DC/DC Conversion without Inductors

Charge pumps are often the best choice for powering an application requiring a combination of low power and low cost. This article discusses the integrated charge pumps available in the market today. It also explains how to calculate the power dissipation in a charge pump.

A familiar problem in system engineering is the subsystem whose power requirements are not met by the main supply. In such cases, the available supply rails are not directly usable, nor is the direct use of battery voltage (when available) always an option. Lack of space can prevent inclusion of the optimal number of cells, and in other cases the declining voltage of a discharging battery is not acceptable for the application.

Voltage converters can generate the desired voltage levels, and charge pumps are often the best choice for applications requiring some combination of low power, simplicity, and low cost. Charge pumps are easy to use, because they require no expensive inductors or additional semiconductors. Although many conventional charge-pump devices are on the market, this article focuses on new integrated products that have become available recently.

Charge Pumps: A General Description

Charge-pump voltage converters use ceramic or electrolytic capacitors to store and transfer energy. Although capacitors are more common and much cheaper than the coils used in other types of DC/DC converters, capacitors can't change their voltage level abruptly. A changing capacitor voltage always follows the exponential function, which imposes limitations that inductive voltage converters can avoid. On the other hand, inductive voltage converters are more expensive.

Capacitive voltage conversion is achieved by switching a capacitor periodically. Passive diodes can perform this switching function in the simplest cases, provided an alternating voltage is available. Otherwise, DC voltage levels require the use of active switches, which first charge the capacitor by connecting it across a voltage source and then connect it to the output in a way that produces a different voltage level.

A common integrated circuit using this principle is the ICL7660, which could be called the prototype of the classic charge pump. It integrates switches and the oscillator so that the switches S1, S3 and S2, S4 work in alternation (Figure 1). The configuration shown inverts the input voltage. With a slight change in the external connections, it can double or divide the input
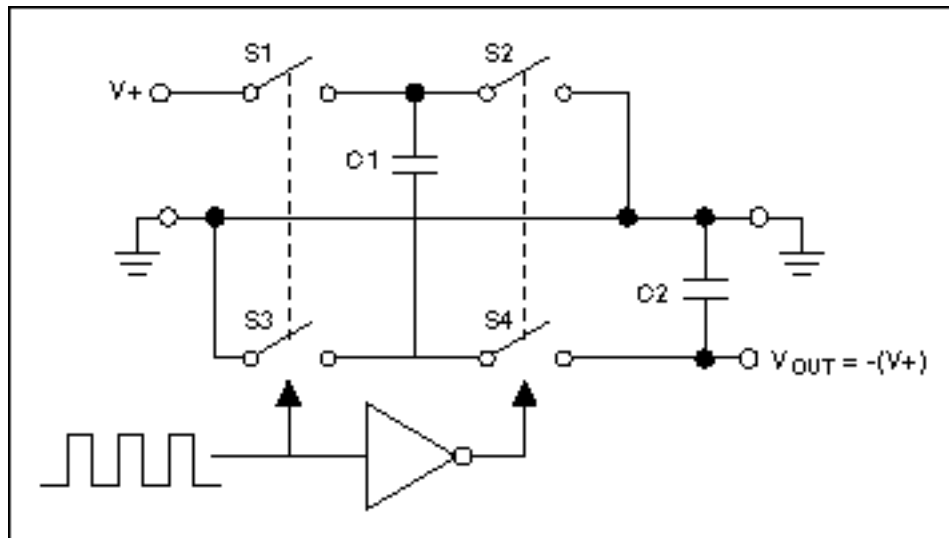
voltage as well.

Figure 1. These essential components illustrate the mechanics of charge-pump operation.

Closing S1 and S3 charges the flying capacitor (C1) to V^+ in the first half cycle. In the second half, S1 and S3 open and S2, S4 close. This action connects the positive terminal of C1 to ground and connects the negative terminal to V_{OUT}. C1 is then in parallel with the reservoir capacitor C2. If the voltage across C2 is smaller than that across C1, charge flows from C1 to C2 until the voltage across C2 reaches -(V+).

An integrated fixed-frequency oscillator drives the periodic switching. This circuit has no output regulation, and the switching frequency remains constant for all loads. Thus, the output-voltage variation depends strongly on the load. With no load, the output voltage corresponds to the negative input voltage: $V_{OUT} = -(V^+)$. As the load increases, V_{OUT} decreases. Output current for the ICL7660 is therefore limited to about 10mA; this is partly due to its low oscillator frequency, and partly due to its integrated analog switches, which are far from ideal. These switches in the "on" state exhibit several ohms of on-resistance. A detailed calculation of the resulting power dissipation will be shown later.

