BY DANIEL PRUESSNER • FAIRCHILD SEMICONDUCTOR

When the power fails: designing for a smart meter's last gasp

POWER-SUPPLY DESIGNERS HAVE SOME OPTIONS FOR COST-EFFECTIVELY PROVIDING ENERGY AFTER POWER LOSS.

Smart-meter designers have an unusual predicament: The meter receives its power from the same bus that the meter is monitoring. When the meter loses power, it must record state information to flash memory or send out a wireless signal—the meter's "last gasp." Some utilities also disconnect subscribers from the grid during power outages to minimize the inrush demands when power is ultimately restored. Disconnecting a subscriber after loss of power also requires stored energy in either electrical or mechanical form.

The problem of efficiently and cost-effectively providing holdup energy typically falls to power-supply designers, who have various options for solving this problem. Here we evaluate the benefits and costs of these options in a flyback switch-mode power supply.

Figure 1 shows a basic offline flyback circuit. The supply accepts 85 to 265V ac and generates a 3.3V-dc, 5W output. The holdup requirement of the load is 50% power, or 2.5W, for 0.5 sec, or 1.25J. The **figure** highlights three sections for energy storage. Option A stores the holdup energy in the high-voltage capacitor, C_{BUS}. Option B stores the energy in a 20V intermediate-voltage capacitor with a downstream dc/dc buck regulator that steps down the voltage to the load's working voltage at 3.3V. Option C is simpler and stores energy in a large capacitor at the output.

ELECTRIC-POTENTIAL ENERGY

Because all of the options involve storing energy as electric potential in a capacitor, you should review the relationship of voltage, capacitance, and potential energy, as the following **equation** shows:

$$U_E=\frac{1}{2}CV^2,$$

where U_E is potential energy, C is capacitance, and V is voltage. The following **equation** calculates a change in the potential energy for a given change in the voltage across the capacitor:

$$\Delta U_E=\frac{C(V_F^2-V_0^2)}{2},$$

where V_F is the final voltage and V_0 is the initial voltage. The following **equation** shows the change in voltage for a given change in potential energy:

$$\Delta V=\sqrt{\frac{2}{C}}\times(\sqrt{U_F}-\sqrt{U_0}),$$

where U_F and U_0 are the final and initial potential energy, respectively.

PRIMARY-SIDE CAPACITANCE

The first option is to increase the capacitance of the high-voltage bulk electrolytic capacitor, C_{BUS}, on the primary side. This capacitor typically stores just enough energy to continue power conversion during the ac cycle valleys—in this case, 1/120 sec, or 8.3 msec, for a full-wave rectified input. When voltage from the line disappears, the converter continues to run and consume energy from C_{BUS}. The voltage on C_{BUS} eventually reaches a point at which the voltage cannot ramp sufficient current through the primary-side inductor to sustain

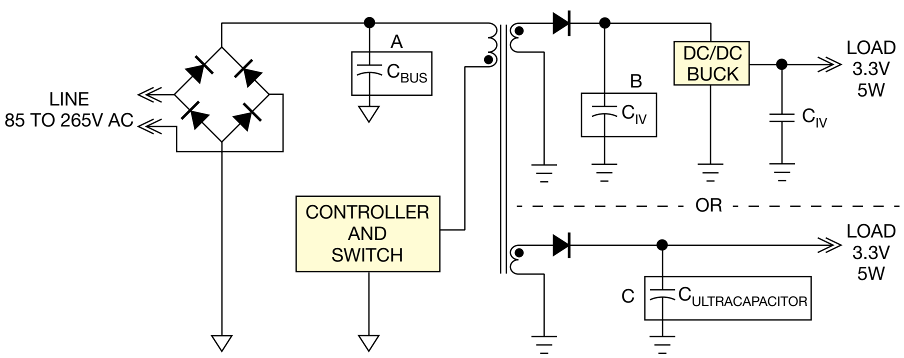

Figure 1 In a basic flyback circuit, Option A stores the holdup energy in the high-voltage capacitor, C_{BUS}. Option B stores the energy in a 20V intermediate-voltage capacitor with a downstream dc/dc buck regulator that steps down the voltage to the load's working voltage at 3.3V. Option C is simpler and stores energy in a large capacitor at the output.

the output. The voltage on the auxiliary output, from which the controller draws its power, also drops to the controller's undervoltage-lockout level. After this drop, the controller shuts off, and the output falls to 0V (**Figure 2**).

