Control and Design Challenges for Synchronous Rectifiers

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Control and Design Challenges for Synchronous Rectifiers

Bing Lu
Outline

• Background
  – Motivation and benefits of using synchronous rectifier

• Control method
  – Control-driven and self-driven
  – Based on $V_{DS}$ sensing
  – Based on volt-second balancing
  – Adaptive control

• Design challenges
  – Selection of SR MOSFET
  – Operation in CCM, noise, bias, EMI, etc.

• Summary
Power Supply Efficiency and Power Density

Higher Power Density with Same Adapter Size

Typical Mark on AC/DC Adapters

- Efficiency standard pushes higher requirement
- High power density requires higher efficiency

4 Point Average Efficiency

<table>
<thead>
<tr>
<th>Year</th>
<th>Efficiency Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0.83</td>
</tr>
<tr>
<td>2004</td>
<td>0.84</td>
</tr>
<tr>
<td>2006</td>
<td>0.85</td>
</tr>
<tr>
<td>2008</td>
<td>0.86</td>
</tr>
<tr>
<td>2010</td>
<td>0.87</td>
</tr>
<tr>
<td>2012</td>
<td>0.88</td>
</tr>
<tr>
<td>2014</td>
<td>0.89</td>
</tr>
<tr>
<td>2016</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Loss Elements in Converters

- Output diode often carries entire load current
- Diode forward voltage drop can be directly related to efficiency loss
- Loss percentage gets worse when output voltage is low

\[
P_{\text{DIODE}} = V_f \cdot I_{\text{OUT}}
\]

Diode Loss Percentage

\[
\eta_{\text{DIODE}} \approx \frac{V_f}{V_{\text{OUT}}}
\]

Can we do better?
By replacing diode with synchronous rectifier, conduction loss can be significantly reduced by low on-resistance.

Higher efficiency can be expected for low voltage applications.

SBRT20M60SP5

CSD18532KCS

$R_{DS(ON)} = 5.3 \text{ mΩ @ 25°C}$
Loss Comparison for a Typical Waveform

- Large conduction loss saved by replacing diode with synchronous rectifier
SR Control in Different Applications

- Some topologies can easily implement SR control without dedicated controller IC
- Flyback, active clamp flyback, LLC, etc. applications usually need dedicated SR-controller, due to its complexity

**Synchronous Buck**

- Complementary driving signal

**Active Clamp Forward Converter**

- Self-driven based on transformer voltage
SR Control Based on $V_{DS}$ Sensing

- Monitoring SR drain-to-source voltage ($V_{DS}$)
  - When body-diode is conducting, $V_{DS}$ crosses $V_{TH_{ON}}$, controller turns ON SR
  - When $V_{DS}$ decreases to $V_{TH_{OFF}}$, current is approaching zero, controller turns OFF SR
SR Control Based on Volt-Second Balancing

- Volt-seconds are balanced in each switching cycle for DCM flyback — it can be used for SR control
  - Less sensitive to noise
- Only valid for DCM, can’t work for LLC or active clamp flyback
Adaptive SR Control

- Adjust SR conduction time to minimize body diode conduction time
- Optimize SR conduction loss
- Complicated control for tuning and dealing with transient
SR Selection: Conduction Loss

- Turn-off threshold is a fixed value
  - Larger $R_{DS(ON)}$ results in smaller turn-off current and less body diode conduction time
  - Smaller $R_{DS(ON)}$ causes larger turn-off current and more body diode conduction time

- $R_{DS(ON)}$ should be chosen with consideration of turn-off threshold

\[
I_{OFF} = \frac{V_{TH\_OFF}}{R_{DS(ON)}}
\]
SR Selection: Switching Loss

\[ P_{SR} = P_{CON} + P_{SW} + P_{DRV} \]

**Conduction loss**

\[ P_{CON} = I_{RSM}^2 \cdot R_{DS(ON)} \]

**Switching loss**

\[ P_{SW} = \frac{1}{2} C_{OSS(eq)} \cdot V_{DS}^2 \cdot f_{SW} \]

**Driver loss**

\[ P_{DRV} = C_{ISS} \cdot V_{DRV}^2 \cdot f_{SW} \]

- Lower \( R_{DS(ON)} \) results in lower conduction loss, but larger \( C_{OSS} \) and \( C_{ISS} \)
- SR should be chosen to consider balance between conduction loss and switching loss
  - Efficiency is measured at 4-point average
  - 10% load efficiency concern
SR Operation in CCM

- High $\frac{di}{dt}$ caused by high voltage and low inductance
- Need to turn off SR really fast

\[
\frac{di}{dt} = \frac{V_O + \frac{V_{IN}}{N_{PS}}}{L_{LK}}
\]

\[
\frac{di}{dt} = \frac{V_{IN}}{N_{PS}} \frac{1}{L_{LK}}
\]

\[
\frac{di}{dt} = \frac{V_O + \frac{V_{IN} + V_{CR}}{N_{PS}}}{L_R \frac{N_{PS}}{N_{PS}^2}}
\]
**V_{DS} Sensing Operation in CCM**

- During CCM operation, $\frac{di}{dt}$ changes significantly.
- Comparator needs to respond fast.

