

# Ultra-Fast USB Battery Charging With Power Dense Switched-Cap Converters

## Introduction

USB has been in use as a standard for connectors and their associated signals and power delivery since 1996. The latest developments applicable to power-supply designs include the USB Type-C® (USB-C) connector and USB Power Delivery (USB PD) specification and USB Programmable Power Supply (PPS) specifications. These enhancements make USB an excellent option as a power source over 100 W.

Compared to more traditional buck or boost converter-based power integrated circuits (ICs), switched-capacitor converters have become the preferred power solution in the USB Type-C ecosystem. Instead of having 90% conversion efficiency, a switched-capacitor converter achieves over 98% conversion efficiency, enabling an efficient and cost-effective solution that takes full advantage of the latest USB Type-C PD PPS standard.

Switched-capacitor converters have also become the preferred new charging solution as portable device vendors engaged in a race to bring the fastest-charging solution to market first. For example, in only a few years, phones have gone from 18 W to 120 W. The latest highly efficient (98.6%) 2-to-1 switched-capacitor fast charging solution charges a 4-Ah battery in 15 minutes, delivering 120 W, from a USB PPS power supply.

## Delivering over 100 W power with USB PD

USB PD is a new protocol that enables faster and more flexible power sources. The USB Implementers Forum developed USB PD concurrently with USB-C, which is the physical connection, and it is a subset of the new USB 3.1 standards.

**Table 1** shows the development of the USB standard. With the development of USB PD and USB-C

connectors, the power source is capable to supplying as much as 100 W of power [1].

USB Standard	USB Port Output Voltage	USB Port Current Limit	USB Port Maximum Power output
USB 2.0	5 V	500 mA	2.5 W
USB 3.1	5 V	900 mA	4.5 W
USB BC1.2	5 V	1.5 A	7.5 W
USB BC1.2 with high-voltage downstream charging port (HVDCCP)	5 V, 9 V, 12 V	1.5 A	18 W
USB PD	5 V, 9 V, 12 V, 20 V	5 A	100 W
USB PD with PPS	Adjustable voltage from 3.3 V to 21 V in 20-mV step	Adjustable current up to 5 A in 50-mA step	100 W

**Table 1.** Development of the USB standard for fast charging.

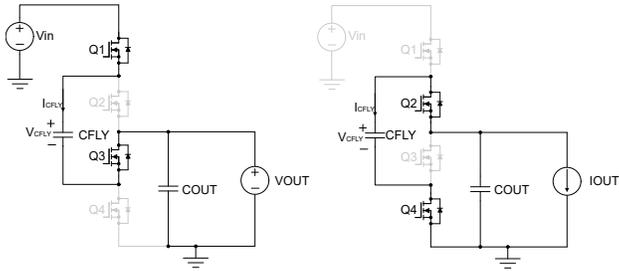
Unfortunately, the traditional regulated buck, boost or buck-boost integrated circuit cannot fully use 100 W of power because of the relatively low efficiency. The unregulated switched-capacitor converter becomes feasible in the system with the development of USB PPS[2]. The ultra-high efficiency of the switched-capacitor converter can take full advantage of the latest USB Type-C PD PPS standard.

## High-efficiency switched-capacitor DC/DC converters

Switched-capacitor DC/DC converters are switching regulators that use only flying capacitors and switches to transfer charges between the input and output. Compared to inductor-based DC/DC converters, switched-capacitor converters offer higher power density (capacitors store 10 to 100 times more energy per volume than inductors), low electromagnetic interference (EMI) and lower cost.

A 2-to-1 switched-capacitor DC/DC converter uses four switches to alternately charge and discharge flying capacitors to deliver power. Figure 1 shows a simplified switched-capacitor circuit and the charging/discharging phase of the flying capacitor. The output voltage is half of the input voltage, and the output current is twice the input current.

**Figure 1. 2-to-1 switched-capacitor converter: flying capacitor charging phase (a); and discharging phase (b).**



It is possible to use an ideal transformer in series with the output impedance ( $R_{OUT}$ ) to model the switched-capacitor converter efficiency [3], including the charge-sharing loss of the flying capacitor and the conduction loss in the resistive components. Switching loss is not included in the model, however, and requires separate analysis.

### Output impedance

There are two asymptotic limits in the output impedance: the slow switching limit and the fast switching limit. The slow switching limit is dominated by the charging sharing loss in the capacitors, assuming that the resistance in the converter is zero. The fast switching limit is dominated by the conduction loss, assuming that the capacitance is infinite and the voltage across the capacitor is constant [3].

