

## **Power Supply Design Seminar**

Topic 1 Presentation:

# **Under the Hood of Flyback SMPS Designs**

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## Topic 1

# Under the Hood of Flyback SMPS Designs

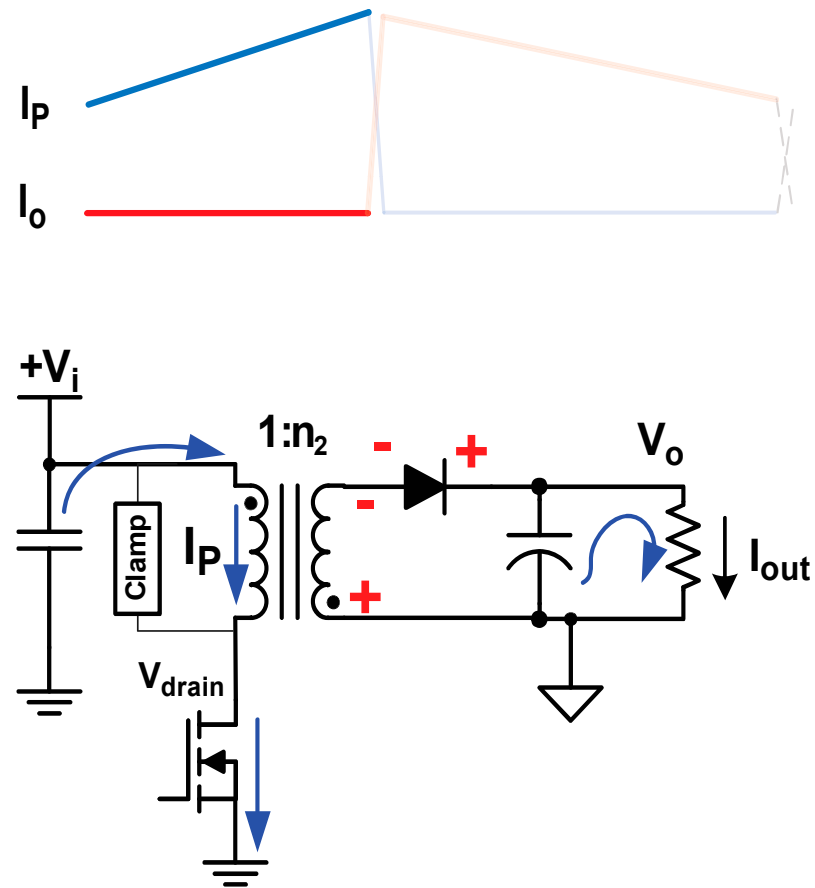
Jean Picard

# Agenda

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

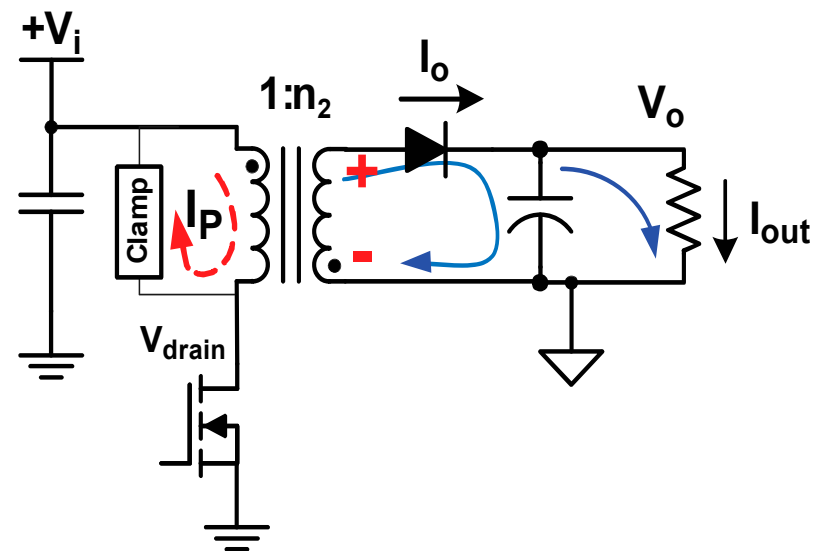
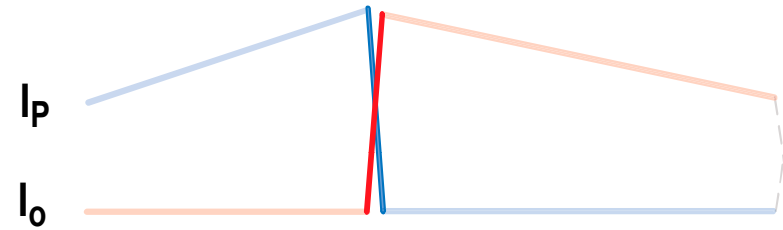
# Transfer of Energy

- FET turns ON
  - Voltage across primary magnetizing inductance  $\cong V_i$ 
    - 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, all the stored energy is transferred
- Pulsating input and output current



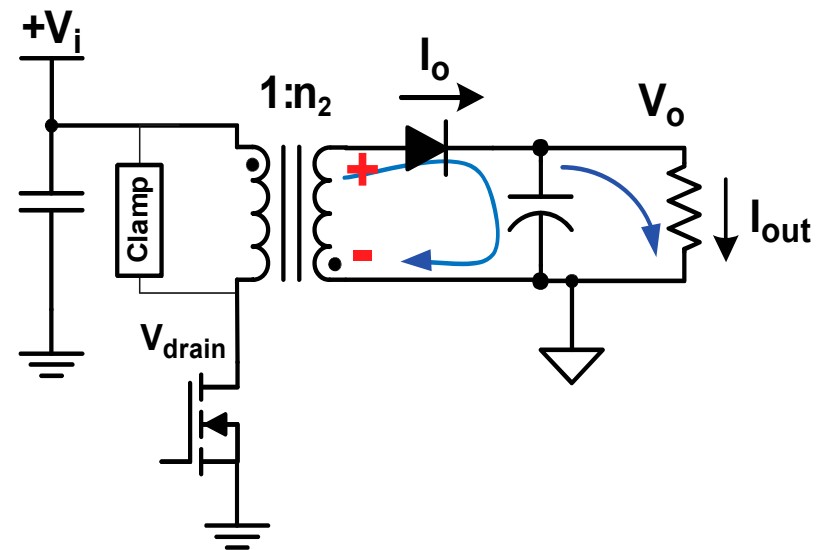
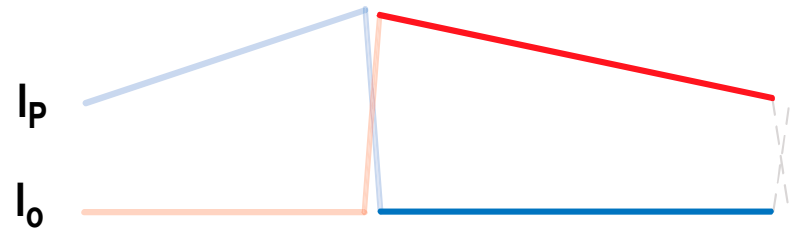
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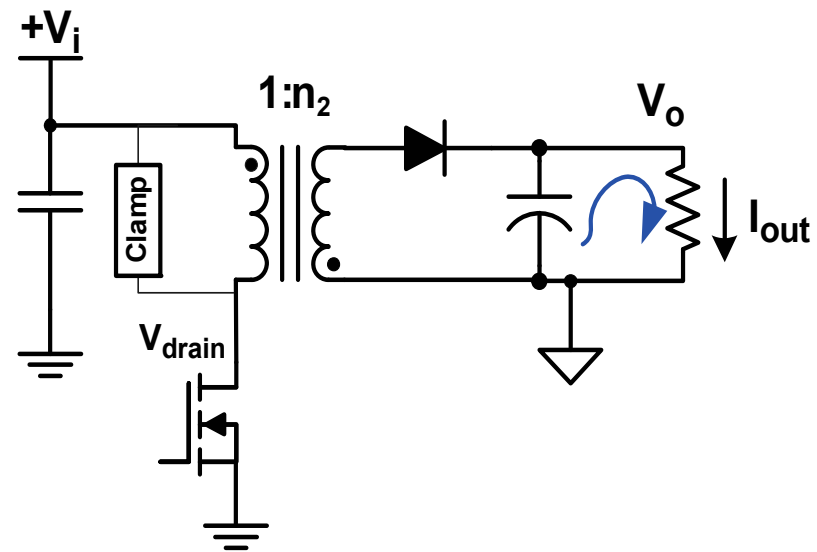
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# Transfer of Energy

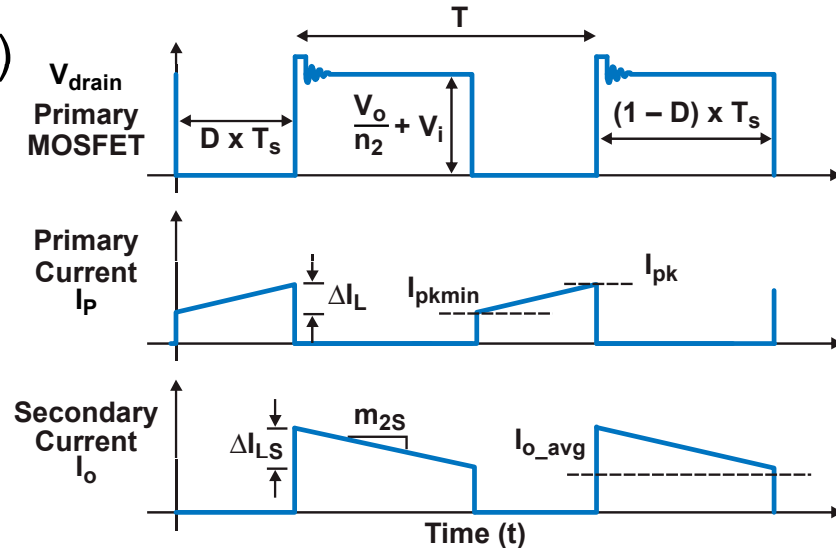
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# CCM versus DCM

