Designing a flyback DC/DC converter

Video 3
Flyback converter design procedure I

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Outline of video series

1. Guidelines for topology selection
2. Fundamentals of flyback converters
3. Flyback converter design procedure I
4. Flyback converter design procedure II
5. Flyback transformer basics
6. Practical issues experienced with flyback converters

Flyback design procedure

- Demonstrated with the LM5155
- Summary of design steps
  - Identify the application's specs: V_{IN} range, V_{OUT}, max P_O, ripple voltages, switching frequency, etc.
  - Select a controller IC
  - Determine transformer specs and max duty cycle: turns ratio, primary inductance, peak current
  - Calculate key parameters: I_{pk}, V_{DSmax}, I_{rms}, PIV
  - Select MOSFET, current sense resistor, rectifier diode, input and output capacitors
  - Determine the loop compensation
    - Non-isolated
    - PSR
    - Isolated
  - Other external components
  - PCB design
  - Test and fine tune

Flyback design procedure – example specs

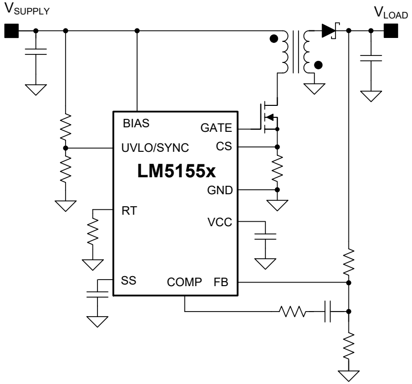
Table 1. Design Parameters

Parameter	
V_{SUPPLY}	18V to 36V
V_{LOAD}	5V
I_{LOAD}	4A
V_{AUX}	10V
I_{AUX}	20mA
P_{OUT_total}	20.2W
f_{SW}	250kHz

Applications with additional output rails will be covered in another video.

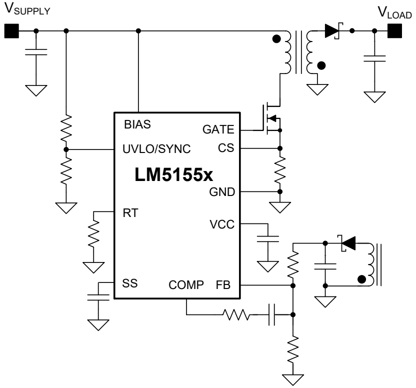
Different flyback types
examples based on LM5155x(-Q1)

Non-Isolated Flyback



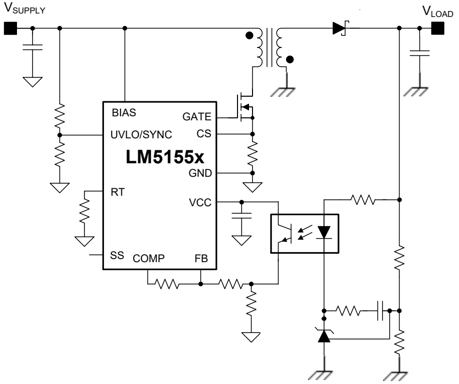
- Simplest
- Tight regulation (1~2%)
- Only non-isolated V_{OUT}

PSR Flyback



- Simpler for isolated V_{OUT}
- No optocoupler needed
- V_{OUT} cross regulated, 5~10%

Isolated Flyback



- Tight regulation for isolated V_{OUT} (1~2%)
- Complex, requiring optocoupler

IC selection

- Converter vs controller
  - V_{INmax} disqualifies the TPS55340 and LM5157x due to limited FET voltage
  - Max power disqualifies the LM500x family due to FET peak current limit
  - LM5155x/56x are a reasonable choice
    - Newer device, better performance
    - ***We recommend using the LM5155x/56x for new designs***
      - LM5156x has optional **spread spectrum** option
      - LM5155x and LM5156x are drop in substitutes
  - Either LM515x or LM515x1 can be used: they have almost the same performance
    - LM5155/56 do not have hiccup OCP
      - Under OCP, it will continue switching with reduced duty cycle
    - LM51551/561 have hiccup OCP
      - Under OCP, it will run in hiccup mode
      - ON for 64 consecutive cycles, followed by OFF for 32k cycles, to prevent overheating

