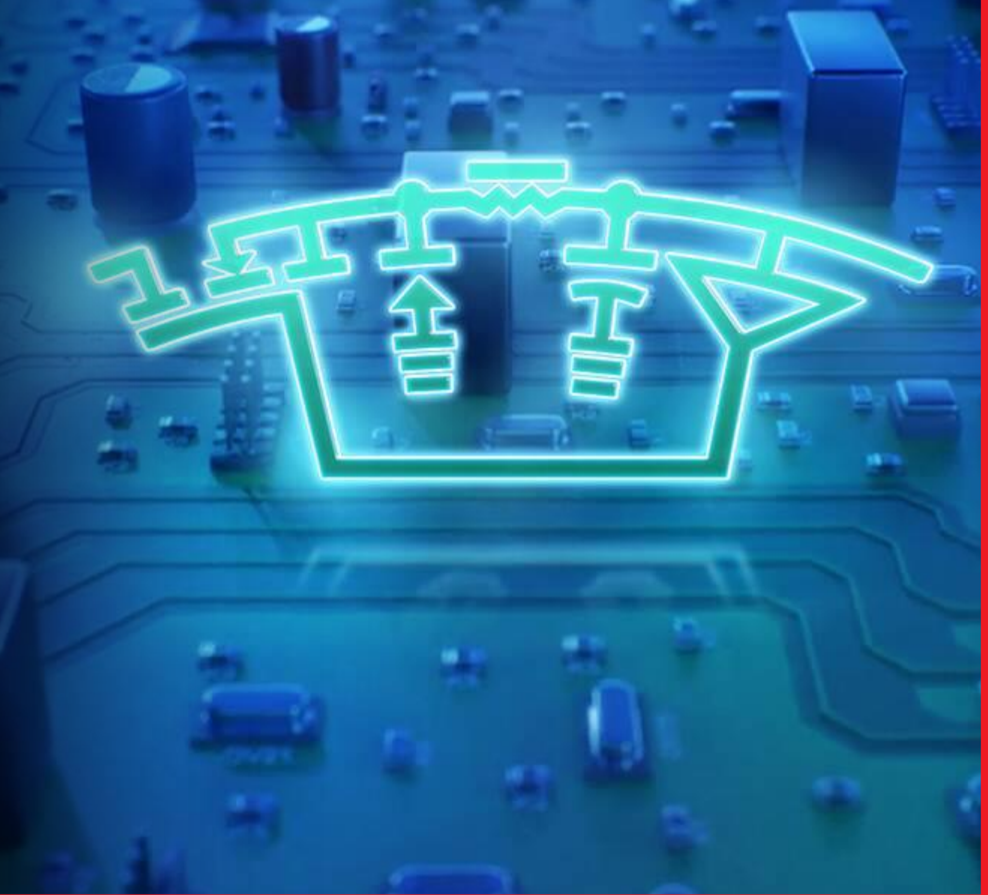
Texas Instruments

Power Supply Design Seminar

Phase-shifted full-bridge converter fundamentals



Authors

Sheng-yang Yu, Ben Lough, Richard Yin and Qing Ye

Agenda

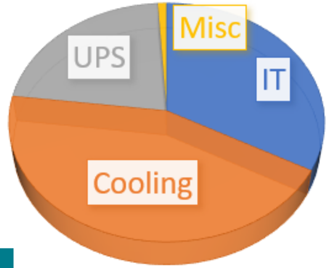
- Why a phase-shifted full bridge (PSFB)?
  - Power trends and the need for soft-switching converters
  - PSFB target applications
- PSFB operation and design considerations
  - How does a PSFB work, and how does it achieve soft switching?
  - Types of output rectifiers for PSFB
  - Voltage spikes on the output rectifier and clamping options
  - Voltage-mode and peak current-mode control
  - Synchronous rectifier (SR) modes of operation
  - Light load management
- PSFB design example
- Summary

Why a PSFB?

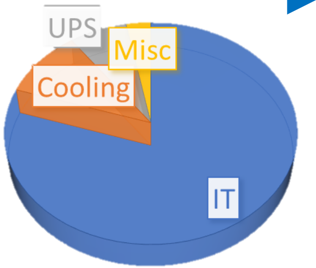
Power trends

- Demands for smaller size, lighter and higher-efficiency systems
- 80 Plus certification and Open Compute Project (OCP) Modular Hardware System-Common Redundant Power Supply (M-CRPS) specifications drive high efficiency

$$PUE = \frac{Total\ Datacenter\ Power}{Actual\ IT\ Power}$$

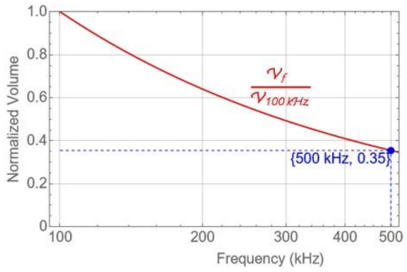


Power-use efficiency (PUE): 3



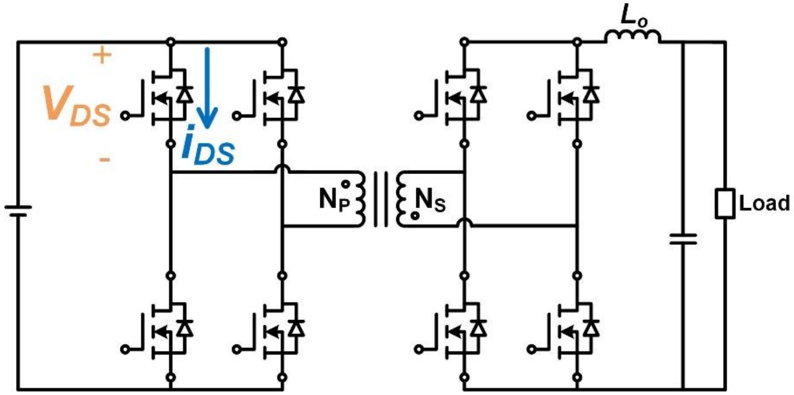
PUE: 1.25

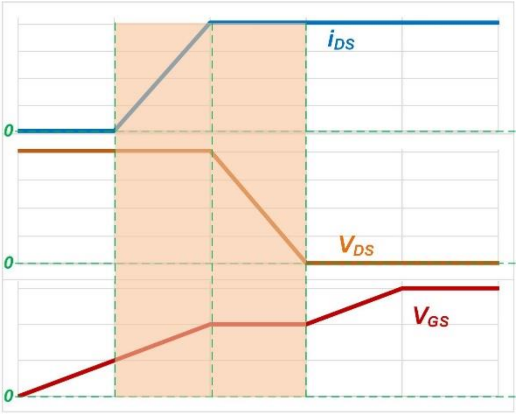
Efficiency at	10% load	20% load	50% load	100% load	Note
80 Plus Titanium	90%	94%	96%	91%	At 230-V_{AC} input
M-CRPS (<2,500 W)	90%	94%	96%	92%	At 240-V_{AC} input
M-CRPS (≥2,500 W)	90%	94%	96%	94%	At 240-V_{AC} input

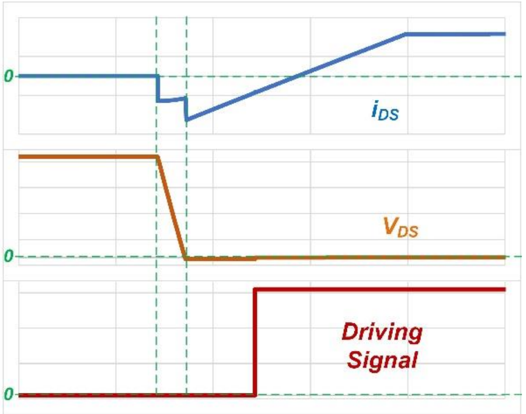


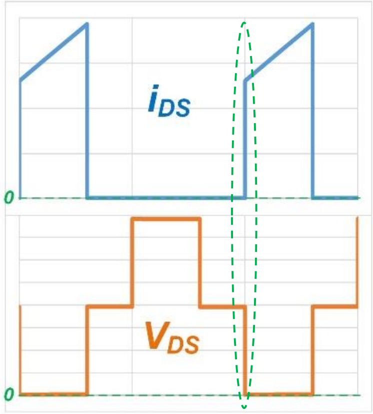
Motivation for soft switching

- Hard-switched turnon
  - MOSFET current/voltage overlap at turnon
  - Trade-off of turnon speed (t_{on} losses) vs. switch-node transient voltages (dV/dt) (EMI noise)
  - Ex: Hard-switched full-bridge converter (HSFB)
- Soft-switched turnon
  - MOSFET V_{DS} discharged before V_{GS} applied
  - Turnon speed not critical for high efficiency
  - Allows higher F_{sw}

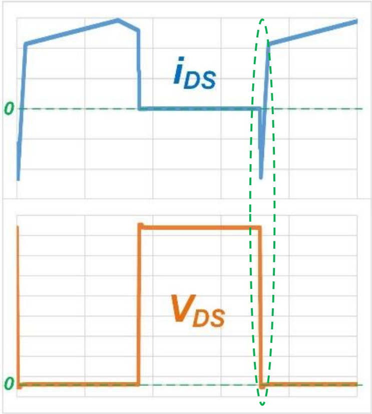






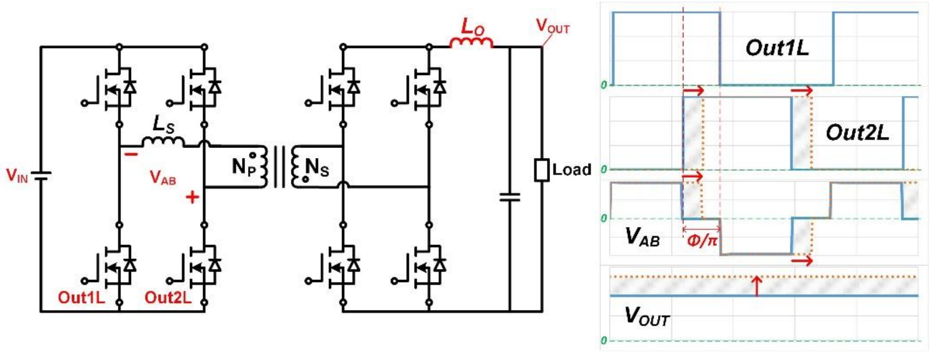


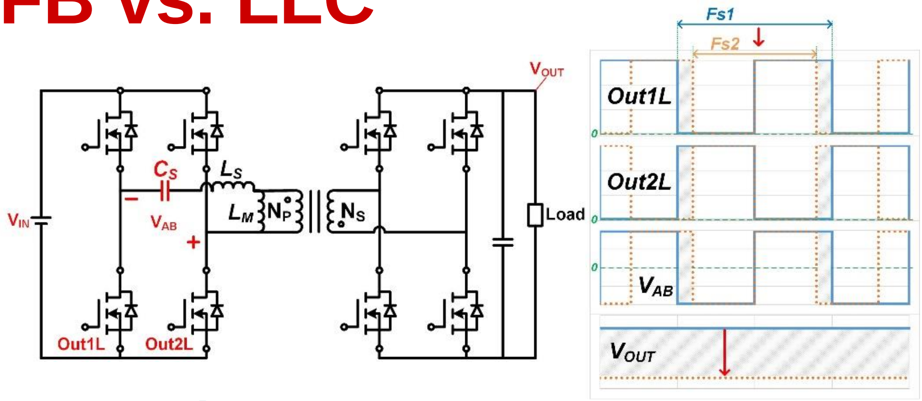
HSFB



PSFB

Topology comparison: PSFB vs. LLC





PSFB converter

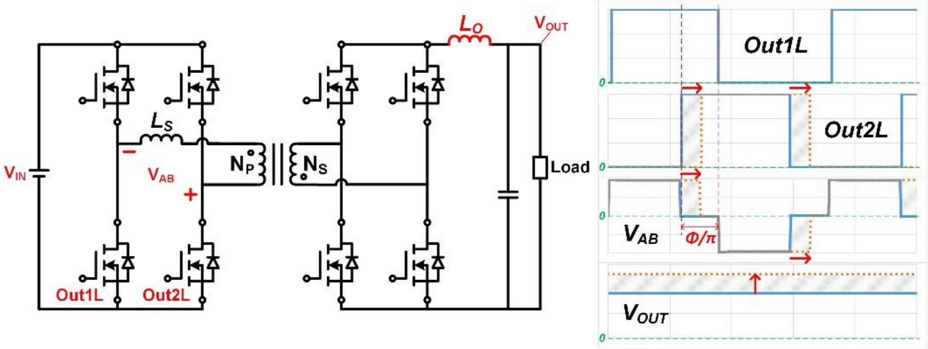
- Uses energy stored in L_S and L_O for zero voltage switching (ZVS)
- **Change phase angle for different V_{OUT}/V_{IN} gain**
- Advantages
  - **Faster transient response**
  - **Capable of wide voltage operating range**
  - Fixed frequency, easy SR control
- Disadvantages
  - Rectifier reverse recovery
  - Lost of ZVS on primary leg(s) at light loads
  - Higher rectifier voltage stress

