DC-DC CONVERTERS: A PRIMER

DC-DC converters are electronic devices used whenever we want to change DC electrical power efficiently from one voltage level to another. They're needed because unlike AC, DC can't simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer.

Typical applications of DC-DC converters are where 24V DC from a truck battery must be stepped down to 12V DC to operate a car radio, CB transceiver or mobile phone; where 12V DC from a car battery must be stepped down to 3V DC, to run a personal CD player; where 5V DC on a personal computer motherboard must be stepped down to 3V, 2V or less for one of the latest CPU chips; where the 340V DC obtained by rectifying 240V AC power must be stepped down to 5V, 12V and other DC voltages as part of a PC power supply; where 1.5V from a single cell must be stepped up to 5V or more, to operate electronic circuitry; where 6V or 9V DC must be stepped up to 500V DC or more, to provide an insulation testing voltage; where 12V DC must be stepped up to +/-40V or so, to run a car hifi amplifier's circuitry; or where 12V DC must be stepped up to 650V DC or so, as part of a DC-AC sinewave inverter.

In all of these applications, we want to change the DC energy from one voltage level to another, while wasting as little as possible in the process. In other words, we want to perform the conversion with the highest possible *efficiency*.

An important point to remember about all DC-DC converters is that like a transformer, they essentially just change the input energy into a different impedance level. So whatever the output voltage level, the output power all comes from the input; there's no energy manufactured inside the converter. Quite the contrary, in fact — some is inevitably used up by the converter circuitry and components, in doing their job.

We can therefore represent the basic *power flow* in a converter with this equation:

Pin = Pout + Plosses

where Pin is the power fed into the converter, Pout is the output power and Plosses is the power wasted inside the converter.

Of course if we had a 'perfect' converter, it would behave in the same way as a perfect transformer. There would be no losses, and Pout would be exactly the same as Pin. We could then say that:

Vin x Iin = Vout x Iout

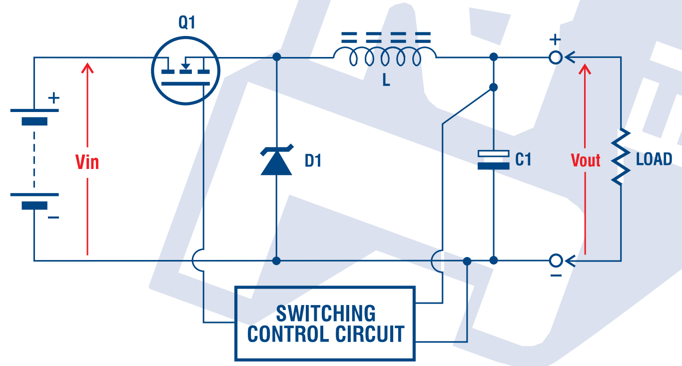

Fig.1: The basic circuit for a Buck type of DC-DC converter. How large Vout is as a proportion of Vin depends on the switching duty cycle for MOSFET Q1.

or by re-arranging, we get:

Vout/Vin = Iin/Iout

In other words, if we step *up* the voltage we step *down* the current, and vice-versa.

Of course there's no such thing as a perfect DC-DC converter, just as there are no perfect transformers. So we need the concept of efficiency, where:

Efficiency(%) = Pout/Pin

Nowadays some types of converter achieve an efficiency of over 90%, using the latest components and circuit techniques. Most others achieve at least 80-85%, which as you can see compares very well with the efficiency of most standard AC transformers.

Many different types

There are many different types of DC-DC converter, each of which tends to be more suitable for some types of application than for others. For convenience they can be classified into various groups, however. For example some converters are only suitable for stepping down the voltage, while others are only suitable for stepping it up; a third group can be used for either.

Another important distinction is between converters which offer full *dielectric isolation* between their input and output circuits, and those which don't. Needless to say this can be very important for some applications, although it may not be important in many others.

