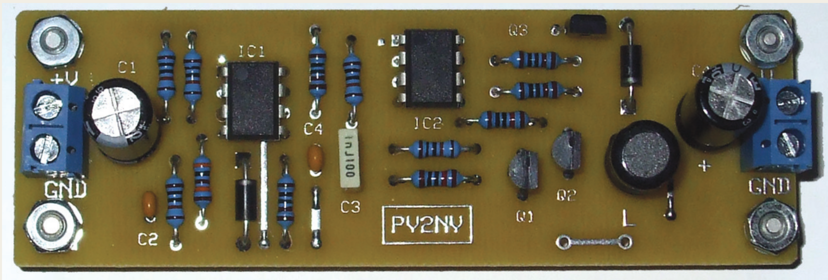
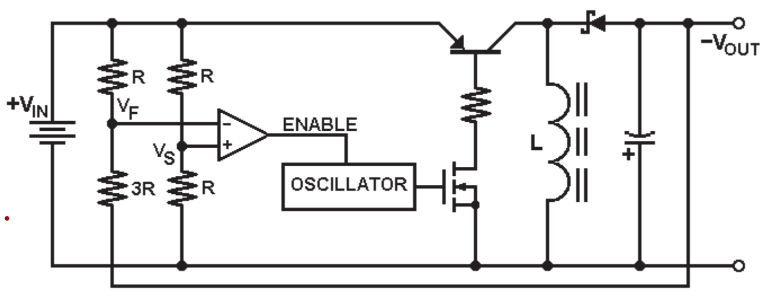
By Jim Stewart

BUILD AN INVERTING DC-DC CONVERTER

It's often the case that you need +V and -V when all you have is +V. For example, you need +12V and -12V, but all that's available is +12V. It would be really handy to have a "black box" that would give you -V out when you put +V in, and work over a range of voltages without adjustment. In this project, we will build just such a thing. It's a voltage mirror that can supply over 100 mA without a significant drop in voltage. The circuit uses a switched inductor as described in the sidebar.



How It Works



■ **FIGURE 1.**

Figure 1 shows a block diagram of the circuit. A square wave oscillator drives a MOSFET that, in turn, drives a PNP switching transistor. The oscillator is enabled/disabled by the output of the comparator. A comparator is just an op-amp that compares a set point voltage (V_S) to a feedback voltage (V_F). Depending on which voltage is higher, the comparator's output goes either high (+V) or low (ground).

When V_{OUT} is the correct voltage, V_S) exceeds V_F by a few micro volts and the oscillator is disabled. The PNP switch is off. When V_S) is less than V_F, the oscillator is enabled and the PNP transistor switches on and off.

V_S) is half the input voltage (V_S) = V/2) as set by the R-R voltage divider. V_F is set by the R-3R divider, and becomes V/2 when the output voltage equals -V. The diode blocks the +V from the output while charging the inductor. It then provides a current path for the discharging inductor to transfer charge to the output capacitor.

Because the diode turns on and off to control the inductor current, it's called a *commutating* diode. Commutating is an old term, often used with DC motors. It means to switch current from one path to another.

This type of circuit is often referred to as a *buck-boost* DC-to-DC converter. The term *buck* refers to the inductor opposing current through it while it charges. The term *boost* refers to the ability of the inductor to increase output voltage when it discharges. In this case, we have an *inverting* converter since a positive input voltage produces a negative output voltage.

The oscillator causes the PNP transistor switch to open and close at a fixed frequency. When the switch closes (transistor ON), the inductor charges up. When the switch opens (transistor OFF), current from the inductor charges up the voltage on the capacitor.

The switching continues until the voltage on the capacitor becomes V_{OUT} = -V_{IN}. At that point, the comparator disables the oscillator and the PNP stays OFF. When voltage across the capacitor drops, the comparator enables the oscillator and the inductor is pumped up again.

