Application Brief

How to Approach a Power-Supply Design – Part 6

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This application brief highlights the workhorse of low-power isolated topologies: the flyback converter. The maximum achievable output power of this topology is typically in the range of 100 W. For output power above this level, using a forward topology can provide better efficiency. These topologies are the topic of the next installations in this series.

Flyback Converters

The flyback topology can step the input voltage up and down, generating an isolated output voltage that can be positive or negative. When switch Q1 is conducting, energy is stored in the air gap of the coupled inductor, often called a flyback transformer. The energy then transfers to the output when switch Q1 stops conducting. Figure 1 is a schematic of a nonsynchronous flyback converter.

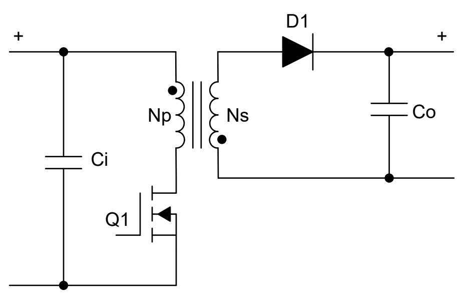

Figure 1. Nonsynchronous Flyback Converter Schematic

Equation 1 calculates the duty cycle in continuous conduction mode (CCM).

$$D = \frac{\left(V_{OUT} + V_f\right) \times \frac{n_p}{n_s}}{V_{IN} + \left(V_{OUT} + V_f\right) \times \frac{n_p}{n_s}} \tag{1}$$

Equation 2 calculates the maximum metal-oxide semiconductor field-effect transistor (MOSFET) stress.

$$V_{Q1} = V_{IN} + \left(V_{OUT} + V_f\right) \times \frac{n_p}{n_s} \tag{2}$$

where

- V_{IN} is the input voltage
- V_{OUT} is the output voltage
- V_f is the diode forward voltage
- n_p / n_s is the turns ratio of the coupled inductor

The nonperfect coupling of the coupled inductor creates an additional voltage spike caused by the excess energy stored in the leakage inductance. Therefore, choose a voltage rating for Q1 that includes reasonable margin. Typically, a clamping circuit can reduce the voltage spike and needs to dissipate the excess energy. Generally, allow the overshoot to reach 50% of the reflected voltage to provide proper commutation of the stored energy to the output.

Equation 3 gives the maximum diode stress.

$$V_{D1} = V_{OUT} + V_{IN} \times \frac{n_s}{n_p} \tag{3}$$

where

- V_{IN} is the input voltage
- V_{OUT} is the output voltage
- n_p / n_s is the turns ratio of the coupled inductor

The flyback converter has pulsed currents at both ends of the converter because of how the converter transfers energy to the secondary side. This fact leads to rather high voltage ripple at both converter ends. For electromagnetic compatibility, additional input filtering can be necessary. If the converter needs to supply a very sensitive load, a second-stage filter at the output can help damp the output voltage ripple.

A flyback converter can be built by using a boost or general-purpose pulse-width modulation controller, because the converter only requires a low-side gate driver. For low output power, a boost converter integrated circuit (IC) (with integrated MOSFETs) can be a viable option.

In terms of dynamic behavior, an optocoupler in the isolated feedback path and right half-plane zero (RHPZ) are the primary limiting factors for the achievable regulation bandwidth of the flyback converter. If there is no optocoupler in the feedback path or the bandwidth is larger than the RHPZ frequency, the maximum achievable bandwidth is roughly one-fifth the RHPZ frequency. However, it is good practice opting for one-tenth the RHPZ frequency for the majority of designs to provide sufficient phase and gain margin. Equation 4 estimates the single RHPZ frequency of the transfer function of the flyback converter.

$$f_{RHPZ} = \frac{V_{OUT} \times (1 - D)^2}{2 \times \pi \times D \times \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2} \times I_{OUT}} \tag{4}$$

where

- V_{OUT} is the output voltage
- D is the duty cycle
- I_{OUT} is the output current
- L_p is the primary inductance of the coupled inductor
- n_p / n_s is the turns ratio of the coupled inductor

Figure 2 through Figure 7 show voltage and current waveforms in CCM for FET Q1, primary inductor Np, and diode D1 in a nonsynchronous flyback converter.

