When can synchronous rectification increase efficiency?

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What will I get out of this session?

• **Purpose:**
  - Explain how SRs work
  - Show when they can be effective
  - Various control methods
  - Downsides to watch out for
  - Design examples

• **Relevant part numbers mentioned:**
  - UCC24612, UCC24610, UCC24630, UCC24624

• **Relevant reference designs:**
  - TIDA-01501 450-W 80+ platinum desktop
  - TIDA-01494 24-V 480/720-W industrial
  - TIDA-01495 24-V 480-W low-profile TV PSU
  - TIDA-01557 12-V 200-W desktop 100 mW stdby
  - TIDA-01622 65-W USB-C PD 30 W/in³ adapter

• **Relevant applications:**
  - Isolated supplies that require high efficiency and/or thermal management
Synchronous rectification – how does it work?

- Diode rectifier “easy” – automatically turns on/off
- Replace diode, with body diode in same direction
- Usually N-channel enhancement-mode device
- SR gate off – body diode conducts, same as rectifier diode
- SR gated on => low-resistance bi-directional conducting channel
- SR gate => high when current flows in body diode
- SR gate => low when current in channel decays to zero
Why use an SR? —> higher efficiency and power density

• To meet necessary efficiency standards
  • E.g. US DoE & EU CoC for external adapters
  • 80 Plus® Platinum etc. for desktop PSUs

• Higher power density for smaller PSU size
  • Compact travel adapters
  • Smaller DIN-rail industrial PSU

• Solve thermal issues and increase reliability
  • Eliminate diode rectifier hot-spot – increase robustness, reliability and life-time
  • Lower total internal power dissipation, lower running costs, less heat to be removed
Diode rectifier loss

- Output diode often carries entire load current
- Diode forward voltage drop is directly related to rectification efficiency
- Efficiency gets worse when output voltage is lower

Diode rectification efficiency

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

Diode loss

\[ P_{DIODE} = V_f \times I_{OUT} \]
Schottky diode vs. synchronous rectifier

- By replacing diode with synchronous rectifier, conduction loss can be significantly reduced
- Higher efficiency can be expected for low voltage applications

SBRT25U60SLP
25-A, 60-V POWERDI5060
V_f 0.37 V @ 10 A 25°C
V_f 0.32 V @ 10 A 125°C

CSD18533Q5B
60-V SON5x6
R_DS(ON) = 8.5 mΩ @ 25°C, Vgs 4.5 V
R_DS(ON) = 15.3 mΩ @ 125°C, Vgs 4.5 V
Loss comparison for a typical flyback rectifier

- Large conduction loss saved by replacing diode with synchronous rectifier

Assuming 50% duty-cycle QR flyback

Flyback secondary side current

SBRT25U60SLP loss model

- 200 mV
- 11 mΩ

CSD1853Q5B loss model

- 14 mΩ

Load current (A)

Conduction loss (W)

Diode loss

SR loss

Forward current (A)

Vf forward voltage drop (mV)
How to calculate LLC SR current?

Approximate the secondary side current as rectified sinusoidal current

\[ I_{S1}(avg) = I_{S2}(avg) = \frac{I_{out}}{2} \]

\[ I_{S1}(rms) = I_{S2}(rms) = \frac{\pi}{4} I_{out} \]
Direct control of SRs

• 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
• For example: PMP8740 uses UCC28950 phase-shift full-bridge controller that controls both the primary side switches and the secondary side SRs
SR control based on $V_{DS}$ sensing – UCC24610

- 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 – UCC24630

- 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
SR selection: conduction loss

Simplified SR control scheme

\[ I_{OFF} = \frac{V_{TH\_OFF}}{R_{DS\(ON\)}} \]

- 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
SR selection: switching loss

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

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

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

Driver loss
\[ P_{DRV} = C_{ISS} \times V_{DRV}^2 \times f_{SW} \]

- 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 di/dt caused by high voltage and low inductance
- Need to turn off SR really fast
V_{DS} sensing operation in CCM

- $\frac{di}{dt}$ is determined by leakage inductance
- 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.
- Beware CCM operation in “diode-mode” – startup and severe overload – where SR driver may have no bias rail.
- Access to the turn-on signal of the main switch would be beneficial, for example: sync. buck.
Dealing with ringing

- 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 turn 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 inductances 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

\[
V_{SENSE} = I_{SR} \cdot R_{DS(ON)} + \left( L_D + L_S \right) \cdot \frac{dI_{SR}}{dt}
\]
When SR current is small, conduction loss is small

- Instead of fully turning on SR into a resistor, SR can be controlled as a voltage source (like a low forward voltage drop 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

PMP21251 and UCC28780EVM-002 use UCC24612 to achieve high efficiency for LLC and active clamp flyback converters
Where to put the SR high-side?

- High-side SR:
  - Harder to drive gate, need level-shift
  - Need high-side bias
  - Better/lower EMI
- Currents on $C_1$ and $C_2$ are flowing in opposite directions and can cancel each other
Where to put the SR low-side?

- Low-side SR:
  - Gate referenced to output ground, easy drive, no level-shift
  - Ground-referenced bias for driver IC
  - Higher/worse EMI
  - When moving rectifier to ground side, cancelation effect is lost
Summary

• SR MOSFET offers much lower on-state drop and conduction loss vs. diode
• SR may not always make sense
  • Depends on output voltage and output current/power level
• Beware the trade-offs between low $R_{ds(on)}$ and high $C_{oss}$
• Beware the impacts of going too low in $R_{ds(on)}$ with $V_{ds}$-sensing control
• Beware of early turn-off and body diode reverse recovery
  • Can actually be worse than short CCM shoot-through
• Beware of the EMI implications of low-side rectifier position
Further reading


• Power Tips: How to Implement Synchronous Rectifiers in a Resonant LLC Half-Bridge

• Power Tips: What’s the best way to drive synchronous rectifiers in a flyback supply?

• Power Tips: Self-drive your synchronous rectifier

• Synchronous rectification boosts efficiency by reducing power loss