The Over-Power Phenomenon in DCM/CCM-Operated Flyback Converters (Part 2): Fixed-Frequency CCM Operation

by Christophe Basso, ON Semiconductor, Toulouse, France

In the previous article, we have seen how a flyback converter operating in discontinuous-conduction mode (DCM) can deliver more power under a high-line input condition than in a low-line situation. In the example discussed in part 1, the converter did not exhibit mode transition, i.e., the converter stayed in DCM over the whole input range.

In high-power adapters, however, it's standard practice to make the converter operate in deep CCM at low line and then transition to light continuous-conduction mode (CCM) or even DCM at high line. Operating in CCM at low line ensures lower conduction losses, while DCM at high line reduces the stress on the secondary-side diode. However, as with the DCM-only case, the power delivered at high line is again higher than that delivered at low line. Here in part 2, we'll discover why this is the case.

The Flyback Converter Operated in CCM

The waveforms associated with the CCM-operated flyback converter (Fig. 1) reveal the presence of a valley and a peak current.

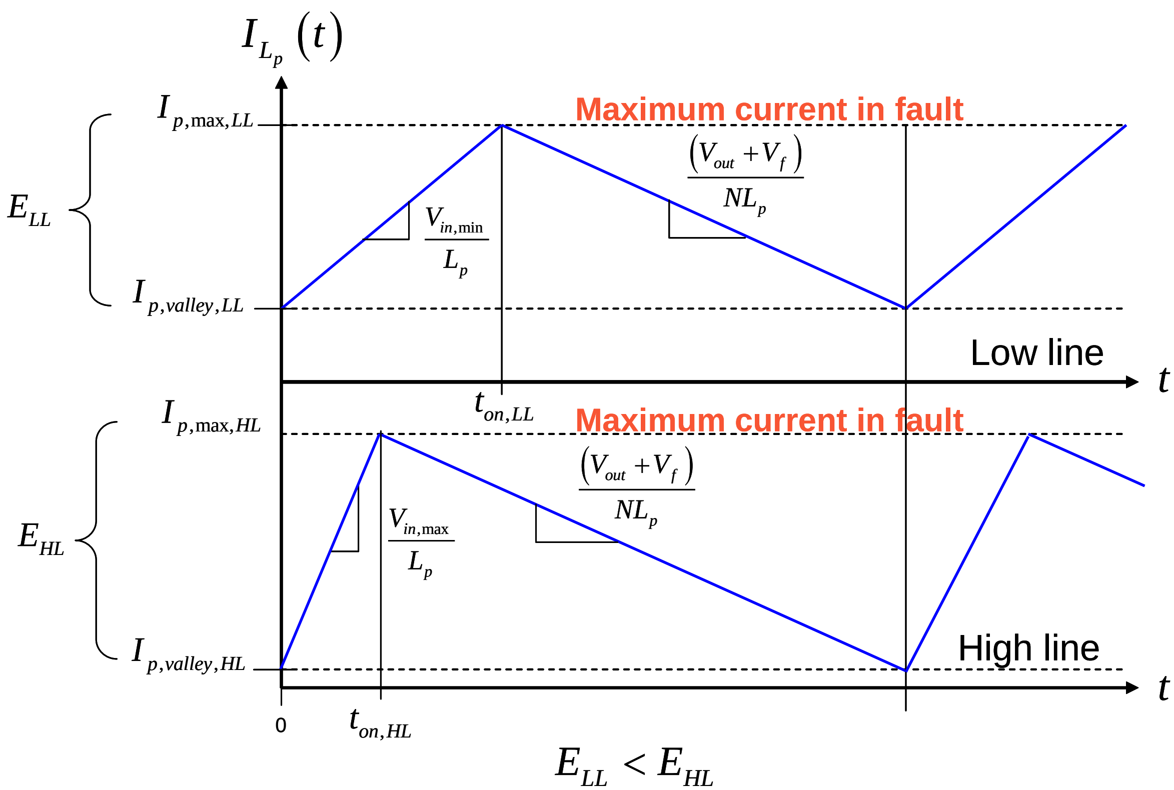

Fig. 1. Under CCM operation, the magnetizing inductor of the transformer, L_p sees a peak current that ramps from a valley point up to a peak.