In this data sheet we're going to look briefly at each of the main types of DC-DC converter in current use, to give you a good overview. We'll start first with those which don't offer input-output isolation, and then progress to those which do.

Non-isolating converters

The non-isolating type of converter is generally used where the voltage needs to be stepped up or down by a relatively small ratio (say less than 4:1), and there is no problem with the the output and input having no dielectric isolation. Examples are 24V/12V voltage reducers, 5V/3V reducers and 1.5V/5V step-up converters.

There are five main types of converter in this non-isolating group, usually called the **buck**, **boost**, **buck-boost**, **Cuk** and **charge-pump** converters. The *buck* converter is used for voltage step-down/reduction, while the *boost* converter is used for voltage step-up. The *buck-boost* and *Cuk* converters can be used for either step-down or step-up, but are essentially voltage polarity reversers or 'inverters' as well. (The Cuk converter is named after its originator, Slobodan Cuk of Cal Tech university in California.)

The *charge-pump* converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

Buck converter

The basic circuit configuration used in the **buck** converter is shown in Fig.1. As you can see there are only four main components: switching power MOSFET Q1, flywheel diode D1, inductor L and output filter capacitor C1. A control circuit (often a single IC) monitors the output voltage, and maintains it at the desired level by switching Q1 on and off at a fixed rate (the converter's **operating frequency**), but with a varying **duty cycle** (the proportion of each switching period that Q1 is turned on).

When Q1 is turned on, current begins flowing from the input source through Q1 and L, and then into C1 and the load. The magnetic field in L therefore builds up, storing energy in the inductor — with the voltage drop across L opposing or 'bucking' part of the input voltage. Then when Q1 is turned off, the inductor opposes any drop in current by suddenly reversing its EMF, and now supplies current to the load itself via D1.

Without going too deeply into its operation, the DC output voltage which appears across the load is a fraction of the input voltage, and this fraction turns out to be equal to the duty cycle. So we can write:

Vout/Vin = D,

or **Vout = Vin x D**

where D is the duty cycle, and equal to **Ton/T**, where T is the inverse of the operating frequency. So by varying the switching duty cycle, the buck converter's output voltage can be varied as a fraction of the input voltage. A duty cycle of 50% gives a step-down ratio of 2:1, for example, as needed for a 24/12V stepdown converter.

How about the *current* ratio between output and input? Well, not surprisingly that turns out to be the reciprocal of the voltage ratio — ignoring losses for a moment, and assuming our converter is perfectly efficient. So a quick rule of thumb is:

Iout/In = Vin/Vout

So when we're stepping down the voltage by 2:1, the input current is only half the value of the output current. Or it *would* be, if it were not for the converter's losses. Because real-world converters aren't perfect the input current is typically at least 10% higher than this.

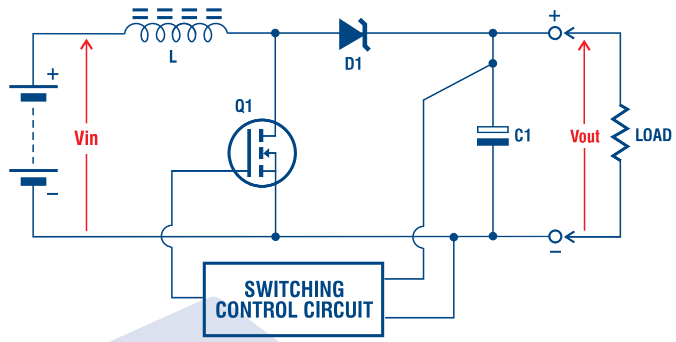

Fig.2: The basic circuit for a Boost converter, which uses virtually the same components but arranged to step the voltage up rather than down. This time the voltage ratio depends on the proportion of the time that Q1 is off.

