Sick of replacing 9V batteries? You need...

'Voltup' - a 1.5V/9V DC/DC converter

Here is a very simple yet very efficient 1.5V to 9V DC-DC converter, which allows you to drastically cut the operating costs of 9V equipment by powering it from a single 'D' size cell. You can choose from a wide variety of primary or secondary cells.

by ANDREW PIERSON

If you own a number of 9V battery operated devices, you will know that running them can be a costly business. A carbon-zinc cell can only develop an EMF of 1.5V, so a 9V battery contains six separate cells connected in series.

Due to their manufacturing costs, 9V batteries are a very expensive way to buy energy. At typical supermarket prices, a 9V No. 216 'heavy duty' battery costs about the same as a single 1.5V 'D' size alkaline cell. The alkaline cell contains much more energy, but with a potential of 1.5V the only way to make use of it was to have six cells in series – a very bulky proposition.

As it happens a much more elegant solution is possible – by using a simple 1.5V to 9V DC-DC converter with the right characteristics for the jobz

The blocking oscillator inverter is very flexible, and I have found that it is possible to develop a modified version which would operate reliably with a supply voltage of only 750mV, which is the lowest practical 'end-point' for primary cells. I have been able to achieve a peak efficiency of approximately 60%, which is a very reasonable figure when the low supply voltage is taken into account.

How much can you expect to save with Voltup? Look at the four discharge characteristic curves in Fig.1, which have each been plotted for a load resistance of 600 ohms (i.e., a starting current of 15mA at 9V). This represents the average current drain of a typical small transistor radio receiver.

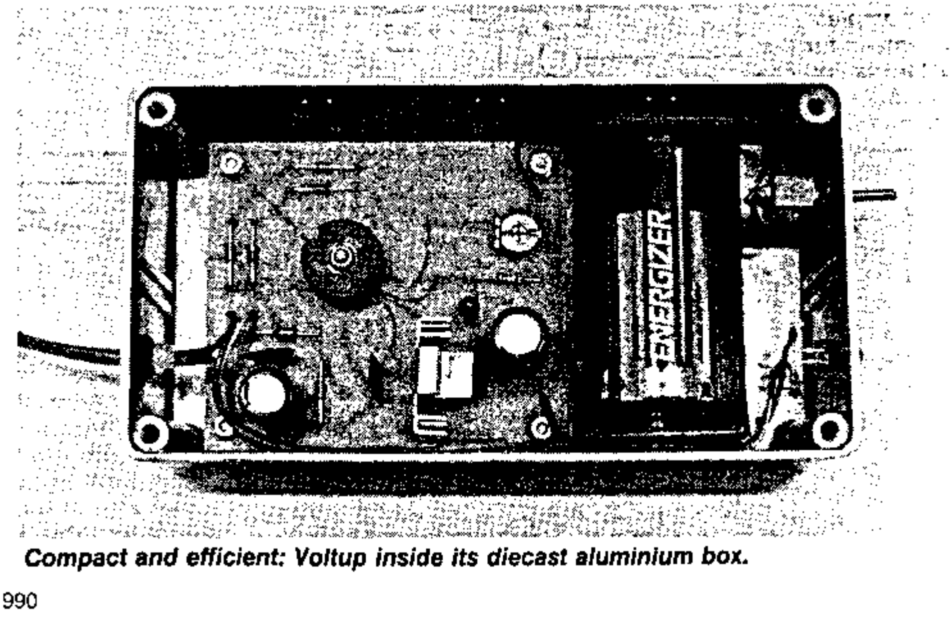
Curve A is the discharge characteristic of a fresh 9V 216-type 'heavy duty' battery, discharged through the nominated load resistance. Curves B, C and D are the discharge characteristics of fresh 1.5V 'D' size cells supplying Voltup, which is in turn driving the nominated load resistance. Curve B is for a 'general purpose' Carbon-Zinc cell; curve C is for a 'heavy duty' Carbon-Zinc cell and curve D is for an alkaline cell. Considering that the power sources for curves A and D cost approximately the same, the ratio of service hours is greater than 7:1!

The common 'heavy duty' D cell (curve C) is no slouch, either. With a typical cost of half that of a 216 battery, the effective ratio of service hours is over 6:1. And as supermarkets frequently discount the prices of D cells of all types, these savings could be much greater if you buy at the right time. Tests were carried out with bargain priced 'general purpose' cells, and they produced a saving of almost 12 times!

Note that the curves in Fig.1 are for continuous discharge. With intermittent duty, the energy yield of carbon-zinc cells will improve considerably. The temperature of the cell will also affect the overall yield, so the ambient temperature was kept constant at 25°C, +/-2°C during the 10-day period necessary to gather the data for plotting Fig.1.