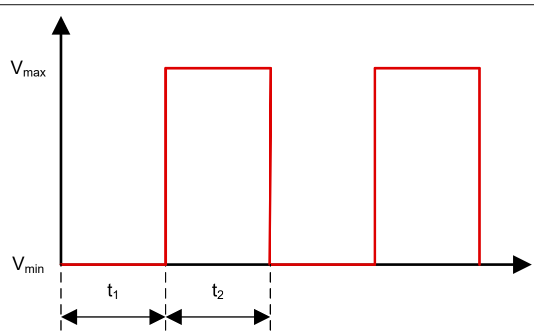

Figure 2. Flyback FET Q1 Voltage Waveform in CCM

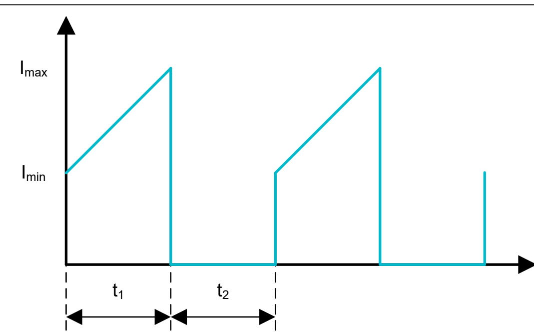

Figure 3. Flyback FET Q1 Current Waveform in CCM

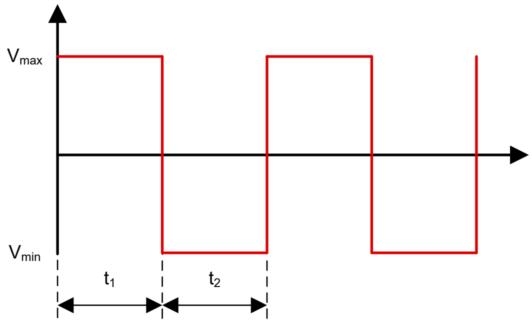

Figure 4. Flyback Primary Inductor Np Voltage Waveform in CCM

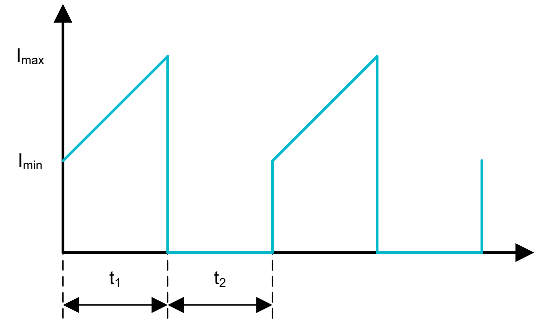

Figure 5. Flyback Primary Inductor Np Current Waveform in CCM

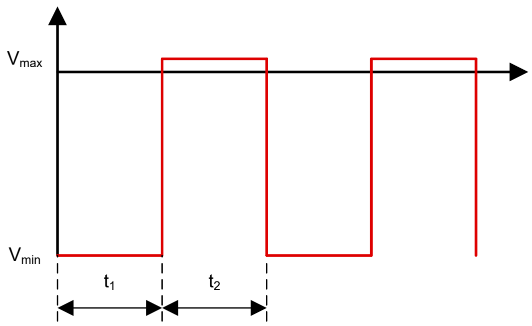

Figure 6. Flyback Diode D1 Voltage Waveform in CCM

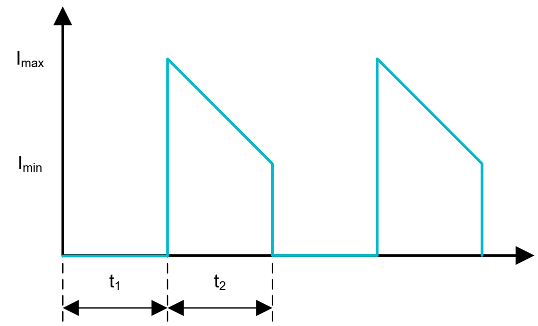

Figure 7. Flyback Diode D1 Current Waveform in CCM

Low-power or low-output-current flyback converters are often designed to operate in discontinuous conduction mode (DCM) to minimize transformer size, weight, and cost. An additional benefit of this approach is that the R_{HPZ} frequency moves to regions higher than 100 kHz, enabling higher regulation bandwidths than in CCM.

Equation 5 calculates the duty cycle in DCM.

$$D = f_{switch} \times \sqrt{2 \times I_{OUT} \times L_p \times \frac{V_{OUT} + V_f}{f_{switch} \times V_{IN}^2}} \quad (5)$$

where

- f_{switch} is the switching frequency
- V_{IN} is the input voltage
- V_{OUT} is the output voltage
- V_f is the diode forward voltage
- I_{OUT} is the output current
- L_p is the primary inductance of the coupled inductor

Figure 8 through Figure 13 show voltage and current waveforms in DCM for FET Q1, primary inductor Np, and diode D1 in a nonsynchronous flyback converter.