A valley current exists because the transformer is not fully demagnetized at the end of a switching cycle and stored energy remains in the core. When the MOSFET power switch closes, its drain current jumps to the valley point and ramps up to the peak value with a slope equal to:

$$S_{on} = \frac{V_{in}}{L_p} \tag{1}$$

However, the pace at which the peak current value is reached depends on the input-line conditions. At low line, the slope is rather mild and the drain current ramps up gently so that the on-time duration is long. At high line, the slope is steeper and the peak current value is reached at a much quicker pace. In this case, the on-time is shorter. The converter topology we are currently interested in operates at a constant frequency. Therefore, since t_{on} reduces at high line, the demagnetization time naturally increases to satisfy the condition $t_{on} + t_{off} = T_{sw}$.

If the input voltage ensures the primary inductor magnetization, the reflected voltage ensures the demagnetization at a constant down slope equal to:

$$S_{off} = \frac{V_{out} + V_f}{NL_p} \tag{2}$$

where N is the turns ratio linking the primary and the secondary windings, V_{out} is the output voltage and V_f is the forward drop of the secondary diode.

The Transition To DCM

Fig. 1 shows the waveforms for the transformer's primary-side inductor at two different line levels. The upper curve represents a low-line condition whereas the lower curve shows the same converter operated at a high-line level. As expected, the on-time is reduced in high line as the slope to reach the peak current setpoint is steeper. However, whatever the input-line level, the reflected voltage on the primary-side inductor does not change. Therefore, if more demagnetization time is available, the inductor has time to deplete to a lower level before the next cycle occurs. The valley current thus decreases eventually to zero, making the converter operate in DCM if the inductance value is not large enough.

The flyback converter works by storing energy during the on-time and then dumping this energy into the secondary side when the power switch opens. In CCM, the energy stored in the inductor can be expressed as the difference between the energy stored when the current peaks and the energy originally stored at the beginning of the on-time:

$$E = \frac{1}{2} L_p I_{peak}{}^2 - \frac{1}{2} L_p I_{valley}{}^2 = \frac{1}{2} L_p \left(I_{peak}{}^2 - I_{valley}{}^2 \right) \tag{3}$$

When a fault condition occurs, the peak current is limited by the pulse width modulation (PWM) controller to a preset maximum value. In spite of propagation delay effects (which were discussed in part 1 of this article), the difference in peak current from low to high line remains small. However, as the valley current decreases under high-line conditions, the equation (3) result naturally tends to increase at high line. Therefore, for a constant peak current and the same inductance, the flyback transformer stores more energy in DCM or light CCM (E_{HL}) than in deep CCM (E_{LL}). As a result, the flyback converter will deliver more power under a high-line condition than it will with a lower input voltage.

Deriving The Variables

To compute the output power (P_{OUT}) under high-line conditions, we must derive the values of the peak and the valley currents. Once these values are known, we can apply equation (3) to determine the energy stored in the inductor, and then multiply that value by the switching frequency (F_{SW}) and converter efficiency (η) to obtain P_{OUT}. First, let us look at the peak current (Fig. 2.)

