When the Power Fails: Designing for a Smart Meter’s Last Gasp

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1/10/2012 5:25 PM EST

Overview

Smart meter designers have an unusual predicament: The meter is powered from the same bus that the meter is monitoring. When power is lost, the meter must record state information to flash memory or send out a wireless signal — the meter’s last gasp. Some utilities also desire to disconnect subscribers from the grid during power outages so that the inrush demands are minimized when power is ultimately restored. Disconnecting the subscriber after power is lost also requires stored energy in either electrical or mechanical form.

The problem of efficiently and cost-effectively providing hold-up energy typically falls to power supply designers. Here we will review three options a power supply designer has to solve this problem and evaluate their benefits and costs in a flyback switch-mode power supply.

The Circuits

Figure 1 shows a basic off-line flyback circuit. The supply accepts 85VAC-265VAC and generates a single 3.3VDC, 5W output.

Figure 1: Basic flyback schematic with highlighted locations for energy storage.
Let us set the holdup requirement of the load to be 50% power (2.5W) for 0.5s, or 1.25J.

Three sections where energy can be stored (A, B, and C) are highlighted in the schematic. Option A stores the hold-up energy in the high voltage capacitor, Cbus. Option B stores the energy in a 20V intermediate voltage capacitor with a down-stream DC/DC buck regulator that steps down the voltage to the load working voltage at 3.3V. Option C is simpler and stores energy in a large capacitor at the output.

**Electric Potential Energy**

Since all the options involve storing energy as electric potential in a capacitor, we should review the relationship of voltage, capacitance, and potential energy shown in the following equation:

\[
U_E = \frac{1}{2} CV^2
\]

To calculate a change in the potential energy for a given change in the voltage across the capacitor, we have:

\[
\Delta U_E = \frac{C(V_f^2 - V_0^2)}{2}
\]

where \(V_f\) is the final voltage, and \(V_0\) is the initial voltage. The change in voltage for a given change in potential energy is:

\[
\Delta V = \sqrt{\frac{2}{C} \left( \sqrt{U_f} - \sqrt{U_0} \right)}
\]

where \(U_f\) and \(U_0\) are the final and initial potential energy, respectively.

**Option A - Primary-Side Capacitance**

The first option is to increase the capacitance of the high voltage bulk electrolytic capacitor on the primary side, \(C_{bus}\).
This capacitor is typically sized to store just enough energy to continue power conversion during the AC cycle valleys — for a full-wave rectified input this is $\frac{1}{120}$ s, or 8.3 ms.

When voltage from the line disappears, the converter will continue to run and consume energy from $C_{bus}$. The voltage on $C_{bus}$ will eventually reach a point where the voltage cannot ramp sufficient current through the primary-side inductor to sustain the output. The voltage on the auxiliary output, from which the controller draws its power, will also drop to the controller’s under-voltage lock-out level. Once this happens, the controller will shut off, and the output will fall to zero. This process is shown in Figure 2.

The supply will need to hold-up the output under all conditions, so we will focus on the worst-case: when source power is disconnected shortly after the AC zero-crossing at low-line input. Since the supply will draw half-power during hold-up, the supply will operate normally— it will have enough voltage to impose across the inductor to reach the required primary-side peak current— down to 70% of the minimum input voltage requirement. We can therefore estimate that the supply will operate down to 70V on $C_{bus}$. We can use (2) to solve for the capacitance needed to provide the 1.25J of hold-up energy. We set $V_0$ to the minimum rectified AC line voltage because the bus ripple voltage will be negligible when the bulk capacitance is large:

$$C_{req} = \frac{2 \cdot \Delta U_E}{V_0^2 - V_f^2} = 510 \mu F$$

This is a very large amount of capacitance needed— and these capacitors need to be rated at a minimum of 400V. One benefit to storing energy in the primary-side is that a large amount of energy can be stored if the minimum line voltage is fairly high. For instance, if the minimum line voltage were 190V$_{AC}$, then the same hold-up would require
only 68 F, which is much more manageable! Figure 3 shows the holdup-time curve for this supply.

Considerations

Storing energy in the primary-side can be expensive. Large-valued high-voltage capacitors can get pricey, and the leakage current through them increases with voltage and value. Most designs try to minimize the primary-side loop to minimize electromagnetic compliance problems. Using very large capacitors (30mm diameter) may make this difficult.

![Figure 3: Calculated holdup time for a 85-265VAC flyback supplying 2.5W power after line disconnect.](image)

Although it is not shown above, the efficiency of the power supply must also be taken into consideration. Energy stored in the primary-side must be processed through the converter (the switch, inductor, secondary-side diodes), and it will be decreased by the efficiency of the converter. Many flyback converters are 75%-85% efficient, so the primary-side energy will need to increased up by 20%.

