Discontinuous Conduction Mode Flyback Transformer Design Guide

Practical First-Pass Design Method

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A flyback transformer is different from a conventional transformer because it intentionally stores energy in the magnetic core during the switch ON-time and then transfers that stored energy to the secondary side during the switch OFF-time.

Flyback converters are commonly operated in either:

- DCM - Discontinuous Conduction Mode
- CCM - Continuous Conduction Mode

This article focuses on a practical first-pass design method for a DCM flyback transformer.

In DCM operation, the secondary current falls completely back to zero before the next primary switch ON-time begins. A practical DCM design should not sit exactly at the CCM/DCM boundary. It should include margin so the transformer remains discontinuous under real-world conditions such as line variation, load variation, inductance tolerance, temperature, and component tolerances.

This method is intended as a first-pass engineering design approach, not a complete final production design. A finished flyback transformer must still be checked for losses, temperature rise, insulation, safety spacing, leakage inductance, EMI, clamp behavior, and manufacturability.

1. Basic Flyback Energy Relationship

During the primary switch ON-time, energy is stored in the primary inductance:

$$E = \frac{1}{2} L_P I_{P(pk)}^2$$

Where:

- E = energy stored per switching cycle
- L_P = primary inductance
- $I_{P(pk)}$ = peak primary current

The output power is related to the energy transferred each switching cycle:

$$P_{OUT} = \eta \left(\frac{1}{2} L_P I_{P(pk)}^2 f_s \right)$$

Where:

- P_{OUT} = output power
- η = estimated converter efficiency
- f_s = switching frequency

It is usually better to design from input power:

$$P_{IN} = \frac{P_{OUT}}{\eta}$$

So the primary energy relationship becomes:

$$P_{IN} = \frac{1}{2} L_P I_{P(pk)}^2 f_s$$

2. Primary Peak Current

During the switch ON-time, the primary current ramps upward according to the inductor voltage relationship:

$$V = L\frac{di}{dt}$$

At minimum input voltage and maximum duty cycle:

$$V_{IN(min)} = L_P \frac{I_{P(pk)}}{D_{MAX} T}$$

Since:

$$T = \frac{1}{f_s}$$

then:

$$V_{IN(min)} D_{MAX} = L_P I_{P(pk)} f_s$$

Combining this with the power equation gives:

$$I_{P(pk)} = \frac{2P_{IN}}{V_{IN(min)} D_{MAX}}$$

This is the peak primary current required to deliver full power at minimum input voltage and maximum duty cycle.

3. Primary Inductance

Once the peak primary current is known, the required primary inductance is:

$$L_P = \frac{V_{IN(min)} D_{MAX}}{I_{P(pk)} f_s}$$

The same result can also be written as:

$$L_P = \frac{V_{IN(min)}^2 D_{MAX}^2}{2 P_{IN} f_s}$$

This primary inductance is the energy-storage inductance of the flyback transformer.

4. Secondary Reset Time and DCM Margin

In a flyback converter, the secondary current must fully reset to zero before the next primary ON-time.

The reflected secondary voltage on the primary side is:

$$V_R = \frac{N_P}{N_S} (V_{OUT} + V_D)$$

Where:

- V_R = reflected secondary voltage on the primary side
- N_P = primary turns
- N_S = secondary turns
- V_D = secondary diode or rectifier voltage drop

The secondary reset duty fraction is approximately:

$$D_{RESET} = \frac{V_{IN(min)} D_{MAX}}{V_R}$$

For DCM operation:

$$D_{MAX} + D_{RESET} < 1$$

In a practical design, margin should be included. A useful first-pass target is:

$$D_{MAX} + D_{RESET} \leq 0.80 \text{ to } 0.90$$

This leaves time for leakage ringing, control delays, tolerances, and real-world variation.

5. Turns Ratio

Choose the desired reset duty cycle, then calculate the required reflected voltage:

$$V_R = \frac{V_{IN(min)} D_{MAX}}{D_{RESET}}$$

The required primary-to-secondary turns ratio is:

$$\frac{N_P}{N_S} = \frac{V_R}{V_{OUT} + V_D}$$

Or:

$$\frac{N_S}{N_P} = \frac{V_{OUT} + V_D}{V_R}$$

A higher reflected voltage reduces secondary reset time, but increases MOSFET voltage stress.

A lower reflected voltage reduces MOSFET voltage stress, but increases reset time and may push the converter toward CCM operation.

