BY JIM WILLIAMS • LINEAR TECHNOLOGY CORP

High-voltage, low-noise dc/dc converters

YOU CAN MAKE A 1-kV DC/DC CONVERTER WITH ONLY 100 µV OF NOISE.

Photomultipliers, avalanche photodiodes, ultrasonic transducers, condenser microphones, radiation detectors, and similar devices require high-voltage, low-current biasing. Additionally, the high voltage must be free of noise. A common requirement is less than 1 mV of noise, and these devices sometimes require noise to be less than a few hundred microvolts. Switching-regulator configurations cannot normally achieve this performance level without employing special techniques. One aid to achieving low noise is the fact that load currents rarely exceed 5 mA. This freedom permits the use of output-filtering methods that are otherwise impractical.

This article describes a variety of circuits featuring outputs of 200 to 1000V with less than 100 µV of output noise in a 100-MHz bandwidth. Special techniques, most notably power stages that minimize high-frequency harmonic content, enable this performance. Although sophisticated, all these examples use standard, commercially available magnetic components. This provision should help you quickly arrive at a manufacturable design.

Before proceeding any further, understand that you should use caution in the construction, testing, and use of the circuits this article describes. High-voltage, lethal potentials are present in these circuits. Use extreme caution in working with and making connections to these circuits. Again, these circuits contain dangerous, high-voltage potentials.

RESONANT ROYER-BASED CONVERTERS

The resonant Royer topology suits low-noise operation due to its sinusoidal power delivery (references 1 and 2). The resonant Royer is attractive because transformers for LCD-backlight service are readily available. These transformers are available from multiple sources, well-proven, and competitively priced. Figure 1's resonant Royer topology achieves 100-µV-p-p noise at 250V output by minimizing high-frequency harmonics in the power-drive stage. The self-oscillating resonant Royer circuitry comprises Q_2, Q_3, C_1, T_1, and L_1. Current flow through L_1 causes the T_1, Q_2, Q_3, and C_1 circuitry to oscillate in resonant fashion, supplying sine-wave drive to T_1's primary with resultant sinelike high voltage appearing across the secondary.

T_1's rectified and filtered output feeds back to amplifier-reference A_1, which biases the Q_1 current sink, completing a control loop around the Royer converter. L_1

ensures that Q_1 maintains constant current at high frequency. Milliampere-level output current allows the presence of a 10-kΩ resistor in the output filter. This resistor greatly aids filter performance with minimal power loss. The low cur-
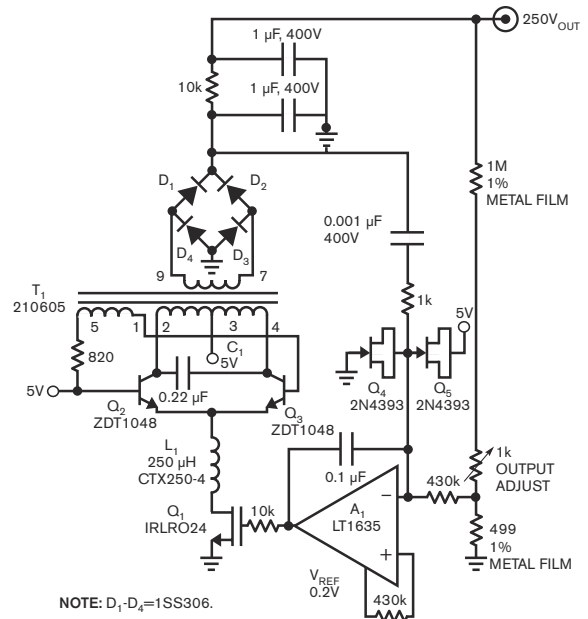

Figure 1 This current-fed resonant Royer converter produces a high-voltage output. Amplifier A_1 biases the Q_1 current sink. This step creates a feedback loop that stabilizes the output voltage. Amplifier A_1's 0.001-µF-capacitor, 1-kΩ-resistor network creates a phase lead relative to the output filter, thereby optimizing transient response. Low-leakage clamp diodes D_5 and D_6 protect A_1.
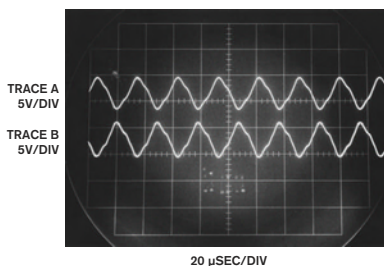

Figure 2 The waveforms of a resonant Royer collector are distorted sinusoids, containing no high-frequency content.