Another advantage of Voltup is that the output voltage derived from an alkaline cell is consistently much higher than that of the 216 battery, at the same relative positions in their respective service periods, leading to superior performance of the device being powered. Later on, we'll discuss the choice of supply cell in greater detail.

Up to now, we have only considered the 216-type battery. However, you may have equipment which uses the 276, 276P, 2362 or 2364 batteries. Since even a brief glimpse of the price tag on one of these can pose a cardiac health risk, Voltup powered by an alkaline or rechargeable cell would seem to be an absolute necessity!



Compact and efficient: Voltup inside its diecast aluminium box.

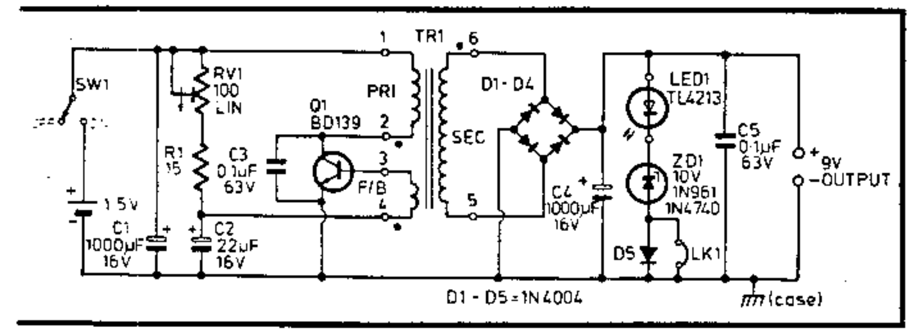


Fig.2: The circuit schematic for Voltup.

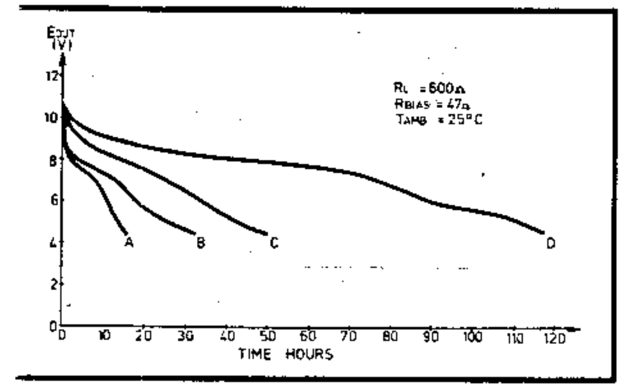


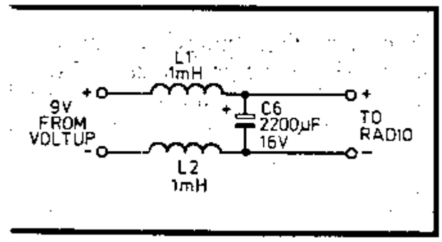
Fig.1: Comparison of the discharge characteristics of a 216-type 9V battery (A) and those obtained with Voltup and D-type 1.5V cells. B is a general purpose cell, C a heavy duty type and D an alkaline cell. As you can see, there's a healthy improvement!

Circuit description

Let us now turn to the circuit schematic (Fig.2), to see how Voltup works.

Transformer TR1, together with Q1, RV1, R1 and C2 form a power blocking oscillator. The base of Q1 is supplied with forward bias via RV1 and R1 we'll call the total resistance R_{bias}) and the feedback winding. C2 is used to partially bypass R_{bias} at the operating frequency of the oscillator.

The primary and feedback windings of TR1 are so phased that the feedback is positive, with the result that the circuit oscillates. As Q1 is alternately switched on and off, the primary of TR1 is connected across the 1.5V supply cell for the first 50% of the oscillation period, and left open-circuit during the remainder. As a result, an alternating magnetic flux is set up within the core of TR1.



This optional output filter is only required if Voltup is used with a radio.

As this flux cuts the secondary winding it induces in it an alternating voltage, which is a symmetrical square wave. This is rectified by the bridge rectifier D1-D4 and filtered by the storage capacitor C4.

A bridge rectifier configuration was chosen because it forces both the power and induction strokes of the blocking oscillator to share the same load (parallel loading), thus equalizing the power in each. By contrast, a voltage doubler configuration would place the rectified outputs from each stroke in series. This would give poorer regulation, together with varying waveform symmetry, and for these reasons it wasn't chosen.

