Edited by Bill Travis

Build a transformerless 12V-to-180V dc/dc converter

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Some transducers for portable or automotive applications need accurately regulated, high-voltage bias and draw little current. To produce such high voltages from a low battery voltage, designers typically use switch-mode dc/dc converters—generally, flyback converters. These converters exhibit high efficiency at medium or high output power. However, for the low output power for biasing some transducers, the fixed amount of power the power-switch driver and the regulator circuitry require can have a detrimental effect on efficiency. Furthermore, the associated transformer is rarely available off the shelf, so it requires a custom-design effort. This effort can account for 70% of the entire design time.

The circuit in **Figure 1** overcomes the transformer-related problem, thanks to a transformerless, switched-capacitor topology that requires only off-the-shelf components. You can describe the operating principles of the circuit by first considering the behavior of a single switched-capacitor cell and then extending the concept to an N-cell voltage multiplier. **Figure 2** represents the equivalent circuit of the first switched-capacitor cell.

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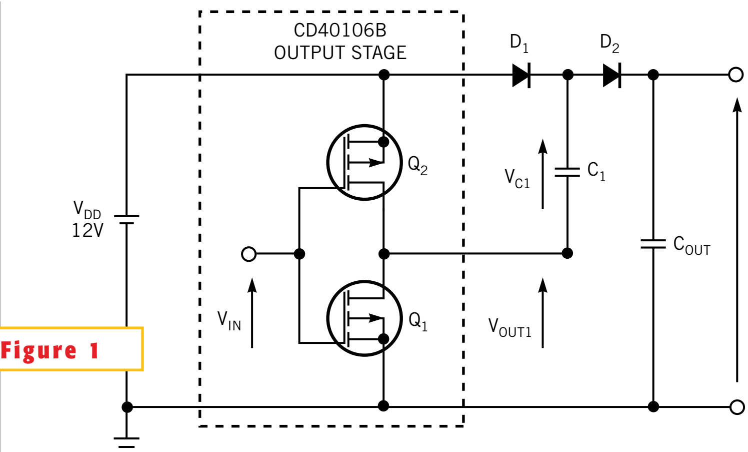
Figure 1



This four-IC circuit uses no transformers and converts 12V to 180V, using off-the-shelf components.

The two complementary MOSFETs, Q_1 and Q_2, mounted in a push-pull configuration, represent the output stage of one CD40106 Schmitt-trigger inverter. The input signal, V_{IN}, drives the push-pull stage, producing a 0 to 12V square wave at 150 kHz. If you assume that V_{IN} is 12V during the first half-period, then Q_1 is on, and Q_2 is off. Consequently, D_1 is forward-biased, and C_1 charges positively to $V_{C1}=V_{DD}-V_D$, where V_D is D_1's forward-voltage drop (0.7V). Meanwhile, D_2 is forward-biased, and C_{OUT} charges to $V_{OUT}=V_{DD}-2V_D$. During the second half-period, the states reverse: V_{IN} is 0V, Q_1 is off, and Q_2 is on, thus connecting the negative terminal of C_1 to the supply voltage. This action forces the positive terminal of C_1 to elevate itself to a voltage higher than the supply voltage, V_{DD}. D_1 now becomes reverse-biased and allows C_2 to charge up again through D_2. If you assume that C_{OUT}'s value is considerably lower than the value of C_1, then you can calculate that V_{OUT} attains the value $V_{OUT}=V_{OUT1}+V_{C1}=2(V_{DD}-V_D)$. Thus, assuming $V_{DD}>>V_D$, you can see that the circuit in **Figure 2** acts as a voltage-doubler cell.