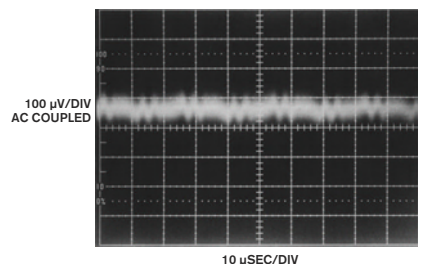Figure 3 The output noise of the circuit in Figure 1 is barely discernible relative to the instrumentation's 100-µV noise floor.

rent requirements permit certain freedoms in the output filter and feedback network (see **sidebar** "Feedback considerations in high-voltage dc/dc converters" at www.edn.com/ms4295). The RC path to A_1's negative input combines with the 0.1-μF capacitor to compensate A_1's loop. D_5 and D_6, low-leakage clamps, protect A_1 during start-up and transient events. Although **Figure 2**'s collector waveforms are distorted, no high-frequency content is present.

The circuit's low harmonic content combines with the RC-output filter to produce a transcendently clean output. Output noise (**Figure 3**) is just discernible in the monitoring instrumentation's 100-μV noise floor (**Reference 3**).

Figure 4's variant of **Figure 1** maintains 100-μV output noise and extends the input-supply range to 32V. Q_1 may require heat-sinking at high input-supply voltage. Converter and loop operation remains the same as in **Figure 1**, although **Figure 4** re-establishes compensation components to accommodate the LT1431 control element.

The previous resonant Royer examples use linear control of converter current to furnish harmonic-free drive. The trade-off is decreased efficiency, particularly as input voltage scales. You can improve efficiency by employing switched-mode current drive to the Royer converter. Unfortunately, such switched drive usually introduces noise. However, you can counter this undesirable consequence.

Figure 5 replaces the linearly operated current sink with a switching regulator. The Royer converter and its loop are the same as in **Figure 4**; **Figure 6**'s transistor-collector waveshape (Trace A) is similar to that of the other circuits. The high-speed, switched-mode current-sink drive (Trace B) efficiently feeds L_1. This switched operation improves efficiency but degrades output noise. **Figure 7** shows switching-regulator harmonic clearly responsible for 3-mV-p-p output noise—about 30 times greater than that of the linearly operated circuits.

Careful examination of **Figure 7** reveals almost no Royer-based residue. Switching-regulator artifacts dominate the noise. Eliminating this switching-regulator-originated noise and maintaining efficiency requires special circuitry, but this circuitry is readily available (**Figure 8**). The resonant Royer converter and its loop are reminiscent of the circuits in the preceding **figures**. The fundamental difference is the LT1534 switching regulator that uses controlled transition times to retard high-frequency harmonic and maintain efficiency. This approach blends switching and linear-current-sink benefits (**Reference 3**). R_V and R_I set the voltage and current-transition rate, respectively, which represents a compromise between efficiency and noise reduction.

Figure 9's Royer collector waveshape (Trace A) is nearly identical to the one that **Figure 5**'s circuit produces. Trace B, depicting LT1534-controlled transition times, markedly departs from its **Figure 5** counterpart. These controlled transition times dramatically reduce output noise (**Figure 10**) to 150 μV p-p—a 20-fold improvement over **Figure 7**'s LTC3401-based results.

Figure 11 is essentially identical to **Figure 8**, except that it produces a −1000V output. A_1 provides low impedance, inverting feedback to the LT1534. **Figure 12a**'s output noise measures less than 1 mV. As before, resonant Royer ripple dominates the noise; no high-frequency content is detectable.
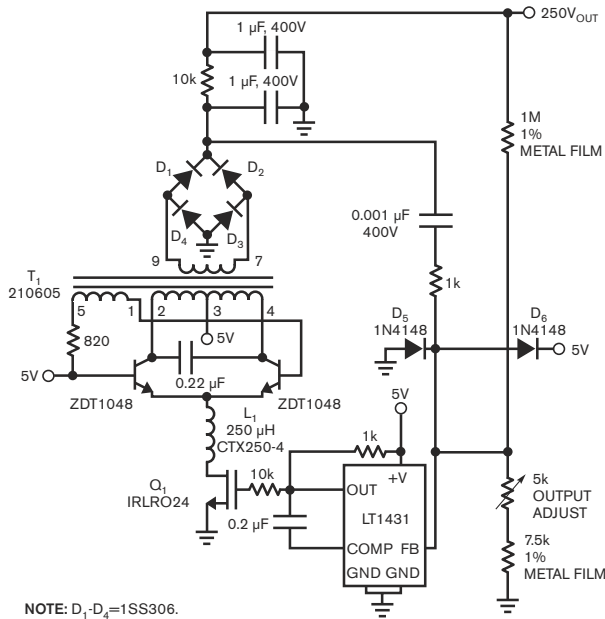
Figure 4 This variant of Figure 1 employs the LT1431 regulator, maintains 100-μV output noise, and extends the input-supply range to 32V. Transistor Q_1 may require a heat sink if input-supply voltages are high.
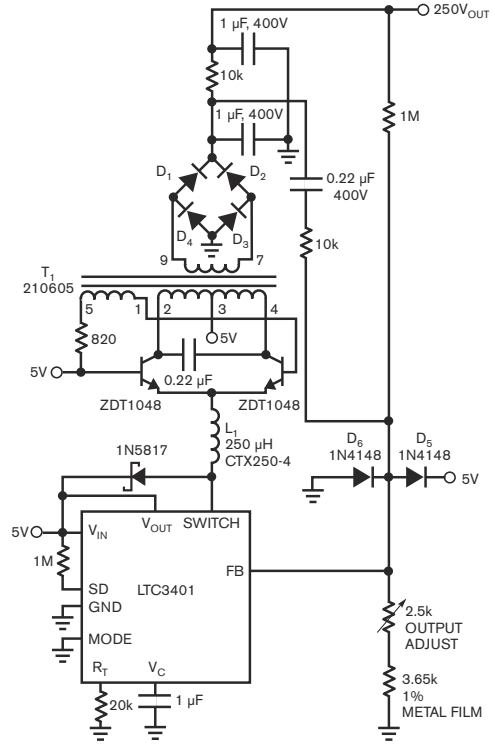

