Power Supply Design Seminar

Topic 1 Presentation:

Under the Hood of Flyback SMPS Designs

Reproduced from
2010 Texas Instruments Power Supply Design Seminar
SEM1900, Topic 1
TI Literature Number: SLUP254

Power Seminar topics and online power-training modules are available at: power.ti.com/seminars

TEXAS INSTRUMENTS

Topic 1

Under the Hood of Flyback SMPS Designs

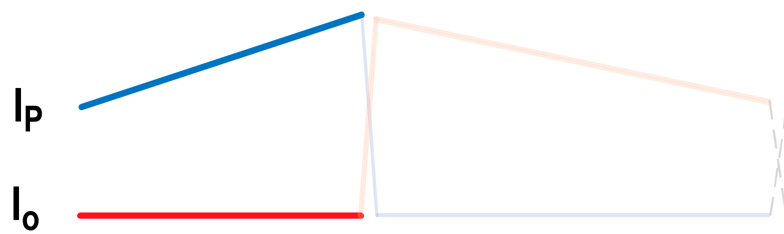
Jean Picard

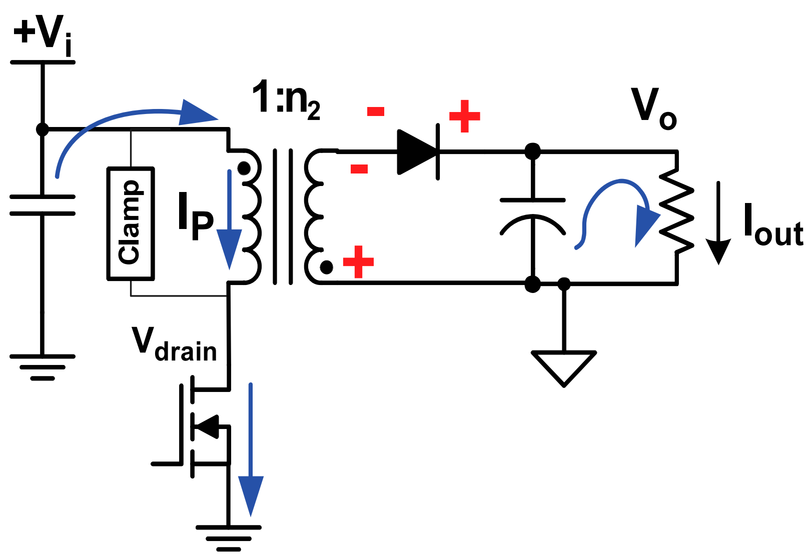
Agenda

1. **Basics of Flyback Topology**
2. Impact of Transformer Design on Power Supply Performance
3. Power Supply Current Limiting
4. Summary

Transfer of Energy

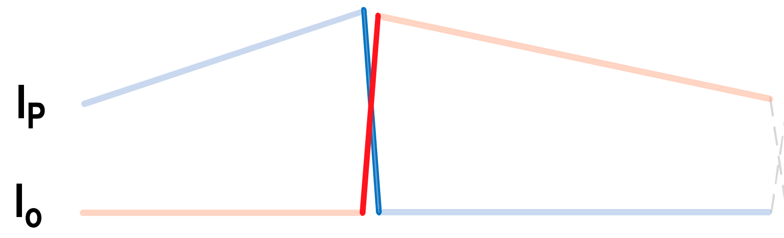
- **FET turns ON**
  - **Voltage across primary magnetizing inductance ≅ V_i**
    - **Energy is stored in flyback transformer: Function of L, D and T_s**
  - **Secondary diode in blocking state**
- FET turns OFF
  - During commutation: Leakage energy absorbed by clamp circuit
  - Stored energy transferred to output through diode
  - If DCM operation, all the stored energy is transferred
- **Pulsating input and output current**

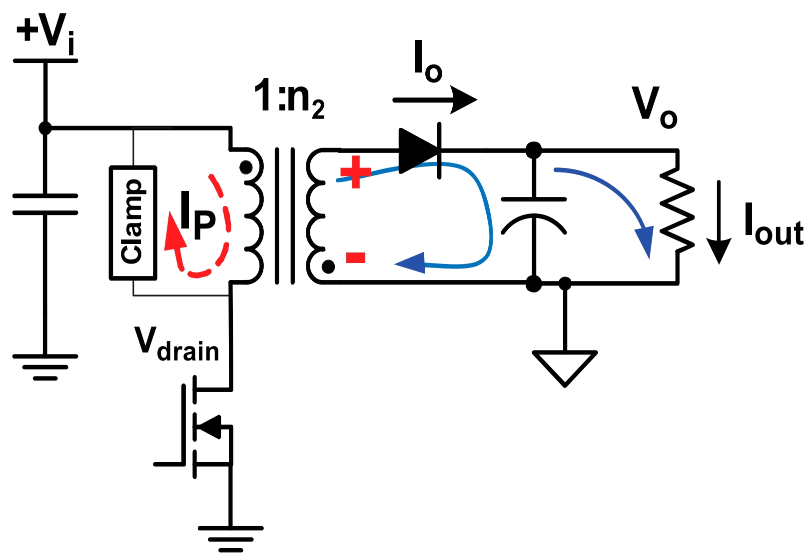




Transfer of Energy

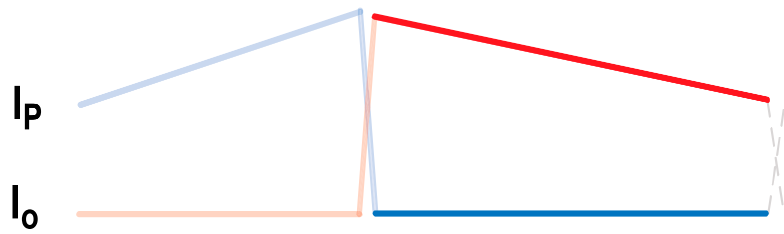
- FET turns ON
  - Voltage across primary magnetizing inductance ≅ V_i
    - Energy is stored in flyback transformer: Function of L, D and T_s
  - Secondary diode in blocking state
- **FET turns OFF**
  - **During commutation: Leakage energy absorbed by clamp circuit**
  - **Stored energy transferred to output through diode**
  - If DCM operation, all the stored energy is transferred
- **Pulsating input <u>and</u> output current**

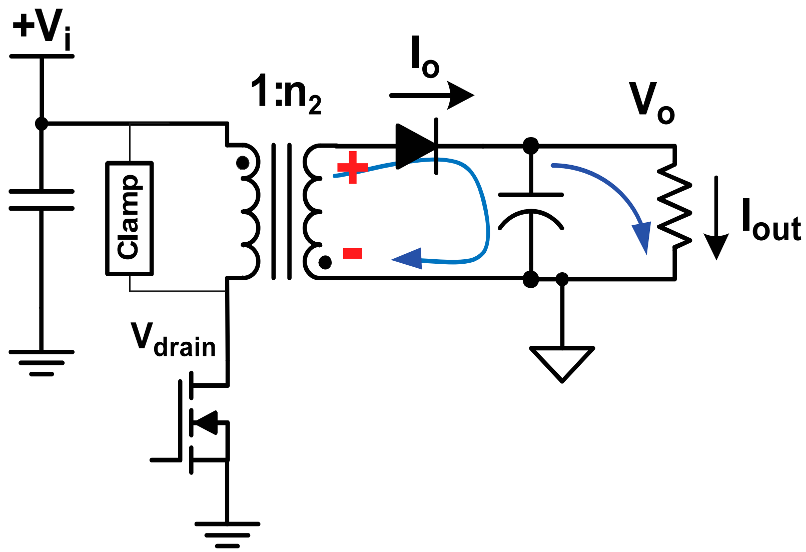




Transfer of Energy

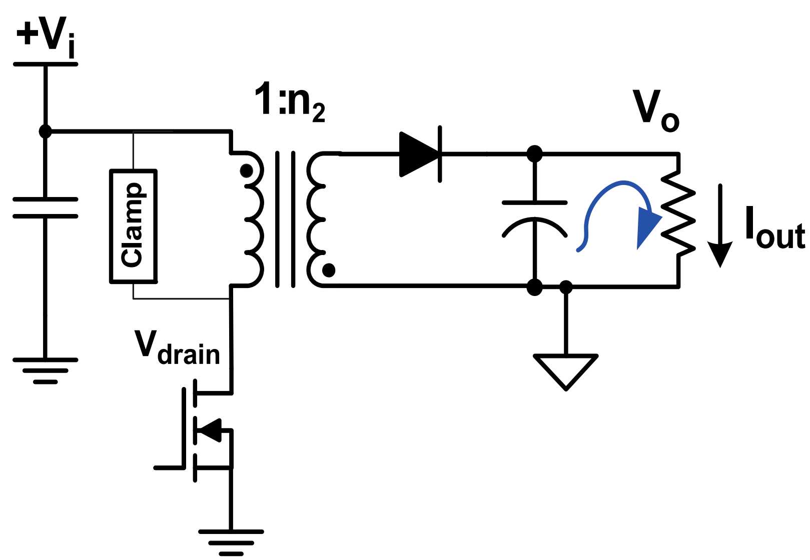
- FET turns ON
  - Voltage across primary magnetizing inductance ≅ V_i
    - Energy is stored in flyback transformer: Function of L, D and T_s
  - Secondary diode in blocking state
- **FET turns OFF**
  - During commutation: Leakage energy absorbed by clamp circuit
  - **Stored energy transferred to output through diode**
  - If DCM operation, all the stored energy is transferred
- **Pulsating input and output current**