The Circuit

Figure 2 shows the schematic. IC1 and IC2 are CMOS op-amps. IC1 is the comparator. IC2 forms a square wave oscillator with frequency given by $f = 1/2.2(R7 \times C3)$. IC2 drives Q2 through R10. IC1 controls the gate of Q1. When Q1 is off, the square wave is applied to the gate of Q2, which toggles Q3 on and off to pump up the inductor.

When Q1 is on, the gate of Q2 is grounded and Q3 stays off. Since there's a single input voltage, each op-amp uses a resistor divider to "split the rail" to create a signal ground.

That allows the negative input to see plus and minus voltages with respect to the positive input. C2 and C4 bypass the signal grounds to the supply voltage ground.

C1 and C5 are low ESR (Equivalent Series Resistance) aluminum electrolytic capacitors. Tantalum capacitors might be a bit better, but are more expensive.

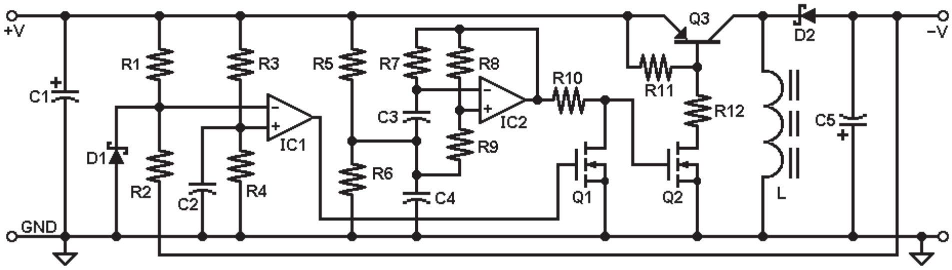
ESR is a measure of how much power the capacitor will dissipate. $P_{DISS} = I^2_{RC} \times ESR$, where I_{RC} is the AC "ripple current" in the capacitor. The capacitors chosen are rated for a maximum ripple current of 840 mA.

D1 and D2 are Schottky diodes. Schottky diodes can go from conducting to non-conducting very quickly, allowing a high switching frequency. They also have a low voltage drop when conducting.

In a switched inductor circuit, much of the power loss can be due to the voltage drop across the commutating diode. D1 is there in case the feedback fails and V_{OUT} becomes too negative.

Q3 is a ZTX550 PNP transistor, chosen because its specifications suit this application well:

- Maximum power dissipation: P_{MAX} = 1 watt @ 25 °C
- Maximum continuous collector current: I_C = one amp
- Maximum collector-base voltage: V_{CBO} = 60 volts
- Maximum saturation voltage: V_{CE} = 0.25 volts @ I_C = 150 mA
- Transition frequency: f_T = 150 MHz minimum
- Package: E -Line (slightly smaller than TO-92)



■ FIGURE 2.

SWITCHED INDUCTORS

Like capacitors, inductors can be charged up. **Figure S1** shows a DC voltage applied to an inductor via a switch. Current (I_{IN}) will increase according to $I = (V/L) \times \Delta t$ where Δt is the length of time the inductor is charging. At maximum current (I_M), the inductor stores energy (W) given by $W = (L\, I^2_M)/2$. The energy is stored in the magnetic field around the inductor.

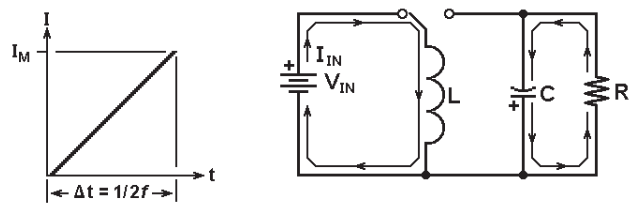


FIGURE S1. Charging an inductor.

Current In Inductor

When the switch is moved from battery to load, the inductor discharges as shown in **Figure S2**.