Figure 5 In this circuit, a switching regulator replaces the linearly operated current sink of Figure 4. This approach minimizes heating, although the output noise increases.

It is worth noting that this noise figure proportionally improves with increased filter-capacitor values. For example, **Figure 12b** indicates only 100-μV noise with 10-times-higher filter-capacitor values, although the capacitors are physically large. The original values represent a reasonable compromise between noise performance and physical size.

PUSH-PULL CONVERTERS

Controlled transition techniques are also directly applicable to push-pull architectures. **Figure 13** uses a controlled transition push-pull regulator in a simple loop to control a 300V output converter. Symmetrical-transformer drive and controlled switching-edge times promote low output noise. The D_1- through D_4-connected damper further minimizes residual aberrations. In this case, the output filter uses inductors, although you could employ appropriate resistor values. **Figure 14** displays smooth transitions at the transformer secondary outputs. (Trace A is T_1 Pin 4, and Trace B is T_1 Pin 7.) The absence of high-frequen-
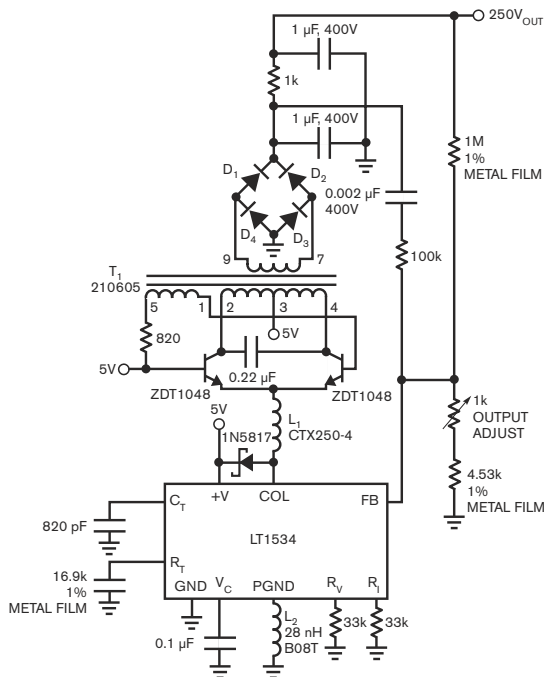
TRACE A 5V/DIV
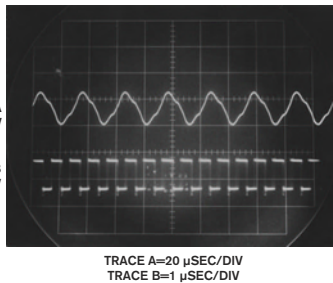TRACE B 5V/DIV
TRACE A=20 μSEC/DIV
TRACE B=1 μSEC/DIV

Figure 6 The resonant Royer collector waveshape (Trace A) is similar to that of the previous circuits. An efficient, high-speed, switched-mode current-sink drive feeds inductor L_1 (Trace B).

cy harmonic results in extremely low noise. **Figure 15**'s fundamental-related output residue approaches the 100-μV measurement noise floor in a 100-MHz bandpass. This performance is spectacularly low noise in any dc/dc converter, and certainly in one providing high voltage. Here, at 300V output, noise represents less than 1 part in 3 million.