LLC series resonant converter

- Uses energy stored in L_M for ZVS
- **Change F_{sw} for different V_{OUT}/V_{IN} gain**
- Advantages
  - Soft switching on output rectifier at $F_{sw} \le f_r$
  - Higher efficiency when $f_{sw} \approx f_r$
- Disadvantages
  - Larger secondary RMS currents
  - SR control more challenging
  - Limited operating range

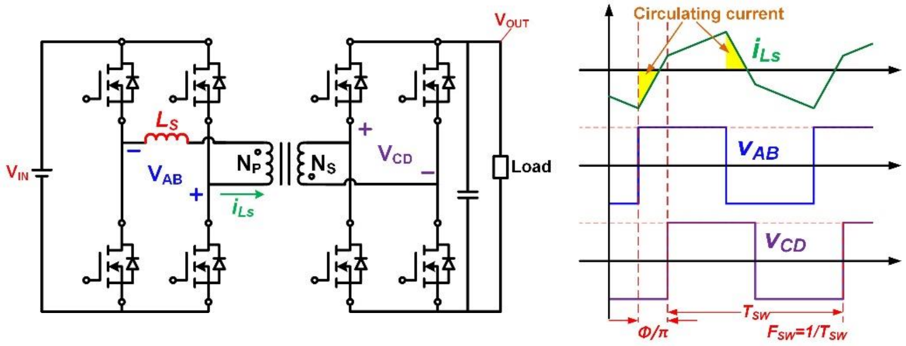
Series resonant f

Topology comparison: PSFB vs. DAB



PSFB converter

- Uses energy stored in L_S and L_O for ZVS
- **V_{OUT}/V_{IN} gain: determined by phase angle between the primary half bridges**
- Lower output ripple current than a dual active bridge (DAB)
- Higher output rectifier stress

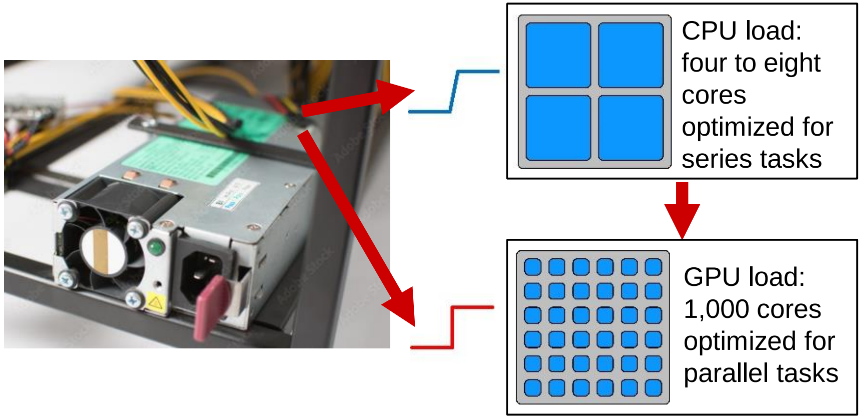


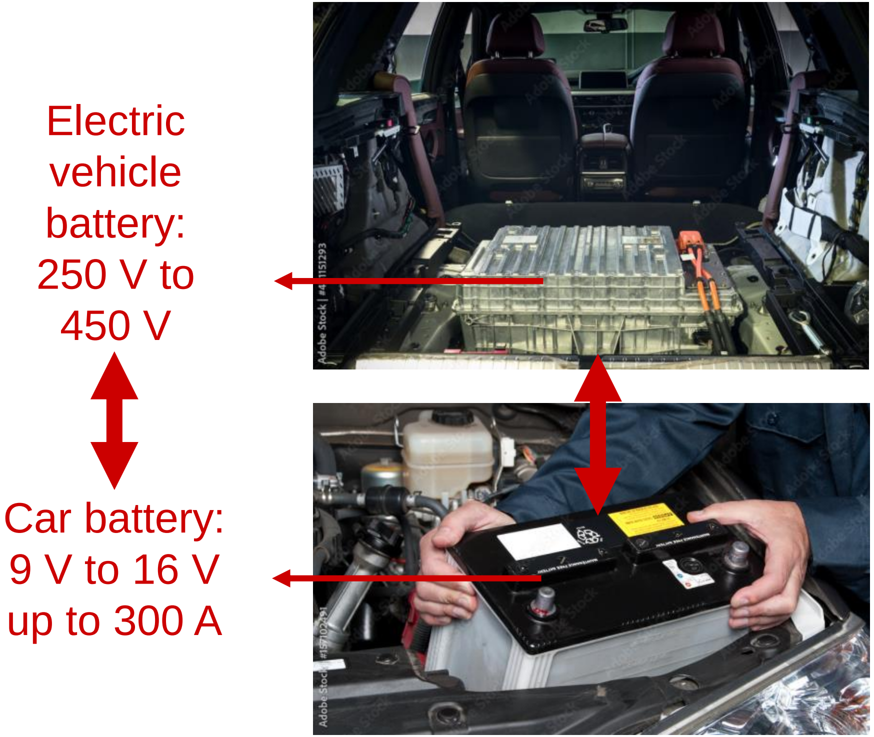
DAB converter

- Uses energy stored in L_S for ZVS
- **V_{OUT}/V_{IN} gain: determined by phase angle between transformer windings**
- Large circulating current with single-phase shift control
- Applying multiple phase-shift control will lower the circulating current
- Higher output ripple current than a PSFB

PSFB target applications

- PSFB can be a good fit for applications with:
  - Fast transient requirements
    - ≥10 A/µs in a server power-supply unit (PSU) 12-V bus with a graphics processing unit (GPU) load
  - Wide input/output ranges
    - High-power battery applications

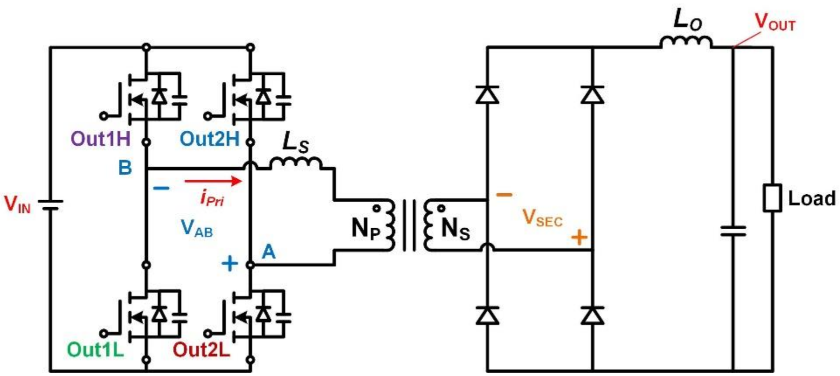


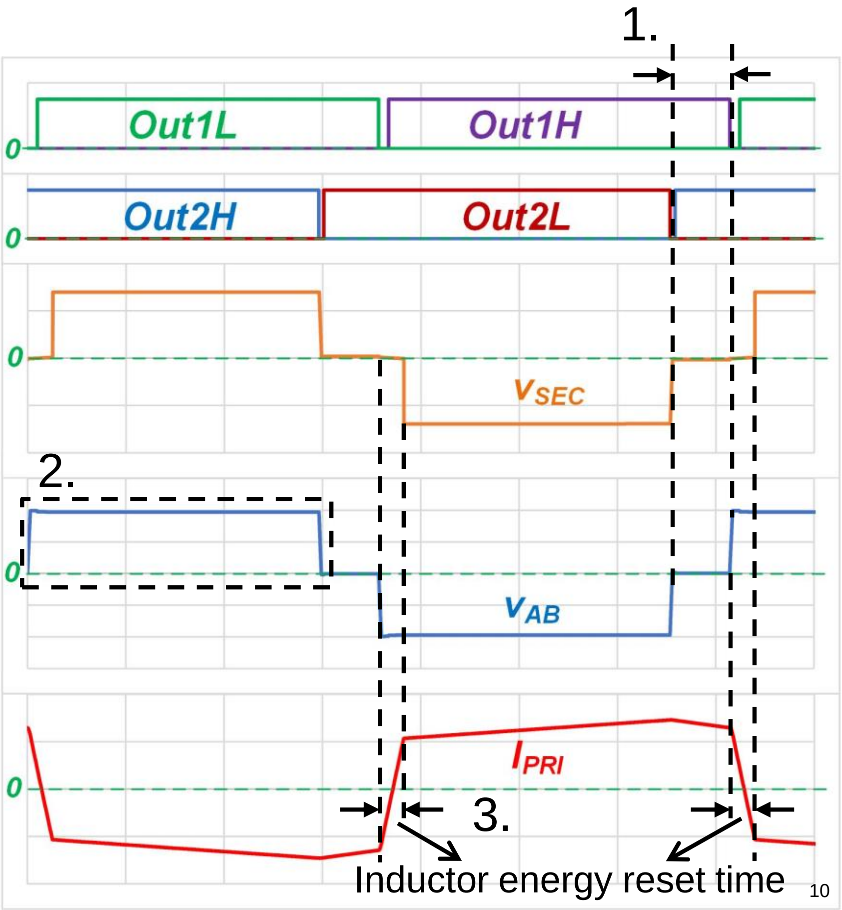


Soft switching and operation

How does a PSFB work?

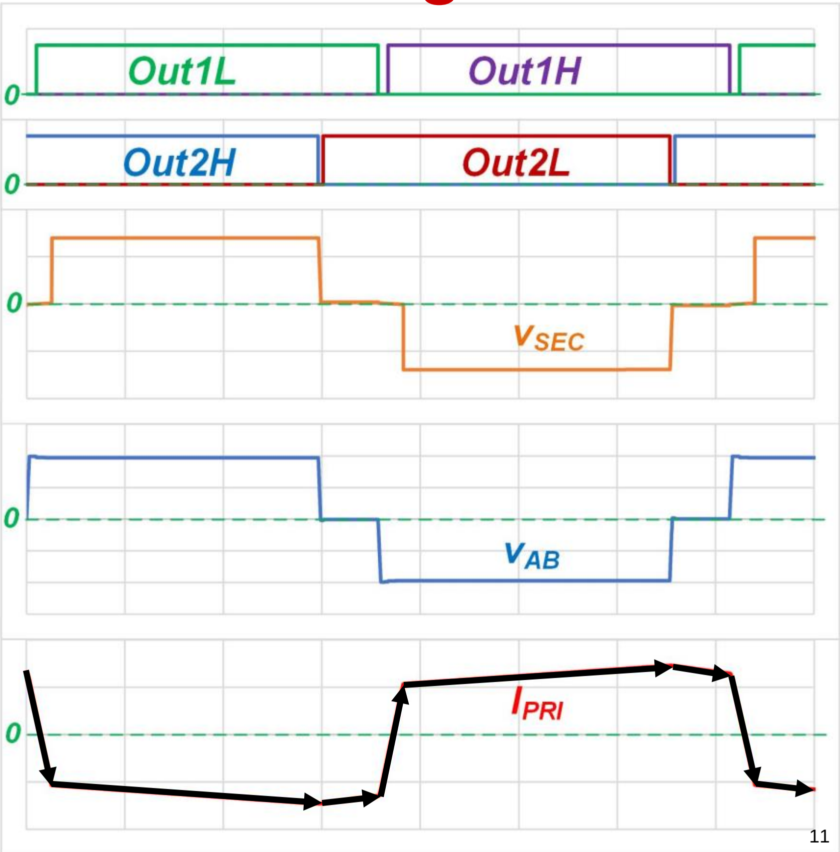
1. Phase shifts to control nonzero voltage transformer pulse width
2. Buck operation on output stage for regulation
3. Duty-cycle loss limits effective duty cycle

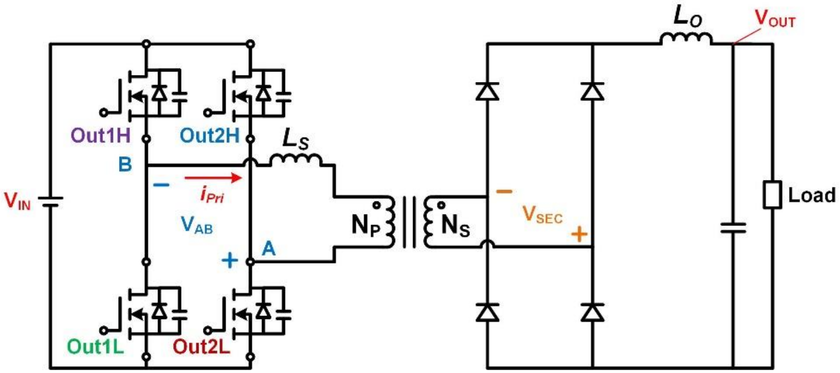




How does a PSFB achieve soft switching?

