A Simple Model for DC/DC Charge Pumps

Introduction

Charge pump regulators provide an excellent DC/DC converter solution for low-power portable applications, typically below 300mA output current. Charge pumps provide enhanced efficiency when compared to LDO regulators and do not need a large, expensive magnetic component required with inductive switching solutions.

The charge pump provides enhanced operating efficiency with higher input and output noise when compared to LDO regulators. Unlike LDO regulators, which can only step down voltage, charge pumps can provide an output voltage which is greater than the input voltage. In addition, charge pumps can generate a negative output voltage from a positive input voltage. A comparison between the operating efficiency of a step-down charge pump and an LDO will be provided in this application note.

Charge pump operating efficiency is typically less than inductive DC/DC switching regulators. In addition, charge pump switching noise can be greater than inductive switching regulators. Like charge pumps, inductive switching regulators provide step-down, step-up, or reverse polarity outputs. Charge pump regulators typically provide a lower cost solution because they do not require an inductor. A comparison between the efficiency of a charge pump and an inductive switching regulator will be provided in this application note.

This application note will cover the operating details of DC/DC step-up (boost) and step-down (buck and LDO) multi-mode charge pumps using two flying capacitors. Charge pump integrated circuits (ICs) control the switching arrangement of the flying capacitors and modulate the switching events and/or duty cycle to maintain a regulated DC output voltage.

The ICs switching network enables parallel or series arrangement of the flying capacitors during alternative charge and discharge periods. The charge pump IC selects the optimum operating arrangement (mode) to maintain the required output voltage for the given input-to-output condition (differential voltage). Typically, MOSFET devices are used to implement the charge pump capacitor switching network. These devices provide small size, low cost, and high-speed switching with minimal losses. Modern charge pump ICs operate at high frequencies (1 to 2MHz) to take advantage of small, inexpensive multi-layer ceramic capacitors (MLCs). MLCs are well suited to charge pumps due to their small size, high energy density, low ESR (equivalent series resistance), low cost, and wide availability.

Once the correct operating mode has been selected, the output voltage is maintained across the output load range by controlling the effective switching frequency and/or duty cycle. Different control methodologies exist and include PWM (pulse width modulation) and PFM (pulsed frequency modulation).

A charge pump equivalent DC model will be presented. The discussion will include operating modes, output resistance, input voltage headroom, and efficiency.

A Simple Charge Pump Model

A simple model of step-down and step-up charge pumps will be provided that simplifies the switching behavior to simple linear elements. The equivalent DC circuit explains charge pump behavior, including the importance of fractional operating modes, efficiency, and output current limitations.

DC/DC charge pumps generate a DC output voltage from a DC input voltage by alternatively charging and discharging a flying capacitor network in series with, or in parallel to, the output load. The following discussion will be limited to step-up and step-down charge pumps with two (2) flying capacitors: $C_{F1}$ and $C_{F2}$. For this discussion, the $C_{F1}/C_{F2}$ network is referred to as $C_{F(\text{CHARGE})}$ during the charge period and $C_{F(\text{DISCHARGE})}$ during the discharge period.
$C_{\text{F(CHARGE)}}$ is connected to the input voltage source during the charge period, when energy is transferred from the input capacitor to the flying capacitors. $C_{\text{F(DISCHARGE)}}$ is connected to the output load during the discharge period, when energy stored during the charge period is delivered to the output load. A step-down charge pump schematic is provided in Figures 1a and 1b and a step-up charge pump schematic is provided in Figures 2a and 2b. The flying capacitor network is connected in parallel or series during charge and discharge periods, as determined by the operating mode (M). For simplicity, the output load is not shown.

**Figure 1a: Step-Down Charge Pump "Charge" Period.**

**Figure 1b: Step-Down Charge Pump "Discharge" Period.**

**Figure 2a: Step-Up Charge Pump "Charge" Period.**

**Figure 2b: Step-Up Charge Pump "Discharge" Period.**

A fixed differential voltage ($V_{\text{DIFF}}$) is applied across $C_{\text{F(CHARGE)}}$ during the charge period when the flying capacitor voltage increases (storing energy). $V_{\text{DIFF}}$ is scaled ($n = 1/2, 1, 2$) and $C_{\text{F(DISCHARGE)}}$ is connected to the output capacitor during the discharge period when the flying capacitor voltage decreases (delivering energy). The value of $V_{\text{DIFF}}$ during the discharge period determines the maximum possible output voltage ($V_{\text{OUT(MAX)}}$). The actual output voltage ($V_{\text{OUT}}$) is less than or equal to $V_{\text{OUT(MAX)}}$ as determined by the control IC, which sets $V_{\text{OUT}}$ by modulating the duty cycle (PWM) and/or switching frequency (PFM) of the charge and discharge events.
For a step-down charge pump:

\[
\text{Eq. 1: } V_{\text{DIFF}} = V_{\text{IN}} - V_{\text{OUT}}
\]

\[
V_{\text{OUT}(\text{MAX})} = n \times V_{\text{DIFF}}
\]

\[
= n \times (V_{\text{IN}} - V_{\text{OUT}})
\]

\[
\frac{V_{\text{OUT}(\text{MAX})}}{V_{\text{IN}}} = \frac{n}{1 + n}
\]

For a step-up charge pump:

\[
\text{Eq. 2: } V_{\text{DIFF}} = V_{\text{IN}}
\]

\[
V_{\text{OUT}(\text{MAX})} = V_{\text{IN}} + n \times V_{\text{DIFF}}
\]

\[
= V_{\text{IN}} + n \times (V_{\text{IN}})
\]

\[
\frac{V_{\text{OUT}(\text{MAX})}}{V_{\text{IN}}} = 1 + n
\]

The output to input voltage ratio is the desired gain of the charge pump.

\[
\text{Eq. 3: } G = \frac{V_{\text{OUT}}}{V_{\text{IN}}}
\]

\(M\) is the charge pump gain. \(M\) is a fixed fraction which is equal to or less than one \((M \leq 1)\) for a step-down charge pump and greater than one \((M > 1)\) for a step-up charge pump (for this reason, multi-mode charge pumps are sometimes referred to as fractional mode charge pumps).

The maximum voltage gain is set by the charge pump operating mode:

\[
\text{Eq. 4: } G \leq M
\]

And,

\[
\text{Eq. 5: } V_{\text{OUT}(\text{MAX})} = M \times V_{\text{IN}}
\]

The mode variable \((M)\) is based on the scaling factor \((n)\) and can be derived from Equations 1 and 2:
Table 1: Scaling Factor (n) Determines Step-Down and Step-Up Charge Pump Operating Mode Variable (M).

<table>
<thead>
<tr>
<th>Scaling Factor n</th>
<th>Step-Down Mode M = n/(1+n)</th>
<th>Step-Up Mode M = 1+n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>1/3</td>
<td>3/2</td>
</tr>
<tr>
<td>1</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2/3</td>
<td>3</td>
</tr>
</tbody>
</table>

The charge pump gain (G) must be adjusted to maintain a constant DC output voltage across the V\text{IN} operating range. For the purposes of the model, an additional modulation resistance (R\text{M}) is added to set the desired gain. R\text{M} is in series with the output load and changes as required to maintain V\text{OUT}.

\[
\text{Eq. 6: } G = \frac{V_{\text{OUT}}}{V_{\text{IN}}} = M - (I_{\text{OUT}} \cdot R_{\text{M}})
\]

\[0 < R_{\text{M}} < \infty\]

The value of M and R\text{M} set dynamically by the control IC.

- The IC senses V\text{DIFF} to determine the optimum M, which sets the maximum charge pump gain.
- R\text{M} is determined by controlling the frequency and/or duty cycle of charge and discharge events.

The maximum output load (I\text{OUT}MAX) is determined by the charge pump output impedance, which is dominated by the output resistance (R\text{OUT}). Distributed parasitic resistance throughout the input-to-output current path contributes to R\text{OUT}. This term includes MOSFET on resistance (R\text{DS(ON)}), trace resistance, and capacitor ESR.

The charge pump equivalent circuit is shown in Figure 3. The model consists of a voltage controlled voltage source (M*V\text{IN}) and series output resistances R\text{M} and R\text{OUT}. This model is valid for both step-down and step-up charge pumps.

\[
\text{Figure 3: Step-Down, Step-Up Charge Pump Equivalent DC Model; Charge Pump IC Dynamically Controls M and R_M for Desired V_{OUT}.}
\]
Eq. 7: \( V_{\text{OUT}} = M \cdot V_{\text{IN}} - [I_{\text{OUT}} \cdot (R_m + R_{\text{OUT}})] \)

Rearranging terms:

Eq. 8: \( V_{\text{IN}} = \frac{V_{\text{OUT}} + [I_{\text{OUT}} \cdot (R_m + R_{\text{OUT}})]}{M} \)