Figure 16 is similar, except that output range varies from 0 to 300V. An LT3439, which contains no control elements, replaces the LT1533. It simply drives the transformer with 50%-duty-cycle, controlled switching transitions. A_1, Q_1, and Q_2 enforce feedback control by driving current into T_1's primary center tap. A_1 compares a resistively derived portion of the output with a user-supplied control voltage. These values produce a 0 to 300V output in response to a 0 to 1V control voltage. An RC network from Q_2's collector to A_1's positive input compensates the loop. Collector waveforms and output-noise signature are nearly identical to those in **Figure 13**. Output noise is 100 μV p-p over the entire 0 to 300V output range.

FLYBACK CONVERTERS

You don't usually associate flyback converters, with their abrupt, poorly controlled energy delivery, with low-noise output. However, careful magnetic selection and layout can
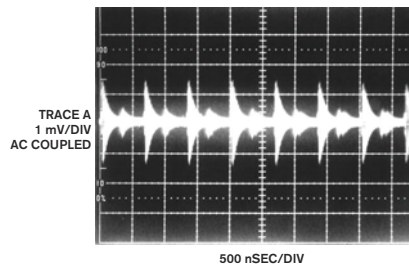

TRACE A 1 mV/DIV AC COUPLED
500 nSEC/DIV

Figure 7 The switching-regulator harmonic in Figure 5 results in 3-mV-p-p output noise.

provide surprisingly good performance, particularly at low output current. **Figure 17**'s design provides 200V from a 5V input (**references 4** and **5**). The scheme is a basic inductor-flyback-boost regulator with some important deviations. Q_1, a high-voltage device, resides between the LT1172 switching regulator and the inductor. This approach permits the regulator to control Q_1's high-voltage switching without undergoing high-
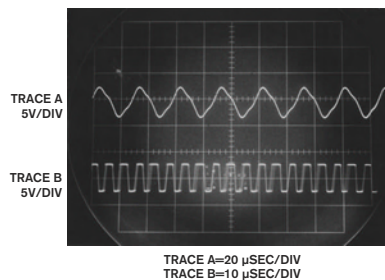

TRACE A 5V/DIV
TRACE B 5V/DIV
TRACE A=20 μSEC/DIV
TRACE B=10 μSEC/DIV

Figure 9 The resonant Royer collector waveshape is identical to that of the LT3401 circuit in Figure 5 (Trace A). The controlled transition times of the LT1534 current sink attenuate the high-frequency harmonics (Trace B).
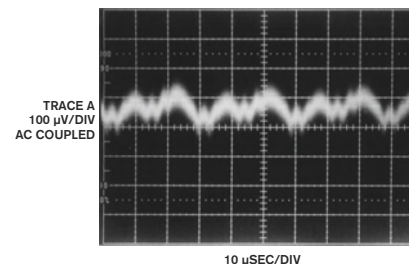

TRACE A 100 μV/DIV AC COUPLED
10 μSEC/DIV

Figure 10 The controlled transition times dramatically lower noise to 150 μV p-p, a 20-fold improvement over that of Figure 7.

NOTE: D_1-D_4=1SS306.

Figure 8 The LT1534 switching regulator features controlled transition times that minimize high-frequency harmonics and maintain low heat dissipation. The approach blends the benefits of switching- and linear-current-sink circuits.
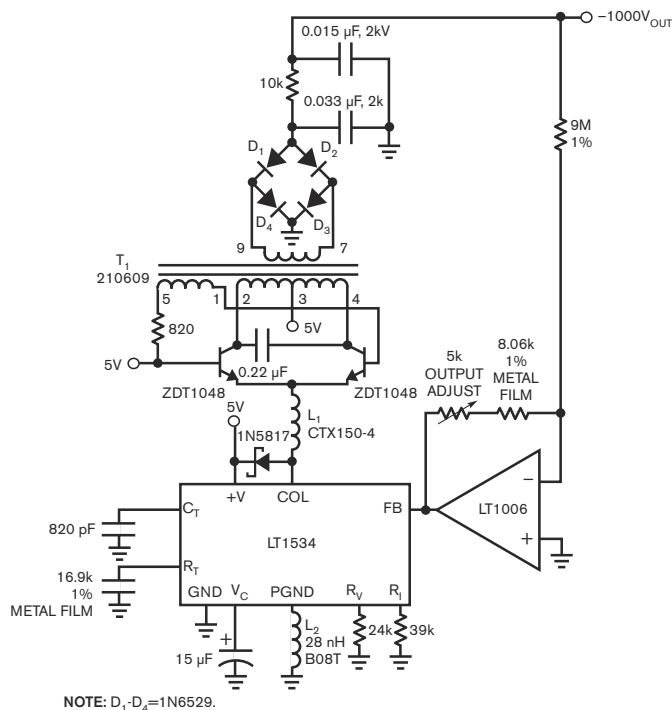
Figure 11 This −1000V negative-output converter uses the controlled-transition-time feature of the LT1534. Amplifier A_1 provides low impedance, inverting feedback to the LT1534 IC.
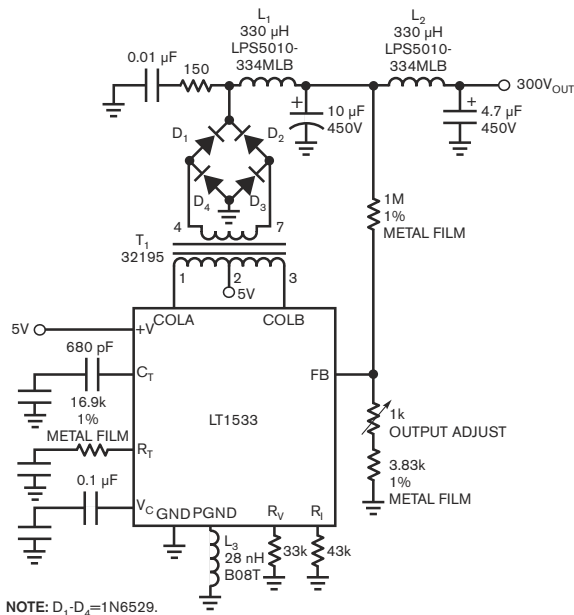