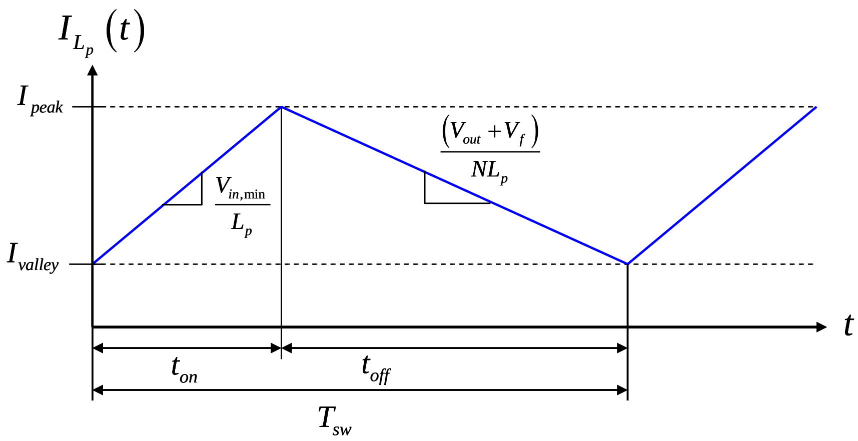

Fig. 2. The CCM waveform of the flyback converter with its associated on and off times.

We have seen in the first part of this article that the peak current excursion is limited by the controller when a fault occurs. However, the total propagation delay (t_{prop}) plays a role and generates overshoot with high input voltages:

$$I_{peak,\max} = \frac{V_{sense,\max}}{R_{sense}} + \frac{V_{in}}{L_p} t_{prop} \tag{4}$$

where R_{sense} is the converter sense resistor, $V_{sense,\max}$ is the maximum authorized sense voltage (0.8 V for the NCP1250), V_{in} is the input voltage and L_p is the primary inductance.

The valley current requires a few lines of algebra to derive it. From Fig. 2, we can write:

$$I_{peak} = I_{valley} + \frac{V_{in}}{L_p} t_{on} \tag{5}$$

Also from observing Fig. 2, we can derive a second equation for the valley current:

$$I_{valley} = I_{peak} - \frac{(V_{out} + V_f)}{NL_p} t_{off} \tag{6}$$

Finally, because we operate with a fixed switching frequency, the following condition must be satisfied:

$$T_{sw} = t_{on} + t_{off} \tag{7}$$

From equation (5) we can extract the on-time value:

$$t_{on} = \frac{L_p (I_{peak} - I_{valley})}{V_{in}} \tag{8}$$

And combining this result with equation (7), we have:

$$t_{off} = T_{sw} - t_{on} = T_{sw} - \frac{L_p (I_{peak} - I_{valley})}{V_{in}} \tag{9}$$

Now replacing t_{off} in equation (6), we obtain:

$$I_{valley} = I_{peak} - \frac{\left(V_f + V_{out}\right)\left(I_{valley}L_p - I_{peak}L_p + T_{sw}V_{in}\right)}{L_p N V_{in}} \tag{10}$$

From which we can solve for I_{valley}:

$$I_{valley} = I_{peak} - \frac{T_{sw}V_{in}\left(V_f + V_{out}\right)}{L_p\left(V_f + V_{out} + NV_{in}\right)} \tag{11}$$

From Fig. 2, we can define the inductor ripple current by the following expression:

$$\Delta I_L = I_{peak} - I_{valley} = \frac{T_{sw}V_{in}\left(V_f + V_{out}\right)}{L_p\left(V_f + V_{out} + NV_{in}\right)} \tag{12}$$

Now that the ripple expression has been derived, we can use it, if necessary, to determine the converter operating modes. By looking at the definitions in equations (8) and (9), the inductor ripple current appears:

$$t_{on} = \frac{\Delta I_L}{V_{in}} L_p \tag{13}$$

$$t_{off} = \frac{N\Delta I_L}{\left(V_{out} + V_f\right)} L_p \tag{14}$$

If the sum of the above time periods equals the switching period and the valley current is greater than zero, the converter operates in CCM. If the first condition is respected but the valley current equals zero, the converter operates at the boundary between CCM and DCM. We call this particular mode the boundary-conduction mode, also referred to as borderline-conduction mode (BCM) or critical-conduction mode (CrM). Finally, if the on- and off-times sum is less than the switching period, then a third time event exists, the deadtime (DT), which confirms full DCM operation. Fig. 3 presents the corresponding waveforms for the three modes of operation.

