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AS THE TREND TOWARD SIZE REDUCTION CONTINUES IN PORTABLE EQUIPMENT, INCLUDING CELLULAR PHONES AND PDA POWER SUPPLIES, SMALLER AND MORE EFFICIENT DC/DC-CONVERSION DEVICES ARE BECOMING CRITICAL. THE CHARGE-PUMP APPROACH OFFERS DESIGN SIMPLICITY AND SMALL SIZE.

Selecting charge-pump dc/dc converters

The demanding power requirements of portable systems force you to address many aspects of design and the reduced cost and size that systems demand. The requirements include smaller pc-board area, lower component count, precise output regulation, higher output currents, lower noise levels, fault protection, and ultra low power dissipation. Although these requirements often seem contradictory, you can use charge-pump dc/dc converters to arrive at a suitable performance-parameter compromise for micropower applications.

Charge pumps, switched capacitors, flying capacitors, and inductorless converters are all different names for dc/dc converters that use a capacitor rather than an inductor or a transformer for energy storage and conversion. Designers have for many years used charge pumps for dc/dc conversion in applications for which the regulation-tolerance, output-current, conversion-efficiency, and noise-generation requirements were not particularly stringent. Recent generations of charge pumps offer improved performance specifications and have become a viable dc/dc-conversion method for cellular phones, portable wireless equipment, notebook computers, PDAs (personal digital assistants), and other applications in which high-density dc/dc conversion is necessary and circuitry real estate is at a premium.

The newest charge-pump ICs are strong alternatives to the inductive-based dc/dc converters in low-current applications for which design simplicity and reduction of component area is the prime objective. **Figure 1** shows a classical boost converter and a charge-pump converter. The component count is clearly much lower for the charge-pump approach. The table in **Figure 1** also shows the total circuit-area saving and the equivalent performances of both converter types. The lack of magnetic components for the charge pump simplifies the design process. However, for applications that have a small V_{IN}-to-V_{OUT} boost differential or high output-load conditions, the inductive-boost method is more viable than the

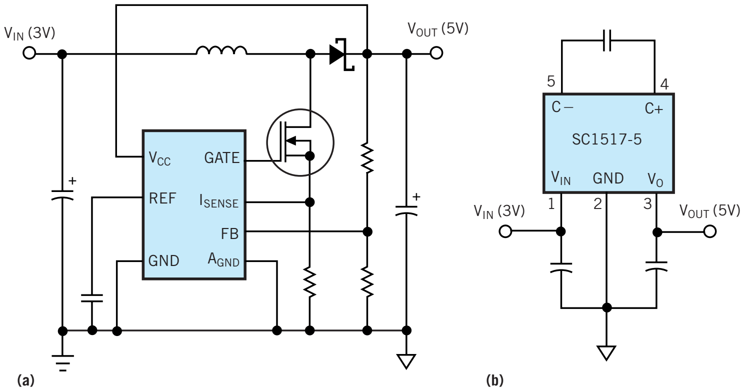


Figure 1

	V_{IN} (V)	I_{IN} (mA)	V_{OUT} (V)	I_{OUT} (mA)	EFFICIENCY (%)	COMPONENT AREA (IN.^{2})	APPROXIMATE HIGH-VOLUME COST
CHARGE-PUMP CONVERTER (SOT-23)	3.01	10.16	4.980	5.03	81.9	0.045	1×
BOOST CONVERTER (SO-8)	3.00	9.92	4.925	5.06	83.7	0.55	3×

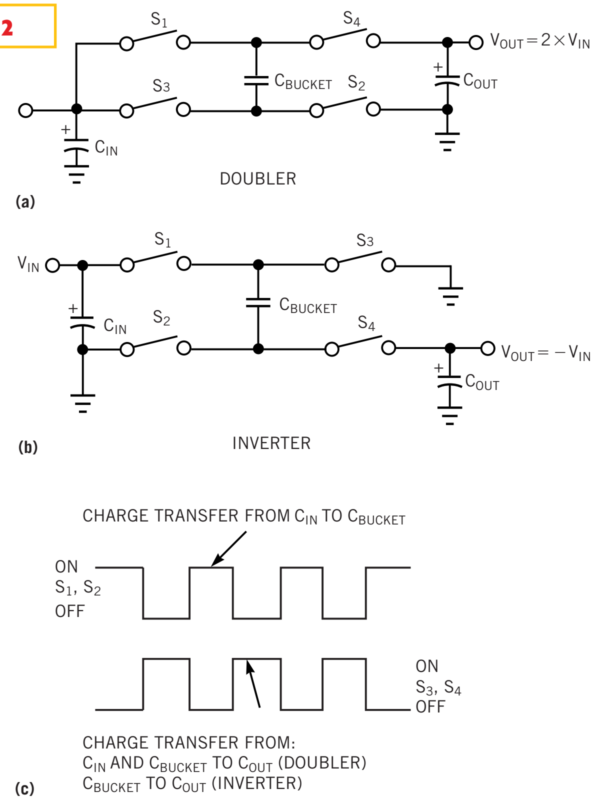
A classical boost converter (a) has a higher component count than a charge-pump converter (b). The table shows similar performance between the two circuits for low-boost-ratio and low-output-current conditions.