Figure 13 This converter circuit features a push-pull drive with controlled transitions and provides a 300V output. The symmetrical-transformer drive and slow edge transitions promote low output noise.
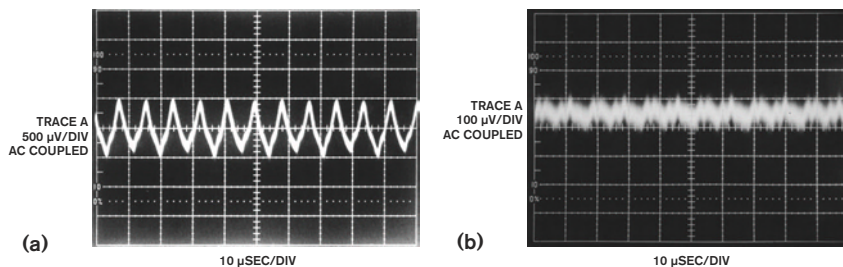

Figure 12 The −1000V converter's output noise measures less than 1 mV—that is, 1 ppm, or 0.0001%—in a 100-MHz bandwidth (a). The resonant Royer ripple voltage dominates the residue. There is no detectable high-frequency content. Output noise decreases to 100 µV by using 10-times-larger filter capacitors than those in Figure 11 (b). The penalty is the size of the capacitors.
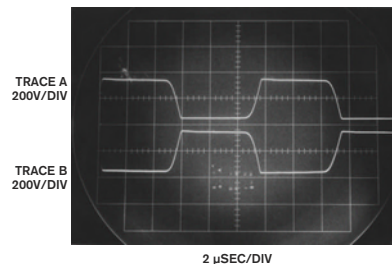

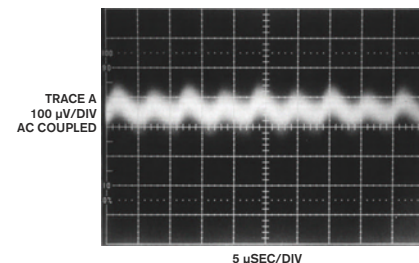Figure 14 The outputs of the transformer secondary have no high-frequency artifacts.

Figure 15 The output noise of the push-pull converter circuit in Figure 13 is barely discernible relative to the instrumentation's 100-µV noise floor. No wideband components appear in the 100-MHz measurement passband.

voltage stress. Q_1, operating as a cascode with the LT1172's internal switch, withstands L_1's high-voltage flyback events (**references 6** through **10**).

Diodes associated with Q_1's source-terminal clamp, L_1, originated spikes arriving through Q_1's junction capacitance. The high voltage is rectified and filtered, forming the circuits' output. The ferrite bead and 100 and 300Ω resistors aid filter efficiency (**references 11** and **12**). Feedback to the regulator stabilizes the loop and the V_C-pin net-

work provides frequency compensation. A 100-kΩ path from L_1 bootstraps Q_1's gate drive to about 10V, ensuring saturation. The output-connected diode provides short-circuit protection by shutting down the LT1172 if the output is accidentally grounded.

Figure 18's traces A and C are LT1172 switch current and voltage, respectively. Q_1's drain is Trace B. Current-ramp termination results in a high-voltage flyback event at Q_1's drain. A safely attenuated version of the flyback appears
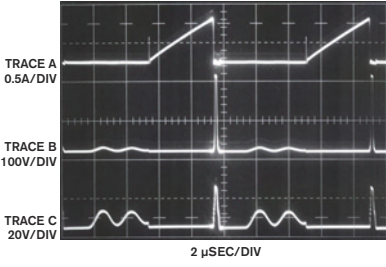
NOTE: D$_1$-D$_4$=1N6529.

