Application Brief

How to Approach a Power-Supply Design – Part 7

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This application brief highlights the forward converter. The output power range of this topology is typically between 100W and 250W. For output power above this level, a better design is possible using a push-pull or half-bridge topology for increased efficiency. These topologies are the topic of the next installations in this series.

Single-Switch Forward Converters

The single-switch forward 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 transferred from the primary to the secondary. Winding Nd and diode D3 provide a path to reset the transformer during demagnetization time. Diode D2 provides a freewheeling path when switch Q1 is not conducting. Figure 1 is a schematic of a nonsynchronous single-switch forward converter.

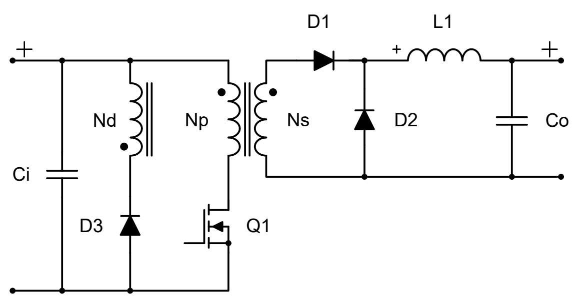

Figure 1. Schematic of a Nonsynchronous Single-Switch Forward Converter

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

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

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 between the primary winding and the secondary winding

The maximum duty cycle is limited to 50% as the transformer needs sufficient time to be reset through the demagnetization winding.

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

$$V_{Q1} = 2 \times V_{IN} + V_f \quad (2)$$

where

- V_{IN} is the input voltage
- V_f is the diode forward voltage

The uncertain coupling of the transformer creates an additional voltage spike caused by the excess energy stored in the leakage inductance. Therefore, choose a voltage rating for Q1 that includes a reasonable margin.

Equation 3 gives the maximum rectifier diode stress as:

$$V_{D1} = \left(V_{IN} + V_f\right) \times \frac{n_s}{n_d} - V_f \quad (3)$$

where

- V_{IN} is the input voltage
- V_f is the diode forward voltage
- n_s / n_d is the turns ratio between the primary winding and the secondary winding

Equation 4 gives the maximum freewheeling diode stress as:

$$V_{D2} = V_{IN} \times \frac{n_s}{n_p} - V_f \quad (4)$$

where

- V_{IN} is the input voltage
- V_f is the diode forward voltage
- n_s / n_p is the turns ratio between the primary winding and the secondary winding

As the forward converter can be seen as a buck converter with a transformer, this converter family also has a continuous output current due to the output LC-filter and the freewheeling path through diode D2. Like a buck converter, the forward converter has a pulsed current at the input. This fact leads to rather high voltage ripple at the converter input. For electromagnetic compatibility, additional input filtering is likely 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 single-switch forward converter can be built by using a boost or general-purpose pulse-width modulation (PWM) controller integrated circuit (IC), as this converter only requires a low-side gate driver.

In terms of dynamic behavior, an optocoupler in the isolated feedback path is the primary limiting factor of the achievable regulation bandwidth for the forward converter. If a high regulation bandwidth is required, the PWM controller can be placed on the secondary side of the converter.

Figure 2 through Figure 11 show voltage and current waveforms in CCM for FET Q1, primary transformer winding Np, rectifier diode D1, freewheeling diode D2, and inductor L1 in a nonsynchronous single-switch forward converter.