charge-pump design. **Table 1** compares the advantages and disadvantages of charge pumps and low-dropout regulators and switching regulators.

As the performance of charge pumps improves and their features become more complex, the selection of the correct device becomes more involved. The list of characteristics and features to consider when choosing and designing with a charge pump includes input-voltage range, output-voltage regulation mode, output current, input current with standby/shutdown, internal versus external bucket capacitor, oscillator frequency, efficiency, short-circuit protection, soft start, thermal protection, power-OK signal, reference voltage, V_{OUT} ripple and capacitor selection, and layout considerations.

The first and most obvious parameter is V_{IN} range. In most cell phones and portable wireless equipment, V_{IN} ranges from approximately 1.65 to 5.5V. This voltage range is a function of the battery type and the number of battery cells in use.

Figure 2



A basic charge pump, which can double (a) or invert (b) the input voltage, transfers charge from input to output via a bucket capacitor based on the operation of oscillator-controlled switches (c).

After you look up the input-voltage range of a device, you should examine the output-voltage-regulation mode. Charge pumps can be either unregulated or regulated. A basic charge-pump circuit, such as a doubler or an inverter, provides an unregulated positive-or-negative output voltage, respectively (**Figure 2**). This type of charge pump produces output voltage as the internal free-running oscillator turns on or off switches S_1 to S_4, thereby transferring charge from the input to the output via the bucket capacitor, C_{BUCKET}. **Figure 2c** shows the timing diagram for the switches. Some variations of the basic doubler exist for which the output voltage is 1.33×V_{IN} or 1.5×V_{IN} instead of 2×V_{IN}. In some cases, you can program an adjustable output voltage via an external resistor divider.

These unregulated charge pumps provide acceptable levels of load regulation, or $\Delta V_{OUT}/\Delta I_{OUT}$, but yield poor line regulation, or $\Delta V_{OUT}/\Delta V_{IN}$. In most cell phones and many portable-system applications, a fixed voltage is available from the battery voltage via a linear regulator. If this fixed voltage is available in the system, an unregulated charge pump is use-

TABLE 1–COMPARISON OF CONVERTERS

Converter type	Advantages	Disadvantages
Charge pump	No magnetic components Ease of design Low component count Small pc-board area Very low power dissipation at shutdown and no-load conditions $V_{OUT}>V_{IN}$ possible	Limited to low-power requirements Limited input-voltage range for practical operation
Low dropout	No magnetic components Ease of design Low component count Low cost Small pc-board area Fast transient-load response	Limited to low- to medium-power requirements due to efficiency Limited V_{OUT}-to-V_{IN} differential (dropout) $V_{OUT}>V_{IN}$ not possible
Switching regulator	Practical for operation over a wide input-voltage range Practical for higher power requirements $V_{IN}<V_{OUT}<V_{IN}$ possible	Magnetic design necessary Higher component count Larger circuit area Higher cost

