CAT661

High Frequency 100 mA CMOS Charge Pump, Inverter/Doubler

Description

The CAT661 is a charge–pump voltage converter. It can invert a positive input voltage to a negative output. Only two external capacitors are needed. With a guaranteed 100 mA output current capability, the CAT661 can replace a switching regulator and its inductor. Lower EMI is achieved due to the absence of an inductor.

In addition, the CAT661 can double a voltage supplied from a battery or power supply. Inputs from 2.5 V to 5.5 V will yield a doubled, 5 V to 11 V output.

A Frequency Control pin (BOOST/FC) is provided to select either a high (typically 135 kHz) or low (25 kHz) internal oscillator frequency, thus allowing quiescent current vs. capacitor size trade-offs to be made. The 135 kHz frequency is selected when the FC pin is connected to V+. The operating frequency can also be adjusted with an external capacitor at the OSC pin or by driving OSC with an external clock.

8–pin SOIC package is available. For die availability, contact ON Semiconductor marketing.

The CAT661 can replace the MAX660 and the LTC660 in applications where higher oscillator frequency and smaller capacitors are needed. In addition, the CAT661 is pin compatible with the 7660/1044, offering an easy upgrade for applications with 100 mA loads.

Features

• Converts V+ to V− or V+ to 2V+
• Low Output Resistance, 10 Ω Max.
• High Power Efficiency
• Selectable Charge Pump Frequency of 25 kHz or 135 kHz; Optimize Capacitor Size
• Low Quiescent Current
• Pin-compatible to MAX660, LTC660 with Higher Frequency Operation
• Available in 8–pin SOIC Package
• These Devices are Pb–Free, Halogen Free/BFR Free and are RoHS Compliant

Applications

• Negative Voltage Generator
• Voltage Doubler
• Voltage Splitter
• Low EMI Power Source
• GaAs FET Biasing
• Lithium Battery Power Supply
• Instrumentation
• LCD Contrast Bias
• Cellular Phones, Pagers
Typical Application

![Figure 1. Voltage Inverter](image1.png)

![Figure 2. Positive Voltage Doubler](image2.png)

**Table 1. PIN DESCRIPTIONS**

<table>
<thead>
<tr>
<th>Pin Number</th>
<th>Name</th>
<th>Circuit Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boost/FC</td>
<td>Frequency Control for the internal oscillator. With an external oscillator BOOST/FC has no effect.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Inverter Mode</strong></td>
</tr>
<tr>
<td>Boost/FC</td>
<td>Oscillator Frequency</td>
<td>Open: 25 kHz typical, 10 kHz minimum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V+: 135 kHz typical, 80 kHz minimum to 135 kHz typical, 40 kHz minimum</td>
</tr>
<tr>
<td>2</td>
<td>CAP+</td>
<td>Charge Pump Capacitor. Positive terminal.</td>
</tr>
<tr>
<td>4</td>
<td>CAP−</td>
<td>Charge pump capacitor. Negative terminal.</td>
</tr>
<tr>
<td>5</td>
<td>OUT</td>
<td>Output for negative voltage.</td>
</tr>
<tr>
<td>6</td>
<td>LV</td>
<td>Low-Voltage selection pin. When the input voltage is less than 3 V, connect LV to GND. For input voltages above 3 V, LV may be connected to GND or left open. If OSC is driven externally, connect LV to GND.</td>
</tr>
<tr>
<td>7</td>
<td>OSC</td>
<td>Oscillator control input. An external capacitor can be connected to lower the oscillator frequency. An external oscillator can drive OSC and set the chip operating frequency. The charge-pump frequency is one-half the frequency at OSC.</td>
</tr>
</tbody>
</table>
# Table 2. ABSOLUTE MAXIMUM RATINGS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ratings</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>V+ to GND</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>Input Voltage (Pins 1, 6 and 7)</td>
<td>-0.3 to (V+ + 0.3)</td>
<td>V</td>
</tr>
<tr>
<td>BOOST/FC and OSC Input Voltage</td>
<td>The least negative of (Out − 0.3 V) or (V+ − 6 V) to (V+ + 0.3 V)</td>
<td>V</td>
</tr>
<tr>
<td>Output Short-circuit Duration to GND (OUT may be shorted to GND for 1 sec without damage but shorting OUT to V+ should be avoided.)</td>
<td>1</td>
<td>sec.</td>
</tr>
<tr>
<td>Continuous Power Dissipation (T_A = 70°C) Plastic DIP SO TDFN</td>
<td>730</td>
<td>mW</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>mW</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>W</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-65 to +160</td>
<td>°C</td>
</tr>
<tr>
<td>Lead Soldering Temperature (10 sec)</td>
<td>300</td>
<td>°C</td>
</tr>
<tr>
<td>ESD Rating – Human Body Model</td>
<td>2000</td>
<td>V</td>
</tr>
<tr>
<td>Operating Ambient Temperature Range</td>
<td>-40 to +85</td>
<td>°C</td>
</tr>
</tbody>
</table>