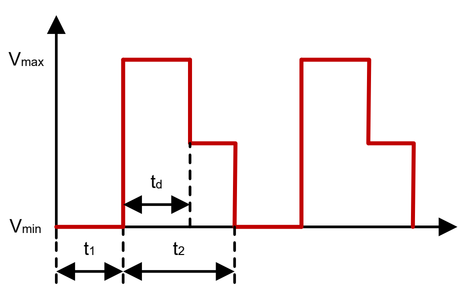

Figure 2. Single-Switch Forward FET Q1 Voltage Waveform in CCM

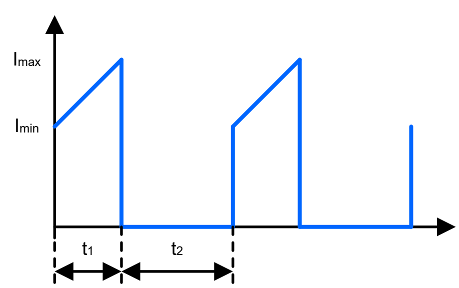

Figure 3. Single-Switch Forward FET Q1 Current Waveform in CCM

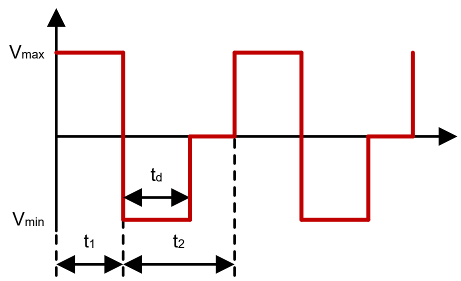

Figure 4. Single-Switch Forward Primary Transformer Winding Np Voltage Waveform in CCM

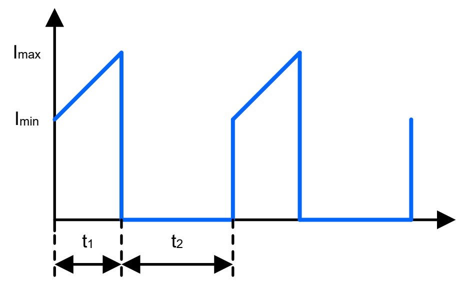

Figure 5. Single-Switch Forward Primary Transformer Winding Np Current Waveform in CCM