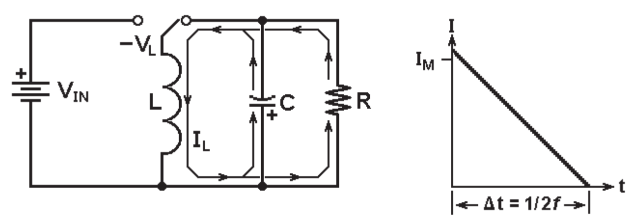


FIGURE S2. Discharging an inductor.

Four important things then happen:

First, the *magnitude* of the inductor current (I_L) just *after* the switch is moved to the load is equal to the current (I_M) just *before* the switch is moved. That's because energy is conserved.

Second, the *direction* of current just after the switch is moved is the same as the direction just before the switch is moved. Again, it's conservation of energy.

Third is the key point: To keep the current I_L flowing in the same direction, the voltage across the inductor will *switch polarity* as the discharging inductor acts like a generator.

Fourth, the voltage across it will become whatever value is necessary to keep the current flowing until all the energy is transferred to the capacitor or dissipated in the load resistance.

PARAMETERS

How are L, f, and R_{LOAD} related to each other in this circuit? We start with the requirement that the input power (P_{IN}) be greater than the output power (P_{OUT}). It's *greater than* instead of *equal to* because efficiency is not 100%; some power is lost. So, we need to find expressions for P_{IN} and P_{OUT}. We then let $P_{IN} > P_{OUT}$ and see what we get. We do it for one oscillator cycle.

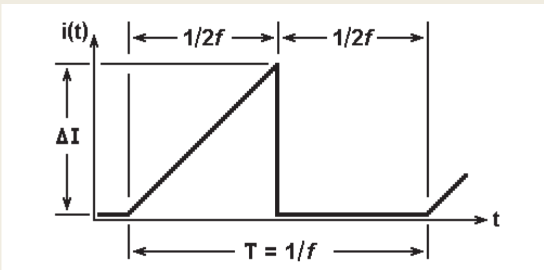


FIGURE P1. I vs. t for one cycle.

Step 1: Find P_{OUT}
For the entire cycle ($T = 1/f$), we have
Equation 1: $P_{OUT} = V^2_{OUT} / R_{LOAD}$

Step 2: Find P_{IN}
$P_{IN} = V_{IN} \times I_{IN}$ where $I_{IN} = I_{DC}$ = average current (I_{AVG}) during the entire cycle
For the first half-cycle, $I_{AVG} = \Delta I/2$ while for second half-cycle $I_{AVG} = 0$
So, for the entire cycle $I_{AVG} = (\Delta I/2 + 0) \div 2 = DI/4$
In a charging inductor, $V = L \times (\Delta I/\Delta t)$, so $\Delta I = (V_{IN} / L) \times \Delta t$
The inductor charges during $\Delta t = T/2 = 1/2f$
So, $\Delta I = V_{IN} / 2fL$
And for the entire cycle $I_{AVG} = \Delta I/4 = V_{IN} / 8fL$
So, $P_{IN} = V_{IN} \times I_{AVG} = V_{IN} \times (V_{IN} / 8fL)$ to give
Equation 2: $P_{IN} = V^2_{IN} / 8fL$

Step 3: Let $P_{IN} > P_{OUT}$ and solve
$P_{IN} > P_{OUT}$ gives $V^2_{IN} / 8fL > V^2_{OUT} / R_{LOAD}$
Invert both sides to get $1/P_{IN} < 1/P_{OUT}$
So, $8fL / V^2_{IN} < R_{LOAD} / V^2_{OUT}$
Re-arrange terms to get $8fL < (V_{IN} / V_{OUT})^2 \times R_{LOAD}$ which gives
Equation 3: $fL < (V_{IN} / V_{OUT})^2 \times (R_{LOAD} / 8)$

And if, $V_{OUT} = V_{IN}$ we get
Equation 4: $fL < R_{LOAD} / 8$

Design Parameters

This design has five important parameters:

- Input voltage: V_{IN}
- Output voltage: V_{OUT}
- Load resistance: R_{LOAD}
- Oscillation frequency: f
- Inductance value: L

The parameters are related to each other by the equation:

f L < $(V_{IN} / V_{OUT})2 \times (R_{LOAD} / 8)$

(To see where the equation comes from, see the **sidebar**.)