Transfer of Energy

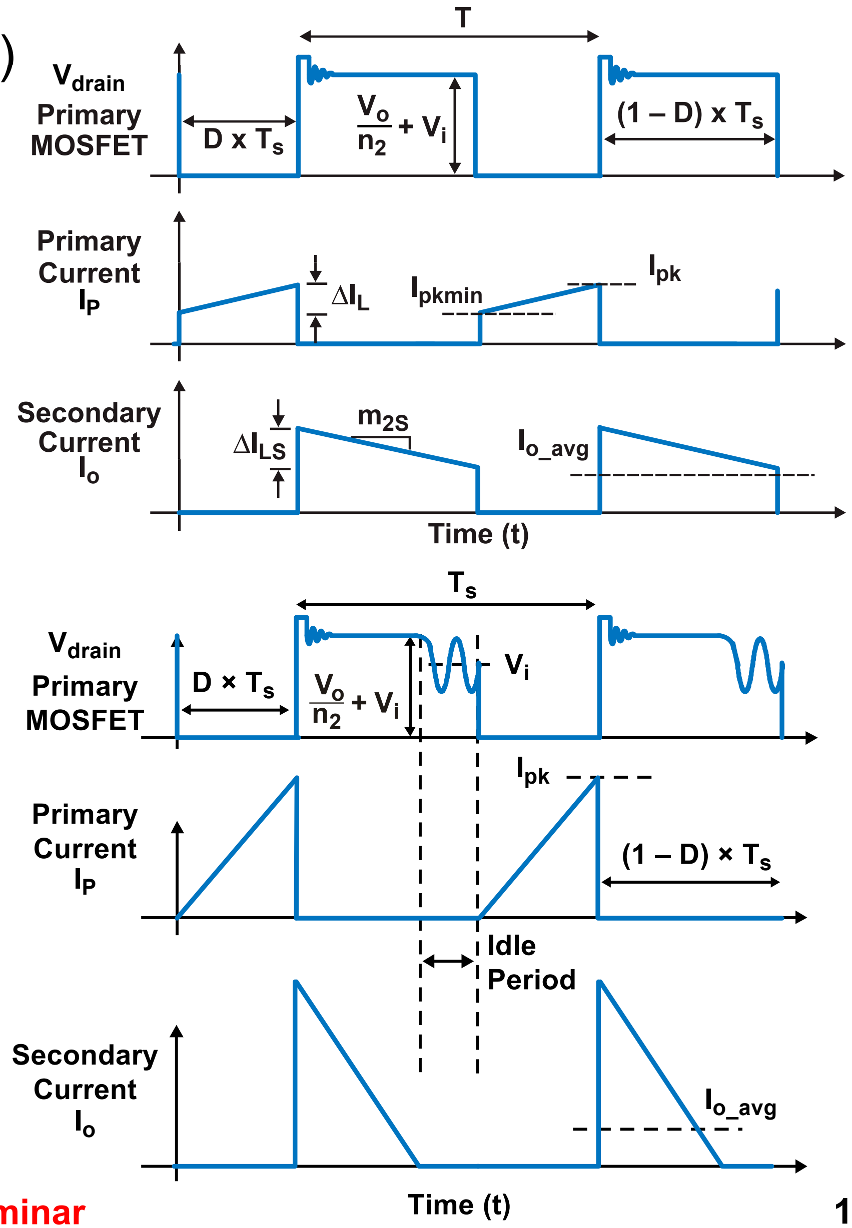
- FET turns ON
  - Voltage across primary magnetizing inductance $\cong V_i$
    - Energy is stored in flyback transformer: Function of L, D and T_s
  - Secondary diode in blocking state
- FET turns OFF
  - During commutation: Leakage energy absorbed by clamp circuit
  - Stored energy transferred to output through diode
  - **If DCM operation, <u>all</u> the stored energy is transferred**
- **Pulsating input <u>and</u> output current**



CCM versus DCM

- Continuous conduction mode (CCM)
  - Small ripple and rms current
  - Lower MOSFET conduction and turn-off loss
  - Lower core loss
  - Lower capacitors loss
  - Can have better “full load” efficiency
  - Smaller EMI and output filters

- Discontinuous conduction mode (DCM)
  - No diode reverse recovery loss
  - Lower inductance value
    - *May* result in a smaller transformer
  - Better “no load” efficiency
  - First-order system
    - Inherently stable
  - No RHPZ problem
  - Slope compensation not needed in CMC



Right-Half-Plane Zero, CCM Operation

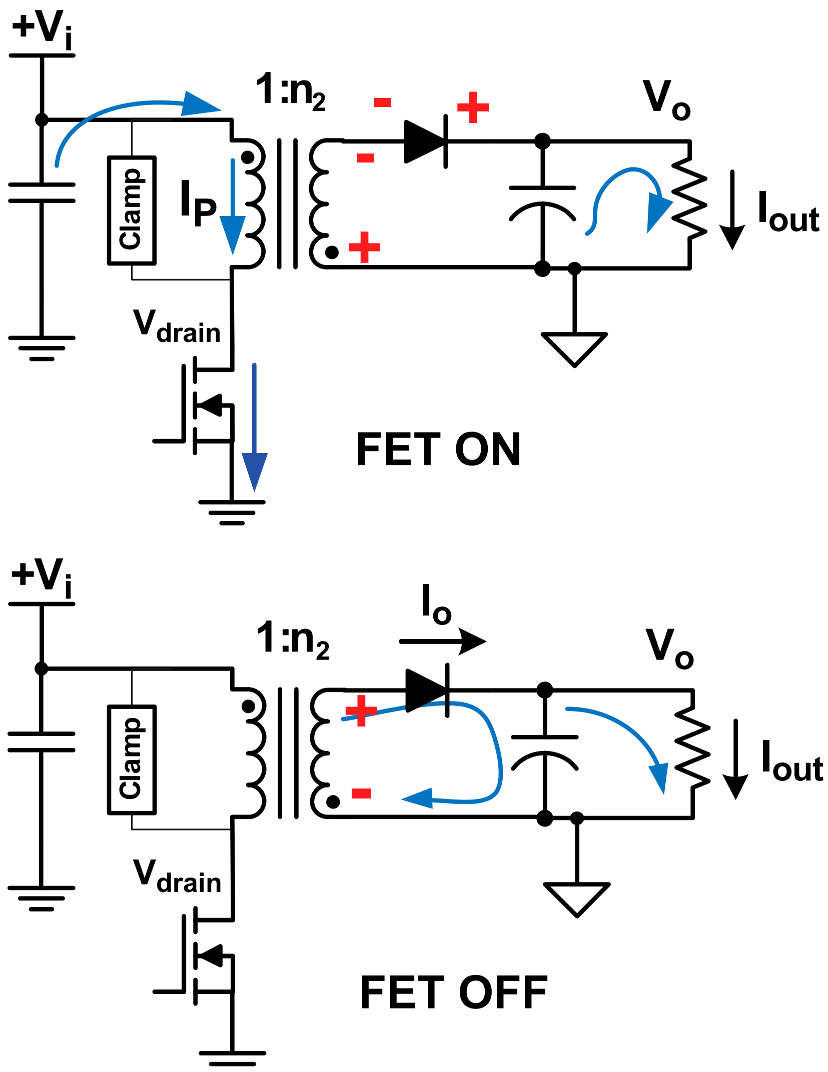
- Energy is delivered during 1 – D
  - Effect of control action during ON time is delayed until next switch turn OFF
- Initial reaction is in opposite direction of desired correction

⇒ RHP Zero

  - Phase decreases with increasing gain

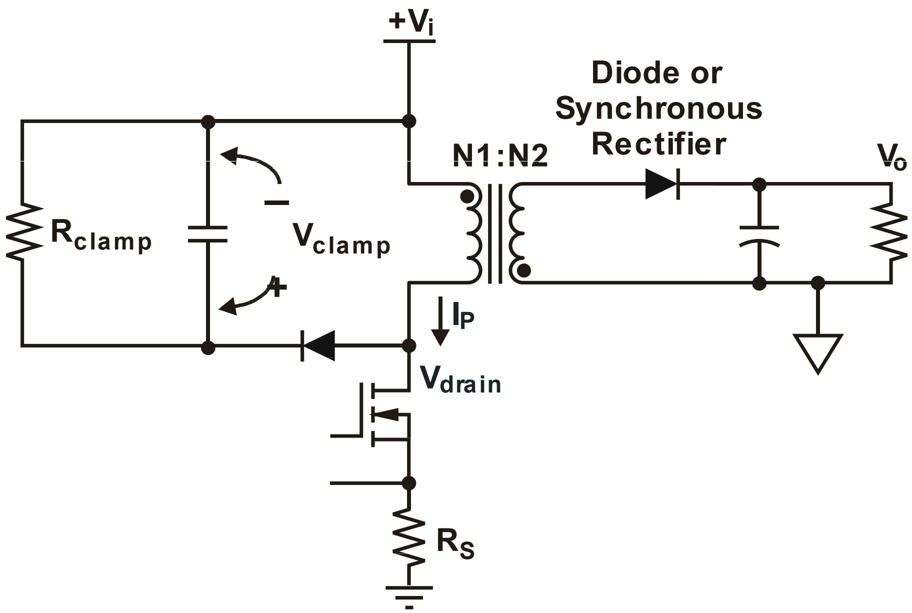
$$f_{RPHZ} = \frac{(1-D)^2 \times V_o}{2\pi L \times D \times I_{out} \times n_2^2}$$

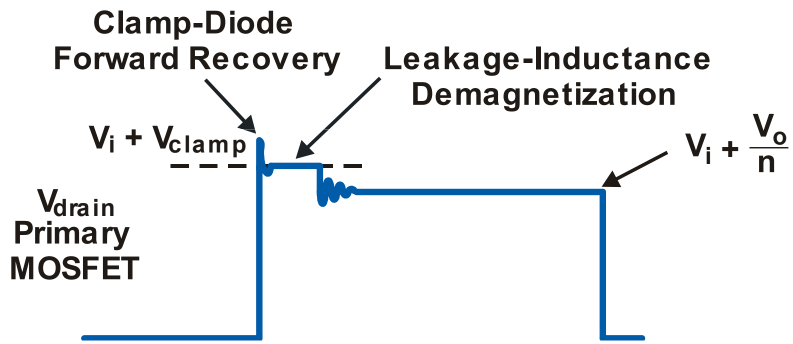
D ↔ Main switch duty-cycle



RCD Clamp Circuit

- During commutation primary-to-secondary, the leakage energy is absorbed by the clamp circuit
  - R_{clamp} dissipates the leakage energy and some magnetizing energy
  - The clamp capacitor ensures a low voltage ripple
  - Use short connection with minimum loop area
- V_{clamp} is maximum at full load and minimum input voltage
  - R_{clamp} selected for a maximum drain voltage in worst case
  - Tradeoff between efficiency, peak drain voltage, output current limit and cross regulation (see ringing effect)





