Small DC-DC Converters

DC-DC converters under the magnifying glass

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Switch-mode power supplies are not among the hobbyist's favourite circuits. The specialised components are often hard to obtain, and mistakes are rewarded with noisy and expensive results. If, however, we stick to low voltages and very low power, there are a few universal and readily-modifiable circuits that illustrate the most important principles.

The function of a DC-DC converter is to change one DC voltage into another. The resulting voltage can be higher, lower, inverted and possibly isolated with respect to the input voltage. There are many types of converter, of which we shall examine a few here.

The basic circuits are shown together in **Figure 1**. The input voltages are labelled U_{in}, the output voltages U_{out}. All the circuits shown here have the common feature that they employ a switch S, a diode D and a coil L to carry out the essential functions of the circuit.

First we will look at the simplest circuit, the so-called step-down or 'buck' converter. This converts an input voltage into a lower output voltage. In outline, its principle of operation is as follows. When switch S is closed a positive voltage appears across the inductor L (since U_{in} is greater than U_{out}). The current in the coil therefore rises linearly, and energy is stored in the coil. When the switch S is opened, current flows through the coil into the output capacitor via diode D. The voltage across the coil, U_L, is now negative, and so the current through the coil falls linearly. The energy stored in the coil is transferred to the output. Switch S is now closed again, and the process repeats itself from the beginning.

The actual voltage appearing at the output depends on how the switch is controlled. In principle there are three patterns of current flow, as illustrated in **Figure 2**. If the current flow in the coil has not reached zero when switch S is closed, there will always be a current flowing in the coil: this is known as 'continuous mode' (CM). If, as shown in **Figure 2(b)**, the current is zero for part of the cycle, the circuit is operating in 'discontinuous mode' (DM). If the switch is turned on when the coil current reaches exactly zero, we speak of CM/DM limit operation.

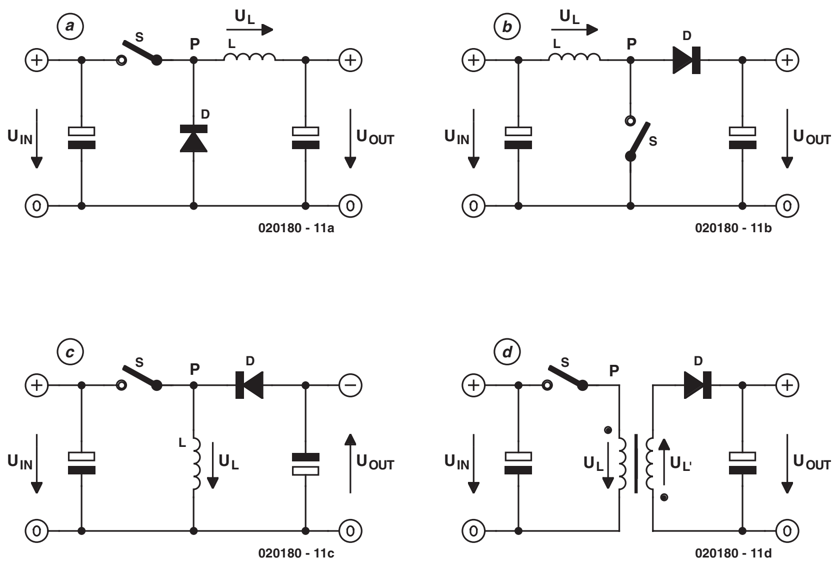

Figure 1. Various DC-DC converters:
(a) buck; (b) boost; (c) buck/boost; (d) flyback.

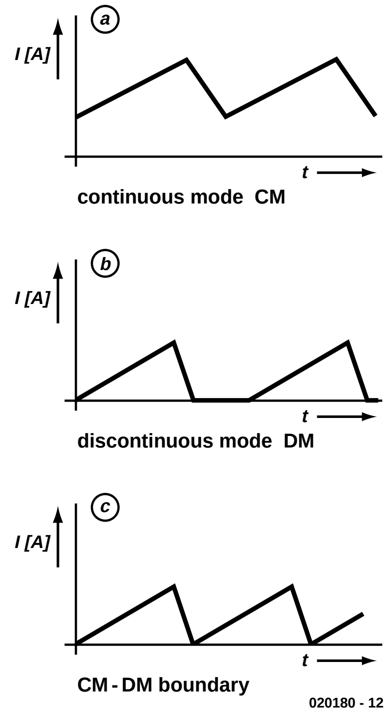

Figure 2. Theoretical current waveforms.