Meanwhile, new pin-compatible circuits (MAX660, MAX860, MAX861, MAX1680, and MAX1681) feature higher switching frequencies and lower on-resistance in the switches. Because their switching frequencies are higher, these new charge pumps operate with smaller capacitors and deliver higher output current. All can be configured as a voltage inverter, doubler, or divider.

The MAX828, MAX829, MAX870, and MAX871, which were designed for inverter applications, reduce the required board area with a smaller package (SOT-23) and smaller external capacitors. New, pin-compatible versions of these devices (MAX1719-MAX1721) provide an additional shutdown pin for switching off the circuit. In that condition, the supply current drops to 1nA, the output disconnects from the input, and the output voltage drops to zero.

Capacitive Voltage Divider

As an example, consider a circuit designed to divide the input voltage by two and double the output current. It offers advantages over linear regulators (which usually convert power into heat) and applications that require a limited output current. A 4mA to 20mA interface, for instance, often provides a relatively high output voltage but a limited pre-set output current. Other applications include the many op amps and µCs that now operate with very low supply voltages. In those circuits, dividing the supply voltage by two theoretically divides the power consumption by four.

The configuration of Figure 2 generates a regulated V_{OUT} (= $V_{IN}/2$) using the capacitive voltage divider C3, C4 and C5, C6. By switching the flying capacitor (C2) alternately between upper and lower halves of this divider, the IC counterbalances any load-dependant voltage differences. The circuit's switching frequency is 35kHz, and its quiescent current is only 36µA. When load currents exceed 1mA, the circuit efficiency exceeds 90%. Given very small load currents (below 100µA), however, even this low 36mA quiescent current leads to a reduction in conversion efficiency. This switched-capacitor configuration provides better regulation than a simple resistive voltage divider can and higher efficiency than that obtained from a simple combination of a voltage divider and an op-amp buffer. The IC specification limits V_{IN} to 5.5V maximum.
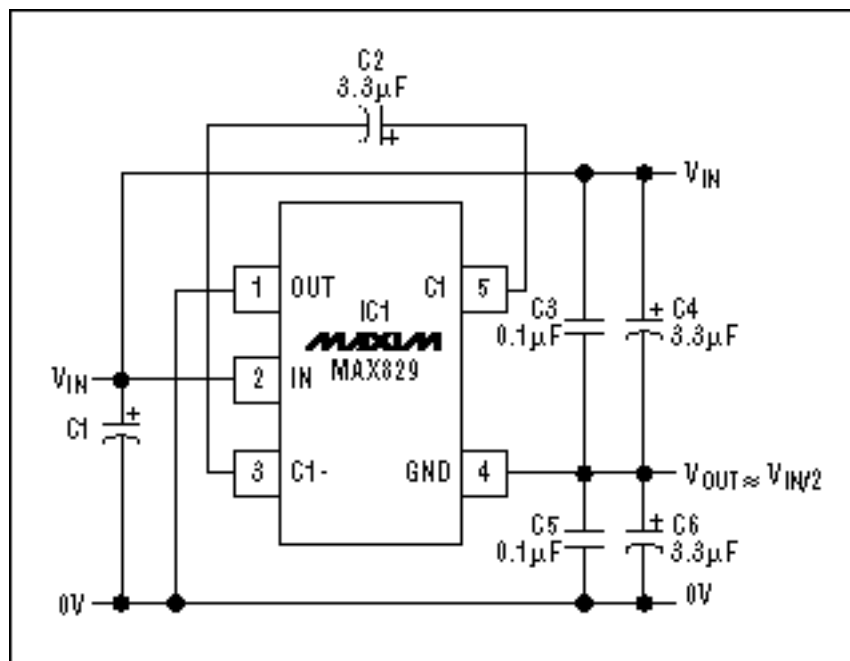

Figure 2. With the connections shown, this inverting charge-pump IC divides the input voltage by two.

Calculating Charge-Pump Power Dissipation

A simple model, in which a capacitor (C1) switches between the output voltage and V$^+$ at frequency f (Figure 3), enables a discussion of charge-pump power dissipation.
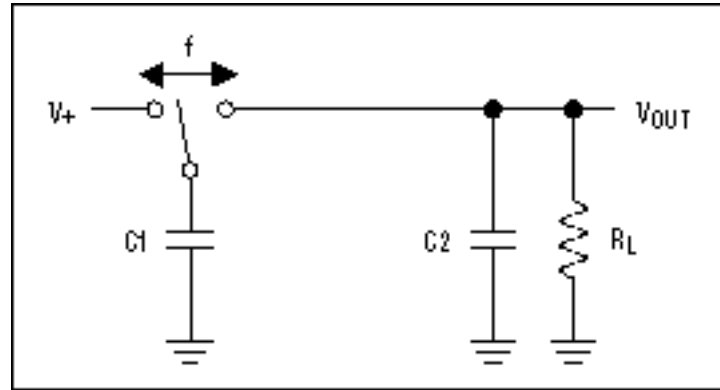

Figure 3. This model of a switched capacitor shows that it behaves like a resistance.

