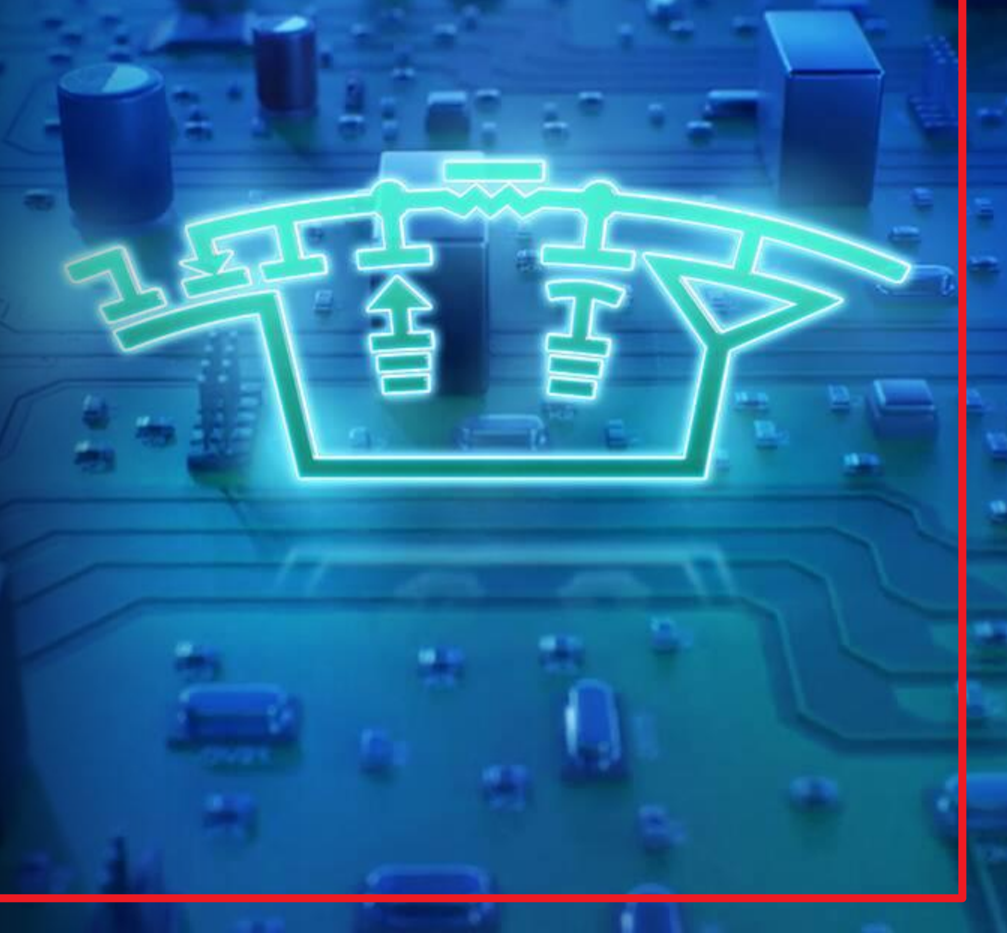
Power Supply Design Seminar

Creating a primary-side regulation flyback converter using a conventional boost controller



Author

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Agenda

- Flyback converters
  - Basics
  - Secondary-side regulation (SSR) vs. primary-side regulation (PSR)
- PSR
  - Detailed look at auxiliary winding waveforms
  - Three different flavors of PSR
  - The problem statement
- Design example using the LM5156-Q1 boost controller
  - Outlining input data and feasibility check
  - Resolving feedback
  - Further optimizations (artificial load, current sensing, snubbers)
- Conclusion and additional materials

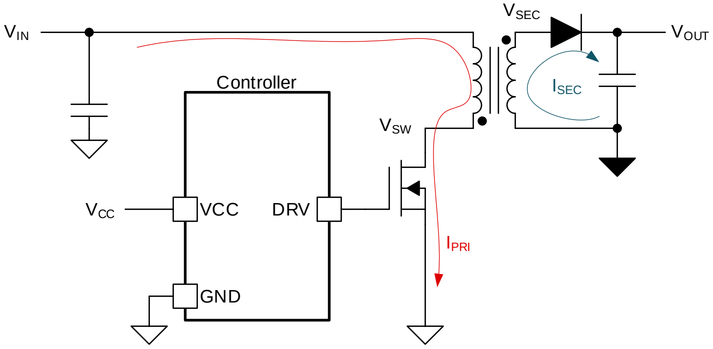
Flyback converter

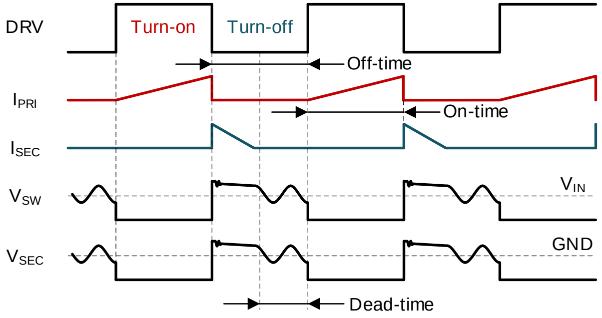
Turnon

- Switch conducts; primary current (I_{PRI}) stores the energy in the coupled inductor
- Secondary-side rectifier is reverse-polarized (secondary voltage [V_{SEC}] < 0)
- Coupled inductor stores the energy

Turnoff

- Switch opens; magnetized coupled inductor changes the polarity (V_{SEC} > 0)
- Secondary current (I_{SEC}) flows though the secondary winding and energizes the load





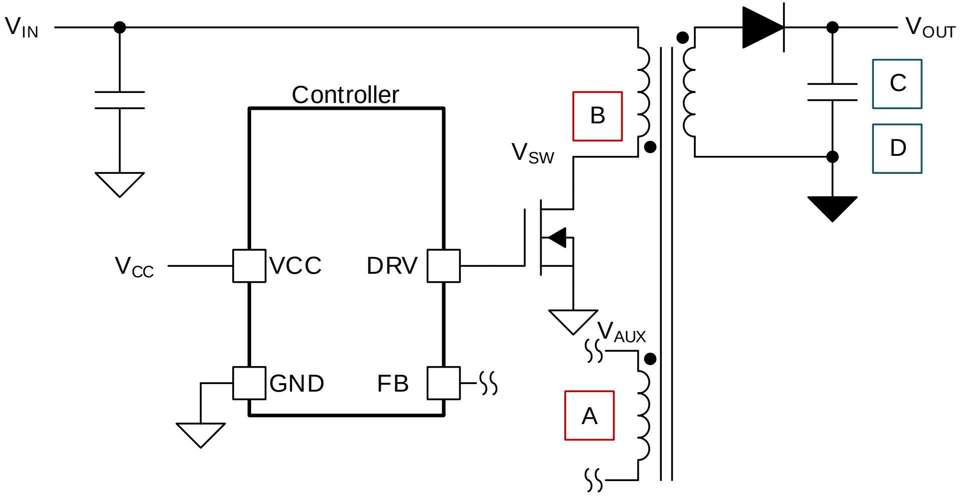
Flyback converter feedback

PSR sensing

- Sensing across the auxiliary winding (A)
- Sensing the reflected voltage on the switch node (B)

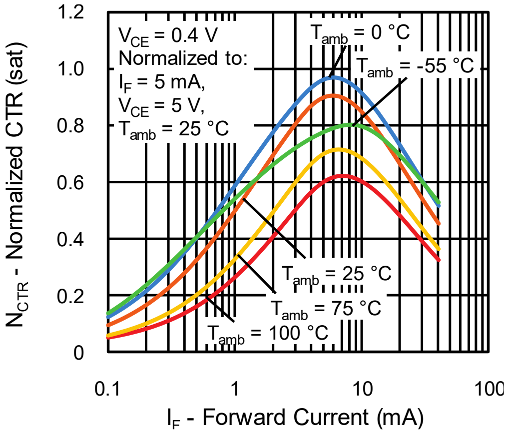
SSR sensing

- Using a resistor divider (C) (nonisolated topologies)
- Using an optocoupler (D)