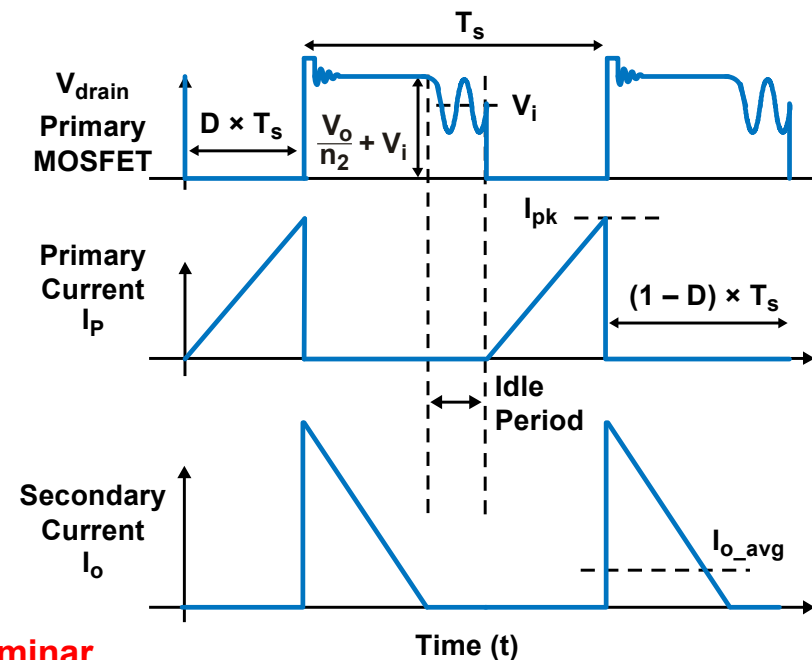
- Continuous conduction mode (CCM)

- 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

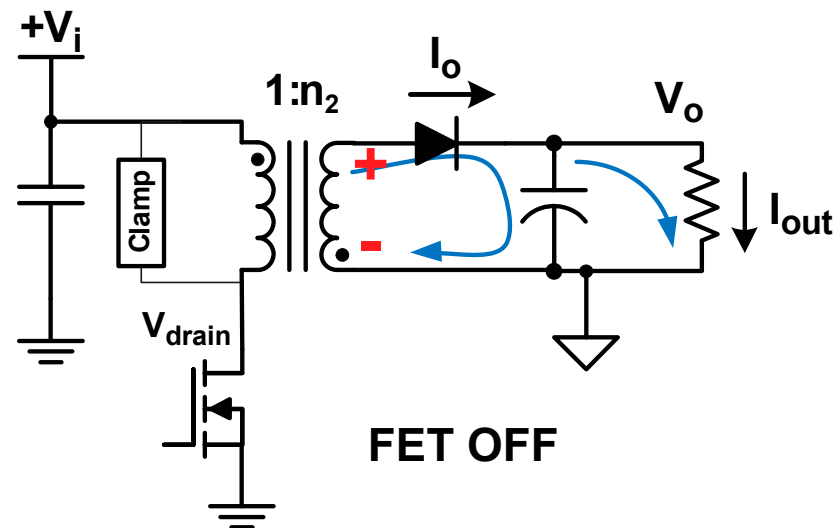
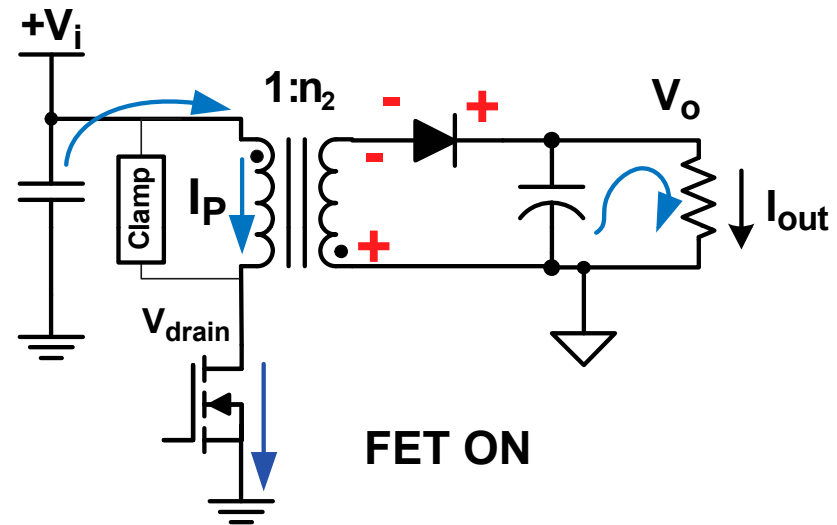
- Energy is delivered during  $1 - D$ 
  - Effect of control action during ON time is delayed until next switch turn OFF
- Initial reaction is in opposite direction of desired correction

⇒ RHP Zero

- Phase decreases with increasing gain

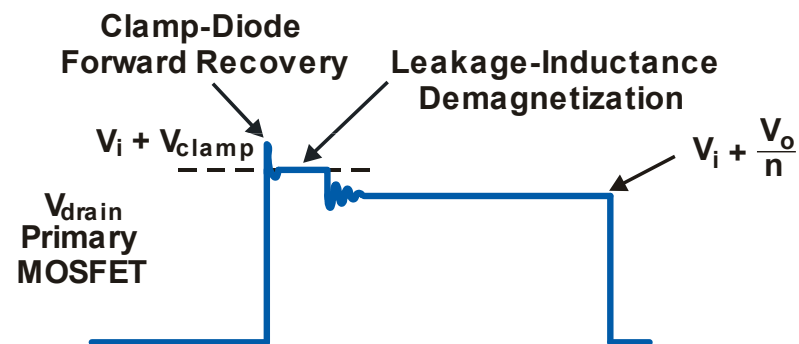
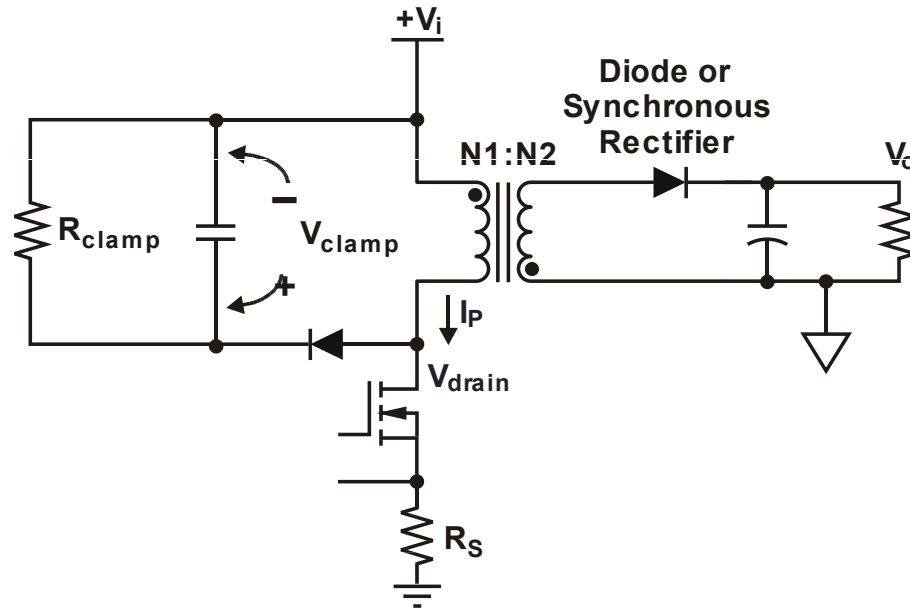
$$f_{\text{RPHZ}} = \frac{(1-D)^2 \times V_o}{2\pi L \times D \times I_{\text{out}} \times n_2^2}$$

$D \leftrightarrow$  Main switch duty-cycle



# RCD Clamp Circuit

- During commutation primary-to-secondary, the leakage energy is absorbed by the clamp circuit
  - $R_{\text{clamp}}$  dissipates the leakage energy and some magnetizing energy
  - The clamp capacitor ensures a low voltage ripple
  - Use short connection with minimum loop area
- $V_{\text{clamp}}$  is maximum at full load and minimum input voltage
  - $R_{\text{clamp}}$  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