This is one of the main flyback design tradeoffs.

6. Secondary Peak Current

The secondary peak current is related to the primary peak current by the turns ratio:

$$I_{S(pk)} = I_{P(pk)} \frac{N_P}{N_S}$$

For a triangular DCM secondary current waveform, the output current is approximately:

$$I_{OUT} \approx \frac{1}{2} I_{S(pk)} D_{RESET}$$

This relationship should be checked against the required output current.

7. RMS Currents for Wire and Copper Loss

Wire size should be selected using RMS current, not simply one-half of peak current.

Copper heating is based on RMS current:

$$P_{CU} = I_{rms}^2 R$$

For a triangular DCM current waveform, the primary RMS current is approximately:

$$I_{P(rms)} = I_{P(pk)} \sqrt{\frac{D_{MAX}}{3}}$$

The secondary RMS current is approximately:

$$I_{S(rms)} = I_{S(pk)} \sqrt{\frac{D_{RESET}}{3}}$$

These RMS values should be used for copper loss and wire-size selection.

8. Minimum Primary Turns

The minimum number of primary turns is set by the maximum allowable flux density.

Starting with:

$$LI = NBA$$

The minimum primary turns are:

$$N_P \geq \frac{L_P I_{P(pk)}}{B_{MAX} A_E}$$

Where:

- B_{MAX} = chosen maximum flux density
- A_E = effective core area

For ferrite flyback designs, B_{MAX} is normally kept below saturation with adequate margin for temperature, tolerance, transient conditions, and core material behavior.

A common first-pass design range is:

$$B_{MAX} \approx 0.18\,\mathrm{T} \text{ to } 0.25\,\mathrm{T}$$

The correct value depends on core material, frequency, temperature rise, loss limits, and application requirements.

9. Secondary Turns

Once the primary turns and reflected voltage are known, the secondary turns can be calculated directly from the selected turns ratio:

$$N_S = N_P \frac{V_{OUT} + V_D}{V_R}$$

In practice, turns must be rounded to whole numbers.

After rounding, re-check:

- Actual turns ratio
- Reflected voltage
- Reset duty cycle
- MOSFET voltage stress
- Diode reverse voltage
- Flux density
- Output voltage range
- Regulation behavior

10. Gapped Core A_L Value

The required gapped A_L value is:

$$A_L = \frac{L_P}{N_P^2}$$

This is the effective inductance per turn squared after the core is gapped.

The air gap stores most of the flyback transformer energy. The gap affects:

- Primary inductance
- Peak flux density
- Fringing flux
- Proximity-effect loss
- EMI
- Temperature rise
- Mechanical tolerance sensitivity

If the required gap is excessive or creates too much fringing loss, the core may be too small.

11. MOSFET Voltage Stress

The MOSFET drain voltage is approximately:

$$V_{DS} \approx V_{IN(max)} + V_R + V_{LEAKAGE}$$

Where:

- $V_{IN(max)}$ = maximum input voltage
- V_R = reflected secondary voltage
- $V_{LEAKAGE}$ = leakage-inductance spike and ringing

The MOSFET voltage rating must include adequate margin above this value.

The approximate energy in leakage inductance is:

$$E_{LEAK} = \frac{1}{2} L_{LEAK} I_{P(pk)}^2$$

The snubber or clamp must safely dissipate or recycle this leakage energy. In practice, clamp voltage and leakage ringing should be verified on the actual circuit waveform.

Leakage voltage stress depends on:

- Leakage inductance
- Peak primary current
- Winding arrangement

- Snubber or clamp design
- PCB layout
- Switching speed

12. Secondary Diode or Rectifier Voltage Stress

The secondary rectifier reverse voltage is approximately:

$$V_{RRM} \approx V_{OUT} + V_{IN(max)} \frac{N_S}{N_P}$$

Additional margin must be included for ringing and leakage effects.

For high-output-current designs, rectifier conduction loss should also be checked.

13. Core Loss

Core loss should be checked using the core manufacturer's loss curves or Steinmetz-type data.

Core loss depends on:

- Core material
- Switching frequency
- Flux swing
- Temperature
- Waveform shape
- Core volume

A flyback transformer usually has a large flux swing because the magnetizing current ramps up during the ON-time and resets during the OFF-time.

Even if the core does not saturate, excessive flux swing can cause unacceptable core loss and temperature rise.

14. Wire Size, Skin Effect, and Proximity Effect

Wire size should be based on RMS current, copper loss, temperature rise, and available winding window area.

