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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• Pulsating input and 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
  - $R_{\text{clamp}}$ 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)
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Transformer’s Leakage Inductance

- Transformer’s leakage inductance represented by $L_{\text{leak2}}$
  - Primary winding is the closest to center gap

- When FET turns OFF
  - $L_{\text{leak2}}$ 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 $V_{\text{clamp}}$
  - Loss of volt-seconds

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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

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

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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
Ringing 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):
  - $\Sigma${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

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

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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

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

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

- 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

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

$\Rightarrow$ 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

If W3 is lightly loaded and W2 is the high-current main output.
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

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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” ($I_{\text{out\_LIM}}$)
  – 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

- $I_{pk\_LIM}$ 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
  - 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

- $K_{ff} \times V_i$ 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
    - \( I_{\text{out,LIM}} \) lower than expected

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

\[
V_i \times D_{\text{new}} \approx V_{\text{clamp}} \times D_{\text{tr}} + \frac{V_o}{n_2} \times (1 - D_{\text{new}} - D_{\text{tr}})
\]
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 $V_{o2}$

$$\frac{V_{o\_short}}{n_2} \times \left( T_s - t_{\_OFF} - D_{tr} \times T_s \right) = V_i \times t_{\_OFF} - V_{\_\_\_clamp} \times D_{tr} \times T_s$$
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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