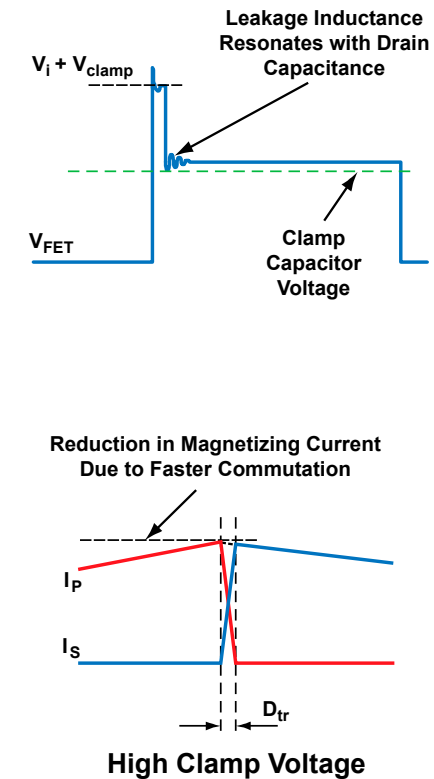
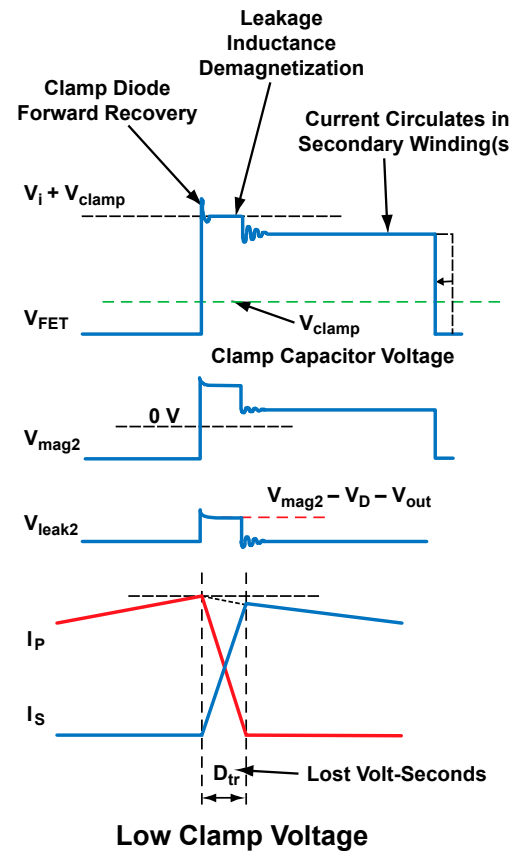
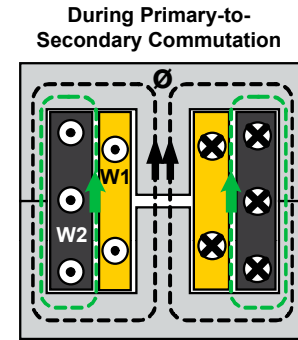
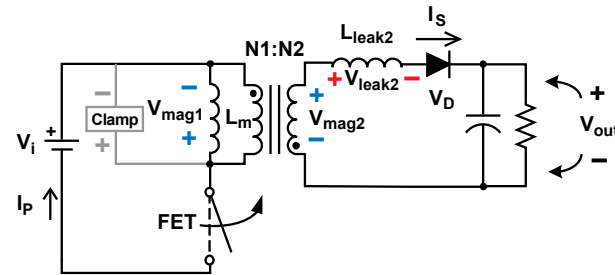
**2. Impact of Transformer Design on Power Supply Performance**

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

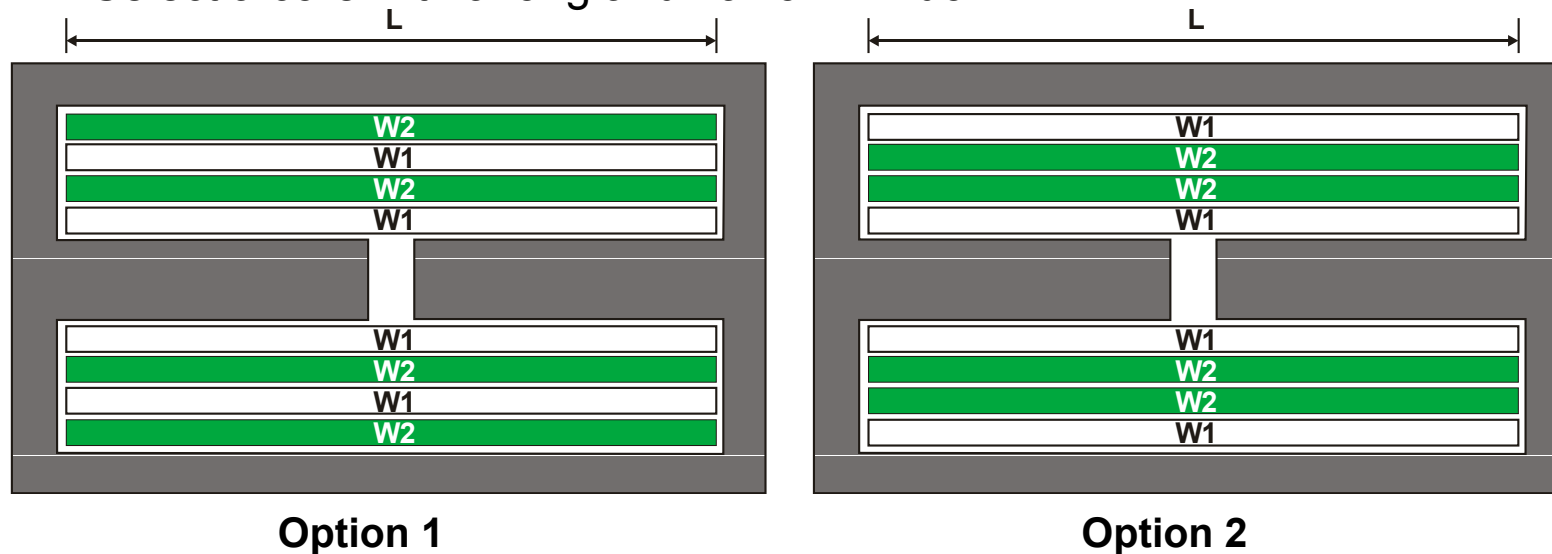


# Effects of Leakage Inductance

- 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



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

# Cross-Regulation – Overview

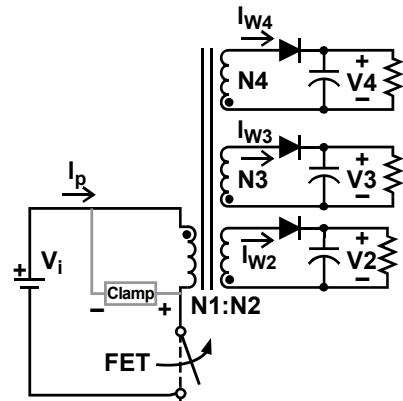
- Multiple-output flyback topology is popular because of its simplicity and low cost
- If the coupling is perfect, the turns ratio directly defines output voltages
- In the real world, “perfect” coupling is not possible
- This often results in poor cross-regulation

# Cross-Regulation Physical Model

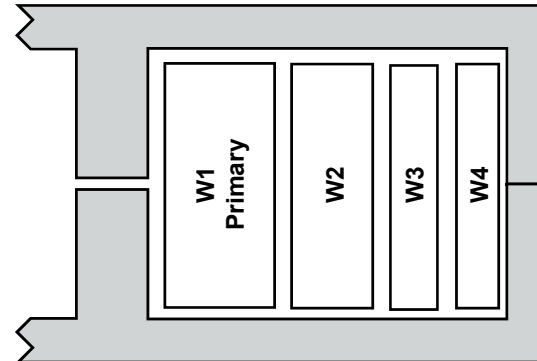
- Transformer windings cannot all be equally well coupled to the gap because of physical separation between them
- Magnetic energy stored between the windings represented as leakage inductances
- Model not applicable to any transformer geometry
- Can become complex if interleaving is used, or if multiple 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



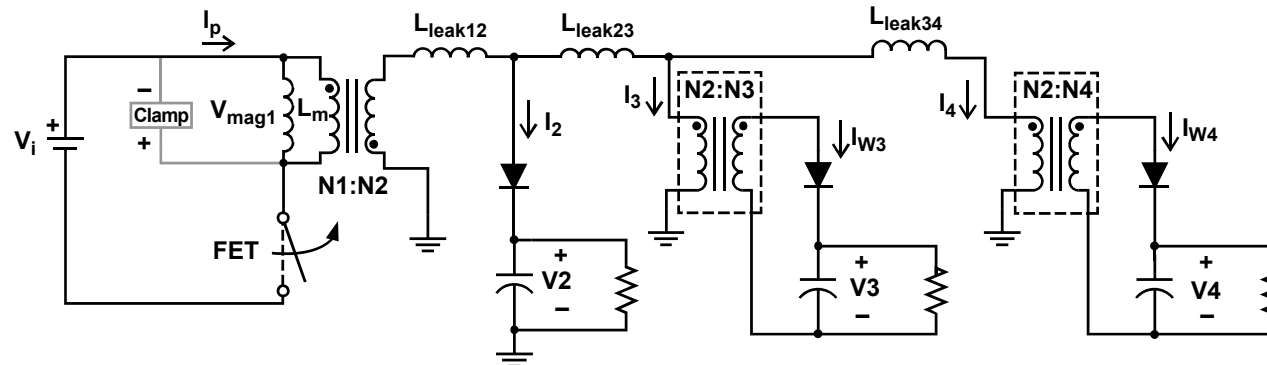
# Cross-Regulation Physical Model



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"

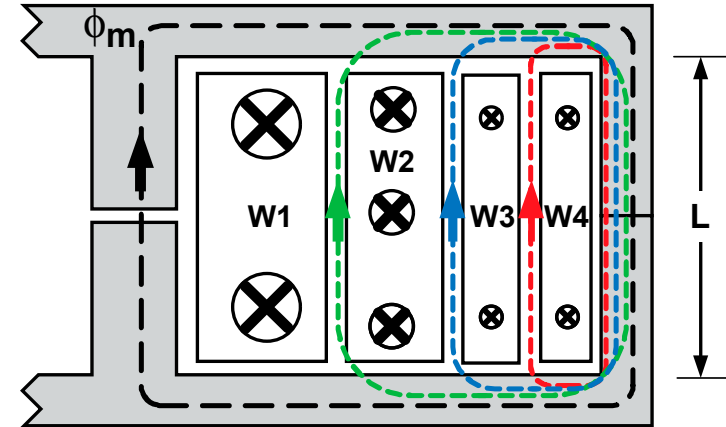
# Flux Lines during Commutation

## Each Secondary Winding with Nominal Load

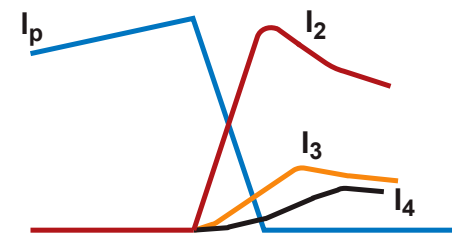
- $\phi_m$  decreases during commutation
- $d\phi/dt$  (decreasing) in each secondary winding is limited by its output voltage
  - Increasing current induced in W2 to W4 to maintain  $\phi_m$  in the gap