- Allows freewheeling current
  - L_S and L_O energy can be used for ZVS





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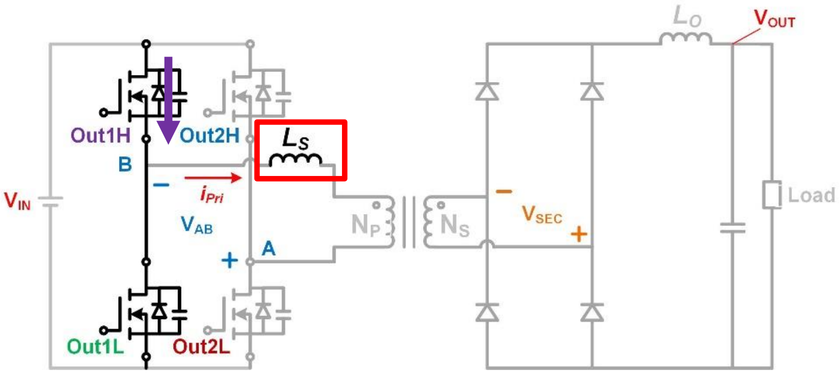
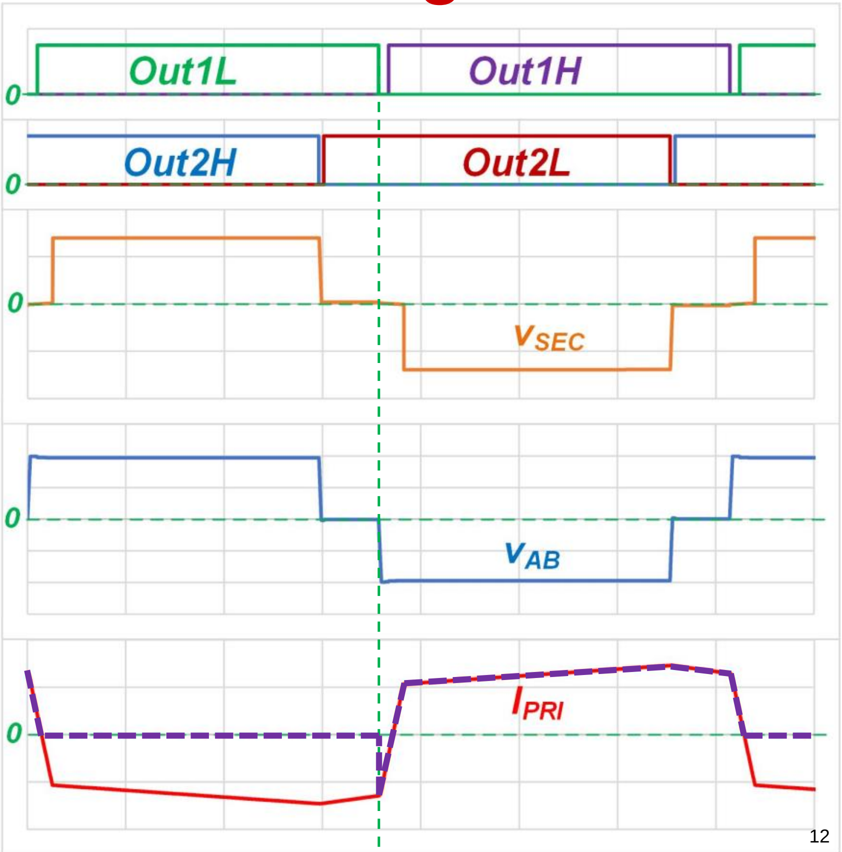
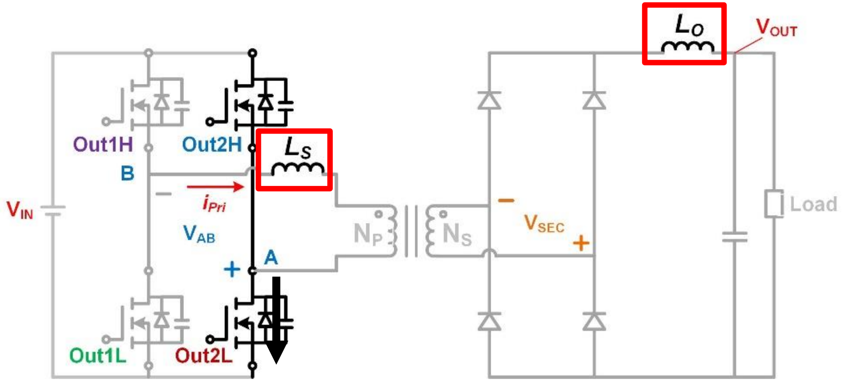
- Leg 1 ZVS: mainly relies on L_S

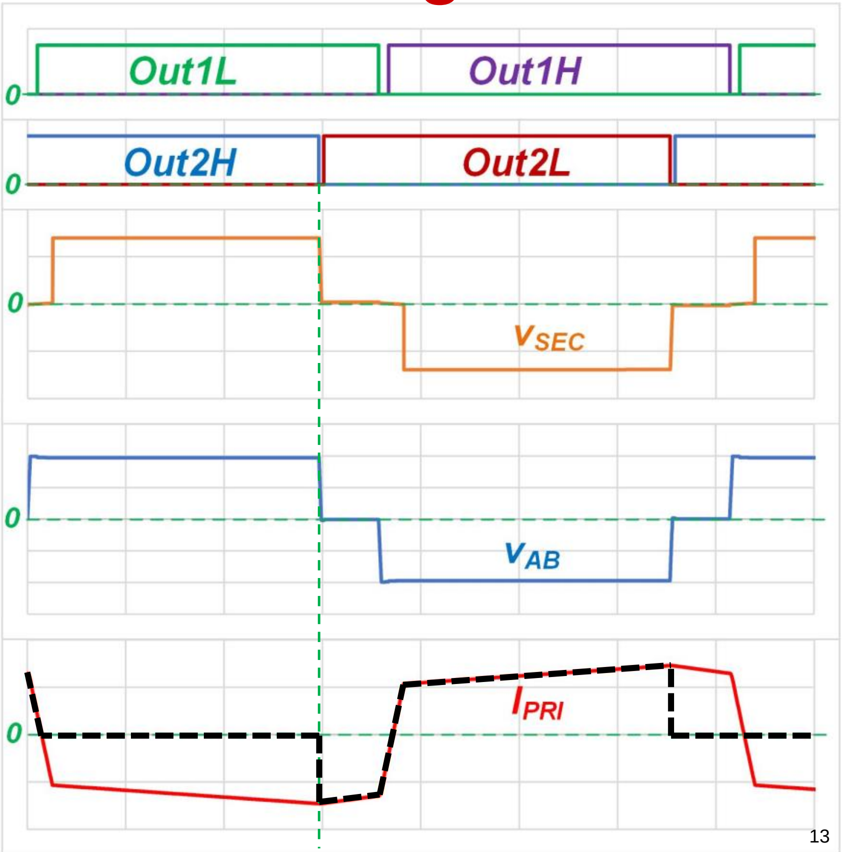




How does a PSFB achieve soft switching?

- Allows freewheeling current
  - L_S and L_O energy can be used for ZVS
- Leg 1 ZVS: mainly relies on L_S
  - Easy to **lose** ZVS at light loads
- Leg 2 ZVS: counts on both L_S and L_O
  - Easy to **keep** ZVS at light loads

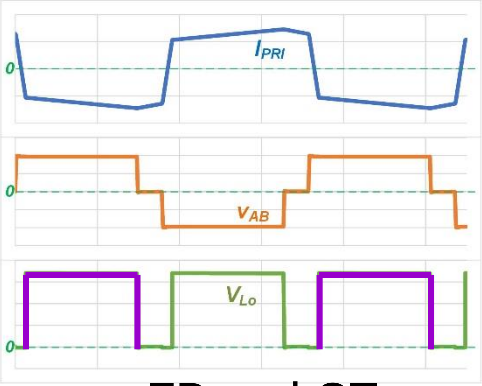




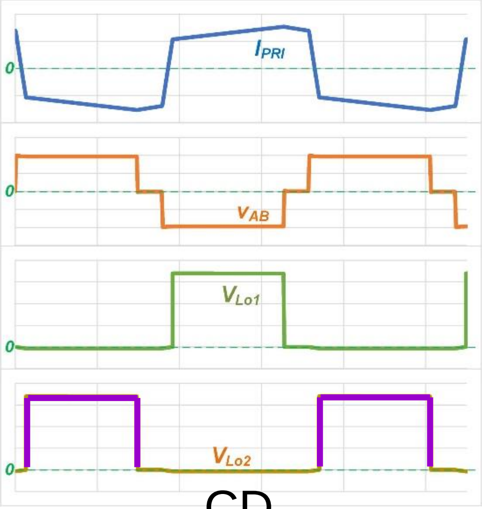
Rectifier and clamp

Output rectifiers for a PSFB

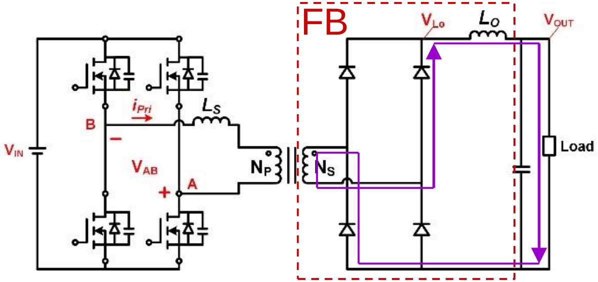
- There are three types of rectifiers:
  - Full-bridge (FB) rectifier
  - Center-tapped (CT) rectifier
  - Current-doubler (CD) rectifier

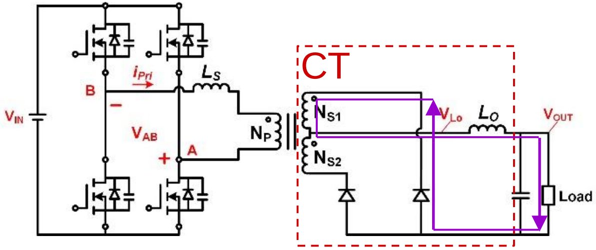


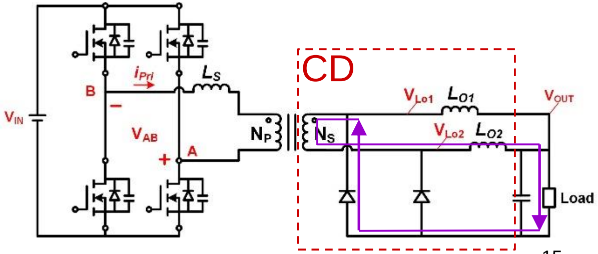
FB and CT



CD







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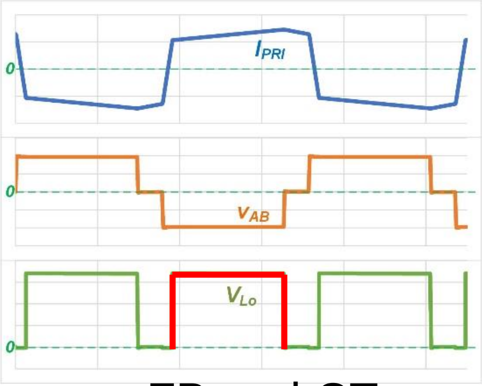
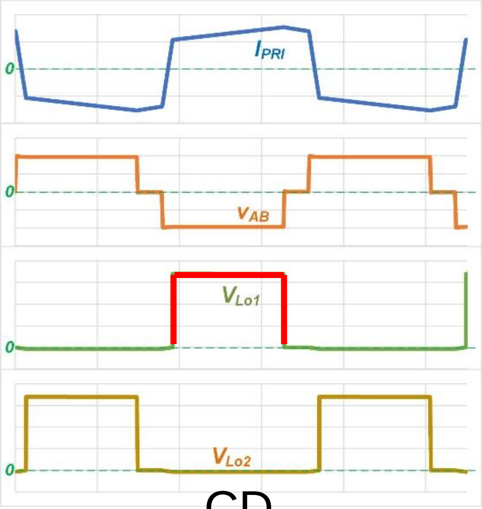