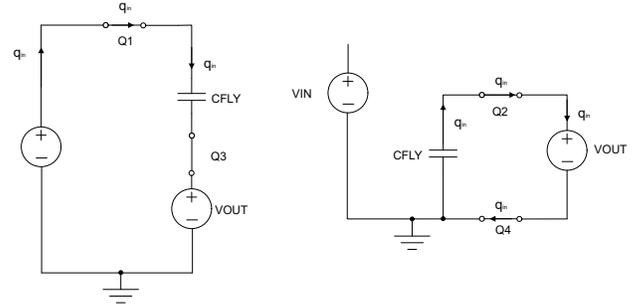
A charge flow vector method derived in [3] calculates the slow and fast switching limits. Equation 1 and Equation 2 express charge flows in the capacitors and switches with respect to output charge and current:

$$q_c^j = a_c^j q_{out} = a_c^j \frac{I_{out}^j}{f_{sw}} \quad (1)$$

$$q_r^j = a_r^j q_{out} = a_r^j \frac{I_{out}^j}{f_{sw}} \quad (2)$$

where,  $q_c^j$  and  $q_r^j$  are the capacitor and switch charge flow vectors in phase  $j$ , and  $a_c$  and  $a_r$  are the charge multiplier vectors.

Figure 2 illustrates the charge flow in the flying capacitor and switches Q1 through Q4 for the 2-to-1 switched-capacitor converter. The duty cycle for both the charging and discharging phases is fixed at 50%.



**Figure 2. Capacitor and switches charge flow: charging, phase 1 (a); discharging, phase 2 (b).**

Based on Figure 2, the input charge is half the output charge. Equation 3 expresses the capacitor charge multiplier,  $a_c$ :

$$a_c = [a_{CFLY\_1}] = -[a_{CFLY\_2}] = \left[\frac{1}{2}\right] \quad (3)$$

Equation 4 expresses the switch charge multiplier,  $a_r$ :

$$a_r = [a_{Q1}, a_{Q2}, a_{Q3}, a_{Q4}]^T = \left[\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, -\frac{1}{2}\right]^T \quad (4)$$

After obtaining the charge multiplier, Equation 5 and Equation 6 calculate the slow and fast switching limits, with details of the analysis available in [3].

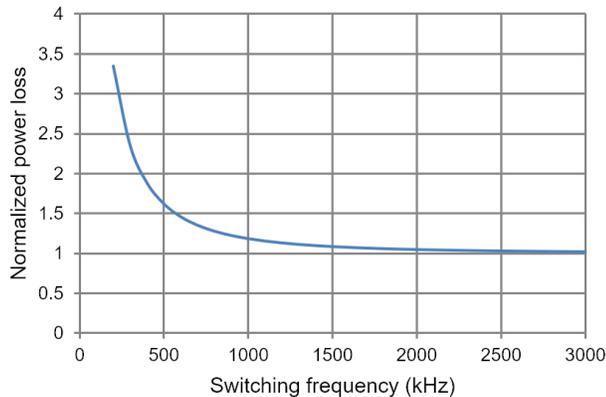
$$R_{SSL} = -\frac{v_{out}}{i_{out}} = \sum \frac{(a_{c,i})^2}{C_{ifsw}} \quad (5)$$

$$R_{FSL} = 2 \sum R_i (a_{r,i})^2 \quad (6)$$

The real switched-capacitor converter contains both charge-sharing loss and conduction loss. Equation 7 could approximate the output resistance for converter design purposes [4], with  $R_{SSL}$  the slow switching limit calculated at the given converter switching frequency.

$$R_{out} \approx \sqrt{R_{SSL}^2 + R_{FSL}^2} \quad (7)$$

**Figure 3** is the power loss based on the output impedance of the 2-to-1 switched-capacitor converter over the switching frequency. The power loss of the fast switching limit is normalized to 1. The power loss continues to drop as the frequency increases because the fast switching limit is inversely proportional to the switching frequency. In a real application, however, you would need to include the switching loss to select the switching frequency.



**Figure 3. Output impedance power loss of the 2-to-1 switched-capacitor converter.**

## Switching losses

A main advantage of switched-capacitor converters is switching loss reduction, as expressed in Equation 8, which includes the IV overlap loss ( $P_{IV}$ ), gate driving loss ( $P_{GATE}$ ), output junction capacitance loss ( $P_{OSS}$ ), dead-time loss ( $P_{DT}$ ) and reverse-recovery loss ( $P_{QRR}$ ). The switched-capacitor converter eliminates the IV, dead-time and reverse-recovery losses.

$$P_{SW} = P_{IV} + P_{GATE} + P_{OSS} + P_{DT} + P_{QRR} \quad (8)$$

## Turnon switching loss

The fixed 50% duty cycle makes it possible to control the voltage across the flying capacitor and output voltage to close to half the input voltage. Until the switches are fully turned on, the current flowing through the device is very small and the switches can achieve close to zero current turn on. The IV overlap loss is almost eliminated during turn on.

The energy stored in the drain-to-source junction capacitance of the switches is lost during the turnon process, so there is junction capacitance loss, as shown in **Equation 9**:

$$P_{DS} = \frac{1}{2} C_{DS} V_{OUT}^2 f_{sw} \quad (9)$$

where,  $C_{DS}$  is the drain-to-source junction capacitance,  $V_{OUT}$  is the output voltage and  $f_{sw}$  is the switching frequency.