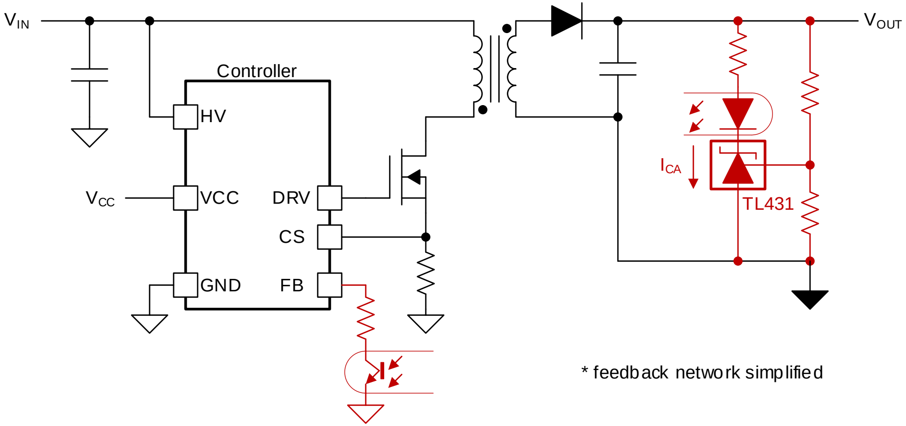


Closing the loop: SSR

- 431-type shunt regulator senses the output and adjusts the current through the optocoupler



Source: Vishay, Application Note 45

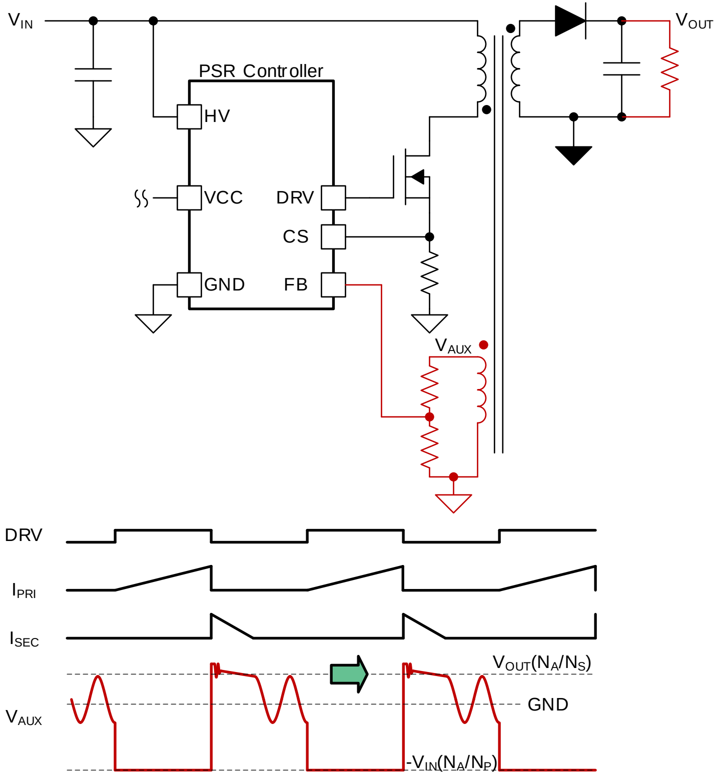


* feedback network simplified

- Current-transfer ratio (CTR) of the optocoupler changes with:
  - Time
  - Temperature
  - Current

Closing the loop: PSR

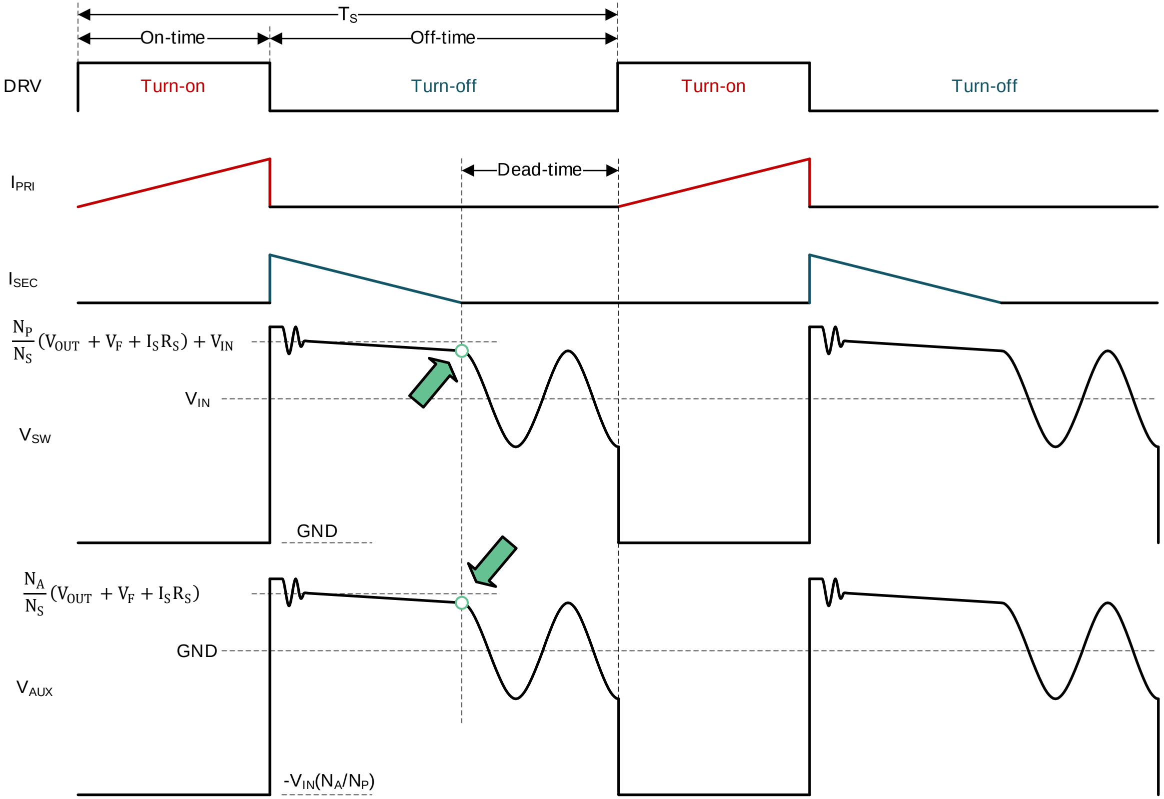
- Auxiliary winding is referenced to the primary side
- Voltage tracks the isolated output
- The controller senses the voltage across the auxiliary winding
- Continuous switching of PSR flybacks is crucial, as it ensures that the auxiliary winding voltage accurately represents the output