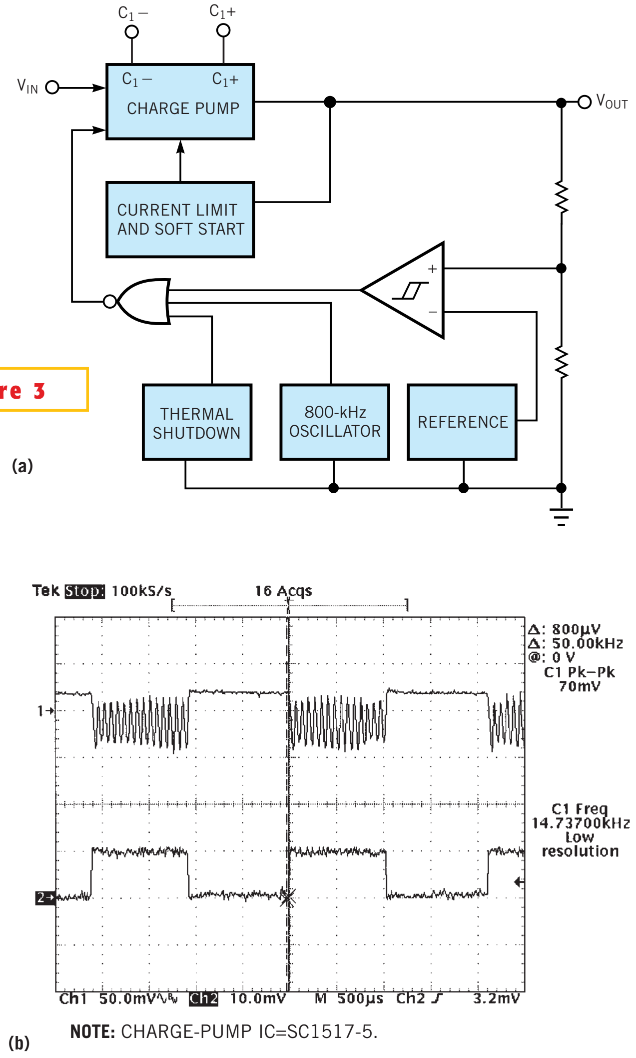
ful and costs less than a regulated version.

The basic unregulated charge pump with a feedback control results in a regulated charge pump that provides both line and load regulation. The control methods for regulated charge pumps are hysteretic and fixed-frequency with linear regulation. In both cases, an internal or external resistor divider senses the output voltage and compares it with a reference voltage.

With hysteretic control, an output voltage that falls below the reference voltage enables the oscillator (**Figure 3a**). During the first clock cycle, the bucket capacitor charges to the input voltage. During the next clock cycle, the total charge consisting of C_{BUCKET} and the input capacitor transfers to the output capacitor. This cycle repeats until the output voltage reaches the upper hysteretic threshold level, at which point the comparator disables the oscillator. The internal comparator continues to enable or disable the oscillator that controls the charge-pump switches based on the output-voltage level.

Figure 3b shows the transient response of a regulated charge pump to a 0- to 10-mA load step. During the load condition, you can see the output-voltage ripple that arises from the hysteresis in the comparator between the reference and the sensed voltage. The hysteretic charge pump can minimize losses due to the oscillator, drivers, and bias generators at lower load conditions. Because at no- or low-load conditions the output voltage does not drop as in the higher load conditions, the internal circuitry is enabled for only short durations to charge the output voltage back to acceptable levels. This short enable time minimizes internal losses and thus prolongs battery-usage time.

Figure 3



NOTE: CHARGE-PUMP IC=SC1517-5.

A hysteretic charge-pump converter uses a comparator to enable and disable the oscillator that controls the charge-pump switches (a). During the load condition, you can see output-voltage ripple due to the hysteresis in the comparator between the reference and the sensed voltages (b).

In a fixed-frequency charge pump with linear regulation, the internal oscillator runs at a fixed frequency when the device is not shut down. The charge pump provides an unregulated voltage to an internal linear regulator that adjusts this voltage to a fixed output. The device achieves regulation by using an internal comparator that senses the output voltage and compares it with an internal reference while adjusting the gate drive to the internal pass MOSFET for a fixed-output voltage (**Figure 4**).

The oscillator frequency that controls the charge pump is usually outside the sensitive frequency spectrums of cellular-communication bandwidths. Unlike the hysteretic converter for which a variable frequency is present at low-load conditions, the design of fixed-frequency converters can restrict any charge-pump-generated switching noise to noncritical bandwidths.