FB and CT



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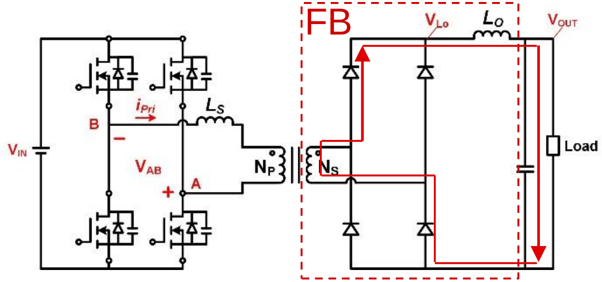
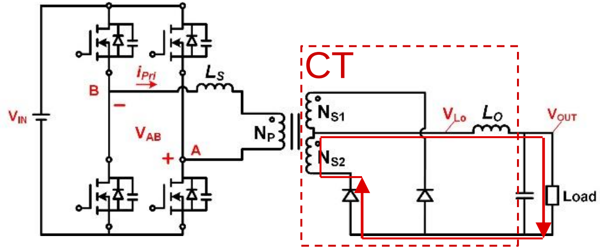
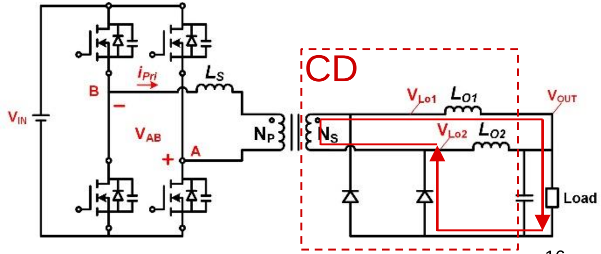
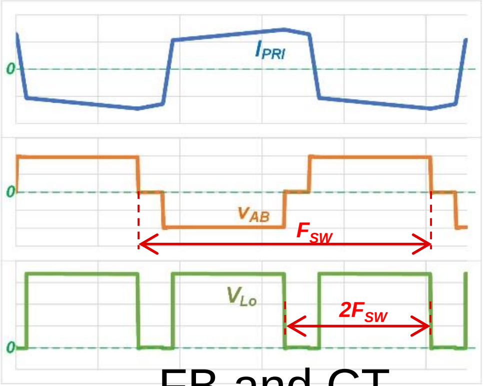




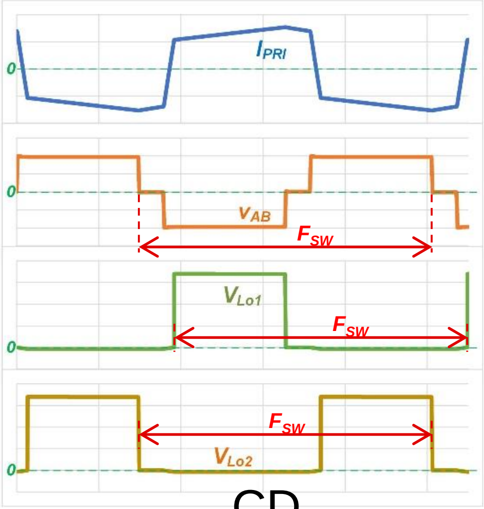


Output rectifiers for a PSFB

Type	Inductor F_{SW}	D range	Ns	Rec	Lo	Characteristics
FB	$2 \times F_{SW,PRI}$	0-100%	1	4	1	Better transformer utilization rate, good for high V_O
CT	$2 \times F_{SW,PRI}$	0-100%	2	2	1	Lowest component count, lower transformer utilization rate
CD	$1 \times F_{SW,PRI}$	**0-50%**	1	2	**2**	Better transformer utilization rate, half i_{Lo}



FB and CT



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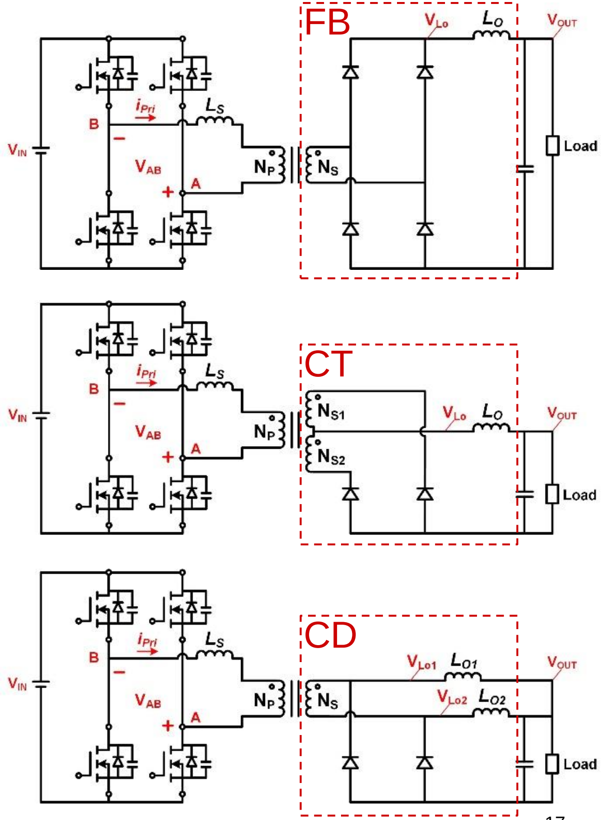
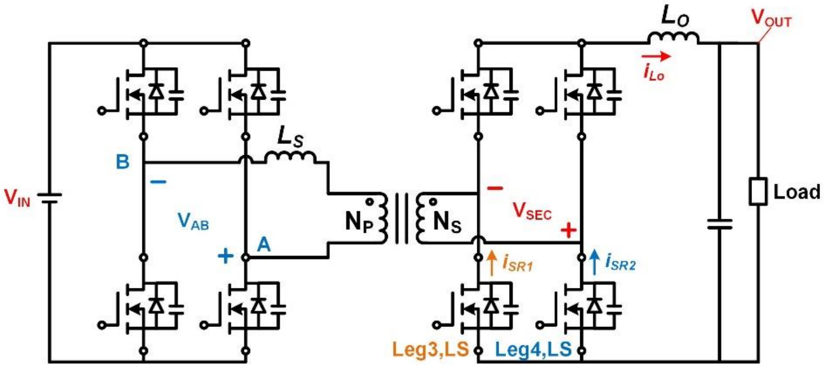
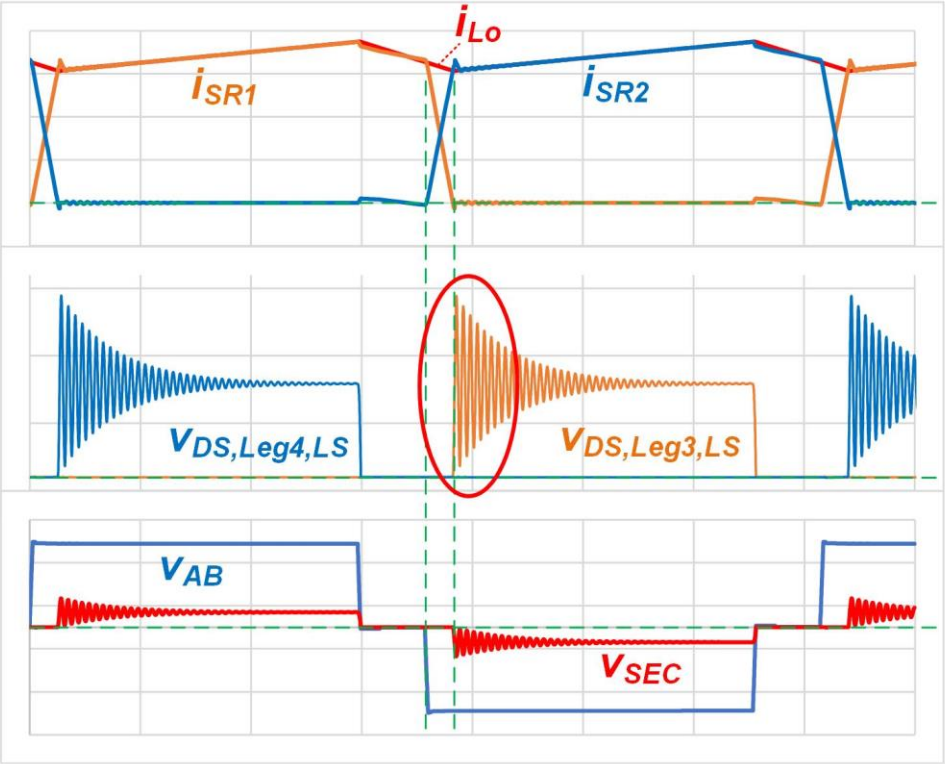


Voltage spikes on the output rectifier

- Transformer winding series inductor resonant with rectifier C_{oss}
- Voltage peak could be as high as $2V_{IN}\frac{N_S}{N_P}$





Clamp rectifier voltage spikes: Passive

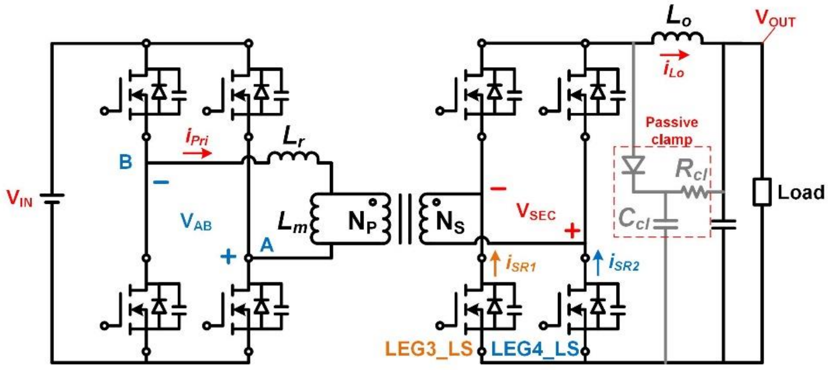
- C_{clamp} as an ideal voltage source

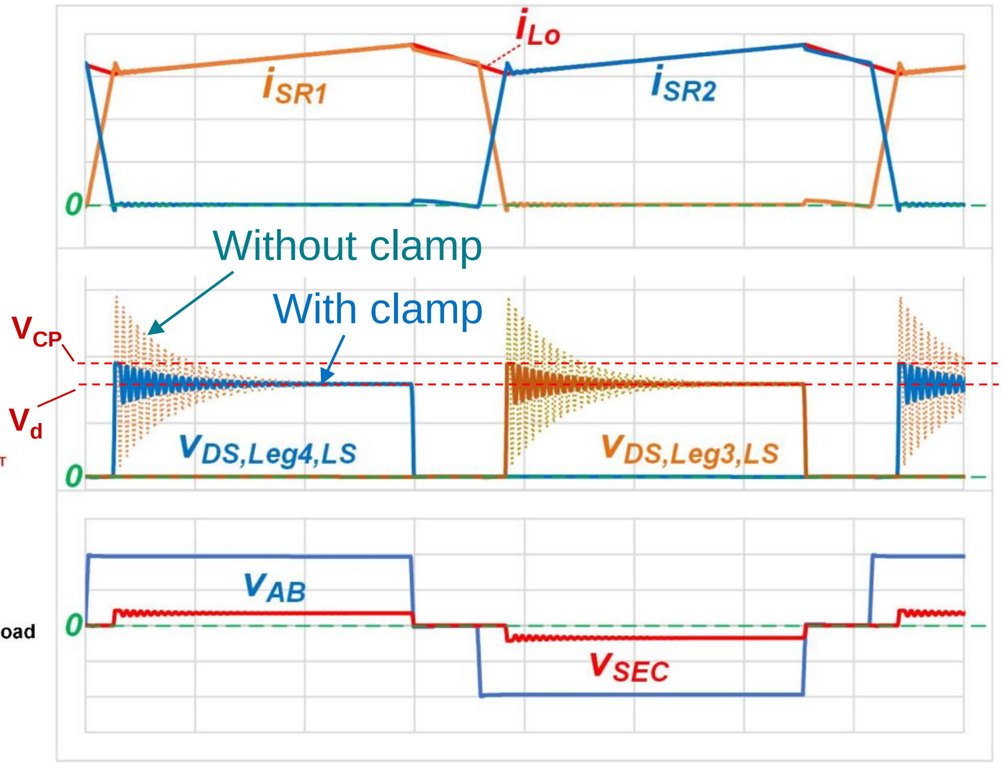
$$R_{cl} = \frac{(V_{CP} - V_{OUT})(V_{CP} - V_d)}{C_{cl} V_{CP} (2V_d - V_{CP}) F_{sw}}$$