Figure 16 This circuit provides full-range adjustability. The control input, V$_{CONTROL}$, sets transformer T$_1$'s drive voltage through Q$_1$ and Q$_2$. A 1-MΩ/3.32-kΩ resistive divider provides feedback that A$_1$'s input capacitors stabilize. Waveforms are similar to those of Figure 13. The output noise is 100 μV p-p.

Figure 17 This converter has an output of 5 to 200V. Transistor Q$_1$ is in cascode with the LT1172 and switches the high voltage. This approach allows a low-voltage regulator to control the output. Diode clamps protect the regulator from transients. Flyback events at L$_1$ bootstrap Q$_1$'s gate drive through the 100-kΩ resistor. The diode that connects to the output and the 300Ω resistor provide short-circuit protection. The ferrite bead and the 100 and 300Ω resistors minimize high-frequency output noise.

at the LT1172 switch. The sinusoidal signature, due to inductor ring-off between conduction cycles, is harmless. **Figure 19**, output noise, comprises low-frequency ripple and wideband, flyback-related spikes measuring 1 mV p-p in a 100-MHz bandpass.

In a transformer-coupled flyback cir-

TRACE A
0.5A/DIV

TRACE B
100V/DIV

TRACE C
20V/DIV

2 µSEC/DIV

Figure 18 Waveforms for the 5 to 200V converter include the LT1172 switch current and voltage (traces A and C, respectively) and Q_1's drain voltage (Trace B). The termination of the current ramp results in a high-voltage flyback event at the drain of Q_1. A safely attenuated version appears at the LT1172 switch. The inductor ring-off between current-conduction cycles creates the sinusoidal signature, but it is harmless.
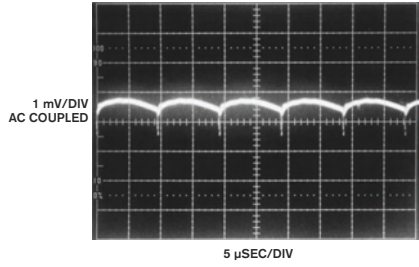

1 mV/DIV
AC COUPLED

5 µSEC/DIV

Figure 19 The output noise of the circuit in Figure 17 is 1 mV p-p in a 100-MHz bandpass. The noise comprises low-frequency ripple and wideband, flyback-related spikes.

cuit, the transformer secondary provides voltage step-up referred to the flyback-driven primary (**Figure 20**). The 4.22-MΩ resistor supplies feedback to the regulator, closing a control loop. A 10-kΩ, 0.68-µF filter network attenuates high-frequency harmonic with minimal voltage drop. **Figure 21** clearly shows flyback-related transients in the output noise, although they are within 300 µV p-p.

The circuit in **Figure 22** employs the

LT3468 photoflash-capacitor charger as a general-purpose, high-voltage dc/dc converter. Normally, the LT3468 regulates its output at 300V by sensing T_1's flyback-pulse characteristic. This circuit allows the LT3468 to regulate at lower voltages by truncating its charge cycle before the output reaches 300V. A_1 compares a divided-down portion of the output with the program input voltage. When the output-derived potential at A_1's negative input exceeds the program voltage at A_1's positive input, A_1's output goes low, shutting down the LT3468. The feedback capacitor provides ac hysteresis, sharpening A_1's output to prevent chattering at the trip point. The LT3468 remains shut down until the
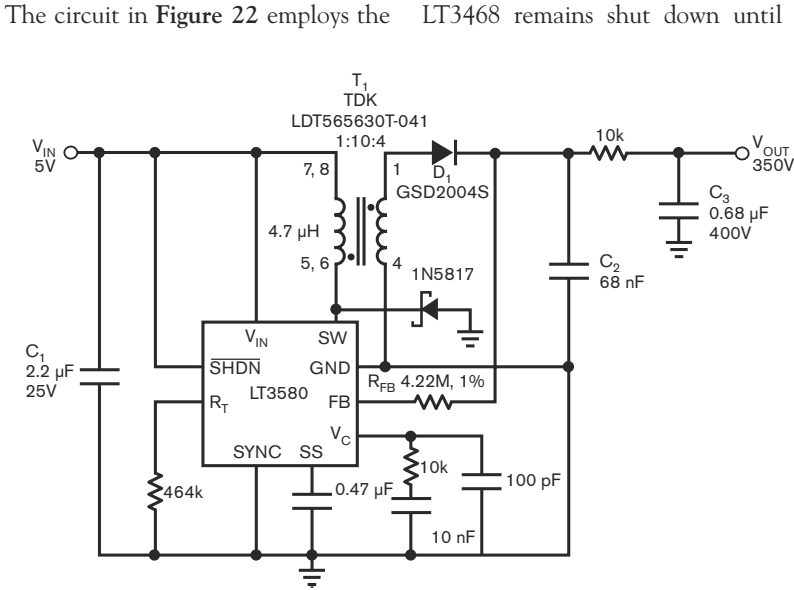

Figure 20 This 5V-powered transformer-coupled flyback converter produces a 350V output (courtesy Albert M Wu, Linear Technology).

output voltage drops low enough to trip A_1's output high, turning it back on. In this way, A_1's duty cycle modulates the LT3468, causing the output voltage to stabilize at a point that the program input determines.