Agenda

1. Basics of Flyback Topology

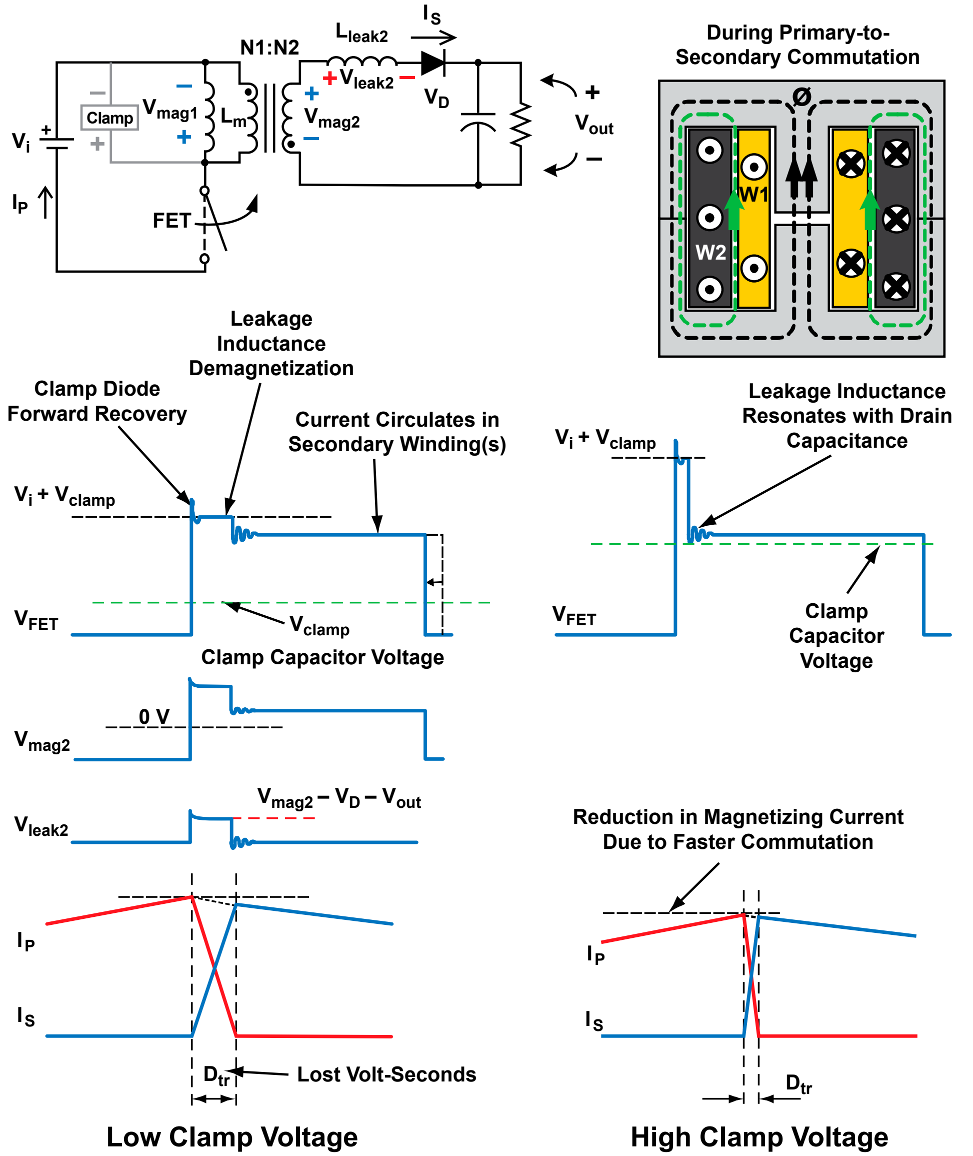
2. Impact of Transformer Design on Power Supply Performance

3. Power Supply Current Limiting

4. Summary

Transformer's Leakage Inductance

- Transformer's leakage inductance represented by L_{leak2}
  - Primary winding is the closest to center gap
- When FET turns OFF
  - L_{leak2} opposes to I_P decrease and I_S increase
  - Magnetizing inductance works to maintain magnetizing current
- Voltage spike on FET during commutation
- Rate of rise of current is influenced by leakage inductance
- Commutation primary-to-secondary is not instantaneous and depends on V_{clamp}
  - Loss of volt-seconds

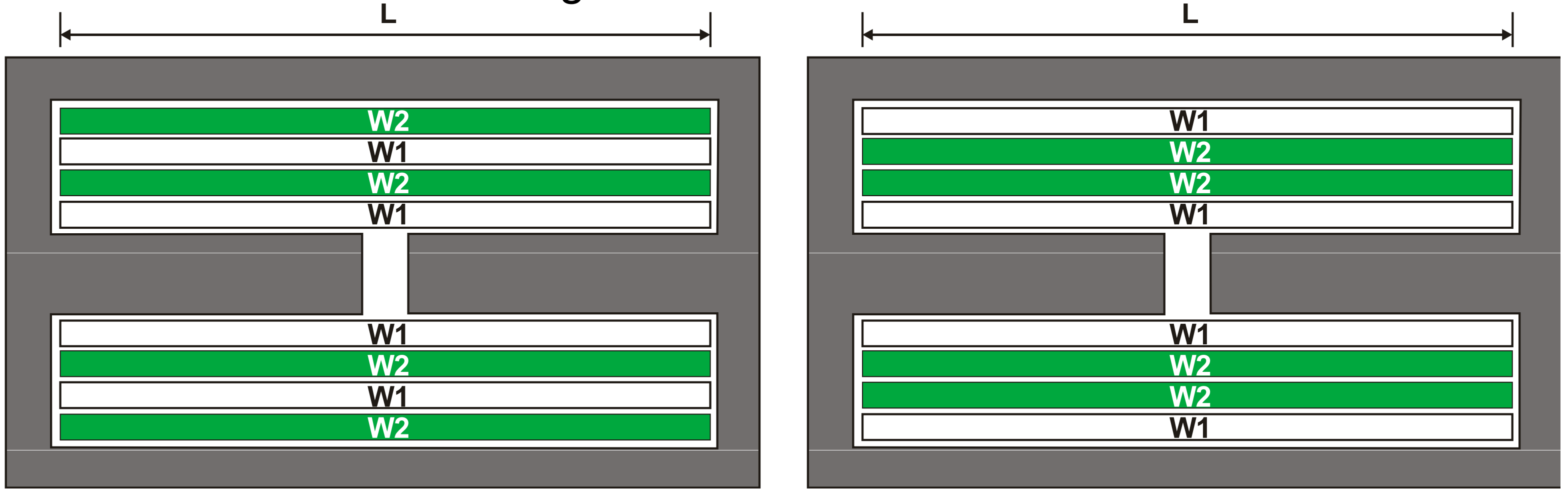


Effects of Leakage Inductance

- Clamp circuits and snubbers needed for primary FET and secondary rectifier(s)
- Lower power-supply efficiency
- Impact on gate-drive strategy if synchronous rectifier is used
- Higher duty cycle and magnetizing current than expected
- Higher H-field radiated emission
- High impact on cross-regulation

How Leakage Can Be Minimized

- Leakage inductance is a function of winding geometry, number of turns and separation between primary and secondary
  - Minimize the separation between the primary and main secondary winding(s)
  - Interleave the primary and main secondary
  - Select a core with a long and narrow window



Option 1 **Option 2**

- Leakage inductance is <u>not</u> lowered with a high permeability core
- Having the winding tightly coupled to the core will <u>not</u> reduce it

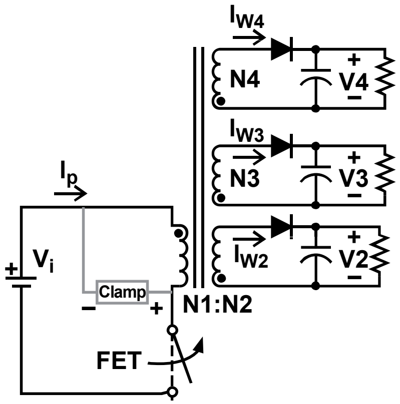
Cross-Regulation – Overview

- Multiple-output flyback topology is popular because of its simplicity and low cost
- If the coupling is perfect, the turns ratio directly defines output voltages
- In the real world, "perfect" coupling is not possible
- This often results in poor cross-regulation

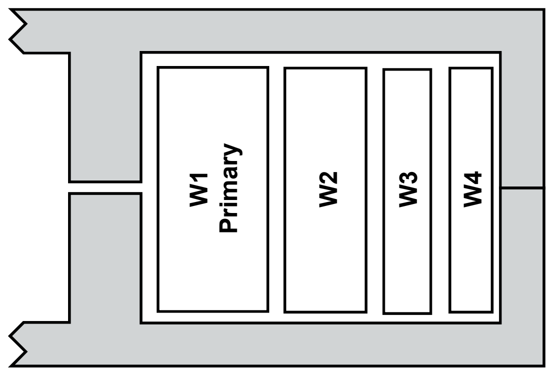
Cross-Regulation Physical Model

- Transformer windings cannot all be equally well coupled to the gap because of physical separation between them
- Magnetic energy stored <u>between</u> the windings represented as leakage inductances
- Model not applicable to any transformer geometry
- Can become complex if interleaving is used, or if multiple secondary windings are wound simultaneously (multifilar)
- Not accurate in situation of lightly loaded secondary outputs
- Good tool to understand how the common flyback transformer geometries work

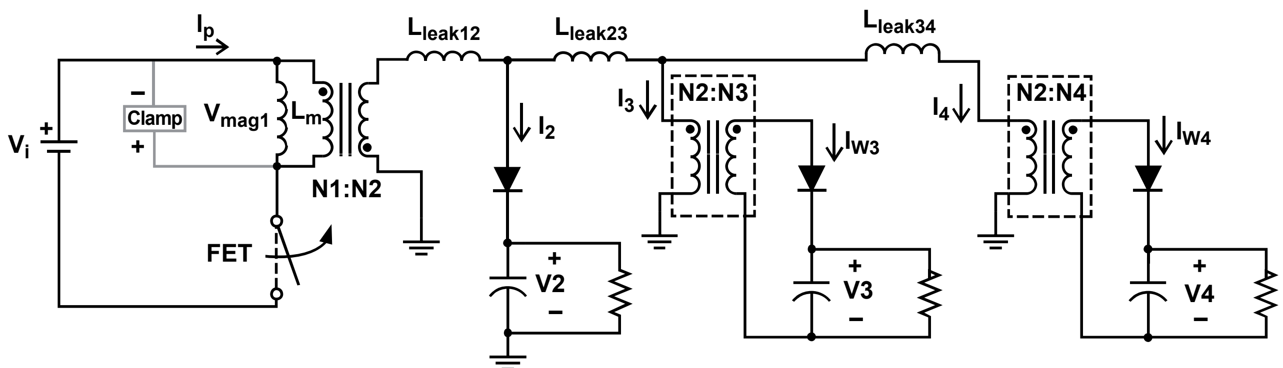
Cross-Regulation Physical Model



Basic Flyback Circuit



Transformer Construction



Transformer Physical Model

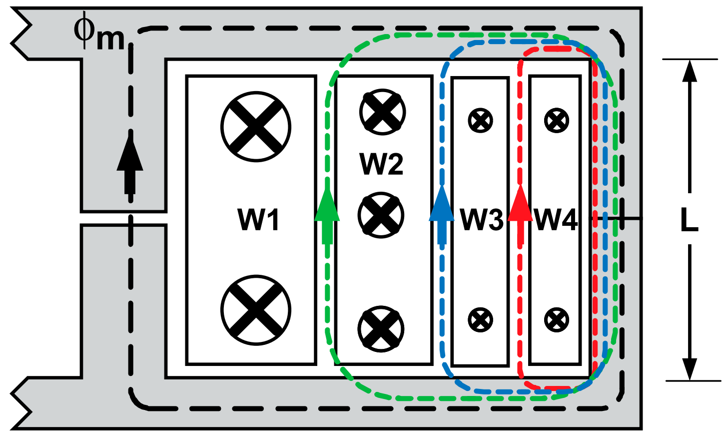
- This circuit is only applicable to the transformer windings stackup shown
- Each leakage inductance considered is between two consecutive secondaries
- Also called "Ladder model"

Flux Lines during Commutation
Each Secondary Winding with Nominal Load

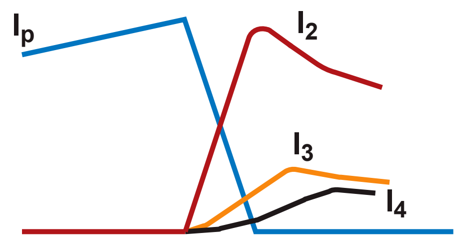
- ϕ_m decreases during commutation
- $d\phi/dt$ (decreasing) in each secondary winding is limited by its output voltage
  - Increasing current induced in W2 to W4 to maintain ϕ_m in the gap

$$e = -N \times \frac{d\phi_m}{dt}$$

- Leakage between W2 and W1
  - W1's voltage limited by clamp
- W1 closest to gap
  - V_{clamp} limits $d\phi_m/dt$ in the gap during commutation
- W2 is next to W1
  - W2 limits the $d\phi/dt$ seen by W3 and W4
  - W3 and W4 output voltage lower than without leakage
- Current commutates progressively from near to remote secondary windings