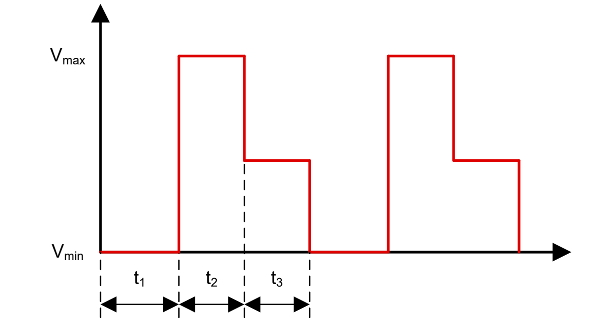

Figure 8. Flyback FET Q1 Voltage Waveform in DCM

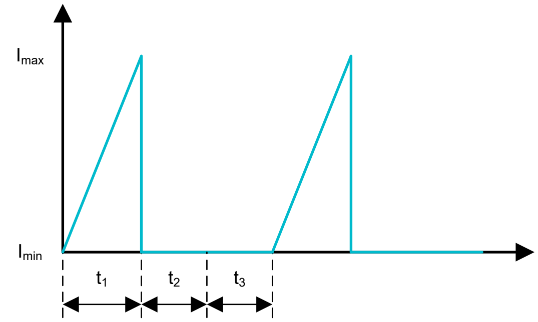

Figure 9. Flyback FET Q1 Current Waveform in DCM

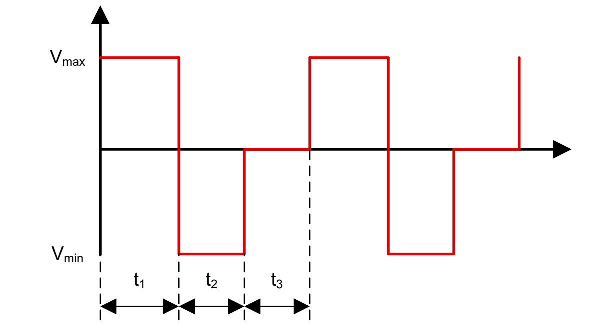

Figure 10. Flyback Primary Inductor Np Voltage Waveform in DCM

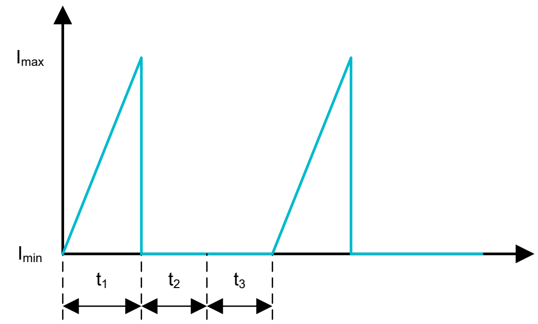

Figure 11. Flyback Primary Inductor Np Current Waveform in DCM

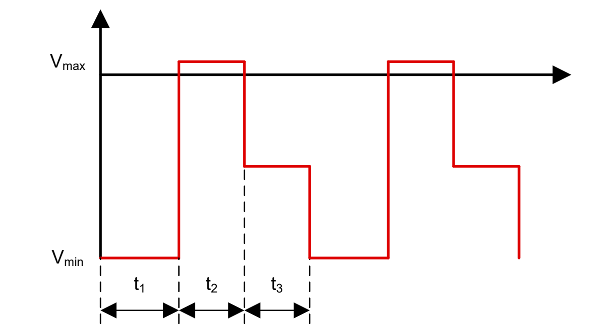

Figure 12. Flyback Diode D1 Voltage Waveform in DCM

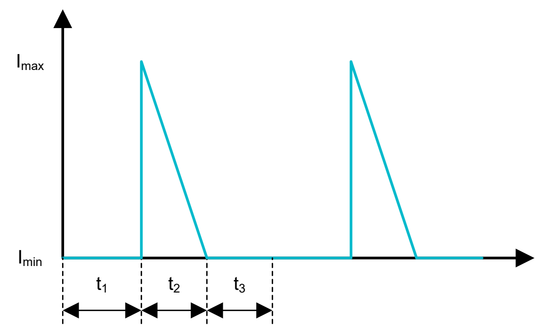

Figure 13. Flyback Diode D1 Current Waveform in DCM

Output Voltage Regulation Concepts

Depending on the application, there are two different options to feed back the isolated output voltage to the controller on the primary side:

- Secondary-side regulation (SSR), typically uses an optocoupler to transfer feedback information from the secondary to the primary side. Optocouplers have a limited bandwidth, which can affect the maximum achievable regulation bandwidth when the RHPZ frequency is rather high. Aging effects of the glass passivation in the optocoupler can be detrimental in certain applications. These applications then need to employ primary-side regulation or an isolated amplifier circuit.
- Primary-side regulation (PSR), relies on information being available on the primary side, such as the rectified voltage on an auxiliary flyback transformer winding. The regulation accuracy depends on the coupling between the secondary and auxiliary winding. A coupling coefficient of > 99% is advisable for good output regulation. The auxiliary winding can allow a minimum of 5 mA to 10 mA of load current for good noise immunity and good regulation. There are other concepts that analyze