If you cascade N voltage-doubler cells in the chainlike structure of **Figure 1**, an extension of the voltage-doubler principle yields $V_{OUT}=(N+1)(V_{DD}-V_D)$. From this equation, you can determine the number, N, of inverters you need to produce a given high output voltage:

$$N=\frac{V_{OUT}}{V_{DD}-V_D}-1.$$

To produce 180V output voltage from a 12V lead-acid battery, which can fluctuate from 11 to 13.5V, an application of the equation with worst-case V_{DD} of 11V yields

$$N=\frac{180}{11-0.7}-1=17.47\approx 18.$$

So, your design requires three CD40106 hex Schmitt-trigger inverters, as **Figure 1** shows. An inspection of the equation $V_{OUT}=(N+1)(V_{DD}-V_D)$ reveals that the 11 to 13.5V fluctuation of the lead-acid battery produces a proportional 195 to 243V output-voltage fluc-

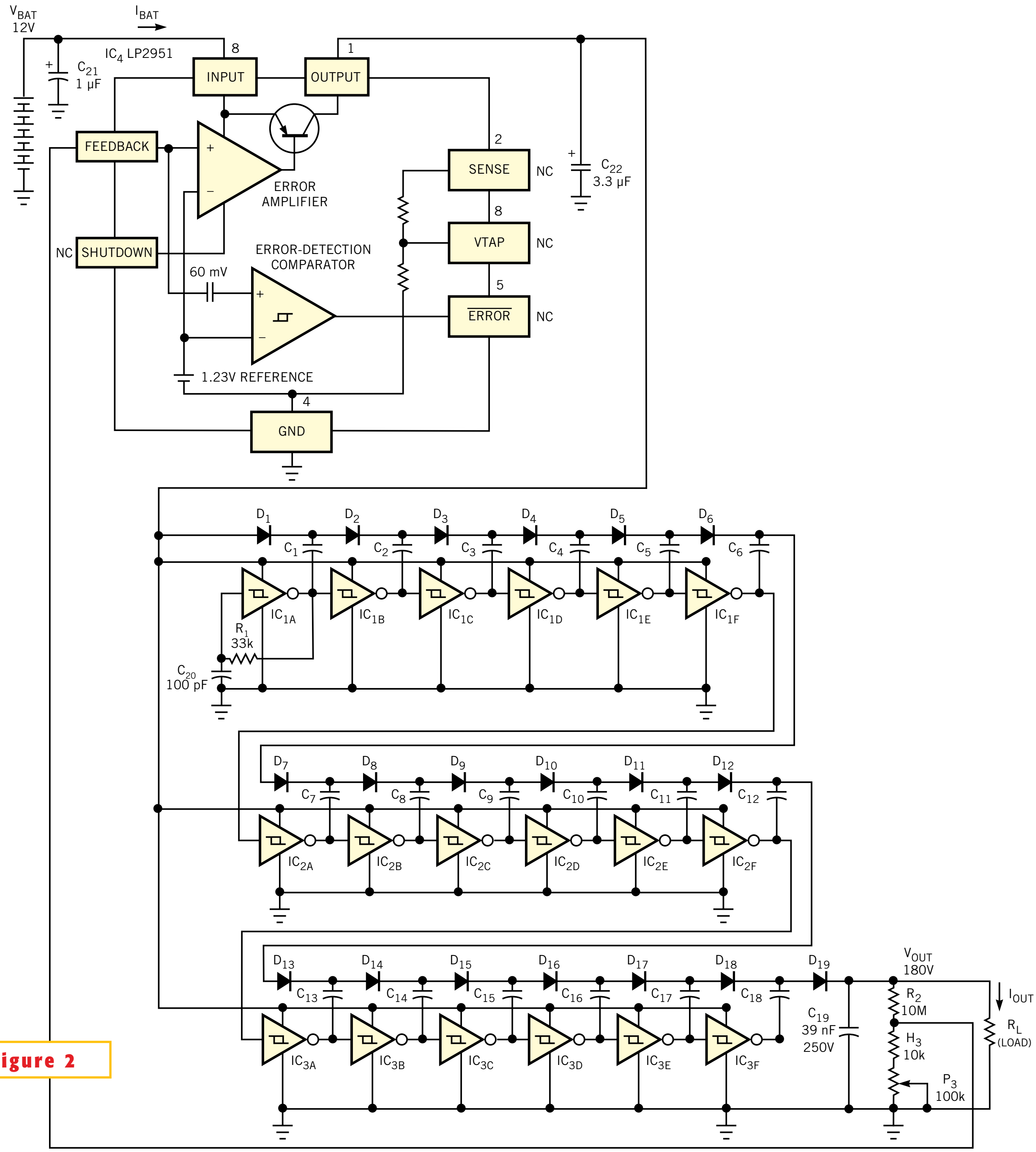


Figure 2

NOTES:
C_1 TO C_{18}: 33 TO 100 nF (63V).
D_1 TO D_{19}: 1N4148 OR EQUIVALENT.
IC_1 TO IC_3: CD 40106B.
IC_4: LP2951 (NATIONAL SEMICONDUCTOR).