TABLE 2–CAPACITOR ESR CHARACTERISTICS

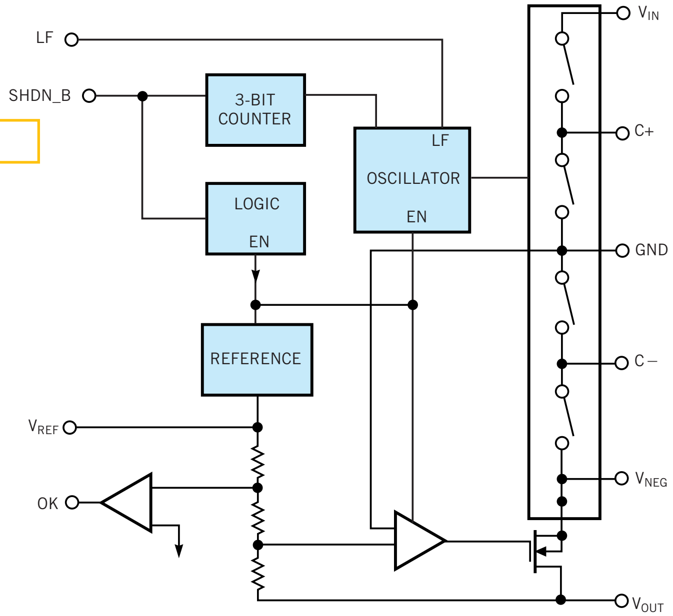
Capacitor type	ESR (Ω)	ESL (nH)
0.1 µF ceramic, 0603 package	0.100	1.60
1 µF ceramic, 1206 package	0.120	0.47
10 µF ceramic, 1206 package	0.075	0.5
47 µF, 16V tantalum D case	0.100	0.60
330 µF, 6.3V Oscon	0.025	2.5
330 µF, 16V aluminum electrolytic	0.143	2.37
820 µF, 4V Oscon	0.012	2.5
1000 µF, 10V aluminum electrolytic	0.053	5

OUTPUT CURRENT

Manufacturers usually specify output current as the minimum current a charge pump can provide while the output voltage is not below $V_{OUT} - V_{DROPOUT}$. For example, the minimum output-current rating for a doubler at a given V_{IN} is at the point where V_{OUT} is below $2 \times V_{IN} - 500$ mV. The charge pump can sustain much higher load currents than the minimum rating if the application can tolerate the output-voltage drop (**Figure 5**).

This dropout point is a function of the internal resistance of the charge pump and the ESR and capacitance value of the C_{BUCKET}. **Figure 6** shows the effect of the ESR and value of C_{BUCKET} on the output current. Ceramic capacitors followed by tantalum types are the preferred type for C_{BUCKET}.

Figure 4



NOTE: CHARGE-PUMP IC=SC1463.

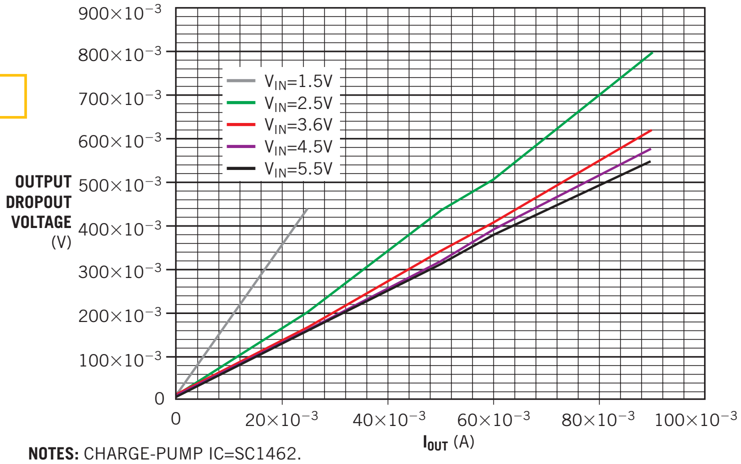
A fixed-frequency-with-linear-regulation charge pump uses an internal comparator to adjust the gate drive to an internal MOSFET.

INPUT CURRENT

Input current is an important parameter in applications for portable systems, such as cellular phones, for which minimum battery discharge is a must. Standby and shutdown modes of operation can minimize input current. During standby, the charge pump is still operational while the output load is at zero. In general, the quiescent current supplying the charge pump is directly proportional to the oscillator frequency. Charge pumps with lower oscillator frequency yield lower quiescent supply current. Also, the hysteretic charge pumps have lower quiescent currents at low-load conditions compared with the fixed-frequency type because the oscillator is enabled only when the output voltage drops.

In shutdown mode, the charge pump and all internal circuitry are disabled, and minimum quiescent current drains from the battery. Typical numbers are in the low-microamp range.

Figure 5



NOTES: CHARGE-PUMP IC=SC1462.
T_A=25°C.

