Power Conditioning Techniques for Batteries

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Declining power requirements for circuitry have made battery operation desirable and common. In many circumstances the battery voltage may be applied directly to circuitry with no special considerations. Other situations require some form of battery power conditioning to supply necessary voltages. At present, most IC regulators are not suitable for battery regulation because of high quiescent current and/or inability to operate at low input voltages. In particular, some switching regulators consume 20mA, many times the total power drain of some low power systems.

Designing battery regulator circuitry involves numerous considerations including efficiency, power output, battery life, circuit complexity, PC board space and cost.

Various linear and switching regulation techniques are applicable, with the best approach determined by specific requirements. Most circuit types provide DC outputs, although AC is sometimes required. General classes of regulators include voltage inverters, step-down circuits and step-up converters.

Negative Voltage Generators

Generating a negative voltage is a common requirement. Figure 1 shows a simple way to do this. The LTC1044 switched-capacitor voltage converter's internal switches synchronously transfer charge from C1 to C2, the output capacitor. When SW1 is closed, C1 charges to 9V. When S1 opens, S2 closes, charging C2, which assumes a negative potential with respect to ground. Continuous clocking
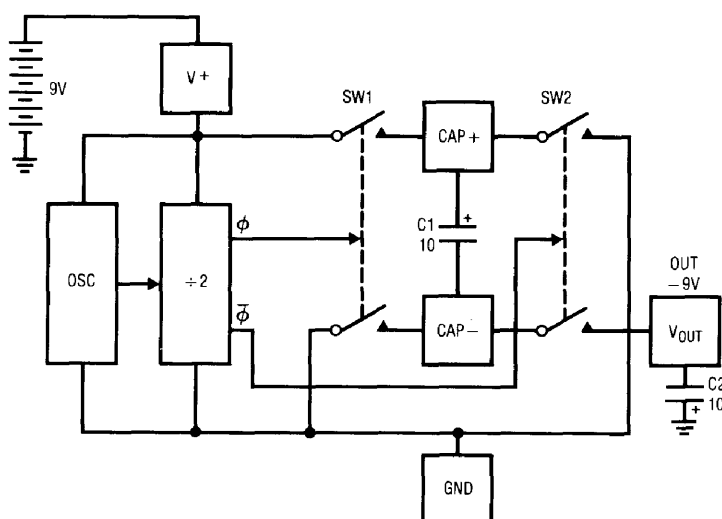

Figure 1. Negative Voltage Generator

keeps V_{OUT} at DC. Due to finite output impedance, loading the output causes a drop in voltage. Figure 2 plots output voltage deviation versus load current. In low current applications or where regulation is not critical, this circuit is adequate. To improve regulation, it is necessary to decrease output impedance. Figure 3 encloses the LTC1044 within the LM10's feedback loop. Because of the LTC1044's voltage inversion, the loop is closed at the op amp's positive input. The voltage converter's losses are compensated by increased drive from the LM10. The 0.1μF capacitor stabilizes the loop and the 47μF unit keeps LM10 output impedance low at the LTC1044's switching frequency. LM10 output swing restrictions limit circuit output to 8.5V. Output regulation, plotted in Figure 2, improves upon Figure 1's basic circuit.
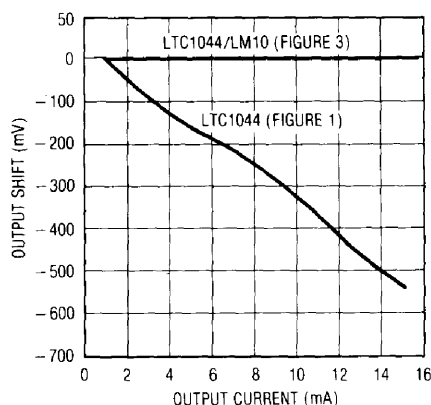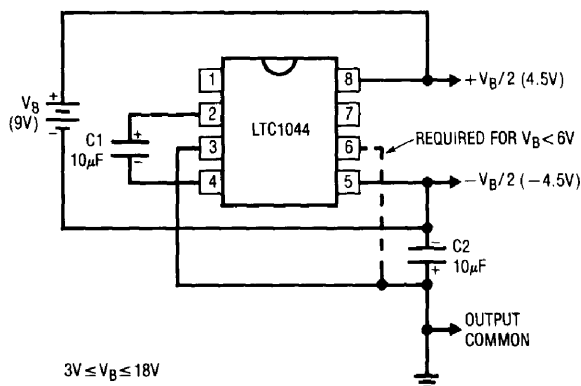
Battery Splitter

