High VOLT Interactive

Where power supply design meets collaboration

When can synchronous rectification increase efficiency?

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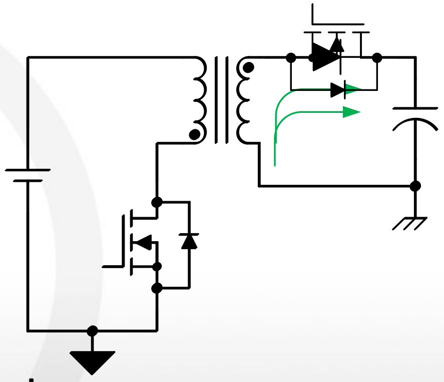
What will I get out of this session?

- **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/in^3 adapter
- **Relevant applications:**
  - Isolated supplies that require high efficiency and/or thermal management

Synchronous rectification – how does it work?

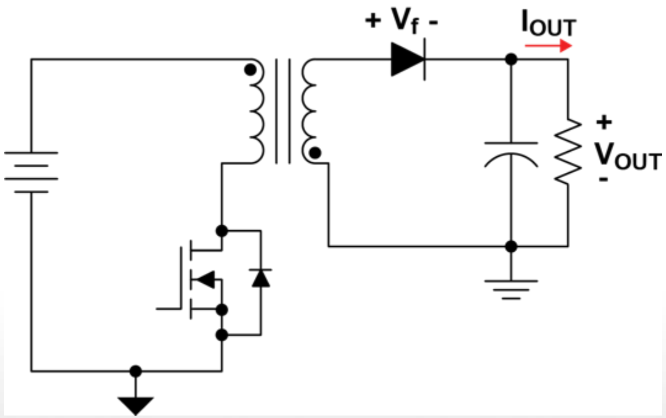
- Diode rectifier “easy” – automatically turns on/off
- Replace diode, with body diode in same direction
- Usually N-channel enhancement-mode device
- SR gate off – body diode conducts, same as rectifier diode
- SR gated on => low-resistance bi-directional conducting channel
- SR gate => high when current 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



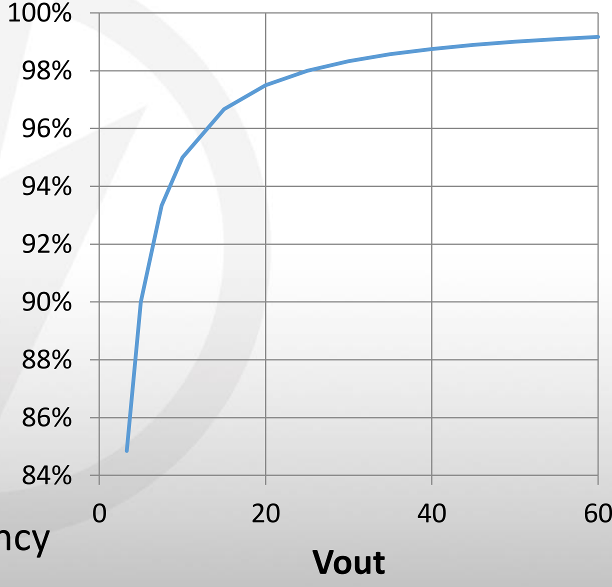
Diode loss

$$P_{DIODE} = V_f \times I_{OUT}$$

Diode rectification efficiency

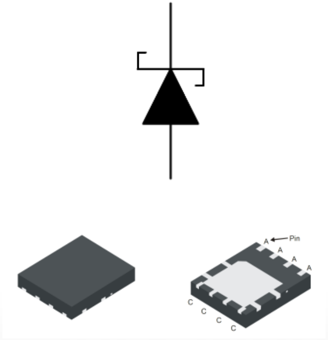
$$\eta_{DIODE} \approx \frac{V_{OUT}}{V_{OUT} + V_f}$$

Rectification efficiency (Fixed V_f = 0.5 V)

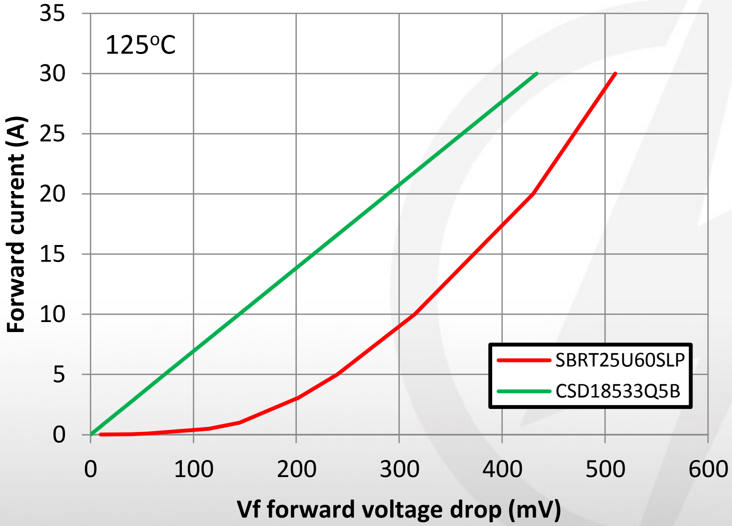


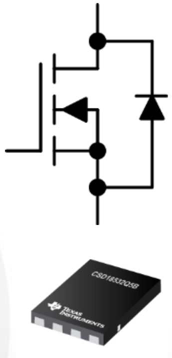
- Output diode often carries entire load current
- Diode forward voltage drop is directly related to rectification efficiency
- Efficiency gets worse when output voltage is lower