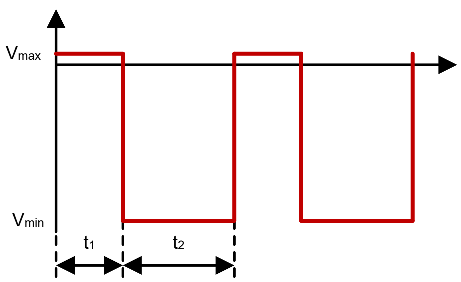

Figure 6. Single-Switch Forward Rectifier Diode D1 Voltage Waveform in CCM

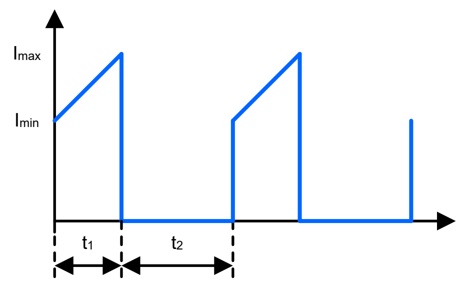

Figure 7. Single-Switch Forward Rectifier Diode D1 Current Waveform in CCM

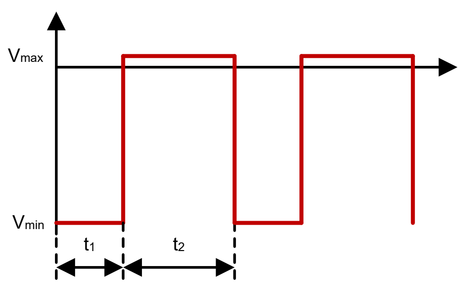

Figure 8. Single-Switch Forward Freewheeling Diode D2 Voltage Waveform in CCM

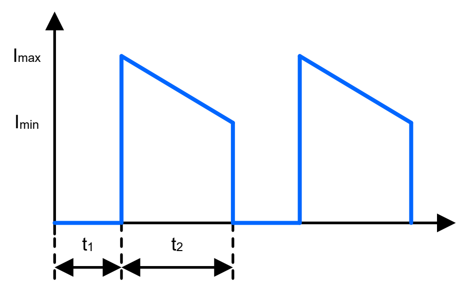

Figure 9. Single-Switch Forward Freewheeling Diode D2 Current Waveform in CCM

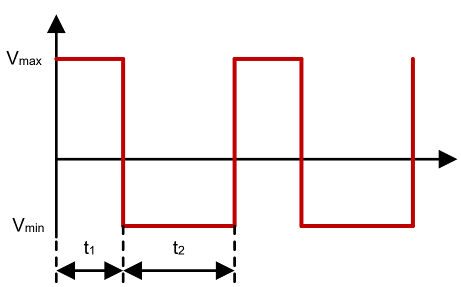

Figure 10. Single-Switch Forward Inductor L1 Voltage Waveform in CCM

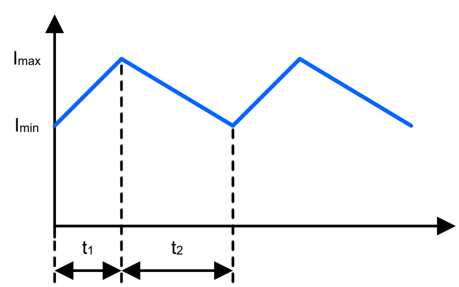

Figure 11. Single-Switch Forward Inductor L1 Current Waveform in CCM

Two-Switch Forward Converters

For high-input voltage levels, a two-switch forward configuration can be leveraged, which enables the use of MOSFETs with a lower breakdown voltage and better performance parameters because the MOSFETs share the overall voltage stress. Figure 12 shows the schematic of a two-switch forward converter. The advantage of using two switches is that demagnetization can be achieved by having two clamping diodes to VIN and GND, allowing the removal of the demagnetization winding. To drive the two switches at the same time, with one of them being on the high-side, a half-bridge gate driver without interlock can be used in combination with a standard PWM controller.

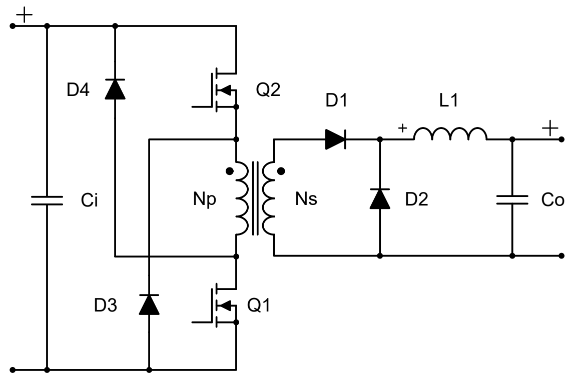

Figure 12. Schematic of a Nonsynchronous Two-Switch Forward Converter

Equation 5 calculates the maximum MOSFET stress in a two-switch forward converter as:

$$V_{Q1/2} = V_{IN} + V_f \tag{5}$$

where

- V_{IN} is the input voltage
- V_f is the diode forward voltage

This equation assumes that voltage stress is evenly distributed among the two MOSFETs. due to board and component parasitics as well as device parameter tolerances. Under certain circumstances the voltage stress is not distributed so evenly due to board and component parasitics as well as device parameter tolerances. Select a MOSFET breakdown voltage with sufficient margin to avoid fatal device failure.

Equation 6 gives the maximum rectifier diode stress as:

$$V_{D1} = \left(V_{IN} + 2 \times V_f\right) \times \frac{n_S}{n_P} - V_f \tag{6}$$

where

- V_{IN} is the input voltage
- V_f is the diode forward voltage
- n_p / n_s is the turns ratio between the primary winding and the secondary winding

Equation 1 and Equation 4 are also applicable for the two-switch forward converter.

Also, with two-switch configuration, the maximum duty cycle is limited to 50% as the transformer needs sufficient time to be reset through the demagnetization diodes.

Figure 13 through Figure 22 show voltage and current waveforms in CCM for FET Q1, primary transformer winding Np, rectifier diode D1, freewheeling diode D2, and inductor L1 in a nonsynchronous two-switch forward converter.