A reservoir capacitor C2 and load R_L are connected to V_{OUT}. The charge transmitted per cycle is

$$\Delta Q = C1(V^+ - V_{OUT}),$$

producing a current I that depends on the frequency f:

$$I = f\Delta Q = fC1(V^+ - V_{OUT}).$$

After changing the equation according to Ohm's Law, an equivalent resistance R_{ERS} for the switched capacitor can be calculated as follows:

$$R_{ERS} = 1/fC1.$$

This equation shows that the resistance and consequently the resistive losses decrease with increasing frequency and higher capacitance. Higher capacitance lowers the output resistance only until the resistance of the switches and the equivalent serial resistance (ESR) of the capacitors exceed RERS. This internal loss (switching loss) can be reduced only by choosing low-ESR capacitors. Switch on-resistance can be lowered through the use of sophisticated new charge pumps.

Switching loss is caused by the voltage difference between the flying capacitor and the output capacitor, as well as by on-resistance in the switches. This voltage difference appears across the switches, causing dissipation in the application. As shown before, a switched capacitor behaves in a way that is similar to a resistance. Thus, you can reduce output resistance and increase the output power by connecting several switched-capacitor devices in parallel.

New Regulated Charge Pumps

Integrated charge pumps that regulate the output voltage are now available. Operating without inductors, they offer regulated output voltages (such as 5V) along with several power-saving modes. Devices such as the MAX682-MAX684 regulated upconverters can operate either in the efficient skip mode or in a fixed-frequency mode with reduced output ripple.

When a drop in output voltage is sensed by the internal comparator, the power-saving skip mode avoids unnecessary switching by activating only the internal oscillator. The result is lower quiescent current and lower switching dissipation, especially for light loads. Skip mode is preferable for low-power applications, because higher levels of quiescent current reduce overall efficiency.

To minimize output ripple, the circuit can oscillate in a fixed-frequency mode that is regulated between 50kHz and 2MHz. Regulation ensures that the flying capacitor is charged through an internal MOSFET, with a charging current that depends on the load. A decreasing output voltage caused by increasing power consumption charges the capacitor with more energy. As benefits of the fixed-frequency mode, the output ripple is lower and the external components are smaller. If you have the impression that charge pumps provide only low output currents of a few milliamps, you will be surprised to learn that the MAX682 delivers as much as 250mA from a 5V output.

Regulated-Charge-Pump Design Idea

An improved design for maintaining a switching frequency that is constant and independent of the input voltage is shown in Figure 4.
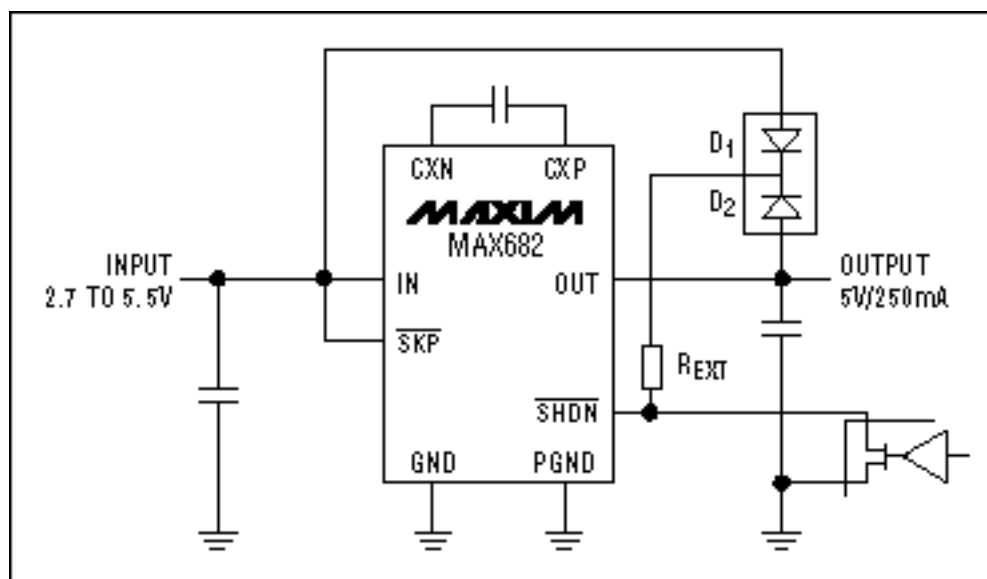

Figure 4. This regulated charge pump maintains a constant switching frequency.