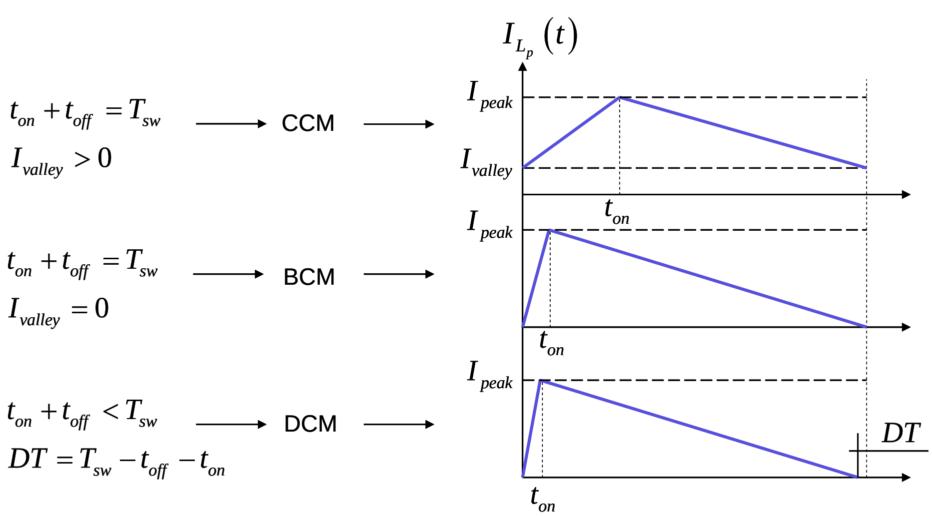

Fig. 3. By looking at the on- and off-time definitions, we have a means to determine the converter operating modes.

Computing The Transmitted Power

Let's assume we have built a 65-W converter featuring the following component values and operating voltages:

$V_{in,HL}$ is the dc input voltage at high line, 370 V

$V_{in,LL}$ is the dc input-voltage at low line, 120 V

V_{out} is the dc output voltage, 19 V

L_p is the transformer primary inductance, 600 µH

t_{prop} is the total propagation delay, 350 ns

R_{sense} is the sense resistor value, 0.33 Ω

V_{sense} is the maximum authorized sense-voltage value, 0.8 V

T_{sw} is the switching period for a 65-kHz frequency, 15.4 µs

N_{ps} is the transformer turns ratio between the secondary and primary sides, 1:0.25

N_{pa} is the transformer turns ratio between the primary and the auxiliary sides, 1:0.18

η_{LL} is the converter efficiency at low line, 85%

η_{HL} is the converter efficiency at high line, 89%

First, we can calculate the peak current in a fault condition at low line and high line:

$$I_{peak,\max,LL} = \frac{V_{sense,\max}}{R_{sense}} + \frac{V_{in,LL}}{L_p} t_{prop} = \frac{0.8}{0.33} + \frac{120}{600u} \times 350n = 2.49\,\mathrm{A} \quad (15)$$

$$I_{peak,\max,HL} = \frac{V_{sense,\max}}{R_{sense}} + \frac{V_{in,HL}}{L_p} t_{prop} = \frac{0.8}{0.33} + \frac{370}{600u} \times 350n = 2.64\,\mathrm{A} \quad (16)$$

The difference in the peak values is 6%, which is not really a big gap. This can be explained by the rather large inductor value. The valley current is the one actually changing between the two input-line conditions:

$$I_{valley,LL} = I_{peak,\max,LL} - \frac{T_{sw} V_{in,LL} \left(V_f + V_{out}\right)}{L_p \left(V_f + V_{out} + N V_{in,LL}\right)} = 2.49 - \frac{15.4u \times 120 \times \left(19 + 0.5\right)}{600u \times \left(19 + 0.5 + 0.25 \times 120\right)} = 1.28\,\mathrm{A} \quad (17)$$

$$I_{valley,HL} = I_{peak,\max,HL} - \frac{T_{sw} V_{in,HL} \left(V_f + V_{out}\right)}{L_p \left(V_f + V_{out} + N V_{in,HL}\right)} = 2.64 - \frac{15.4u \times 370 \times \left(19 + 0.5\right)}{600u \times \left(19 + 0.5 + 0.25 \times 370\right)} = 0.99\,\mathrm{A} \quad (18)$$