If Voltup were to be operated in an unloaded condition and without protection, the induction stroke from the blocking oscillator would push the output voltage up to dangerous levels. LED1, ZD1 and D5 (a component that is optionally selected after testing) form a simple 'crowbar' protection circuit, which starts to conduct at about 11V, and simply draws sufficient current to stabilize the output at about 12V. The quiescent current of a typical transistor radio will normally provide sufficient load to prevent the protection circuit from operating, so the conversion efficiency will not be adversely affected.

C1 ensures that the inverter's AC supply impedance will remain low as the 1.5V supply cell is discharged. C3 is used to reduce radiated RF energy, and also to curb any tendency toward parasitic oscillation in Q1, which has a much higher transition frequency (f_T) than is required for this application. The value of C3 is not large enough to significantly degrade the oscillator's switching time, and it therefore has little effect upon the overall conversion efficiency. C5 reduces RFI by keeping the output DC supply rail impedance low at radio frequencies.

If Voltup is used to power a radio receiver, the extra components L1, L2 and C6 are required. These are fitted to the 9V output connector, and serve three important functions.

The RF chokes L1 and L2 isolate the 9V supply lead from the RF circuitry in the receiver. This reduces any tendency for the lead to pick up signal by becoming a counterpoise antenna. Also, any remaining harmonics of the oscillator's operating frequency which fall within the tuning range are prevented from reaching the receiver.

Capacitor C6, in combination with the DC resistance of L1 and L2, forms a current dump (reservoir) circuit which is able to supply the peak demands of class B audio output stages without imposing a violently swinging load on the converter. This reduces the likelihood of Voltup being instantaneously overloaded by large current peaks, and also minimises interference by reducing frequency 'swish'.

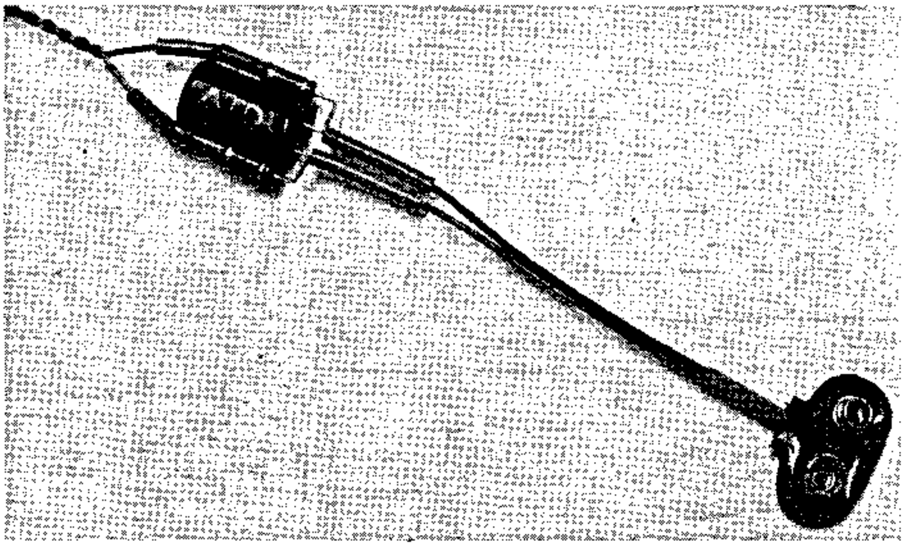
The above circuit description has been necessarily brief, as the operation of power blocking oscillators is very complex. For more information on how these interesting devices operate and how they can be put to work for you, I would refer you to the series of articles which are shortly to be described in *Electronics Australia*. Voltup was designed using the guidelines to be given in this series, with minor modifications to allow for operation at very low supply rail potentials.

Performance

When the design of this project was being considered, a very important requirement was for the relationship between the input and output voltage (i.e., the 'transfer characteristic') to be as linear as possible, and to extend down to the lowest practical end-point voltage of the supply cell. Fig.3 shows that this has been achieved, with operation being possible down to below 700mV.

Of critical importance in a very low voltage power blocking inverter is the choice of forward bias resistor, R_{bias}. The intrinsic base-emitter voltage of Q1 (V_{BE}) must be subtracted from the lowest input voltage likely to be encountered, and this leaves very little potential available to generate base current, especially when the supply cell is nearing the end of its life.

Voltup converter



How the optional filter components L1, L2 and C6 are fitted into the 9V output lead, for use with a radio.

The value of R_{bias} must therefore be low enough to produce an adequate load current capability, but if it is too low conversion efficiency will suffer, particularly at low output load currents. In order to cater for all output load requirements and still keep the efficiency as high as possible, the value of R_{bias} has been made adjustable between 115 ohms and 15 ohms.