![Diagram](image-url)
**V_{DS} Sensing Operation in CCM**

- \( \frac{di}{dt} \) is determined by leakage inductor
- Comparator needs to respond fast to minimize negative current
Diode Operation in CCM

- Diode causes negative current due to reverse recovery
  - Fast reverse recovery time results in less negative current
  - Less $Q_{RR}$ results in less switching loss
- Turning off SR too late is similar to large reverse recovery current

SR Body Diode and Reverse Recovery Loss
(Based on 100 kHz Estimation)

<table>
<thead>
<tr>
<th>SR</th>
<th>$Q_{RR}$</th>
<th>Reverse Recovery Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1@ 30 V $V_{DS}$</td>
<td>127 nC</td>
<td>0.381 W</td>
</tr>
<tr>
<td>SR2@ 75 V $V_{DS}$</td>
<td>385 nC</td>
<td>2.887 W</td>
</tr>
</tbody>
</table>
Early vs. Late Turn-Off

- Ideally, SR should turn off late but not too late to cause too much negative current
- Bottom line, shoot through time should be shorter than body diode reverse recovery time
Noise at Turn-On and Turn-Off of SR

- Due to parasitic circuit elements, ringing waveforms can often be observed after SR is turned on and off.
- When ringing voltage approaches controller thresholds, ringing might cause false trigger (turn off too soon after turn-on or turn on too soon after turn-off).
- Minimum on-time and off-time can help to blank ringing and avoid false trigger.
Dealing with Noise

- Turn-on blanking is required to avoid false turn-off
- Turn-off blanking is required to avoid false turn-on
• Due to sinusoidal current shape, SR controller could interpret initial low current as current approaching zero and turns off SR too early
• To avoid early turn-off, a minimum on-time is required until current rises above turn-off threshold ($V_{TH\_OFF}$)
Parasitic Inductor Impacts on SR Operation

$L_D$ and $L_S$ are packaging parasitic inductors and can’t be eliminated.

Negative $\frac{di}{dt}$ on $L_D$ and $L_S$ causes voltage drop and offsets $R_{DS(ON)}$ drop.

Voltage drop causes SR early turn-off and generates more conduction loss.

Low package inductance devices should be used.

\[
V_{SENSE} = - \left[ I_{SR} \cdot R_{DS(ON)} + \left( L_D + L_S \right) \cdot \frac{dI_{SR}}{dt} \right]
\]
**V_{DS}** Sensing and Proportional Gate Drive

- When SR current is small, conduction loss is small, increasing conduction loss a little won’t impact efficiency much
  - Instead of fully turning on SR into a resistor, SR can be controlled as a voltage source (much lower than diode)

- This extra control makes SR gate drive voltage proportional to current
  - Speed up turn-off, easier for CCM operation
  - Higher voltage drop, less sensitive to parasitic inductor
Natural EMI Cancellation of Flyback

- At MOSFET turn-off
  - MOSFET drain voltage rises, generates current on $C_2$
  - Diode anode voltage rises, generates current on $C_1$

- Currents on $C_1$ and $C_2$ are flowing in opposite directions and can cancel each other
Why Moving Rectifier to Ground Side Is Worse

- When moving rectifier to ground side
  - $C_1$ has no current because voltage potential across it is zero
  - At MOSFET turn-off
    - MOSFET drain rises $\rightarrow$ diode cathode falls $\rightarrow$ current flowing through $C_2$
- Cancelation effect is lost
How to Power SR Controller

- Easiest way to power SR controller is from output voltage
  - Put SR on return path, shares same ground as output
- Driver loss might be significant if output voltage is high
  - Aux winding can be used to save driving loss
- Special applications require wide $V_{DD}$ range, for example, USB-PD
When SR is on high side, SR MOSFET source is on switching node
- Aux winding provides most efficient way
- RCD or linear regulator can be used to create $V_{DD}$, but efficiency is much lower
Standby Power Requirements

• Efficiency standards for external power supplies (EPS)
  - For less than 49 W rated power
  - European Commission, Tier 2 – January 2016 75 mW
  - U.S. Department of Energy – Feb. 10th, 2016 100 mW

![No-load consumption score chart](chart)

• Lower standby power is desired even for design margin and system functions such as USB-PD control
Keep SR IC in Sleep Mode

- SR IC consumes ~1 mA during normal operation, with 20 V output, it is already 20 mW
- SR IC can be kept in sleep mode based on converter timing
  - Modern controller often burst with high power and frequency-based detection is more reliable
Typical Measurement Waveform

- Much reduced conduction loss
- Watch out for body diode conducting
Summary

- Power supplies are getting more and more efficient
- Diode conduction loss can be improved by replacing with synchronous rectifier
  - Conduction loss reduction
  - Extra switching loss and driving loss
- SR can be controlled with different methods, $V_{DS}$ sensing is most popular
- Things to watch out for:
  - Select suitable MOSFET (not lowest $R_{DS\_ON}$ MOSFET)
  - Make sure enough blanking time
  - Fast turn-off in CCM condition
  - Parasitic inductors
  - How to power controller
  - EMI consideration
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