We want the magnitudes of V_{IN} and V_{OUT} to be equal, so the equation becomes:

f L < $(R_{LOAD} / 8)$

For our circuit, L = 220 mH, f = 45 kHz, and R_{LOAD} = 100 Ω. To see if those values work, we need to verify that f L is less than R_{LOAD} / 8.

$f L = (45 \times 10^3) \times (220 \times 10^{-6}) = 9900 \times 10^{-3} = 9.9\ \Omega$

$R_{LOAD} / 8 = 100/8 = 12.5\ \Omega$

Since 9.9 is less than 12.5, the circuit should work. Note that increasing the load resistor makes f L even less than R_{LOAD} / 8.

Note: The above calculation just lets us verify that the values we use are in the ballpark. It's not an exact description.

I replaced the 220 µH inductor with one that was 330 µH and it worked just fine. Also, the value of an inductor usually drops as the DC current through it increases.

Performance

1. Mirror Effect: A 1 kΩ load was connected to the output and V_{OUT} was measured for various values of V_{IN}. The results are shown in **Table 1**. Note that the differences are more or less constant. That means the circuit has a fixed offset of about 0.11 volts. That could be "zeroed out" by adjusting R1 or R2.

2. Efficiency (η): V_{IN} was set to +12V and a 110 Ω load was connected to the output. Input current was measured to obtain input power $P_{IN} = V_{IN} \times I_{IN}$. Output power was V^2_{OUT} / 110 Ω. The result was:

I_{IN} = 150 mA
P_{IN} = 12V x 150 mA = 1.80 watts
$P_{OUT} = (11.86\ V)^2$ / 110 Ω = 1.28 watts

$\eta = (P_{OUT} / P_{IN}) \times 100\%$ = (1.28W / 1.80W) x 100% = 71.1% efficiency

3. Load Regulation: With 12 volts in, V_{OUT} was 11.87 volts with a 1 kΩ load and 11.86 volts with a 110 Ω load. That gives a load regulation of:

LOAD-REG = [(11.87 - 11.86) / 11.87] x 100 % = 0.08%

A load regulation of 0.08% is not bad for such a simple circuit.

4. Ripple Voltage: With V_{IN} = 12 volts and a 110 Ω load on the output, ripple voltage was 50 mV_{PP} as measured with an oscilloscope.

V_{IN}	V_{OUT}	Difference
6.0V	- 5.90V	0.10V
7.0V	- 6.89V	0.11V
8.0V	- 7.89V	0.11V
9.0V	- 8.89V	0.11V
10.0V	- 9.88V	0.12V
12.0V	- 11.87V	0.13V
12.0V	- 11.86V across 110 Ω	0.14V
15.0V	- 14.86V	0.14V