During Primary-to-Secondary Commutation Current in All Windings



Secondary Currents During Commutation Based on Physical Model

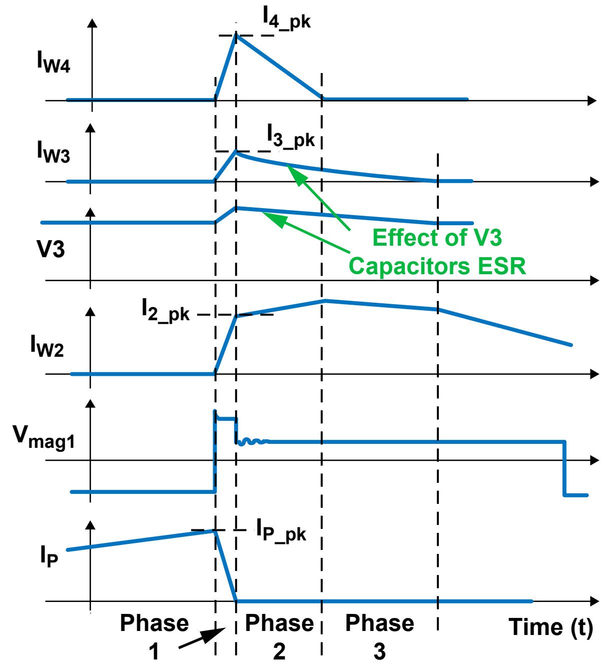
Ringing Effect

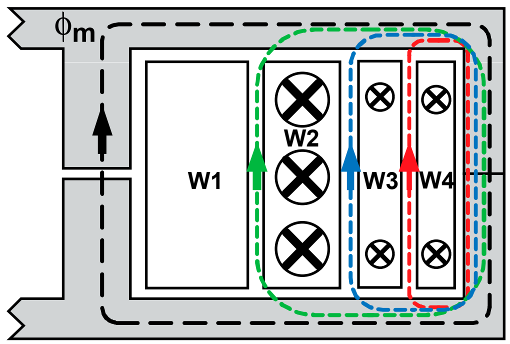
- High dV/dt when main switch turns off if main output is heavily loaded
- Transformer leakage inductance and parasitic capacity ⇒ auxiliary secondary voltage tends to “ring”
- If auxiliary output fully loaded ⇒ this ringing is clamped
- If lightly loaded ⇒ voltage overshoot with peak detector effect
- Much higher (sometimes > 2 x nominal value!) auxiliary output voltage at light load
  - Primary clamp voltage has high impact on result
- Most existing transformer models fail to predict this
- This effect can be mitigated (but not eliminated)
  - Minimize leakage inductance *between secondary* windings
  - Locate the highest power secondary(ies) closest to the primary
- Other solutions include a post-regulator, series resistor or minimum load

Cross-Regulation Example
Auxiliary Output Lightly Loaded

- W2 (high current output) heavily loaded, W4 lightly loaded
  - W4's output received too much energy during Phase 1 due to ringing
  - W2's output did not receive enough energy
- At end of commutation (Phase 1):
  - Σ{reflected secondary currents} ⇔ magnetizing current
- V4 went too high
  - Phase 2: high dϕ/dt (decreasing) in W4
    - $I_{W4} \Rightarrow$ 0 A rapidly
  - I_{W2} increases to maintain ϕ_m in the gap
- After I_{W4} crosses 0 A, W2's and W3's di/dt change to maintain the downslope of the magnetizing current and flux

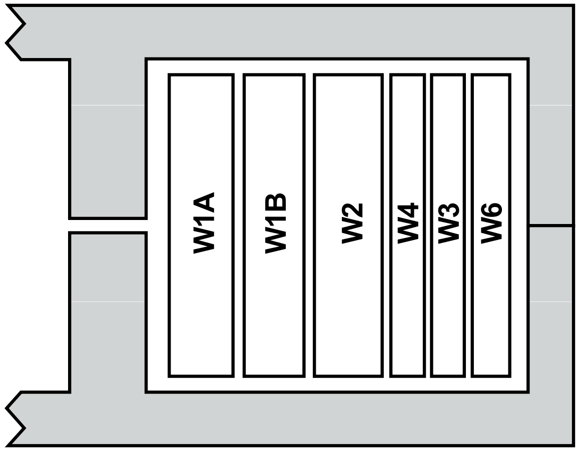
$$H \times \delta = \frac{\phi_m}{A \times \mu} \times \delta = \sum N \times I$$

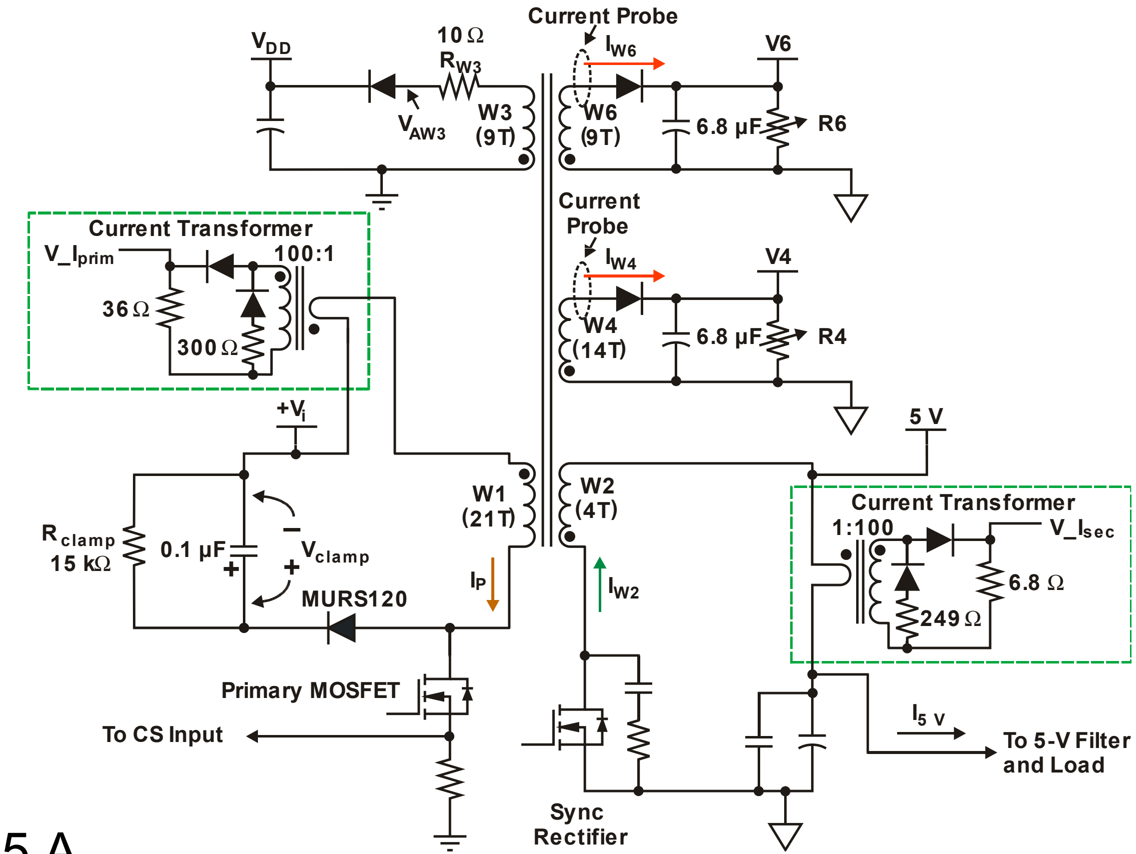




Phase 2: No Primary Current

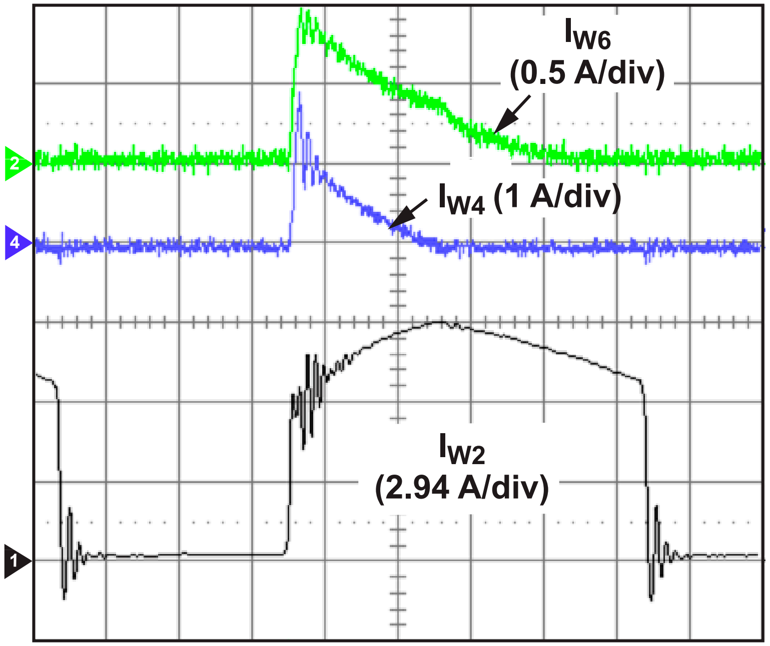
Test Results



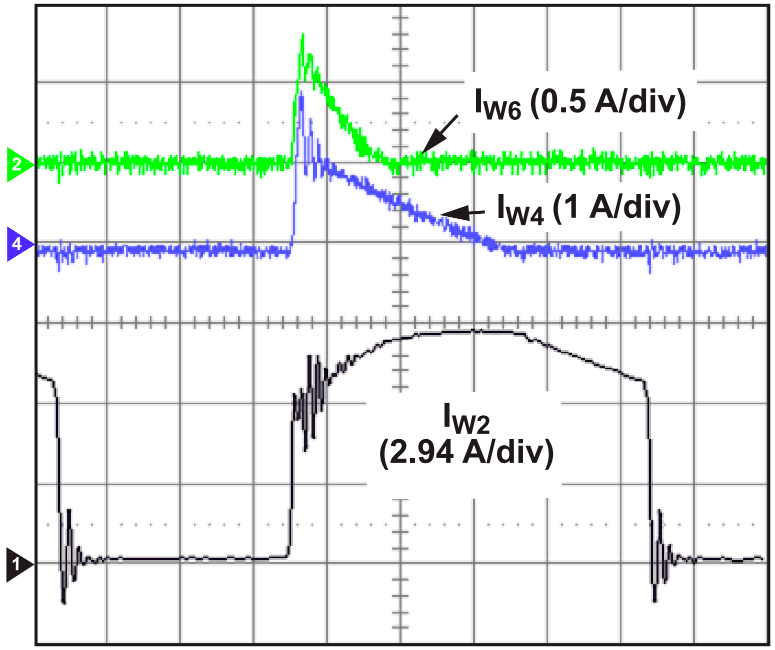


- Input voltage: 48 V
- 5-V output load: 0 A to 5 A
- Auxiliary outputs:
  V6 (10 V at 0 to 140 mA) and
  V4 (18 V at 0 to 200 mA)
- Switching frequency: 250 kHz
- Primary magnetizing inductance: 70 µH