Output current depends on the level of V_{IN} and dropout voltage.

INTERNAL VERSUS EXTERNAL

The bucket capacitor can be either internal or external to the charge pump. A capless charge pump integrates the C_{BUCKET} capacitance within the IC. In applications, for handheld instruments, in which minimizing circuit area is a must, the capacitorless charge pump eliminates the need for an external bucket capacitor.

You can integrate the C_{BUCKET} if you increase the internal oscillator frequency, hence reducing the capacitance value necessary for the charge transfer (**Figure 6b**). In general, due to the higher oscillator frequency, a charge pump with no capacitor has higher quiescent currents and lower efficiency. The lower efficiency is due to increased losses from raising the oscillator frequency (**Figure 7**). Also due to the smaller SOT-23 packages that provide further space saving, charge pumps with no capacitor yield lower output currents.

The savings in circuit-board area offset this loss in efficiency and higher quiescent currents. In cases in which space saving is not the main goal and efficiency is important, charge pumps with external capacitors can yield better performance. External C_{BUCKET} capacitors can have various advantages over capacitorless charge pumps. The value of the external capacitance can be much higher than that of the integrated type. As the value of C_{BUCKET} increases, the oscillator frequency can decrease. The reduction in frequency minimizes losses and thus increases efficiency. An external C_{BUCKET} has additional advantages. You can use the capacitance area saved on the IC for more features or higher output current capabilities. Also, the charge-pump design can account for higher output-current capabilities.

OSCILLATOR FREQUENCY

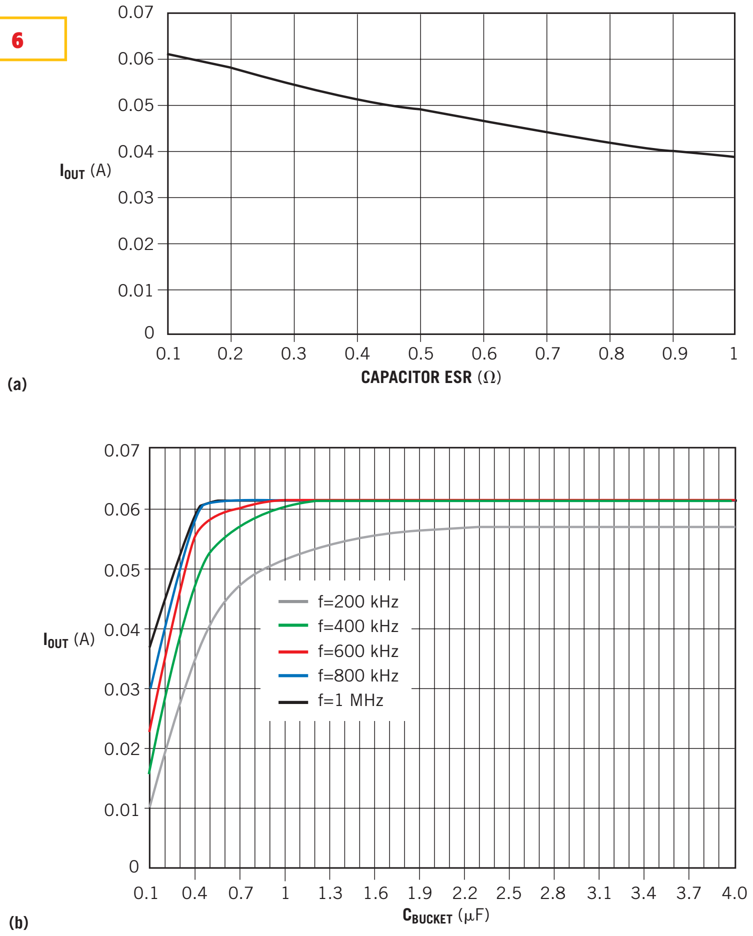
You can evaluate the oscillator frequency according to the following factors. First, the efficiency decreases as the oscillator frequency increases. Second, you may want to use a device with a programmable oscillator frequency to optimize a performance parameter. For example, setting the oscillator to a low frequency results in low quiescent currents, and setting it to a high frequency allows you to use a smaller capacitor. Next, if the application is noise-sensitive, you need to ensure that the oscillator frequency will not interfere with any of the carrier frequencies in the circuit. Finally, you may want to consider synchronizing the oscillator frequency to an external clock for ease of noise-spectrum filtration.

