SWITCHED CAPACITOR VOLTAGE CONVERTERS

INTRODUCTION
In the previous section, we saw how inductors can be used to transfer energy and perform voltage conversions. This section examines switched capacitor voltage converters which accomplish energy transfer and voltage conversion using capacitors.
The two most common switched capacitor voltage converters are the voltage inverter and the voltage doubler circuit shown in Figure 4.1. In the voltage inverter, the charge pump capacitor, C1, is charged to the input voltage during the first half of the switching cycle. During the second half of the switching cycle, its voltage is inverted and applied to capacitor C2 and the load. The output voltage is the negative of the input voltage, and the average input current is approximately equal to the output current. The switching frequency impacts the size of the external capacitors required, and higher switching frequencies allow the use of smaller capacitors. The duty cycle - defined as the ratio of charging time for C1 to the entire switching cycle time - is usually 50%, because that generally yields the optimal charge transfer efficiency.
After initial start-up transient conditions and when a steady-state condition is reached, the charge pump capacitor only has to supply a small amount of charge to the output capacitor on each switching cycle. The amount of charge transferred depends upon the load current and the switching frequency. During the time the pump capacitor is charged by the input voltage, the output capacitor C2 must supply the load current. The load current flowing out of C2 causes a droop in the output voltage which corresponds to a component of output voltage ripple. Higher switching frequencies allow smaller capacitors for the same amount of droop. There are, however, practical limitations on the switching speeds and switching losses, and switching frequencies are generally limited to a few hundred kHz.
The voltage doubler works similarly to the inverter; however, the pump capacitor is placed in series with the input voltage during its discharge cycle, thereby accomplishing the voltage doubling function. In the voltage doubler, the average input current is approximately twice the average output current.
The basic inverter and doubler circuits provide no output voltage regulation, however, techniques exist to add regulated capability and have been implemented in the ADP3603/3604/3605/3607.
There are certain advantages and disadvantages of using switched capacitor techniques rather than inductor-based switching regulators. An obvious key advantage is the elimination of the inductor and the related magnetic design issues. In addition, these converters typically have relatively low noise and minimal radiated EMI. Application circuits are simple, and usually only two or three external capacitors are required. Because there is no need for an inductor, the final PCB component height can generally be made smaller than a comparable switching regulator. This is important in many applications such as display panels.

Switched capacitor inverters are low cost and compact and are capable of achieving efficiencies greater than 90%. Obviously, the current output is limited by the size of the capacitors and the current carrying capacity of the switches. Typical IC switched capacitor inverters have maximum output currents of about 150mA maximum.

Switched capacitor voltage converters do not maintain high efficiency for a wide range of ratios of input to output voltages, unlike their switching regulator counterparts. Because the input to output current ratio is scaled according to the basic voltage conversion (i.e., doubled for a doubler, inverted for an inverter) regardless of whether or not regulation is used to reduce the doubled or inverted voltage, any output voltage magnitude less than 2VIN for a doubler or less than |VIN| for an inverter will result in additional power dissipation within the converter, and efficiency will be degraded proportionally.
SWITCHED CAPACITOR VOLTAGE CONVERTERS

- No Inductors!
- Minimal Radiated EMI
- Simple Implementation: Only 2 External Capacitors (Plus an Input Capacitor if Required)
- Efficiency > 90% Achievable
- Optimized for Doubling or Inverting Supply Voltage - Efficiency Degrades for Other Output Voltages
- Low Cost, Compact, Low Profile (Height)

- Parts with Voltage Regulation are Available:
  ADP3603/ADP3604/ADP3605/ADP3607

Figure 4.2

The voltage inverter is useful where a relatively low current negative voltage is required in addition to the primary positive voltage. This may occur in a single supply system where only a few high performance parts require the negative voltage. Similarly, voltage doublers are useful in low current applications where a voltage greater than the primary supply voltage is required.
**CHARGE TRANSFER USING CAPACITORS**

A fundamental understanding of capacitors (theoretical and real) is required in order to master the subtleties of switched capacitor voltage converters. Figure 4.3 shows the theoretical capacitor and its real-world counterpart. If the capacitor is charged to a voltage \( V \), then the total charge stored in the capacitor, \( q \), is given by \( q = CV \). Real capacitors have equivalent series resistance (ESR) and inductance (ESL) as shown in the diagram, but these parasitics do not affect the ability of the capacitor to store charge. They can, however, have a large effect on the overall efficiency of the switched capacitor voltage converter.