The IC's internal switching frequency is controlled via current into its shutdown pin. The governing equation is taken from the data sheet:

$$R_{EXT} = 45000(V_{IN} - 0.69V)/f_{OSC}, \text{ with } R_{EXT} \text{ in k}\Omega \text{ and } f_{OSC} \text{ in kHz.}$$

Normally, you calculate the value of the external shutdown resistor with the given input voltage and the desired switching frequency. In this case, however, the equation shows that switching frequency and current in the shutdown pin depend on the input voltage V_{IN}. If the input voltage varies, the switching frequency varies too.

Two diodes direct current into the shutdown pin. D1 ensures a reliable start-up by directing current from the input to the shutdown pin when supply voltage is first turned on. When the output voltage achieves 5V or rises higher than V_{IN}, the switching frequency becomes constant because D2 conducts current from the stable output voltage. A tiny diode array in a 3-pin SOT-23 package (BAV70) is recommended for the D1-D2 combination. Note that a shutdown function is still available. Driving the shutdown pin to ground with an open-drain MOSFET simply short-circuits the preset-frequency current to ground.

Regulated Inverter

Many applications need an additional negative voltage such as -5V. Such a voltage can be generated with a regulating charge-pump inverter (MAX868) and a few external components (Figure 5). When charging, the left-hand switches close and the right-hand switches open. Both flying capacitors are charged in parallel, and the load is serviced entirely by charge stored in the output capacitor. During discharge, the switches reconfigure to connect the flying capacitors in series. When connected to the output capacitor, they then transfer charge as required to maintain output-voltage regulation.
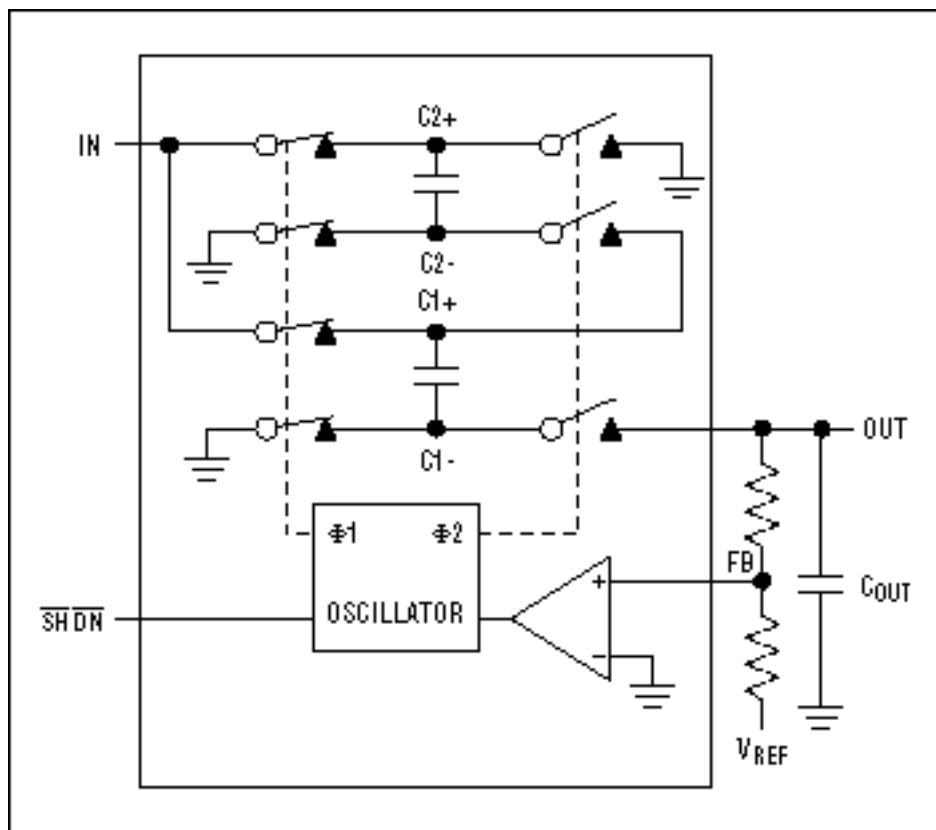
Figure 5. Internal components illustrate the operation of this regulated charge-pump inverter (MAX868).