Option B - Intermediate Voltage

Option B is to add a secondary DC/DC regulator on the isolated side of the supply. A synchronous buck regulator fulfills this function with minimal parts: several products exist in the market that integrate the controller with high-side and low-side switches and drivers. The buck regulator would operate at a higher frequency than the flyback and would provide lower voltage ripple to the load.

Holdup energy is stored at an intermediate voltage on the secondary side. Since the secondary side is regulated, this provides a less varied quantity of stored energy. This is
in contrast with storing energy in the primary-side, where the line voltage may vary– and the holdup energy will vary with the line voltage squared. The energy storage in the secondary capacitor is straight-forward:

\[
U_e = \frac{1}{2} \cdot C_{iv} (V_{iv}^2 - V_{out}^2),
\]

where \( V_{iv} \) is the intermediate voltage and \( C_{iv} \) is the intermediate-voltage capacitance feeding the DC/DC converter.

In flyback designs current only flows through the secondary of the transformer during part of the switching cycle. This means that the output current ripple is very large on a RMS vs. DC basis, and it is up to the output capacitor to smooth the time-varying current into DC. Capacitors need to be rated for the heating that is caused by the parasitic resistance (effective series resistance, or ESR) that impedes the current ripple. This can frequently lead to over-sizing the output capacitors to meet end-product lifetime or MTBF goals.

With the secondary regulator, the current draw from the intermediate voltage will be a fraction of the load current. For our example, we set \( V_{iv} \) B 20V. In this case, full-load DC draw of 1.52A would draw 0.25A from the 20V rail. Because of the significantly reduced current (and therefore current ripple), \( C_{iv} \) can be sized based on the hold-up energy requirement and will have insignificant heating. Figure 4 shows the extra components for the secondary regulator.

![Figure 4: Option B Schematic. Secondary DC/DC converter is a buck and requires an additional inductor and capacitor.](image)

**Considerations**

A secondary-side regulator will provide much lower voltage ripple than a standard flyback output will. The additional parts will add to BOM or PCB space costs; however, these parts can all be sourced as SMD components. The regulated intermediate voltage will provide a more reliable minimum and maximum holdup time compared to primary-side energy storage.

**Option C - Supercapacitor**
The final option is to store energy directly in the load capacitors. Supercapacitors are very dense capacitors—both in terms of capacitance-per-volume and capacitance-per-dollar. This makes them well suited for storing hold-up energy directly at the output.

Many supercapacitors are designed for low voltage: 2.3V to 4V. To store 1.25J at 3.3V, about 1.1F of capacitance will be required. This will hold the output within 10% for 0.5s.

At boot-up the capacitors will look like a short on the output. Many modern flyback controllers have built-in over-load and short-circuit protection. These features will need to be slowed down in order for the supply to boot properly. Unfortunately, this will also slow down the feedback of the supply— the gain bandwidth of the supply is dependent upon the output capacitance.

Considerations

Because the output is regulated, this option will also have reliable minimum and maximum holdup times. As mentioned, booting into a large capacitance can pose a challenge for protection features and for sequencing with other supplies that may exist in the meter.

Conclusions

Each option for storing energy requires extra or specialized parts. Figure 5 shows the parts and cost comparison for each option.

<table>
<thead>
<tr>
<th>Option</th>
<th>Parts</th>
<th>Cost (@ 10k units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary side</td>
<td>400V 560uF capacitor (less $0.20 of the 10uF needed for other designs)</td>
<td>$3.26</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1600uF capacitor, FAN2103 DC/DC, 10uH inductor</td>
<td>$2.04</td>
</tr>
<tr>
<td>Voltage</td>
<td>2x2F, 2.4V supercapacitor</td>
<td>$3.12</td>
</tr>
</tbody>
</table>

Figure 5: Cost comparison of options

Storing energy in the primary-side is the simplest way to increase hold-up time; however, it is the least robust solution—with the hold-up time varying more than 1:100 across the line range.

Storing energy in the output capacitors is also fairly straightforward, provided that the application can accommodate the relaxed protection features. The supply will have slower over-load protection and short-circuit protection in order to boot up into the large output capacitance.

Finally, storing energy in an intermediate voltage is the most complicated— it requires the design of an additional powertrain. However, the benefits are significant; the supply will:
be responsive, have a well defined holdup time, and will be 30% cheaper versus the other storage options.

**About the Author**

Daniel Pruessner is a graduate of the University of Texas at Dallas, where he received his BSEE. He worked in power transmission and distribution at the Dow Chemical Company before joining Fairchild Semiconductor in 2009. He is a part of Fairchild’s Americas Global Power Resource Lab, where he helps customers solve power supply problems. He is active in designing off-line switch mode power supplies for smart meter, lighting, and consumer electronics applications.