This circuit illustrates the operating principle of the basic voltage-doubler cell.

tuation. This variation is unacceptable for biasing applications requiring accuracy. The obvious solution to this problem is to regulate the output voltage, V_{OUT}. You could use either of two regulation techniques: Connect a high-voltage regulator directly to the output terminal, V_{OUT}, or control the low-supply voltage, V_{DD}, of the CMOS inverters to indirectly regulate the output voltage, V_{OUT}. Because of the high cost and low efficiency of linear high-voltage regulators, the circuit in **Figure 1** uses the second regulation technique.

The key element of the feedback loop

is the low-cost, low-dropout regulator, IC_4, the LP2951 from National Semiconductor (www.national.com). The output of this regulator produces the variable-supply voltage, V_{DD}, to the 16 Schmitt-trigger inverters (IC_1 to IC_3). With this arrangement, IC_4 has to deal with input voltages ranging from only 11 to 13.5V. The output voltage, V_{OUT}, feeds back to IC_4's error amplifier via the resistive divider, R_2, R_3, and P_3. IC_{1A}, the first multiplier cell, produces the square waveform that the 18-cell, switched-capacitor voltage multiplier needs. Using the feedback network (R_1, C_1), this Schmitt-trigger inverter constitutes a free-running oscillator that produces a 150-kHz square waveform at its output. **Tables 1** and **2** show the measured electrical characteristics of the regulated 12-to-180V dc/dc converter. The input-regulation characteristic in **Table 1** proves that the output voltage does not fluctuate significantly for battery voltages ranging from 11 to 14V. From the output-regulation characteristic in **Table 2**, you can see that the overall power efficiency attains 61%, the maximum output current reaches 1 mA, and the peak-to-peak output ripple voltage does not exceed 0.2V.□

TABLE 1—INPUT REGULATION AT I_{OUT}=20 μA

V_{BAT} (V)	V_{OUT} (V)
11	180.3
12	180.3
13	180.3
14	180.3

TABLE 2—OUTPUT REGULATION AND EFFICIENCY AT V_{BAT}=12V

I_{OUT} (mA)	V_{OUT} (V)	Ripple p-p (V)	I_{BAT} (mA)	Efficiency (%)
0	180.3	0.08	3.4	NA
200	180.6	0.1	7.6	40
400	180.7	0.1	11.7	52
800	180.2	0.15	19.8	61
1000	179	0.2	25	60

Build a simple one-chip phototimer

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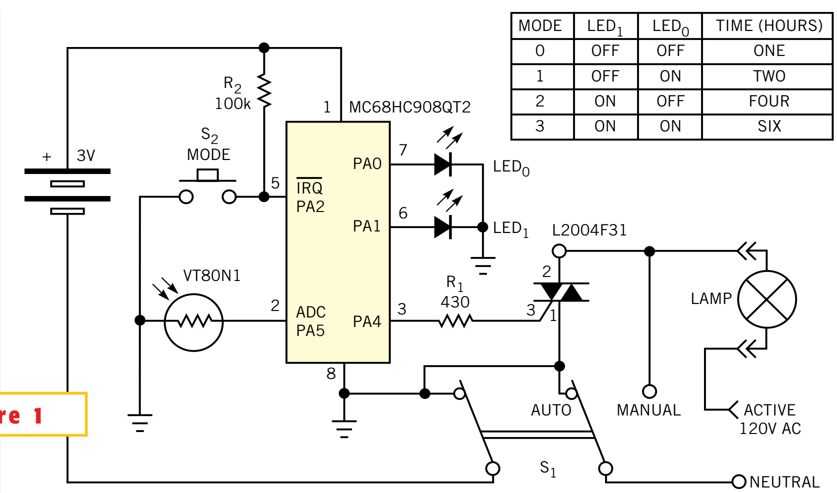
Recently, I needed to automatically switch on a lamp when it became dark and keep it on for a given time. Trying not to reinvent the wheel, I looked through what was available on the market, but I could not find an inexpensive device that satisfied the requirement. Some products worked like a photoswitch, lighting a lamp when it becomes dark and keeping it on while it is dark—in other words, the whole night. Others were designed as timers to turn a load on and off at a given time and had no correlation with darkness. These devices had more functions than I needed, and they were rather expensive. As a result, I had to design the phototimer from scratch, and it turned out to be simple and inexpensive. The phototimer (**Figure 1**) is based on the low-end, eight-pin flash microcontroller MC68HC908QT2 from Motorola (www.motorola.com).