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

NOTE: T_A = Ambient Temperature

# Table 3. ELECTRICAL CHARACTERISTICS

(V+ = 5 V, C1 = C2 = 100 µF, Boost/FC = Open, C_OSC = 0 pF, and Test Circuit is Figure 3 unless otherwise noted. Temperature is T_A = T_MIN to T_MAX unless otherwise noted.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>VS</td>
<td>Inverter: LV = Open, R_L = 1 kΩ</td>
<td>3.0</td>
<td></td>
<td>5.5</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverter: LV = GND, R_L = 1 kΩ</td>
<td>1.5</td>
<td>5.5</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Doubler: LV = OUT, R_L = 1 kΩ</td>
<td>2.5</td>
<td>5.5</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Supply Current</td>
<td>IS</td>
<td>BOOST/FC = open, LV = Open</td>
<td>0.2</td>
<td>0.5</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BOOST/FC = V+, LV = Open</td>
<td>1</td>
<td>3</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Output Current</td>
<td>IOUT</td>
<td>OUT is more negative than −4 V</td>
<td>100</td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>RO</td>
<td>C1 = C2 = 10 µF</td>
<td>3.5</td>
<td>10</td>
<td></td>
<td>Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BOOST/FC = V+ (C1, C2 ESR ≤ 0.5 Ω)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C1 = C2 = 100 µF (Note 5)</td>
<td>3.5</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oscillator Frequency (Note 6)</td>
<td>FOSC</td>
<td>BOOST/FC = Open</td>
<td>10</td>
<td>25</td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BOOST/FC = V+</td>
<td>80</td>
<td>135</td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>OSC Input Current</td>
<td>IOSC</td>
<td>BOOST/FC = Open</td>
<td>±2</td>
<td>±10</td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>PE</td>
<td>R_L = 1 kΩ connected between V+ and OUT, T_A = 25°C (Doubler)</td>
<td>96</td>
<td>98</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_L = 500 Ω connected between GND and OUT, T_A = 25°C (Inverter)</td>
<td>92</td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>I_L = 100 mA to GND, T_A = 25°C (Inverter)</td>
<td>88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Conversion Efficiency</td>
<td>VEFF</td>
<td>No load, T_A = 25°C</td>
<td>99</td>
<td>99.9</td>
<td></td>
<td>%</td>
</tr>
</tbody>
</table>

4. In Figure 3, test circuit electrolytic capacitors C1 and C2 are 100 µF and have 0.2 Ω maximum ESR. Higher ESR levels may reduce efficiency and output voltage.
5. The output resistance is a combination of the internal switch resistance and the external capacitor ESR. For maximum voltage and efficiency keep external capacitor ESR under 0.2 Ω.
6. FOSC is tested with C_OSC = 100 pF to minimize test fixture loading. The test is correlated back to C_OSC = 0 pF to simulate the capacitance at OSC when the device is inserted into a test socket without an external C_OSC.
Voltage Inverter

**Figure 3. Test Circuit Voltage Inverter**

**TYPICAL OPERATING CHARACTERISTICS**

(Typical characteristic curves are generated using the test circuit in Figure 3. Inverter test conditions are: $V_+ = 5 \text{ V}$, $LV = \text{GND}$, BOOST/FC = Open and $T_A = 25^\circ \text{C}$ unless otherwise indicated. Note that the charge–pump frequency is one–half the oscillator frequency.)

