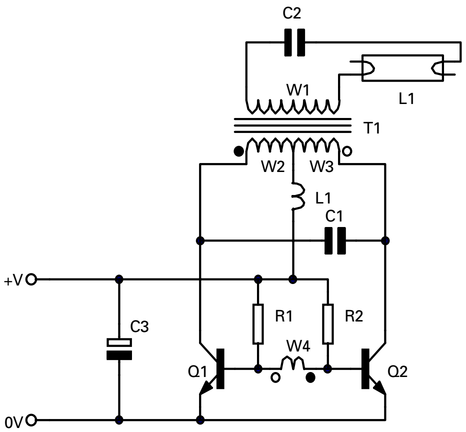

Figure 3.
Generalised Royer Converter.

waveform). The circuit looks simple but this is very deceptive: many components interact, and while the circuit is capable of operation with widely varying component values, (useful during development) optimisation is required for each design to achieve the highest possible efficiencies.

Transistors Q1 and Q2 are alternatively saturated by the base drive provided by the feedback winding W4. The base current is defined by resistors R1 and R2. Supply inductor L1 and primary capacitance C1 force the circuit to run sinusoidally thereby minimising harmonic generation and RFI, and providing the preferred drive waveform to the load. Voltage step-up is achieved by the W1:(W2 + W3) turns ratio. C2 is the secondary winding ballast capacitor, and effectively sets the tube current.

Prior to the tube striking, or when no tube is connected, the operating frequency is set by the resonant parallel circuit comprising the primary capacitance C1, and the transformer's primary winding W2+W3. Once the tube has struck, the ballast capacitor C2 plus distributed tube and parasitic capacitances are reflected back through the transformer, and the operating frequency is lowered.

The secondary load can become dominant in circuits with a high transformer turns ratio, Eg. those designed to operate from very low DC input voltages.

Each transistor's collector is subject to a voltage= $2 \times \pi/2 \times V_S$, (or just $\pi \times V_S$) where V_S is the DC input voltage to the converter. (The $\pi/2$ factor being due to the relationship between average and peak values for a sinewave, and the x2 multiplier being due to the 2:1 autotransformer action of the transformer's centre-tapped primary). This primary voltage is stepped up by the transformer turns ratio Ns:Np, to a high enough level to reliably strike the tube under all conditions:- starting voltage is dependent on display housing, location of ground planes, tube age, and ambient temperature.

The basic converter shown in Figure 3 is a valid and useful circuit that has been utilised for many systems and indeed offered as a sub-system by several manufacturers.

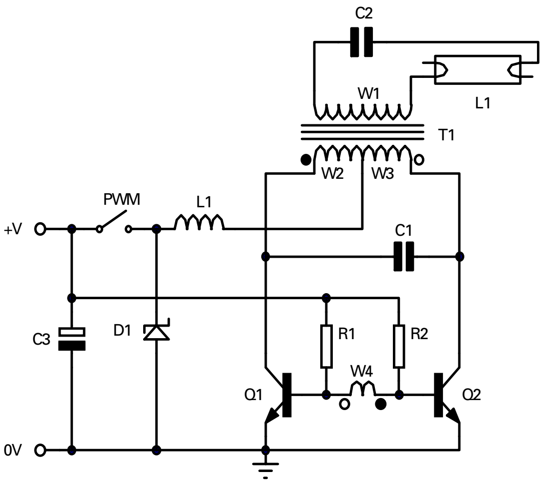

Figure 4a.
Royer Converter With PWM Control - High Side Current Fed Version.