Figure 23's 250V-dc output (Trace B) decays down about 2V until A_1 (Trace A) goes high, enabling the LT3468 and restoring the loop. This simple circuit works well, regulating over a programmable 0 to 300V range, although its inherent hysteretic operation mandates the unacceptable 2V output-ripple noted. The loop-repetition rate varies with the input voltage, output setpoint, and load, but the ripple is always present.

The circuit in **Figure 24** greatly reduces ripple amplitude, although complexity increases. The circuit's postregulator reduces the output ripple and noise of **Figure 22**'s circuit to only 2 mV. A_1 and the LT3468 are identical to **Figure 23**'s circuit, except for the 15V zener diode in series with the 10-MΩ/100-kΩ feedback divider. This component causes C_1's voltage, and hence Q_1's collector, to regulate 15V above the $V_{PROGRAM}$ input-dictated point. The $V_{PROGRAM}$ input also routes to the A_2-Q_2-Q_1 linear postregulator. A_2's 10-MΩ/100-kΩ feedback divider has no zener diode, so the postregulator follows the $V_{PROGRAM}$ input with no offset. This arrangement forces 15V across Q_1 at all output voltages. This figure is high enough to eliminate undesirable ripple and noise from the output and keep Q_1's dissipation low.

Q_3 and Q_4 form a current limit, protecting Q_1 from overload. Excessive current through the 50Ω shunt turns on Q_3. Q_3 drives Q_4, shutting down the LT3468. Simultaneously, a portion of Q_3's collector current turns on Q_2 hard, shutting off Q_1. This loop dominates the normal regulation feedback, protecting the circuit until you remove the overload.

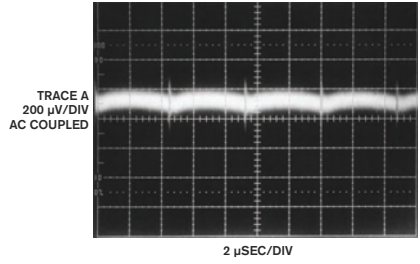**Figure 25** shows just how effective the postregulator is. When A_1 (Trace A) goes high, Q_1's col-

lector (Trace B) ramps up in response. Note the LT3468's switching artifacts on the ramp's upward slope. When the A_1-LT3468 loop is satisfied, A_1 goes low and Q_1's collector ramps down. The output postregulator (Trace C), however, rejects the ripple, showing only 2 mV of noise. The slight blurring of the trace derives from A_1-LT3468 loop jitter.

CIRCUIT CHARACTERISTICS

Table 1 (at www.edn.com/ms4295) summarizes and notes the salient characteristics of the circuits in this article. This **table** is only a generalized guideline and not an indicator of capabilities or limits. Too many variables and exceptions exist to accommodate the cate-
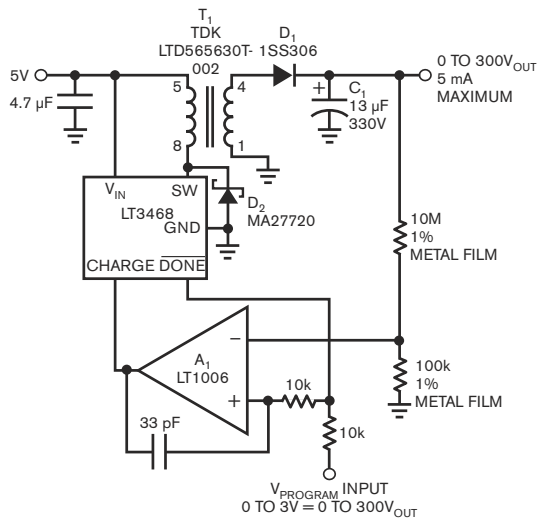

Figure 22 This regulator output is voltage-programmable between 0 and 300V. Amplifier A_1 controls the regulator output by modulating the duty cycle of the LT3468/T_1 dc/dc converter's power delivery.