- Clamp resistor dissipates

$$P_{R_{cl}} = \frac{(V_{CP} - V_{OUT})^2}{R_{cl}}$$

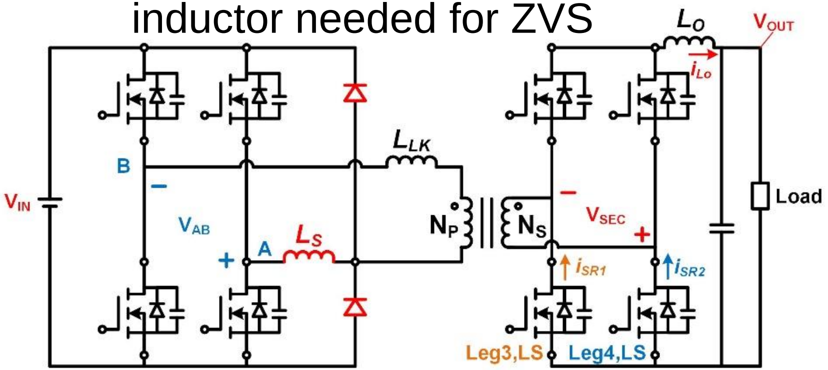
Smaller R_{cl}
$\Rightarrow$ Lower V_{CP}
$\Rightarrow$ Larger P_{Rcl}

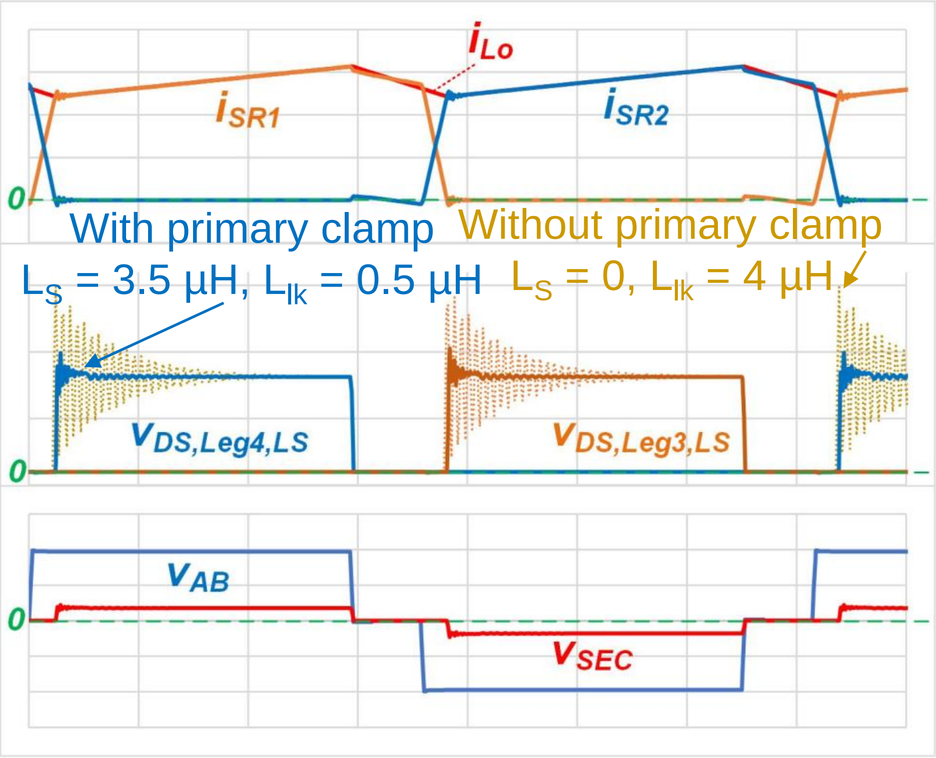




Clamp rectifier voltage spikes: Primary clamp

- Pros:
  - Allows L_S energy recycling
  - Allows well-coupled transformer windings for lower rectifier voltage stress
- Cons:
  - Additional diodes and discrete series inductor needed for ZVS

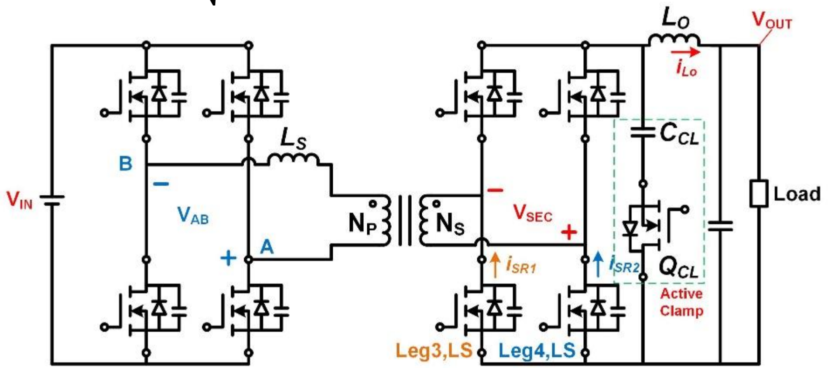


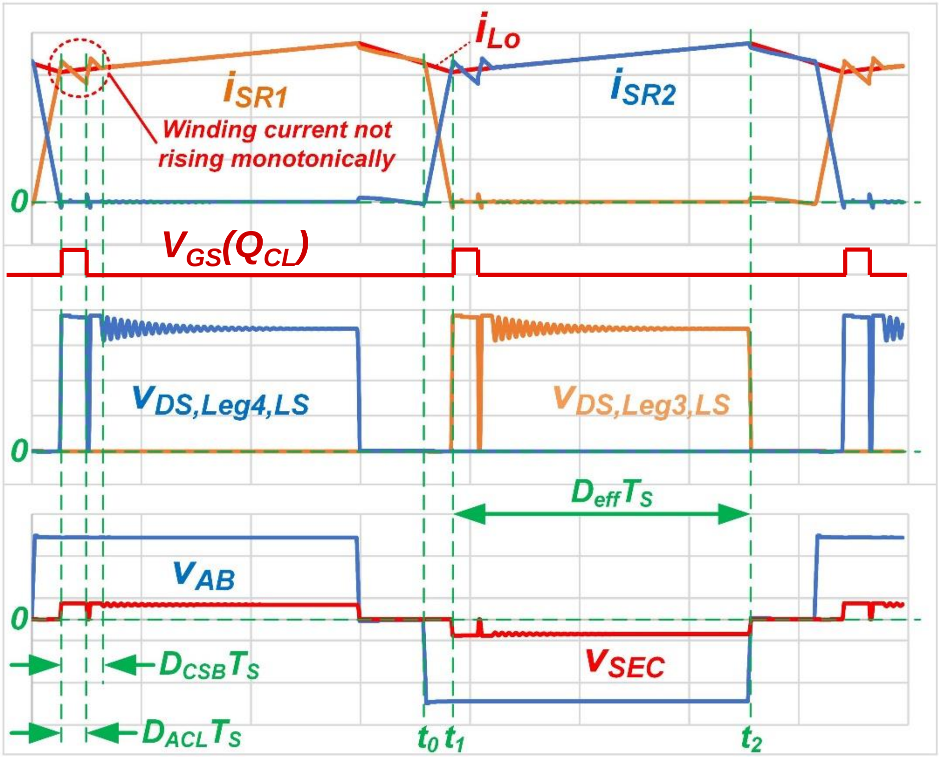


Clamp rectifier voltage spikes: Active clamp

- Turn on Q_{CL} after t_1 to allow rectifier voltage to clamp to $V_{C_{CL}}$
- Size C_{CL} capacitance for relatively low ripple voltage:

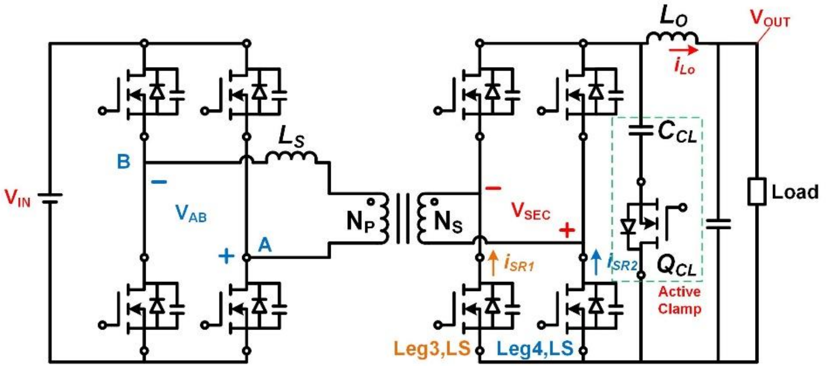
$$2\pi\sqrt{\left(\frac{N_S}{N_P}\right)^2 \times L_S \times C_{CL}} \gg T_S$$