A common need in many systems is to obtain positive and negative supplies from a single battery. Where current requirements are small, the circuit shown in Figure 4 is a simple solution. It provides symmetrical ± output voltages, both equal to one half the input voltage. The output voltages are referenced to pin 3 (output common). If the input voltage between pin 8 and pin 5 exceeds 6V, pin 6 should also be connected to pin 3, as shown by the dashed line. Higher current requirements are served by an LT1010 buffer. The splitter circuit shown in Figure 5 can source or sink up to ±150mA with only 5mA quiescent current. The output capacitor, C2, can be made as large as necessary to absorb current transients. An input capacitor is also used on the buffer to avoid high frequency instability that can be caused by high source impedance.
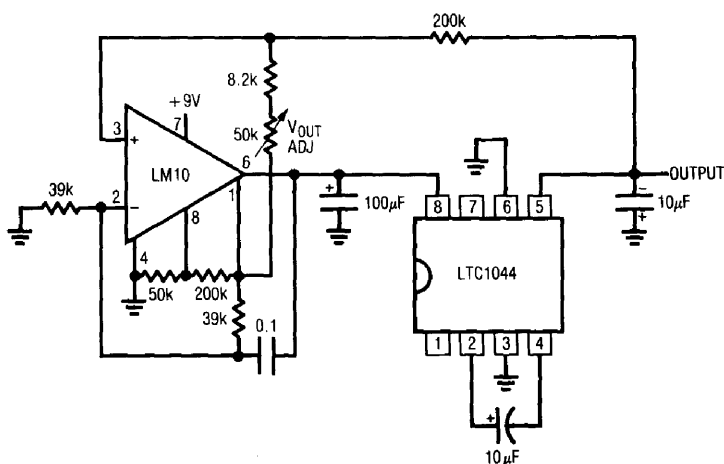

Figure 2
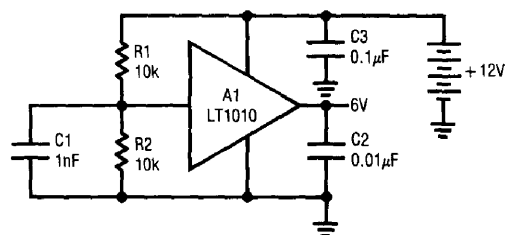

Figure 3. Regulated Negative Voltage Converter

Figure 4. Battery Splitter

Figure 5. High Current Battery Splitter

LINEAR
TECHNOLOGY

Low Dropout Regulator

Linear regulators for batteries are a good way to get low noise, fast transient response regulation. It is desirable to achieve this performance with a very low regulator drop-out voltage to maximize battery life. This can be done with PNP pass elements, but their base current never arrives at the load, decreasing efficiency. Additionally, the PNP's voltage gain complicates loop dynamics, often resulting in relatively poor transient response.

The circuit illustrated in Figure 6 offers extremely low dropout and the fast transient response of an NPN pass element. Quiescent current is 760μA and the 100mA capacity output is short circuit protected. Normally, NPN pass-based regulators have high dropout voltages be-cause of voltage drops in the emitter-follower connected pass transistor. This 6V powered design drives the NPN pass base from a 12V source generated by the LTC1044

voltage doubler. The transistor operates as a voltage over-driven emitter-follower. The emitter's ability to follow the collector is limited only by $V_{CE}SAT$. The voltage overdriven base removes V_{BE} drop, normally the dominant loss, as a consideration. The LTC1044 doubles the battery voltage and powers the LT1013 dual op amp. A1, with 12V output capability, feedback controls the 6V collector-biased tran-sistor. The 100Ω resistor prevents parasitic high frequency oscillation and the LT1004 serves as a reference. The out-put is trimmed by varying A1's feedback divider and the 0.003μF capacitor compensates the loop. A2 provides short circuit protection by forcing A1's output low if bat-tery current exceeds 150mA. A2's low offset and high open loop gain allow using the 0.01Ω current sense resistor, re-ducing voltage drop losses. At 100mA output, the shunt has only 1mV across it.
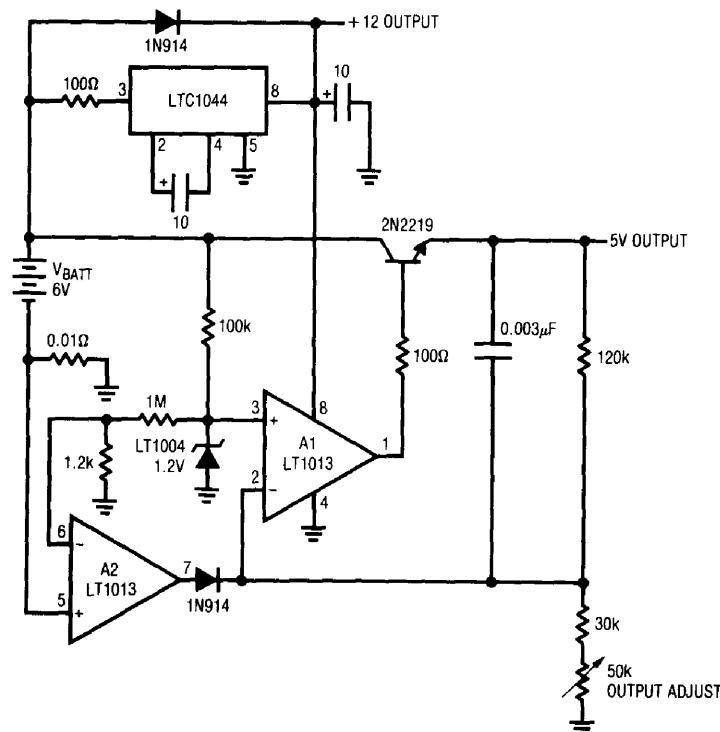

Figure 6. Low Dropout 5V Regulator

Figure 7 illustrates dropout data for the regulator. At 10mA load, dropout is only 0.016V, with 0.94V occurring at 100mA loading. Transient response is shown in Figure 8. Waveform A controls an output load which is either zero or 100mA. Waveform B is the regulator's AC-coupled output. Transient response is clean and quick, with little tailing or aberration.