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

- Leakage between W2 and W1
  - W1's voltage limited by clamp
- W1 closest to gap
  - $V_{\text{clamp}}$  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

# Ringling Effect

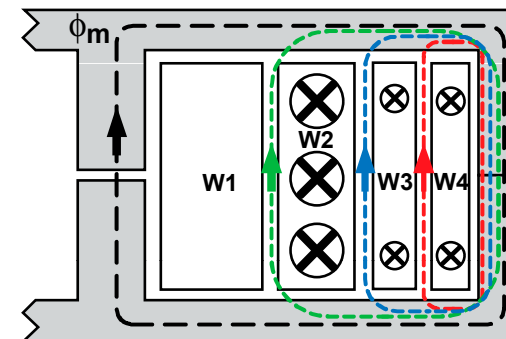
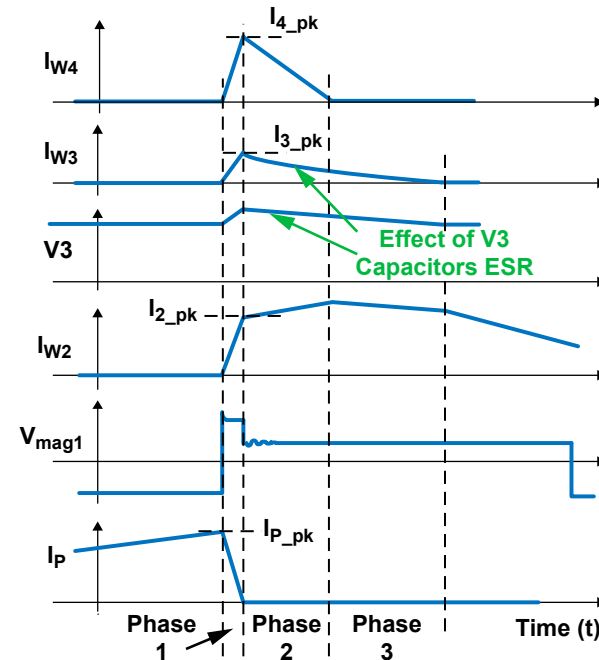
- High  $dV/dt$  when main switch turns off if main output is heavily loaded
- Transformer leakage inductance and parasitic capacity  $\Rightarrow$  auxiliary secondary voltage tends to “ring”
- If auxiliary output fully loaded  $\Rightarrow$  this ringing is clamped
- If lightly loaded  $\Rightarrow$  voltage overshoot with peak detector effect
- Much higher (sometimes  $> 2 \times$  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

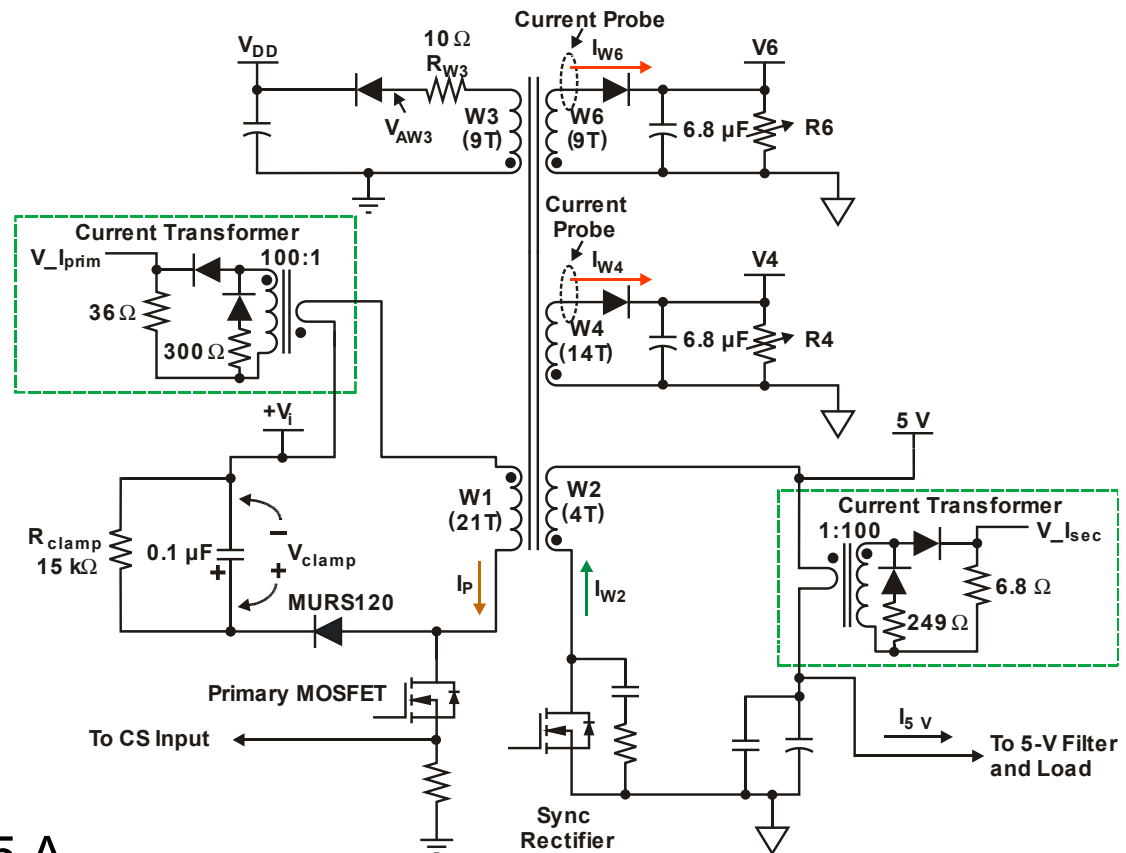
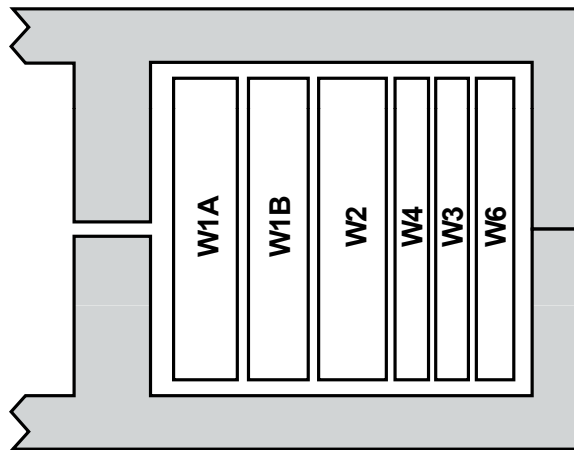
- W2 (high current output) heavily loaded, W4 lightly loaded
  - W4's output received too much energy during Phase 1 due to ringing
  - W2's output did not receive enough energy
- At end of commutation (Phase 1):
  - $\Sigma\{\text{reflected secondary currents}\} \Leftrightarrow$  magnetizing current
- V4 went too high
  - Phase 2: high  $d\phi/dt$  (decreasing) in W4
    - $I_{W4} \Rightarrow 0$  A rapidly
  - $I_{W2}$  increases to maintain  $\phi_m$  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

