By Daniel R. Kemppainen, N8XJK

A 12 V dc Boost Regulator for Battery Operation

A dc-dc boost switching converter is the answer to low voltage battery problems for mobile, portable or emergency-power operation.

Battery low charge state conditions, combined with voltage drops in wiring, can cause reduction in output power, transmit signal distortion or even total shutdown in many radios. One solution to this problem is to build a switch-mode power supply (SMPS) to maintain the dc input voltage. An SMPS can offer boosted power levels and allow longer operating times from a given battery. This article describes how to build and test one from both new and recycled parts for about $50.

Overview

This SMPS is a simple boost supply, designed to make up the difference between battery voltage and a preferred output voltage level at the cost of some additional current draw from the battery. It was designed for an output current of about 25 A. When turned off, the battery voltage (less one diode voltage drop) is present at the output terminals of the supply. No power transfer relays or switches are required. The supply can be set up to operate on demand or continuously, depending on user requirements. A switch or relay contact is used to switch the power supply control power off when not in use. This reduces power consumption during periods of inactivity or when voltage is sufficient to power the radio.

Two "on demand" inputs are provided to enable the voltage boost function. One of the inputs is a simple remote enable input, and requires only a battery voltage signal. This can be used in conjunction with a control signal from a radio to key the supply or it can be enabled by a toggle switch for manual operation. The other input is an RF detector. The RF detector can be used to monitor the RF output of the attached radio and allow the voltage boost to take place when the radio is transmitting. The RF detector attaches directly to the antenna lead of most radios using a coax T fitting or a coupling transformer. This design has been tested with radios transmitting from several watts to 100 W. Operation at higher power levels may require some circuit modifications. The completed supply is shown in Figure 1.

Circuit Description

The SMPS uses a push-pull design topology. Its schematic appears in Figure 2. The positive battery terminal is connected to the center tap of the primary of the switching transformer T1. The secondary of T1 is also a center tapped winding, with its center tap also attached to the battery voltage. The voltages seen on the secondary legs of T1 are the battery voltage plus the voltage of the transformer windings. This configuration allows the transformer to supply only the difference between the output and battery voltages. In addition, the power requirements of the transformer and switching transistors are reduced. This also allows battery voltage to be present at the output of the supply when it is switched off.

Figure 1 (above)— The completed boost regulating switching supply. It is shown with an aluminum sheet that acts both as a mounting base and a heat sink.

MOSFET transistors Q5 and Q6[1] alternately switch the legs of the primary winding of T1 to ground, creating an ac flux waveform in the transformer. The secondary legs of transformer T1 are rectified by the dual Schottky diode D7. Inductor L1 and eight 3300 µF capacitors form a low pass filter to smooth the rectified waveform.

A switch-mode power supply controller, U1, handles the voltage regulation. The controller used in this supply is an LM3524D.[2] The LM3524D uses pulse width modulation to control the time that switching transistors Q5 and Q6 are turned on. By varying the pulse width, the ac voltage of the transformer is varied and the output voltage is maintained.

A simple battery voltage monitor circuit is used to monitor low battery conditions. The low voltage protection circuit shuts down the LM3524D in the event that battery voltage falls below a minimum level. The protection voltage is jumper selectable to 9, 10 or 11 V. The circuit uses an LM339[3] quad comparator in conjunction with a +5 V dc reference voltage provided by the LM3524D controller IC. When the protection circuit is tripped, the supply boost function is disabled and battery voltage is present at the output of the supply. A reset of the battery protection circuit is accomplished by cycling the power switch.

Collecting the Parts

The inductor and transformer are custom parts that will need to be made for

[1]Notes appear on page 41.