LM5155x (-Q1)
2.2MHz Wide VIN Non-synchronous Boost/SEPIC/Flyback Controller

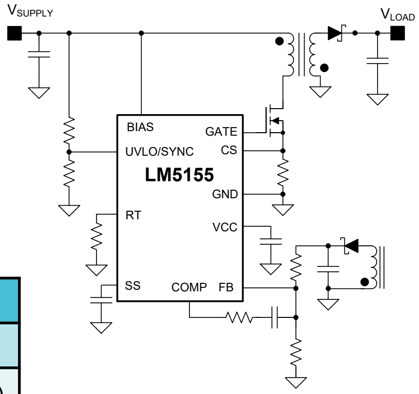
Features

- AEC-Q100 grade 1 qualified (T_A = -40ºC to 125ºC, T_J = -40ºC to 150ºC)
- Wide input range : **3.5V~ 45V**
  (2.97V ~ 16V when BIAS=VCC, 1.5V~45V when BIAS≥2.97V)
- Programmable frequency 100kHz to **2.2MHz** with clock synchronization
- Shutdown I_Q ≤5uA
- Non-switching I_Q ≤ 450uA
- 1.5A peak gate driver
- 100mV current limit threshold <u>with optional hiccup mode protection</u>
- 1.0V +/-1% reference
- Adjustable slope compensation
- Programmable line UVLO
- Adjustable soft-start
- PGOOD indicator
- OVP protection
- Thermal shutdown
- 12pin-WSON package (3mmx2mm); -Q1 has Wettable Flanks

Benefits

- Boost/SEPIC/Flyback(Non-isolated/isolated) configurable
- Wide VIN for a variety of power rails including 1-cell battery
- Switching frequency out of AM band
- Small solution size at 2.2MHz
- Low shutdown I_Q reduces battery drain in battery-powered application
- Low current limit threshold minimizes power loss
- Optional hiccup mode for sustained overload / short-circuit protection
- Allows high step-up ratio using SYNC

PSR Flyback



Applications

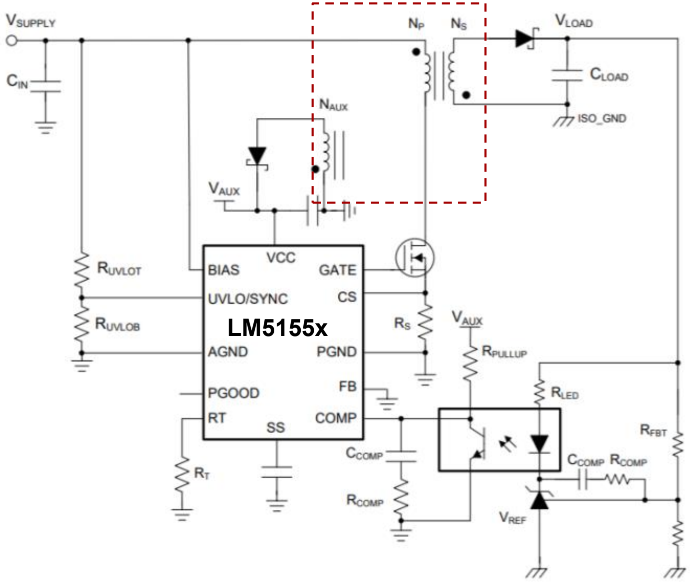
- General purpose Boost / Sepic
- Battery powered application
- Automotive LED headlights
- Industrial Flyback power supply/ Primary side controlled flyback

Hiccup mode protection	
Disabled	**Enabled**
LM5155 (-Q1)	LM51551 (-Q1)

IC supply through bias winding

- Adding the bias winding to off-load the internal LDO and reduce IC power dissipation
  - Also applies to PSR and non-isolated designs

Isolated Flyback



Switching frequency

- The targeted flyback is a hard switching circuit
  - faster switching causes greater switching losses
- 100 kHz to 400 kHz are commonly chosen frequencies
- 250 kHz is a good trade-off between solution size and efficiency

$$R_T = \frac{2.21 \times 10^{10}}{f_{SW}} - 955 = \frac{2.21 \times 10^{10}}{250\text{kHz}} - 955 = 87.44\text{k}\Omega$$

A standard value of 86.6kΩ is chosen for R_T.