When switch S_1 is in the Manual position, the microcontroller disconnects from the battery, and the lamp immediately switches on. When this switch is in the Auto position, the microcontroller waits until it becomes dark and, after that, switches the lamp on for a predetermined time that the designer chooses. This project has time settings for one hour and two, four, and six hours. During initialization, the timer sets the one-hour delay as the default. You set the other delays by the pushbutton mode, switch S_2. LED_0 and LED_1 indicate the prevailing mode. After the delay time, the microcontroller switches the lamp off and waits for the next night to automatically repeat the process.

An advantage of the MC68HC908QT2 is that it generates the time delay with its internal oscillator (12.8 MHz with 5% tolerance), meaning that you need not use RC timing circuitry and struggle with component tolerances. I took some additional steps to simplify the design. The microcontroller's PA5 input has an internal, 30-kΩ pullup resistor, so there is no need for an external resistor for the photocell. The LTL-4231T-R1 LEDs from LiteOn (www.liteon.com) come with built-in in resistors. You could also eliminate resistor R_2, but, in this case, Mode1 would be the start-up default mode. The Teccor (www.teccor.com) L2004F31 logic triac needs 3-mA gate current from the microcontroller, and it can deliver 4A load current. **Listing 1** is the C program for controlling the phototimer. You can download the routine from the Web version of this Design Idea at www.edn.com.

You can also modify the timer. You can easily add time-delay modes making software changes plus adding indicating LEDs; available microcontroller pins lim-

Figure 1



MODE	LED_1	LED_0	TIME (HOURS)
0	OFF	OFF	ONE
1	OFF	ON	TWO
2	ON	OFF	FOUR
3	ON	ON	SIX

This simple phototimer allows you to program the switch-on time after darkness falls.

it the number of LEDs you can add. For more advanced projects, you can even use a seven-segment display, either directly or via a decoder, for time indication. You can eliminate the Auto/Manual switch by modifying Mode 0, for, example, as a continuous mode to light the lamp just after power-up, without waiting for night. You can use any type of microcontroller in the project. For example, using the 16-pin microcontroller MC68HC908QY2 from the same Motorola family allows you to increase the number of bidirectional I/O lines to 13. Also, instead of the photocell, you could use a different kind of sensor— temperature, pressure, or motion, for example—to activate the time delay.□

Solenoid trip circuit works at battery's end of life

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This Design Idea involves a low-power motion-detector circuit that operates from battery power for extended times. Part of the design includes a solenoid-operated trip mechanism that triggers whenever it detects motion. The drive circuit for the solenoid in the original design worked fine as long as the battery was fresh but failed as the battery got into the middle of its life, even though sufficient energy remained in the battery to operate the solenoid. The culprit was the battery's internal resistance. The internal resistance of a standard alkaline cell increases as the cell's life accumulates, whereas the cell's open-circuit voltage hardly changes. This increased resistance causes a sharp drop in supply voltage whenever the drive circuit attempts to energize the solenoid. This drop upsets the drive circuit, preventing reliable operation.

The original design solved this problem by using a large electrolytic capacitor across the battery supply. This capacitor functioned as an energy reservoir and prevented the supply voltage from sagging so dramatically, allowing the device to continue functioning much further into the battery's life. However, the electrolytic was bulky and expensive, and presented an awkward packaging problem.