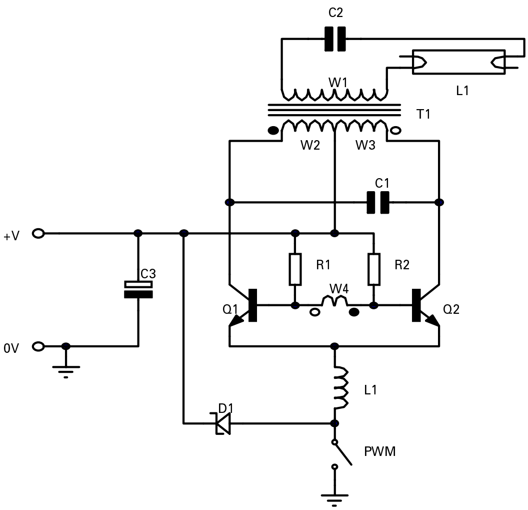

Figure 4b.
Royer Converter With PWM Control - Low Side (or tail) Current Fed Version.

Backlight Converters Within Control Loops

Variations on the basic topology are possible, perhaps the most important being to include the converter within a control loop. This can be used to regulate the tube current:- this maximises tube lifetime, ensures a constant light output as the battery pack voltage decreases, and enables adjustment of tube brightness. The usual form of the circuit is to employ a Buck or step-down converter (directly from the battery pack to increase efficiency) feeding the centre tap of the transformer, or the emitter current of the transistors, depending on the controller's technology and capability. Figures 4a and 4b show these arrangements in conceptual form. The controller can monitor the tube current directly in the secondary, or in some recent systems, by the primary current. This latter method allows the tube to be fully floating thus minimising HV losses.

Figure 5 shows a circuit published by linear IC manufacturer LINEAR TECHNOLOGY CORP. that exhibits a significant efficiency improvement over previous designs; primarily due to the choice of the **ZETEX FZT849**. It is based on the Buck converter current fed Royer scheme of Figure 4b, and monitors the lamp's current directly by averaging the positive half cycles of lamp current, and applying this signal to the controller's feedback pin. The electrical conversion efficiency using this form of circuit can be very high, the stated value for Figure 5 being 88%. Higher efficiencies up to 92% are possible by using larger transformers to reduce copper and core losses.

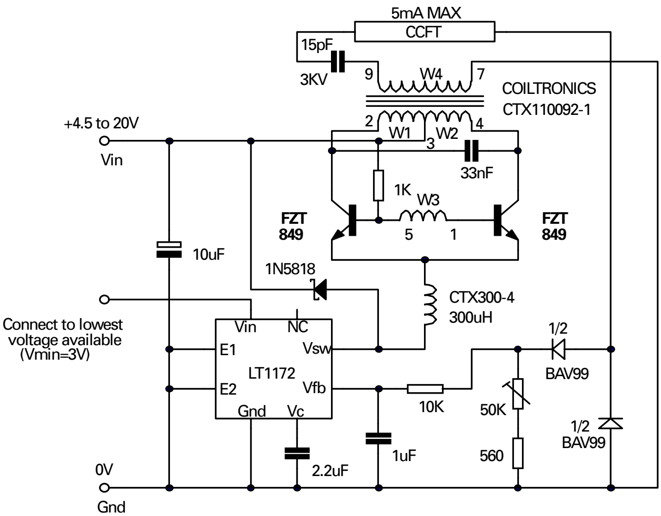

Figure 5.
Linear Technology LCD Backlight Converter.

Figure 6 shows Linear Technology's latest design using the LT1182 and the Zetex ZDT1048 dual transistor. The LT1182 provides a low component count circuit and contains all control functions for the Royer converter, and the control/switch for the LCD contrast converter within one package. Primary Royer converter current is sensed by the IC, so that the CCFL tube can be operated in a "floating" mode thereby decreasing losses in the secondary circuit. The FZT849 transistors, or the ZDT1048 dual package are preferred options for this converter circuit.

Detailed reports on these circuits can be found via the references listed.

Figure 7 shows an oscillograph of the transistor's operating conditions in such a circuit. The Collector-Emitter voltage peaks at 28V (less than π x V_S due to the lamp load); the Emitter current is almost constant at 0.5A (with a ripple component dependent on the Buck inductor); and the base voltage appears as a clipped (due the transistor's V_{BE}) version of the primary waveform.