A common first-pass current density range is:

$$J \approx 2 \text{ to } 4 \, \frac{\text{A}}{\text{mm}^2}$$

A value near:

$$J \approx 3 \, \frac{\text{A}}{\text{mm}^2}$$

is a reasonable starting point for many designs, but high-frequency effects must also be considered.

The required copper area is approximately:

$$A_{CU} = \frac{I_{rms}}{J}$$

At high switching frequencies, solid wire may not be appropriate due to skin effect and proximity effect.

For copper, skin depth is approximately:

$$\delta \approx \frac{66}{\sqrt{f}}$$

Where:

- δ = skin depth in mm
- f = frequency in Hz

At 100 kHz:

$$\delta \approx \frac{66}{\sqrt{100000}} \approx 0.21\,\text{mm}$$

Litz wire, multiple parallel strands, foil, or carefully selected wire arrangements may be required depending on current, frequency, and winding geometry.

15. Window Fill

After selecting turns and wire sizes, check the bobbin window.

A first-pass rule is that bare copper area should generally not exceed 35% to 40% of the available winding window area.

The finished winding uses more space than bare copper because of:

- Wire insulation
- Tape
- Margins
- Layer insulation
- Triple-insulated wire
- Sleeving
- Winding buildup
- Manufacturing tolerance

If the winding does not fit comfortably, the core/bobbin is likely too small.

16. Insulation, Creepage, Clearance, and Safety

A practical flyback transformer design must include insulation and safety requirements.

Important items include:

- Primary-to-secondary isolation requirement
- Working voltage
- Hi-pot test voltage
- Creepage distance
- Clearance distance
- Basic, supplementary, or reinforced insulation
- Tape system
- Margin tape
- Triple-insulated wire
- Bobbin material and safety approvals
- Winding separation
- Temperature class

The electrical design may work mathematically, but the transformer is not complete until the insulation system and safety spacing are correct.

17. Leakage Inductance and EMI

Flyback transformer leakage inductance affects:

- MOSFET voltage spike
- Snubber loss
- Efficiency
- Ringing
- EMI
- Output noise
- Semiconductor stress

Reducing leakage often requires tighter coupling between primary and secondary windings.

However, tighter coupling can increase primary-to-secondary capacitance, which can worsen common-mode EMI.

The winding structure is a tradeoff between:

- Low leakage inductance
- Low capacitance
- Proper insulation spacing

- Manufacturability
- Thermal performance

Common winding techniques include:

- Primary-secondary-primary sandwich windings
- Split primary windings
- Faraday shields
- Sectioned windings
- Margin winding
- Triple-insulated wire
- Controlled layer structure

The best winding method depends on the application.

Worked Example

Design Requirements

Assume the following design:

- Input voltage: 18 VDC to 36 VDC
- Output voltage: 12 VDC
- Output current: 2.5 A
- Output power: 30 W
- Switching frequency: 100 kHz
- Estimated efficiency: 85%
- Maximum duty cycle: 45%
- Desired reset duty cycle: 40%
- Secondary diode drop: 0.5 V
- Selected core effective area: $60\,\mathrm{mm}^2$
- Target maximum flux density: 0.20 T

Step 1 - Input Power

$$P_{IN} = \frac{P_{OUT}}{\eta}$$

$$P_{IN} = \frac{30\,\mathrm{W}}{0.85}$$

$$P_{IN} = 35.3\,\mathrm{W}$$

Step 2 - Peak Primary Current

$$I_{P(pk)} = \frac{2P_{IN}}{V_{IN(min)}D_{MAX}}$$

$$I_{P(pk)} = \frac{2(35.3)}{18(0.45)}$$

$$I_{P(pk)} = 8.7\,\mathrm{A}$$

Step 3 - Primary Inductance

$$L_P = \frac{V_{IN(min)}D_{MAX}}{I_{P(pk)}f_s}$$

$$L_P = \frac{18(0.45)}{8.7(100000)}$$

$$L_P \approx 9.3\,\mu\text{H}$$

Step 4 - Reflected Voltage

$$V_R = \frac{V_{IN(min)} D_{MAX}}{D_{RESET}}$$

$$V_R = \frac{18(0.45)}{0.40}$$

$$V_R = 20.25\,\text{V}$$

Step 5 - Turns Ratio

$$\frac{N_P}{N_S} = \frac{V_R}{V_{OUT} + V_D}$$

$$\frac{N_P}{N_S} = \frac{20.25}{12 + 0.5}$$

$$\frac{N_P}{N_S} = 1.62$$

Therefore:

$$\frac{N_S}{N_P} = 0.617$$

Step 6 - Secondary Peak Current

$$I_{S(pk)} = I_{P(pk)} \frac{N_P}{N_S}$$

$$I_{S(pk)} = 8.7(1.62)$$

$$I_{S(pk)} = 14.1\,\text{A}$$

Step 7 - RMS Currents

Primary RMS current:

$$I_{P(rms)} = I_{P(pk)}\sqrt{\frac{D_{MAX}}{3}}$$

$$I_{P(rms)} = 8.7\sqrt{\frac{0.45}{3}}$$

$$I_{P(rms)} = 3.4\,\mathrm{A}$$

Secondary RMS current:

$$I_{S(rms)} = I_{S(pk)}\sqrt{\frac{D_{RESET}}{3}}$$

$$I_{S(rms)} = 14.1\sqrt{\frac{0.40}{3}}$$

$$I_{S(rms)} = 5.1\,\mathrm{A}$$

These RMS values should be used for copper loss and wire sizing.

Step 8 - Minimum Primary Turns

$$N_P \geq \frac{L_P I_{P(pk)}}{B_{MAX} A_E}$$

$$N_P \geq \frac{(9.3 \times 10^{-6})(8.7)}{(0.20)(60 \times 10^{-6})}$$

$$N_P \geq 6.7$$

Choose:

$$N_P = 8 \text{ turns}$$

Step 9 - Secondary Turns

$$N_S = N_P \frac{V_{OUT} + V_D}{V_R}$$

$$N_S = 8\frac{12 + 0.5}{20.25}$$

$$N_S = 4.9$$

Choose:

$$N_S = 5 \text{ turns}$$

Actual turns ratio:

$$\frac{N_P}{N_S} = \frac{8}{5}$$

$$\frac{N_P}{N_S} = 1.6$$

This is very close to the target ratio.

Step 10 - Required A_L Value

$$A_L = \frac{L_P}{N_P^2}$$

$$A_L = \frac{9.3\,\mu\text{H}}{8^2}$$

$$A_L = 0.145\,\mu\text{H/turn}^2$$

$$A_L = 145\,\text{nH/turn}^2$$

The core should be gapped to approximately this A_L value.

Step 11 - MOSFET Voltage Stress

$$V_{DS} \approx V_{IN(max)} + V_R + V_{LEAKAGE}$$

Ignoring leakage spike for the first estimate:

$$V_{DS} \approx 36 + 20.25$$

$$V_{DS} \approx 56.25\,\text{V}$$

A real design must include leakage spike and ringing margin. Clamp voltage and leakage ringing should be verified on the actual circuit waveform.

Step 12 - Secondary Rectifier Voltage Stress

$$V_{RRM} \approx V_{OUT} + V_{IN(max)} \frac{N_S}{N_P}$$

$$V_{RRM} \approx 12 + 36 \left(\frac{5}{8}\right)$$

$$V_{RRM} \approx 34.5\,\mathrm{V}$$

A 60 V or 100 V rectifier may be appropriate depending on ringing, margin, and application requirements.

Example Summary

For this example, the first-pass transformer design is approximately:

- Primary inductance: $9.3\,\mu\mathrm{H}$
- Primary peak current: 8.7 A
- Primary RMS current: 3.4 A
- Secondary peak current: 14.1 A
- Secondary RMS current: 5.1 A
- Primary turns: 8 turns
- Secondary turns: 5 turns
- Turns ratio: 8:5
- Target A_L: $145\,\mathrm{nH/turn}^2$
- Reflected voltage: approximately 20 V
- Estimated MOSFET voltage before leakage spike: approximately 56 V
- Estimated secondary rectifier reverse voltage before ringing: approximately 35 V

This is not a finished transformer design, but it is a realistic first-pass starting point.

A final design must still be checked for:

- Core loss
- Copper loss
- Temperature rise
- Winding fit
- Leakage inductance
- Clamp/snubber design
- EMI
- Creepage and clearance
- Hi-pot requirements

- Insulation system
- Manufacturing tolerances
- Production repeatability

Engineering support: Advanced Magnetics Design provides custom transformer, inductor, choke, and magnetic-component design support, including flyback transformer design review, reverse engineering, failure analysis, obsolete part replacement, and manufacturable transformer documentation packages.

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