By controlling the 'on' period of the switch (or its mark-space ratio) the output voltage and transferred power can be controlled. So much for theory; now let us look at a simple practical circuit.

LED driver

The circuit [1] in **Figure 3** drives an LED from an input voltage of 9 V with high efficiency. Note that European equivalents have been substituted for some of the components used in the original design. How does this circuit work?

Transistor T1 plays the role of switch S. Diode D1 and coil L1 form the other parts of the step-down converter. When the circuit is turned on, R3 provides a base current for T2 (since the forward voltage of D2 is greater that 0.7 V) and T2 starts to conduct. T2 now supplies T1 with a base current, and so it starts to conduct as well. The voltage at point P rises and T2 is supplied with a much higher base current.

The voltage at point P now being 9 V, the current in L1 begins to rise. The rate of rise of the current in the coil is determined by its inductance and by the voltage across it. The rising current results in a voltage drop across R1. When this reaches 0.7 V (at about 70 mA) T3 also begins to conduct and removes the base current from T1. The current in L1 cannot now rise further, and so the voltage at point P begins to fall. T2 is then turned off and finally also T1. The current through L1 now flows through D1 until it falls to zero; then the voltage at T2 rises again and the process repeats from the beginning. The transistors function as a thyristor tetrode with positive feedback, which creates an oscillation. T3 ensures that T1 is turned off at the preset current, and the circuit functions in CM/DM limit operation. A photograph of the prototype appears in **Figure 4**.

Modifications

If you try to use this circuit to power another circuit, rather than an LED, you will find that it does not oscillate under higher loads. This is because the load will prevent R3 turning on T2 at power-up. A capacitor (0.1 µF) between point P and the base of T2 will help avoid this problem. It is also a good idea to connect an electrolytic capacitor (10 µF) across the output to smooth the voltage. The converter is unregulated and acts as a current source rather than as a voltage source. For many simple applications this will however be entirely adequate.

5 V to 12 V step-up converter

Can a step-up converter be designed in the same way? Let us first look at the basic operation of the step-up, or 'boost' converter, as illustrated in **Figure 1(b)**. When switch S is closed, the coil voltage U_L is equal to the input voltage and the coil current rises linearly. When switch S is opened the coil will ensure that the current continues to flow, independent of how high the output voltage is: this current now flows through diode D. In the steady state the output voltage is higher than the input voltage and the coil voltage U_L is negative, which leads to a linear fall in the current flowing in the coil. In this phase energy is again transferred from the coil to the output.

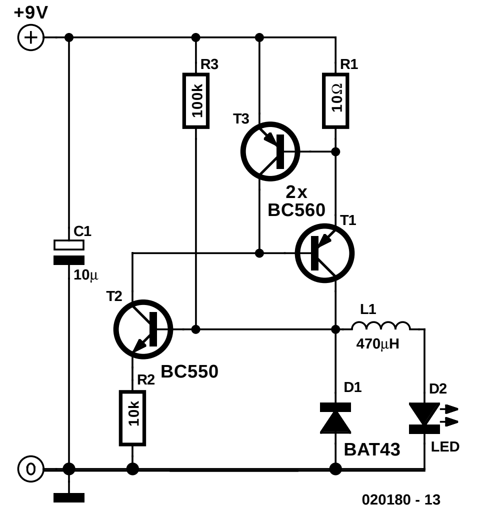

Figure 3. Down-converter driving an LED.

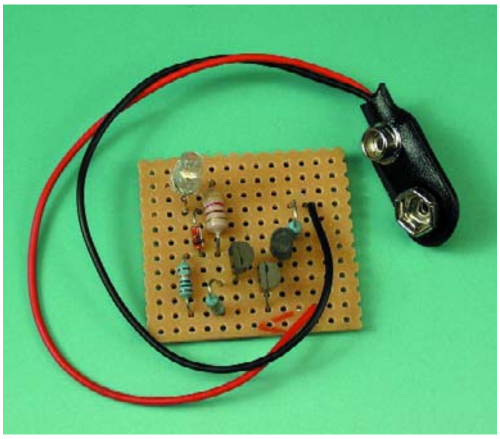

Figure 4. Prototype LED driver circuit.

Switch S is now closed again and the process is repeated.