**Figure 4. Supply Current vs. Input Voltage**

**Figure 5. Supply Current vs. Temperature**

(No Load)

**Figure 6. Output Resistance vs. Input Voltage**

**Figure 7. Output Resistance vs. Temperature**

(50 $\Omega$ Load)
Voltage Doubler

Figure 14. Test Circuit Voltage Doubler

**TYPICAL OPERATING CHARACTERISTICS**

(Typical characteristic curves are generated using the circuit in Figure 14. Doubler test conditions are: \( V^+ = 5 \) V, \( LV = \text{GND} \), \( \text{BOOST/FC} = \text{Open} \) and \( T_A = 25^\circ \) C unless otherwise indicated.)

**Figure 15. Supply Current vs. Input Voltage (No Load)**

**Figure 16. Output Resistance vs. Input Voltage**

**Figure 17. Supply Current vs. Oscillator Frequency**

**Figure 18. Output Voltage Drop vs. Load Current**
Application Information

Circuit Description and Operating Theory

The CAT661 switches capacitors to invert or double an input voltage.

Figure 19 shows a simple switch capacitor circuit. In position 1 capacitor C1 is charged to voltage V1. The total charge on C1 is Q1 = C1V1. When the switch moves to position 2, the input capacitor C1 is discharged to voltage V2. After discharge, the charge on C1 is Q2 = C1V2.

The charge transferred is:

\[ \Delta Q = Q_1 - Q_2 = C_1 \times (V_1 - V_2) \]

If the switch is cycled “F” times per second, the current (charge transfer per unit time) is:

\[ I = F \times \Delta Q = F \times C_1 \times (V_1 - V_2) \]

Rearranging in terms of impedance:

\[ I = \frac{(V_1 - V_2)}{1/FC_1} = \frac{V_1 - V_2}{REQ} \]

The 1/FC1 term can be modeled as an equivalent impedance REQ. A simple equivalent circuit is shown in Figure 20. This circuit does not include the switch resistance nor does it include output voltage ripple. It does allow one to understand the switch-capacitor topology and make prudent engineering tradeoffs.

For example, power conversion efficiency is set by the output impedance, which consists of REQ and switch resistance. As switching frequency is decreased, REQ, the 1/FC1 term, will dominate the output impedance, causing higher voltage losses and decreased efficiency. As the frequency is increased quiescent current increases. At high frequency this current becomes significant and the power efficiency degrades.

The oscillator is designed to operate where voltage losses are a minimum. With external 150 \( \mu \)F capacitors, the internal switch resistances and the Equivalent Series Resistance (ESR) of the external capacitors determine the effective output impedance.

A block diagram of the CAT661 is shown in Figure 21.

![Figure 19. Switched-Capacitor Building Block](http://onsemi.com)

![Figure 20. Switched-Capacitor Equivalent Circuit](http://onsemi.com)
Oscillator Frequency Control
The switching frequency can be raised, lowered or driven from an external source. Figure 22 shows a functional diagram of the oscillator circuit.