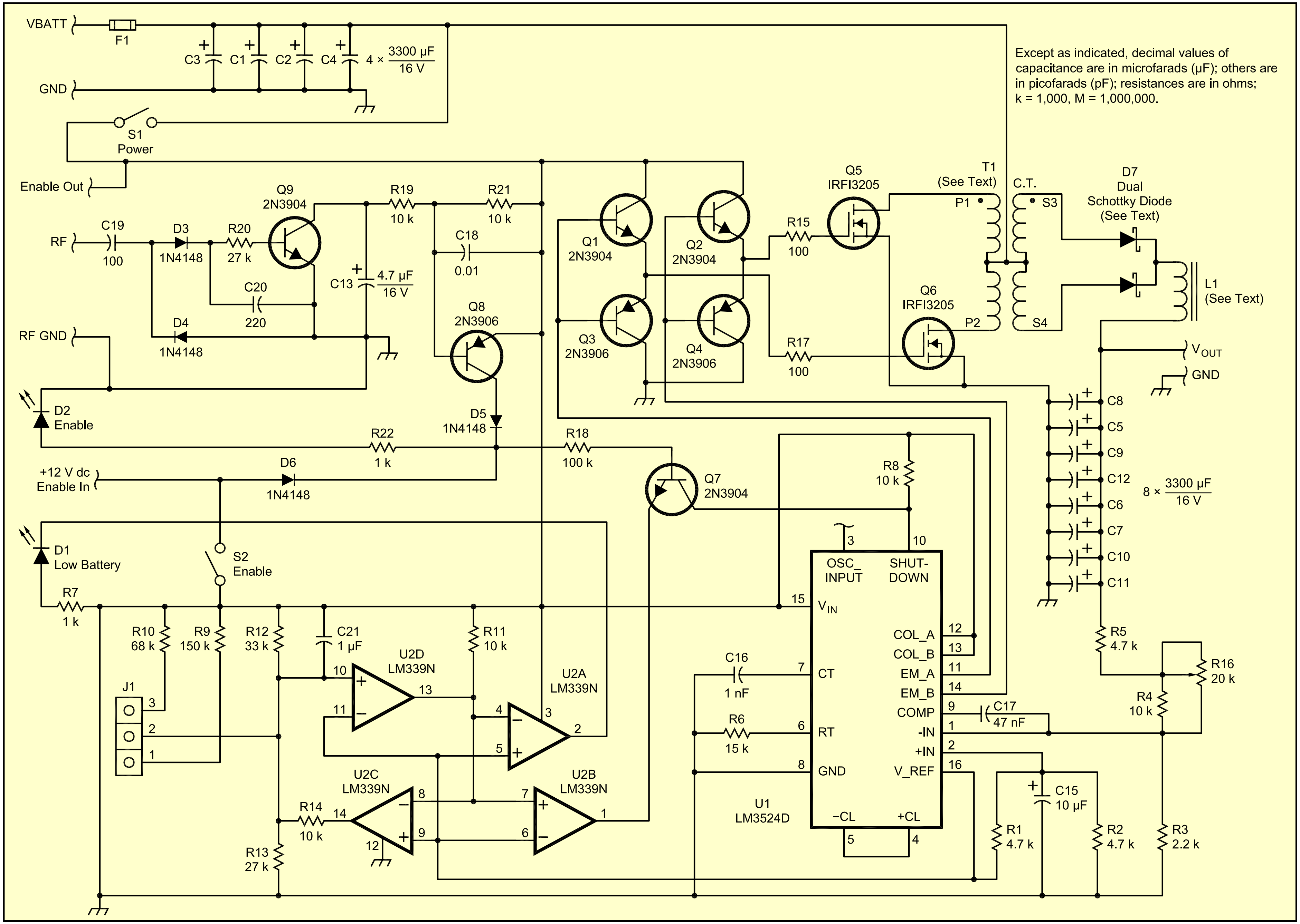

Figure 2—Schematic diagram of the boost regulator. A detailed parts list is available at **www.arrl.org/files/qst-binaries/boost_reg.zip**.

the supply. A good source of these components is an old PC power supply. For this SMPS, an AT-style computer power supply was chosen. The inductor and transformer will need to be disassembled and rewound before building this supply. Details can be found on the ARRLWeb.[4] The dual Schottky diode (D7) can also be salvaged from the same surplus power supply. Capacitors C1 through C12 are specific, and will need to be ordered new. The rest of the parts are common and can be replaced, provided that close matches can be found.

Detailed directions for disassembly of the transformer core, transformer winding calculations, directions for winding the transformer and inductor, the PC-board layout, a complete parts list, and construction preparation and assembly instructions can also be found on the ARRL Web site (see Note 4).