The circuit in **Figure1** solves the problem by incorporating feedback in such a way that any drop in supply voltage only turns on the drive circuit harder. In testing, this circuit functioned even when the nominally 6V battery sags as low as 2V. Q_1 is a 3A, high-beta, low-saturation-voltage pnp transistor that drives the solenoid. To energize the solenoid, Q_1 has to turn on hard to minimize voltage drop and get the most from the battery's life. The circuit achieves the full turn-on by using three sections of an LP339 quad comparator in parallel. The LP339 is similar to the venerable LM339 but with lower power consumption, making it more suitable for battery-powered applications. Interestingly enough, it also has higher output drive. The three parallel devices provide approximately 200 mA to the base of Q_1, sufficient for Q_1 to supply 2A to the solenoid and remain well-saturated. The design requires no current-limiting resistor in series with the base of Q_1 because the outputs of the LP339 are naturally current-limited to approximately 60 or 70 mA each.

Once the trip mechanism triggers, S_1 opens, removing all power from the circuit. The device remains in this state until you manually reset the trip mechanism. An entire trip event takes only about 10 msec, thus conserving the battery and preventing excessive power dissipation in Q_1 and the LP339. The remaining section of the LP339 implements a single-section window comparator. A window comparator is necessary because motion detectors are commonly ac-coupled circuits. You must apply the detection threshold equally to positive or negative excursions. In other words, any excursion outside the window should trigger detection. In a quiescent state with no input signal, the network comprising R_3, R_5, and dual-diode D_2

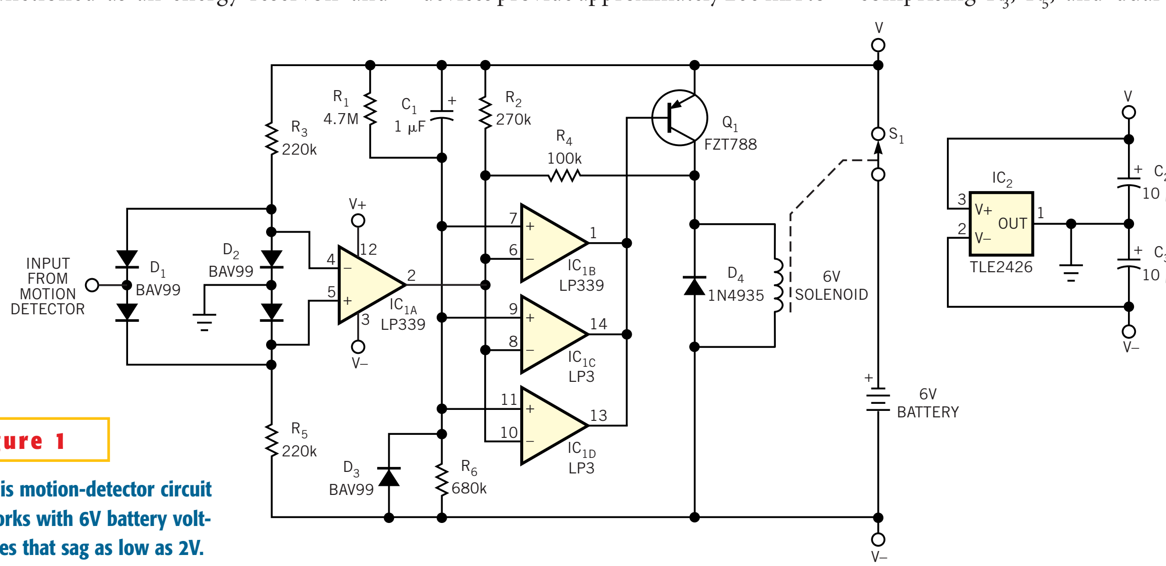

Figure 1

This motion-detector circuit works with 6V battery voltages that sag as low as 2V.

keeps the negative input of IC_{1A} one diode drop above ground and the positive input one diode drop below ground. This level keeps IC_{1A}'s output and, hence, the negative inputs of IC_{1B}, IC_{1C}, and IC_{1D}, low. Because R_1 and R_6 bias the positive input of IC_{1B}, IC_{1C}, and IC_{1D} at approximately 0.75V, the comparators' outputs remain off.