Schottky diode vs. synchronous rectifier



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



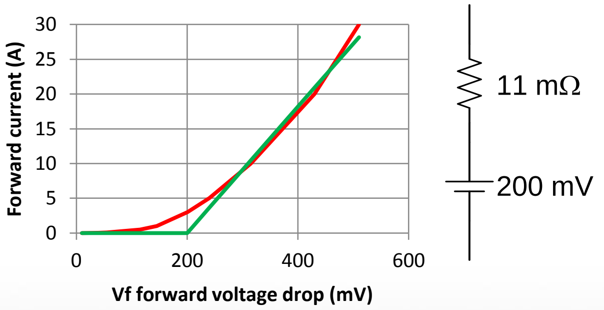


CSD18533Q5B
60-V SON5x6
$R_{DS(ON)}$ = 8.5 mΩ @ 25°C, Vgs 4.5 V
$R_{DS(ON)}$ = 15.3 mΩ @ 125°C, Vgs 4.5 V

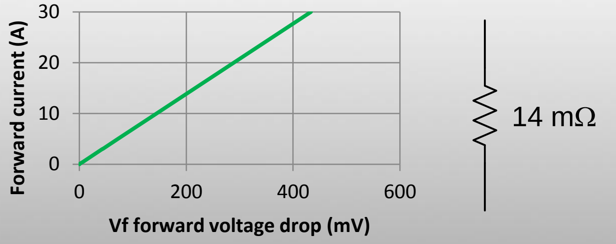
- By replacing diode with synchronous rectifier, conduction loss can be significantly reduced
- Higher efficiency can be expected for low voltage applications

Loss comparison for a typical flyback rectifier

SBRT25U60SLP loss model

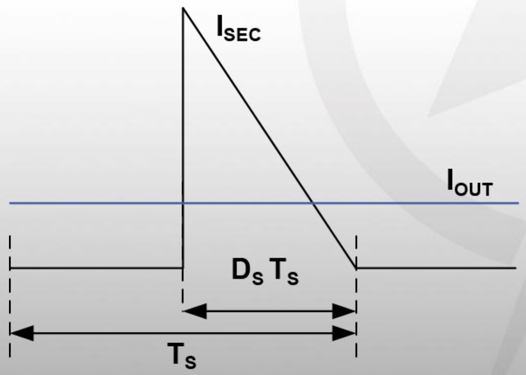


CSD18533Q5B loss model

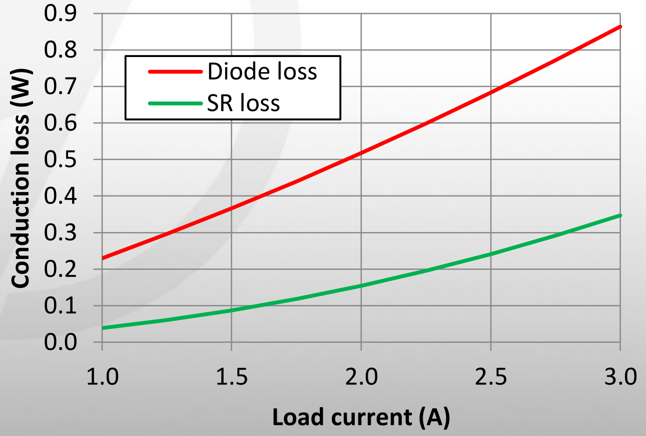


- Large conduction loss saved by replacing diode with synchronous rectifier

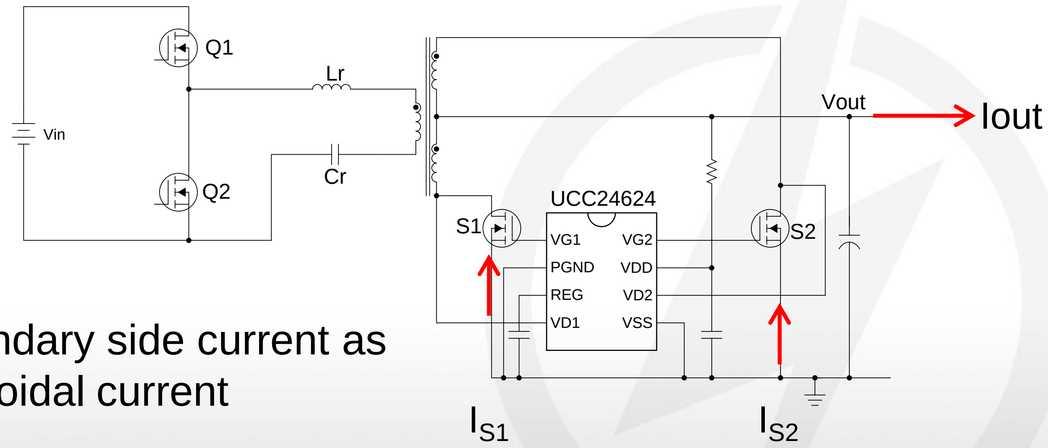
Flyback secondary side current



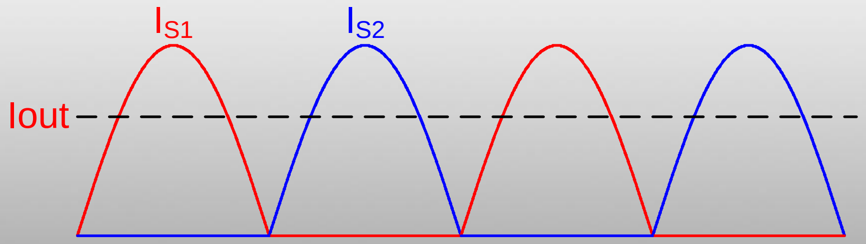
Assuming 50% duty-cycle QR flyback



How to calculate LLC SR current?