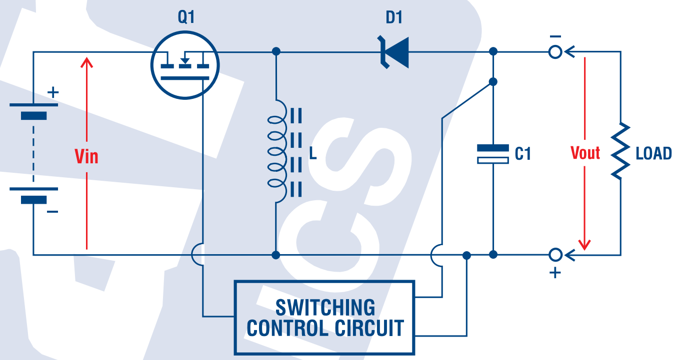

Fig.3: In the Buck-Boost converter, the components are used in yet another way, to provide either voltage stepup or stepdown — but with polarity reversal or 'inversion' as well.

Boost converter

The basic **boost** converter is no more complicated than the buck converter, but has the components arranged differently (Fig.2) in order to step up the voltage. Again the operation consists of using Q1 as a high speed switch, with output voltage control by varying the switching duty cycle.

When Q1 is switched on, current flows from the input source through L and Q1, and energy is stored in the inductor's magnetic field. There is no current through D1, and the load current is supplied by the charge in C1. Then when Q1 is turned off, L opposes any drop in current by immediately reversing its EMF — so that the inductor voltage adds to (i.e., 'boosts') the source voltage, and current due to this boosted voltage now flows from the source through L, D1 and the load, recharging C1 as well.

The output voltage is therefore higher than the input voltage, and it turns out that the voltage step-up ratio is equal to:

Vout/Vin = 1/(1-D)

where 1-D is actually the proportion of the switching cycle that Q1 is **off**, rather than on. So the step-up ratio is also equal to:

Vout/Vin = T/Toff

If you work it out, you find that a 2:1 step-up ratio is achieved with a duty cycle of 50% (Ton = Toff), while a 3:1 step-up needs a duty cycle of 66%.

Again, if we assume that the converter is 100% efficient the ratio of output current to input current is just the reciprocal of the voltage ratio:

Iin/Iout = Vout/Vin

So if we step up the voltage by a factor of 2, the input current will be twice the output current. Of course in a real converter with losses, it will be higher again.

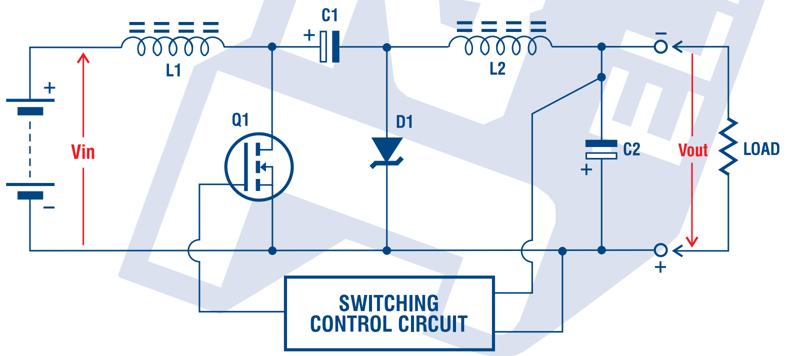

Fig.4: The Cuk converter, which can again step the voltage either up or down, also inverting the polarity. In this case there's also less ripple at both input and output.

Buck-boost converter

The main components in a **buck-boost** converter are again much the same as in the buck and boost types, but they're configured in a different way again (Fig.3).