Low Power Switching Regulator

The low dropout linear regulator is efficient only when its input and output voltages are close. Situations requiring substantial voltage drop to achieve the desired regulated output need switching techniques to maintain good efficiency. Figure 9 shows a simple battery-powered switching regulator. It provides 5V out from a 9V source with 80%

efficiency and 50mA output capability. Assume Q1 is on. Its collector (Trace A, Figure 10) voltage rises, forcing current (Trace B) through the inductor. The output voltage (Trace C) rises, causing A1's output to rise. Q1 cuts off and the output decays through the load. The 100pF capacitor ensures clean switching. The cycle repeats when the output drops low enough for A1 to turn on Q1. The $1\mu F$ capacitor ensures low battery impedance at high frequencies, preventing "sag" during switching. Short circuit protection is as shown in Figure 6's circuit. In some applications the switching-induced noise on the regulated output may be troublesome. Figure 11 eliminates the noise by adding a low-dropout series regulator at the switching circuit's output. The switching loop's operation is similar to Figure 9 except that the voltage across the 2N5434 FET series pass element is controlled. The switching loop
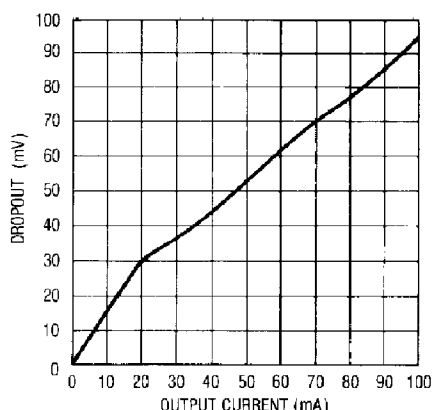

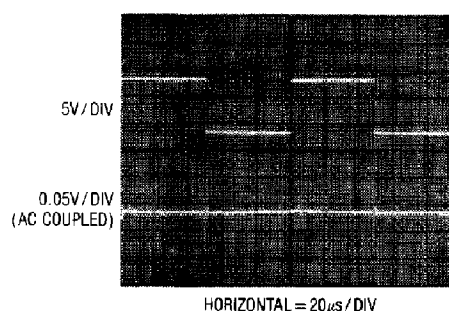Figure 7. Dropout vs Load for Figure 6

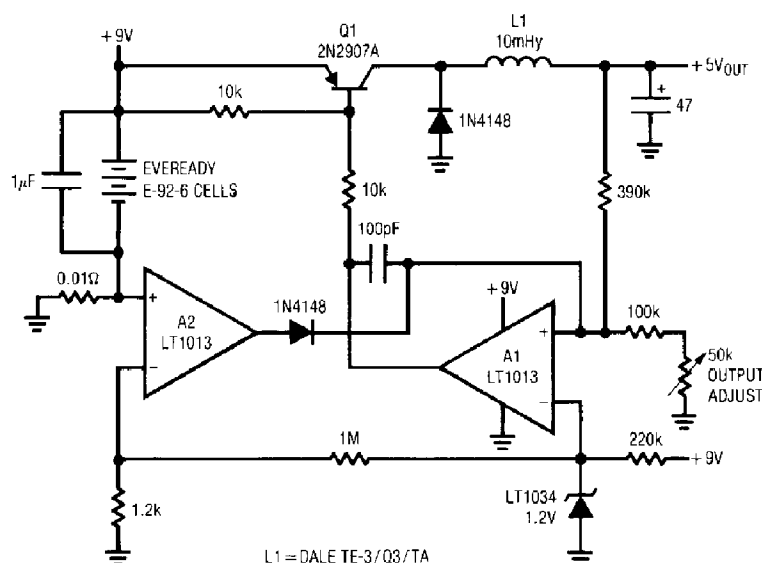Figure 8. Transient Response of Figure 6's Circuit

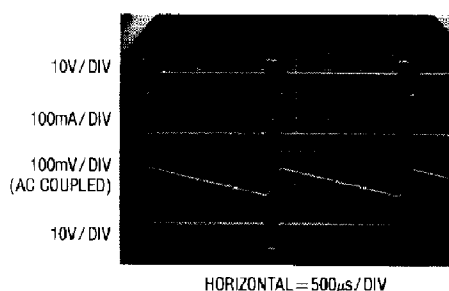Figure 9. Low Power Switching Regulator

Figure 10. Figure 9's Operating Waveforms

forces this voltage to equal V_D, regardless of input or loading conditions. The FET, a low R_{ON}, low pinch-off unit, combines with A2 to form a simple, low dropout series pass regulator. The LT1004 is the reference and the 1000pF capacitor provides roll-off. This circuit will supply 25mA of noise-free, regulated power with short circuit current set by the FET's 30mA I_{DSS}. The overall 75% effi-

ciency is not quite as good as the basic switching circuit due to the 6mW (0.250V x 0.025A) dissipated in the FET.