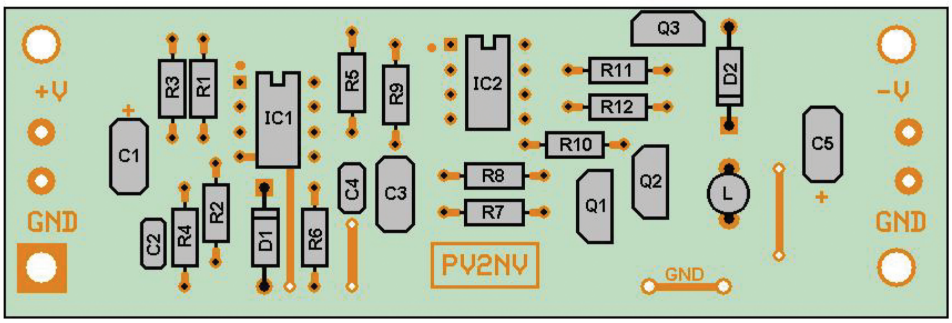
Table 1: V_{OUT} vs. V_{IN}

Construction

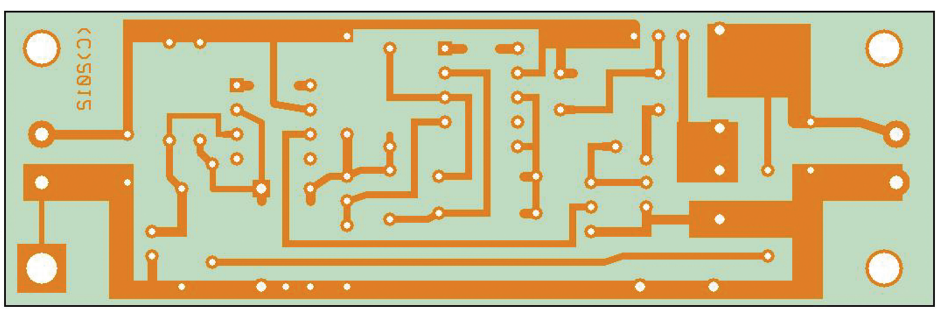
The printed circuit board (PV2NV) component layout is shown in **Figure 3**. The optional terminal blocks are not shown. The solder side is shown in **Figure 4**. An ExpressPCB file (PV2NV.PCB) is available at the article link.

There is a mounting hole at each corner of the board that's big enough for a #4 screw. The mounting hole with the square outline is connected to circuit ground by a thin strip of copper, so mounting the board to a metal chassis will connect ground to the chassis. If that's not desirable, you can cut the strip.

Board dimensions are 3.8 inches by 1.25 inches.



■ **FIGURE 3.**



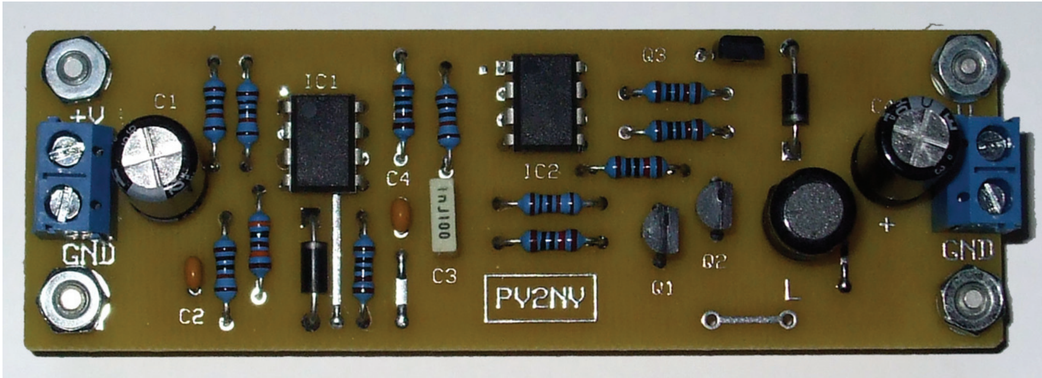
■ **FIGURE 4.**

A set of parts is available from the *Nuts & Volts* Webstore at **http://store.nutsvolts.com**.

Procedure

If you have a lead forming tool (**Figure 5**), bend the resistor and diode leads to a 0.4 inch spacing. Such tools (Electronix Express part #0664ST010; Jameco part #106884) are inexpensive and handy to have. (When inserting components into the board, bend the leads slightly on the solder side to secure them in place.)

■ **FIGURE 5.**



■ **FIGURE 6.**

Here is a suggested sequence for mounting the components:

- Insert R3, R1, R5, R9, and solder. Clip off excess leads.
- Insert R4, R2, R6, and solder. Clip off excess leads.
- Insert R11, R12, R10, R8, R7, and solder. Clip off excess leads.
- Insert D1, D2, Q1, Q2, Q3, and solder. Clip off excess leads.
- Insert IC1 then IC2. Verify pin 1 is in the proper hole and then solder.
- Insert the inductor and capacitors. Note polarity of C1 and C5. Solder and clip off excess leads.
- If using terminal blocks (optional), mount and solder them.
- Clean off the solder side with some rubbing alcohol and a scrub brush. Give the assembled board a good visual inspection and fix any problems you find.