EFFICIENCY

In applications such as cellular telephones, the full-load condition is a small percentage compared with the light load or the standby/shutdown mode for which the load is at a minimum. This unique load condition and the inherently low input-supply current in a charge pump enables maximum usage efficiency of the battery. Also, with the correct charge pump and operating conditions, your design can achieve high efficiencies (**Figure 7**).

During the initial charge-pump start-up, the circuit may generate large current spikes while charging the output capacitors and load. A soft-start option in a charge pump limits the current to an acceptable level until the output capacitors are charged, at which point the charge pump is ready for normal operation.

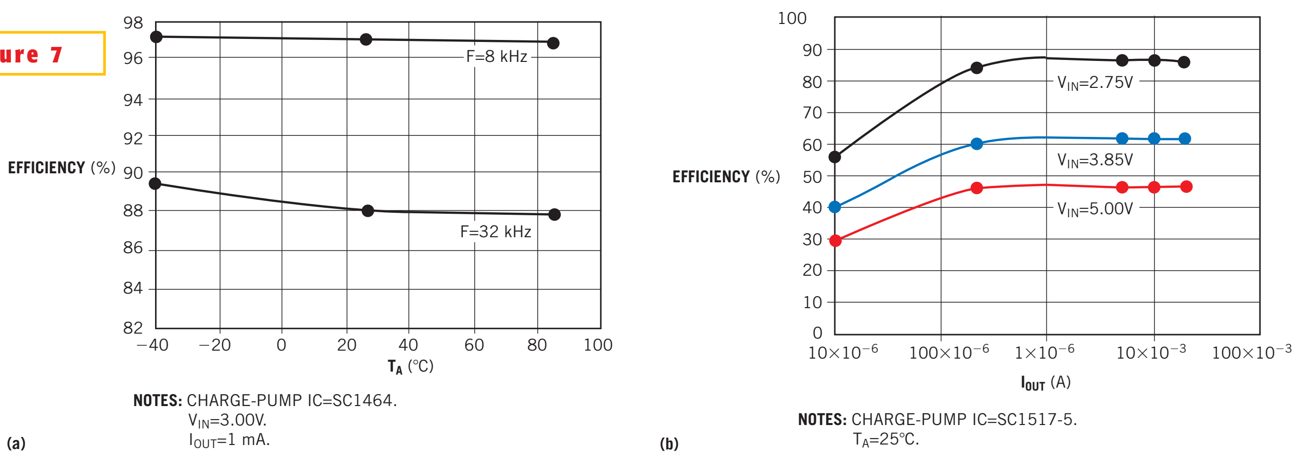
Figure 6



Both the ESR (a) and the value (b) of the bucket capacitor have an effect on the output current.

Another important option is short-circuit protection. A short circuit at the output can cause device stress or failure if no protection circuitry exists. With protection, the device senses the short circuit at the output, enables current-

Figure 7



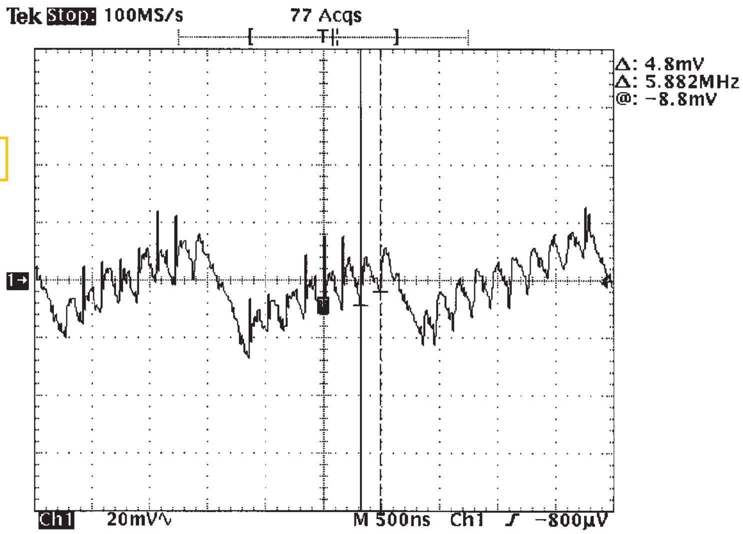
NOTES: CHARGE-PUMP IC=SC1464.
V_{IN}=3.00V.
I_{OUT}=1 mA.

NOTES: CHARGE-PUMP IC=SC1517-5.
T_A=25°C.