High Current, "Inductorless," Switching Regulator

Figure 12 shows another high efficiency battery-driven regulator, but this circuit features a 1A output capacity.
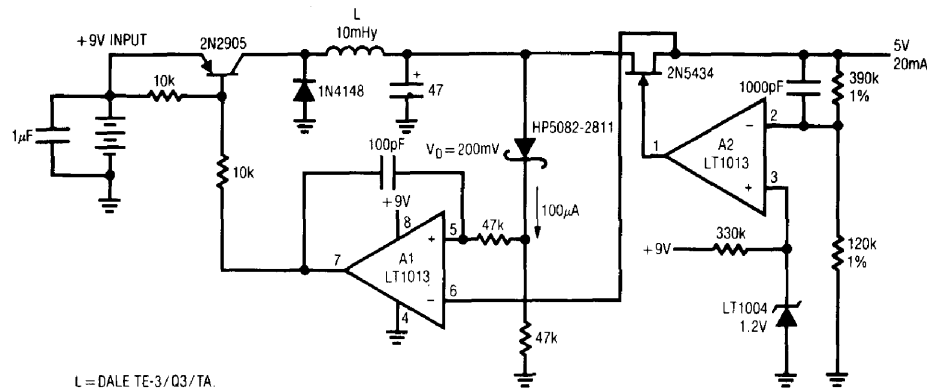

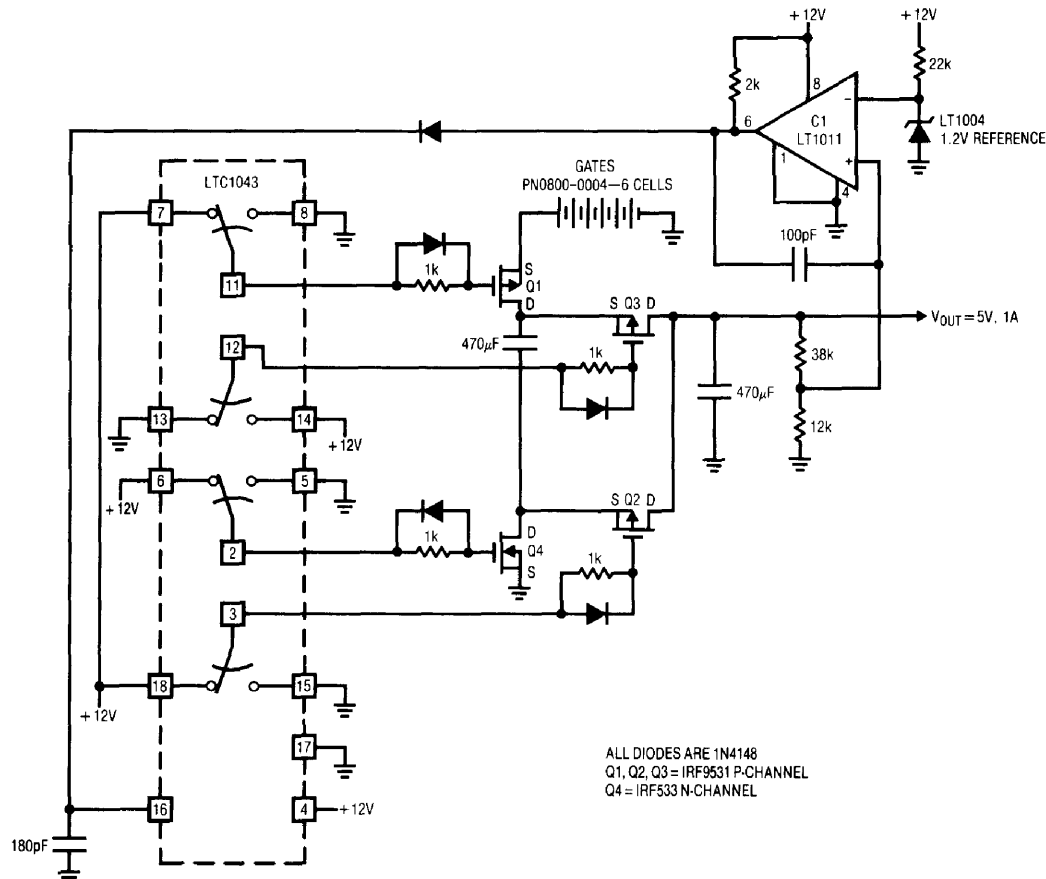Figure 11. Switching Preregulated Linear Regulator

Figure 12. "Inductorless" High Current Switching Regulator

Additionally, it does not require an inductor, an unusual feature for a switching regulator operating at this current level.