Fig.4 shows the relationship between output load current and output voltage when R_{bias} is equal to 47 ohms (32mA maximum output) and 15 ohms (50mA max. output). These are representative characteristics only, as they are influenced by the DC gain parameter (h_{FE}) of Q1. The points to plot Fig.4 and the following efficiency measurements were taken from a circuit in which the h_{FE} of Q1 was 77 at Ic = 200mA. This would be a typical figure (about twice the minimum and half the maximum specification).

With R_{bias} = 47 ohms, the overall conversion efficiency of Voltup was 59% at 10mA load current and 57% at 25mA. When R_{bias} was lowered to 15 ohms the efficiency was 44% at 10mA load current and 52% at 40mA. The minimum value of R_{bias} (15 ohms) was arrived at by calculations based on the 47 ohm curve in Fig.4, and should allow a reasonable high current characteristic if the h_{FE} of Q1 falls near its lower specification limit of 40.

When Voltup is being driven from an alkaline cell and is supplying considerable output current, the drop in efficiency at low values of R_{bias} will make little difference to operating costs, due to the increased energy yield of the cell at high current densities. RV1 has been included mainly for low current applications, where the user wishes to maximize battery life.

When R_{bias} is equal to 115 ohms (i.e., when RV1 is turned fully anticlockwise) the output current is further limited, but the overall conversion eficiency rises above 60%.

When Voltup is overloaded Q1 cannot maintain saturation during its ON period, so the oscillation amplitude rapidly diminishes and the input current sharply increases. The output voltage therefore falls away quickly, accompanied by a commensurate fall in efficiency. Voltup can take this treatment, but it clearly isn't conducive to long battery life.

Note that the characteristics in Fig.4 are plotted for the maximum input supply voltage (1.5V). With 1.5V input, up to 360mW of output power is available from Voltup when R_{bias} = 15 ohms (i.e., when RV1 is turned fully clockwise). Obviously, the maximum currents and power available will be reduced as the supply cell's terminal voltage falls during use.

Voltup operates at frequencies ranging from approximately 10kHz (R_{bias} = 15 ohms, 1.5V input and a 200 ohm load) to 50kHz (R_{bias} = 115 ohms, 750mV input and no-load).

When a radio receiver is being powered, the 9V DC feed from Voltup is via the two RF isolation chokes, L1 and L2. Since these have a maximum resistance of some 18 ohms each, they will result in a total voltage drop of about 900mV when the average small transistor radio is operated at maximum volume. The isolation components L1, L2 and C6 need only be fitted when a radio receiver is being powered; they can be omitted for all other purposes. The data given (including the graphs) does not take account of these components.

Construction

Using the component overlay as a guide, mount R1, all capacitors and all diodes. Be particularly careful that the electrolytic capacitors and diodes are correctly orientated. Mount RV1 and fit the link LK1, which should be formed into a 'U' shape so that, if necessary, it can be cut easily during the testing procedure.

Now, it's time to wind the transformer. If you haven't wound transformers before, don't panic. This one has very few turns and no great skill is required to wind it.

Two important things to remember during the winding process are firstly to always wind in the same direction, and also to identify all leads with a tag indicating which winding it is, and whether the lead is a start or a finish.

In this case the bobbin has four slots; two on each side, 180° apart. The pri-

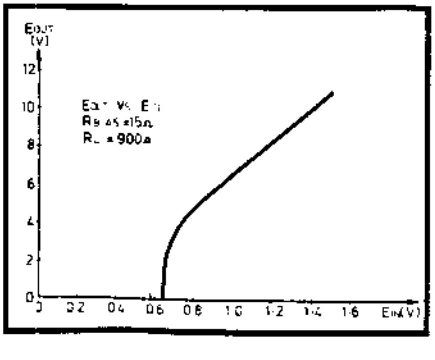


Fig.3 (left): Output voltage vs input voltage for Voltup. Note that it operates for inputs down to below 700mV.