Cross-Regulation Test Results with Main Output Fully Loaded



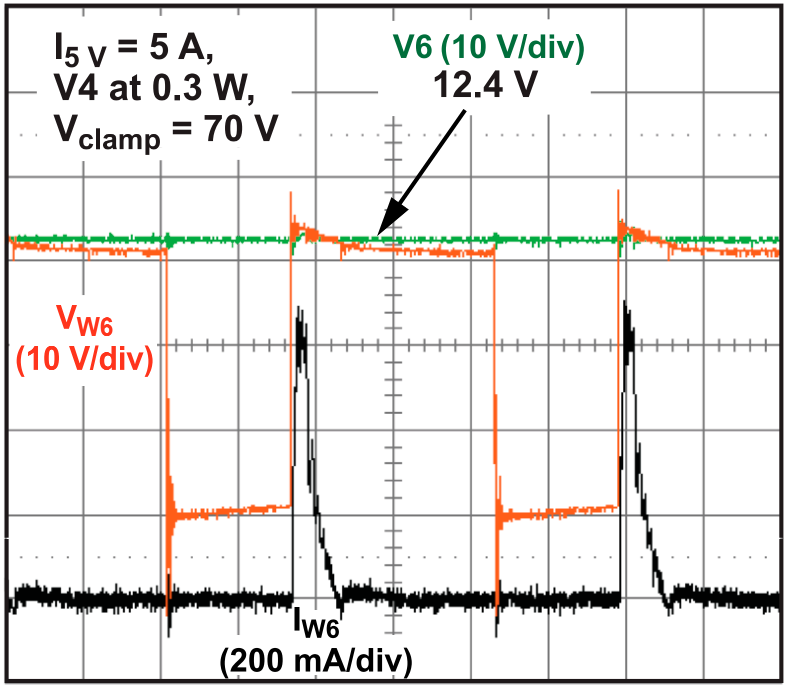
V6 at 1.6 W, V4 at 2.5 W,
$I_{5\ V}$ = 5 A



V6 at 0.5 W, V4 at 3.6 W,
$I_{5\ V}$ = 5 A

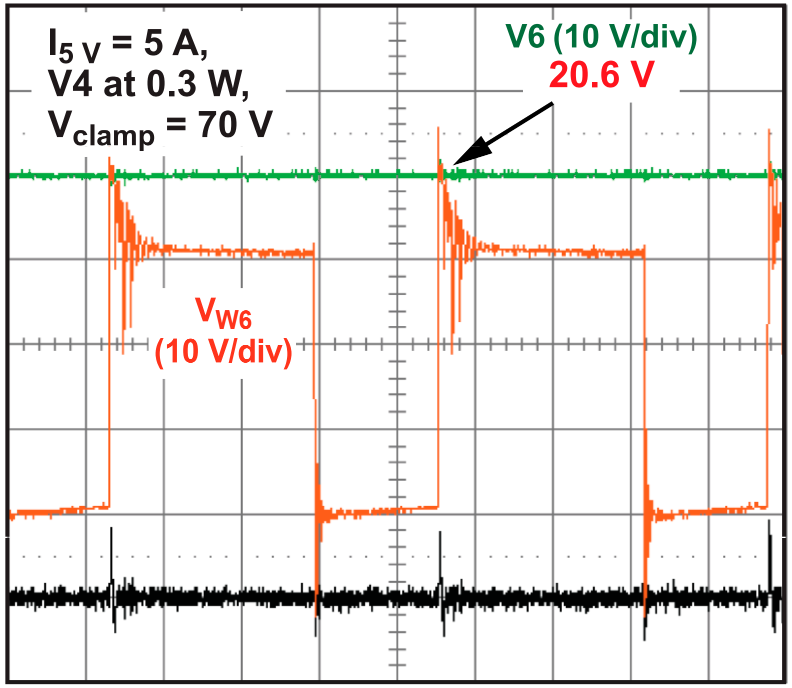
- The two auxiliary outputs operate in DCM
- Notice the change of slope of I_{W2} when I_{W4} or I_{W6} crosses 0 A

Cross-Regulation Test Results: Lightly Loaded Auxiliary with Main Output Fully Loaded



Time (1 µs/div)

V6 at 0.5 W

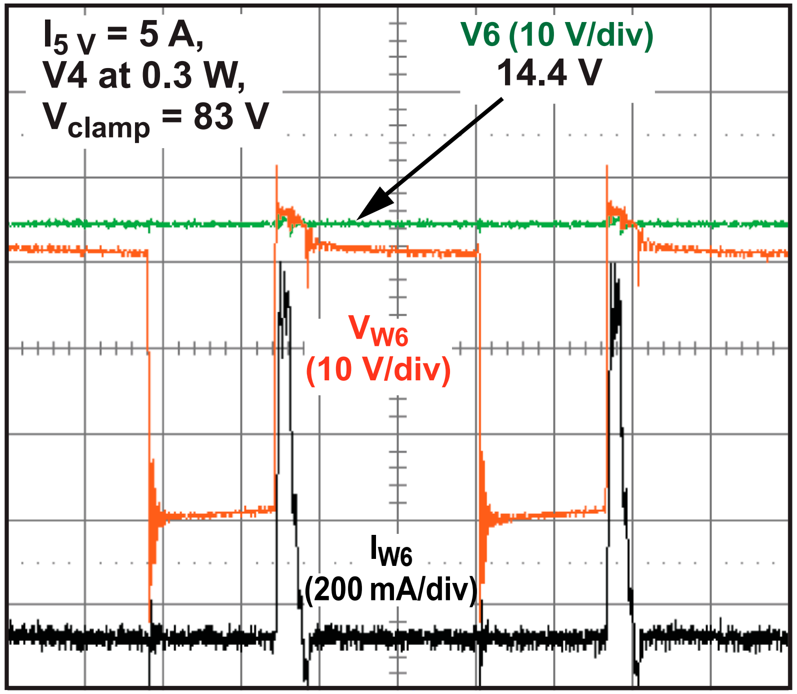


Time (1 µs/div)

V6 at < 5 mW

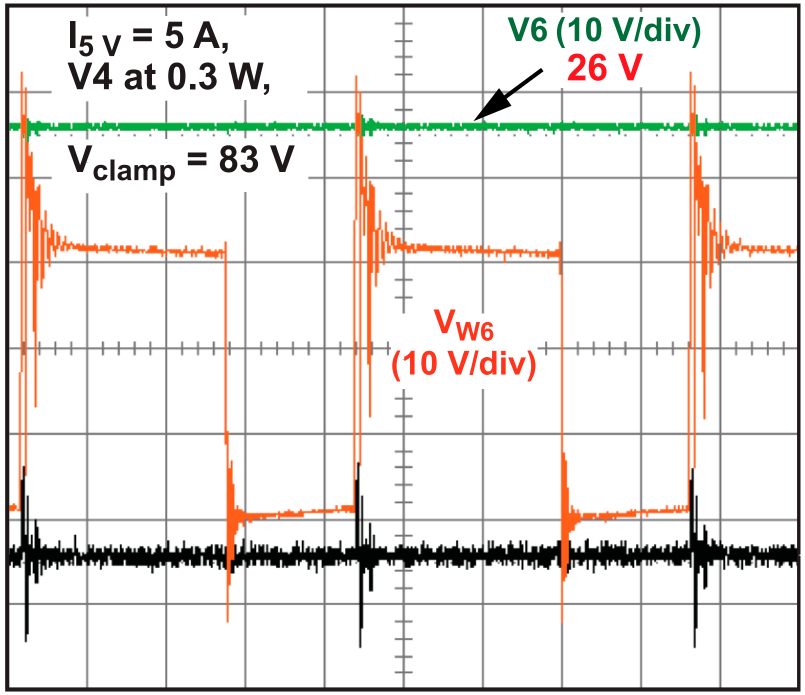
- At minimum load, V6 (10 V nominal) goes up to 20.6 V

Cross-Regulation Test Results with Main Output Fully Loaded : Impact of Clamp Voltage



Time (1 µs/div)

V6 at 0.5 W



Time (1 µs/div)

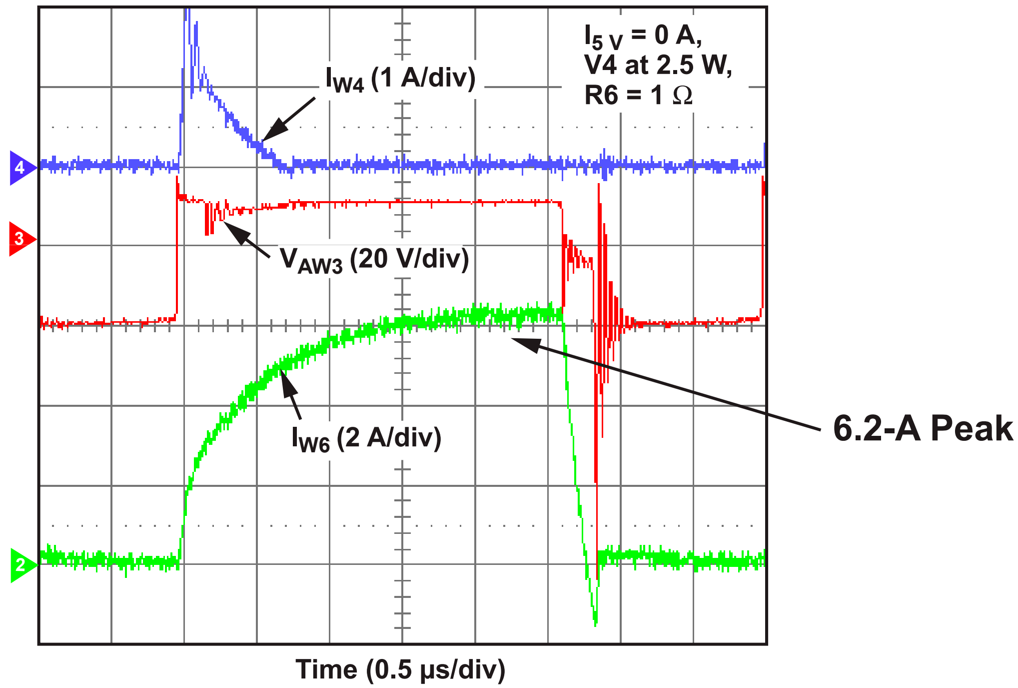
<u>V6 at < 5 mW</u>

- RCD resistor has been increased for higher V_{clamp}: 70 V ⇒ 83 V

⇒V6 increased significantly in both cases

Overload Test at Auxiliary Output: Impact of Leakage

- There was no hiccup mode even at more than 3 A!
- The overloaded winding is unable to take all the energy because of leakage, W3 having in fact a better coupling to primary than W6
  – Enough energy delivered by W3 to V_{DD} to maintain switching