The LTC1043 switched-capacitor building block provides non-overlapping complementary drive to the Q1-Q4 power MOSFETs. The MOSFETs are arranged so that C1 and C2 are alternately placed in series and then in parallel. During the series phase, the +12V battery's current flows through both capacitors, charging them and furnishing load current. During the parallel phase, both capacitors deliver current to the load. Traces A and B, Figure 13, are the LTC1043-supplied drives to Q3 and Q4 respectively. Q1 and Q2 receive similar drive from pins 3 and 11. The diode-resistor networks provide additional non-overlapping drive characteristics, preventing simultaneous drive to the series-parallel phase switches. Normally, the output would be one half of the supply voltage, but C1 and its associated components close a feedback loop, forcing the output to 5V. With the circuit in the series phase, the output (Trace C) heads rapidly positive. When the output exceeds 5V, C1 trips, forcing the LTC1043 oscillator pin (Trace D) high. This truncates the LTC1043's triangle wave oscillator cycle. The circuit is forced into the parallel

phase and the output coasts down slowly until the next LTC1043 clock cycle begins. C1's output diode prevents the triangle down-slope from being affected and the 100pF capacitor provides sharp transitions. The loop regulates the output to 5V by feedback-controlling the turn-off point of the series phase. The circuit constitutes a large scale switched-capacitor voltage divider which is never allowed to complete a full cycle. The high transient currents are easily handled by the power MOSFETs and overall efficiency is 83%.

Voltage Step-Up Circuits—Simple Voltage Doubler

All of the previous circuits condition battery output to a lower voltage. Many applications call for a voltage above the battery output. Figure 14 shows a simple way to double available battery voltage using the LTC1044 switched-capacitor voltage converter. As shown, the IC functions in similar fashion to Figure 12's circuit, at greatly reduced power levels. This circuit will drive low power 74-CMOS loads (V_{SUPPLY} 3V-15V) for extended periods of time from two small cells. Efficiency exceeds 90% for load currents below 1.75mA. Figure 15 plots output voltage versus loading.
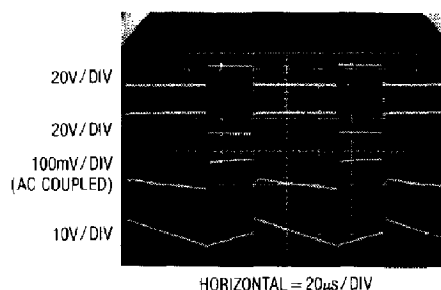
20V/DIV
20V/DIV
100mV/DIV (AC COUPLED)
10V/DIV

HORIZONTAL = 20μs/DIV

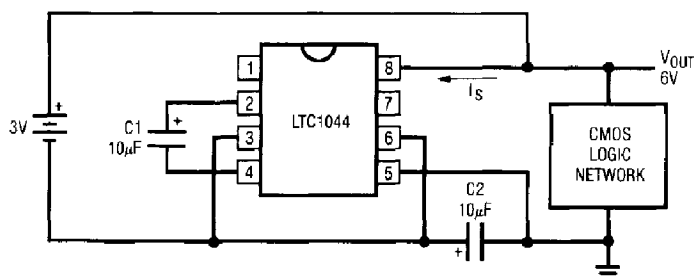**Figure 13. "Inductorless" Regulator's Waveforms**
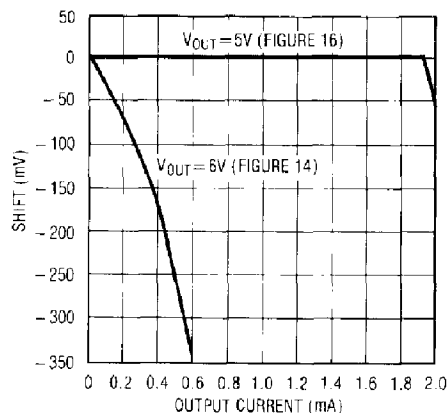
Figure 14. Voltage Doubler