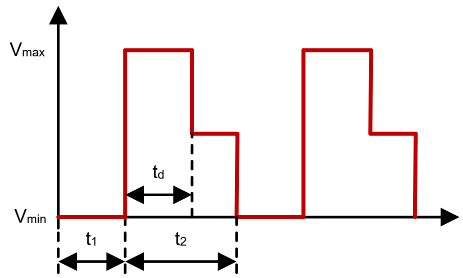

Figure 13. Two-Switch Forward FET Q1 Voltage Waveform in CCM

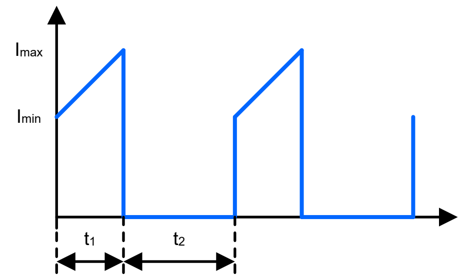

Figure 14. Two-Switch Forward FET Q1 Current Waveform in CCM

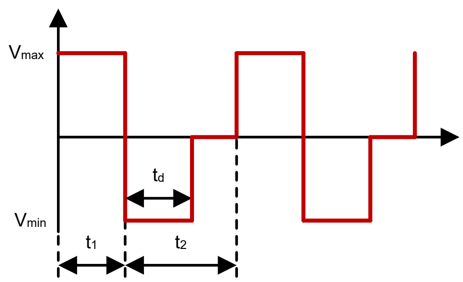

Figure 15. Two-Switch Forward Primary Transformer Np Voltage Waveform in CCM

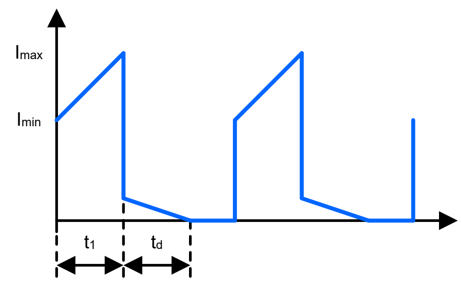

Figure 16. Two-Switch Forward Primary Transformer Np Current Waveform in CCM

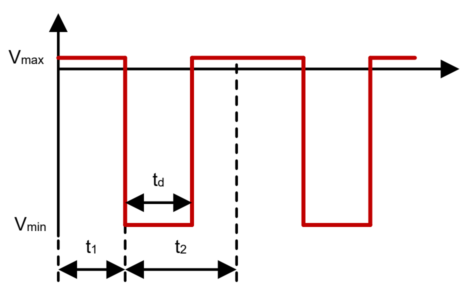

Figure 17. Two-Switch Forward Rectifier Diode D1 Voltage Waveform in CCM

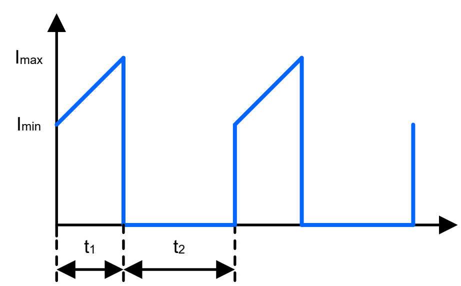

Figure 18. Two-Switch Forward Rectifier Diode D1 Current Waveform in CCM

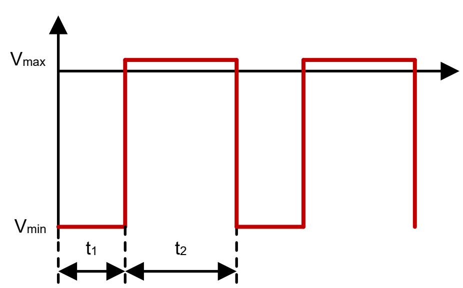

Figure 19. Two-Switch Forward Freewheeling Diode D2 Voltage Waveform in CCM

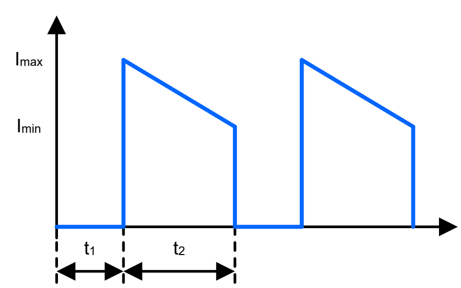

Figure 20. Two-Switch Forward Freewheeling Diode D2 Current Waveform in CCM

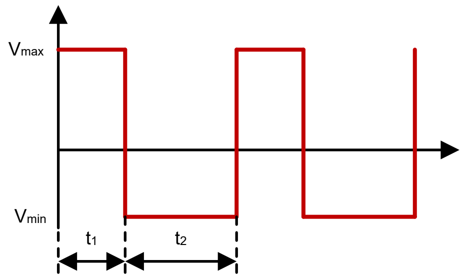

Figure 21. Two-Switch Forward Inductor L1 Voltage Waveform in CCM

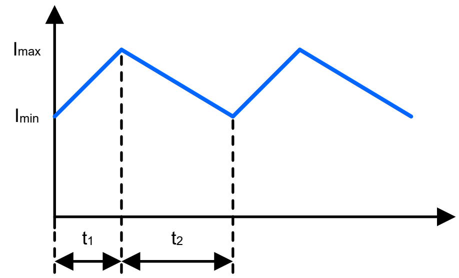

Figure 22. Two-Switch Forward Inductor L1 Current Waveform in CCM

Active-Clamp Forward Converters

A third option to configure this topology is to use an active-clamp circuit on the primary side to recover energy from the leakage inductance of the transformer and feed the energy back to the input capacitor, boosting efficiency and enabling larger output power levels than the other two configurations. The active-clamp configuration also allows duty cycles larger than 50%. Figure 23 shows the schematic of a nonsynchronous active-clamp forward converter using an N-channel MOSFET for the clamping circuit.