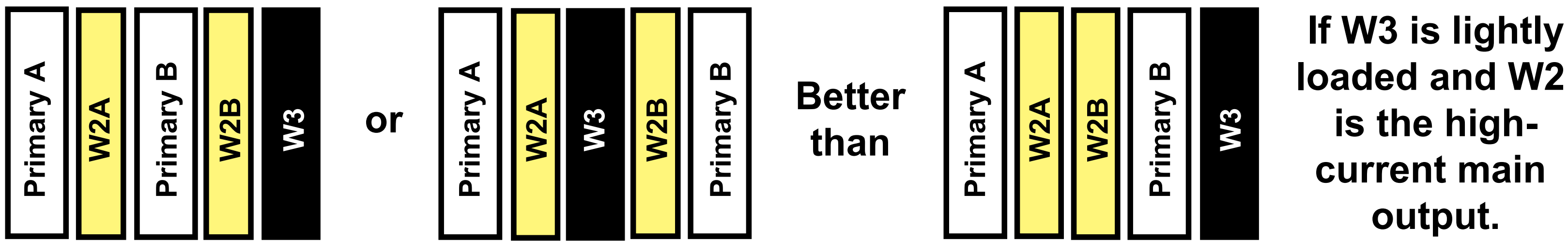


Benefits of Good Cross-Regulation

- Good control of auxiliary outputs in spite of load variations
- Better control of gate drive voltage amplitude, less gate drive losses
- Lower rms current in output capacitors, lower dissipation
- May allow the controller to reach hiccup mode more easily when the main output is short-circuited for better protection
  - Not necessarily true if the short-circuit is applied to an **auxiliary** output!

How Cross-Regulation can be Improved

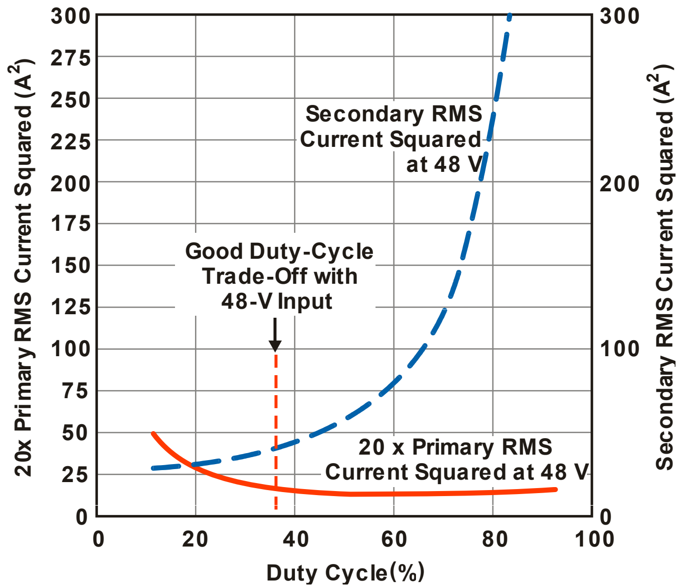
- The high current winding must have the best coupling to primary
- Minimize leakage between all secondary windings
- Optimize, not minimize, the leakage inductance of auxiliary windings to *primary*
- Use winding placement to control leakage inductance
  - Winding stackup
  - Spread each winding over the full width of the bobbin for better coupling



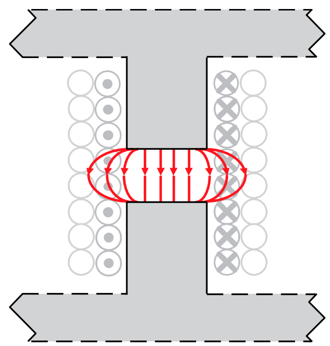
- Operate main output in CCM
- Try to avoid operating the auxiliary outputs in DCM. In some cases, consider using resistance in series with the diode
- Consider winding more than one auxiliary secondary simultaneously (multifilar)
- Lower clamp voltage may help
  - Trade-off between cross regulation, efficiency, peak drain voltage and current limit
  - Some other types of clamp circuits may provide better results than the RCD clamp

Impact of Transformer Design on Flyback Efficiency

- The following guidelines can be used during transformer design to optimize the converter efficiency
  - Minimize leakage inductance from primary to main (high-current) secondary
  - Minimize transformer high frequency conduction loss
    - Multifilar or Litz wires when necessary
    - Interleaving
    - Select core shape for minimum number of layers
  - Optimize the transformer turns ratio for best efficiency
  - Select CCM operation

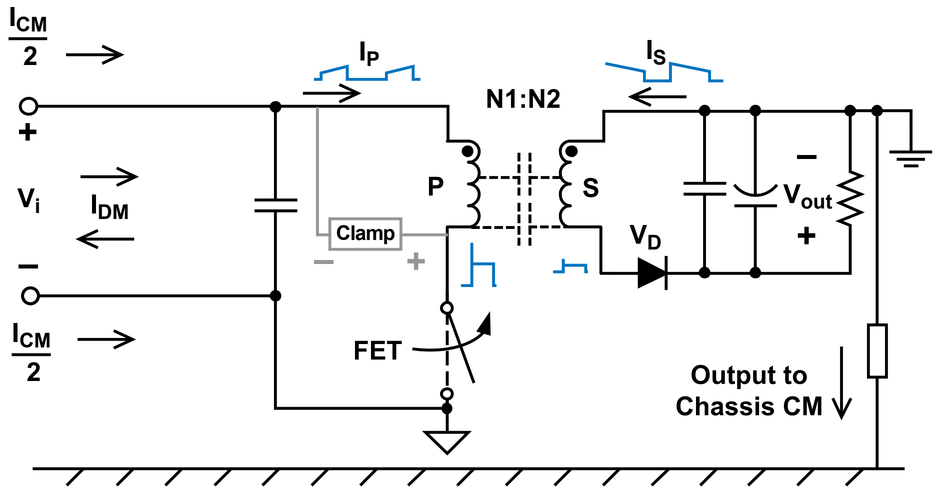


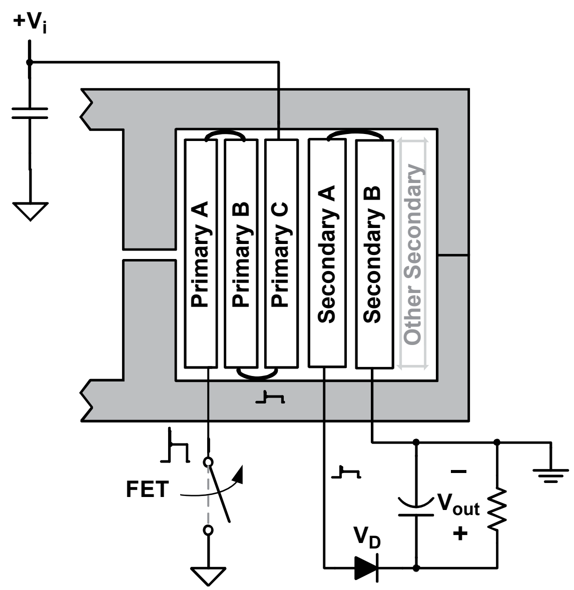
- Other factors also have an indirect impact on efficiency
  - Cross-regulation
    - V_{DD} rail used for gate drive
    - Output capacitors rms current
  - Impact of fringing flux from gap
    - Worse with planar transformers



Flyback and EMI

- Flyback ⇒ I_P and I_S pulsate
  - Use low Z caps, minimize loop areas
  - Output filter often required
- Interwinding capacitance ⇒ CM CE
- Transformer and diode configuration impact effective capacitance
  - Less if facing windings at same AC potential
  - Diode versus synchronous rectifier
  - Flyback ≠ Forward
- Better to start with end connected to primary MOSFET
  - Shields V_{drain} E-field
  - Reduces interwinding capacity effect on CE
- Minimize leakage for low H-field RE
- Interleaving reduces H-field RE but *may* increase effective P-S interwinding capacitance
- Center-gap transformer





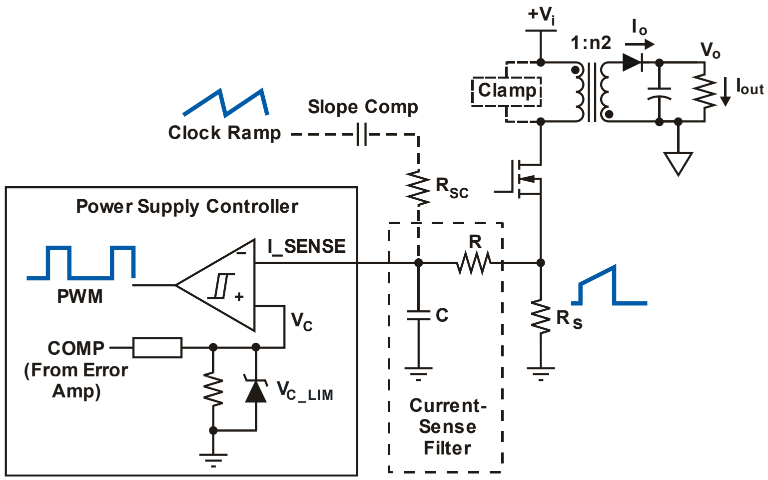
Agenda

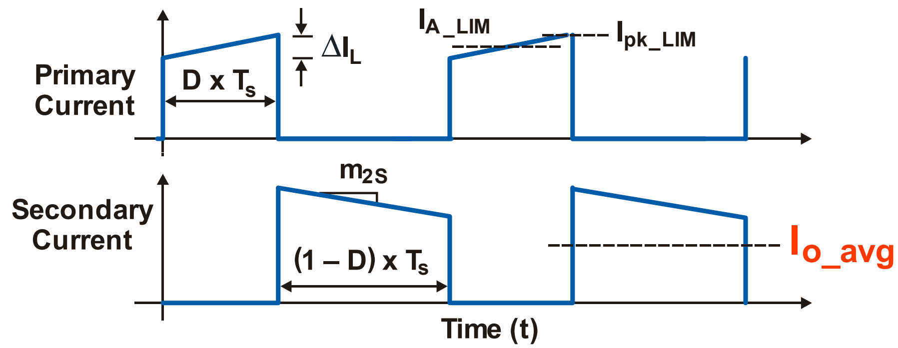
1. Basics of Flyback Topology
2. Impact of Transformer Design on Power Supply Performance
3. **Power Supply Current Limiting**
4. Summary