In order to turn the circuit of **Figure 3** into a step-up converter we first need to turn all the transistors upside-down, so that switch S is now connected to ground as the outline circuit in **Figure 1** indicates. The positions of diode D1 and coil L1 also need to be exchanged. The feedback between T1 and T2 is modified, and we arrive at the circuit shown in **Figure 5**.

Zener diode D2 allows us to regulate the output voltage to 12 V. If the output voltage is too high, the operating point of T2 is shifted so that T1 is turned on for a shorter period (or even not at all). At an output current of 20 mA the output voltage will be 12.6 V; with a 5 V input voltage the input current will be around 64 mA. This corresponds to an efficiency of 77 %, not at all bad for such a simple circuit. The prototype circuit is shown in **Figure 6**.

Regulated step-down converter

Can we make things even simpler, using only two transistors? Indeed we can: **Figure 7** shows a regulated step-down converter producing 12 V from 20 V. It is described in the references [2]: again, European equivalents have been substituted for some components.

The key components of the step-down converter are transistor T1, diode D1 and coil L1. The PNP/NPN feedback combination will be recognised here. In this converter T1 is controlled not by the maximum coil current, but via RC-combination C2/R4. The Zener diode D2 and the connection of the emitter of T2 to the output together provide voltage regulation. An efficiency of up to 90 % is claimed for this converter.

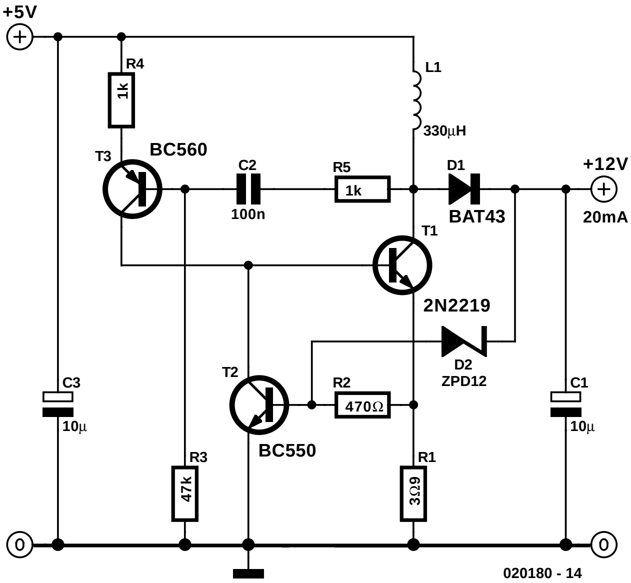

Figure 5. Regulated 5 V to 12 V converter.

1.2 V to 5 V step-up converter

This step-down converter can also be modified to make a step-up converter. The result

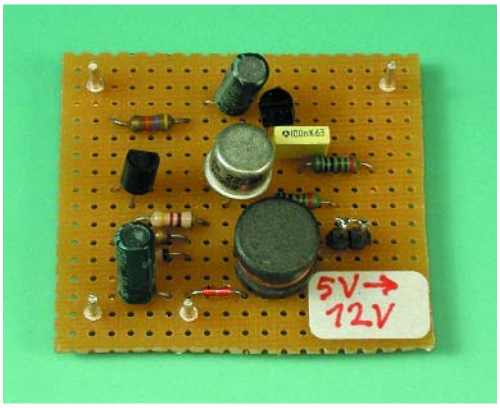

Figure 6. Construction of the converter shown in Figure 5.

can be seen in **Figure 8**. Compared to the circuit of **Figure 5** this arrangement has the advantage that it works perfectly from an input voltage of 1.2 V. Transistor T1, coil L1 and diode D1 form the step-up converter. Regulation is achieved via Zener diode D4, which here operates via the base of T2.

This circuit allows the supply for a 5 V system to be obtained from a NiCd cell (1.2 V). The circuit can deliver at most 10 mA at 5 V, which is enough for today's low-power microcomputer circuits.

Sometimes a low-current negative voltage supply is also required, for example for an operational amplifier or as bias for an LCD. Such functionality can be added to this circuit. Capacitor C4 and diodes D2 and D3 form a simple charge pump converter, providing an unregulated –5 V at up to 0.5 mA.

The efficiency of this circuit is around 60 %. This is certainly not all that impressive, but with a low input voltage every voltage drop brings a penalty. If the collector-emitter voltage drop of the switching transistor is 0.2 V when turned on, already 20 percent of the energy is being wasted. The transistors must be driven fully on, which demands a high base current; but this again reduces the efficiency of the circuit.