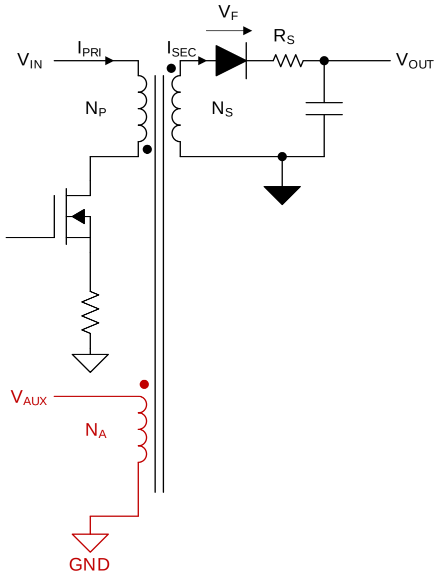


SSR vs. PSR

Parameter	SSR with an optocoupler	PSR
Light-load behavior	**Good light-load regulation**	Requires minimal load
Feedback	Complex feedback network using 431-type regulator and optocoupler	**Sampled reflected output voltage**
Initial output-voltage accuracy	**Excellent**	Average
Load regulation	**Very good load regulation (<1%)**	Average load regulation (>1%)
Reliability	Optocoupler aging factor affects reliability	**Excellent**
Transient response	Limited by optocoupler bandwidth	Mostly limited by the switching frequency
Cost	Average	**Improved because of the optocoupler removal**
Self-biasing	Requires auxiliary winding	**Leverages auxiliary winding for both bias and feedback**

Detailed look at the auxiliary winding waveforms



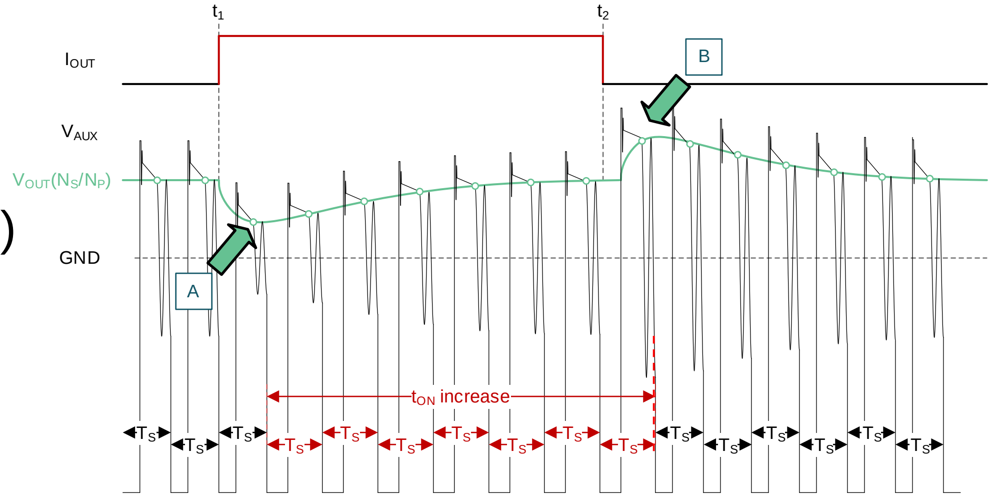


- Ideal sampling point is when I_{SEC} drops to zero

Auxiliary winding waveforms during load transient

- Current increase at t_1 causes output voltage (V_{OUT}) drop
- Controller finds current demand increase (A) within one switching cycle (T_S)
- Controller **increases** on-time (t_{ON})
- Switching frequency (f_{SW}) **decreases**
- V_{OUT} returns to desired level after several cycles
- At t_2 the process repeats with inverse logic (B)

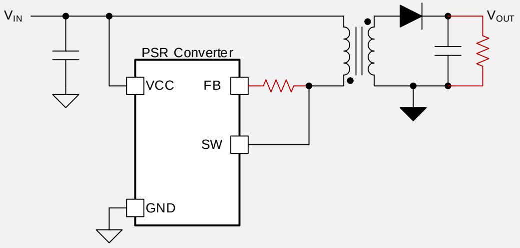
Quasi-resonant PSR controller example



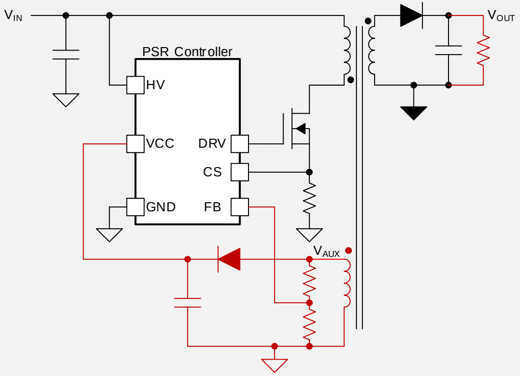
waveforms are not in scale

○ Discriminator and sampler circuit sampling points (UCC28700-Q1)

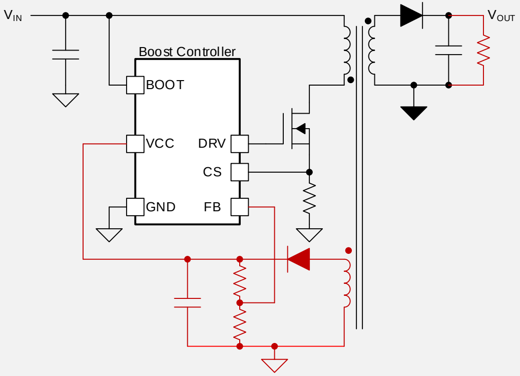
Three flavors of PSR



Low-voltage (<100-V) flyback converters (LM5180) allow for **direct sensing of the reflected V_{OUT}** across the main primary winding



High-voltage PSR flyback controllers (UCC28700) integrate a special **sampler circuit** that samples auxiliary winding "at the right time"



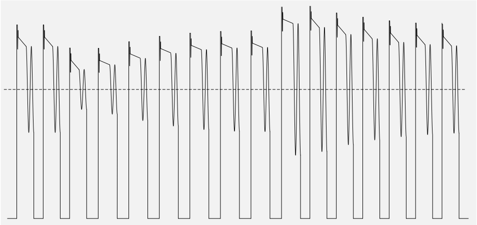
Universal pulse-width modulation or boost controllers (LM5156) **regulate a filtered auxiliary winding voltage** with additional rectification

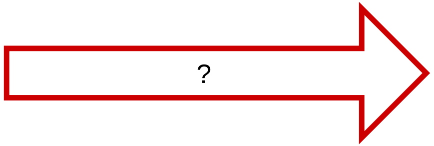
Problem statement

- V_{AUX} waveform is composite and carries a lot of information
- V_{AUX} provides accurate V_{OUT} information only once per period when I_{SE} drops to zero
- PSR regulators feedback use **sample and hold**
- Standard boost controllers expect **continuous** feedback voltage

How do you convert the auxiliary winding waveform?