**STORED CHARGE IN A CAPACITOR**

![Diagram of a capacitor with ideal and actual components](image)

If an ideal capacitor is charged with an ideal voltage source as shown in Figure 4.4(A), the capacitor charge buildup occurs instantaneously, corresponding to a unit impulse of current. A practical circuit (Figure 4.4 (B)) will have resistance in the switch (RSW) as well as the equivalent series resistance (ESR) of the capacitor. In addition, the capacitor has an equivalent series inductance (ESL). The charging current path also has an effective series inductance which can be minimized with proper component layout techniques. These parasitics serve to limit the peak current, and also increase the charge transfer time as shown in the diagram. Typical switch resistances can range from 1Ω to 50Ω, and ESRs between 50mΩ and 200mΩ. Typical capacitor values may range from about 0.1µF to 10µF, and typical ESL values 1 to 5nH. Although the equivalent RLC circuit of the capacitor can be underdamped or overdamped, the relatively large switch resistance generally makes the final output voltage response overdamped.
The law of conservation of charge states that if two capacitors are connected together, the total charge on the parallel combination is equal to the sum of the original charges on the capacitors. Figure 4.5 shows two capacitors, C1 and C2, each charged to voltages V1 and V2, respectively. When the switch is closed, an impulse of current flows, and the charge is redistributed. The total charge on the parallel combination of the two capacitors is \( q_T = C_1 \cdot V_1 + C_2 \cdot V_2 \). This charge is distributed between the two capacitors, so the new voltage, \( V_T \), across the parallel combination is equal to \( q_T/(C_1 + C_2) \), or

\[
V_T = \frac{q_T}{C_1 + C_2} = \frac{C_1 \cdot V_1 + C_2 \cdot V_2}{C_1 + C_2} = \left(\frac{C_1}{C_1 + C_2}\right)V_1 + \left(\frac{C_2}{C_1 + C_2}\right)V_2.
\]

This principle may be used in the simple charge pump circuit shown in Figure 4.6. Note that this circuit is neither a doubler nor inverter, but only a voltage replicator. The pump capacitor is C1, and the initial charge on C2 is zero. The pump capacitor is initially charged to VIN. When it is connected to C2, the charge is redistributed, and the output voltage is VIN/2 (assuming C1 = C2). On the second transfer cycle, the output voltage is pumped to VIN/2 + VIN/4. On the third transfer cycle, the output voltage is pumped to VIN/2 + VIN/4 + VIN/8. The waveform shows how the output voltage exponentially approaches VIN.
Figure 4.7 shows a pump capacitor, C1, switched continuously between the source, V1, and C2 in parallel with the load. The conditions shown are after a steady state.
condition has been reached. The charge transferred each cycle is \( \Delta q = C_1(V_1 - V_2) \). This charge is transferred at the switching frequency, \( f \). This corresponds to an average current (current = charge transferred per unit time) of

\[
I = f \Delta q = f C_1(V_1 - V_2),
\]

or

\[
I = \frac{V_1 - V_2}{f \cdot C_1}.
\]

CONTINUOUS SWITCHING, STEADY STATE

Notice that the quantity, \( 1/f \cdot C_1 \), can be considered an equivalent resistance, "R", connected between the source and the load. The power dissipation associated with this virtual resistance, "R", is essentially forced to be dissipated in the switch on resistance and the capacitor ESR, regardless of how low those values are reduced. (It should be noted that capacitor ESR and the switch on-resistance cause additional power losses as will be discussed shortly.)