A good reference for ferrite core applications and design is the *Ferrite Core Design Manual*, available from Magnetics, PO Box 11422, Pittsburgh, PA 15238; **www.mag-inc.com/ferrites/fc601.asp**.

The Filter Inductor, L1

The only inductor used in the circuit is L1. The inductor is used in conjunction with eight 3300 µF high frequency electrolytic capacitors to make the output low pass filter section of the power supply. The approximate value of L1 is 9 µH and it must be capable of handling currents of up to 25 A. Nine turns of wire on the salvaged toroid core will produce the 9 µH inductance. Ten paralleled 24 gauge copper wires work well for the winding. Each strand needs to be about 18 inches long. Plan on a total length of about 15 feet of wire for the winding. Strip, twist and tin the leads before inserting the inductor into the circuit board.

Supply Boost Enable Circuit

The supply enable circuit is designed to allow the supply to boost voltage when required. Two inputs allow the circuit to function. The first is a simple 12 V input and the second is an RF detection input. The ENABLE input feeds current into D6, supplying current to the base of Q7 through R18 and to the ENABLE LED through R22. The ENABLE function can also be manually forced by closing S2, the ENABLE switch. Feeding current into the base of Q7 allows comparator U2B to pull the shutdown pin low, thus enabling the LM3524D.

The RF INPUT enables the supply when RF is present. The RF INPUT feeds current into the base of Q9 through D3, causing C13 to be discharged and half of the supply voltage to appear at the base

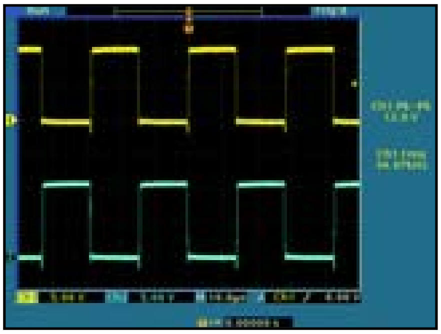

Figure 3—MOSFET gate driver waveforms shown with no MOSFET devices attached. Note the 180° phase shift between phases.

of Q8. Transistor Q8 then feeds current into D5, enabling the supply just as the ENABLE input would. The charge time of the 4.7 µF capacitor, C13, sets up a small delay that keeps the supply enabled after the RF signal is removed.

To test the ENABLE circuit, apply power to the supply and close the power switch. Supply a 12 V signal to the ENABLE input or close the ENABLE switch. The ENABLE LED should come on. Remove the 12 V feeding the ENABLE input, and the ENABLE LED should go off.

To test the RF INPUT, apply an RF signal to the RF INPUT. It is important to note that a 2 V peak-to-peak signal will be the minimum needed at the RF INPUT to enable the supply. The supply ENABLE LED should light up in the presence of RF, and go off about a quarter of a second after removing the RF signal. The turn-off time may vary slightly, depending on the strength of the RF source.

Battery Low Voltage Protection Test

The battery low voltage protection circuit was designed to protect the battery from being discharged too far. The circuit works by comparing a sample of the battery voltage to a reference voltage. The LM339 comparator is used to compare the battery voltage to the reference provided by the LM3524D. The controller circuit is shut down when a low voltage condition has been detected. R12 and R13 form the voltage divider used to sample battery voltage. R9 and R10 and the jumper J1 act in parallel with R12 to vary the voltage divider ratio. U2D compares the sample battery voltage to a reference voltage. When the voltage falls below the reference, U2D pulls its output pin to ground. U2C then seals the circuit by pulling the voltage going to U2D down even further. U2A acts as a simple switch turning on the low voltage LED. U2B allows Q7's emitter to go high, allowing R8 to pull up the shutdown pin on the LM3924 and thereby disabling the supply.

To test the low voltage protection circuit, simply apply power and a ground to the supply and close the power switch. With the power switch closed, remove the 12 V input from the supply. After a few seconds, the LOW BATTERY voltage LED should light up and stay on. Before depleting the voltage stored in the input capacitors C1 through C4, reconnect power to the supply. The LOW BATTERY voltage LED should still be on. Turn the power switch off for a few seconds, and then back on again. This should reset the battery protection circuit and the LOW BATTERY LED should be off.