Power Supply Current Limiting – Overview

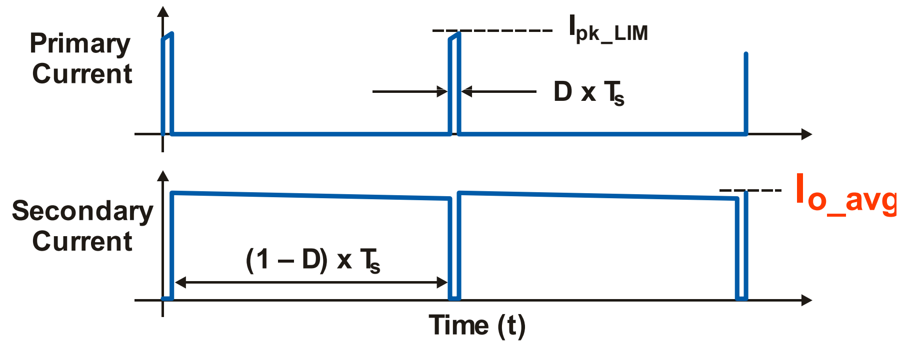
- Current-limiting characteristic of power supply defines:
  - Output power beyond which output voltage falls out of regulation. Corresponds to the "output load-current limit" (I_{out_LIM})
  - Output current in overload situations
    - including short-circuits
- Current-limiting characteristic is influenced by parasitics
  - Turn-off delays, leakage inductance,…

Understanding Current Limit – Flyback Power Supply with Peak CMC in CCM





Just at Current Limit, Output Begins to Fall Out of Regulation



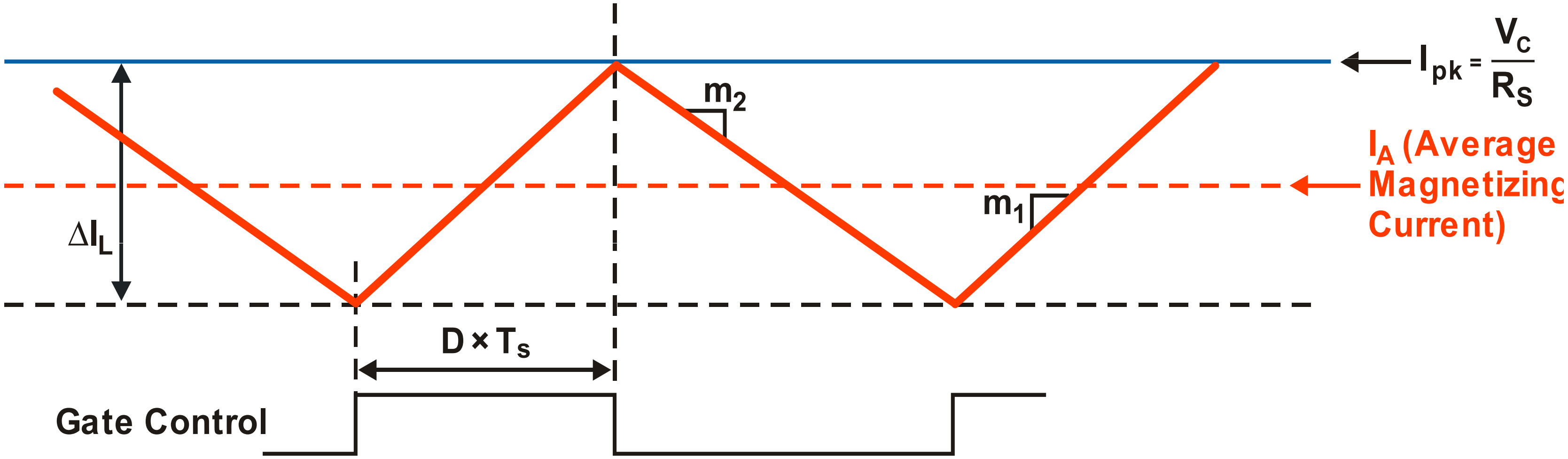
Output Short Circuit

- I_{pk_LIM} is the primary peak current limit
- I_{o_avg} is the output current
- If short-circuit, I_{o_avg} can be much higher than when current limit has just been reached

$$I_{out} = I_{o\_avg} = \frac{I_A}{n_2} \times (1 - D)$$

Current-Limit Model – Basic Representation

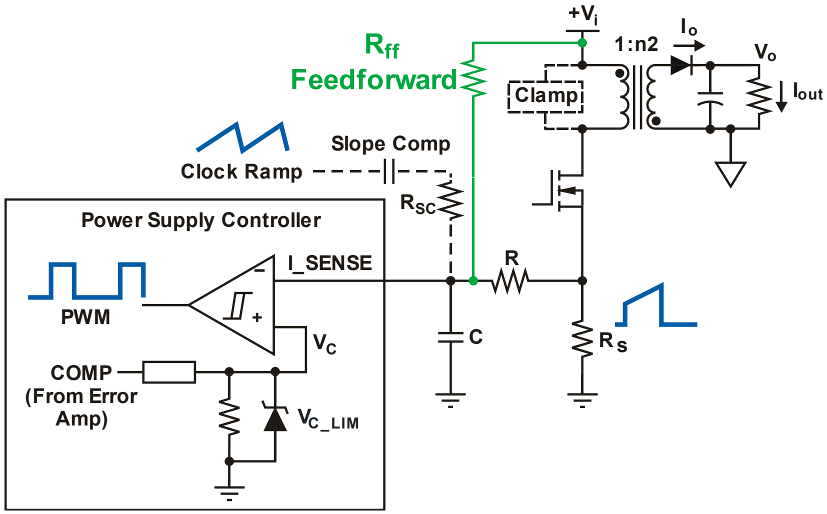
- Peak CMC in CCM, fixed switching frequency

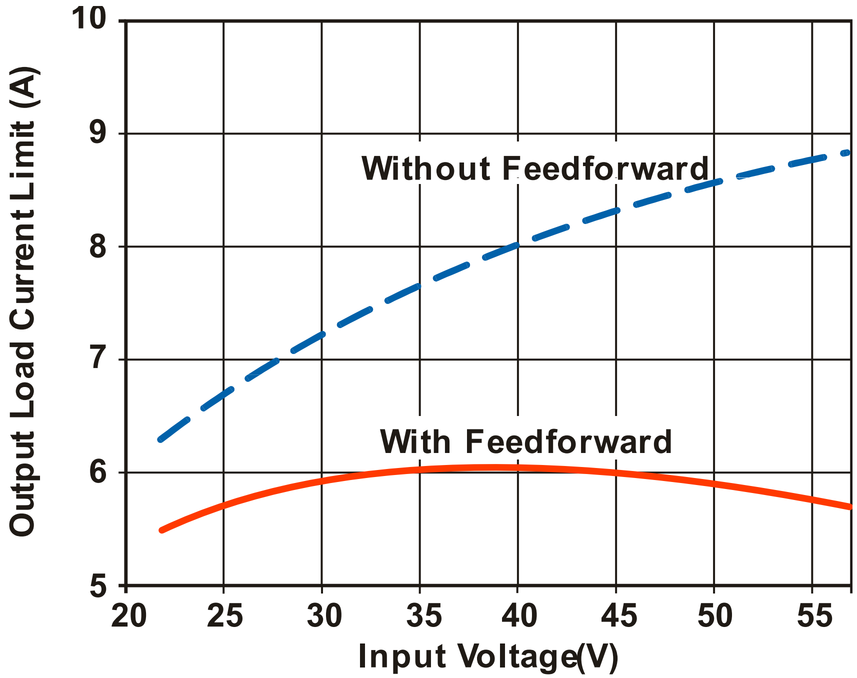


Neglecting DC voltage drops:

$$m_2 = \frac{\Delta I_L}{(1-D)\times T_S} \approx \frac{V_o}{n_2 \times L} \qquad D = \frac{V_o}{n_2 \times V_i + V_o}$$

Influence of Input DC Voltage on Output Load Current Limit – Impact of Feedforward

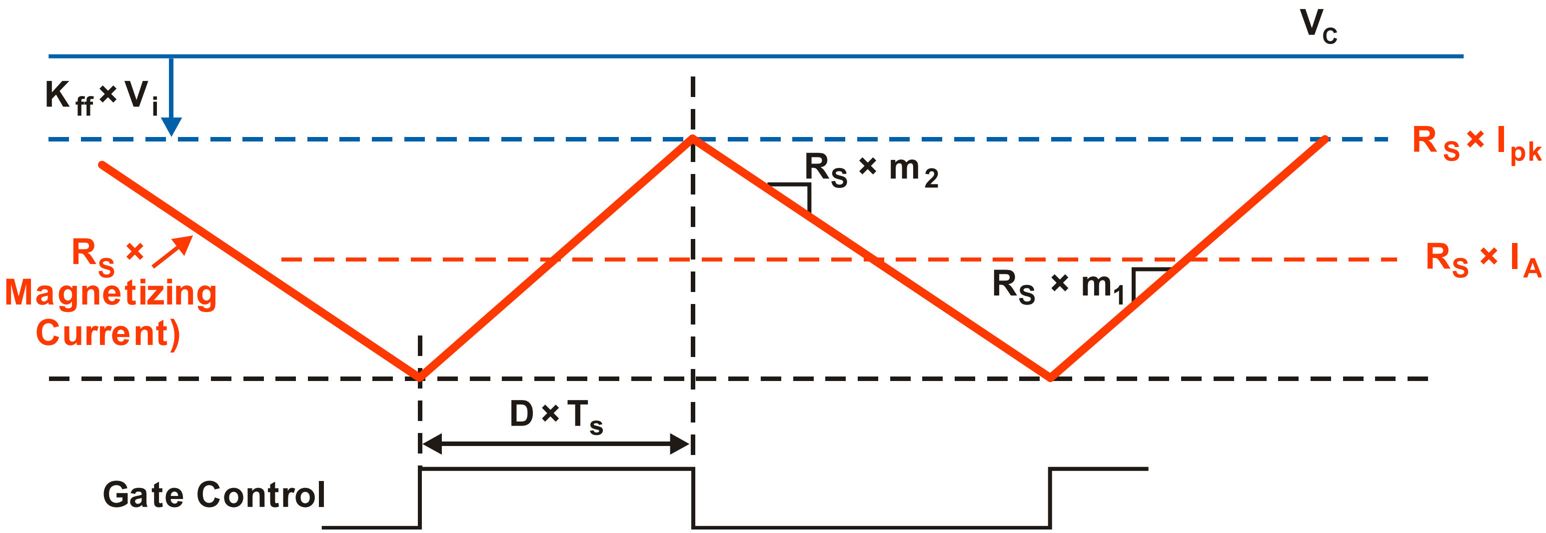




If $V_i \uparrow \Rightarrow (1 - D) \uparrow \Rightarrow I_{out\_LIM}$ increases