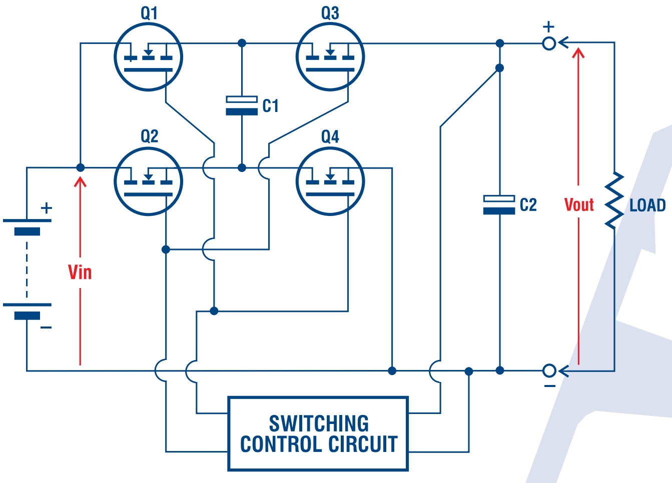

Fig.5: A basic Charge-Pump converter which doubles the input voltage.

This allows the voltage to be stepped either up or down, depending on the duty cycle.

Here when MOSFET Q1 is turned on, inductor L is again connected directly across the source voltage and current flows through it, storing energy in the magnetic field. No current can flow through D1 to the load, because this time the diode is connected so that it's reverse biased. Capacitor C1 must supply the load current in this 'Ton' phase.

But when Q1 is turned off, L is disconnected from the source. Needless to say L again opposes any tendency for the current to drop, and instantly reverses its EMF. This generates a voltage which forward biases D1, and current flows into the load and to recharge C1.

With this configuration the ratio between the output and input voltages turns out to be:

$$Vout/Vin = -D/(1-D)$$

which again equates to

$$Vout/Vin = -Ton/Toff$$

So the buck-boost converter steps the voltage *down* when the duty cycle is less than 50% (i.e., Ton < Toff), and steps it *up* when the duty cycle is greater than 50% (Ton > Toff).

But note that the output voltage is always reversed in polarity with respect to the input — so the buck-boost converter is also a voltage *inverter*. When the duty cycle is exactly 50%, for example, Vout is essentially the same as Vin — except with the opposite polarity. So even when it's not being used to step the voltage up or down, the buck-boost converter may be used to generate a negative voltage rail in equipment operating from a single battery.

As before, the ratio between output and input currents is simply the reciprocal of the voltage ratio, if we ignore losses.

Cuk converter

The basic circuit of a **Cuk** converter is shown in Fig.4, and as you can see it has an additional inductor and capacitor. The circuit configuration is in some ways like a combination of the buck and boost converters, although like the buck-boost circuit it delivers an inverted output. Note that virtually all of the output current must pass through C1, and as ripple current — so C1 is usually a large electrolytic with a high ripple current rating and low ESR (equivalent series resistance), to minimise losses.

When Q1 is turned on, current flows from the input source through L1 and Q1, storing energy in L1's magnetic field. Then when Q1 is turned off, the voltage across L1 reverses to maintain current flow. As in the boost converter current then flows from the input source, through L1 and D1, charging up C1 to a voltage somewhat higher than Vin and transferring to it some of the energy that was stored in L1.

Then when Q1 is turned on again, C1 discharges through via L2 into the load, with L2 and C2 acting as a smoothing filter. Meanwhile energy is being stored again in L1, ready for the next cycle.

As with the buck-boost converter, the ratio between the output voltage and the input voltage again turns out to be:

$$Vout/Vin = -D/(1-D) = -Ton/Toff$$

Where the minus sign again indicates voltage inversion.

So like the buck-boost converter, the Cuk converter can step the voltage either up or down, depending on the switching duty cycle. The main difference between the two is that because of the series inductors at both input and output, the Cuk converter has much lower current ripple in both circuits. In fact by careful adjustment of the inductor values, the ripple in either input or output can be nulled completely.

Charge-pump converter

All of the converters we've looked at so far have depended for their operation on storing energy in the magnetic field of an inductor. However there's another type of converter which operates by storing energy as electric charge in a capacitor, instead. Converters of this type are usually called **charge-pump** converters, and they're a development from traditional voltage doubling and 'voltage multiplying' rectifier circuits.