In a typical switched capacitor voltage inverter, a capacitance of 10\( \mu \)F switched at 100kHz corresponds to "R" = 1\( \Omega \). Obviously, minimizing "R" by increasing the frequency minimizes power loss in the circuit. However, increasing switching frequency tends to increase switching losses. The optimum switched capacitor operating frequency is therefore highly process and device dependent. Therefore, specific recommendations are given in the data sheet for each device.
I. CHARGE PUMP TOPOLOGIES
One of the best-known topologies is the voltage doubler. Fig. 1 shows the configuration and the necessary voltage doubler charge pump.

Fig. 1. Voltage doubler charge pump.

The operation of a charge pump can be divided into two phases: In Phase 1, also called the charge phase, the switches S2 and S3 are closed and the flying capacitor $C_F$ is ideally charged to $V_{IN}$. During this time, the output capacitor $C_{OUT}$ supplies the load and is therefore being discharged.

In Phase 2, also called the transfer phase, the switches S1 and S4 are closed and the flying capacitor $C_F$ is placed in series to the input voltage. These two voltage sources charge the output capacitor $C_{OUT}$ and supply the load.

Phases 1 and 2 have a duty cycle of 50%, i.e. both have the same duration, $\Delta t$.

To transfer energy from the input to the output, the phases are periodically repeated with a frequency of several hundred kiloHertz. A control circuitry and an oscillator control the operation of the charge pump.

The output voltage ripple depends on the time of the charge phase and on the capacitor size and its ESR. During the charge phase the output capacitor $C_{OUT}$ supplies the load and is therefore being discharged. The longer the charge phase, the more charge is removed from the capacitor. The ESR of the output capacitor has an influence due to the fact that current through the capacitor is reversed every cycle – during the charge cycle current flows out of the output capacitor, and during the transfer cycle charge flows into the capacitor. The output voltage ripple can now be reduced by reducing either the charge time, i.e. increasing the switching frequency, or by reducing the ESR or by increasing the size of the output capacitor. All three possibilities have their boundary: ESR is present in every capacitor, $C_{OUT}$ is normally limited due to board space and...
cost and the frequency is fixed by the design of the control circuit. For further reduction of the output voltage ripple, a new topology was invented: the pushpull charge pump. Fig. 2 shows the basic circuitry of such a charge pump. In this topology, two charge pumps are used instead of one. These two charge pumps operate 180° phase shifted. While charge pump 1 is in charge phase, charge pump 2 is in transfer phase, and vice versa. The output is therefore continuously supplied from the input, thus reducing the ripple to a minimum (e.g. 5mV p-p for TPS60100), resulting in only a small spike that occurs during the turnover from one transferring charge pump to the other.

In Fig. 3, the difference in output voltage ripple of a single-ended charge pump to a pushpull version can be seen. The measurements are made with the TPS60100 in both configurations with the same ceramic capacitors:

- $C_{IN} = 10 \mu F$
- $C_{F1} = 2.2 \mu F$
- $C_{OUT} = 22 \mu F + 1 \mu F$
In a voltage tripler, the two phases of a charge pump can also be observed. During Phase 1 (charge phase) the switches S2, S5, S3 and S6 are closed and the two flying capacitors CF, and CF2 are charged in parallel, ideally up to the input voltage VIN (the capacitors have to be the same value). The output capacitor COUT supplies the load. In transfer phase, the switches S1, S4 and S7 are closed while all others are open and the two flying capacitors are placed in series to the input voltage to supply the load and charge the output capacitor, ideally to the output voltage
$$V_{OUT} = 3 \cdot VIN.$$ 

Fig. 3. Output voltage ripple comparison between (A) single-ended and (B) push-pull charge pump.

Fig. 4. Voltage tripler.

Fig. 5 shows the topology of a charge pump that operates in 1.5-times transfer. Two phase switching is also applicable to this example. In the charge phase, the switches S3, S4 and S5 are closed and the flying capacitors are charged in series to half the input voltage (the two capacitors have to be the same value). During this phase the
load is supplied by the output capacitor COUT. In the transfer phase, the switches S1, S2, S6 and S7 close and the two flying capacitors CFX are placed in parallel to each other and in series to the input voltage, therefore the output capacitor COUT is ideally charged to \( V_{OUT} = 1.5 \cdot V_{IN} \).

*Fig. 5. 1.5-times transfer charge pump.*