Assembly is now complete. A photograph of the assembled board is shown in **Figure 6**.

PARTS LIST

ITEM	DESCRIPTION
R1:	100 kΩ, 1/4W, 1%
R2:	301 kΩ, 1/4W, 1%
R3:	100 kΩ, 1/4W, 1%
R4:	100 kΩ, 1/4W, 1%
R5:	1 kΩ, 1/4W, 1%
R6:	1 kΩ, 1/4W, 1%
R7:	10 kΩ, 1/4W, 1%
R8:	100 kΩ, 1/4W, 1%
R9:	100 kΩ, 1/4W, 1%
R10:	10 kΩ, 1/4W, 1%
R11:	1 kΩ, 1/4W, 1%
R12:	1 kΩ, 1/4W, 1%
L:	220 µH Digi-Key part #811-1316-ND or equivalent
C1:	220 µF, 35V Digi-Key part #493-1578-ND or equivalent
C2:	0.1 µF, 50V, ceramic
C3:	1 nF film, 5% Digi-Key part #399-5871-ND or equivalent
C4:	0.1 µF, 50V, ceramic
C5:	220 µF, 35V Digi-Key part #493-1578-ND or equivalent
Q1:	2N7000
Q2:	2N7000
Q3:	ZTX550 PNP
D1:	Schottky, one amp, 1N5819 or equivalent
D2:	Schottky, one amp, 1N5819 or equivalent
IC1:	CA3140
IC2:	CA3140

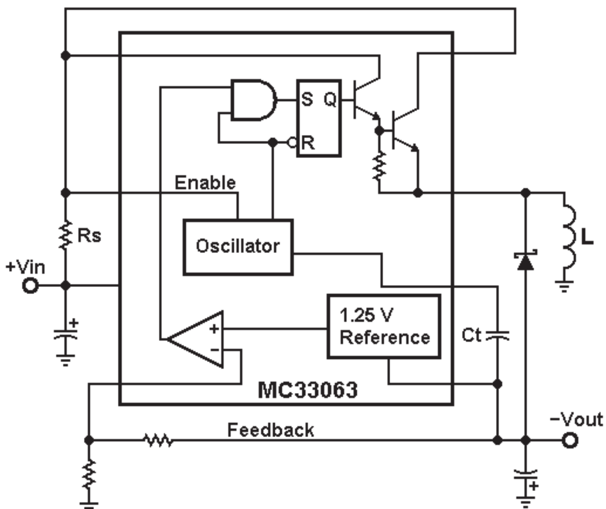
Printed Circuit Board: An ExpressPCB file called PV2NV.PCB is available for download from the article link.

Terminal Blocks (optional): Two-position, 5 mm spacing, Jameco part #2094485 or equivalent.

Testing

Now for the moment of truth: Apply V_{IN} and measure $-V_{OUT}$ with your multimeter. Verify that the magnitudes of V_{IN} and V_{OUT} are equal. If not, remove power and examine the board. Check for the usual suspects:

- Any solder bridges or bad solder joints?
- Are components in the right place?
- Are any components missing?
- Are the cathode and anode of a diode swapped?
- Are the transistors in backwards?
- Are the polarities of the electrolytic caps reversed?
- Do the ICs have pin 1 in the correct hole?



■ **FIGURE 7.**

Wrapping Up

Most buck-boost converters use pulse width modulation (PWM) to control the voltage applied to the inductor. Feedback voltage is compared to a fixed reference voltage and the pulse width is adjusted to obtain the desired output voltage. An example circuit using the MC33063 IC is shown in **Figure 7**.

Note that the output voltage of such a circuit depends only on the reference and does not change with the input voltage. For our circuit, output voltage is a mirror image of input voltage. Since I've never seen a similar circuit, I'm tempted to think there aren't any like it. That, however, is not very likely. **NV**