Approximate the secondary side current as rectified sinusoidal current

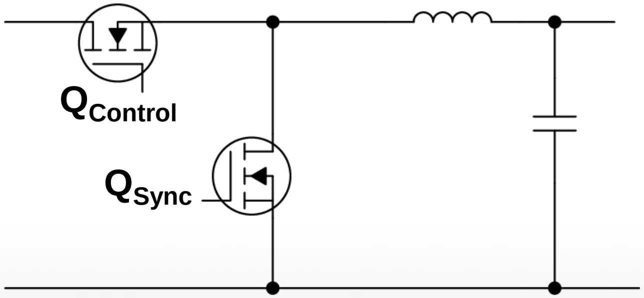


$$I_{S1}(avg) = I_{S2}(avg) = \frac{I_{out}}{2}$$

$$I_{S1}(rms) = I_{S2}(rms) = \frac{\pi}{4} I_{out}$$

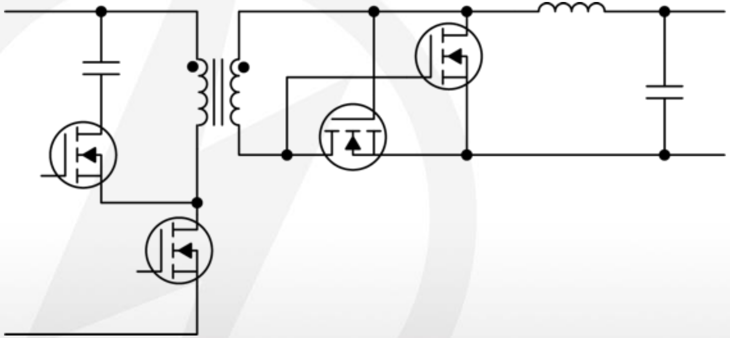
Direct control of SRs

Synchronous buck



Complementary driving signal

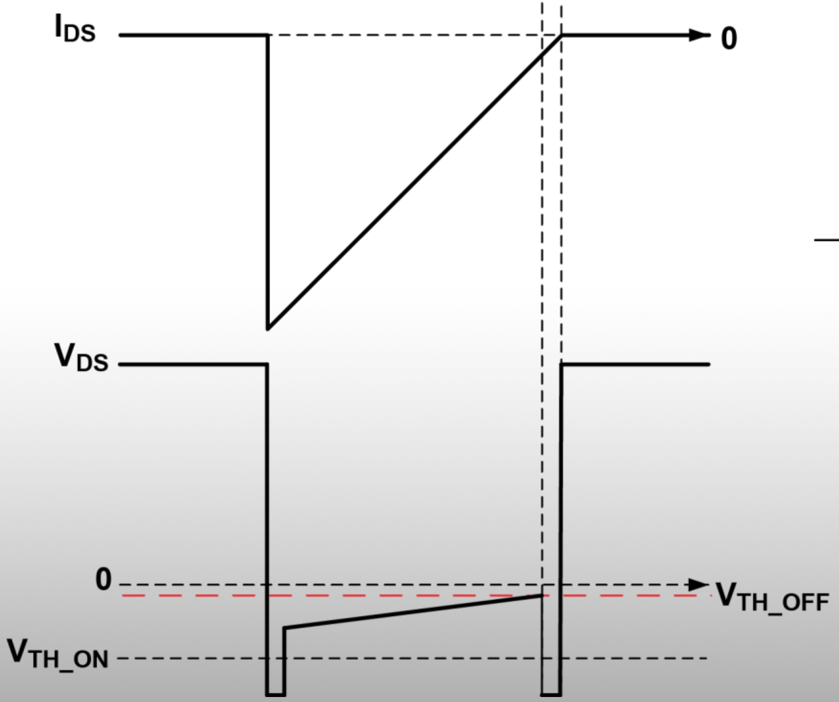
Active clamp forward converter

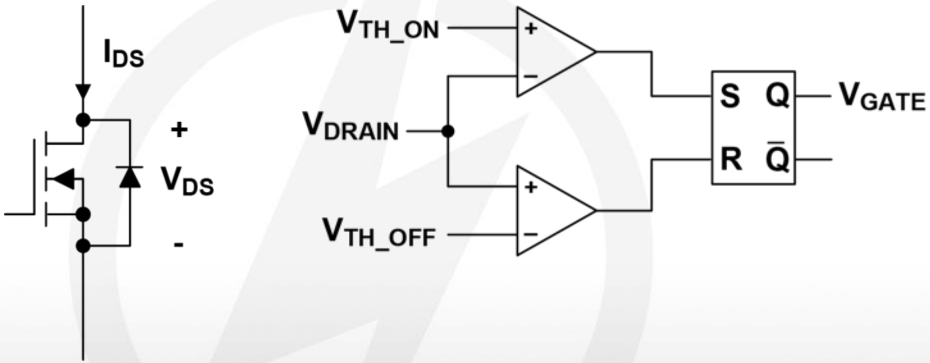


Self-driven based on transformer voltage

- 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

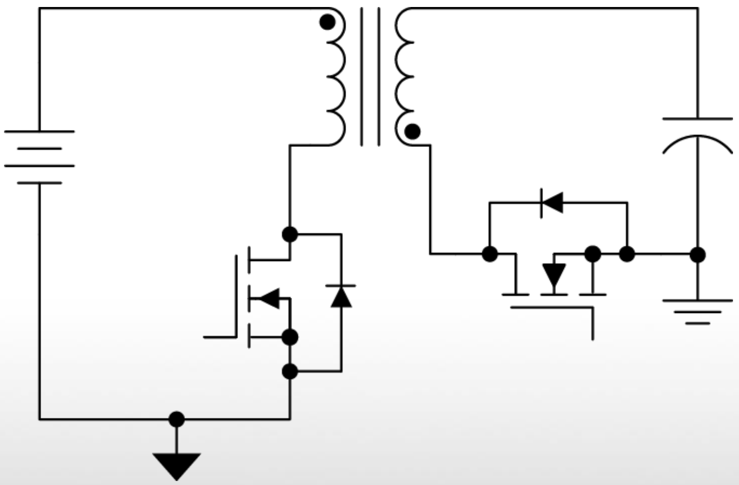
SR control based on V_{DS} sensing – UCC24610