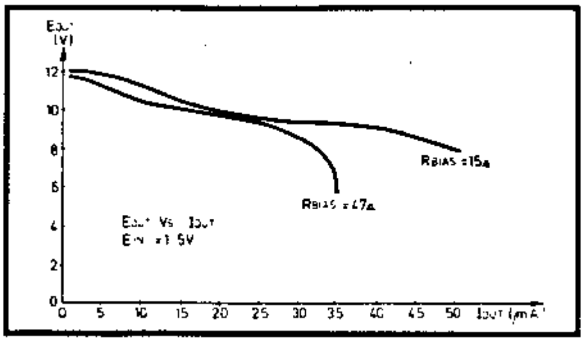
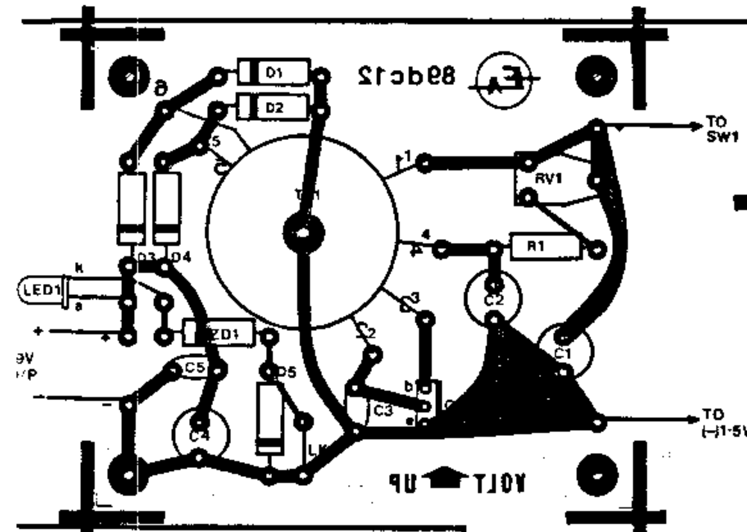
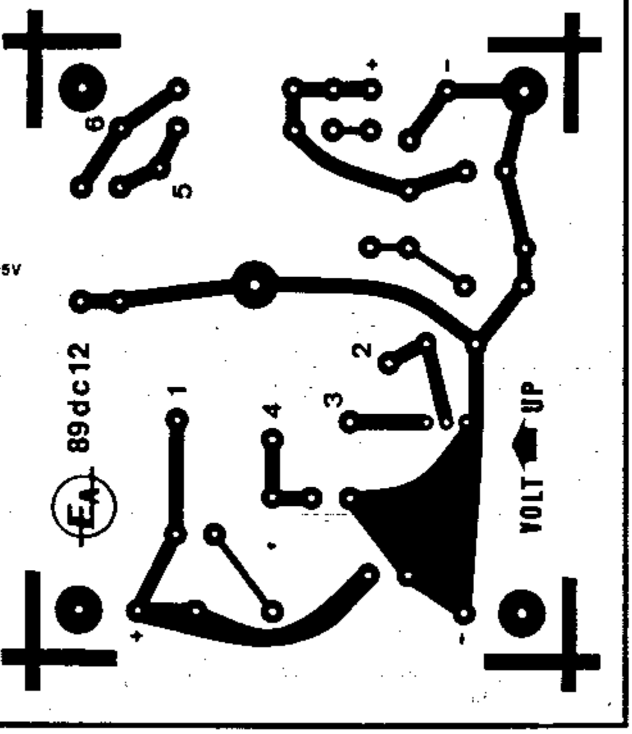


Fig.4 (right): Output voltage regulation characteristic for two different values of bias resistor, and 1.5V input.



The PCB wiring overlay at left should help you with the assembly of Voltup. Take special care with the transformer connections.



This PCB etching pattern is shown actual size, for those who etch their own boards.

ary (6 turns, 26 B&S) is wound first the left hand side of the bobbin, ith the start and finish passing through e same slot on the left. The feedback nding (1 turn, 26 B&S) is then wound the right hand side of the bobbin, ith its start and finish passing through e same slot on the right.

Apply a couple of layers of insulation pe to keep the windings in place, and en rotate the bobbin 180° axially, to ing the two unused slots uppermost. he secondary (52 turns, 30 B&S) can en be neatly scramble wound (i.e., t in distinct layers), with its start entring through the slot on the left and finish passing out through the slot on e right. The job can now be finished f by applying a couple of layers of inlation tape.

After ensuring that the mating faces the cores are clean, assemble the ansformer and hold it together temporily with the 3/4" 6BA bolt and nut. he leads can now be dressed (shaped fit the PC board), cut to length and e ends tinned. Remember that, by nvention, the starts of windings are entified by a dot on the circuit scheatic.

To assist you further, the transformer nnections are numbered identically on oth the PCB overlay and the circuit hematic.

Mount the transformer on the PC oard with the 6BA bolt and nut. Place e head of the bolt, together with a 3A flat washer, on the track side of e PC board, and use a 6BA flat nylon asher and a 6BA nut against the core. his arrangement will avoid any metal-ferrite pressure points. Tighten the olt firmly (but not excessively), and lder all the transformer leads to their rrect points.