To maximize efficiency, it is best to operate at this highest possible operating mode (M). For the ideal case, assume \( R_{\text{OUT}} = 0 \Omega \). As \( V_{\text{IN}} \) drops, the charge pump transitions from higher mode (M+) to a lower mode (M-) at the \( V_{\text{IN}} \) transition voltage. Assume \( R_m = 0 \Omega \) at the transition voltage:

Eq. 9: \( V_{\text{IN}}(M+) = \frac{V_{\text{OUT}}}{M+} \)

In practice, \( R_{\text{OUT}} > 0 \) and additional voltage headroom (\( \Delta V(M+) \)) is required to ensure \( V_{\text{OUT}} \) regulation at the higher operating mode (M+). \( \Delta V(M+) \) is the input voltage needed to compensate for the voltage drop due to \( R_{\text{OUT}} \). Minimum \( \Delta V(M+) \) is desired to maintain high operating efficiency. \( \Delta V(M+) \) can be calculated from Eq. 10.

Eq. 10: \( \Delta V(M+) = V_{\text{IN}} - V_{\text{IN(IDEAL)}} \)
\[
= \frac{(V_{\text{OUT}} + I_{\text{OUT}} \cdot R_{\text{OUT}})}{M+} - \frac{V_{\text{OUT}}}{M+}
= \frac{I_{\text{OUT}} \cdot R_{\text{OUT}}}{M+}
\]

\( \Delta V(M+) \) is a measure of input voltage headroom that is required for transitions to higher M+ operating modes. Poor DC regulation (\( V_{\text{OUT}} \) droop) results if this requirement is not met.

**Charge Pump Efficiency**

Charge pump input current is equal to the output current scaled by the charge pump operating mode variable \( M \).

Eq. 11: \( I_{\text{IN}} = M \cdot I_{\text{OUT}} \)

Efficiency (EFF) is the output power divided by input power.

Eq. 12: \( \text{EFF} = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \)
\[
= \frac{(V_{\text{OUT}} \cdot I_{\text{OUT}})}{(V_{\text{IN}} \cdot I_{\text{IN}})}
= \frac{(V_{\text{OUT}} \cdot I_{\text{OUT}})}{(V_{\text{IN}} \cdot M \cdot I_{\text{OUT}})}
= \frac{V_{\text{OUT}}}{V_{\text{IN}} \cdot M} \)
Efficiency versus $V_N$ is shown for different fractional operating modes for a 1.5V output step-down charge pump and 7.5V output step-up charge pump. Since $R_{OUT} = 0\Omega$ at the transition threshold, the efficiency passes through 100%. Additional input voltage appears across $R_{M}$, resulting in reduced efficiency. In this way, the operation of the charge pump is similar to a linear or LDO regulator.

![Graph 1: Step-Down Charge Pump Ideal Efficiency Curves, $V_{OUT} = 1.5V$.](image1)

![Graph 2: Step-Up Charge Pump Ideal Efficiency Curves, $V_{OUT} = 7.5V$.](image2)

The step-down charge pump IC may regulate in 1X linear or 1X switched mode.

The 1X linear mode disconnects the flying capacitors and regulates the MOSFET $R_{DS(ON)}$ in the linear region to maintain a regulated DC output voltage (in the identical fashion as linear or LDO step-down regulators). Switching events are eliminated providing low input and output noise. Additional circuitry is typically required to control the operation while in 1X linear mode.

![Circuit Diagram: Step-Down Charge Pump Equivalent Circuit Operating in 1X Linear Mode.](image3)

The 1X switched mode regulates the switching events by alternatively connecting the $C_F$ network between $V_{IN}$ and $V_{OUT}$, as shown in Table 1. As with all charge pumps, energy is stored during the charge interval and discharged to the output during the discharge interval. Modulating the switching events increases and decreases the effective modulation resistance ($R_M$), as necessary, to maintain $V_{OUT}$. This technique generates input and output noise typical with step-down charge pumps, but requires no additional control circuitry.