Figure 15

Figure 16 addresses Figure 14's regulation fall-off with increasing current. As in Figure 12, feedback techniques are used to compensate for the voltage converter's output impedance. The LTC1044 is connected in a voltage doubler mode, with the 10μF value used to pump up the 100μF capacitor. Q1 and Q2 serve as a bidirectional switch, allowing the pump up action to be interrupted. The circuit regulates by using an LM10 op amp reference to control the switch. When output voltage decays low enough (Figure 17, Trace A), the LM10's reference amplifier swings high (Trace B), driving the op amp negative (Trace C) and both transistors come on. This allows the LTC1044 to pump charge to the 100μF capacitor. For each charge cycle, the output takes a voltage step. When the output steps high enough, the LM10 switches and the cycle repeats. Repetition rate is load dependent, with typical values of 1Hz–400Hz. Response hysteresis is set by the loop's gain-bandwidth to 40mV. The feedback network fixes the 5V output within 0.025V for loads up to 2mA (plotted in Figure 15).
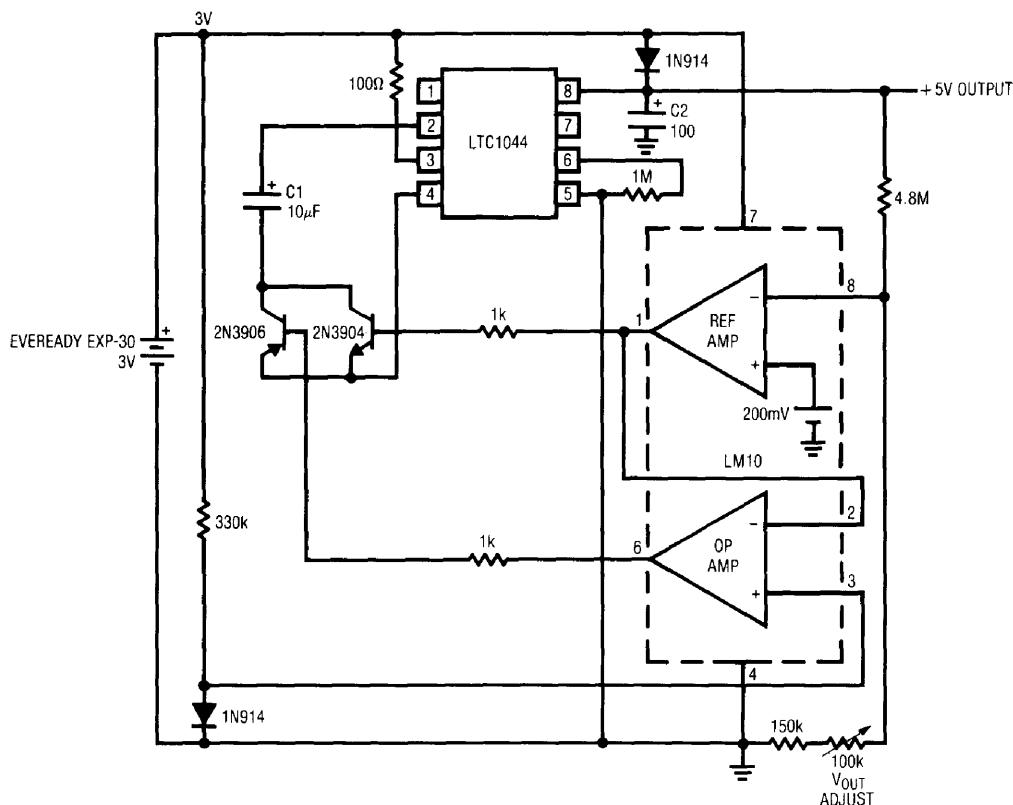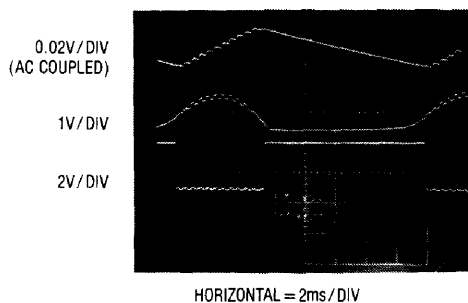
Figure 16. Regulated Voltage Up Converter

Figure 17. Up Converter's Waveforms

The circuit in Figure 18 is conceptually similar, but uses a transformer to get greater voltage gain. This allows a 5V output from a single 1.5V cell. Q2, Q3 and T1 form a self-oscillating DC-DC converter, controlled by the Q1 switch. As in Figure 16, an LM10 closes feedback around this battery step-up converter. With only 1.5V at the input, particular attention must be paid to switch saturation losses. The Germanium transistors specified have under 50mV drop, less than silicon types. Germanium output diodes also contribute low forward drop losses. The 0.004μF capacitor sets hysteresis at 20mV, preventing erratic loop dynamics. An RC damper in T1's primary

eliminates parasitic high frequency oscillation modes. Figure 19 shows operation, with Q1's collector (Trace A) going high when circuit output voltage (Trace D) falls below the loop setpoint. Traces B and C are the LM10 output and Q2's collector, respectively. Note that the output's ramp steps up in similar fashion to Figure 16's capacitively-driven circuit. As with Figure 16, loop oscillation frequency is directly load dependent, with typical values of 1Hz–250Hz. This circuit will supply a 5V, 150μA load (about 25 CMOS SSI ICs) for 3000 hours from a single 1.5V "D" battery.
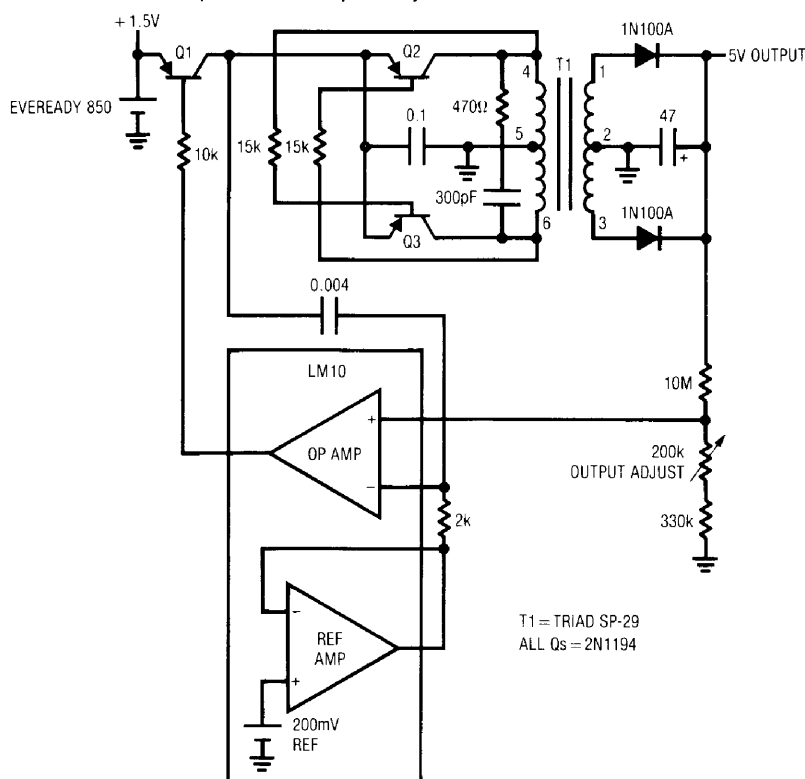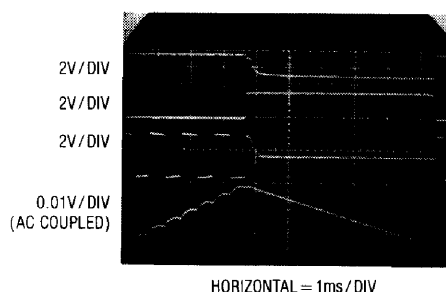