If you want to be sure of getting the est possible high current output characteristics, or if you wish to optimise efficiency at low load currents by means of RV1, you should make sure that Q1 has a gain of at least 80. Use a transistor tester or the circuit in Fig.5 to check the current gain, which in the latter case will be equal to the collector current in milliamps. Take the reading immediately after power is applied, and then switch off. Do not test the transistor for more than a few seconds, as considerable heat can be generated.

Before mounting Q1, fit the clip-on heatsink. Although the H-3415 heatsink (Dick Smith Electronics) is designed for the TO-220 case, it fits the BD139 quite well. Lift up the spring clip, and slip the body of the BD139 in as far as it will go, ensuring that the collector mounting surface is in contact with the large face of the H-3415 heatsink.

It's worth mentioning here that Q1 normally dissipates very little power, and the heatsink will be required only under conditions of gross overload. Make sure that the transistor leads adequately clear the surface of the heatsink, and also that the bottom of the heatsink rests against the PC board for added rigidity. Double check the transistor connections before soldering; the emitter lead should be facing the edge of the PC board.

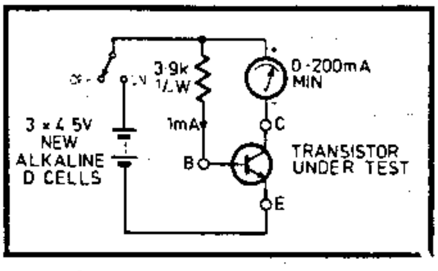


Fig.5: Simple transistor test circuit.

A metal diecast box is used for both acoustic and RF screening purposes, and also because the lid is readily removable for battery replacement. Drill the holes for the power switch, the warning LED, the output cable grommet and the four countersunk mounting holes for the PC board.

Make up a twisted twin output lead about 1m long and attach it to the PC board. Fit a short length of spaghetti sleeving or heatshrink tubing to this lead where it will pass through the grommet. Also attach the leads which will connect to the LED, the negative battery lead and the positive lead which will go to the power switch.

Mount the PC board on 1/4" long 4BA spacers using the four countersunk-head bolts. The spacers used must be metal types, as one of them forms the single-point earth link between the track side of the PC board and the case.

Attach the battery holder by means of

double-sided foam adhesive tape. If you're using the battery holder sold by Dick Smith Electronics, you will need to place a piece of insulation tape on each side of the box so that the solder lugs don't touch it. A better choice is the Tandy battery holder, which has leads already attached, and also doesn't have any protruding lugs.

Complete the wiring to the power switch and the LED. If Voltup is to be used under very high ambient lighting conditions, it would be a good idea to choose a high-intensity LED.

Incidentally, **NEVER APPLY POWER WITH THE LED DISCONNECTED!** Also, make doubly sure that the LED is connected the right way around – i.e., with the cathode (the short lead) connected to ZD1.

As a means of strain relief, lock a small cable tie (Dick Smith Electronics H-1970 or similar) around the output lead where it exits the box via the grommet. If a radio receiver is to be powered, fit the isolation components L1, L2 and C6 to the end of the output lead, using the arrangement shown in the photograph. Secure the chokes to the body of the capacitor by means of insulation tape or silicone adhesive sealant.

If equipment other than radio receivers is to be powered, do not fit these components, as they degrade Voltup's performance slightly. When wiring the battery 'snap' connector, remember that since it is 'masquerading' as a battery, it will be necessary to reverse the connections (i.e., the black lead will be connected to the positive output). Sheath all connections with heatshrink tubing, or similar.

Testing

Turn RV1 2/3 clockwise. Then insert a fresh 1.5V cell into the holder, and switch on the power. (Use an ordinary carbon-zinc cell for these tests, as its poorer regulation will give better protection if things go wrong.)

If the warning LED illuminates within a few seconds, all is probably in order. If there is no sign of life after this time, switch off IMMEDIATELY and recheck the placement of all components, particularly the transformer connections.

If the circuit does not oscillate and also draws excessive current, the most likely cause is incorrect phasing of the primary or feedback windings. Try reversing the connections to either the primary or the feedback windings, BUT NOT BOTH. If the circuit fails to draw any current at all, check RV1 and R1 for mechanical failures, and also test Q1 in the circuit of Fig.5.

When Voltup is working, measure the no-load output voltage and if it is below 11.5V, cut out the link LK1. If you wish to check the maximum output current capability, you will need a 1.5V regulated DC power supply. In order to cater for all possible component variations, we'll set the maximum output power specification at 320mW, although you'll almost certainly do much better than this.