Determine Transformer – $N_S : N_P$

- **Transformer turns ratio**

$$D = \frac{\frac{N_P}{N_S} \cdot V_{LOAD}}{V_{SUPPLY} + \frac{N_P}{N_S} \cdot V_{LOAD}}$$

This example targets a duty cycle close to 0.4.

Yes, you can use a different number as long as it is smaller than IC max duty. Try to avoid extreme values.

This is an iteration process until you find a proper value.

$$N_{S\_calc} = \frac{(V_{LOAD}) \cdot (1 - D_{MAX}) \cdot N_P}{V_{SUPPLY\_min} \cdot D_{MAX}} = \frac{(5V) \cdot (1 - 0.4) \cdot 1}{18V \cdot 0.4} = 0.417$$

Choose an easy ratio of two integers: $N_S : N_P = 0.5 : 1$

Yes, you can choose $N_S : N_P = 0.4 : 1$ or other close number for the ratio of two integers. When designing for multiple rails, you need to get to the nearest integer ratios between all the windings.

Determine Transformer – D_{MAX}, N_{AUX}

Now: $N_S : N_P = 0.5$

$$D_{MAX} = \frac{\frac{N_P}{N_S} \cdot V_{LOAD}}{V_{SUPPLY\_min} + \frac{N_P}{N_S} \cdot V_{LOAD}} = \frac{\frac{1}{0.5} \cdot 5V}{18V + \frac{1}{0.5} \cdot 5V} = 0.357$$

$$D_{MIN} = \frac{\frac{1}{0.5} \cdot 5V}{36V + \frac{1}{0.5} \cdot 5V} = 0.217$$

$$N_{AUX\_calc} = N_S \cdot \frac{V_{AUX}}{V_{LOAD}} = 0.5 \cdot \frac{10V}{5V} = 1$$

Transformer turns ratio: $N_P : N_S : N_{AUX} = 1 : 0.5 : 1 = 2 : 1 : 2$

If you choose $N_S : N_P = 0.4 : 1$ in previous step, you will get $N_{AUX} = 0.8$, or $N_P : N_S : N_{AUX} = 1 : 0.4 : 0.8$.

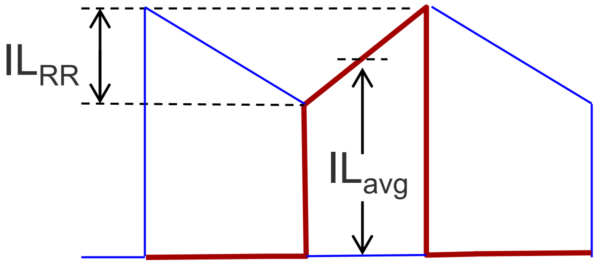
Then, you have less options in designing the actual transformer. See next page.

Transformer turns ratio selection

$N_P : N_S : N_{AUX}$	1 : 0.5 : 1	1 : 0.4 : 0.8
Possible design options	• 2 : 1 : 2 • 4 : 2 : 4 • 6 : 3 : 6 • 8 : 4 : 8 • 10 : 5 : 10 • 12 : 6 : 12 • 14 : 7 : 14 • 16 : 8 : 16 • …	• ~~2.5 : 1 : 2~~ • 5 : 2 : 4 • ~~7.5 : 3 : 2~~ • 10 : 4 : 8 • ~~12.5 : 5 :10~~ • 15 : 6 : 12 • ~~17.5 : 7 :14~~ • 20 : 8 : 16 • …