Requisite Transistor Characteristics

The relatively low operating frequency as required by the backlighting Royer Converter (to minimise HV parasitic capacitance losses), and the ease of transformer drive, makes this circuit particularly suitable for bipolar transistor

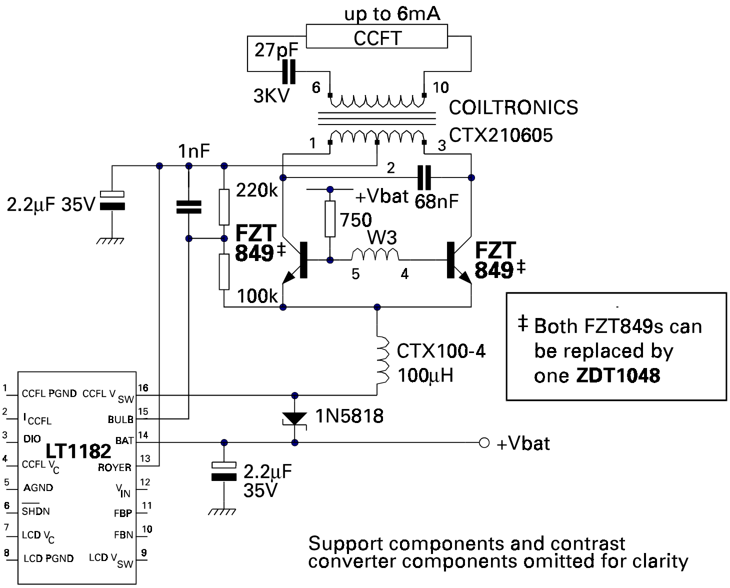

Figure 6.
Linear Technology Floating Tube LCD Backlight Converter.

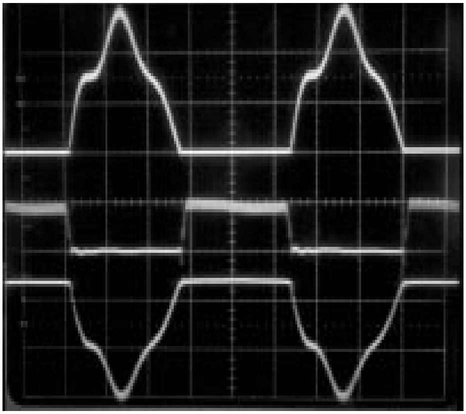

Figure 7.
Royer Converter Operating Waveforms: V_{CE} 10V/div; I_E 0.5A/div; V_{BE} 2V/div respectively, 2μs/div horizontal .

implementation. This isn't to exclude MOSFET based designs (some IC vendors have specified MOS as this suits their technology) but in terms of equivalent on-resistance and silicon efficiency, the low voltage bipolar device has no equal. For example, the **ZETEX ZTX849** E-Line (TO-92 compatible) transistor exhibits a $R_{CE(sat)}$ of 36mΩ. This can only be matched by a much larger (and expensive) MOSFET die, only available in TO-220, D-Pak, and similar larger packages.

The important transistor characteristics are voltage rating, $V_{CE(sat)}$, and h_{FE}, and are detailed below.

The voltage rating required deserves some thought with respect to the standard transistor breakdown parameters, as it is possible to over-specify a device on grounds of voltage rating, and thereby incur a reduction in efficiency due to unnecessary on-resistance losses. The primary breakdown voltage BV_{CBO}, of a planar bipolar transistor depends on the epitaxial layer - specifically its thickness and resistivity. The breakdown voltage of most interest to the designer is usually that attained across the Collector-Emitter (C-E) terminals. This value can vary between the primary breakdown BV_{CBO} and a much lower voltage dependent on the state of the base terminal bias.