Based on these two values, we can compute the transmitted power at both input levels:

$$P_{out,LL} = \frac{1}{2} L_p \left(I_{peak,\max,LL}{}^2 - I_{peak,\max,LL}{}^2\right) F_{sw} \eta_{LL} = 0.5 \times 600u \times \left(2.49^2 - 1.28^2\right) \times 65k \times 0.85 \approx 76\,\mathrm{W} \quad (19)$$

$$P_{out,HL} = \frac{1}{2} L_p \left(I_{peak,\max,HL}{}^2 - I_{peak,\max,HL}{}^2 \right) F_{sw} \eta_{HL} = 0.5 \times 600u \times \left(2.64^2 - 0.99^2 \right) \times 65k \times 0.89 = 104\,\mathrm{W} \quad (20)$$

The numerical data correspond to the design of a 19-V adapter for a notebook. Based on the computed power levels, we can extract the maximum current delivered by the adapters at the two input extremes:

$$I_{out,LL} = \frac{P_{out,LL}}{V_{out}} = \frac{75.9}{19} = 3.99\,\mathrm{A} \quad (21)$$

$$I_{out,HL} = \frac{P_{out,HL}}{V_{out}} = \frac{104}{19} = 5.47\,\mathrm{A} \quad (22)$$

The original design was targeting an output current of 3.3 A as a nominal value. As indicated above, the current grows beyond 5 A under high-line conditions. As explained in part 1, you will have to oversize the output diode and its heatsink so that it can sustain such a current, which is well outside the nominal value. One way to overcome this problem is to implement a circuit limiting the peak current at high line.

Over-Power Protection (OPP)

OPP can be implemented in several ways as highlighted in part 1. Capitalizing on a proprietary technique, the recent NCP1250 from ON Semiconductor leaves the beaten paths and explores a new solution based on the auxiliary winding signal. Such a solution appears in Fig. 4.

The auxiliary winding sees a signal swinging negatively to $-N_{pa}V_{in}$ during the transistor on-time. When this negative signal is properly scaled down via a resistor network, it can be directly subtracted from the 0.8-V internal reference voltage of the controller. That way, at low line, the maximum peak-current limit is barely affected. However, as the input line level increases, the 0.8-V reference starts to decrease down to a value determined by the external network. A means to compensate the power delivery increase now exists and this technique has proven to be very efficient.