## Turnoff switching loss

During the turnoff process, current in the converter becomes zero when all of the switches are off. The voltage across the switches remains zero, as no current can charge the junction capacitance. The switches realize zero-voltage turnoff and eliminate the IV overlap loss. Dead-time and reverse-recovery loss are eliminated as well because there is no current flow during dead time.

## Gate driving loss

Gate driving loss is also part of the switching loss (see **Equation 10**):

$$P_{GATE} = \frac{1}{2} Q_{GS} V_{GATE} f_{sw} \quad (10)$$

where, the  $Q_{GS}$  is the gate-to-source charge of the switch,  $V_{GATE}$  is the gate turnon voltage and  $f_{sw}$  is the switching frequency.

**Equation 11** calculates the overall power loss of the switched-capacitor converter, also plotted in **Figure 4**:

$$P_{SC} = P_{OUT} + \sum P_{GATE} + \sum P_{DS} \quad (11)$$

The slow switching impedance is inversely proportional to the switching frequency, while the switching loss is proportional to switching frequency. There is an optimized switching frequency for the switched-capacitor converter after determining the topology and capacitor.

**Figure 4. Overall power loss of the 2-to-1 switched-capacitor converter**

## Dual-phase interleaved switched-capacitor converter

Part of the slow switching power loss is consumed in the switches as extra conduction loss because of the current spikes when connecting two different voltage capacitors. The current spikes increase the current root-mean-square (RMS) value and cause extra conduction loss. Increasing the switching frequency is one way to reduce the RMS current; however, the switching loss increases.

A dual-phase interleaved topology is one way to reduce the RMS current without increasing the switching loss. A dual-phase topology enables continuous current flow from the input source; therefore, it is possible to reduce the input voltage ripple. **Figure 5** compares the switching field-effect transistor (FET) current waveforms between single- and dual-phase interleaved using same total flying capacitor in simulation. To deliver the same output current and output power, the current ripple in single phase is significantly larger compared with dual phase; thus, the conduction loss is much smaller in the dual-phase, interleaved switched-capacitor converter under the same device size.

**Figure 5.** Simulated switching FET current waveforms comparison of Q1/Q3 current in single-phase switched capacitor (a); dual-phase switched capacitor (b).

## High-power-density switched-capacitor converter

**Table 2** compares the power density among a traditional two-level buck converter, three-level buck converter [5] and switched-capacitor IC with similar input and output voltage ranges.

The power rating of the converters is limited by 1.4-W overall power loss. The DSBGA IC package is used for all of the topologies. The total solution size assumes an extra 20% for board layout in addition to the size of the IC and energy storage components. The switched-capacitor converter has four times higher power density compared to the two-level buck converter and 90%

higher power density compared to the three-level buck converter.

Topology	Power Rating at 1.4-W Loss	IC Die Size	Inductor or Capacitor Size	Total Solution Size	Maximum Height	Power Density
Two-level buck [6]	15 W	7 mm <sup>2</sup>	17.6 mm <sup>2</sup>	30 mm <sup>2</sup>	1.2 mm	0.42 W/mm <sup>3</sup>
Three-level buck [5]	20 W	6.1 mm <sup>2</sup>	5 mm <sup>2</sup>	14 mm <sup>2</sup>	1.2 mm	1.19 W/mm <sup>3</sup>
Switched capacitor	40 W	9.6 mm <sup>2</sup>	7.7 mm <sup>2</sup>	22 mm <sup>2</sup>	0.8 mm	2.26 W/mm <sup>3</sup>

**Table 2.** Power density comparison.

## Switched-capacitor converter application: fast charging for portable devices

One of the applications for a switched-capacitor converter is a battery charger for portable devices. The customizable capability of the USB PPS allows the unregulated switched-capacitor converter to charge the battery at a 50% fixed-duty cycle. The power loss in portable devices is limited by the thermal profile; sometimes the temperature rise is limited to as low as 10°C. Battery chargers need to have a small footprint. The high efficiency and high power density of switched-capacitor converters could push the charging power much higher compared with the inductor-based regulated converter.

The **BQ25980** [10] is a switched capacitor-based two-cell battery fast charger that can help achieve more than 98% efficiency between 2 A and 8 A, as shown in **Figure 6**. Placing two of the **BQ25980** devices in parallel achieves the 120 W power together with 2.4 W/mm<sup>3</sup>. The battery charges from 0% to 100% within 15 minutes [11].

**Figure 6.** BQ25980 switched-capacitor converter efficiency.

## Conclusion

A switched-capacitor converter has higher efficiency and power density compared to an inductor-based converter. With the USB PPS adapter and USB Type-C connector, two 98.6% peak efficiency switched-capacitor converters used in a battery charging system

enable 120 W of fast charging with as little as 15 minutes of charging time, greatly improving the user experience.

## Related Websites

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