Fast-charging a supercapacitor from energy harvesters

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Supercapacitors are an essential energy storage mechanism in self-powered systems. Their high-energy capacities combined with their ability to provide high-power output make them ideal for ultra-low power wireless sensor node systems. Supercapacitors, however, discharge significantly during periods of low-energy harvesting input.

Energy harvesting ICs used to charge supercapacitors suffer from low efficiency during the initial charging stages until the supercapacitor reaches a nominal voltage. This causes a long wait for the supercapacitor to charge up to usable levels each time the system comes back up from a deep-sleep state, significantly hindering the widespread adoption of supercapacitors. This article describes ways to speed-up charging of a supercapacitor by more than 20 times when compared to existing systems. The solutions presented in this article use a solar cell as the energy harvester. These solutions are equally applicable to other energy harvesting sources as well.

A simple diode charger

The simplest way to charge a supercapacitor from a solar cell is through a diode. The supercapacitor can charge up to the open-circuit voltage of the solar cell under the prevailing light conditions, taking into account losses due to the diode. Figure 1 shows how a supercapacitor can be charged with the help of a diode. An auxiliary over-voltage protection circuit is required in most systems to protect the supercapacitor and the ensuing load electronics.
The simplicity of this solution makes it attractive for use in low-cost solar accessories. However, this method has multiple drawbacks. Firstly, it only works with multi-cell solar cells where the open-circuit voltage of the solar cells is larger than the over-voltage setting of the supercapacitor or the required load voltage. Thermoelectric harvesters that output low voltages cannot use this method to charge storage elements.

Further, this circuit regulates the solar cell to one diode drop above the voltage on the storage medium. This means that as the voltage on the storage medium moves around, based on load conditions, the solar cell regulation point also moves. For storage cells with a wide discharge curve or supercapacitors whose voltage can move significantly depending on the load demands, this is not a good solution since the solar cell is regulated to a voltage far from its maximum power point. The auxiliary over-voltage protection circuit needed in most low-power electronic systems also consumes quiescent current, which can affect system efficiency during periods of low-light.

![Figure 2. Measured waveform of a 120 mF supercapacitor being charged using a diode](image)

A key advantage of the diode charger is the time it takes to charge supercapacitors from a completely discharged state. **Figure 2** shows how a 120 mF supercapacitor is charged from a completely discharged state using a 3S solar cell with a short circuit current $I_{SC} = 1$ mA and an open circuit voltage $V_{OC} = 2$V. The pink trace corresponds to the solar cell output ($V_{IN}$), while the blue trace is the voltage of the supercapacitor ($V_{SUP}$). The supercapacitor takes around 205 seconds to charge from 0V to 1.8V. The difference in the voltage between $V_{IN}$ and $V_{SUP}$ is the drop across the diode. The time taken to charge the supercapacitor to a voltage of $V_x$ using the diode charger can be approximated to Equation 1:

$$t_{diode} \approx \frac{C_{SUP} \times V_x}{I_{SC}}$$  \hspace{1cm} (1)
For a 120 mF supercapacitor to charge up to 1.8V with 1 mA $I_{\text{SC}}$, Equation 1 gives a time of 216 seconds, which is very close to the observed time. Even though the charge time is low for the diode charger, the disadvantages mentioned preclude this solution from being used in a wide variety of energy harvesting systems.

**Supercapacitor charging using a boost charger IC**

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![Figure 3. Schematic for charging a supercapacitor using a boost charger IC](image)

The shortcomings of charging through a diode can be overcome with integrated circuits designed specifically to interface with energy harvesting devices. One such device is the bq25504, which is an ultra-low quiescent current charger IC designed to perform maximum power point tracking (MPPT) of the attached energy harvester. **Figure 3** shows how a supercapacitor can be charged using this device. Only the essential pins are shown for clarity. The resistors $R_{\text{OV1}}$ and $R_{\text{OV2}}$ are used to set the over-voltage threshold of the supercapacitor. The resistors $R_{\text{OK1}}$, $R_{\text{OK2}}$ and $R_{\text{OK3}}$ are used to set the upper and lower thresholds of the VBAT_OK signal, which can be used to control the system load to prevent the supercapacitor from over discharging. The solar cell is connected to the VIN_DC pin.

Since a supercapacitor usually discharges all the way down to 0V when no harvesting input is present for an extended time, the system needs to startup from no energy present in the energy storage capacitors. Most dedicated energy harvesting charger ICs have a cold-start feature that
enables charging of storage elements from a completely discharged state – as long as the input source is above a certain voltage, which is 330 mV for this example.