[The breakdown mechanism is caused by the avalanche multiplication effect, whereby free electrons can be imparted with sufficient energy by the reverse bias electric field such that any collisions can lead to ionisation of the lattice atoms. The free electrons thus generated are then accelerated by the field and produce further ionisation. This multiplication of free carriers increases the reverse current dramatically, and so the junction effectively clamps the applied voltage. The base terminal can obviously influence the junction current – thereby modulating the voltage required for a breakdown condition.]

Figure 8 shows how the breakdown characteristic is seen to vary for different circuit conditions. The BV_{CEO} rating (or when the base is open circuit) allows the Collector-Base (C-B) leakage current I_{CBO} to be effectively amplified by the transistor's β thus significantly increasing the leakage component to I_{CEO}. Shorting the Base to the Emitter (BV_{CES}) provides a parallel path for the C-B leakage, and so the voltage required for breakdown is higher than the open base condition. BV_{CER} denotes the case between the open and shorted base options:- R indicating an external base-emitter resistance, the value of which is typically 100 to 10kΩ. BV_{CEV} or BV_{CEX} is a special case where the base-emitter is reverse biased; this can provide a better path for the C-B leakage, and so this rating yields a voltage close to, or coincident with the BV_{CBO} value.

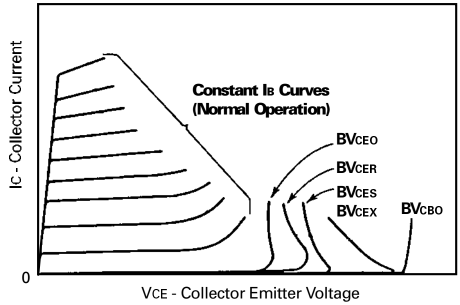

Figure 8.
Voltage Breakdown Modes of Bipolar Transistor.

Figure 9 shows a curve tracer view of the relevant breakdown modes of the **ZTX849** transistor, including a curve showing the device in the "on" state. Curves 1 and 2 are virtually coincident and show BV_{CBO} and BV_{CES} respectively. Curve 3 shows the BV_{CEV} case with an applied base bias (V_{EB}) of -1V. Curve 4 shows BV_{CEO} at approximately 36V. Curve 5 is a BV_{CE} curve, showing how the breakdown condition is affected by a positive base bias of 0.5V.

The BV_{CEV} rating has particular relevance to the Royer Converter, as can be surmised from Figure 7. Examination of this will show that the transistor only experiences the high C-E voltage when the base voltage has been taken negative by the feedback winding, these

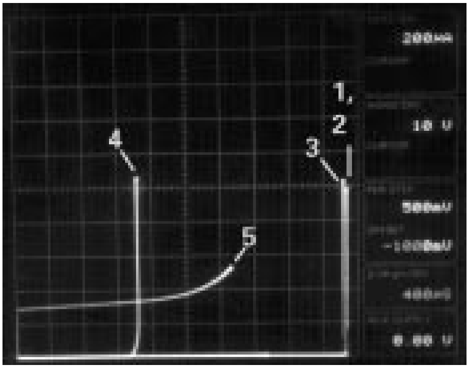

Figure 9.
Breakdown modes of the ZTX849 Bipolar Transistor.

events of course being in perfect synchronism. An expanded view of the C-E and B-E waveforms is shown in Figure 10.

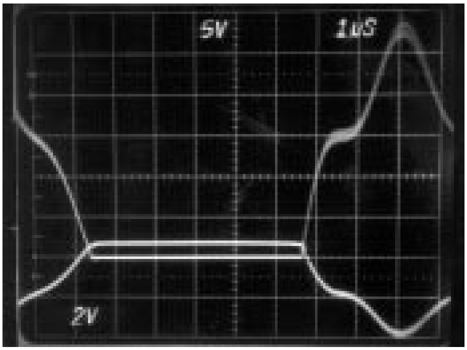

Figure 10.
Royer Converter: V_{CE} and V_{BE} Waveforms 5V/ div and 2V/ div respectively.