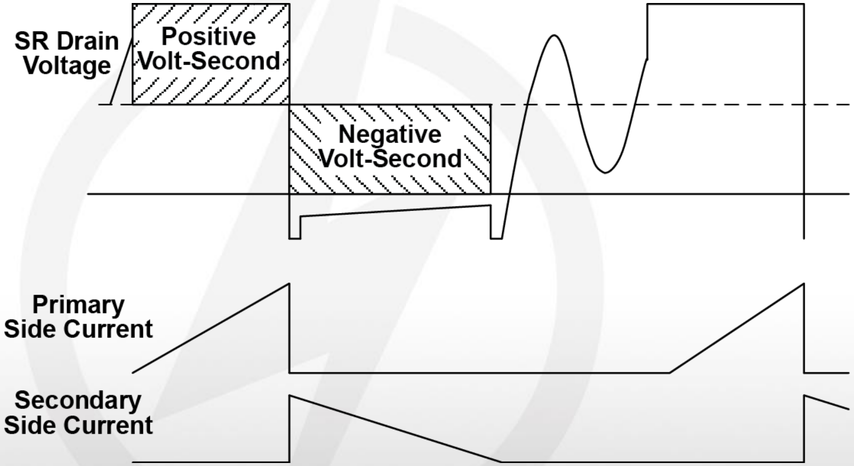




- Monitoring SR drain-to-source voltage (V_{DS})
  - When body-diode is conducting, V_{DS} crosses V_{TH_ON}, controller turns ON SR
  - When V_{DS} decreases to V_{TH_OFF}, current is approaching zero, controller turns OFF SR

SR control based on volt-second balancing – UCC24630

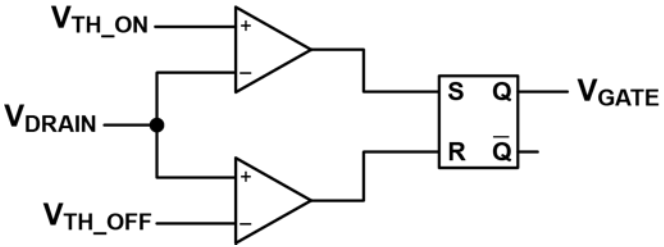




- Volt-seconds are balanced in each switching cycle for DCM flyback — it can be used for SR control – less sensitive to noise
- Only valid for DCM, can't work for LLC or active clamp flyback

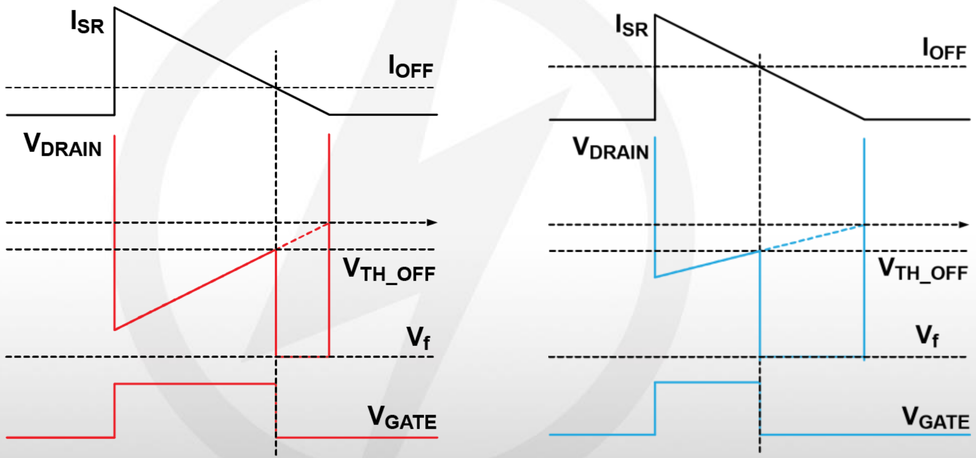
SR selection: conduction loss

Simplified SR control scheme



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

Higher $R_{DS(ON)}$ **Lower $R_{DS(ON)}$**



- 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

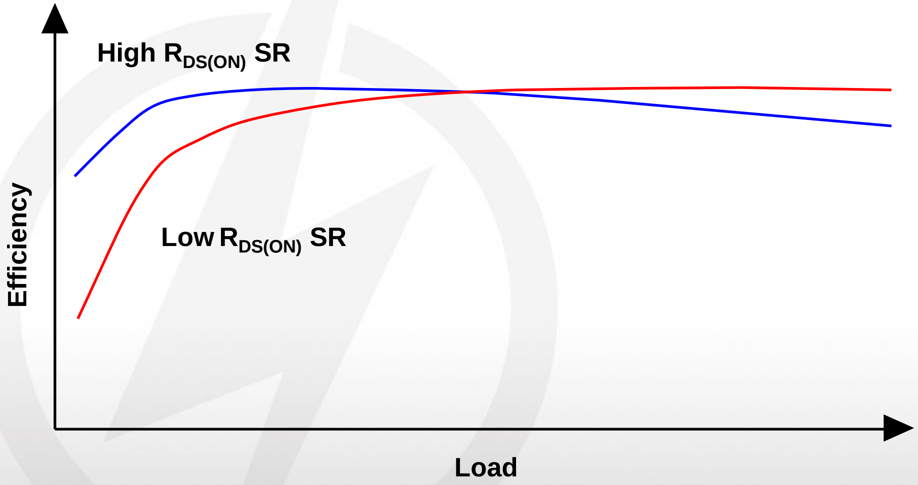
SR selection: switching loss

$$P_{SR} = P_{CON} + P_{SW} + P_{DRV}$$

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

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

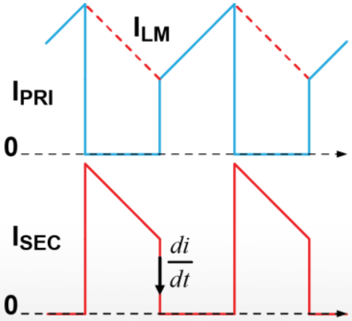
Driver loss $P_{DRV} = C_{ISS} \times V_{DRV}^{2} \times f_{SW}$