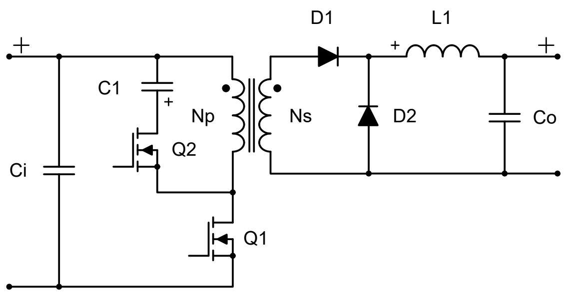

Figure 23. Schematic of a Nonsynchronous Active-Clamp Forward Converter

Figure 24 through Figure 35 show voltage and current waveforms in CCM for FET Q1, FET Q2, primary transformer winding Np, rectifier diode D1, freewheeling diode D2, and inductor L1 in a nonsynchronous active-clamp forward converter.

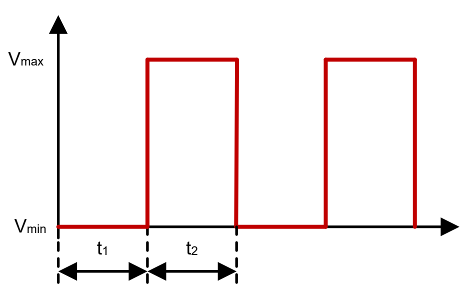

Figure 24. Active-Clamp Forward FET Q1 Voltage Waveform in CCM

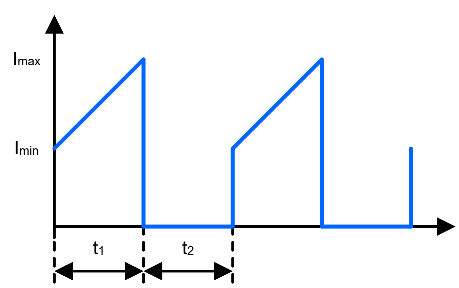

Figure 25. Active-Clamp Forward FET Q1 Current Waveform in CCM

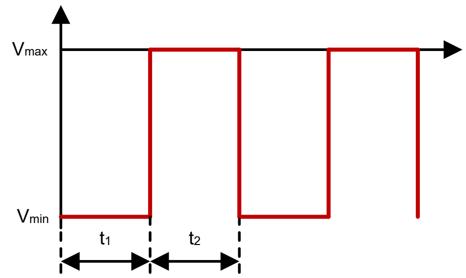

Figure 26. Active-Clamp Forward FET Q2 Voltage Waveform in CCM

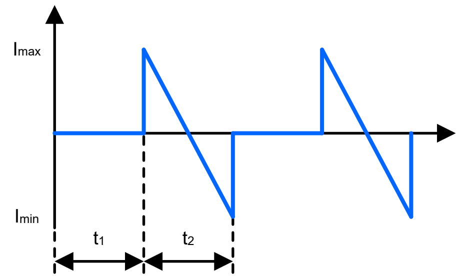

Figure 27. Active-Clamp Forward FET Q2 Current Waveform in CCM

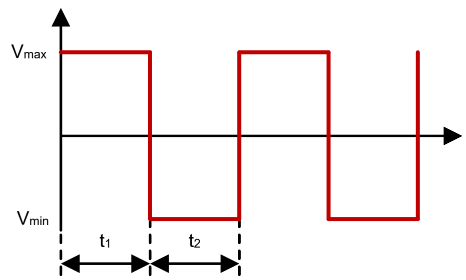

Figure 28. Active-Clamp Forward Primary Transformer Np Voltage Waveform in CCM

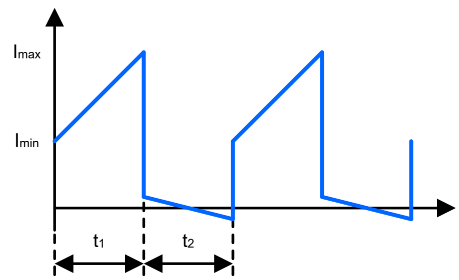

Figure 29. Active-Clamp Forward Primary Transformer Np Current Waveform in CCM

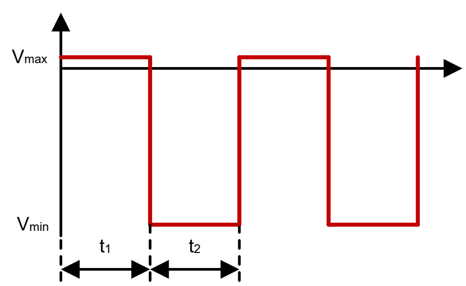

Figure 30. Active-Clamp Forward Rectifier Diode D1 Voltage Waveform in CCM

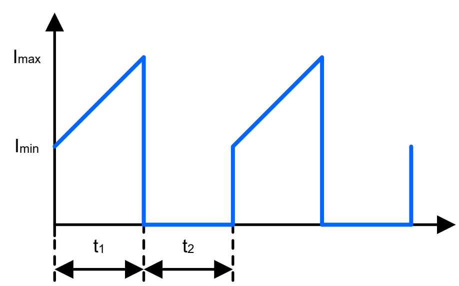

Figure 31. Active-Clamp Forward Rectifier Diode D1 Current Waveform in CCM

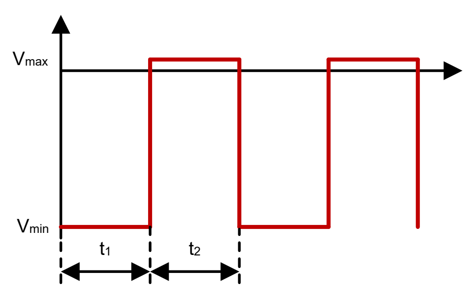

Figure 32. Active-Clamp Forward Freewheeling Diode D2 Voltage Waveform in CCM

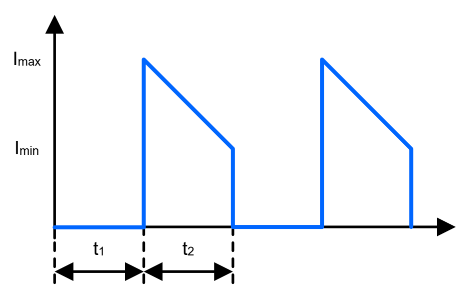

Figure 33. Active-Clamp Forward Freewheeling Diode D2 Current Waveform in CCM