5 V to ±12 V and more

The only remaining variation on the power supply circuit is the inverting converter, which produces a negative output voltage from a positive input. The basic principle is shown in **Figure 1(c)**. When switch S is closed the current in the coil rises linearly. If the switch is now opened, a current continues to flow in the coil, and this current must now flow through diode D. This is how the negative output voltage arises. There is a small difference between this converter and the previous ones: at no point in the operation of the inverting converter is there direct transfer of energy from input to out-

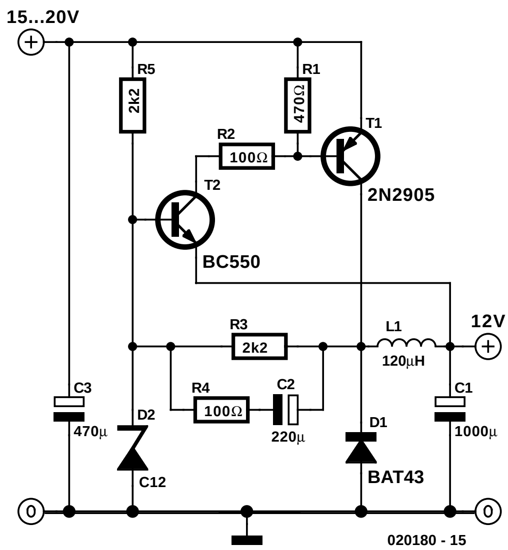

Figure 7. Regulated down-converter using two transistors.

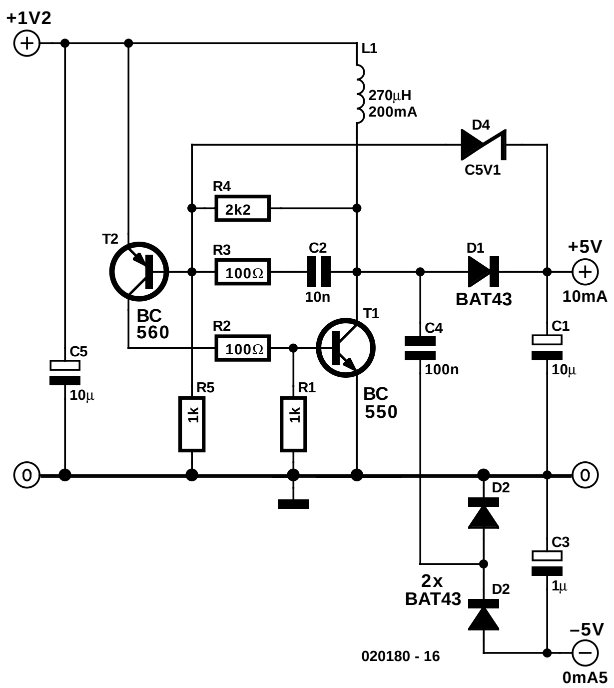

Figure 8. Boost converter from 1.2 V to 5 V.

put. Instead, all the energy is first stored in the inductor. In contrast, in the buck and boost converters energy is transported directly from input to output at certain moments. According to its mode of operation, the output voltage of the inverting converter can be greater or lesser in magnitude than the input voltage. For this reason, this type of converter is known as the 'buck-boost' or 'step-up/step-down' converter. The experimental circuit shown in **Figure 10** is set up to produce an output of

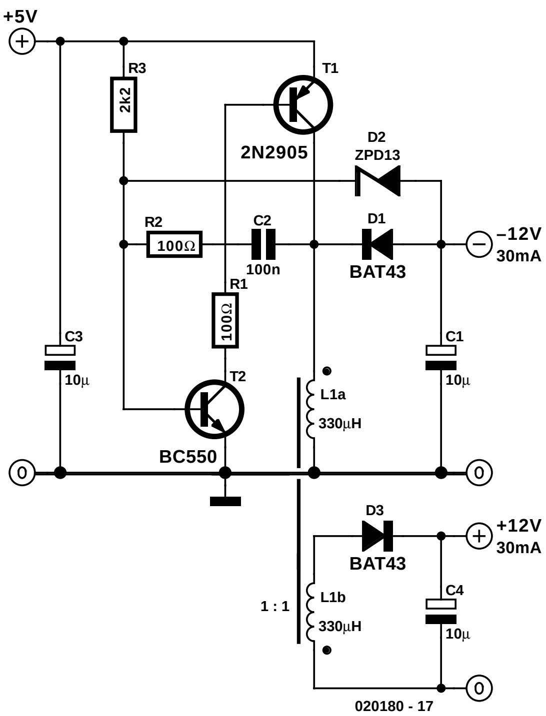

Figure 10. Combined inverting/flyback converter.