Auxiliary Winding Waveform

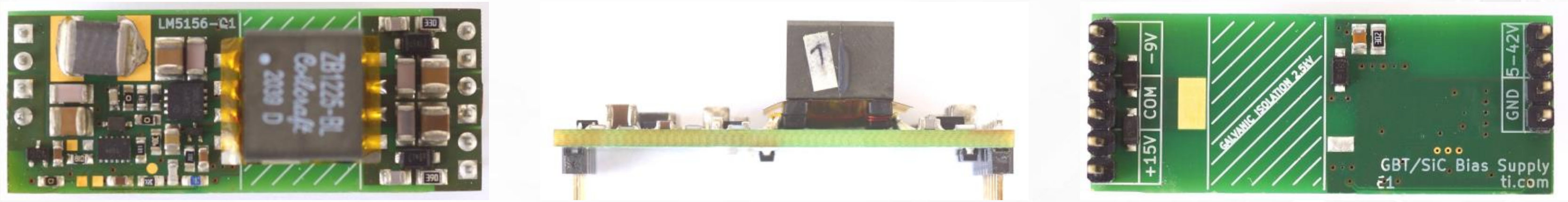




Expected Feedback Voltage Waveform

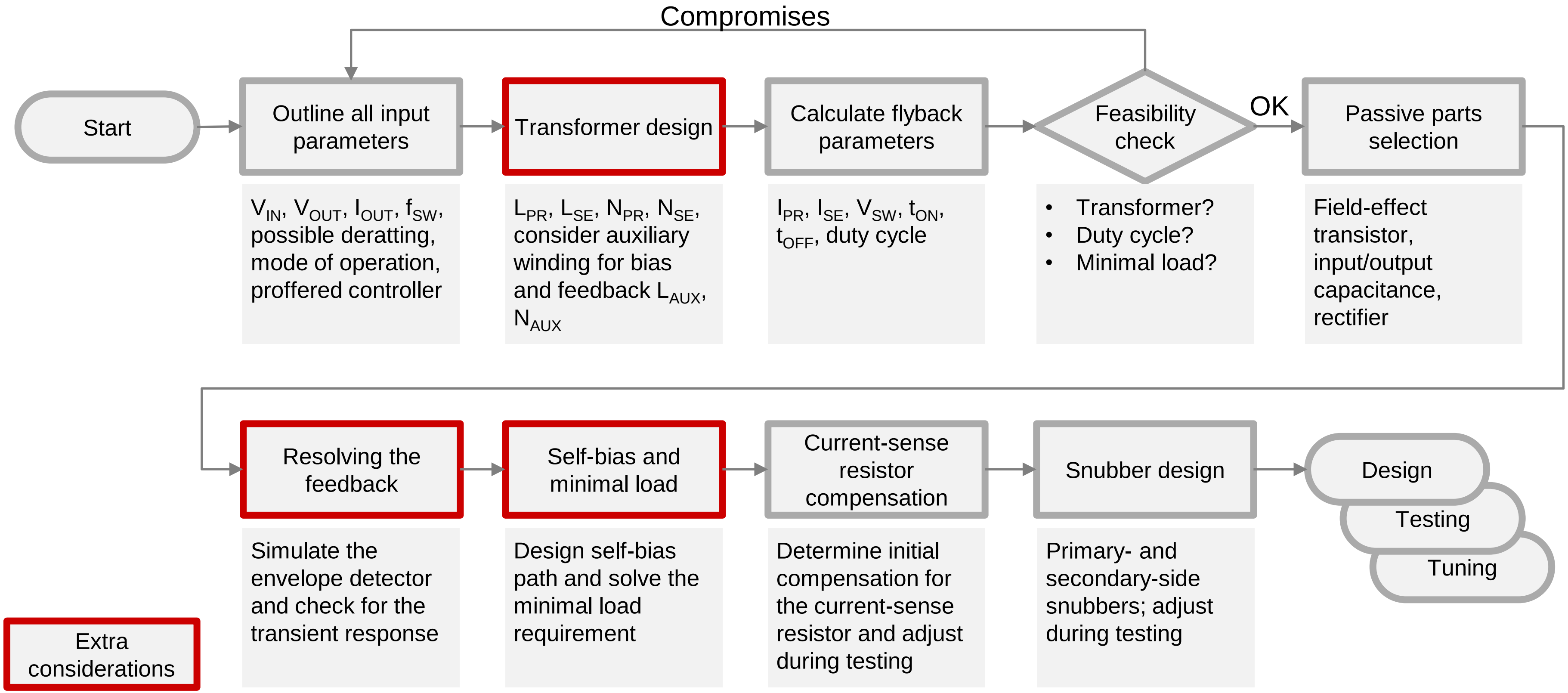
Step-by-step design example

Isolated gate-driver bias supply with the LM5156-Q1 boost flyback controller



17 x 44 x 14mm (W x L x H)

Suggested PSR flyback design flow



Compromises

Start

Outline all input parameters

V_{IN}, V_{OUT}, I_{OUT}, f_{SW}, possible deratting, mode of operation, proffered controller

Transformer design

L_{PR}, L_{SE}, N_{PR}, N_{SE}, consider auxiliary winding for bias and feedback L_{AUX}, N_{AUX}

Calculate flyback parameters

I_{PR}, I_{SE}, V_{SW}, t_{ON}, t_{OFF}, duty cycle

Feasibility check

- Transformer?
- Duty cycle?
- Minimal load?

OK

Passive parts selection

Field-effect transistor, input/output capacitance, rectifier

Resolving the feedback

Simulate the envelope detector and check for the transient response

Self-bias and minimal load

Design self-bias path and solve the minimal load requirement

Current-sense resistor compensation

Determine initial compensation for the current-sense resistor and adjust during testing

Snubber design

Primary- and secondary-side snubbers; adjust during testing

Design

Testing

Tuning

Extra considerations

Define converter parameters

- Isolated gate-driver bias supply powered from the 12-V vehicle battery

Parameter	Specification
Input voltage (V_{IN})	6 V_{DC}-42 V_{DC} (52-V transient)
Output voltage (V_{OUT})	+15 V, –9 V (V_{OUT} = 24 V)
Output current (I_{OUT})	180 mA
Switching frequency (f_{SW})	400 kHz
Mode of operation	Discontinuous conduction mode (DCM)
Primary-to-secondary isolation	Basic, 2.5 kV
Controller	LM5156-Q1

Identify corner cases

- No frequency fallback or boundary conduction mode (BCM) is possible. A conventional controller either:
  - Operates with constant f_{SW}
  - Enters pulse-skipping mode when V_{OUT} exceeds the regulated level
- Transformer turns ratio and inductance have to allow for DCM at f_{SW}
- Worst-case scenarios – extreme duty cycles:
  - $V_{IN(MIN)}$ and $I_{OUT(MAX)}$ result in a maximal duty cycle
  - $V_{IN(MAX)}$ and $I_{OUT(MIN)}$ result in a minimal duty cycle
- The Power Stage Designer™ software iterative process suggests transformer L_{PRI} = 4 µH, L_{SEC} = 16 µH, turns ratio N_P:N_S = 1:2

Feasibility check for worst-case scenarios

Power Stage Designer software finds the minimal load for V_{IN} = 42 V

Parameter	Minimum duty condition	Maximum duty condition	LM5156-Q1 device data sheet specification
On-time	0.13 µs	1.57 µs	Minimum 130 ns (Figure 8-12)
Off-time	0.43 µs	0.76 µs	
Duty cycle	5.10%	62.86%	Maximum 92.8% (Figure 8-16)
Zero time	1.94 µs	0.16 µs	
Maximum primary current (I_{PR})	1.33 A	2.36 A	
Maximum secondary current (I_{SE})	0.66 A	1.18 A	
Required minimum load ($I_{L(MIN)}$)	**60 mA**		

Alternatively, the controller enters pulse-skipping mode

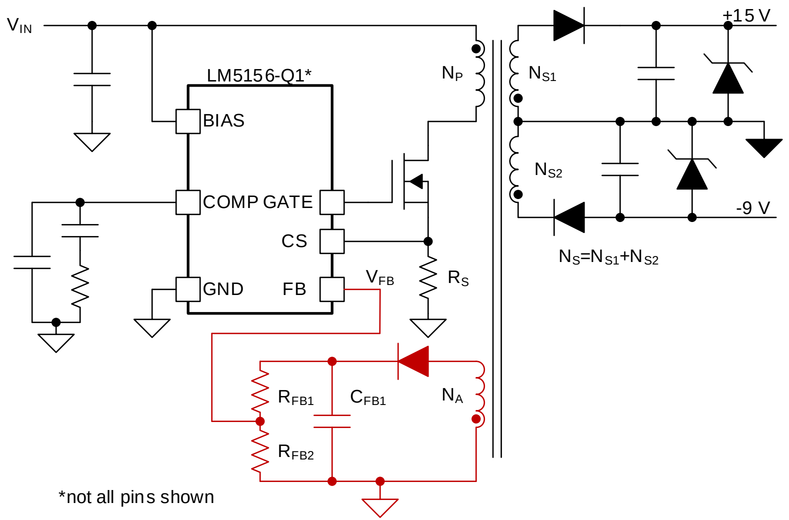
First design review

- Magnetics supplier confirms that the transformer design is reasonable
- The LM5156-Q1 can support required duty cycles even at f_{SW} = 400 kHz
- The converter requires a ≊60-mA artificial load at V_{IN} = 42 V for constant f_{SW}, which negatively impacts efficiency at light loads (≊5 mA at V_{IN} = 12 V)
- Allowing the controller to enter pulse-skipping mode is a good compromise between:
  - Reducing the artificial load, thus increasing efficiency
  - Reducing the transient response in pulse-skipping mode

Designer decision: Does this solution still satisfy expectations?