and use just the reflected voltage on the primary winding for regulation, making the auxiliary winding obsolete if the input can supply the controller in an efficient way. When using primary-side regulation, the voltage drop across the secondary rectifier changes with the load current. This effect is not compensated by the control IC unless the IC has a dedicated, integrated feature. TI has controllers that take the voltage sample at the end of the demagnetization time when the secondary current has ramped down to 0 A. This removes the effect of the diode voltage drop, since the diode is not conducting any current. A good, nonsynchronous primary-side regulation design without such a feature has a ±5% deviation of the output voltage across the load and input voltage range.

It is possible to generate multiple isolated outputs with a flyback by adding additional secondary windings to the coupled inductor. But if these multiple outputs are also isolated from each other, only one of them can be regulated properly. Choosing the winding with the highest current level for regulation is good practice for most designs to achieve satisfactory regulation results.

Using synchronous rectification for load currents over 2 A is advisable, especially when efficiency needs to be high or when external heat sinks need to be avoided. The synchronous rectifier can either be controlled from the primary side or use a self-driven concept, with the latter typically the more cost-effective option.

Additional Resources

- Watch the TI training video: Topology Tutorial: What is a Flyback?
- Design your power stage with Power Stage Designer.
- Download the Power Topologies Handbook and Power Topologies Quick Reference Guide.