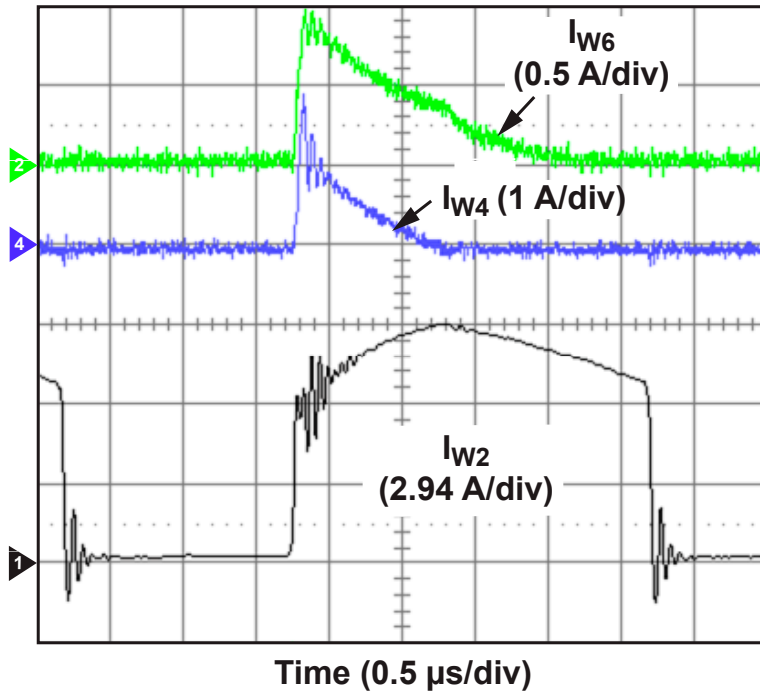
# Test Results



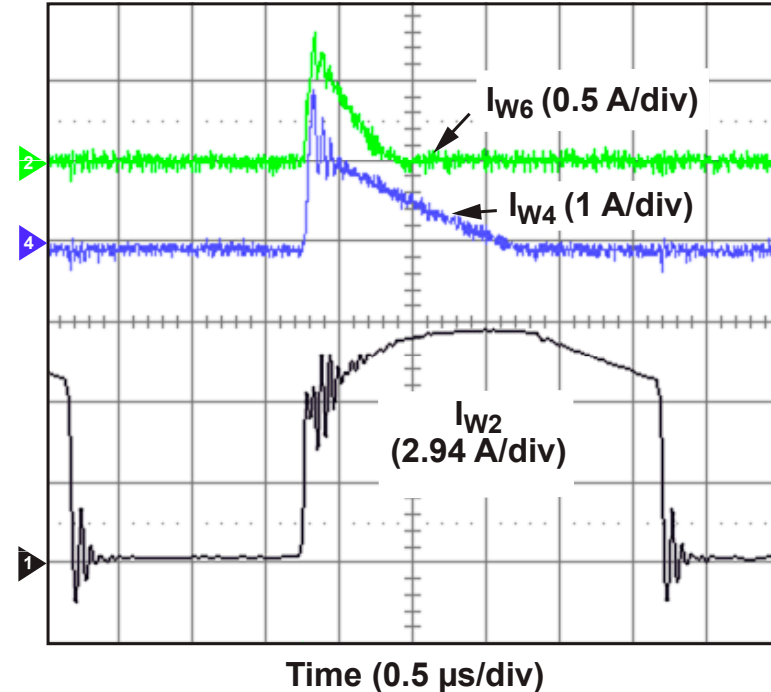
- Input voltage: 48 V
- 5-V output load: 0 A to 5 A
- Auxiliary outputs:  
V6 (10 V at 0 to 140 mA) and  
V4 (18 V at 0 to 200 mA)

- Switching frequency: 250 kHz
- Primary magnetizing inductance: 70 μH

# Cross-Regulation Test Results with Main Output Fully Loaded



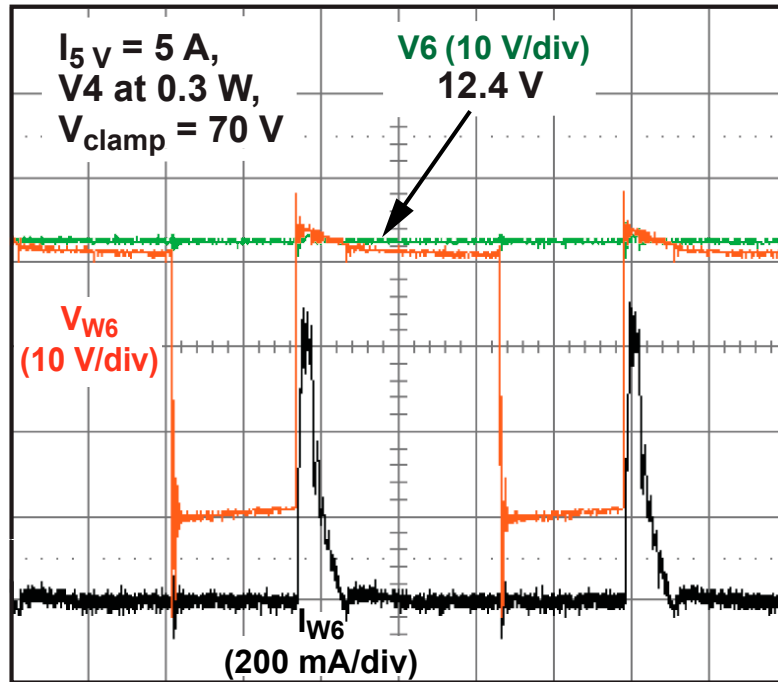
V6 at 1.6 W, V4 at 2.5 W,  
 $I_{5V} = 5$  A



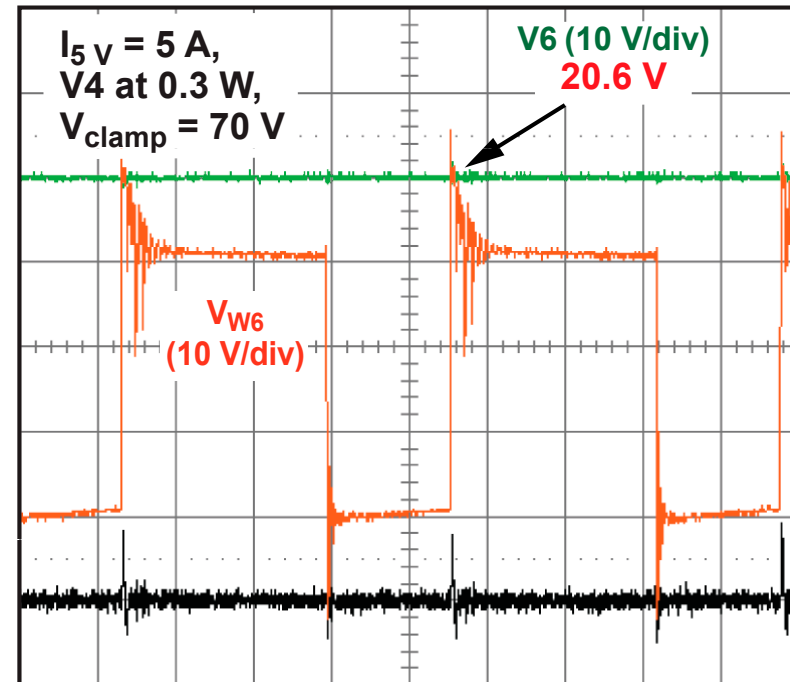
V6 at 0.5 W, V4 at 3.6 W,  
 $I_{5V} = 5$  A

- 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



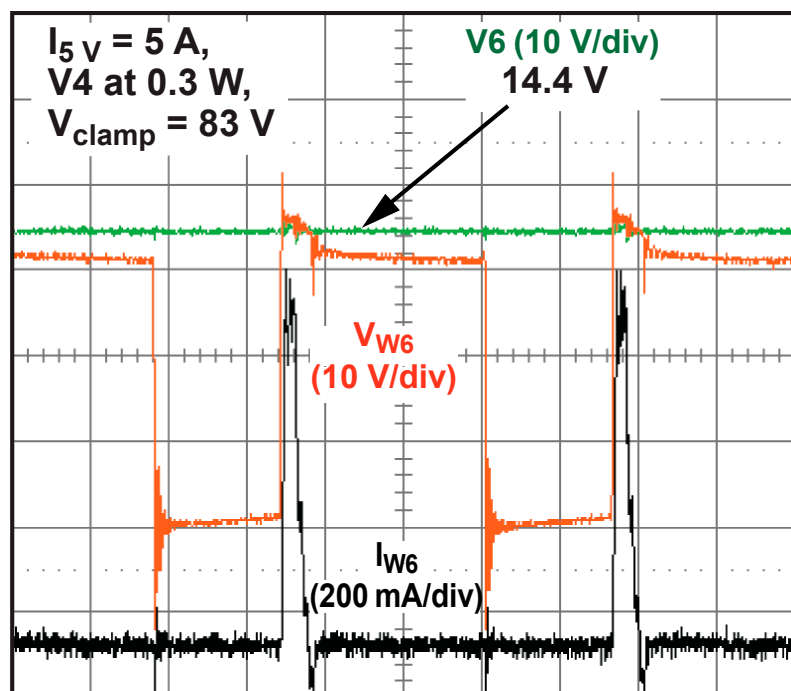
**V6 at 0.5 W**



**V6 at < 5 mW**

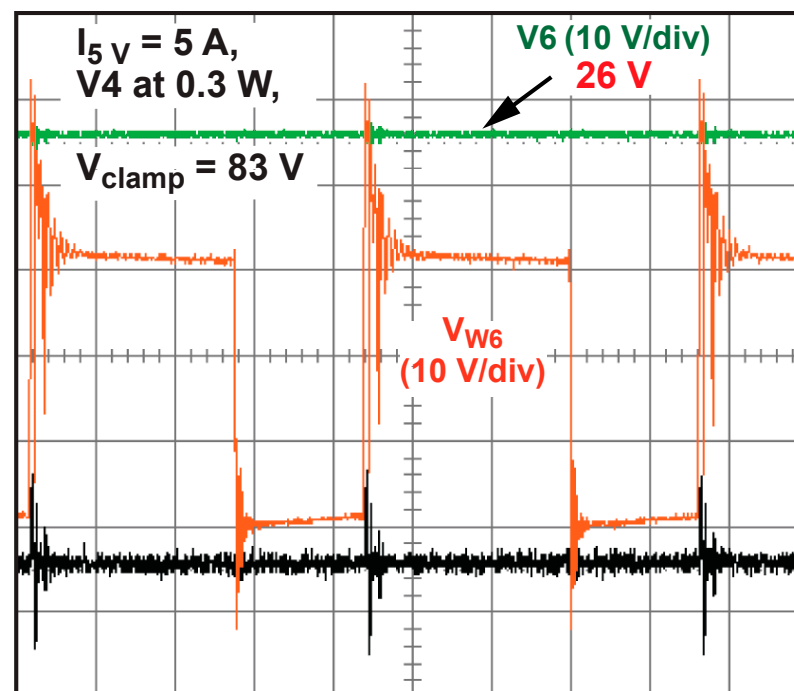
- At minimum load, V6 (10 V nominal) goes up to 20.6 V

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



Time (1  $\mu\text{s}/\text{div}$ )

**V6 at 0.5 W**



Time (1  $\mu\text{s}/\text{div}$ )