- 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

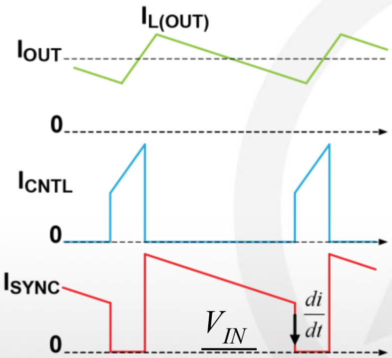
SR operation in CCM

Flyback



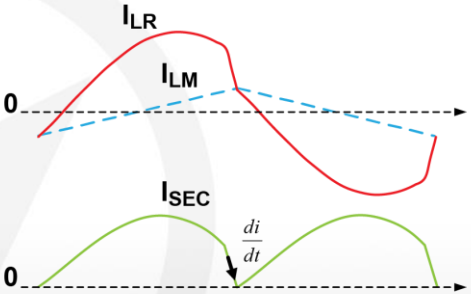
$$\frac{di}{dt} = \frac{V_O + \frac{V_{IN}}{N_{PS}}}{L_{LK}}$$

Forward



$$\frac{di}{dt} = \frac{\frac{V_{IN}}{N_{PS}}}{L_{LK}}$$

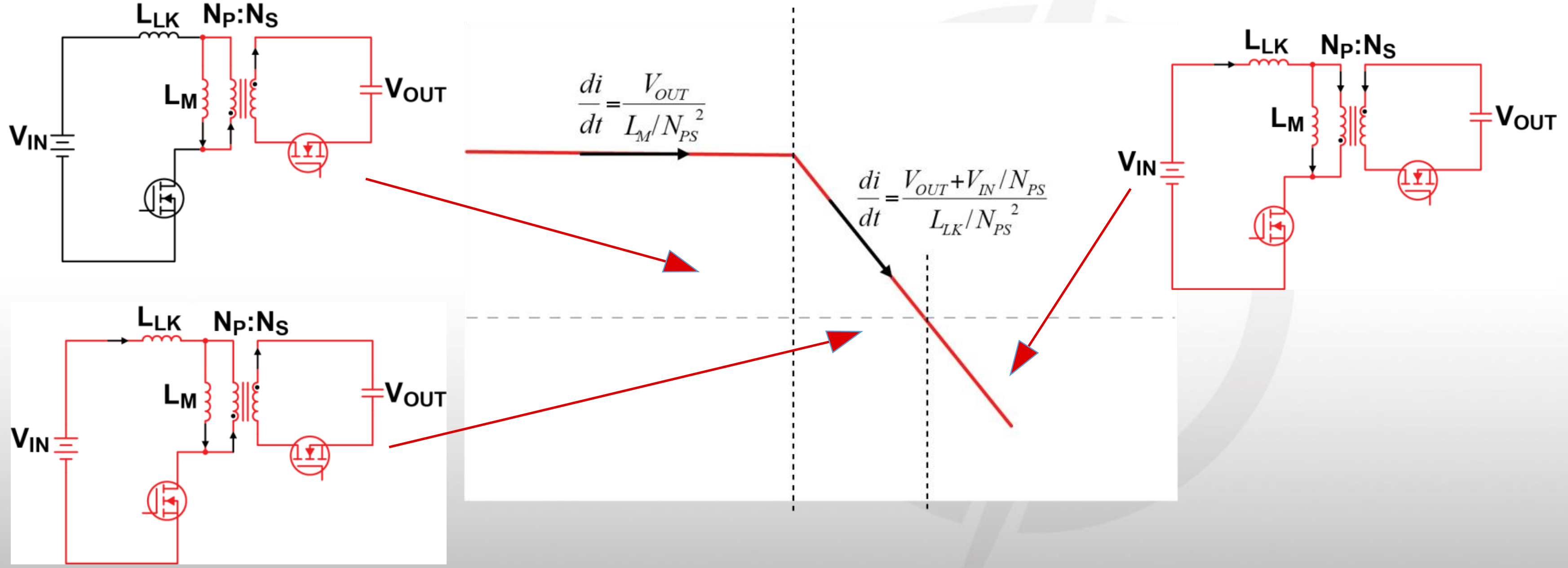
LLC



$$\frac{di}{dt} = \frac{V_O + \frac{V_{IN} + V_{CR}}{N_{PS}}}{\frac{L_R}{N_{PS}^2}}$$