The supply must hold up the output under all conditions, so we will focus on the worst case: when source power disconnects shortly after the ac zero-crossing at low line input. Because the supply draws half-power during holdup, the supply operates normally. It has enough voltage to impose across the inductor to reach the required primary-side peak current—down to 70% of the minimum input voltage requirement. You can therefore estimate that the supply can operate down to 70V on C_{BUS}. Solve for the capacitance to provide the 1.25J of holdup energy and set V_0 to the minimum rectified ac line voltage because the bus-ripple voltage is negligible when the bulk capacitance is large:

$$C_{REQ}=\frac{2\times\Delta U_E}{V_0^2-V_F^2}=510\ \mu F.$$

This capacitance is large, and these capacitors must have a minimum voltage of 400V. One benefit of using the primary side is that it can store a large amount of energy if the minimum line voltage is fairly high. For instance, if the minimum line voltage were 190V ac, then the same holdup would require only 68F. **Figure 3** shows the holdup-time curve for this supply.

Storing energy in the primary side can be expensive. Large-value, 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 capacitors with diameters of 30 mm may make this task difficult.

You must also take into consideration the efficiency of the power supply. Energy stored in the primary side must be processed through the converter, which includes the switch, the inductor, and the secondary-side diodes, and the efficiency of the converter will decrease this energy. Many flyback converters are 75 to 85% efficient, so the primary-side energy must increase by 20%.

INTERMEDIATE VOLTAGE

Option B involves adding a secondary dc/dc regulator on the isolated side of the supply. A synchronous buck regulator fulfills this function with minimal parts. Several available products integrate the controller with high- and low-side switches and drivers. The buck regulator would operate at a higher frequency than the flyback converter and would provide lower voltage ripple to the load.

Holdup energy is stored at an intermediate voltage on the secondary side. The regulated secondary side provides a less varied quantity of stored energy—in contrast with storing energy in the primary side, in which the line voltage may vary and the holdup energy varies with the line voltage squared. The energy storage in the secondary capacitor is straightforward:

$$U_E=\frac{1}{2}\times C_{IV}(V_{IV}^2-V_{OUT}^2),$$

where C_{IV} is the intermediate-voltage capacitance feeding the dc/dc converter and V_{IV} is the intermediate voltage.

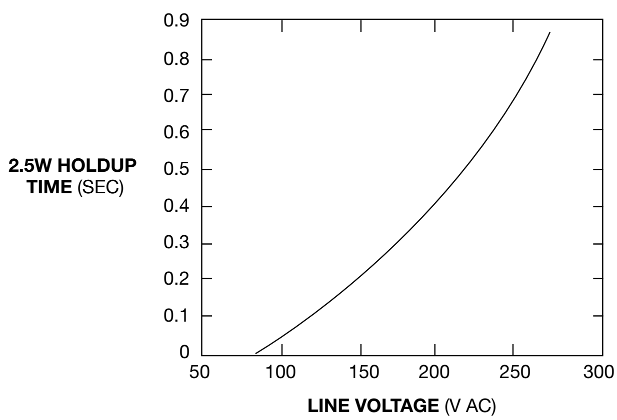

Figure 3 One benefit of storing energy in the primary side is that it can store a large amount of energy if the minimum line voltage is fairly high. For instance, if the minimum line voltage were 190V ac, then the same holdup would require only 68F, which is more manageable, as this curve shows.