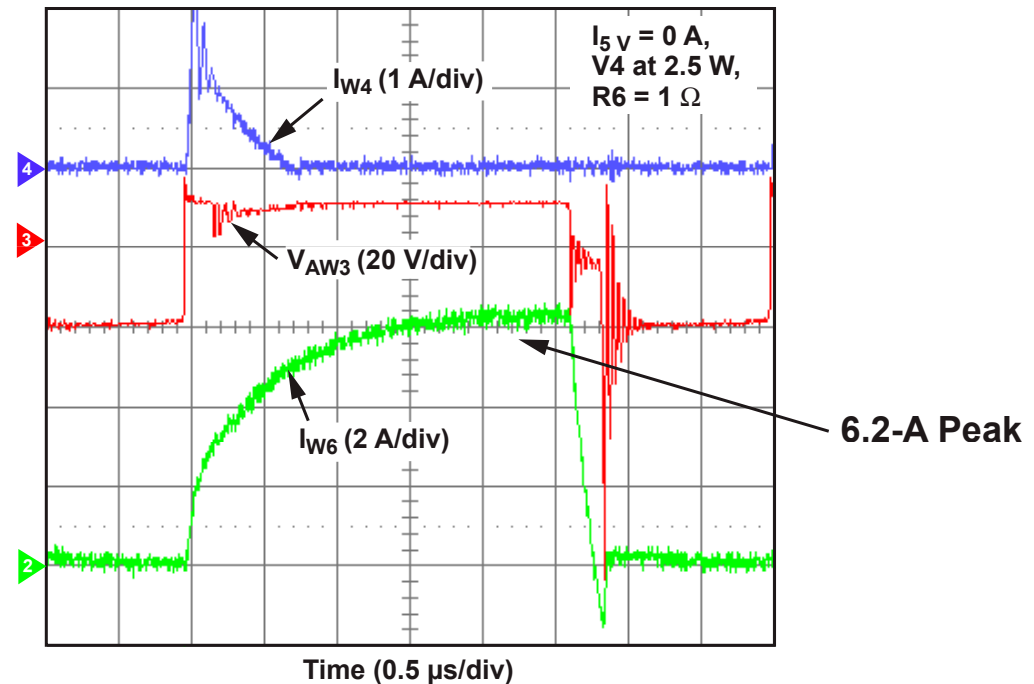
**V6 at < 5 mW**

- RCD resistor has been increased for higher  $V_{\text{clamp}}$ :  $70\text{ V} \Rightarrow 83\text{ V}$   
 $\Rightarrow V_6$  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

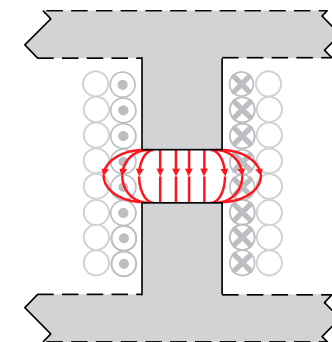
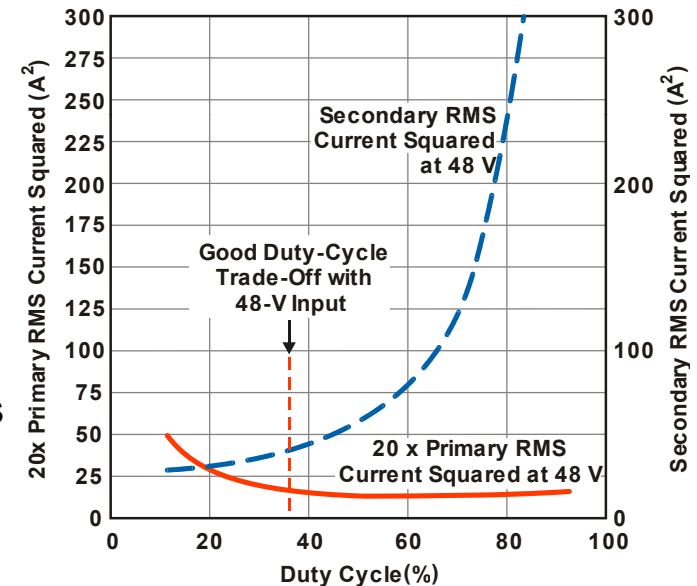
- The high current winding must have the best coupling to primary
- Minimize leakage between all secondary windings
- Optimize, not minimize, the leakage inductance of auxiliary windings to *primary*
- Use winding placement to control leakage inductance
  - Winding stackup
  - Spread each winding over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

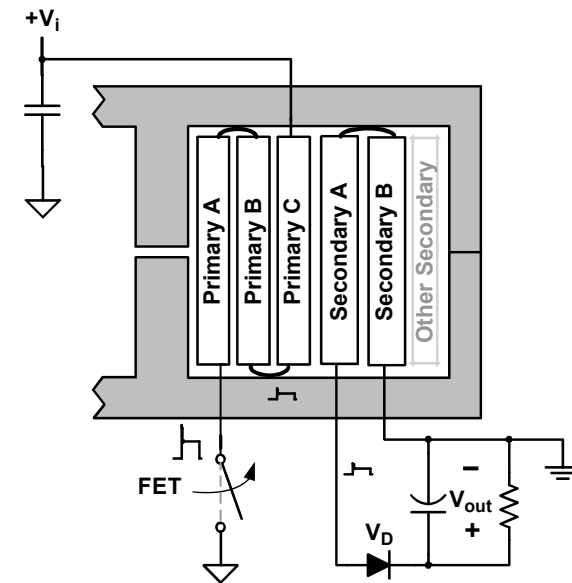
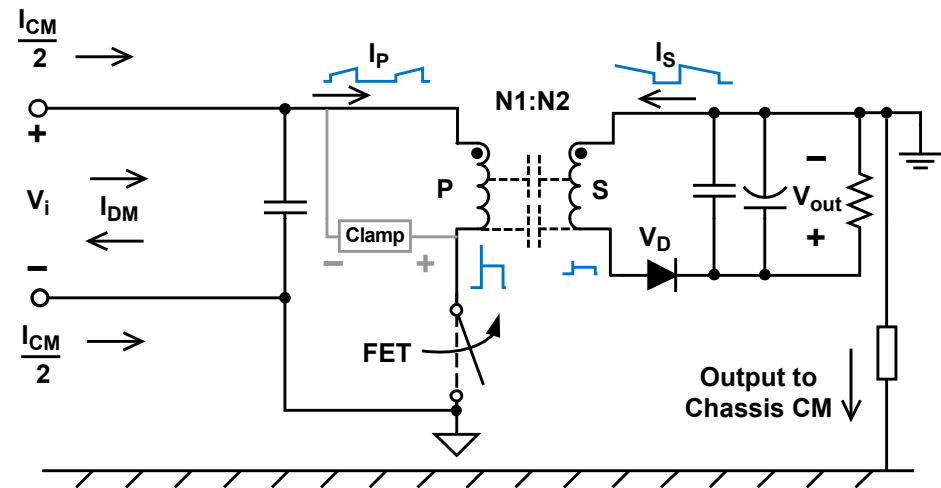
# Impact of Transformer Design on Flyback Efficiency

- 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  $\Rightarrow I_p$  and  $I_s$  pulsate
  - Use low Z caps, minimize loop areas
  - Output filter often required
- Interwinding capacitance  $\Rightarrow$  CM CE
- Transformer and diode configuration impact effective capacitance
  - Less if facing windings at same AC potential
  - Diode versus synchronous rectifier
  - Flyback  $\neq$  Forward
- Better to start with end connected to primary MOSFET
  - Shields  $V_{\text{drain}}$  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



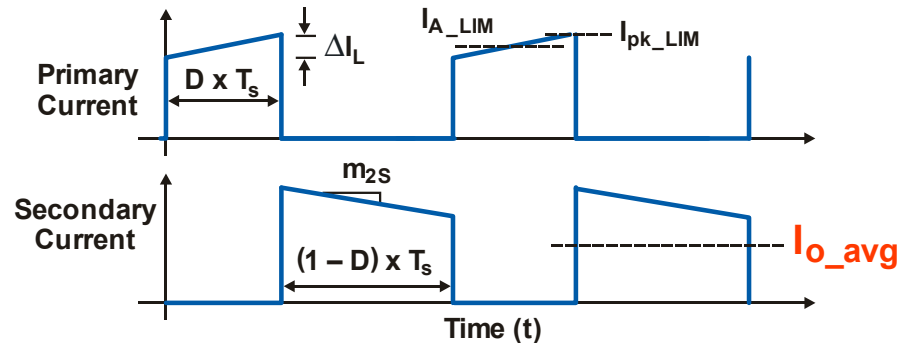
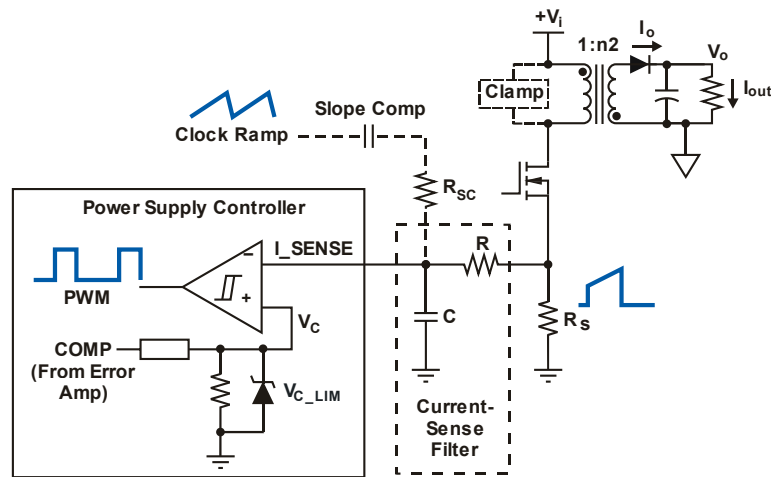
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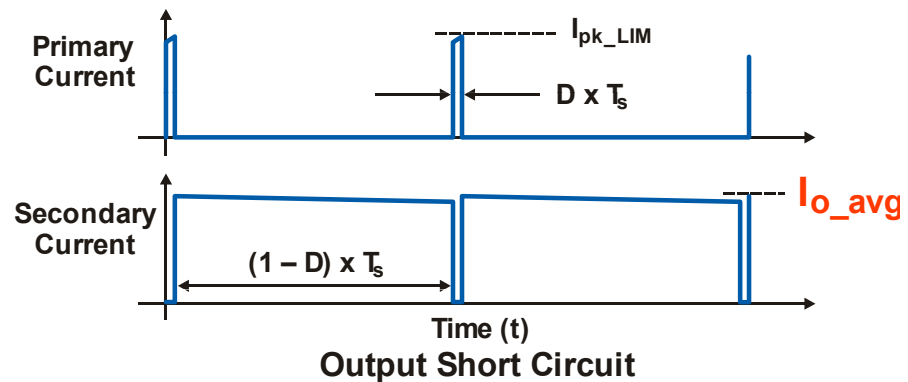
# Power Supply Current Limiting – Overview