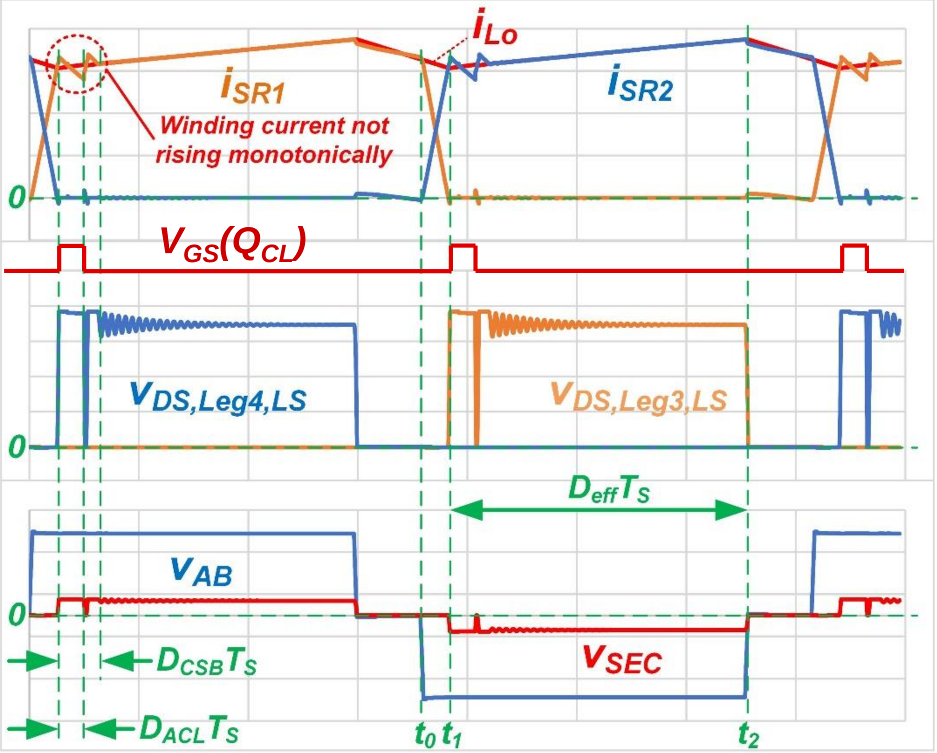




Clamp rectifier voltage spikes: Active clamp

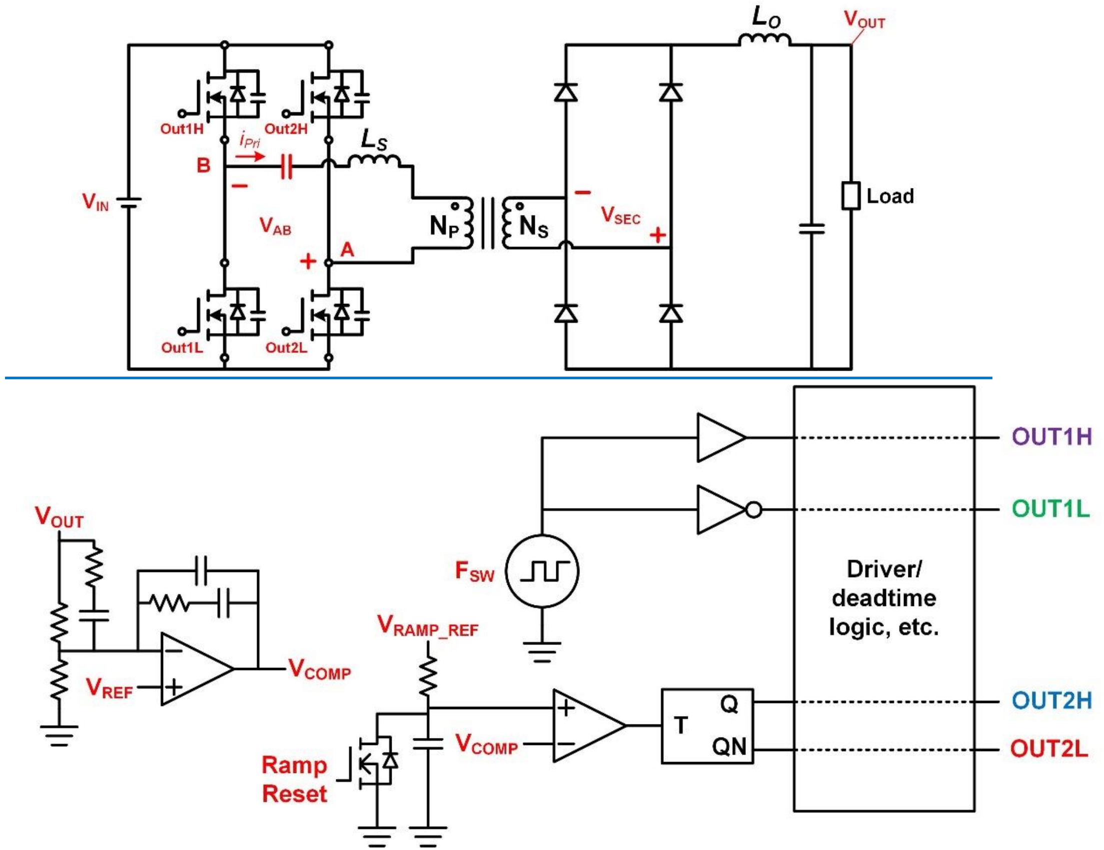
- Creates current distortion on i_{PRI} and i_{SR}
  - Makes peak current-mode control difficult
- Q_{CL} only needs to conduct for a very short period to clamp
  - Longer $D_{ACL}T_S$ => larger i_{CL} and wider nonmonotonic current duration

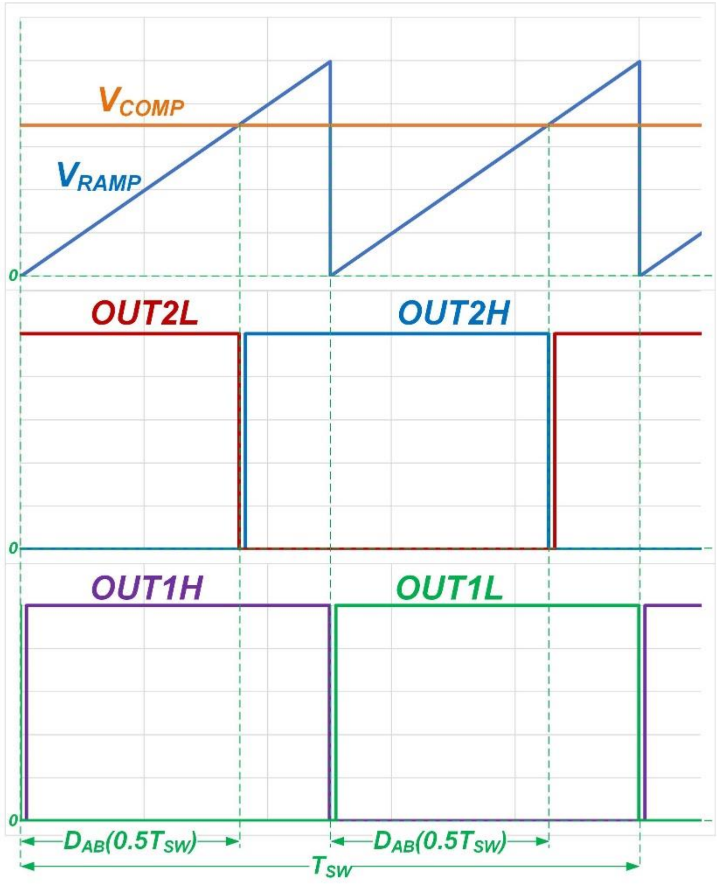




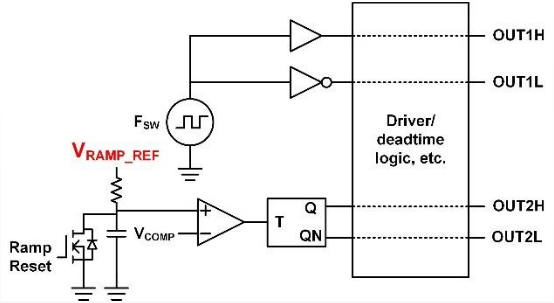
Control

PSFB control



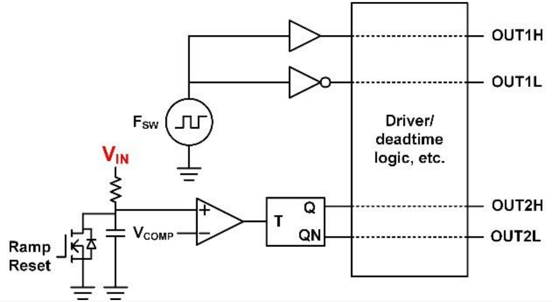


Modes of PSFB control



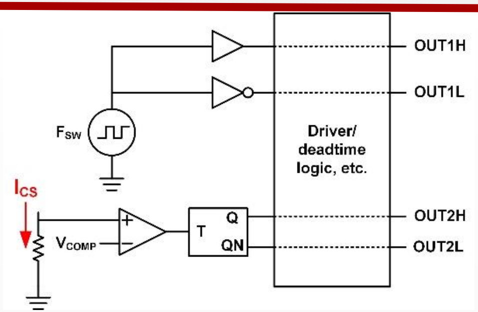
Voltage-mode control

- One high-side/low-side pair directly controlled by clock at the switching frequency
- Second high-side/low-side pair controlled by T flip-flop



Voltage-mode control with feedforward

- Voltage ramp reference is fed from V_{IN} or a voltage proportional to V_{IN}
- Immediate response to changes in input voltage

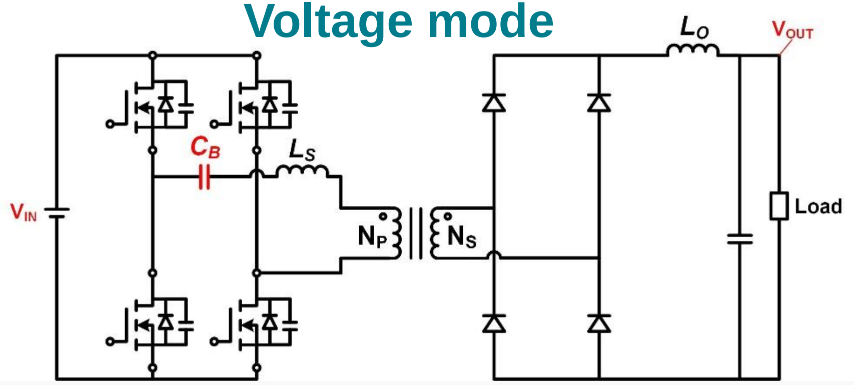


Peak current-mode control

- Current information from power stage replaces ramp signal
- Current-sense (CS) resistor plus amplifier or CS transformer common methods

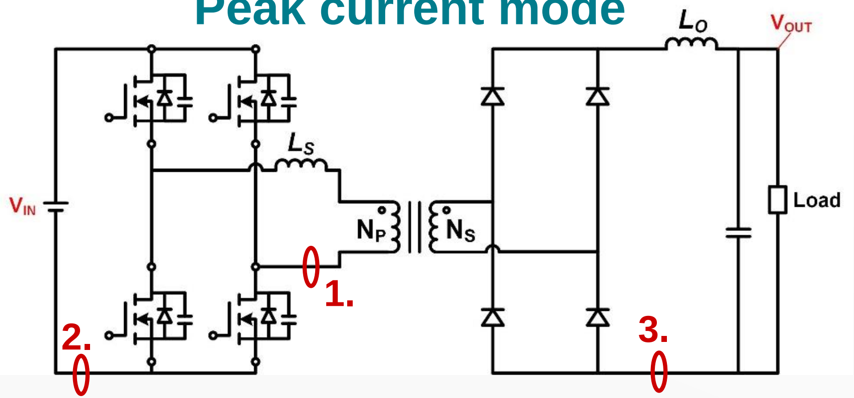
Voltage mode vs. peak current mode

Voltage mode



- DC blocking capacitor, C_B, is required to prevent transformer saturation
- Blocking capacitor will increase PSU footprint and voltage stress on SRs

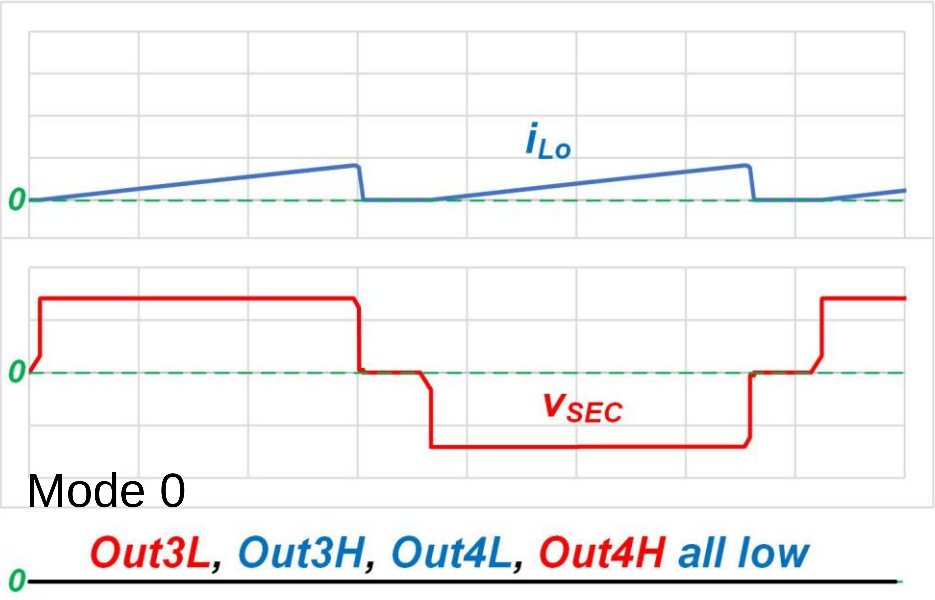
Peak current mode

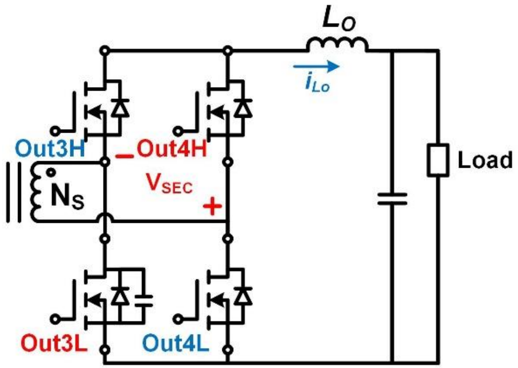


1.
   - CS transformer core automatically resets
   - Contains no DC current information
2.
   - CS transformer reset more challenging
   - Higher parasitic loop inductance
3.
   - Resistor plus CS amplifier is common
   - Missing magnetizing current information

Different modes of SRs in a PSFB

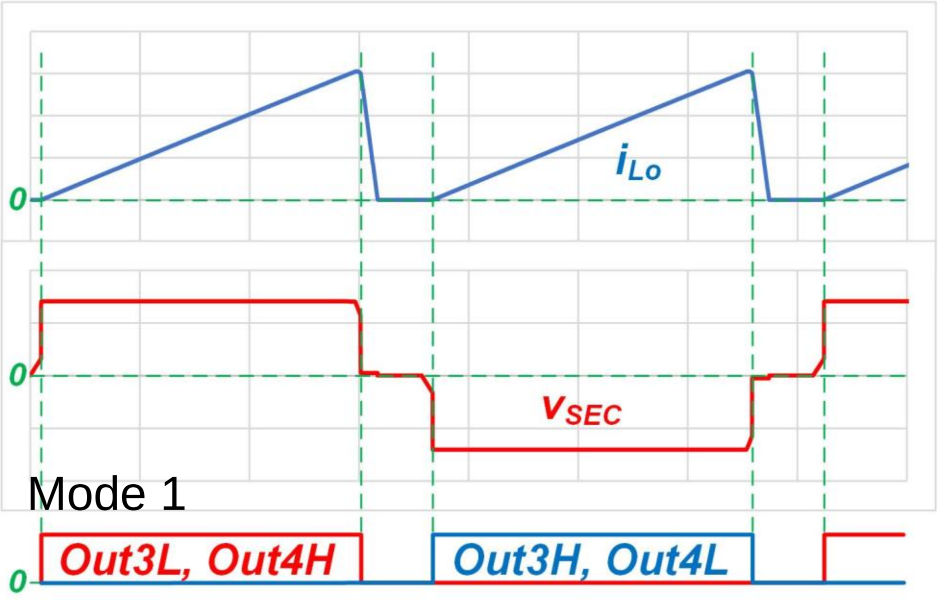
- Mode 0: diode conduction (discontinuous conduction mode [DCM])