Resolving the feedback

- Use diode as a half-wave rectifier (peak detector)
- Detector (filter) must be able to track the output transient



*not all pins shown

- Set the auxiliary winding turns ratio such that the rectified voltage allows for self-biasing (such as 15 V)

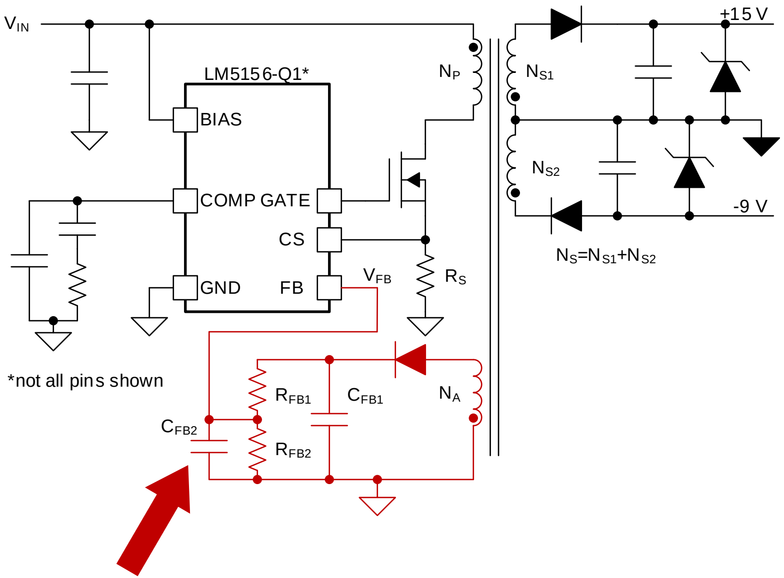
$$V_{VCC} \approxeq V_{OUT} \times \frac{N_A}{N_S}$$

- Calculate the resistor divider to match the feedback voltage (V_{FB})

$$V_{FB} = V_{OUT} \times \frac{N_A}{N_S}\left(\frac{R_{FB2}}{R_{FB1} + R_{FB2}}\right)$$

Resolving the feedback

- A passive, second-order filter is recommended to filter out the V_{AUX} envelope
- Capacitors C_{FB1} and C_{FB2} define the filter time constant (τ)
- Use a simulation tool to find out optimal C_{FB1} and C_{FB2} values



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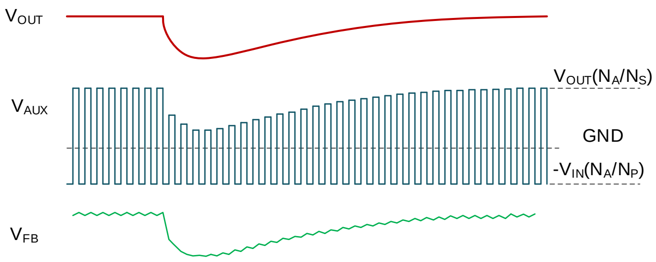
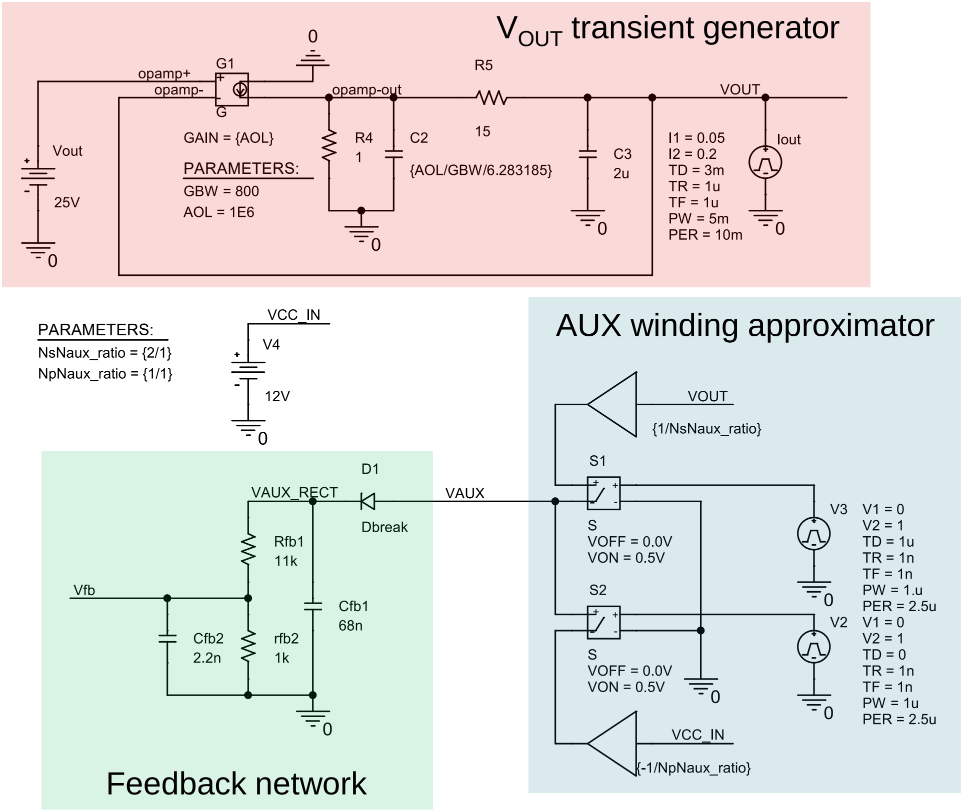
Resolving feedback: Simulation in PSpice

Three steps

1. Generate desired V_{OUT} transient response
2. Approximate the V_{AUX}
3. Adjust the rectifier-filter transient response using C_{FB1} and C_{FB2}

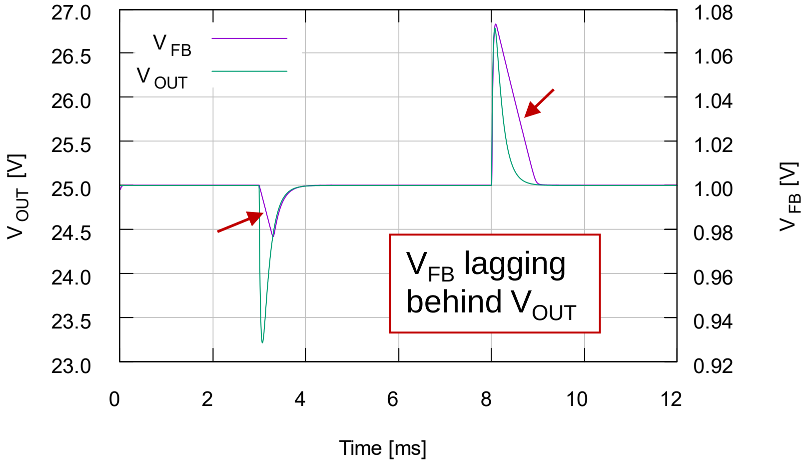




Simulated filter (peak detector) response

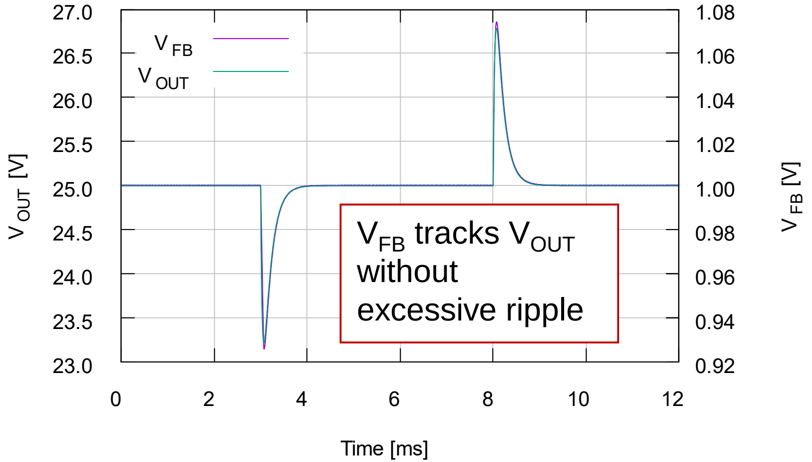
Check that V_{FB} is able to track V_{OUT}