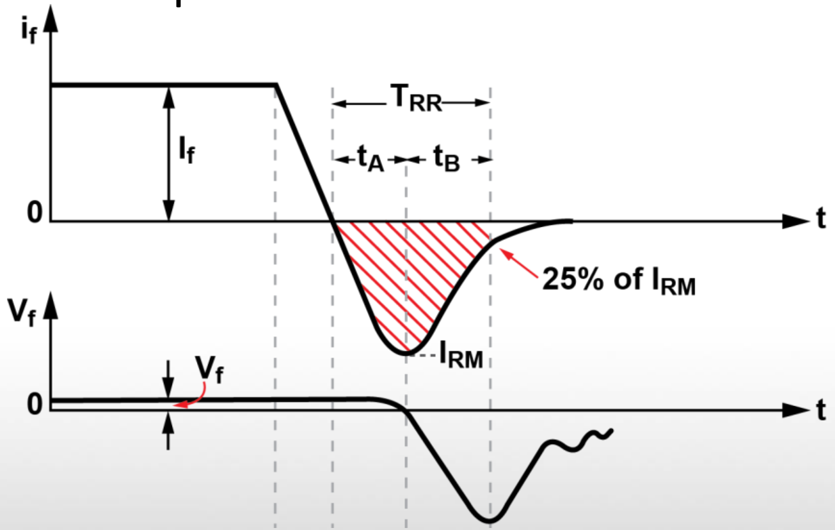
- High di/dt caused by high voltage and low inductance
- Need to turn off SR really fast

V_{DS} sensing operation in CCM



- di/dt is determined by leakage inductance
- Comparator needs to respond fast to minimize negative current

Diode operation in CCM



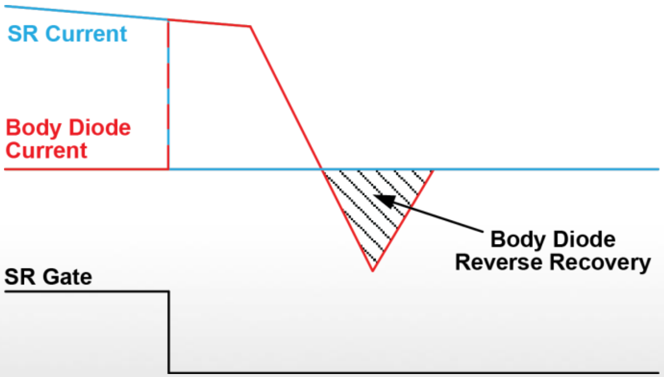
SR body diode and reverse recovery loss
(Based on 100 kHz estimation)

SR	Q_{RR}	Reverse recovery loss
SR1@ 30 V V_{DS}	127 nC	0.381 W
SR2@ 75 V V_{DS}	385 nC	2.887 W

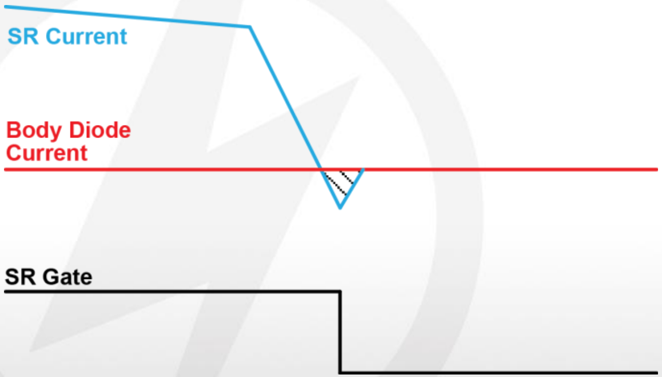
- Diode causes negative current due to reverse recovery
  - Fast reverse recovery time results in less negative current
  - Less Q_{RR} results in less switching loss
- Turning off SR too late is similar to large reverse recovery current