The operating mode ensures adequate gain and sets the operating efficiency. Table 1 shows the operating mode as a function of $V_{IN}$ and $\Delta V(M)$. As previously shown, the input voltage headroom ($\Delta V(M)$) is dependent on the output current ($I_{OUT}$), output resistance ($R_{OUT}$) and the operating mode (M).
<table>
<thead>
<tr>
<th>Topology</th>
<th>Operating Mode (M)</th>
<th>$V_{IN}$ Range (ideal)</th>
<th>Equivalent Schematic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>Charge Period</td>
</tr>
<tr>
<td>Step-Down Charge Pump</td>
<td>1X (1)</td>
<td>$V_{IN} \times 1 + \Delta V(1)$ \leq V_{OUT} \leq V_{IN} \times 2/3 + \Delta V(2/3)$</td>
<td><img src="image1" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td></td>
<td>2/3X (2/3)</td>
<td>$V_{IN} \times 2/3 + \Delta V(2/3)$ \leq V_{OUT} \leq V_{IN} \times 1/2 + \Delta V(1/2)$</td>
<td><img src="image3" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td></td>
<td>1/2X (1/2)</td>
<td>$V_{IN} \times 1/2 + \Delta V(1/2)$ \leq V_{OUT} \leq V_{IN} \times 1/3 + \Delta V(1/3)$</td>
<td><img src="image5" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td></td>
<td>1/3X (1/3)</td>
<td>$V_{IN} \times 3 + \Delta V(3)$ \leq V_{OUT}$</td>
<td><img src="image7" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td>Step-Up Charge Pump</td>
<td>3/2X (3/2)</td>
<td>$V_{IN} \times 3/2 + \Delta V(3/2)$ \leq V_{OUT} \leq V_{IN} \times 2 + \Delta V(2)$</td>
<td><img src="image9" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td></td>
<td>2X (2)</td>
<td>$V_{IN} \times 2 + \Delta V(2)$ \leq V_{OUT} \leq V_{IN} \times 3 + \Delta V(3)$</td>
<td><img src="image11" alt="Charge Period Diagram" /></td>
</tr>
<tr>
<td></td>
<td>3X (3)</td>
<td>$V_{IN} \times 3 + \Delta V(3)$ \leq V_{OUT}$</td>
<td><img src="image13" alt="Charge Period Diagram" /></td>
</tr>
</tbody>
</table>

Table 1: Charge Pump Operating Mode versus Input Voltage.
For example, assume $R_{\text{OUT}} = 1\Omega$ and $I_{\text{OUT(MAX)}} = 300\text{mA}$. $V_{\text{IN}}$ headroom is calculated using Eq. 13:

$$\text{Eq. 13: } +\Delta V(M) = \frac{I_{\text{OUT}} \times R_{\text{OUT}}}{M}$$

$$= \frac{0.3\text{A} \times 1.0}{M}$$

$$= 0.3 \frac{\text{V}}{M}$$

For a step-down charge pump:

$$+\Delta V(1) = 0.30\text{V}$$
$$+\Delta V(2/3) = 0.45\text{V}$$
$$+\Delta V(1/2) = 0.60\text{V}$$
$$+\Delta V(1/3) = 0.90\text{V}$$

For a step-up charge pump:

$$+\Delta V(3/2) = 0.20\text{V}$$
$$+\Delta V(2) = 0.15\text{V}$$
$$+\Delta V(3) = 0.10\text{V}$$

Figures 7 and 8 provide efficiency versus input voltage characteristics at $I_{\text{OUT}} = 0\text{mA}$ and $300\text{mA}$ and $R_{\text{OUT}} = 1\Omega$. Efficiency can be significantly reduced with headroom voltage applied.

**Figure 7: Step-Down Charge Pump**
Actual Efficiency ($V_{\text{OUT}} = 1.5\text{V}$, $I_{\text{OUT}} = 300\text{mA}$, $R_{\text{OUT}} = 1.0\Omega$).

**Figure 8: Step-Up Charge Pump**
Actual Efficiency ($V_{\text{OUT}} = 7.5\text{V}$, $I_{\text{OUT}} = 300\text{mA}$, $R_{\text{OUT}} = 1.0\Omega$).
Summary
This application note summarizes the benefits and limitations of charge pump DC/DC converters for low-current portable applications, typically below 300mA output current. Charge pumps provide higher operating efficiency and increased input and output noise when compared to LDO regulators. They are a cost-effective solution and do not require a magnetic component, as required with inductive switching regulators.

Multi-mode step-down and step-up DC/DC charge pumps utilizing two flying capacitors were presented. An equivalent DC model was provided which predicts charge pump efficiency and maximum output current. The model includes a voltage-dependent voltage source, a series modulation resistance (R_M) and output resistance (R_OUT). The mode variable M is selected by the charge pump IC to maintain maximum efficiency, while output regulation is achieved by modulating the switching duty cycle and/or frequency. The operating mode determines the flying capacitor arrangement, sets charge pump fractional input-to-output gain, and impacts the input voltage headroom.