τ is too long



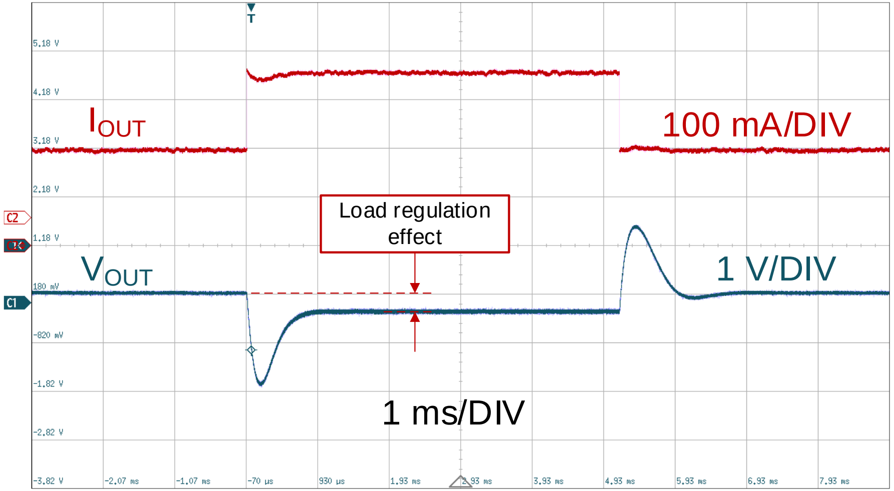
V_{FB} lagging behind V_{OUT}

τ is optimal

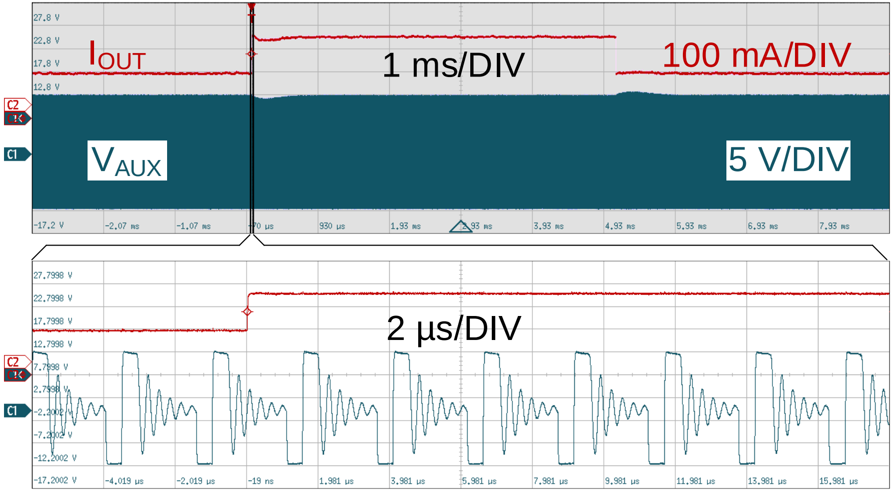


V_{FB} tracks V_{OUT} without excessive ripple

V_{OUT} transient response and V_{AUX} feedback



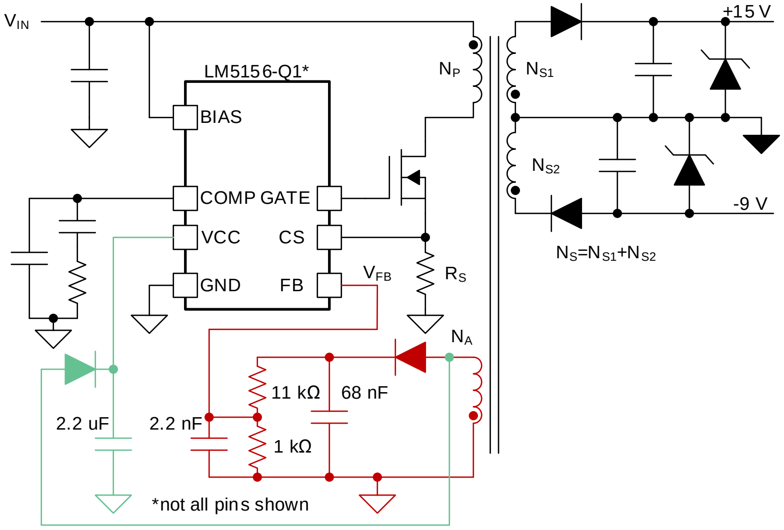
V_{OUT} transient response for I_{OUT} from 45 mA to 135 mA



V_{AUX} transient response for I_{OUT} from 45 mA to 135 mA

Biasing scheme to improve light-load efficiency

- The feedback and self-power have different requirements
- Self-power (bias) from the auxiliary winding requires large bulk capacitance to keep the voltage rail stable
- The feedback path requires a fast transient response to quickly track the V_{OUT}
- Two separate paths offer the best performance without compromises



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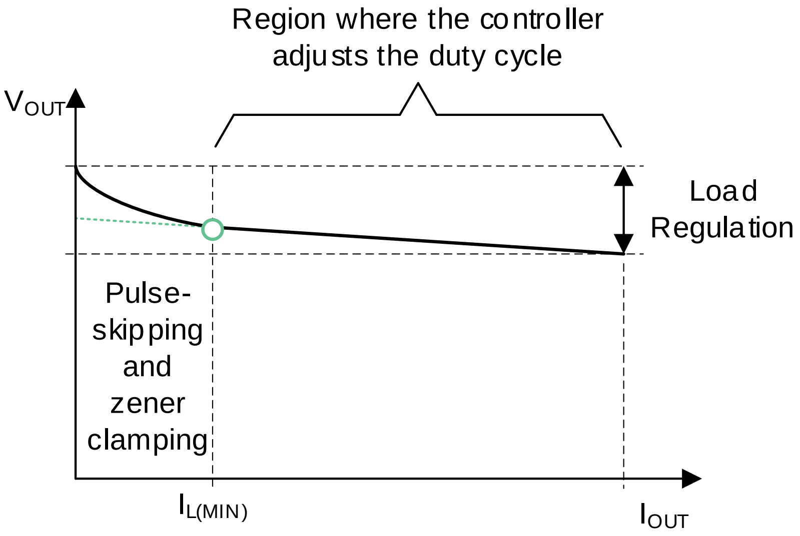
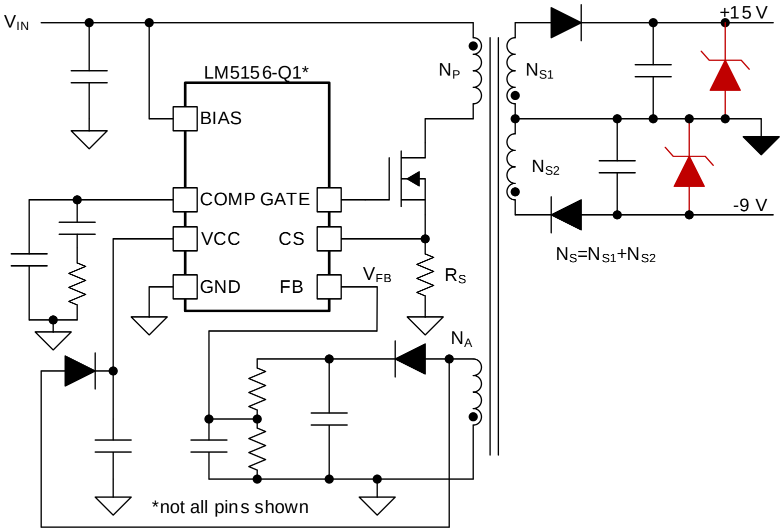
Solving the minimal load