- 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

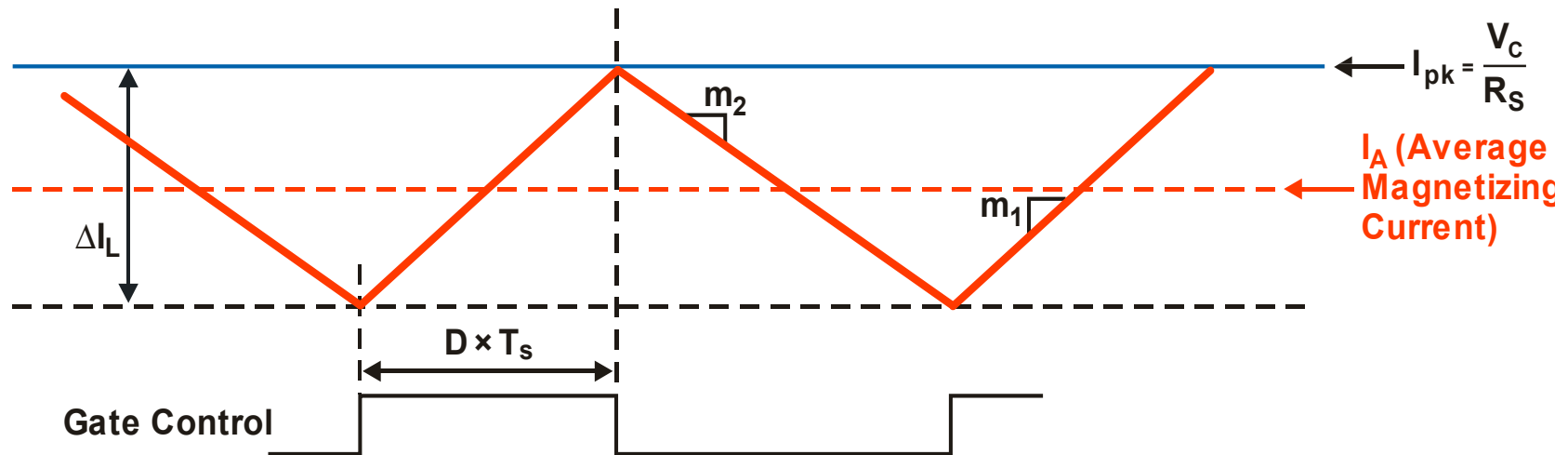
- $I_{pk\_LIM}$  is the primary peak current limit
- $I_{o\_avg}$  is the output current
- If short-circuit,  $I_{o\_avg}$  can be much higher than when current limit has just been reached

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



# Current-Limit Model – Basic Representation

- Peak CMC in CCM, fixed switching frequency

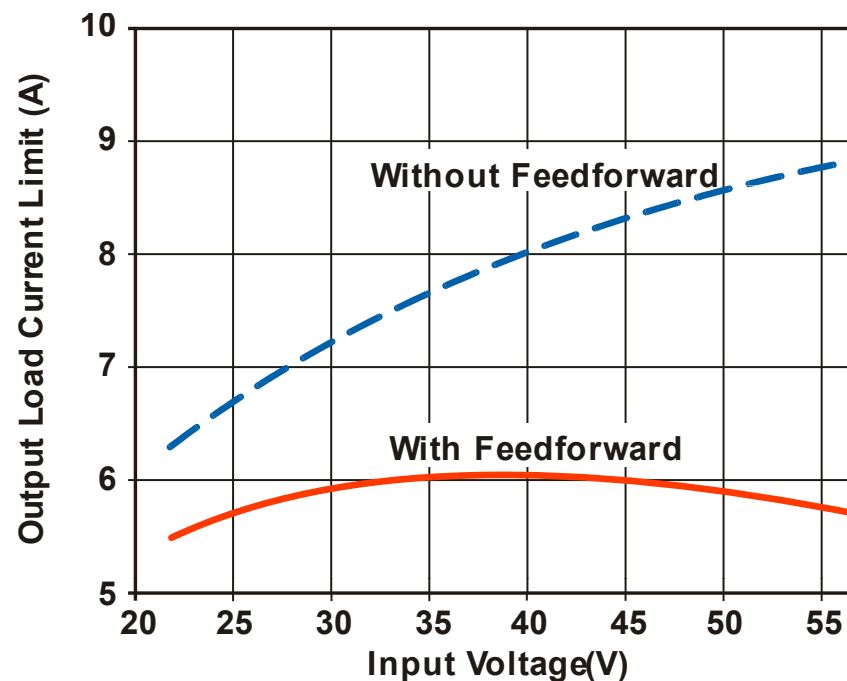
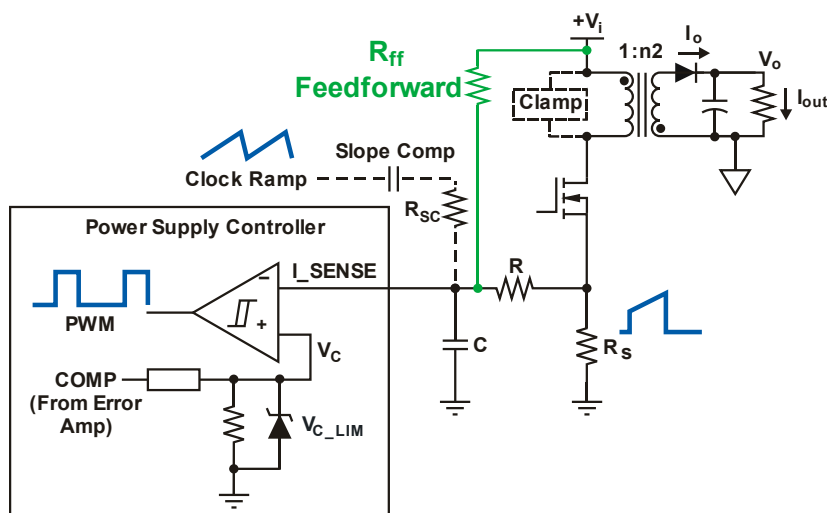


Neglecting DC voltage drops:

$$m_2 = \frac{\Delta I_L}{(1-D) \times T_s} \approx \frac{V_o}{n_2 \times L}$$

$$D = \frac{V_o}{n_2 \times V_i + V_o}$$

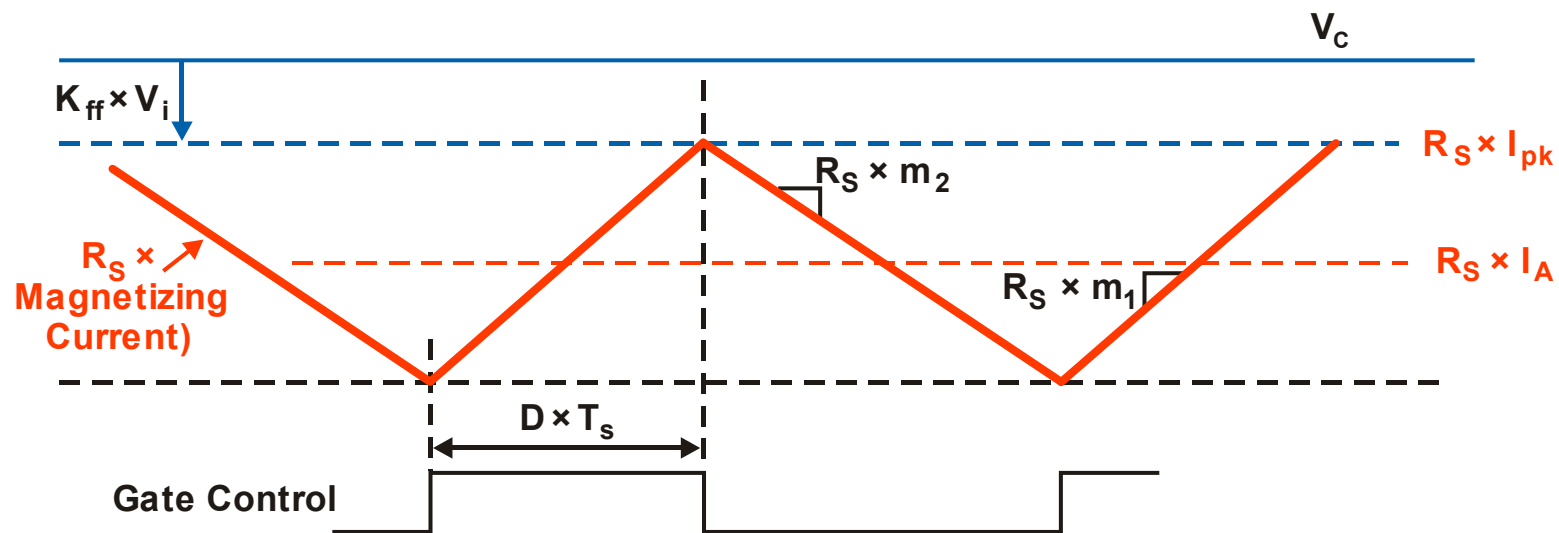
# Influence of Input DC Voltage on Output Load Current Limit – Impact of Feedforward