The basic circuit for a voltage doubling charge-pump converter is shown in Fig.5, and as you can see, it mainly uses four MOSFET switches and a capacitor C1 — usually called the 'charge bucket' capacitor.

Operation is fairly simple. First Q1 and Q4 are turned on, connecting C1 across the input source and allowing it to charge to Vin. Then these switches are turned off, and Q2 and Q3 are turned on instead. C1 is now connected in series with the input voltage source, across output reservoir capacitor C2. As a result some of the charge in C1 is transferred to C2, which charges to twice the input

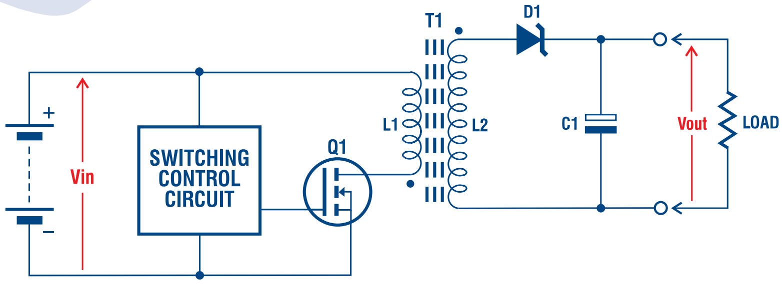

Fig.6: The Flyback converter, which offers isolation as well as a high voltage step-up factor. It's mainly used for lower power applications.

voltage. This cycle is repeated at a fairly high frequency, with C2 providing the load current during the part of the cycle when Q2 and Q3 are turned off.

As you can see all of the energy supplied to the load in this type of converter flows through C1, and as ripple current. So again this capacitor needs to have a relatively high value, have low ESR (to minimise losses) and be able to cope with a heavy ripple current.

A slightly different circuit configuration from that shown in Fig.5 can be used to deliver an inverted voltage of the same value as Vin, instead of a doubled voltage. This type of converter finds use in generating a negative supply rail for electronic circuits running from a single battery.

On the whole, though, the fact that charge-pump converters rely for their operation on charge stored in a capacitor tends to limit them to relatively low current applications. However for this type of operation they're often cheaper and more compact than inductor-type converters.

Isolating converters

All of the converters we've looked at so far have virtually no electrical isolation between the input and output circuits; in fact they share a common connection. This is fine for many applications, but it can make these converters quite unsuitable for other applications where the output needs to be completely isolated from the input. Here's where a different type of inverter tends to be used — the isolating type.

There are two main types of isolating inverter in common use: the 'flyback' type and the 'forward' type. Like most of the non-isolating converters, both types depend for their operation on energy stored in the magnetic field of an inductor — or in this case, a transformer.

Flyback converter

The basic circuit for a **flyback** type converter is shown in Fig.6. In many ways it operates like the buck-boost converter of Fig.3, but using a transformer to store the energy instead of a single inductor.

When MOSFET Q1 is switched on, current flows from the source through primary winding L1 and energy is stored in the transformer's magnetic field. Then when Q1 is turned off, the transformer tries to maintain the current flow through L1 by suddenly reversing the voltage across it — generating a 'flyback' pulse of back-EMF.

Q1 is chosen to have a very high breakdown voltage, though, so current simply can't be maintained in the primary circuit. But because of transformer action an even higher flyback pulse is induced in secondary winding L2. And here diode D1 *is* able to conduct during the pulse, delivering current to the load and recharging filter capacitor C1 (which provides load current between pulses).

So as you can see, the flyback converter again has two distinct phases in its switching cycle. During the first phase Q1 conducts and energy is stored in the transformer core via the primary winding L1. Then in the second phase when Q1 is turned off, the stored energy is transferred into the load and C1 via secondary winding L2.