Factors that affect efficiency include T_A and frequency (a) and I_{OUT} and V_{IN} (b).

limiting circuitry, and indefinitely disables the charge pump. After you remove the short circuit, enabling the charge pump resumes normal operation.

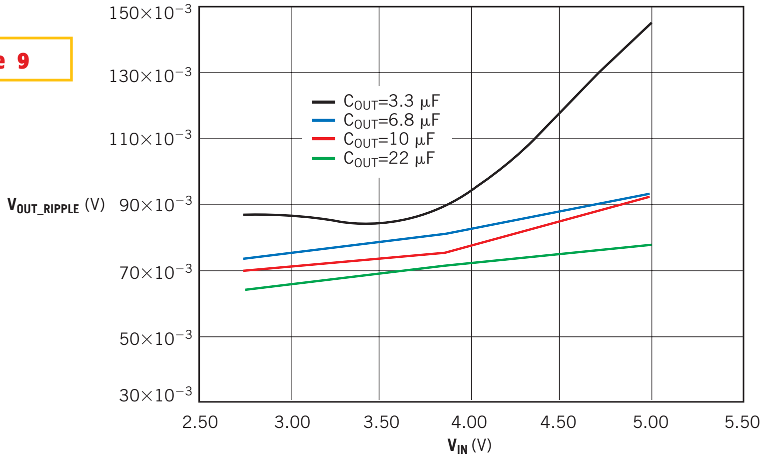
Figure 8



Low-frequency ripple due to comparator hysteresis consists of a high-frequency component.

Charge pumps can also have thermal shutdown. During a short-circuit condition at the output, the on-resistance of the internal switches limits the output current. Power dissipation in a switch is a function of the current and resistance: $P_D = I^2_{RMS} \times R_{DS(ON)}$. This power dissipation and the thermal-dissipation capability of the packaged die determine the junction temperature during a short-circuit condition: $T_J = P_D \times \Theta_{JA} + T_A$, where T_A is the ambient temperature and Θ_{JA} is the junction-to-ambient thermal resistance. If you don't remove the short-circuit condition and there is no internal protection, failure might occur. Thermal-shutdown circuitry senses the die temperature, disables the internal switches or oscillator until the die temperature reaches an acceptable level, and then enables the charge pump. This cycle repeats indefinitely without device failure until the short-circuit condition no longer exists.

Figure 9



NOTES: CHARGE-PUMP IC=SCI517-5.
I_{OUT}=10 mA.

Different values of output capacitance produce different values of ripple voltage.

You can use a power-OK CMOS output as a control signal to enable other circuitry after the charge pump achieves regulated output or to indicate a possible fault condition at the output of the charge pump.

An available integrated reference voltage can save cost and space, and you can use this voltage as a control reference for other circuitry in the application.

The peak-to-peak output ripple voltage depends on the oscillator frequency, the hysteresis window of the comparator, the ESR of C_{OUT} and C_{BUCKET}, and the value of C_{OUT} and C_{BUCKET}.

The first two factors are fixed and depend on the charge-pump device you use. However, you can optimize the ESR and capacitance values of C_{BUCKET} and C_{OUT} for the best performance and reduction of the output ripple. The following formula gives an approximation for output ripple:

$$V_{OUT\_RIPPLE} = \frac{I_{OUT}}{2 \times F_{OSC} \times C_{BUCKET}} + I_{OUT} \times ESR\_C_{BUCKET}.$$

From **Figure 8** you can see that the low-frequency ripple due to the hysteresis of the comparator consists of a high-frequency ripple. This high-frequency ripple is a function of the ESR of the capacitance at the output. Using output capacitors with low ESR can minimize this ripple. **Figure 9** shows the effect of output-capacitance value on the ripple voltage, in this case using multilayer ceramic capacitors with ESR less than 0.1Ω. **Table 2** shows typical capacitor characteristics.

You should follow standard power-board layout to ensure proper charge-pump operation. To minimize stray inductance, you should use large power planes or traces and reduce the distances between input, output, and the load. All related components should sit as close as possible to the charge pump.□

AUTHOR'S BIOGRAPHY

Obalit Khorshid is an applications engineer at Semtech Corp (Newbury Park, CA, www.semtech.com), where he develops power-conversion products for customer-application requirements. He holds a BSEE from California State University (Northridge, CA) and is a member of the American Assyrian Engineering Society.