The CAT661 oscillator has four control modes:

<table>
<thead>
<tr>
<th>BOOST/FC Pin Connection</th>
<th>OSC Pin Connection</th>
<th>Nominal Oscillator Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>Open</td>
<td>25 kHz</td>
</tr>
<tr>
<td>BOOST/FC = V+</td>
<td>Open</td>
<td>135 kHz</td>
</tr>
<tr>
<td>Open or BOOST/FC = V+</td>
<td>External Capacitor</td>
<td>−</td>
</tr>
<tr>
<td>Open</td>
<td>External Clock</td>
<td>Frequency of external clock</td>
</tr>
</tbody>
</table>

If BOOST/FC and OSC are left floating (Open), the nominal oscillator frequency is 25 kHz. The pump frequency is one-half the oscillator frequency.

By connecting the BOOST/FC pin to V+, the charge and discharge currents are increased, and the frequency is increased by approximately 6 times. Increasing the frequency will decrease the output impedance and ripple currents. This can be an advantage at high load currents. Increasing the frequency raises quiescent current but allows smaller capacitance values for C1 and C2.

If pin 7, OSC, is loaded with an external capacitor the frequency is lowered. By using the BOOST/FC pin and an external capacitor at OSC, the operating frequency can be set.

Note that the frequency appearing at CAP+ or CAP− is one-half that of the oscillator.

Driving the CAT661 from an external frequency source can be easily achieved by driving Pin 7 and leaving the BOOST pin open, as shown in Figure 22. The output current from Pin 7 is small, typically 1 µA to 8 µA, so a CMOS can drive the OSC pin. For 5 V applications, a TTL logic gate can be used if an external 100 kΩ pull-up resistor is used as shown in Figure 23.

![Figure 21. CAT661 Block Diagram](http://onsemi.com)
Capacitor Selection

Low ESR capacitors are necessary to minimize voltage losses, especially at high load currents. The exact values of C1 and C2 are not critical but low ESR capacitors are necessary.

The ESR of capacitor C1, the pump capacitor, can have a pronounced effect on the output. C1 currents are approximately twice the output current and losses occur on both the charge and discharge cycle. The ESR effects are thus multiplied by four. A 0.5 Ω ESR for C1 will have the same effect as a 2 Ω increase in CAT661 output impedance.

Output voltage ripple is determined by the value of C2 and the load current. C2 is charged and discharged at a current roughly equal to the load current. The internal switching frequency is one-half the oscillator frequency.

\[
VRIPPLE = \frac{I_{OUT}}{F_{OSC} \times C2} + \frac{I_{OUT} \times ESR_{C2}}{C2}
\]

For example, with a 25 kHz oscillator frequency (12.5 kHz switching frequency), a 150 μF C2 capacitor with an ESR of 0.2 Ω and a 100 mA load peak-to-peak ripple voltage is 45 mV.

<table>
<thead>
<tr>
<th>VRIPPLE (mV)</th>
<th>IOUT (mA)</th>
<th>FOSC (kHz)</th>
<th>C2 (μF)</th>
<th>C2 ESR (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>100</td>
<td>25</td>
<td>150</td>
<td>0.2</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>135</td>
<td>150</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5. VRIPPLE vs. FOSC

Figure 22. Oscillator

Figure 23. External Clocking
Capacitor Suppliers
The following manufacturers supply low-ESR capacitors:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Capacitor Type</th>
<th>Phone</th>
<th>WEB</th>
<th>Email</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVX/Kyocera</td>
<td>TPS/TPS3</td>
<td>843–448–9411</td>
<td><a href="http://www.avxcorp.com">www.avxcorp.com</a></td>
<td><a href="mailto:avx@avxcorp.com">avx@avxcorp.com</a></td>
<td>Tantalum</td>
</tr>
<tr>
<td>Vishay/Sprague</td>
<td>595</td>
<td>402–563–6866</td>
<td><a href="http://www.vishay.com">www.vishay.com</a></td>
<td>–</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Sanyo</td>
<td>MV–AX, UGX</td>
<td>619–661–6835</td>
<td><a href="http://www.sanyo.com">www.sanyo.com</a></td>
<td><a href="mailto:Svcsales@sanyo.com">Svcsales@sanyo.com</a></td>
<td>Aluminum</td>
</tr>
<tr>
<td></td>
<td>HC/HD</td>
<td></td>
<td></td>
<td></td>
<td>Aluminum</td>
</tr>
</tbody>
</table>

Capacitor manufacturers continually introduce new series and offer different package styles. It is recommended that before a design is finalized capacitor manufacturers should be surveyed for their latest product offerings.