Early vs. late turn-off

Turn off SR early

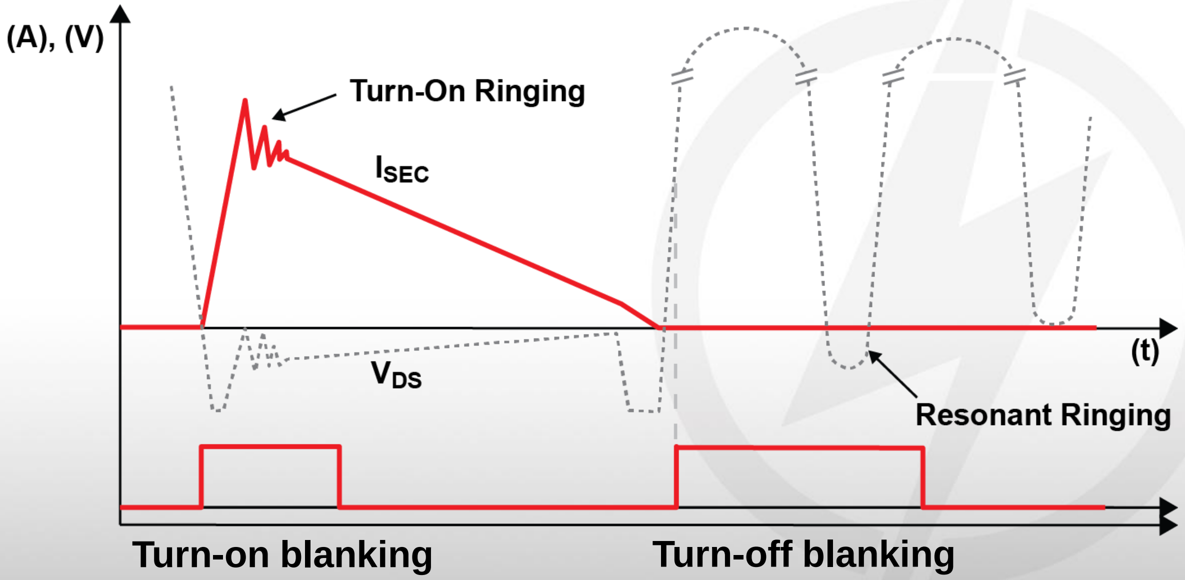


Turn off SR late



- 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

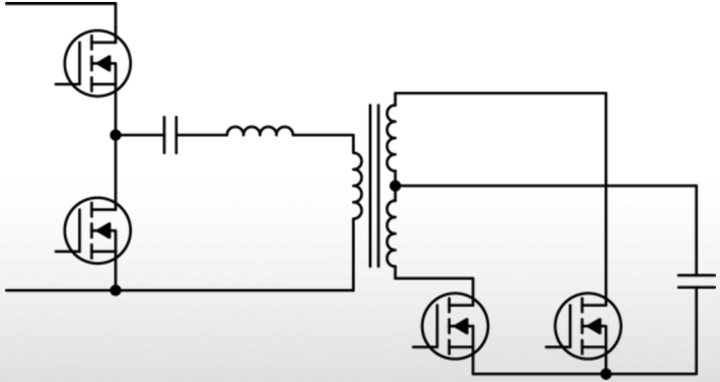
Dealing with ringing



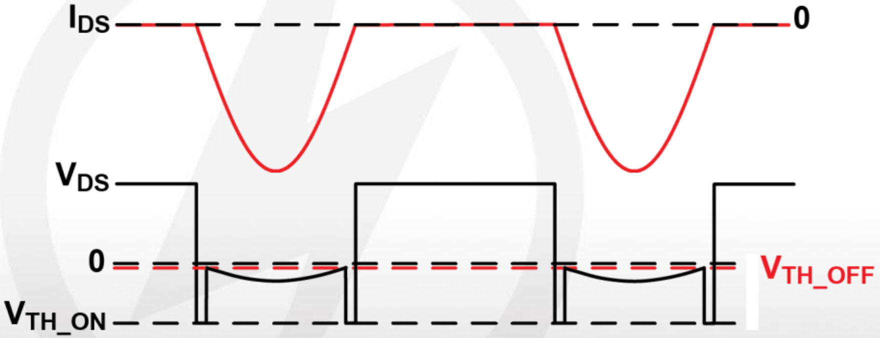
- Turn-on blanking is required to avoid false turn-off
- Turn-off blanking is required to avoid false turn-on

Special current shape, LLC converter

LLC resonant converter

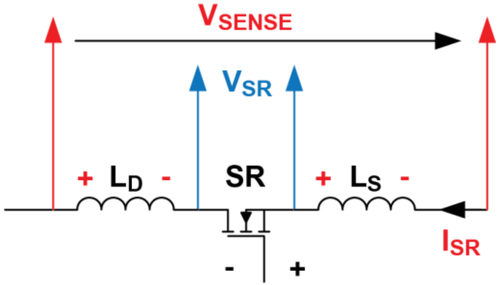


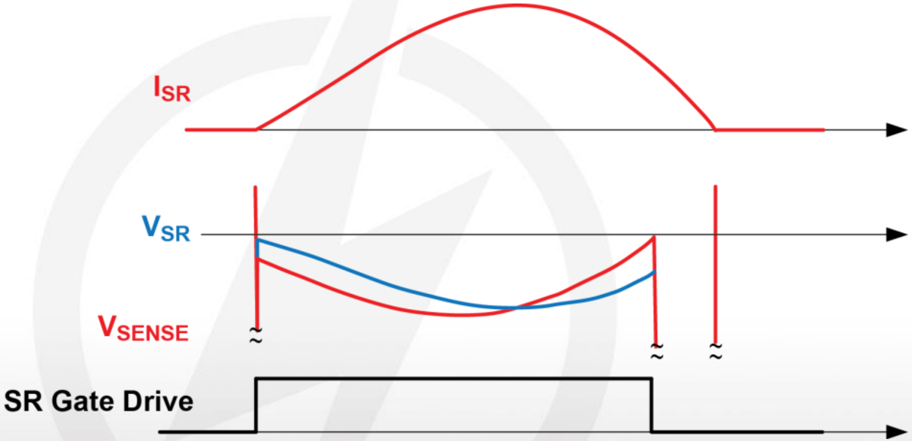
SR voltage and current



- 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

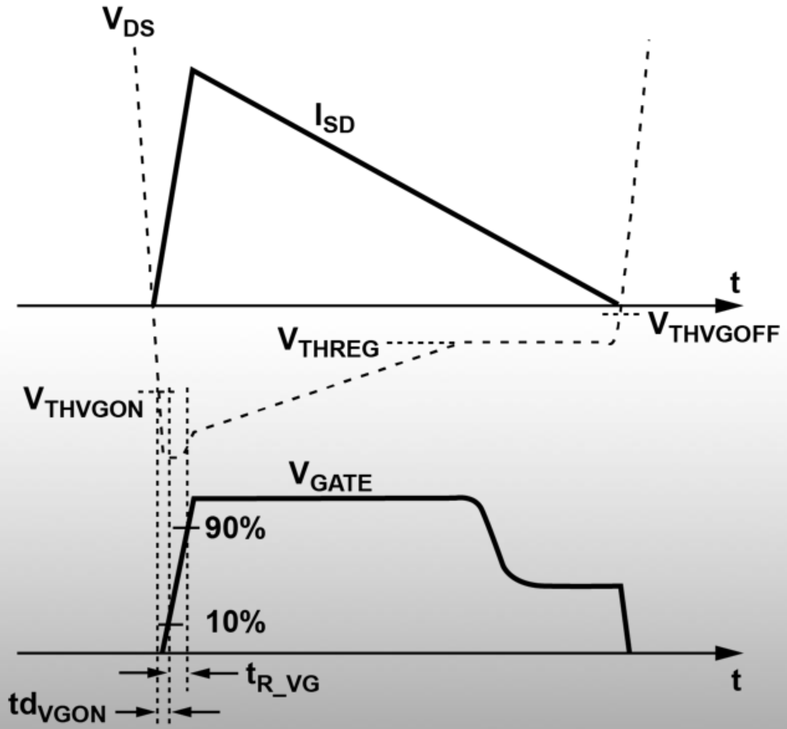




$$V_{SENSE} = -\left[I_{SR} \cdot R_{DS(ON)} + \left(L_D + L_S\right) \cdot \frac{dI_{SR}}{dt} \right]$$