–12 V from an input voltage of 5 V. The basic circuit is the same as that shown in **Figure 3** and **Figure 7**.

Isolating converters

There only remains to explain how to create an isolated supply. The basic principle is shown in **Figure 1(d)**. Instead of a simple coil we have an inductor with two windings. When switch S conducts, the current in the first (or primary) winding rises linearly, as in the inverting converter. Energy is stored in the inductor. Now switch S is opened and now no current can flow in the primary winding; instead current flows in the secondary winding via diode D. Energy is transferred from the inductor to the output. This type of converter is called a 'flyback' converter because the energy flows to the output when the transistor is turned off. As in the case of the inverting converter, all the energy must

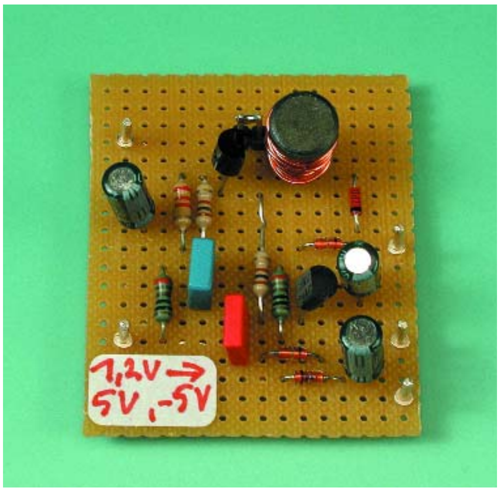

Figure 9. Construction of the converter shown in Figure 8.

be stored in the inductor. For this reason we often speak of 'an inductor with two windings' rather than a transformer.

Since the flyback converter and the inverting converter are so similar, no new circuit diagram is needed. We simply add a second winding to the coil in the inverting converter (observing polarity!) and thus obtain an electrically isolated output. The turns ratio is 1:1, and so the output voltages are the same. By using a different ratio a flyback converter with a considerably higher or lower output voltage can be constructed, without the use of extreme values of switching mark-space ratio. In the circuit of **Figure 10** only the output of the inverting converter is regulated; the flyback output is not. The circuit has an efficiency of around 60 % and it can conveniently be used to provide a positive and a negative supply for operational amplifiers from a 5 V input.

Coils

The only special components in our circuits are the inductors, about which a few remarks are in order. Many of the small inductors that are readily available are not suitable for these applications because of their high DC resistance. Larger devices designed for higher currents are generally suitable. Particularly simple to use are the so-called 'bobbin cored' inductors, as shown in **Figure 11**: the diameter and height are both approximately 10 mm. These are sometimes found in PC power supplies and can be dismantled and rewound. In our example wire with a diameter of between 0.2 mm and 0.3 mm was used. The large air gap helps ensure that the core material does not become saturated.

When winding the double inductors for the flyback converter a close coupling between the two windings is needed. In the coil for the converter of **Figure 10** this was achieved by using a bifilar winding, i.e., using two parallel wires.

Conclusion

As we have seen, a variety of switch-mode power supplies can easily be built. These kinds of economical converter find frequent use in low-cost electronic equipment, causing headaches for service engineers who find that the entire circuit stops working when any one component fails. That is unfortunately the disadvantage of these so-called self-oscillating converters.

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Figure 11. Bobbin core for inductors.

Further reading:

We hope this article has whetted your appetite for efficient switch-mode power supplies. The following websites provide further information.

Motorola (ON-Semiconductor)	http://www.onsemi.com
Texas Instruments / Unitrode	http://www.ti.com
Linear Technology	http://www.linear-tech.com
Maxim	http://www.maxim-ic.com
Infineon	http://www.infineon.com
ST Microelectronics	http://www.st.com
International Rectifier	http://www.irf.com

References:

[1] J S. Rohrer, 'LED Switching Driver Cuts Current Draw to 3 mA', *Electronic Design*, August 7 2000, page 130.

[2] Eugene E. Mayle, 'Low-Cost Step-Down Regulator', *Electronic Design*, February 6 1995, page 118.