Controlling Loss in CAT661 Applications
There are three primary sources of voltage loss:

1. Output resistance: 
   \[
   VLOSS = ILOAD \times ROUT, \text{where} \ ROUT \text{is the CAT661 output resistance and} \ ILOAD \text{is the load current.}
   \]

2. Charge pump (C1) capacitor ESR: 
   \[
   VLOSS_{C1} = 4 \times ESRC1 \times ILOAD, \text{where} \ ESRC1 \text{is the ESR of capacitor C1.}
   \]

3. Output or reservoir (C2) capacitor ESR: 
   \[
   VLOSS_{C2} = ESRC2 \times ILOAD, \text{where} \ ESRC2 \text{is the ESR of capacitor C2.}
   \]
   Increasing the value of C2 and/or decreasing its ESR will reduce noise and ripple.
   The effective output impedance of a CAT661 circuit is approximately:
   \[
   R_{\text{circuit}} = \frac{1}{\frac{1}{4 	imes ESRC1} + \frac{1}{ESRC2}}
   \]
Typical Applications

Voltage Inversion Positive–to–Negative

The CAT661 easily provides a negative supply voltage from a positive supply in the system. Figure 24 shows a typical circuit. The LV pin may be left floating for positive input voltages at or above 3.3 V.

Positive Voltage Doubler

The voltage doubler circuit shown in Figure 25 gives $V_{OUT} = 2 \times V_{IN}$ for input voltages from 2.5 V to 5.5 V.
Precision Voltage Divider

A precision voltage divider is shown in Figure 26. With load currents under 100 nA, the voltage at pin 2 will be within 0.002% of \( V+/2 \).

![Figure 26. Precision Voltage Divider (Load \( \leq 100 \text{nA} \)](image)

Battery Voltage Splitter

Positive and negative voltages that track each other can be obtained from a battery. Figure 27 shows how a 9 V battery can provide symmetrical positive and negative voltages equal to one–half the battery voltage.

![Figure 27. Battery Splitter](image)
Cascade Operation for Higher Negative Voltages

The CAT661 can be cascaded as shown in Figure 28 to generate more negative voltage levels. The output resistance is approximately the sum of the individual CAT661 output resistance.

\[ V_{OUT} = -N \times V_{IN} \]

where \( N \) represents the number of cascaded devices.

Parallel Operation

Paralleling CAT661 devices will lower output resistance. As shown in Figure 29, each device requires its own pump capacitor, \( C_2 \), but the output reservoir capacitor is shared with all devices. The value of \( C_2 \) should be increased by a factor of \( N \), where \( N \) is the number of devices.

\[ \frac{R_{OUT}}{C_0} = \frac{R_{OUT \text{ (of CAT661)}}}{N \text{ (NUMBER OF DEVICES)}} \]
SOIC–8, 150 mils
CASE 751BD
ISSUE O
DATE 19 DEC 2008

PIN # 1 IDENTIFICATION

TOP VIEW

SIDE VIEW

END VIEW

Notes:
(1) All dimensions are in millimeters. Angles in degrees.
(2) Complies with JEDEC MS-012.

Symbol | Min | Nom | Max
--- | --- | --- | ---
A | 1.35 | 1.75 |
A1 | 0.10 | 0.25 |
b | 0.33 | 0.51 |
c | 0.19 | 0.25 |
D | 4.80 | 5.00 |
E | 5.80 | 6.20 |
E1 | 3.80 | 4.00 |
e | 1.27 BSC |
h | 0.25 | 0.50 |
L | 0.40 | 1.27 |
θ | 0° | 8° |

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