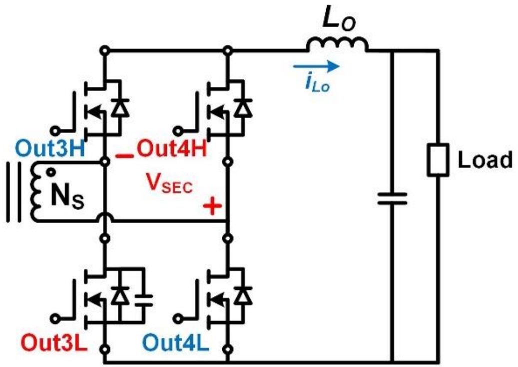




Different modes of SRs in a PSFB

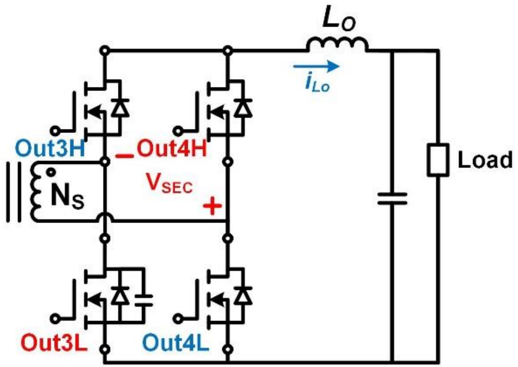
- Mode 1: SR channel conduction only during inductor charging period
  - Avoids reverse current conduction

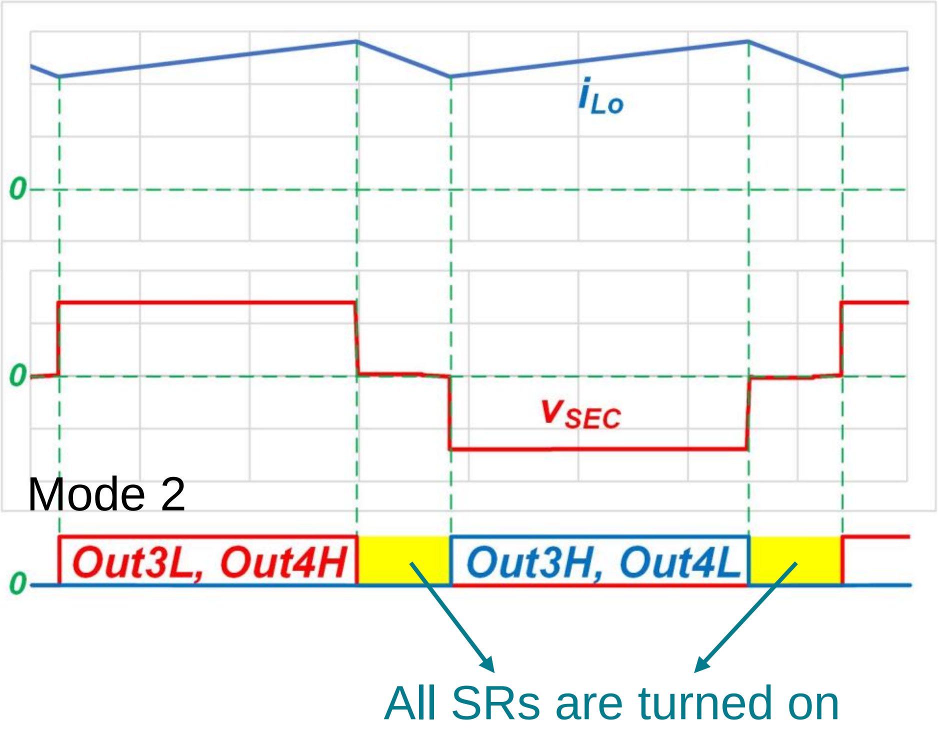




Different modes of SRs in a PSFB

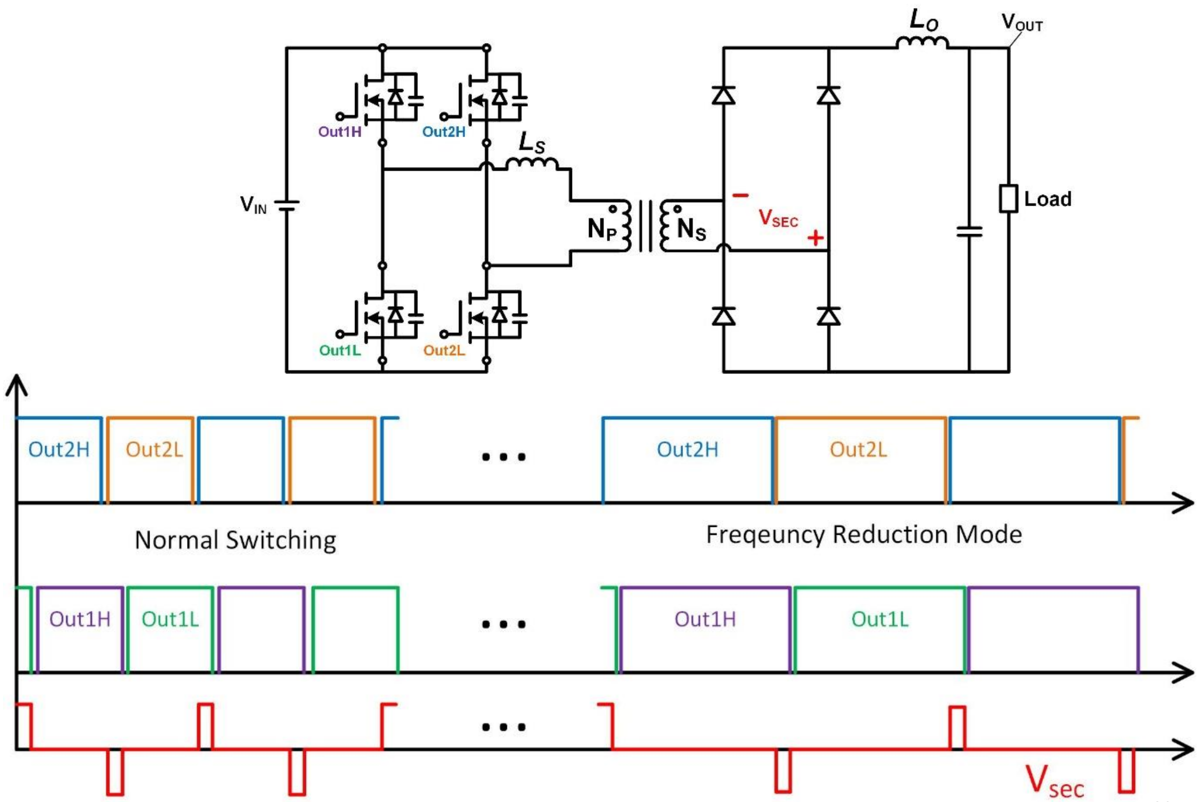
- Mode 2: turn on all rectifiers/FETs during freewheeling period
  - Lower conduction losses at heavy loads





Light-load management: Frequency reduction mode

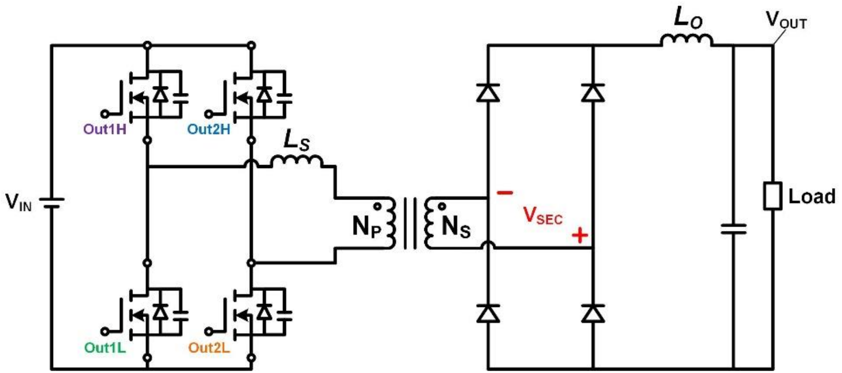
- The PSFB continuously switches
- Able to reduce effective duty cycle while maintaining a minimum on-time
- Gate-drive transformer not recommended (saturation)

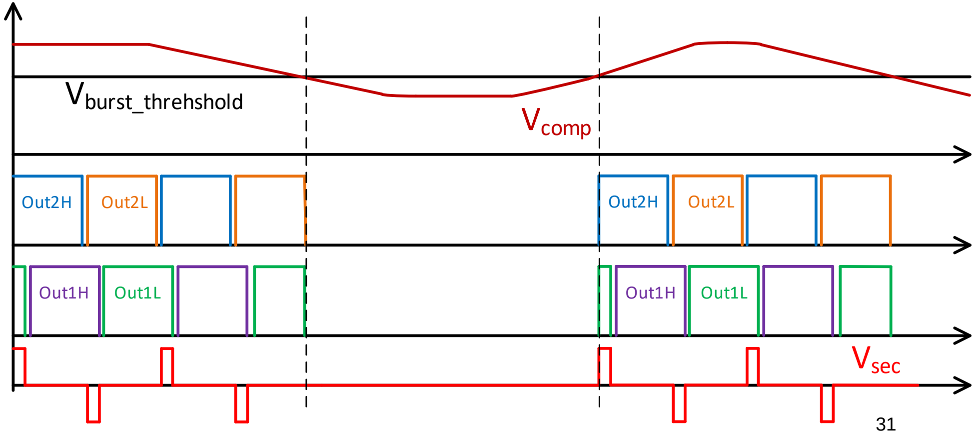


Light-load management: Hysteretic burst mode

- When V_{comp} becomes <$V_{burst_}$threshold, the PSFB stops switching
- When V_{comp} becomes >$V_{burst\_threshold}$, the PSFB resumes switching

	Frequency reduction mode	Hysteretic burst mode
Transient response	Reduced control loop bandwidth when in FR mode	Fast
CPU utilization	Large, need to compute required F_{SW}	Small, enable/disable pulse-width modulation (PWM) based on comparator
Output ripple	Small	Larger compared to FR mode