The internal oscillator frequency (450kHz) is sufficiently high to ensure small external capacitors and high output current. Controlled by a comparator, the oscillator becomes active only when the output voltage is lower than its threshold. This regulation enables the circuit to provide constant output voltages as high as $-2V_{IN}$. At the same time, it draws minimum quiescent currents at light loads.

Buck/Boost Combination

Another problem common in battery-powered applications is a battery voltage that ranges above and below the regulated output voltage. The output voltage of a Li+ cell varies from 3.6V to 1.5V during its lifetime, before being recharged. To derive a constant 3.3V from this changing input, a combined buck/boost converter is required. At first, it downconverts the full battery voltage (3.6V) to 3.3V. When the battery voltage drops below 3.3V, the step-up converter function guarantees the regulated 3.3V output voltage.

Though usually complicated, this approach can now be implemented with a simple charge-pump IC called the MAX1759. Operating from input voltages in the range 1.6V to 5.5V, it generates an output either fixed (3.3V) or adjustable (2.5V to 5.5V) and delivers output currents up to 100mA. It comes in a 10-pin µMAX package and operates with three external capacitors. An additional shutdown mode disconnects output from input while lowering the quiescent current to 1µA.

Charge-Pump Overview

Tables 1 and 2 list all regulated and unregulated charge pumps available from Maxim, including those with special functions and all those mentioned in the text. These tables enable designers to choose a suitable charge pump according to the required package, functions, and output current.

Table 1. Unregulated Charge Pumps

Part Number	Input Voltage	Output Voltage	Output Current	Switching Frequency	Features
MAX828/829	1,5V to 5,5V	-Vin	25mA	12k/35kHz	Inverter; 5-SOT23 package
MAX1720	1,5V to 5,5V	-Vin	25mA	12kHz	Inverter; low quiescent current, shutdown, 5-SOT23 package
MAX1719/1721	1,5V to 5,5V	-Vin	25mA	125kHz	Inverter; 5-SOT23 package, shutdown
MAX870/871	1,4V to 5,5V	-Vin	25mA	125k/500kHz	Inverter; 5-SOT23 package
MAX1682/1683	2V to 5,5V	2*Vin	30mA	12k/35kHz	Doubler; 5-SOT23 package
ICL7660 MAX1044	1,5V to 10V	-Vin 2*Vin	10mA	10kHz	Doubler or inverter; DIP, 8-SO
MAX860/861	1,5V to 5,5V	-Vin 2*Vin	50mA	6k-50k-130 kHz	Doubler or inverter; 8-SO µMAX
MAX861	1,5V to 5,5V	-Vin 2*Vin	50mA	13k-100k-250 kHz	Doubler or inverter; 8-SO µMAX

| MAX1680 | 2V to 5,5V | -Vin 2*Vin | 125mA | 125k - 250kHz | Doubler or inverter; 8-SO µMAX |
| MAX1681 | 3V to 5,5V | -Vin 2*Vin | 125mA | 500k - 1MHz | Doubler or inverter; 8-SO µMAX |

Table 2. Regulated Charge Pumps

Part Number	Input Voltage	Output Voltage	Output Current	Switching Frequency	Features
MAX619	2V to 3,6V	+5V	50mA	500kHz	Regulated 5V, 8-SO package
MAX682	2,7V to 5,5V	+5V	250mA	50k to 2MHz	Regulated 5V, 8-SO µMAX package
MAX683	2,7V to 5,5V	+5V	100mA	50k to 2MHz	Regulated 5V, 8-SO µMAX package
MAX684	2,7V to 5,5V	+5V	50mA	50k to 2MHz	Regulated 5V, 8-SO µMAX package
MAX868	2,7V to 5,5V	Up to -2*Vin	30mA	up to 450kHz	Variable inverted voltage; µMAX package
MAX1673	2,0V to 5,5V	Up to -1*Vin	125mA	350kHz	Variable inverted voltage; fixed frequency
MAX1759	1,6V to 5,5V	2,5V to 5,5V	100mA	1,5MHz	Buck/boost converter

More Information

ICL7660:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1044:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1673:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1680:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1681:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1682:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1683:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1719:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1720:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1721:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX1759:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX619:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX682:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX683:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX684:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX828:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX829:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX860:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX861:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX868:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX870:   QuickView -- Full (PDF) Data Sheet -- Free Samples

MAX871:   QuickView -- Full (PDF) Data Sheet -- Free Samples