The circuit trips if the input goes more than two diode drops above or below ground. For example, if the circuit's input goes below ground, the negative input of IC_{1A} pulls down until it is lower than the positive input. If the input goes up, the positive input of IC_{1A} pulls up until it is higher than the negative input. Either case results in the output of IC_{1A}'s going high. This action in turn causes the IC_{1B}, IC_{1C}, and IC_{1D} outputs to turn on, turning on Q_1 and energizing the solenoid. R_4 provides positive feedback. If Q_1 even starts to turn on, the partial turn-on causes IC_{1B}, IC_{1C}, and IC_{1D} to turn on more, precipitating a latch-up to ensure that Q_1 turns on all the way. Thus, all possible battery energy is delivered to the solenoid. C_1 provides further positive feedback when the supply sags. D_3 protects the LP339's inputs from being driven more than a diode drop below ground when the power-supply sag is severe.

A beneficial side effect of the time constant formed by C_1 and R_6 is to prevent false triggers on start-up by holding off the IC_{1B}, IC_{1C}, and IC_{1D} stage until the motion detector has had time to stabilize. IC_2 is a "ground-generator" chip, used to create a circuit ground midway between the supply rails. In contrast to the original circuit, everything in this circuit is going in the proper direction to ensure positive actuation of the solenoid once it reaches a trip threshold. The circuit uses only common, low-cost, and small components. The circuit offers full usage of battery life and needs no bulky energy-reservoir capacitor.□

Servo loop improves linear-regulator efficiency

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Linear regulators are easy to implement and have better noise and drift characteristics than switching approaches. Their largest disadvantage is inefficiency: excess energy dissipated as heat. Several well-known techniques are available to minimize the input-to-output voltage across a linear regulator. I had been looking for an inexpensive, easy-to-implement, and efficient preregulator to reduce the dropout voltage of a linear regulator. Closed-loop, self-oscillating preregulators built around a switching transistor, a comparator, and a filter are difficult to predict in terms of frequency. Thus, the power-mains input filter is also difficult to implement. The best option is a fixed-frequency preregulator combined with a linear, low-dropout regulator. The arrangement shown in **Figure 1** fulfills all the requirements. The LM2576T-ADJ, IC_1, switcher uses a 52-kHz fixed frequency. The LT1085, IC_2, is a good choice for the linear regulator. The preregulator feedback loop uses an operational amplifier, IC_3.

When the servo loop is closed, the feedback voltage for IC_1 is:

$$V_{FB} = V_A \frac{R_3}{R_3+R_4}\left[1+\frac{R_5}{R_6}\right] - V_{OUT}\frac{R_5}{R_6}. \quad (1)$$

If $R_3=R_5$ and $R_4=R_6=kR_3$, **Equation 1** becomes:

$$V_{FB} = V_A \frac{R_3}{R_3+kR_3}\left[1+\frac{R_3}{kR_3}\right] - V_{OUT}\frac{R_3}{kR_3} = \frac{V_A - V_{OUT}}{k}. \quad (2)$$

Equation 2 yields the relationship $V_A - V_{OUT} = V_{DROPOUT} = kV_{FB}$. You can set the dropout voltage according to the linear-regulator requirements. If you select an LT1085, maximum $V_{DROPOUT}$ is 1.5V; for the LM2576T, $V_{FB}=1.23V$ and if $k=1.5$, $V_{DROPOUT}=1.89V$, slightly higher than the value in the data sheet. The dropout voltage is the same regardless of the output voltage and thus ensures reasonable efficiency. (The overall efficiency is greater than 56% for $V_{OUT}=5V$ at 3A and at least 72% for $V_{OUT}=30V$ at 3A.) The output voltage, V_{OUT}, ranges from 0 to 30V, and V_{IN} must be at least 5V greater than the maximum V_{OUT}. IC_3 has no special requirements, and IC_2 may be any kind of linear regulator. C_6 reduces the output ripple, and C_2 filters some of the 52-kHz noise on the control line coming from IC_3. The result is a simple, robust, and high-performance laboratory power supply that can supply 3A in a 0 to 30V output-voltage range, using only a small heat sink.□