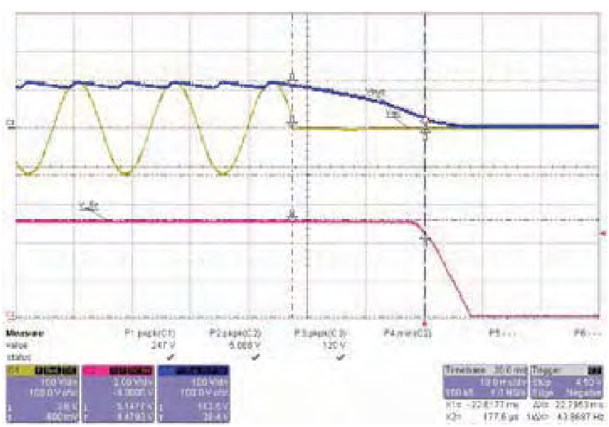

Figure 2 The voltage on the auxiliary output, from which the controller draws its power, also drops to the controller's undervoltage-lockout level. After this drop, the controller shuts off, and the output falls to 0V.

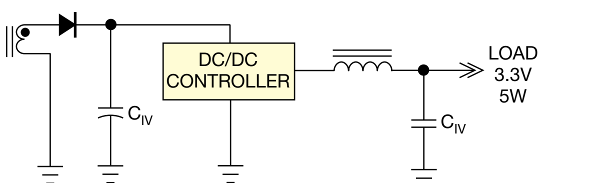

Figure 4 Because of the significantly reduced current and, therefore, current ripple, you can size C_{IV} based on the holdup-energy requirement, and it will have an insignificant amount of heating.

TABLE 1 PARTS AND COST COMPARISON

Option	Parts	Price (10,000)
Primary side	400V, 560-µF capacitor (minus 20 cents of the 10 µF needed for other designs)	$3.26
Intermediate voltage	1600-µF capacitor, FAN2103 dc/dc, 10-µH inductor	$2.04
Supercapacitor	2x2F, 2.4V supercapacitor	$3.12

In flyback designs, current flows through the secondary of the transformer only during part of the switching cycle, meaning that the output-current ripple is large on an rms-versus-dc basis, and it is up to the output capacitor to smooth the time-varying current into dc. Designers must rate capacitors for the effective-series-resistance-caused heating, which impedes the current ripple. This requirement can frequently lead to oversizing the output capacitors to meet end-product lifetime or mean-time-between-failure goals.

With the secondary regulator, the current draw from the intermediate voltage is a fraction of the load current. For this example, with a V_{IV} of 20V, a 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, you can size C_{IV} based on the holdup-energy requirement, and it will have an insignificant amount of heating. **Figure 4** shows the extra components for the secondary regulator.

A secondary-side regulator provides lower voltage ripple than does a standard flyback output. The additional parts will add to bill-of-materials or PCB-space costs; however, you can source these parts as SMD components. The regulated intermediate voltage will provide a more reliable minimum and maximum holdup time than that of primary-side energy storage.

SUPERCAPACITOR

The final option is to store energy directly in the load capacitors. Supercapacitors are dense in both capacitance per volume and capacitance per dollar. This feature makes them well-suited for storing holdup energy directly at the output. Many supercapacitors have voltage of only 2.3 to 4V. Storage of 1.25J at 3.3V requires approximately 1.1F of capacitance. This amount holds the output within 10% for 0.5 sec.

At boot-up, the capacitors look like a short circuit on the output. Many modern flyback controllers have built-in overload and short-circuit protection. These features will need to be slowed down for the supply to boot properly. Unfortunately, this slowdown combined with the increased output capacitance will greatly reduce the bandwidth of the supply feedback and will reduce transient response performance.

Because the output is regulated, this option also has reliable minimum and maximum holdup times. Booting into a large capacitance can pose a challenge for protection features and for sequencing with other supplies in the meter.

Each option for storing energy requires extra or specialized parts. **Table 1** shows the parts and cost comparison for each option.

Storing energy in the primary side is the simplest way to increase holdup time; however, it is the weakest approach, with the holdup time varying more than 1-to-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 requires slower overload and short-circuit protection to boot up into the large output capacitance. Storing energy in an intermediate voltage is the most complicated approach. It requires the design of an additional power train. However, the benefits are significant: The supply is responsive, has a well-defined holdup time, and is 30% cheaper than the other storage options. EDN

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