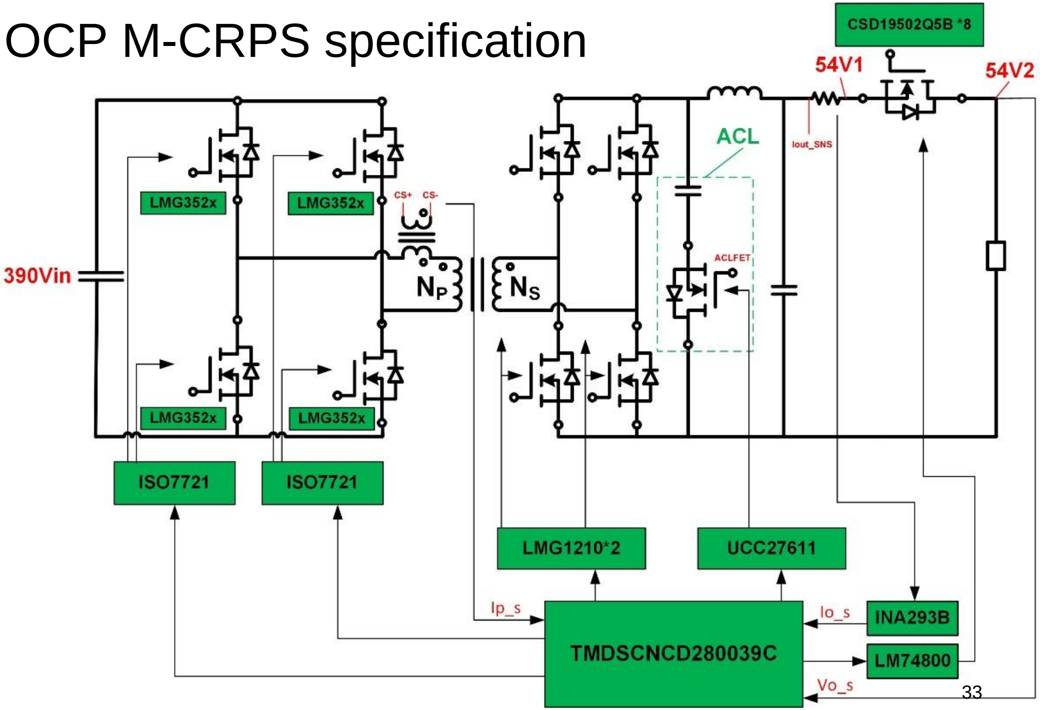


PSFB design example

PSFB design example: PMP22951

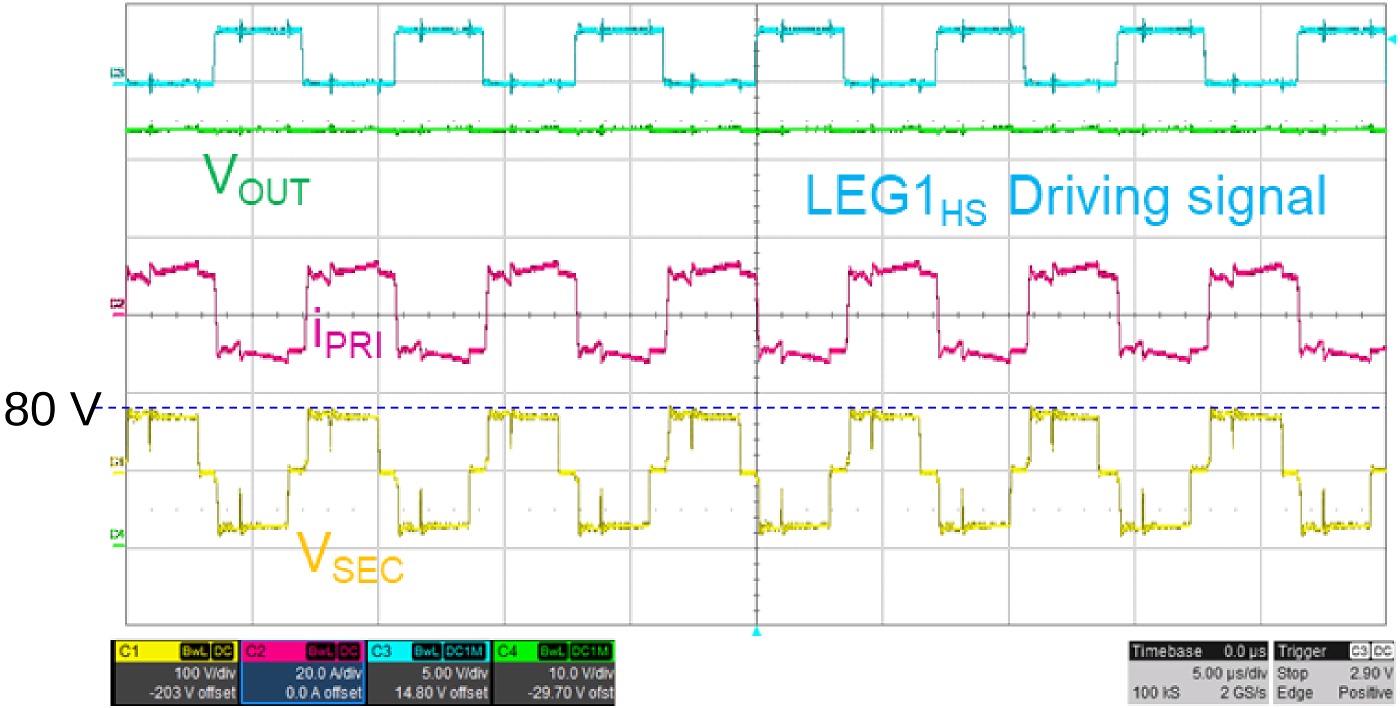
- Input voltage: 390 V_{nom}, 340 V_{min}
- Output: 54-V/3-kW max, targeting OCP M-CRPS specification

54-V, 3-kW Phase-Shifted Full Bridge with Active Clamp Reference Design



3-kW steady-state waveforms

- 140-kHz operation



M-CRPS load transient, 50% load step (3 A to 31 A)

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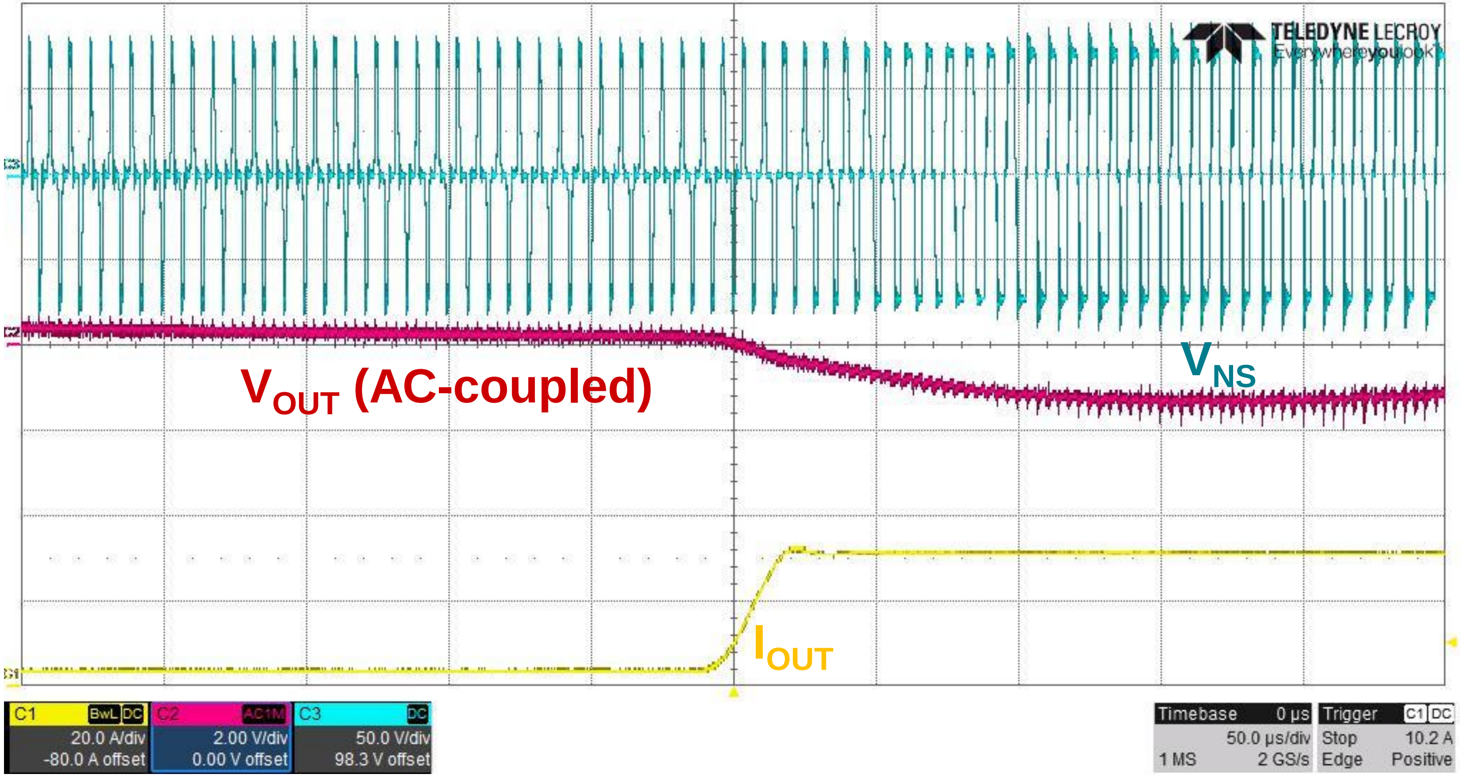
M-CRPS load transient, 50% load step (3 A to 31 A)



Summary

- A PSFB is a good candidate for applications that require a wide input/output voltage range and fast load transient response
- Characteristics among a PSFB and other isolated topologies
- PSFB operation principles
- Discussed different types of rectifiers, rectifier clamping options, modes of control
- Showcased a PSFB reference design meeting M-CRPS specifications with active clamping
- Calls to action in the following slides

Calls to action: Power trends and specifications

- **Power trends:**
  - Yin, Richard. “Power Tips #109: Five major trends in power supply design for servers.” EDN Power Tips series, August 2022. https://www.edn.com/five-major-trends-in-power-supply-design-for-servers/
- **80 Plus standard:**
  - https://www.clearesult.com/80plus/program-details#program-details-table
- **OCP M-CRPS specification:**
  - https://www.opencompute.org/wiki/Server/Working
- **OCP Open Rack v3 specification:**
  - https://www.opencompute.org/wiki/Open_Rack/SpecsAndDesigns

Calls to action: Topology comparisons

- **Resonant converter vs. DAB:**
  - Yu, Sheng-Yang, et al. "Designing a high-power bidirectional AC/DC power supply using SiC FETs." Texas Instruments Power Supply Design Seminar SEM2400, literature No. SLUP399, 2020. https://www.ti.com/seclit/ml/slup399/slup399.pdf
- **Resonant converter vs. PSFB:**
  - Gillmor, Colin. "Comparison of PSFB and FB-LLC for high power DC/DC conversion" in Texas Instruments video library.
    - Part 1: https://www.ti.com/video/5979520091001
    - Part 2: https://www.ti.com/video/5980232599001
    - Part 3: https://www.ti.com/video/5980257698001
    - Part 4: https://www.ti.com/video/5980260615001
    - Part 5: https://www.ti.com/video/5980344049001
    - Part 6: https://www.ti.com/video/5980375024001

Calls to action: PSFB operation and rectifiers

- **PSFB operation and how to achieve PSFB soft switching:**
  - Sabate, J.A., et al. “Design considerations for high-voltage high-power full-bridge zero-voltage-switched PWM converter.” In Proc. APEC, 1990, pp. 275-284.
- **PSFB output rectifiers:**
  - Balogh, Laszlo. “The current-doubler rectifier: an alternative rectification technique for push-pull and bridge converters.” Texas Instruments application note, literature No. SLUA121. https://www.ti.com/lit/an/slua121/slua121.pdf

Calls to action: PSFB clamping options

- **Passive clamp:**
  - Lin, Song-Yi, et al. "Analysis and design for RCD clamped snubber used in output rectifier of phase-shift full-bridge ZVS converters." In IEEE Transactions on Industrial Electronics 45, no. 2 (April 1998), pp. 358-359.
- **Primary clamp:**
  - Redl, Richard. "Optimum ZVS Full-Bridge DC/DC Converter with PWM Phase-Shift Control: Analysis, Design Considerations, and Experimental Results." In Proc. APEC, 1994, pp. 159-165, vol. 1.
- **Active clamp:**
  - Yu, Sheng-Yang, et al. "Achieving high converter efficiency with an active clamp in a PSFB converter." Texas Instruments Analog Design Journal, literature No. SLYT835, Q1 2023. https://www.ti.com/lit/an/slyt835/slyt835.pdf

Calls to action: PSFB control and design examples

- **PSFB control:**
  - Wang, Shi-song, et al. “Small-Signal Modeling of Phase-Shift Full-Bridge Converter with Peak Current Mode Control.” 2020 IEEE ASEMD, Tianjin, China, 2020, pp. 1-2.
  - Ahmed, M.R., et al. “Enhanced Models for Current-Mode Controllers of the Phase-Shifted Full Bridge Converter with Current Doubler Rectifier.” In IEEE ECCE Asia 2019, pp. 3271-3278.
  - Vlatkovic V., et al. “Small-signal analysis of the phase-shifted PWM converter.” Published in IEEE Transactions on Power Electronics 7, issue 1 (January 1992): pp. 128-135.
  - Basso, Christophe. “Transfer Functions of Switching Converters.” Faraday Press, 2021.
- **Design examples:**
  - 3-kW (400 V to 12 V) Phase-Shifted Full Bridge with Active Clamp Reference Design: https://www.ti.com/tool/PMP23126
  - 3-kW (400 V to 54 V) Phase-Shifted Full Bridge with Active Clamp Reference Design: https://www.ti.com/tool/PMP22951

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