Figure 4. Measured waveform of a 120 mF supercapacitor being charged using the boost charger IC

Figure 4 shows how the 120 mF supercapacitor is charged from a completely discharged state using the same 3S solar cell with $I_{SC} = 1$ mA and $V_{OC} = 2$V as before. The supercapacitor takes around 6000 seconds (1 hour 40 minutes!) to charge from 0V to 1.8V.

In our example, the boost charger IC starts in cold-start-mode where $V_{IN}$ is regulated close to 330 mV. During cold-start, the supercapacitor connected to the VBAT pin is charged from $V_{STOR}$ through an internal diode, causing a 0.3V difference from $V_{STOR}$ to $V_{SUP}$. Once $V_{STOR}$ reaches 1.8V, which is the internal threshold for the IC to exit cold-start mode, the device enters the regular charger mode and the charging is much more efficient. This is evident from the sharp change in the slope of the charging curve. During regular charge-mode before the over-voltage condition is reached, the solar cell regulates to ~1.6V, which is close to its MPP. The charging stops once the supercapacitor reaches the over-voltage set point of 4.2V, set using resistors $R_{OV1}$ and $R_{OV2}$.

The advantages of using a boost charger IC to charge a supercapacitor include being able to use one- and two-cell solar cells, which provide on average more power for the same solar cell area compared to multi-cell solar cells. The IC with its in-built over-voltage protection circuitry helps to protect the supercapacitor and the load electronics. The user-programmable VBAT_OK levels are used to signal the load circuits to turn ON/OFF. Further, once the device enters the regular charger mode, the IC’s MPPT functionality helps to regulate the solar cell at its maximum power point,
thereby extracting the optimal power out of the solar cell.

The big disadvantage with using this method to charge a supercapacitor is that the time it takes for the supercapacitor to charge from a completely discharged state is prohibitively long. Since efficiency during cold-start for the device is around 7-10%, and since the voltage of the solar cell is regulated close to 0.33V during cold-start, the power transferred to the supercapacitor is very low. This significantly increases the charge time. Once the voltage on the supercapacitor reaches ~1.8V, the device is much more efficient and outperforms the diode charging solution. The time taken to charge a supercapacitor to $V_x$ using a boost charger during cold-start is given by Equation 2:

$$t_{bg25504} \approx \frac{C_{SUP} \cdot V_x^2}{2 \cdot I_{SC} \cdot V_{CS} \cdot \eta_{CS}}$$

where $V_{CS}$ is the cold-start voltage and $\eta_{CS}$ is the efficiency of charger during cold-start. For a 120 mF supercapacitor to charge up to 1.8V with 1 mA $I_{SC}$, Equation 2 gives a time of 6545 seconds, assuming an average cold-start efficiency of 9%. Again, this number is very close to that observed during measurements.

**Supercapacitor charging using a combination of charger and buck converter**

Supercapacitor charging using a combination of charger and buck converter

![Figure 5. Schematic for charging a supercapacitor using a combination of charger and buck converter](image-url)
The challenge when charging a supercapacitor from a completely discharged state using just a charger IC is that the majority of the charging occurs using the less efficient cold-start feature of the charger. To overcome this, supercapacitor charging using a combination of a charger and buck converter is proposed.

Figure 5 shows one such implementation using the bq25570, an ultra-low quiescent current charger + buck converter IC. It incorporates all the charging functionality within the boost charger IC mentioned earlier, and has an integrated high-efficiency buck converter that can deliver up to 100 mA load current. The resistors $R_{\text{VOL1}}$ and $R_{\text{VOL2}}$ typically are used to set the buck converter’s output voltage. In this case, however, since the supercapacitor is connected at the output of the buck converter, the same resistors instead set the over-voltage threshold of the supercapacitor. The resistors $R_{\text{OK1}}$, $R_{\text{OK2}}$ and $R_{\text{OK3}}$ are used to set the upper and lower thresholds of the VBAT_OK level, which can be used to control the system load to prevent the supercapacitor from discharging too much. The solar cell is connected to the VIN_DC pin.