Next, test the threshold voltage for the low battery protection circuit. Start by connecting a voltmeter or oscilloscope across the battery input to the supply. Set the battery protection voltage to 11 V by removing the voltage select jumper J1. Connect power to the supply, and cycle the POWER switch OFF and then ON. Remove the input voltage to the supply, and watch for the LOW BATTERY LED to come on. Take note of the voltage at which the LED turns on. This voltage should be very close to 11 V. Reconnect power and cycle the power switch. Repeat this test for the 10 V (jumper toward fuse) and the 9 V (jumper away from fuse) threshold settings.

Switching Regulator IC

The switching regulator is the heart of the circuit. The regulator uses pulse width modulation to vary how long the switching transistors Q5 and Q6 stay on for each switching cycle. By adjusting the pulse width of the switching transistors, the output voltage can be kept at a constant level. The switching regulator monitors the output through a voltage divider as a 2.5 V dc signal. Resistors R3, R4, R5 and R16 form the voltage divider that provides the feedback voltage. R16 is variable, allowing for adjustment of the output voltage. The reference signal comes from the LM3524D's internal 5 V reference and is divided down by the voltage divider formed by R1 and R2.

The next test will verify that the switching frequency is correct, the feedback network is working, and the gate driver transistors are operating correctly. After D7, Q5 and Q6 are removed from the supply, tie the supply positive input to the supply positive output. Turn variable resistor R16 fully clockwise. This will help to ensure that the output voltage setting is above the input voltage. Attach a voltage source to the supply, and close the power switch. Check that the input voltage to the supply is around 12-13 V dc.

Using an oscilloscope or a frequency

counter, check the frequency at the nodes between R15 and Q5 and R17 and Q6. This should be about 35 kHz, with a 50% duty cycle for each transistor. If the frequency is not within a few kilohertz of 35 kHz, the timing capacitor or resistor (C16 or R6) will need to be adjusted. The waveform should have fast rising and falling edges. Figure 3 shows a sample of the gate driver waveforms without Q5 and Q6 attached.

With the oscilloscope or frequency counter still attached to the nodes between R15 and Q5 or R17 and Q6, turn the voltage adjust resistor all the way to the left. This will set the minimum output voltage to around 9 V dc, well below the input voltage. The switching drive signals should be a steady 0 V signal, indicating that the output voltage is above the current voltage setting. When the test is complete, center the output voltage potentiometer. This should set the supply to around 13.3 V dc.

Putting It All Together

After operation of the switching regulator IC, RF detect and enable inputs and the battery voltage protection circuit have all been verified, mount the switching transistors (Q5 and Q6) and rectifier diode (D7). It is important that a heat sink is attached to the switching transistors and rectifier diode. The transistors come in an electrically isolated package and need only heat sink grease between them and the sink. The diode is not an electrically isolated package and it requires electrical isolation between its package and the heat sink. The insulating pad originally used to isolate the diode from the heat sink in the PC should also be used.

The first test with the switching transistors and rectifier diodes should be done with a low current fuse (5 A) or a pair of 100 W, 12 V light bulbs in series with the battery. If light bulbs are used, set the battery protection circuit to 9 V. Hook a voltmeter and a small 12 V automotive tail lamp or similar small load to the output of the supply. Hook the supply to the 12 V battery. With the power switch off, the 12 V load should be energized, and the meter should read the battery voltage minus one diode voltage drop (0.5-0.6 V).

Close the power switch. No LEDs should be on. If the battery protection LED is on, check the input voltage to the supply and cycle the power switch. Enable the supply with the RF DETECT input or ENABLE input and watch the output voltage. The voltage should jump up slightly when the ENABLE LED comes on. If no change in voltage is detected, turn R16 clockwise until an increase is detected. As long as the battery protection LED is off, the ENABLE LED is on, and the output voltage setting is higher than the input voltage, the supply should be running. Set the output voltage to a desired level by adjusting R16. The supply is now running, and will regulate the minimum output voltage.