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

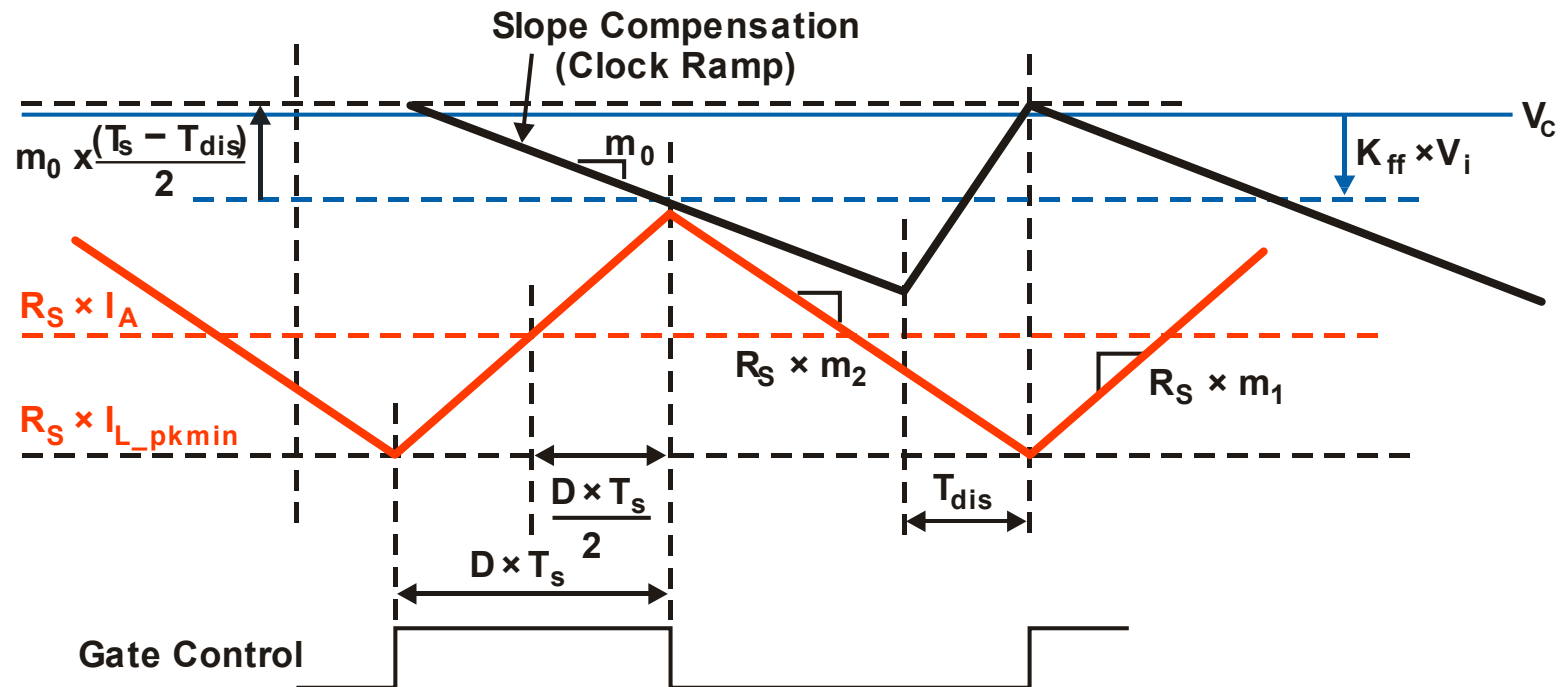
- With feedforward, output load current limit becomes almost independent of input voltage
  - $\Rightarrow$  Better control during overload, less stress on power circuitry
  - $\Rightarrow$  Power limit
  - $\Rightarrow$  Cost and/or size reduction
- Feedforward also improves line noise rejection

# Current Limit Model – With Feedforward



- $K_{ff} \times V_i$  is the feedforward contribution
  - Subtracting it from  $V_c$  is identical to adding it to current feedback

# Current Limit Model – Adding Slope Compensation



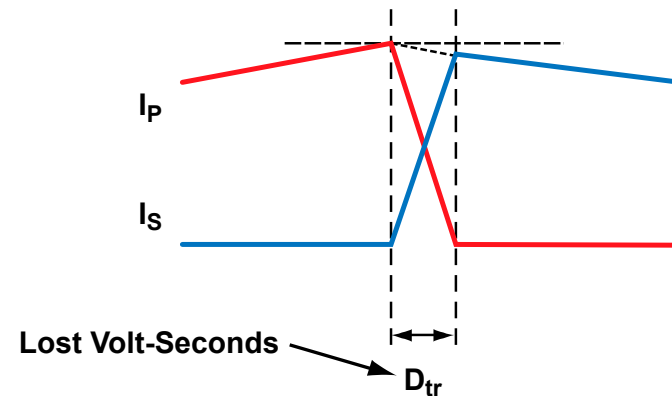
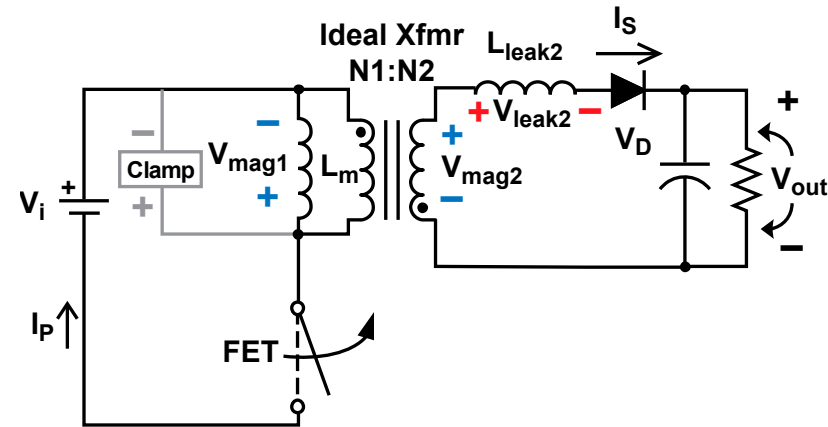
- Slope compensation to avoid subharmonic oscillation at duty-cycle close to or higher than 50%
- For easier understanding, slope compensation contribution subtracted from  $V_C$ .
  - Equivalent to slope compensation added to current feedback
  - In that circuit representation, the slope compensation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

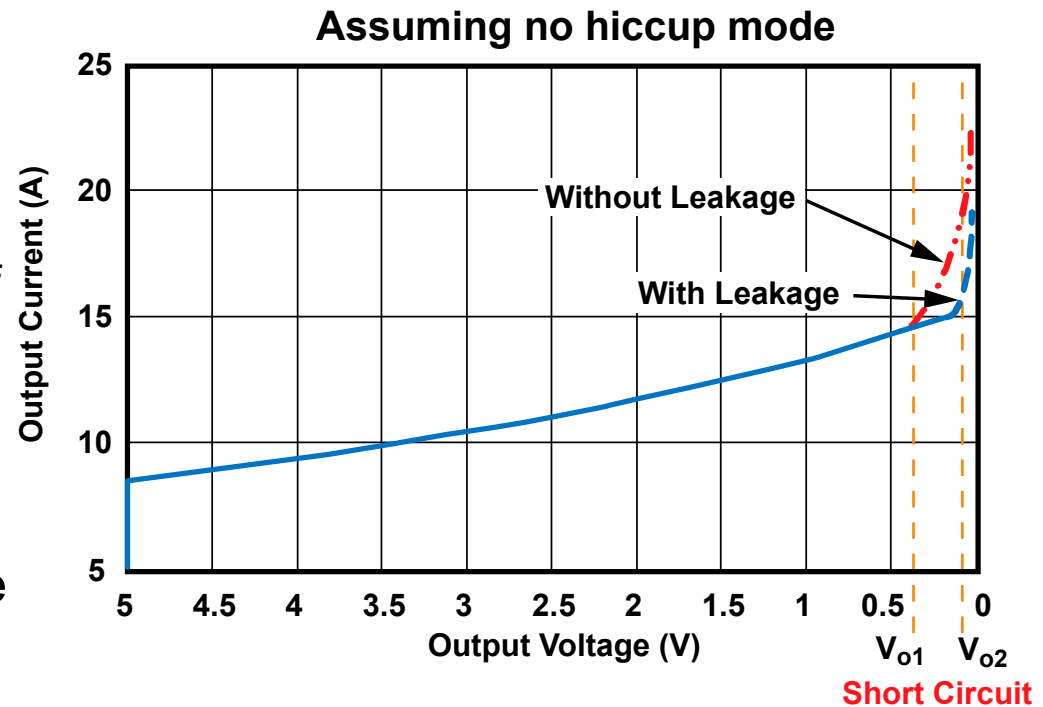


- Leakage inductance helps however to keep control of the output current in output short-circuit situation

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

# Current Limit During Overload – Example with Combined Effects

- In overload: Output current increases  $\Rightarrow$  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  $V_{o2}$



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

# 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



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