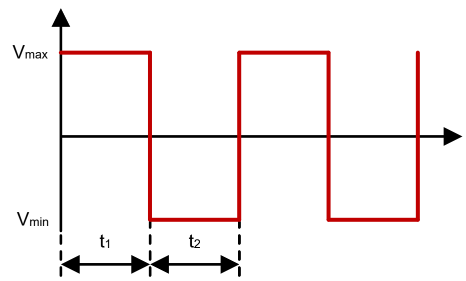

Figure 34. Active-Clamp Forward Inductor L1 Voltage Waveform in CCM

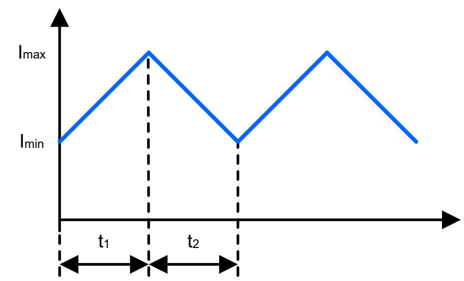

Figure 35. Active-Clamp Forward Inductor L1 Current Waveform in CCM

Output Voltage Regulation Concepts

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

- 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. Aging effects of the glass passivation in the optocoupler can be detrimental in certain applications. These applications then need to employ an optocoupler replacement, such as an isolated amplifier circuit or an opto-emulator.
- Placing the controller on the secondary side can help achieve higher regulation bandwidths by eliminating the optocoupler in the feedback loop. However, an auxiliary power supply for start-up and short-circuit conditions is required to supply the PWM controller on the secondary. In addition, the MOSFETs on the primary side need to be driven with an isolated gate drive circuit, which can be implemented either with a dedicated isolated gate drive IC or with a discrete circuit leveraging a gate drive transformer and a non-isolated driver.

Using synchronous rectification for load currents over 3A 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 Forward Converter?”
- Design your power stage with Power Stage Designer.
- Download the *Power Topologies Handbook* and *Power Topologies Quick Reference Guide* .

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