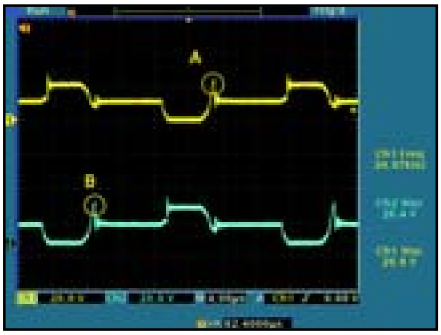

Figure 4—The drain to source voltages of Q5 and Q6 while operating the supply at a load of 300 W. The input voltage was between 10 and 11 V dc. The output voltage was set to 14 V dc. Note points A and B showing the transients generated during MOSFET turn-off.

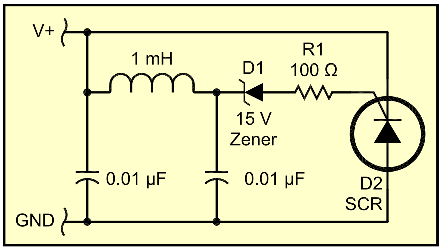

Figure 5—A sample crowbar circuit. Values shown are recommended starting points. Determine the exact values experimentally, depending on the SCR and Zener diode used and the clamp voltage desired.

A final check of the supply should now be made. The transient voltages on the switching transistors now need to be checked. This check is important and should not be skipped. This test will be run several times, with an increase in the load on the supply each time. The minimum peak voltage that will normally be seen is double the supply voltage. This is because the switching transformer acts as an autotransformer when each transistor is ON. This voltage should not be of any concern, but the voltage that is of concern is the transient voltage generated when the switching transistors turn OFF. This occurs when the voltage across the transistor starts to rise from the 0 V level (see Figure 4). The changing current in the transformer, combined with any leakage inductance, cause these transients to be generated. The peak voltages need to be below the rated 55 V of the switching transistors.

Attach an oscilloscope or peak detecting voltmeter from the drain lead (center lead) of Q5 and Q6 to ground, and attach a 1 A load to the supply. Enable the supply and check the peak voltage across each of the transistors. If peak voltages are close to the transistor breakdown voltage (55 V) under light loading, stop the testing immediately. The switching transformer will need to be rewound with tighter spacing between all of the windings.

Repeat the previous test with a large load on the supply. Remove the current limiting from the battery, and place a 30 A fuse in the fuse holder. Attach a load of around 100 W to the supply. A 100 W automotive light bulb works well for this. You may have trouble with the battery protection circuit when trying to enable the supply with the 100 W light bulb attached. If so, leave the voltage on the ENABLE input to the supply, then cycle the power switch. The supply has a built-in soft-start circuit that will bring the output voltage up slowly when the ENABLE input is powered before closing the power switch. It may be necessary to use this feature when testing the supply with large light bulb loads. With the 100 W load attached, check the transient voltages to make sure they are below the 55 V rating of the transistors. If the transients are low, repeat the test with 200-300 W of load. If any of the tests reveal transients close to the 55 V maximum, the transformer will need to be rewound with tighter spacing between the windings.

Final Notes

The power supply can be mounted in an enclosure, provided that enough cooling is available for the switching transistors. The level of power drawn and the state of charge of the battery will determine the heat sink requirements. Basically, if the heat sink or cases of the transistors are too hot to touch, a bigger heat sink or more air flow is required.

A set of optional high frequency "snubbers" can be added to the switching transformer and the switching transistors. The snubbers are basically a series RC network used to reduce the high frequency ringing that can occur during switching transitions. Place the snubbers from each leg of the transformer to the center tap of the transformer, and from the drain lead (center) of the switching transistors to ground. A 220 pF ceramic capacitor in series with a 220 Ω resistor is a good starting point for each snubber. It is best to determine the exact values experimentally. Find values that reduce the ringing without dissipating excessive heat in the resistors.

It is highly recommended that a crowbar circuit be included on the output of the supply. If a malfunction were to occur in the supply feedback circuit, the output voltage could rise enough to cause damage to any attached equipment. The crowbar circuit watches the output voltage of the supply and shorts the output—blowing fuse F1—if the voltage gets too high. The simple circuit shown in Figure 5 uses a Zener diode in series with the gate of an SCR. A small current limiting resistor and an RF filter are included. The current limiting resistor prevents damage to the gate of the SCR, and the filter prevents RF on the 12 V line from tripping the crowbar circuit. Values for the capacitors, inductors, resistors and the Zener diode will depend on the particular SCR used and the crowbar voltage desired. Although the values shown in the circuit are a good starting point, it is best to determine the exact values experimentally. When testing the crowbar circuit, use a large 12 V light bulb in series with the battery or voltage source. This can save the cost of several fuses.