- L_D and L_S are packaging parasitic inductances and can't be eliminated
- Negative 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

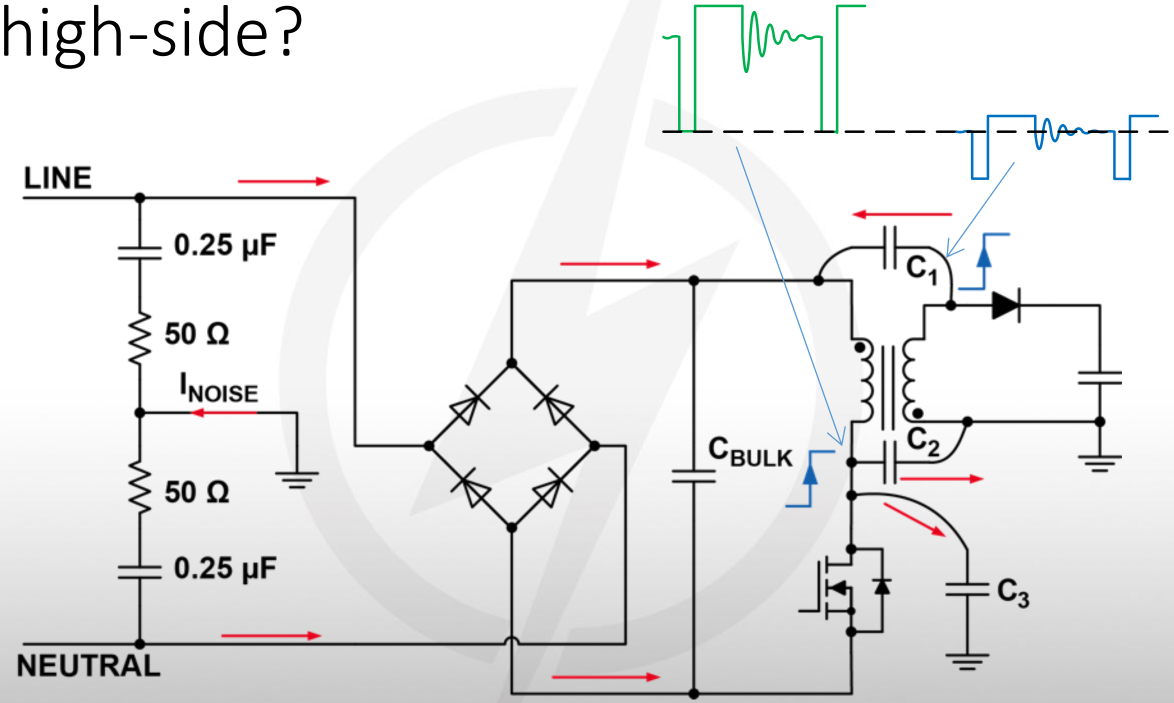
V_{DS} sensing and proportional gate drive – UCC24612, UCC24624



- 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

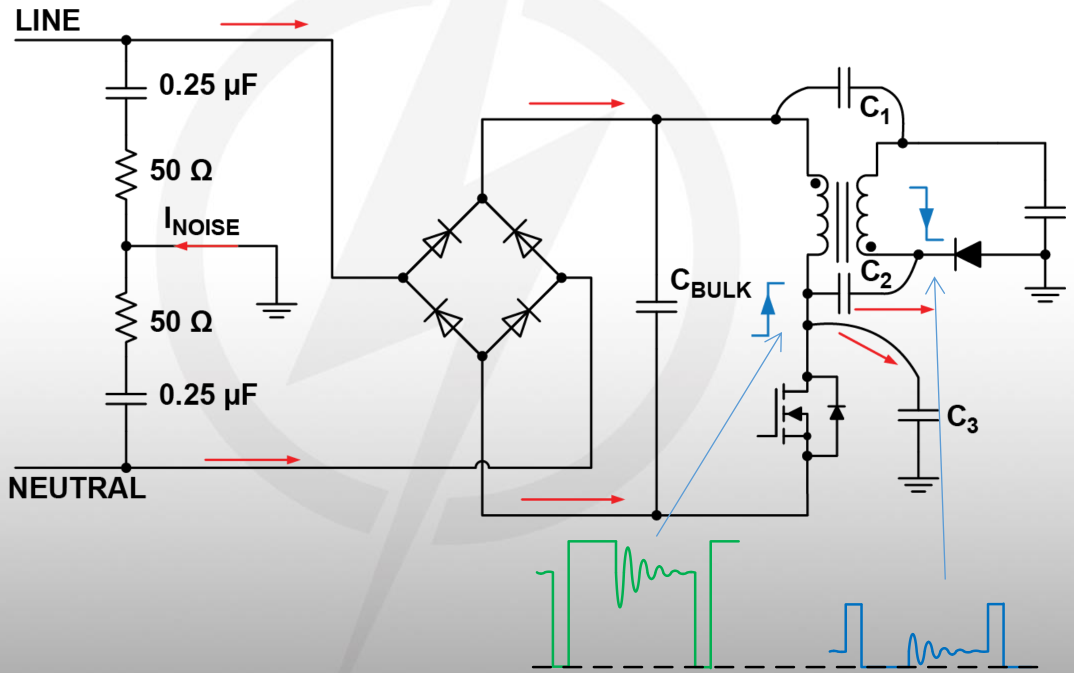
Where to put the SR high-side?

- 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

- "Control and design challenges for synchronous rectifiers," TI Power Supply Design Seminar 2017/8, http://www.ti.com/lit/slup378
- 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