The ratio between output and input voltage of a flyback converter is not simply a matter of the turns ratio between L2 and L1, because the back-EMF voltage in both windings is determined by the amount of energy stored in the magnetic field, and hence depends on the winding inductance, the length of time that Q1 is turned on, etc. However the ratio between L2 and L1 certainly plays an important role, and most flyback converters have a fairly high turns ratio to allow a high voltage step-up ratio.

Because of the way the flyback converter works, the magnetic flux in its transformer core never reverses in polarity. As a result the core needs to be fairly large for a given power level, to avoid magnetic saturation. Because of this flyback converters tend to be used for relatively **low power** applications — like generating high voltages for insulation testers, Geiger counter tubes, cathode ray tubes and similar devices drawing relatively low current.

Although it's not shown in Fig.6, a third small winding can

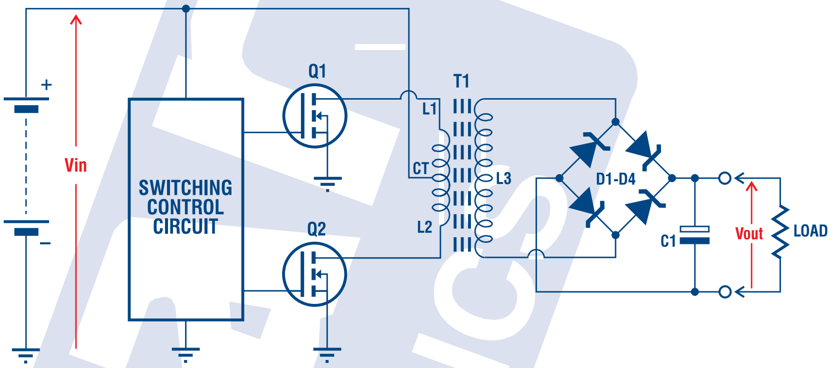

Fig.7: The basic circuit for a Forward converter, in its most popular push-pull form.

be added to the flyback transformer to allow sensing of the flyback pulse amplitude (which is reasonably close to the output voltage Vout). This voltage can be then fed back to the MOSFET switching control circuit, to allow it to automatically adjust the switching to regulate the output voltage.

Forward converter

In contrast with the flyback converter, where there are two distinct phases for energy storage and delivery to the output, the **forward** converter uses the transformer in a more traditional manner, to transfer the energy directly between input and output in the one step.

The most common type of forward converter is the push-pull type, and the basic circuit for this type is shown in Fig.7. As you can see there are now two switching MOSFETs, Q1 and Q2, connected to either end of a centre-tapped primary winding on the transformer. The positive side of the input voltage source is connected to the centre tap.

In operation, the switching control circuit never turns Q1 and Q2 on at the same time; they're turned on alternately. And since their sources are connected back to the negative side of the input voltage, this means that the input voltage is first connected across one half of the primary winding, and then across the other. So current flows first in L1, and then in L2.

This cycle is repeated over and over, continuously and at a relatively high rate — often many tens or even hundreds of kilohertz. So in effect, the action of Q1 and Q2 is to convert the DC input voltage into a high frequency AC square wave.

As a result the transformer's secondary delivers the same

AC square wave, with a peak voltage (during each half-cycle) equal to:

Vac(pk) = Vin x (L3/L1)

Where L3 and L1 (=L2) are the number of turns on each winding, not the inductance. So if secondary winding L3 has 10 times the number of turns as each side of the primary, the transformer's peak output voltage will be 10 times the input voltage.

As you can see, diodes D1-D4 are connected directly across the secondary winding as a bridge rectifier. So the AC square wave that appears across L3 will be rectified back into high voltage DC, to feed the load and maintain the charge on filter capacitor C1. And if we ignore the diode voltage drops, the DC output voltage Vout will be equal to the peak AC output from the transformer — or in other words,

Vout = Vin x (L3/L1)

If you like, then, the forward converter is basically just a way of being able to use a transformer for DC, by converting the DC energy into AC so the transformer can handle it. After being transformed the AC is then rectified back into DC.