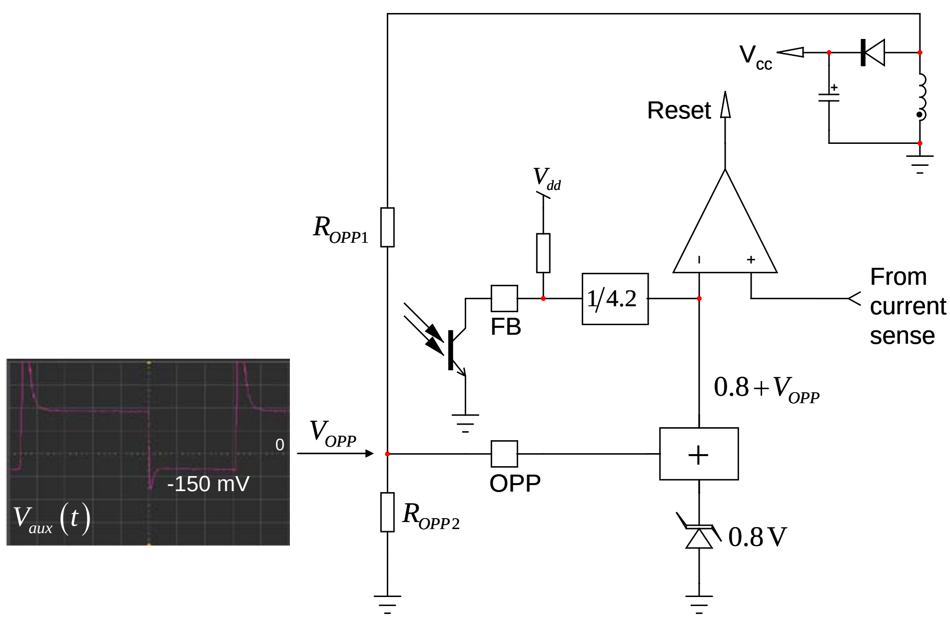

Fig. 4: The OPP circuitry in the NCP1250 reduces the final peak current setpoint at no power dissipation cost.

To calculate the amount of OPP needed, we can start from the power delivered at low line (76 W) and set it as the goal for maximum power output under high-line conditions. Using equations (19) and (20) while assuming the operating mode (CCM) is maintained, we have:

$$P_{\max,LL} = \frac{1}{2} L_p \left(I_{peak,\max,HL}{}^2 - \left(I_{peak,\max,HL} - \Delta I_{L,HL} \right)^2 \right) F_{sw} \eta_{HL} \tag{23}$$

From this equation, we extract the value of the compensated peak current that we must set at high line to limit the delivered power:

$$I_{peak,\max,HL} = \frac{F_{sw} L_p \eta_{HL} \Delta I_{L,HL}{}^2 + 2P_{\max,LL}}{2F_{sw} L_p \eta_{HL} \Delta I_{L,HL}} \tag{24}$$

To obtain the voltage imposed by the controller, we must remove the propagation delay contribution and include the current-to-voltage conversion gain via the sense resistor R_{sense}:

$$\Delta V = V_{sense} - \left(I_{peak,\max,HL} - \frac{V_{in,HL}}{L_p} t_{prop} \right) R_{sense} \tag{25}$$

Once compensation is implemented, we obtain the following current value:

$$I_{peak,\max,HL} = \frac{V_{sense} - \Delta V}{R_{sense}} + \frac{V_{in,HL}}{L_p} t_{prop} \tag{26}$$

To compute the compensation level, we must first evaluate the inductor ripple at high line using equation (12):

$$\Delta I_{L,HL} = \frac{370 \times (0.5 + 19)}{65k \times 600u \times (0.5 + 19 + 0.25 \times 370)} = 1.65\,\mathrm{A} \tag{27}$$

Knowing this value, we can apply equation (24) to derive the desired target for the high-line peak current:

$$I_{peak,\max,HL} = \frac{65k \times 600u \times 0.89 \times 1.65^2 + 2 \times 75.9}{2 \times 65k \times 600u \times 0.89 \times 1.65} = 2.15\,\mathrm{A} \tag{28}$$

This value is 490 mA less than the peak current value obtained using equation (16). We must therefore act on the internal reference voltage of 0.8 V to decrease its value to finally impose the peak current suggested by equation (28). The reduction of the reference voltage amounts to:

$$\Delta V = 0.8 - \left(2.15 - \frac{370}{600u} \times 350ns \right) \times 0.33 = 0.8 - 0.638 = 0.162\,\mathrm{V} \tag{29}$$

According to Fig. 4, the negative swing is proportional to the auxiliary voltage. Therefore, based on the negative amplitude delivered by this winding during the on-time, $-N_{pa}V_{in}$, we can calculate the divider network. For biasing purposes, we recommend the ground-resistor value (R_{OPPL}) remain under 2 kΩ. If we fix it to 1.6 kΩ, the resistor connected to the auxiliary winding can be calculated as follows:

$$R_{OPPH} = \frac{\left(V_{in,HL} N_{pa} - V_{OPPHL}\right) R_{OPPL}}{V_{OPPHL}} = \frac{(370 \times 0.18 - 0.162)}{0.162} \times 1.6k = 656\,\mathrm{k}\Omega$$