gorical statement the **table** implies. The interdependence of circuit parameters makes summarizing or rating various approaches a hazardous exercise. There is simply no intellectually responsible way to streamline the selection and design process if you want optimum results. A meaningful choice must be the outcome of laboratory-based experimentation.
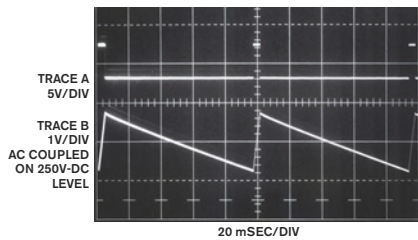
Too many interdependent variables and surprises exist for a systematic, theoretically based selection. Tables such as this one seek authority through glib simplification, and simplification is disaster's deputy. Nonetheless, **Table 1** (at www. edn.com/ms4295), in all its glory, lists input-supply range, output voltage, and current, along with comments for each circuit.**EDN**
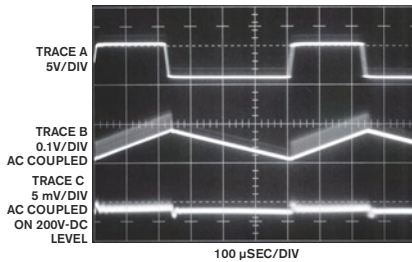
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6 Williams, Jim, and Albert Wu, "Simple Circuitry for Cellular Telephone/

Figure 23 The duty-cycle-modulated operation of the circuit in Figure 22 shows that the high-voltage output (Trace B) ramps down until A_1 (Trace A) goes high. This approach enables the LT3468/T_1 to restore the output. The loop-repetition rate varies with input voltage, output setpoint, and load.

Figure 25 The low-ripple output (Trace C) is apparent in the postregulator's operation. Traces A and B are the output of A_1 and Q_1's collector, respectively. The blurring of the trace, right of the photo's center, derives from loop jitter.
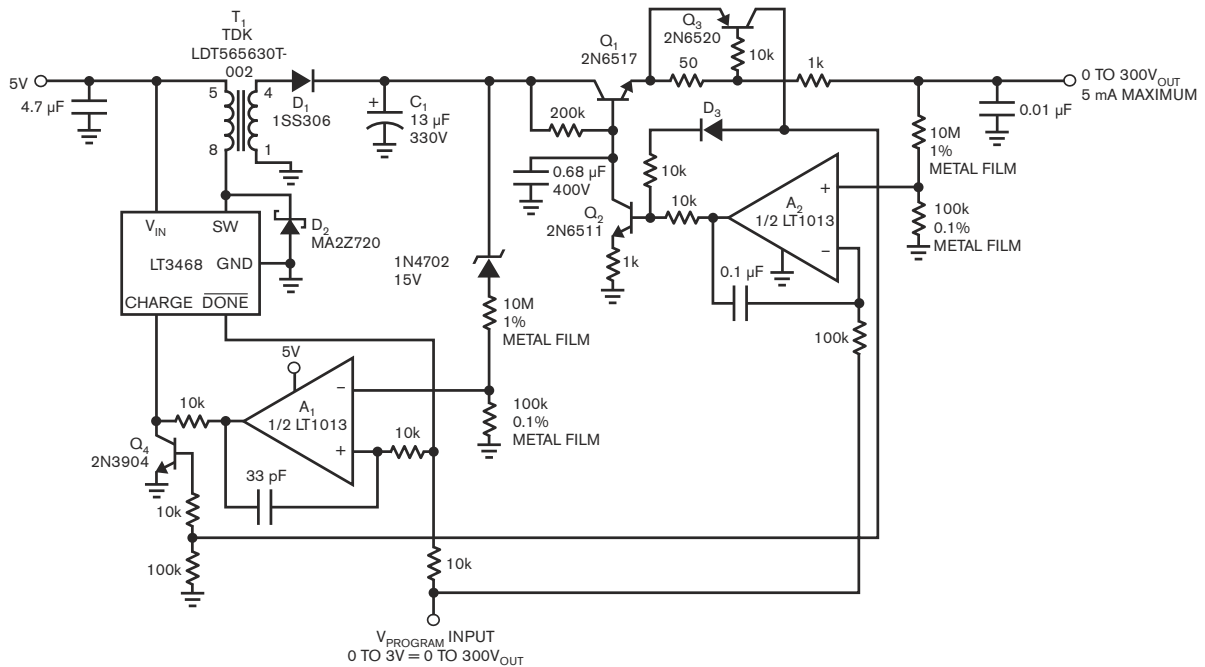

Figure 24 Adding postregulation to the circuit of Figure 22 reduces the output ripple from 2V to 2mV. An LT3468-based dc/dc converter, similar to the one in Figure 22, delivers high voltage to the collector of Q_1. Amplifier A_2 and Q_1 and Q_2 form a tracking, high-voltage linear regulator. The zener diode sets Q_1's collector-to-emitter voltage to 15V, ensuring tracking with minimal power dissipation. Transistors Q_3 and Q_4 limit the short-circuit output current.

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