- There are two options:
  - Resistors as a dummy load
  - Zener diodes

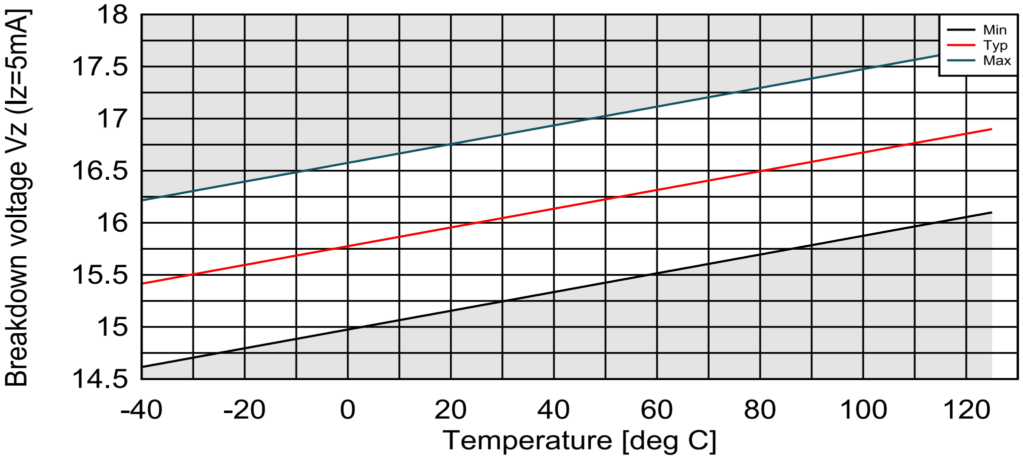




- The controller can't further reduce t_{ON}
- V_{OUT} increases, Zener diodes sink current
- Pulse-skipping occurs

Zener diodes and their accuracy

- Zener diodes are inexpensive but not very accurate
- Diodes with approximately:
  - $V_Z < 4.7$ V have a negative temperature coefficient
  - $V_Z > 4.7$ V have a positive temperature coefficient
- Out-of-the-box accuracy varies

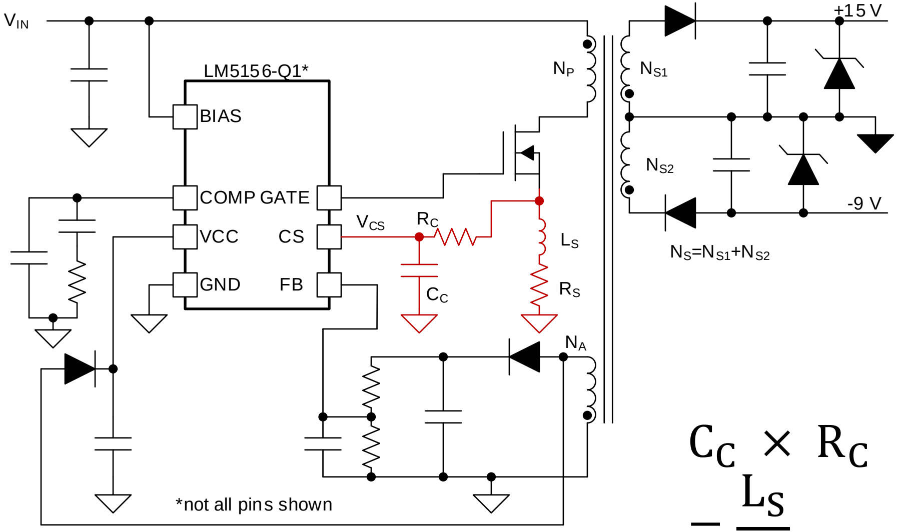


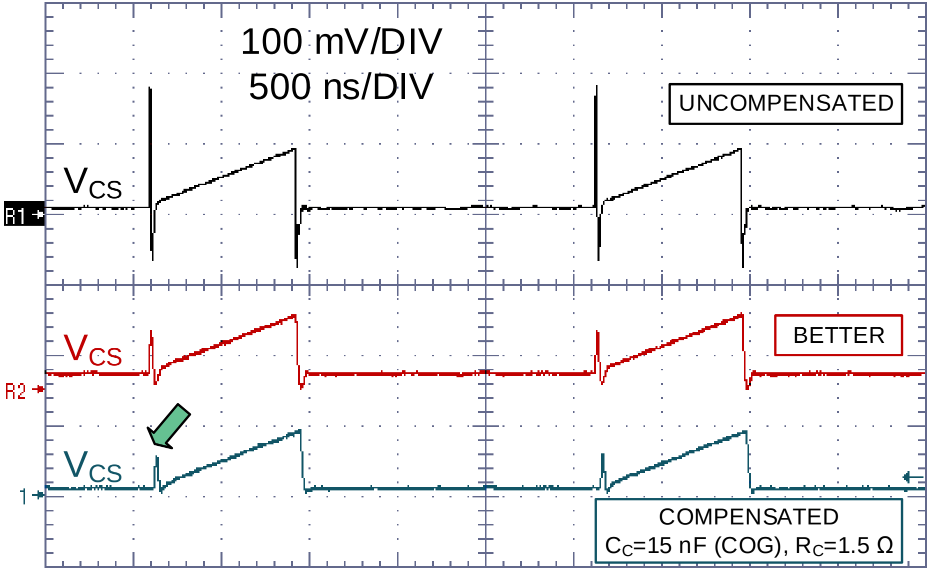
MMSZ16T1G Zener diode tolerance field for I_Z=5 mA

Parameter	MMSZ10T1G (V_Z = 10 V)	MMSZ16T1G (V_Z = 16 V)
Lowest Zener voltage	8.9 V	14.6 V
Highest Zener voltage	11.4 V	17.7

Compensating the current-sense resistor

- Ringing on the current-sense resistor may cause false overcurrent events
- Compensation network is necessary



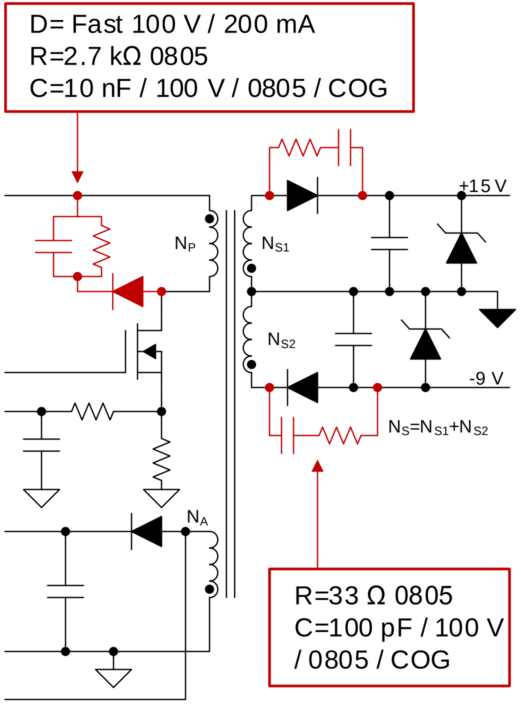


$$C_C \times R_C = \frac{L_S}{R_S}$$

(The example uses a 0.33Ω 0603 shunt resistor)