(30)

OPP At Work

To check the validity of our calculations, we have used the component values given above. We have entered the formulas in Mathcad and then plotted the power variations with and without OPP implementation. In these calculations, it is assumed that the efficiency varies linearly from 85% to 89%, which were the values specified for low-line and high-line conditions, respectively. The results appear in Fig. 5 and depict how the output power runs away at high line.

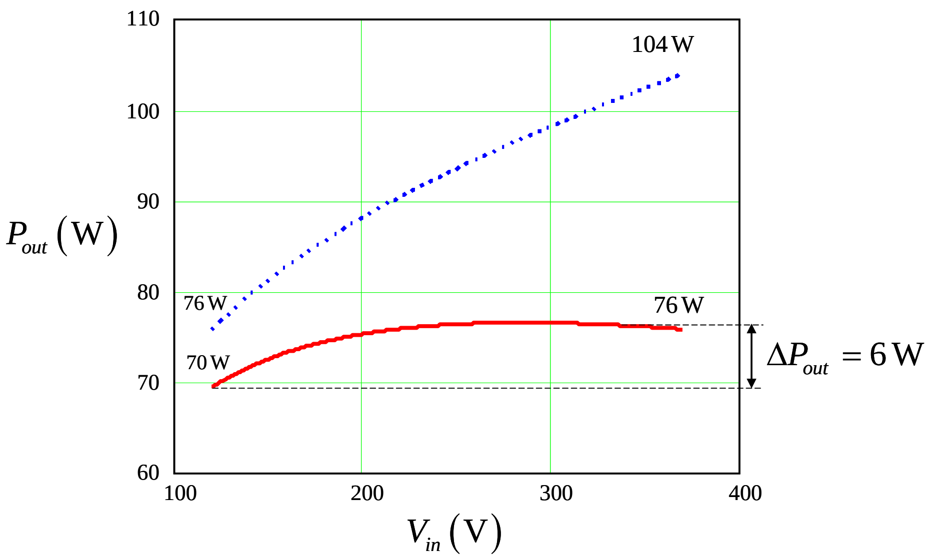

Fig. 5. As expected, the power delivered at high line is way beyond the converter capability at low line.

If we now apply the correction, which consists of reducing the peak-current setpoint as the input voltage grows, we can see a nice curvature of the delivered power, which now remains well within control.

Conclusion

In part 1, we explained why a flyback converter operated in the discontinuous-conduction mode delivers more power at high line than at low line. The main offender was the propagation delay during the turn-off event. In CCM, the increase of power at high line comes from the transition of the CCM converter into DCM, naturally increasing the stored energy in the transformer's primary inductor. Again, decreasing the peak-current setpoint as the input line increases represents an efficient way of limiting the available output power.

Reference:

C. Basso. The Over-Power Phenomenon In DCM/CCM-Operated Flyback Converters (Part 1) How2Power Today, October 2010.

About The Author

Christophe Basso is an application engineering director at ON Semiconductor in Toulouse, France. He has originated numerous integrated circuits among which the NCP120X series has set new standards for low standby power converters. SPICE simulation is also one of his favorite subjects and he authored a second book, "Switch-Mode Power Supplies: SPICE Simulations and Practical Designs", published by McGraw-Hill in 2008. His work was positively reviewed in several magazines and in a recent PELS newsletter. Christophe holds a BSEE-equivalent from the Montpellier University, France and a MSEE from the Institut National

Polytechnique de Toulouse, France. He holds 17 patents on power conversion and often publishes papers in conferences and trade magazines.

For further reading on power protection, see the How2Power Design Guide, search the Design Area category and select Power Protection as the subcategory.