Firstly, make sure that RV1 is turned fully clockwise. With 1.5V input, the output potential across a 200 ohm load should be greater than 8.0V. (If the isolation components have been fitted, place the load across the supply side of the RF chokes.)

If you have a CRO, you can look at the voltage waveform between the negative rail and the collector of Q1. The no-load amplitude should be 3V p-p, and with a 200 ohm load the lowest point of the swing (the saturation voltage of Q1) should be about +300mV.

After testing is complete, you can attend to a small sound-proofing matter. Cut a 50mm x 65mm piece of 25mm 'Innerbond' or foam plastic, and place it over the transformer area of the PC board, with one corner resting against the pillar and the corner diagonally opposite resting in the heatsink of Q1. This, together with the acoustic damping afforded by the closed diecast box, will render the inverter very quiet at high power levels.

At low power, the core magnetostriction is much weaker and the frequency of operation is higher, thus resulting in complete inaudibility. If the noise level increases after prolonged use, re-tension the transformer core mounting nut.

Using Voltup

With 1.5V input and a suitable load resistor representing the maximum output current required, adjust RV1 so that the output potential is 8.0V. If a transistor radio is to be powered, set RV1 at about 2/3 clockwise.

For maximum current output, turn RV1 fully clockwise and fit an alkaline cell. This is also the safest course to follow if Voltup is to be used in a number of different situations. Note that the maximum current setting procedure (if used) is designed to maximize efficiency, and is NOT intended for routine current limiting purposes.

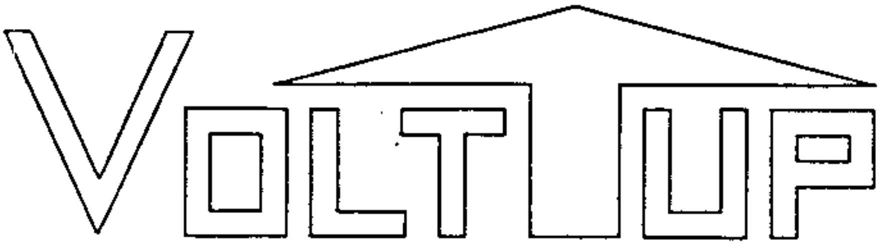
If Voltup is used to power a transistor radio, the output lead MUST be fitted with the isolation components L1, L2 and C6 as previously described. The quiescent current drain of a typical small receiver is between 10 and 15mA, with peak current demands of 30mA or more. Attach the output connector of Voltup to the battery connector in the radio, and place the isolation components in the battery compartment. It may be necessary to file a small 'mousehole' in the battery compartment cover to bring out the lead.

Leave the switch on the radio in the ON position, and use the power switch on Voltup instead. This is where the warning LED comes in handy. If you forget and turn the radio switch off (perhaps the user will be a non-technical person), the warning LED will come on as a reminder that Voltup is still active.

RF interference

If Voltup is built and used with a radio receiver exactly as described, broadcast band interference from the converter should be reduced to a very low level. Stations of reasonable strength can be received, totally free from interference. However, because of the great variety of different receivers which could be used, it is impossible to give a guarantee that very distant stations will always be free of interference, which is evident as a 'swishy' heterodyne.

If the receiver is placed directly adjacent to Voltup, the magnetic leakage field from the converter transformer will couple directly to the ferrite loopstick antenna in the receiver, and interference will be heard. This is only a short range effect, and will disappear when the two units are separated by about 100mm.



Actual-size artwork for the author"s front-panel logo.

Choosing a 1.5V cell

When considering the choice of cell type, remember that the overall regulation figure is the sum of the characteristics of both the supply cell and Voltup. The curves in Fig.4 were plotted using a regulated power supply, and so they reflect only the regulation characteristics of Voltup itself.

Under practical operating conditions, the drop in cell voltage under load must be taken into account. That's why the output voltage of Voltup is initially higher than 9V (see Fig. 1).

In use, the cell voltage won't stay at 1.5V for very long, and the number of secondary turns has been chosen to provide a good compromise in performance for all common primary cell types and their inevitable drop in voltage during use. When the load current is moderate but high peak demands are required, it is wise to choose a supply cell with good regulation characteristics.

Because of the current density at which they must operate, conventional carbon-zinc (i.e., 'general purpose') cells should generally be used only when the 9V output current does not exceed 10mA. Curves B and C in Fig.1 show that the general purpose cell is obviously down in performance compared to the heavy duty type, when driving a typical 9V radio receiver. However, general purpose cells are often available at such ridiculously low prices that you just can't afford to ignore their cost-effectiveness.