Figure 18. Single Cell Up Converter

HORIZONTAL = 1ms/DIV

Figure 19. Figure 18's Waveforms

Regulated, 15V$_{OUT}$, 6V Driven Converter

Figure 20 shows a 15V output converter which delivers up to 50mA from a 6V battery. Efficiency is 78%. This flyback class converter functions by feedback-controlling the frequency of inductive flyback events. The inductor's output, rectified and filtered to DC, biases the feedback loop to establish a stable output. If the converter's output is below the loop setpoint, A2's inputs unbalance and current is fed through the 1MΩ resistor at A1. This ramps the 1000pF value positive (Trace A, Figure 21). When this ramp exceeds the 0.5V potential at A1's positive input, the amplifier switches high (Trace B). Q2 comes on, discharging the capacitor to ground. Simultaneously, regenerative feedback through the 220pF value causes a positive-going pulse at A1's positive input (Trace C), sustaining A1's positive output. Q1 comes on, allowing inductor (L1) current (Trace D) to flow. When A1's feedback pulse

decays, its output goes low, turning off Q1. Q1's collector (Trace E) is pulled high by the inductor's flyback and the energy is stored in the 100μF capacitor. The capacitor's voltage, which is the circuit output, is sampled by A2 to close a loop around the A1-Q1 combination. This loop forces A1 to oscillate at whatever frequency is required to maintain the 15V output. A1's fixed width output pulse prevents L1 from ever saturating, preventing destructive Q1 currents. The 0.1μF capacitor at A2 furnishes stable loop compensation, with the LT1004 serving as a reference. Regulation is within 0.05% over a wide range of output loads and temperature coefficient is typically 50ppm/°C.

The relatively high voltage-high power output of this circuit suits mixed linear-digital systems requirements well.
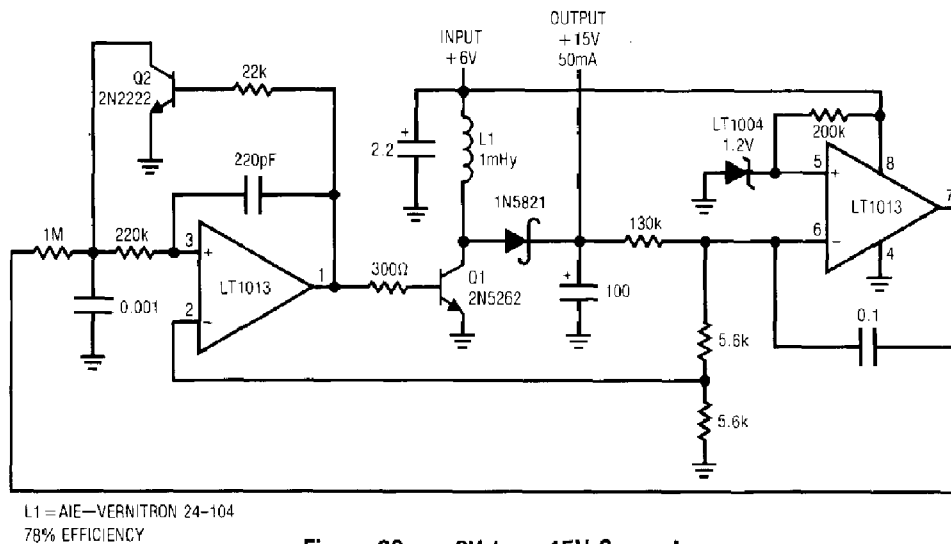

L1 = AIE—VERNITRON 24-104
78% EFFICIENCY
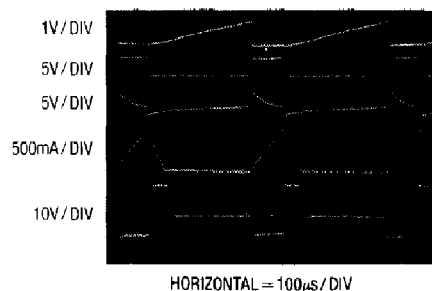
Figure 20. + 6V-to- + 15V Converter

HORIZONTAL = 100μs/DIV

Figure 21. Figure 20's Waveforms

Bipolar Output Flyback Converter

Figure 22 shows a way to obtain positive and negative 15V outputs from a single inductor. The circuit works by alternately determining which end of the inductor is allowed to flyback. The resultant positive and negative peaks are rectified, stored and regulated to produce a bipolar output. The 30kHz clock drives the 74C74 flip-flop, producing a square wave at Q1 (Trace A, Figure 23).