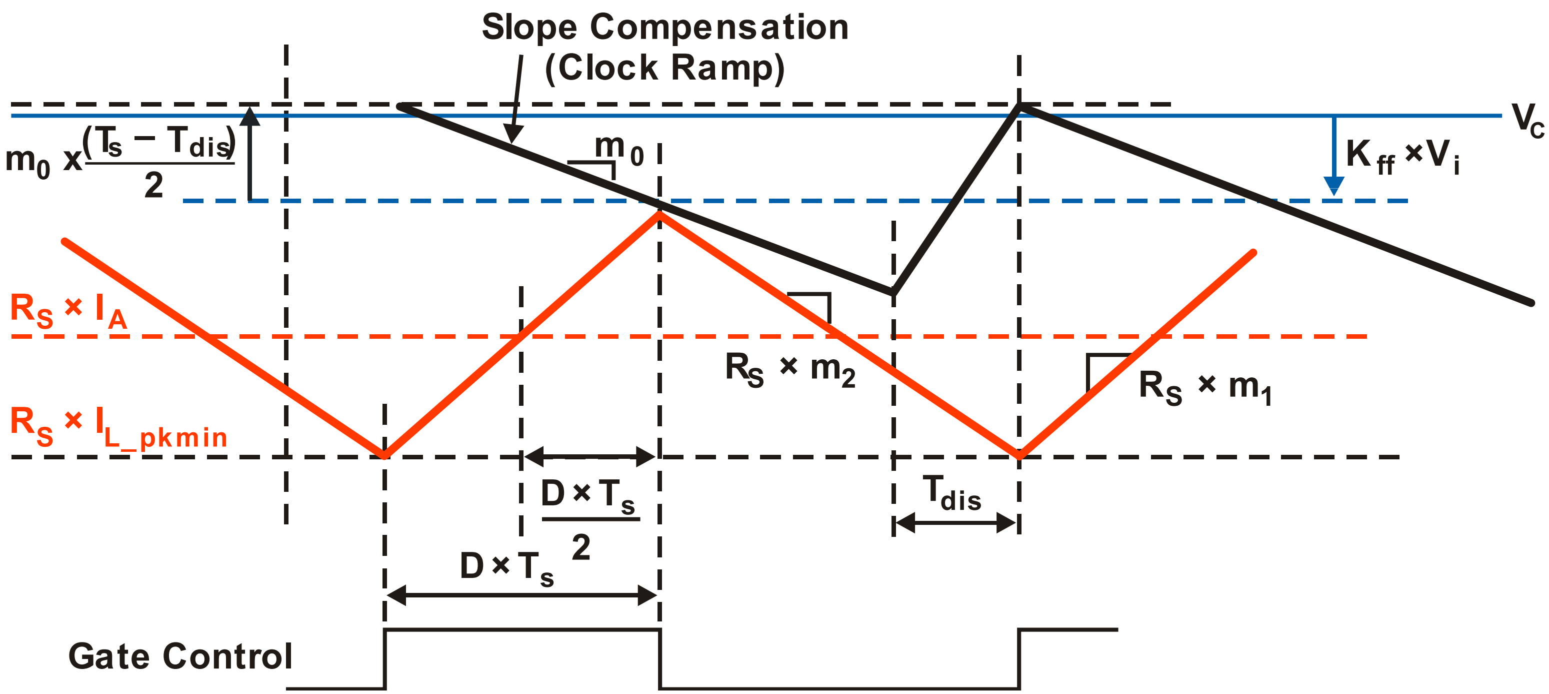
- With feedforward, output load current limit becomes almost independent of input voltage
  - ⇒ Better control during overload, less stress on power circuitry
  - ⇒ Power limit
  - ⇒ Cost and/or size reduction
- Feedforward also improves line noise rejection

Current Limit Model – With Feedforward



- K_{ff} x V_i is the feedforward contribution
  – Subtracting it from V_c is identical to adding it to current feedback

Current Limit Model – Adding Slope Compensation



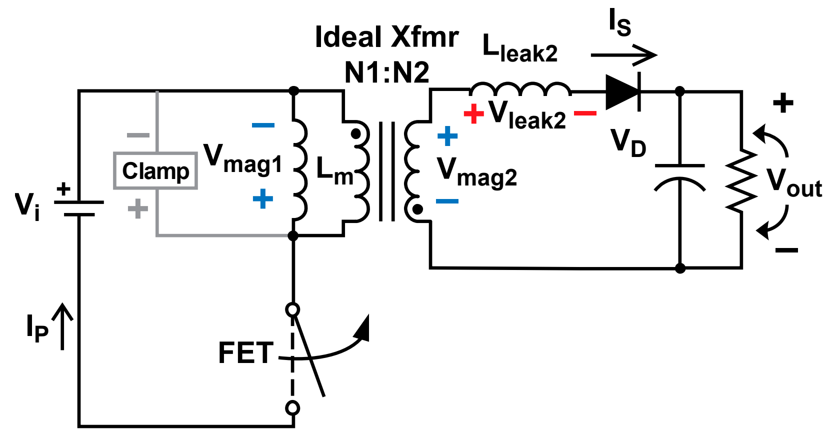
- Slope compensation to avoid subharmonic oscillation at duty-cycle close to or higher than 50%
- For easier understanding, slope compensation contribution subtracted from V_C.
  - Equivalent to slope compensation added to current feedback
  - In that circuit representation, the slope compensation is capacitively-coupled

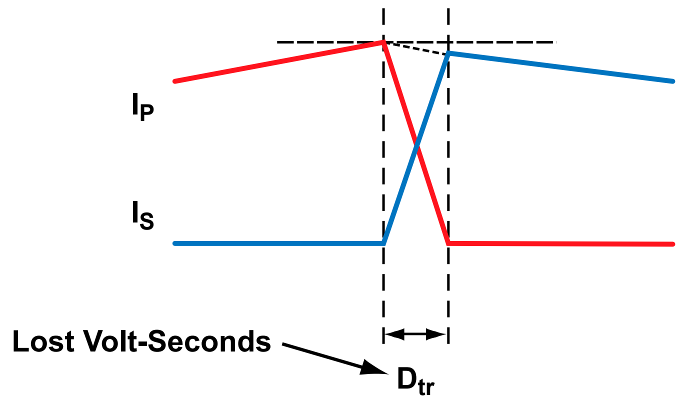
Current Limit Model – With all Delays, Slope Compensation and Feedforward

- For a more accurate, parasitics must be included in the analysis
- Parasitic delays
  - RC filter time delay
  - Turn off delay, including current comparator and gate drive
  - FET turn-on delay from onset of slope compensation ramp
- See Topic 1, Appendix A, in the Seminar Manual for detailed equations

Influence of Transformer Leakage on Output Load Current Limit

- Rate of rise of current is influenced by leakage, commutation primary-to-secondary is not instantaneous
  - ⇒ Loss of volt-seconds (also influenced by the clamp voltage)
  - ⇒ Duty-cycle and average magnetizing current have to increase to maintain the output voltage
  - ⇒ Higher conduction loss
  - ⇒ Higher transformer peak current than expected
    - -> I_{out_LIM} lower than expected
- Leakage inductance helps however to keep control of the output current in output short-circuit situation

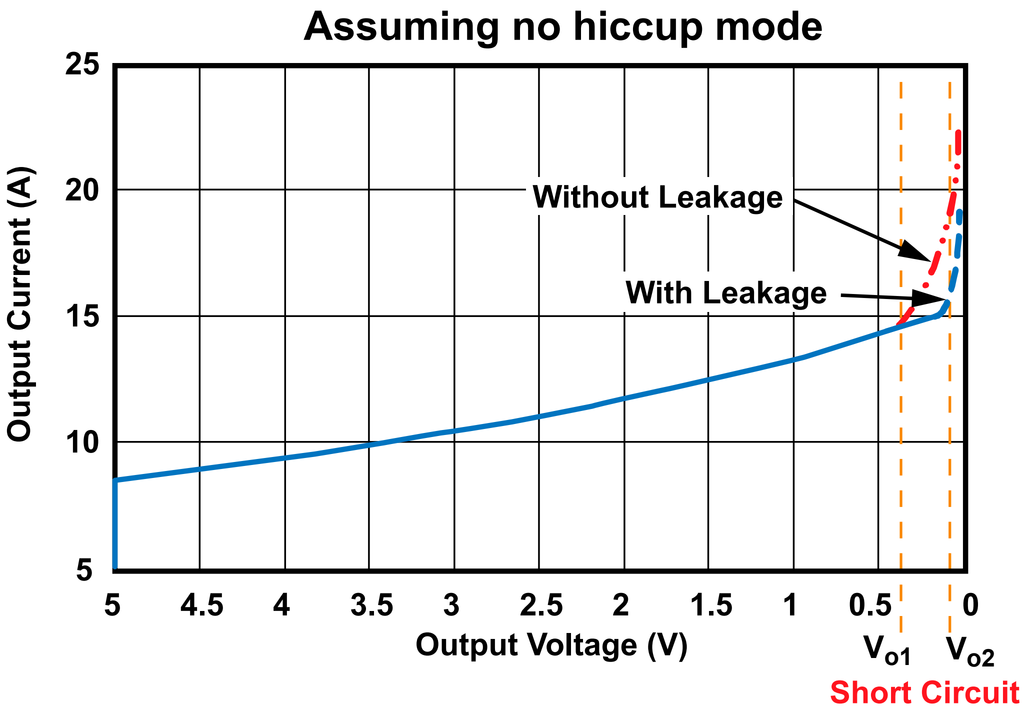




$$V_i \times D_{new} \approx V_{clamp} \times D_{tr} + \frac{V_o}{n_2} \times (1 - D_{new} - D_{tr})$$

Current Limit During Overload – Example with Combined Effects

- In overload: Output current increases ⇒ output voltage decreases
  - Short-circuit: output current much higher than at onset of current limit
- Parasitic turn off delays may result in an out of control current if volt-seconds balance is not possible at the transformer
  - Transformer's leakage inductance helps to maintain that balance
  - If no leakage, the imbalance occurs starting at V_{o1}
  - With leakage, the imbalance occurs only from V_{o2}



$$\frac{V_{o\_short}}{n_2} \times \left(T_S - t_{del\_OFF} - D_{tr} \times T_S\right) =$$

$$V_i \times t_{del\_OFF} - V_{clamp} \times D_{tr} \times T_S$$

Summary

- The flyback power transformer is the key element of the converter, for optimum efficiency and cross-regulation
- Parasitics have a strong influence on flyback converter's behavior, particularly under overload or short-circuit conditions
- The primary clamp circuit design is a trade-off between:
  - Efficiency
  - Peak drain voltage
  - Output current limit
  - Cross-regulation
- Simple feedforward technique can be used to optimize the converter and the system, lowering worst-case components stress and reducing the overall cost and size

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI E2E™ Community Home Page
e2e.ti.com

Product Information Centers

Americas Phone +1(972) 644-5580

Brazil Phone 0800-891-2616

Mexico Phone 0800-670-7544

Fax +1(972) 927-6377
Internet/Email support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone
European Free Call 00800-ASK-TEXAS (00800 275 83927)
International +49 (0) 8161 80 2121
Russian Support +7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax +(49) (0) 8161 80 2045
Internet support.ti.com/sc/pic/euro.htm
Direct Email asktexas@ti.com

Japan

Phone Domestic 0120-92-3326
Fax International +81-3-3344-5317
Domestic 0120-81-0036
Internet/Email International support.ti.com/sc/pic/japan.htm
Domestic www.tij.co.jp/pic

Asia

Phone
International +91-80-41381665
Domestic Toll-Free Number

Note: Toll-free numbers do not support mobile and IP phones.

Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	1-800-425-7888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

Fax +8621-23073686
Email tiasia@ti.com or ti-china@ti.com
Internet support.ti.com/sc/pic/asia.htm

A122010

TEXAS INSTRUMENTS