Snubber circuits

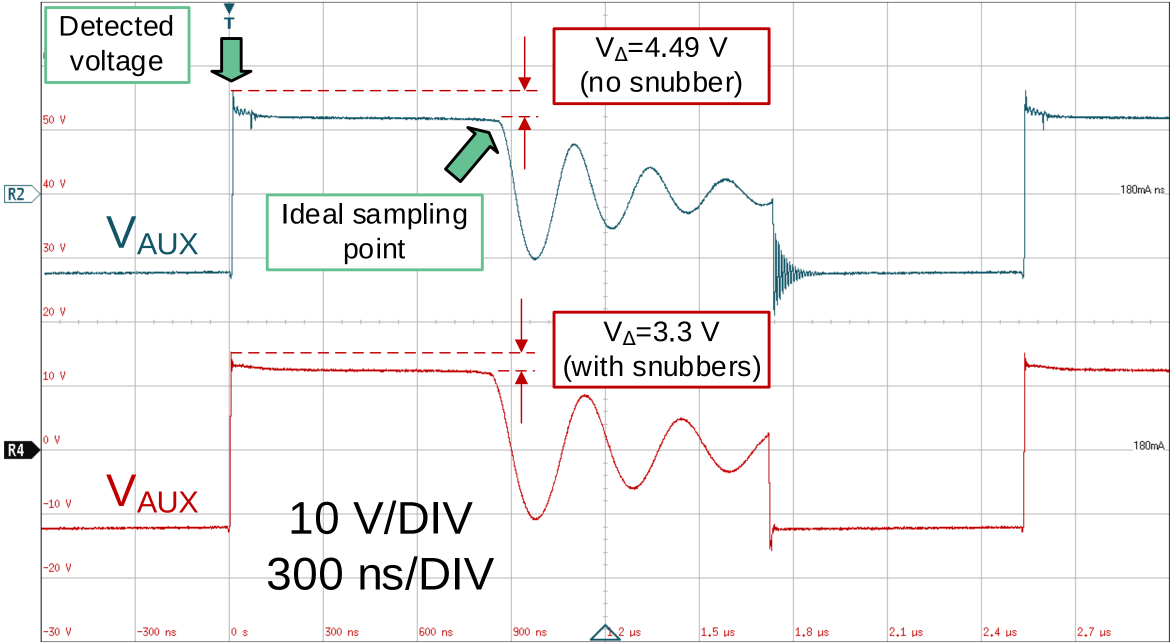
- Snubber circuits reduce ringing that:
  - Causes electromagnetic interference (EMI)
  - Stress the power transistor during the turnoff transient
- The ringing also negatively affects the auxiliary waveform and affects feedback
- Ringing is proportional with I_{OUT}



D= Fast 100 V / 200 mA
R=2.7 kΩ 0805
C=10 nF / 100 V / 0805 / COG

R=33 Ω 0805
C=100 pF / 100 V / 0805 / COG

V_{AUX} waveforms with and without snubber circuits



Detected voltage

Ideal sampling point

V_{Δ}=4.49 V (no snubber)

V_{Δ}=3.3 V (with snubbers)

V_{AUX}

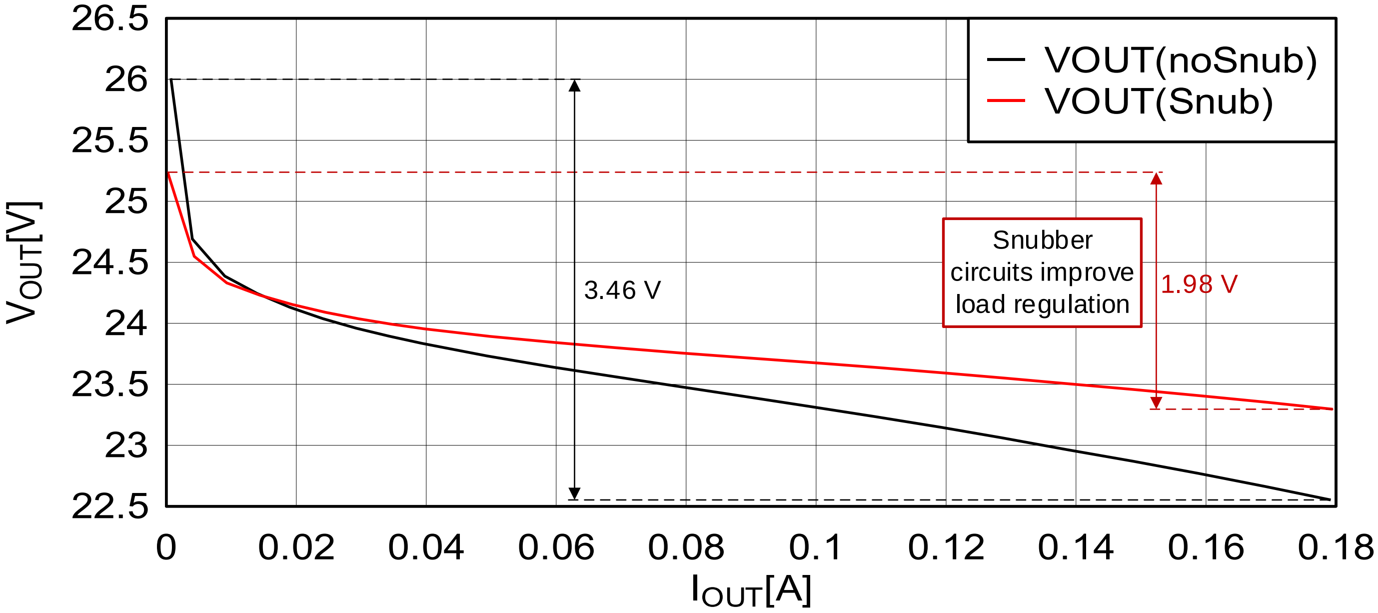
V_{AUX}

10 V/DIV

300 ns/DIV

V_{AUX} waveforms for I_{OUT} = 180 mA

Snubber circuit effect on load regulation



Snubber circuits improve load regulation

Conclusion

- PSR flybacks are popular for low-cost isolated DC/DC converters
- A PSR flyback with a conventional boost controller requires these considerations for feedback:
  - Identify the minimum and maximum duty cycle for the given operating conditions
  - Design the V_{AUX} envelope detector (filter) such that it tracks the V_{OUT}
  - Minimize ringing using snubbers
  - Split the self-bias and feedback paths to enable a fast transient response
  - Add a compensation network to the current-sensing resistor
  - Design the compensation with the envelope detector in mind, accounting for a higher phase margin
  - Verify the transient response for the minimal, maximal and nominal input voltage

Resources and more reading

UCC28700-Q1 Datasheet, chapter 7.4.1

- How the discriminator and sampler circuit works

LM5180-Q1 Datasheet, chapter 7.3.2

- How the frequency fallback, BCM and PSR work

Power Stage Designer software

- Essential tool for initial component selection

Under the Hood of Flyback SMPS Designs (SLUP261)

- In-detail description of flyback converters

TI Drive (access code rn4N8w;r)

- Design resources for this presentation

PSPICE-FOR-TI

- PSpice® for TI design and simulation tool

access code rn4N8w;r

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