This waveform is fed to the 74C00 gate network. The RC networks prevent unwanted pulses due to flip-flop delay. G2 and G3's outputs appear as Traces B and C, respectively, and bias Q1 and Q2. The logic alternately turns Q1 and Q2 off when the inductor flies back. Although inductor drive current (Trace D) always flows in the same direction, the alternate switching allows positive and negative flyback action at the transistor's collectors. Trace E shows Q1's collector and Trace E is Q2's output. The ringing, due to incomplete damping, is common at low power converter outputs and is not deleterious to circuit operation. The LT1013 dual op amp and the FETs form a dual low dropout ± 15V regulator with 30mA output capability. These mirror image circuits function similarly to the one shown in Figure 11.
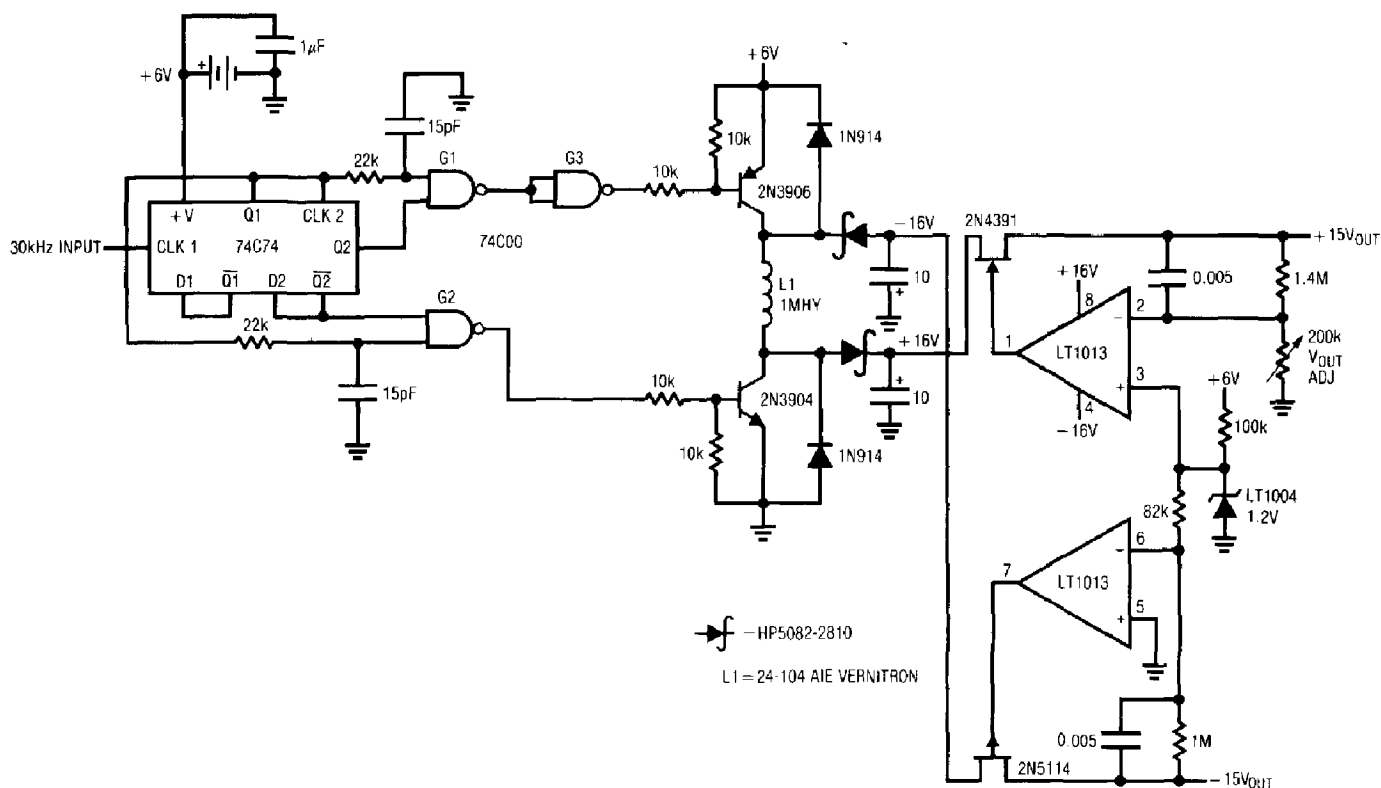

Figure 22. Single Inductor, Dual Polarity Regulator

A = 5V/DIV
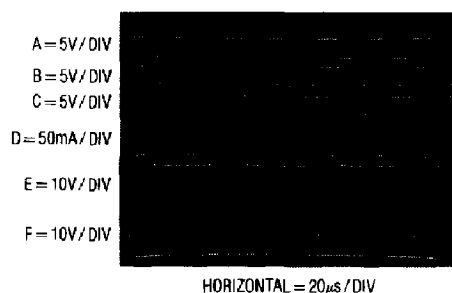B = 5V/DIV
C = 5V/DIV
D = 50mA/DIV
E = 10V/DIV
F = 10V/DIV

HORIZONTAL = 20µs/DIV

Figure 23. Figure 22's Waveforms