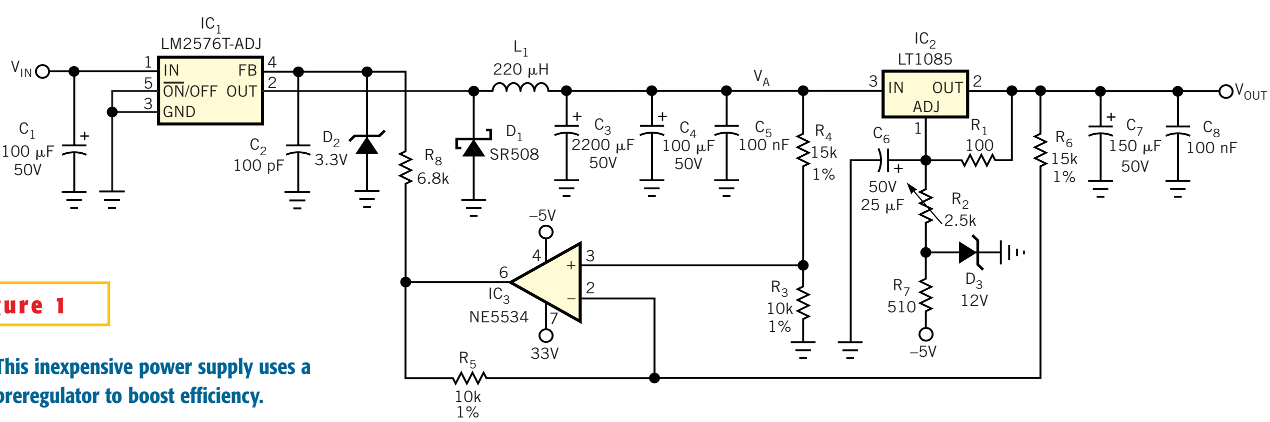

Figure 1

This inexpensive power supply uses a preregulator to boost efficiency.

Boole helps simplify wiring and save money

Jean-Bernard Guiot, Mulhouse, France

To safely observe the positions of two cylinders, you need two signals: one circuit, X, which is open only when both cylinders are in a safe position (two normally closed switches in parallel), and one circuit, Y, which is closed only when both cylinders are in a safe position (two normally open switches in series, **Figure 1**).

This redundancy enables the detection of errors, such as a short circuit within a cable. The Boolean-logic equations of these two circuits are $X=\overline{A}+\overline{B}$, and $Y=A \bullet B$. The problem is that most small limit switches are SPDT (single-pole, double-throw) switches, with which you cannot configure the circuit of **Figure 1**. Using Boolean arithmetic, you can derive $X=\overline{A}+\overline{B}=\overline{A}+A\overline{B}$, which corresponds to the schematic in **Figure 2**. You can easily make a circuit equivalent to that of **Figure 2** using two ordinary SPDT limit switches (**Figure 3**).□

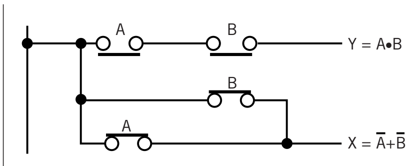

Figure 1 This circuit offers redundancy in machine-control applications.

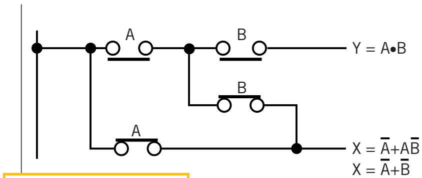

Figure 2 Boolean arithmetic proves that this circuit is equivalent to that of Figure 1.

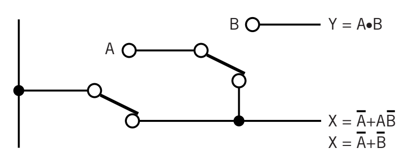

Figure 3 Further simplification yields this circuit, which uses only two SPDT switches.