Needless to say, once we have the energy in the form of AC we can use the transformer to do pretty well anything we want — step it up, step it down, or any combination of the two. This becomes simply a matter of manipulating the turns on the secondary winding, adding other secondary windings if we want to have multiple outputs, and so on.

Because the forward converter reverses the polarity of magnetic flux in the transformer core for each alternate half-cycle, there's much less tendency to cause saturation than in the flyback converter. So the transformer can be significantly smaller, for the same power level. This together with the 'tighter' and more predictable relationship between input and output voltage makes the forward converter much more suitable for **high power** applications.

One important application for forward converters is in car hifi amplifiers, where they're used to step up the relatively low battery voltage to higher voltage supply rails, to allow the amplifiers to develop higher power output.

Another common use for the forward DC-DC converter is as the heart of many modern multi-voltage 'switch mode' power supplies, as found in computers, TV sets and many other types of electronic equipment. In these cases the incoming AC mains voltage is generally rectified straight away to produce 340V DC (in the case of 240V mains voltage), which is then used to drive the forward converter. There may be three, four or even more secondary windings on the transformer, to produce the various low voltage DC supplies needed by the electronic circuitry.

Efficiency

As mentioned earlier, the perfect DC-DC converter would be one where none of the incoming DC energy is wasted in the converter; it would all end up converted and fed to the output. Needless to say this doesn't occur in the real world.

Inevitably practical converters have losses — voltage drops due to resistance in the inductor or transformer windings, 'on resistance' in the MOSFETs, forward voltage drop in the rectifier diodes, eddy current and hysteresis losses in the inductor or transformer, and so on. It's the job of the converter designer to reduce all of these losses to the lowest possible level, to make the converter as *efficient* as possible.

You may have wondered, for example, why we've shown MOSFETs used as switches in most of the converter circuits. That's because modern MOSFETs make the most efficient electronic switches of high DC currents. When they're 'off' they are virtually an open circuit, and when they're 'on' they are very close to a short circuit — typically only a few milliohms. So they waste very little power.

For the same reason, the diodes used in most modern DC-DC converters are of the Schottky or 'hot carrier' metal-semiconductor junction type (as shown in our schematics). These have a significantly lower forward voltage drop than silicon diodes, and hence waste less power.

Synchronous rectification

For even *higher* efficiency, some converters drop the diodes altogether and use extra MOSFET switches instead — driven by the same circuitry used to drive the main switching MOSFETs, so they're turned on at just the right time for efficient gating or rectification of the output. This is known as **synchronous rectification**.

Synchronous rectification can be used in virtually any of the DC-DC converters we've looked at here. All that's involved is replacing each diode or diodes used in the basic converter with a suitable MOSFET, driven with a control signal that turns it on during the same part of the converter's cycle that the diode would normally conduct.

As a conducting MOSFET has much lower voltage drop than a conducting diode (even a Schottky diode), this achieves a very worthwhile further increase in converter efficiency. Even buck-type stepdown converters with 2-3V output can use synchronous rectification to achieve efficiencies as high as 94% — about 5% higher than is possible with Schottky diodes.

Operating frequency

Finally, you may be wondering why most modern DC-DC converters operate at a relatively high frequency, compared with the 50-60Hz of the AC power mains.

The answer is simple: when you use a high frequency, this allows the use of smaller inductors, transformers and capacitors in order to handle the same power level. And this in turn allows a reduction in both the size and material cost of the converters.

Of course moving to a higher operating frequency also increases some kinds of losses. Once you go beyond a few hundred hertz iron can't be used in the inductor or transformer core, for example — its losses are too great. So ferrite material must be used instead, but this allows very efficient operation at many hundreds of kilohertz.

Progress is being made all the time in developing materials and components that work efficiently at high frequencies, though, and already some DC-DC converters operate very efficiently at around 1MHz. In the future, they'll probably go even higher as engineers strive to make them even smaller and more efficient.