It may be desirable to add additional filtering and shielding to the supply. No testing of the electromagnetic interference (EMI) generated by this supply has been done. The generated EMI should not be very great, but it may be strong enough to be received by an attached radio. This, of course, will depend on your antenna and mode of operation. For this reason, it is recommended that you use the RF enable circuit, whenever possible. Many radios have problems with low input voltage only when transmitting and not when receiving. The RF detect circuit has been designed to supply full power to the radio when transmitting, and it allows pass-through battery voltage to be supplied while receiving. This reduces the EMI generated by the supply and received by the radio.

Figure 6 shows oscilloscope voltage traces of the supply in operation. The supply was powering a radio that was being used to transmit SSB voice. In this case, the RF input was used to enable the supply and boost the rig voltage only when transmitting. Trace 1 shows the output voltage of the supply. The corresponding RF envelope is shown in trace 2. The terminal voltage of the battery was approximately 11 V dc, while the boosted output voltage was set at 13.8 V dc. The supply regulation action can be clearly seen as the higher levels of voltage shown in trace 1 after RF excitation turned the supply on. In this case, the supply was being tested from a weak battery, similar to that of typical operating conditions.

This simple supply can be built by anyone—no background in switch-mode power conversion is required. To simplify the parts list, the sometimes hard-to-find magnetic components are recycled from a common power supply. The rest of the components are available from a single distributor, to make ordering easy. Even the most difficult task (winding the switching transformer) should take no more than an hour. Anyone who has had some experience with soldering and coil winding can build and test this power supply.[5] A little extra money, a few spare parts and some free time are all that are required.

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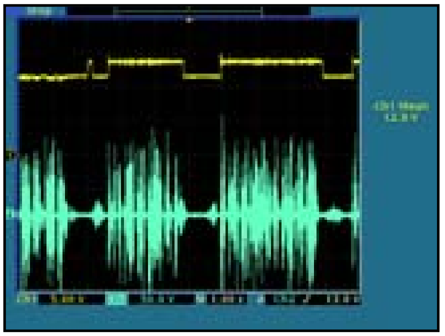

Figure 6—The supply in operation. Trace 1 shows supply output voltage. Trace 2 shows the RF voltage at the input of the RF detector. The time base is set to 1 s/cm. The zero reference baseline for trace 1 is at arrow 1. The battery voltage is about 11 V dc (a weak battery) and the boost voltage is set to 13.8 V dc. The first two seconds the supply is OFF. It comes on with RF excitation, as shown by the lower trace. It can also be enabled with 12 V dc to the ENABLE input or by operation of the ENABLE switch.

Notes

[1]IRFI3205 power MOSFET; International Rectifier (**www.irf.com/product-info/datasheets/data/IRFI3205.pdf**).

[2]LM3524D regulating pulse width modulator; National Semiconductor (**www.national.com/pf/LM/LM3524D.html**).

[3]LM339 low voltage quad comparator; National Semiconductor (**www.national.com/pf/LM/LM339.html**).

[4]**www.arrl.org/files/qst-binaries/boost_reg.zip**.

[5]The author may be able to supply a professionally built PC board. If interested in procuring a board, write or e-mail the author at the address shown at the end of the article. If enough requests are received, details as to cost and availability will be supplied.

With a lifelong love for science and electronics, Daniel Kemppainen, N8XJK, has been a ham for more than 10 years. As is obvious from this article, his area of interest includes switching power conversion, but he's also interested in high power audio amplifier design. Daniel is a design engineer dealing with analog and digital electronics, data acquisition systems and programming for the Windows *operating system. He has both Associate's and Bachelor's degrees in Electrical Engineering Technology. You can reach him at 25403 E Acorn St, Calumet, MI 49913 or at* **drk@pasty.com**.

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