[Note: The voltage applied by the feedback winding must not exceed the BV_{EBO} of the transistor. This is specified at 5V usually, against an actual of 7.5 to 8.5V].

The $V_{CE(sat)}$ and h_{FE} parameters have a direct bearing on the circuit's electrical conversion efficiency. This is especially true of low voltage battery powered systems, due to the high current levels involved. Selection of standard LF amplifier transistors provides far from ideal results; these parts are for general purpose linear and non-critical switching use only. The high $V_{CE(sat)}$ inherent to these parts, and low current gain could reduce circuit efficiency to less than 50%. For example, the stated $V_{CE(sat)}$ maximum measured at 500mA, for the **FZT849** SOT223 transistor, and a LF device sometimes quoted as a suitable Royer Converter transistor are 50mV and 0.5V respectively. Eg.

	$V_{CE(sat)}$	$@I_C$	I_B
FZT849	50mV	0.5A	20mA
BCP56	0.5V	0.5A	50mA

To address the $V_{CE(sat)}$ issue, large power transistors are occasionally specified. Unfortunately their capacitance, and characteristic low base transport factor (a feature of Epitaxial Base devices) can lead to problems with cross-conduction losses due to long storage and switching times. The current gain is also important, as the losses in the base bias can be significant to the overall figure; judicious selection of the bias resistor to ensure a minimum $V_{CE(sat)}$ while preventing base overdrive needs to consider supply variation, maximum lamp current, and transistor h_{FE} minimum value and range.

For the above reasons, transistors designed and optimised for high current switching applications offer the most cost-effective and efficient solutions. The table presented in Appendix C lists several **ZETEX** transistors that are eminently suitable for the Royer converter. All of these parts offer outstanding $V_{CE(sat)}$ and high current performance for their size, and many are so-called "Super-β" transistors; thereby helping to simplify and improve drive current requirements. Figure 11 shows the $V_{CE(sat)}$ exhibited by the ZTX1048A for a range of forced gain values. This device is one of the ZTX1050 series of transistors that employ a scaled up variant of the highly efficient Matrix geometry, developed for the ZETEX "SuperSOT" series. This enables a $V_{CE(sat)}$ performance similar to the ZTX850 series at the low to moderate currents relevant to this application, though utilising a smaller die, and therefore providing a cost and possibly a space saving advantage.

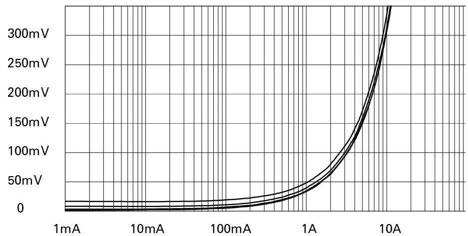

Figure 11.
$V_{CE(sat)}$ v I_C for the ZTX1048A Bipolar Transistor: Forced gains of 10,20,50,100.

Package Options

ZETEX can offer a range of packages to allow complete circuit size and layout optimisation. Figure 12 illustrates these, from the TO92 compatible E-Line through-hole package, to surface mount options SOT23, SOT223, and SM-8.

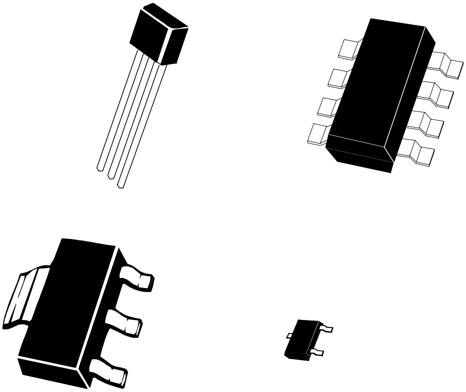

Figure 12.
Package Options.

The SM-8 is a dual island, eight leaded package that possesses the same body dimensions as the industry standard SOT223. These attributes allow it to replace the two Royer Converter transistors with a single package two chip device, yielding a significant cost and space saving.