For output currents in the range 5mA-15mA, the 'heavy duty' cell is a good choice. Based on typical supermarket prices, the cost-effectiveness 'break even' point for manganese dioxide alkaline cells (compared to heavy duty types) occurs at an output current of about 15mA.

Alkaline cells have the marvellous quality of increasing their energy yield as the current demand is increased, and so extra power can be delivered at very little cost. Therefore, alkaline cells are recommended for output currents in the range 15mA-50mA, and for all applications where Voltup is set to the maximum power level.

Not included in Fig.1 is the 'super heavy duty' or zinc chloride cell. These ypes offer higher capacity, better low emperature performance, superior leak resistance and increased shelf life, when compared to carbon-zinc cells. Their performance characteristics fall between hose of the 'heavy duty' and alkaline ypes.

If you wish to use a rechargeable nickel-cadmium cell with Voltup, increase the secondary winding to 58 turns to compensate for the reduced (but more constant) supply voltage.

A more desirable rechargeable power source would be a D size 2V Lead-Acid gel-cell. These have two terminals on top, so you would need to rearrange the physical layout inside the box, as well as organising some means of charging the cell. The advantages of a 2V supply are that Voltup will operate at a higher efficiency, and that more output current can be delivered. Of course, you would need to scale down the number of secondary turns to provide the correct output voltage.

Other uses

For those applications which require only a few milliamps of output current, I would suggest reducing the number of secondary turns so that with the specified load current, the chosen value of R_{bias} and a fresh supply cell the LED is dimly illuminated – i.e., the crowbar protection circuit is just on the point of dropping out. This will enable maximum conversion efficiency (and therefore maximum battery life) to be achieved.

If an accurately regulated supply is required (e.g., for instruments, etc.), the best course is to use two or three supply cells in series, and drive Voltup via a feedback regulator circuit. This technique is described in Part 1 of my series of articles on DC-DC converters, while examples of this type of regulator are given in Part 3.

There is no reason why the number of secondary turns cannot be increased to raise the output voltage, as there is some free space available on the bobbin. If necessary, a finer gauge of wire can be used to wind the secondary. Remember that the zener diode in the protection circuit must also be changed so that the output voltage will be limited to about 4/3 of the working voltage when the crowbar circuit operates.

As described here, Voltup can be built using readily available hardware. However, by making use of an efficiently shielded custom made case, a smaller transformer and a more compact PC card, its volume could easily be reduced to less than a half of what it is now. Alternatively, the electronics of Voltup could be incorporated into new equipment, so changing our ideas about how we use batteries.

And there you have Voltup – my contribution to energy conservation. Have you just bought your last 9V battery?

PARTS LIST

1	PC board, 70 x 80mm, code 89dc12
2	Ferrite potcores, Philips P18/11-3B7 (4322 020 21500)
1	Single section former for above (4322 021 30270)
1	Diecast aluminium box, 150 x 80 x 50mm
1	SPST switch, 1A DC minimum rating

Resistors

1	15 ohm 5% 1/4W carbon or metal film (R1)
1	100 ohm trimpot, 1/4W carbon (RV1)

Capacitors

2	0.1uF 63V disc ceramic (C3, C5)
1	22uF 16VW TAG tantalum (C2)
2	1000uF 16VW electrolytic, PCB mounting type (C1, C4)

Semiconductors

5	1N4002/1N4004 silicon diodes (D1-D5)
1	10V/400mW (or 1W) zener diode (1N961/1N4740 or similar – ZD1)
1	Red LED (LED1)
1	BD139 silicon power transistor (Q1)

Optional

(For use with radio receivers):

2	1mH RF chokes with axial leads (L1, L2)
1	2200uF 16VW electrolytic capacitor, PCB type (C6)

Miscellaneous

Clip-on heatsink for Q1 (DSE H-3415 or equivalent); single D cell battery holder; 9V battery 'snap' connector; 4 x 6BA, 3mm or 1/8" bolts, countersunk-head, 12mm (1/2") long; 4 each shakeproof washers and nuts to suit above; 4 x 4BA metal spacers, 6mm (1/4") long; 1 x 6BA cheese-head bolt 18mm (3/4") long with matching nut, nylon washer and flat washer; self-fluxing enamelled copper winding wire for winding TR1 (approx. 750mm of 26 B&S, 2.5m of 30 B&S); LED mounting bezel; small PVC grommet; small cable tie; hookup wire; tinned copper wire; adhesive foam mounting tape; insulation tape; 50 x 65mm rectangle of 25mm 'Innerbond' or foam plastic; spaghetti sleeving or heatshrink tubing.