The entire system is similar to that explained in the previous section, except that the supercapacitor is now connected to the buck converter output. The advantage of this method is that the charger part of the combination only needs to charge the smaller 100 µF capacitor above 1.8V during cold-start. The bigger supercapacitor is charged through the main charger and buck converter, which is much more efficient. Now the supercapacitor can be charged much faster.
Figure 6 shows how the 120 mF supercapacitor is charged from a completely discharged state using the same 3S solar cell with $I_{SC} = 1$ mA and $V_{OC} = 2$ V as used before. The supercapacitor takes around 220 seconds to charge from 0V to 1.8V. This is around 27 times faster than charging through just the charger IC. Looking at the $V_{IN}$ trace in Figure 6, the bq25570 spends almost all of the time in the regular charge-mode, and the input is regulated around the solar cell’s MPP.

The key enabler to charging the supercapacitor at the buck converter output is the continuous under-voltage protection feature within the buck converter. This continuously monitors the UV threshold on $V_{STOR}$ and disables the buck converter when the voltage on $V_{STOR}$ falls below the 2V threshold. Without this feature, the smaller 100 µF capacitor collapses the moment the buck converter is enabled to charge the supercapacitor. The $V_{STOR}$ node is regulated near 2V while the supercapacitor charges up. Once the supercapacitor reaches the $V_{OUT}$ set point of 1.8V, the charger brings $V_{STOR}$ up to the over-voltage set point of 4.2V. The time taken to charge the supercapacitor to $V_X$ is given by Equation 3:

$$t_{bq25570} \approx \frac{C_{SUP} \times V_X^2}{2 \times I_{SC} \times V_{MPP} \times \eta_{CHG} \times \eta_{BUCK}}$$

where $V_{MPP}$ is the maximum power point of the solar cell, $\eta_{CHG}$ is the efficiency of the regular charger when $V_{STOR}$ is at the UV threshold, and $\eta_{BUCK}$ is the average efficiency of the buck converter while the supercapacitor is charging up. For a 120 mF supercapacitor to charge up to 1.8V with 1 mA $I_{SC}$, Equation 3 gives a time of 205 seconds, assuming the charger is 85% efficient and the buck converter gives an average efficiency of 70% while the supercapacitor is charging up. The efficiency of the buck converter improves to nearly 90% once the voltage on the supercapacitor goes above 1.5V.

**Charger only vs. diode charger**

While charging using the combination charger and buck converter has all the advantages of a charger only solution, does its charge time from a completely discharged state compare favorably to charging with a diode? By dividing Equation 3 by Equation 1, we get the ratio of charging times (Equation 4):

$$\frac{t_{bq25570}}{t_{diode}} = \frac{V_X}{2 \times V_{MPP} \times \eta_{CHG} \times \eta_{BUCK}}$$

Assuming an ideal diode charger and a 100% efficient charger and buck converter, we can see that for a solar cell with its MPP at 80% of its OCV, the ratio comes out to 1/1.6 or 0.625. Thus, under ideal conditions, the charger + buck converter combination should be 1.6 times faster than the diode charger. The non-idealities of the charger and buck converter reduce this speedup factor.
**Figure 7. Comparison of supercapacitor charging times using a diode charger and energy harvester.**

**Figure 7** demonstrates this dependence of the charging time on the efficiency of the charger and buck converter within the bq25570. **Figure 7a** shows the charging of the 120 mF supercapacitor from a 1 mA $I_{SC}$, 3V $V_{OC}$ solar cell with the help of the diode charger. **Figure 7b** shows the charging of the same supercapacitor using the bq25570 with the under-voltage level set to 2V. At 2V $V_{STOR}$, the charger and buck converter efficiencies are lower. Hence, we can see that the diode charger is slightly faster. To improve charge time, the internal under-voltage setting is changed to 2.7V in **Figure 7c**, which improves the charger and buck converter efficiencies. This makes the bq25570 charge a supercapacitor faster than the diode charger.

**Summary**

By using the combination of a charger and buck converter to charge a supercapacitor, a host of benefits can be obtained over existing methods. The proposed solution is significantly better in terms of charging time versus existing boost charger ICs. Compared to the diode charger, the proposed method enables charging from single, two-cell solar cells and thermoelectric harvesters, as well as performs MPPT of the attached energy harvester. This helps to extract more power out of the energy harvester during regular operating conditions. The in-built over-voltage function and $V_{BAT_OK}$ thresholds help to signal the user on the voltage conditions of the supercapacitor, leading to more informed system management. All of these benefits are obtained while being faster than the diode charger. Using these features, some of the key limiting factors in using supercapacitors can be overcome, leading to more widespread adoption of supercapacitors in self-powered systems.

**Reference**

- For more information, download these datasheets: bq25504, bq25570

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