For example, the ’1048A transistor is available as an uncommitted dual within the SM8 package as the **ZDT1048.**

Conclusions

The advanced transistor geometries, and optimised processing employed by **ZETEX** leads to a range of transistors that are ideally suited to the LCD backlighting inverter application. Attention has been applied to specifying a range of devices relevant to, and exhibiting a superior performance within the Royer inverter topology.

References

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Bright, Pittman and Royer.
Westinghouse Electric Corp.,
Electrical Manufacturing Dec 1954.

“Techniques for 92% Efficient LCD Illumination”
Applications Note 55 August 1993
Jim Williams
Linear Technology Corp.,

“A Fourth Generation of LCD Backlight Technology - Component and Measurement Improvements Refine Performance” Application Note 65 October 1995
Jim Williams
Linear Technology Corp.

“Switching and Linear Power Supply, Power Converter Design”
A. Pressman
Hayden Press.

Appendix A

LT1070, 1170 Series Switching Regulators
LT1182, 1183 CCFL/LCD Contrast Dual Switching Regulator
Linear Technology Corporation,
1630 McCarthy Blvd.,
Milpitas, CA 95035-7487
TEL: (408) 432 1900

Linear Technology (UK) Ltd.,
TEL:(01276) 677676

Linear Technology KK
Tokyo, 102 JAPAN
TEL: 81-3-3237-7891

Appendix B

CCFL Inverter Transformer and Inductor Manufacturers

Coiltronics Inc.,
TEL: (407) 241-7876
(Transformers and inductors)
Represented by METL in the UK
TEL: 01844-278781

Sumida Electric Co., Ltd.
Tokyo 125 JAPAN
TEL: 03-3607-5111
(Inductors)
Represented by ACAL Electronics Ltd.,in the UK
TEL: 0344-727272

Sumida Electric (USA) Co., Ltd
TEL: (708) 956-0666
(Transformers and Inductors)

Coilcraft
TEL: (708) 639-6400
(Inductors)

Coilcraft (UK)
TEL: 0181-301-3553

Newport Components Ltd.,
TEL: 01908-615232
(Inductors)

Pico Electronics Inc.,
NY 10552
TEL: (914) 699-5514
(Inductors)
Represented by Ginsbury Electronics Ltd., in the UK
TEL: 01634-290040

Appendix C
ZETEX Royer Converter Transistors

Device	BV_{CEV} * V	BV_{CES} / BV_{CBO} V	B_{VEBO} V	I_C (DC) A	h_{FE}	@ I_C / V_{ce} A / V	$V_{CE(sat)}$ V	@ I_C / I_B A / A	Package	Surface Mount Option
ZTX849	_	80	6	5	100 - 300	1 / 1	25mV typ 50mV Max	0.5 / 0.02	E-Line	FZT849 (SOT223)
ZTX869	_	60	6	5	300 min	1 / 1	20mV typ 50mV Max	0.5 / 0.01	E-Line	FZT869 (SOT223)
ZTX689B	_	50(typ)	5	3	450 min	1 / 2	60mV typ	0.5 / 0.005	E-Line	FZT689B (SOT223)
FMMT619 (SuperSOT)	_	50	5	2	200 min	1 / 2	55mV typ 125mV typ 200mV Max	0.5 / 0.01 1.0 / 0.01	SOT23	-
ZTX1048A	50	50	5	4	300 - 1200	1 / 2	24mV typ 45mV Max	0.5 / 0.02	E-Line	ZDT1048 (SM-8)
ZTX1049A	80	80	5	4	300 - 1200	1 / 2	35mV typ 60mV Max	0.5 / 0.02	E-Line	ZDT1049 (SM-8)

* If specified. For those devices that don't include a BV_{CEV} test, the actual value will be close to the BV_{CES}/BV_{CBO} figure - please refer to text.