Determine Transformer – L_M

- **Primary inductance L_M.** This determines the inductor ripple current for CCM.
  - Recommended ripple current to be within 30% to 70%
  - Higher ratio leads to smaller L_M



$$\frac{IL_{RR}}{IL_{avg}} = 60\% \text{ (selected)}$$

$$L_{M\_calc} = \frac{{N_P}^2 \cdot {V_{SUPPLY\_max}}^2 \cdot {V_{LOAD}}^2}{IL_{RR} \cdot f_{SW} \cdot P_{OUT\_total} \cdot \left(N_S \cdot V_{SUPPLY\_max} + N_P \cdot |V_{LOAD}|\right)^2}$$

$$L_{M\_calc} = \frac{1^2 \cdot 36V^2 \cdot 5V^2}{0.6 \cdot 250kHz \cdot 20.2W \cdot \left(0.5 \cdot 36V + 1 \cdot |5V|\right)^2} = 20.6\mu H$$

Choose $L_M = 21\ \mu H$

Parameters dependent on transformer

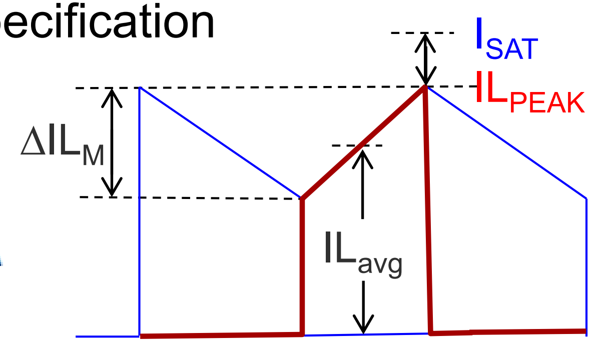
- Once the turns ratio and primary inductance are determined, the following key parameters can be calculated:
  - Primary peak current $\mathbf{I_{PEAK}}$, determining $\mathbf{R_S}$ and the transformer $\mathbf{I_{SAT}}$
  - Primary RMS current $\mathbf{I_{RMS}}$, determining the conduction losses in MOSFET and transformer winding
  - $\mathbf{V_{DS}}$, determining the MOSFET voltage rating
  - **PIV** (or V_R), determining the rectifier diode voltage rating

Primary peak current and saturation current

- **Peak current**, determines the transformer min I_{SAT} specification

$$\Delta IL_M = \frac{V_{SUPPLY} \cdot D}{L_M \cdot f_{SW}} = \frac{18V \cdot 0.357}{21\mu H \cdot 250kHz} = 1.224A$$

$$IL_{PEAK} = \frac{P_{OUT\_total}}{V_{SUPPLY\_min} \cdot D} + \frac{\Delta IL_M}{2} = \frac{20.2W}{18V \cdot 0.357} + \frac{1.224A}{2} = 3.75A$$



Choose an I_{SAT} of 30% greater than IL_{PEAK} for operation margin

$I_{SAT} \geq 1.3 \times 3.75A = 4.88A$ (**Wurth** 750317933 is selected, I_{SAT} = 6A)

- **Summary** of Transformer Selection

Parameter	Value
Turns Ratio (N_P:N_S:N_{AUX})	1:0.5:1 (2:1:2)
Primary winding inductance (L_M)	21µH
Primary winding saturation current (I_{SAT})	6A **>4.88A**

Video 1 to 3 Summary – Video 4 to 6 Outlook

- **We discussed**
  - **Topology selection guidelines** based on power level
    - Flyback and SEPIC topologies comparison and their suitable applications
  - **Fundamentals of flyback:** operating modes and key parameters
  - **Design procedure of the transformer** demonstrated with LM5155 example

- **We will discuss**
  - **Design procedure ongoing** demonstrated with LM5155 example**, for non-isolated, PSR and isolated applications**
  - **Flyback transformer basics**, and the need of an air gap
  - **Frequently asked questions** including multi rails, light load regulation, and high input voltage solutions, and **commonly seen mistakes**

Tools and application collaterals

Most important: E2E Forum https://e2e.ti.com/support/

All the following are available in the product folders on https://www.ti.com/

1. Flyback EVMs and user's guides
2. Excel design calculators
3. WEBENCH™ Power Designer support
4. PSpice® models
   - Transient model supports flyback
   - We are adding more average models for flyback loop simulation
5. Application notes
6. Reference designs
   - You can find many flyback reference designs at: https://www.ti.com/reference-designs/index.html