Technical Article

Improving phase-shifted full-bridge efficiency using an active snubber

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The phase-shifted full bridge (PSFB) shown in Figure 1 is popular in applications >500 W because it can achieve soft switching on its input switches for high converter efficiency. Although switching losses are greatly reduced, you can still expect to see high-voltage stress on the output rectifier, as its parasitic capacitance resonates with the transformer leakage inductance—modeled as L_r in Figure 1. The voltage stress of the output rectifier could be as high as $2V_{IN}N_S/N_P$, where N_P and N_S are the transformer primary and secondary windings, respectively.

Limiting the maximum voltage stress on the output rectifier traditionally requires a passive snubber [1] such as a resistor-capacitor-diode (RCD) snubber, but the use of a passive snubber will dissipate power, resulting in an efficiency penalty.

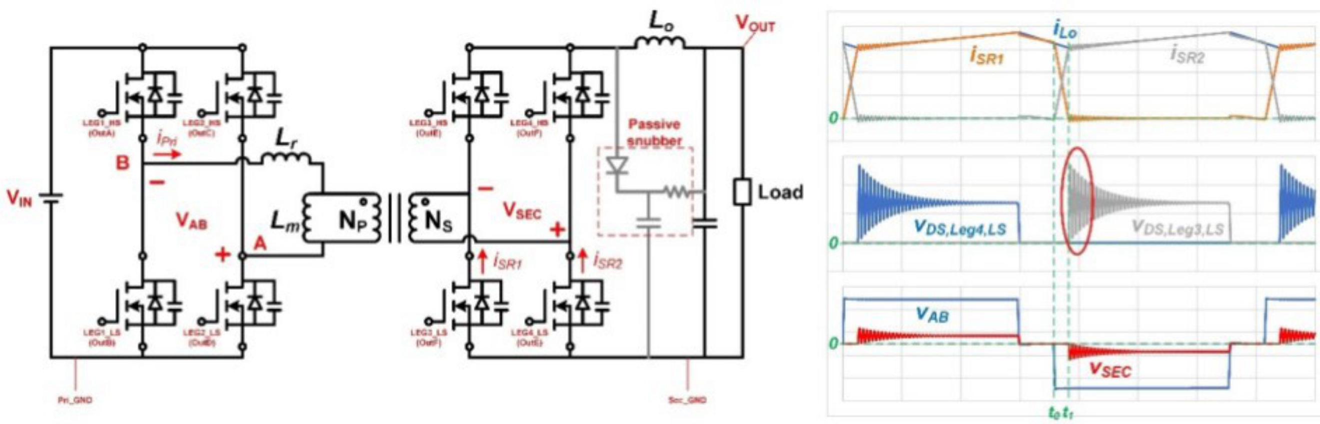

Figure 1. A PSFB power stage with a passive clamp and waveforms, the use of the passive clamp dissipates power which leads to an efficiency penalty. Source: Texas Instruments

Alternatively, you could apply an active snubber to clamp the rectifier voltage stress without dissipating any power in the snubber circuit (assuming an ideal switch) [2]. Figure 2 shows the insertion of an active clamp leg (ACL) formed by a capacitor (C_{CL}) and a MOSFET (Q_{CL}) before the output inductor. When the output winding voltage becomes non-zero, energy will transfer from the primary winding to the secondary winding to energize the output inductor while also conducting current through the Q_{CL} body diode to charge C_{CL}, even if Q_{CL} isn't turned on. You can turn on Q_{CL} after its body diode has already conducted current to ensure zero voltage switching (ZVS) on Q_{CL}.

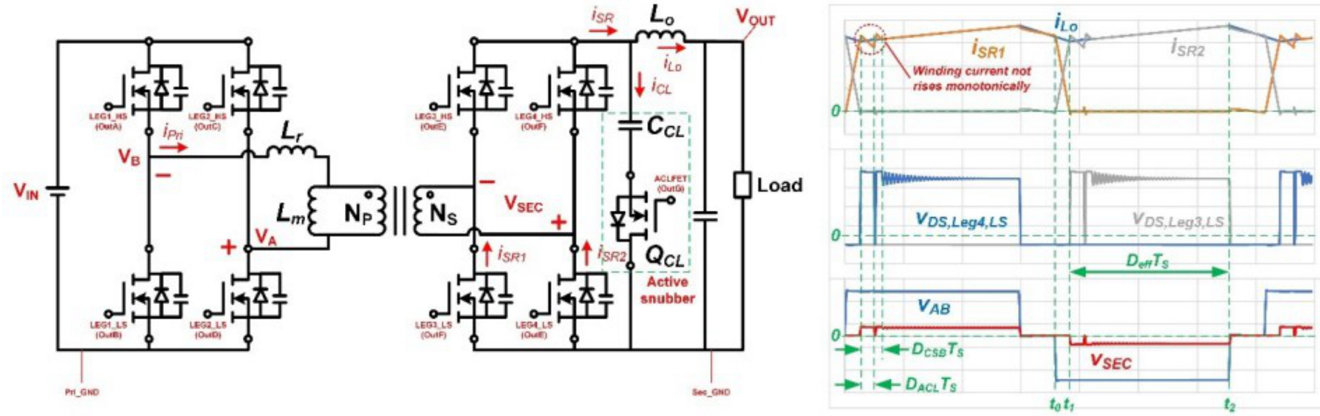

Figure 2. A PSFB power stage with an active clamp and waveforms, unlike the passive snubber, the active snubber doesn't dissipate the ringing energy on the power resistor but circulates the energy in the LC resonant tank as a lossless snubber. Source: Texas Instruments

It's important to turn on Q_{CL} before the current in the active clamp MOSFET (i_{CL})polarity changes to allow the current-second balance on C_{CL} to be complete by the beginning of the effective duty cycle ($D_{eff}T_S$). In other words, Q_{CL} only needs to be turned on long enough for the current-second balance of the active snubber to work as intended, clamping the output rectifier voltage to the C_{CL} voltage (V_{CL}). In other words, Q_{CL} doesn't need to conduct throughout the full $D_{eff}T_S$, but for a relatively short period of time instead. As such, Q_{CL} can have a fixed on-time—that is, the Q_{CL} on time ($D_{ACL}T_S$) is constant—while keeping $D_{eff}T_S$ always greater than the duration where the current-second balance ($D_{CSB}T_S$) is complete.

This approach addresses one of the challenges when using an active snubber in that the transformer winding current does not rise monotonically—which is an issue if you are using peak current-mode control. This happens because the active snubber capacitor energy also participates in energizing the output inductor, rather than solely relying on energy transfer from the primary side. Since $D_{eff}T_S$ is larger than $D_{CSB}T_S$, peak current detection can occur when the transformer current is rising monotonically. And because you can expect higher efficiency for a PSFB with a larger D_{eff}, you can design the PSFB to have a larger D_{eff} at mid to heavy loads, where $D_{eff} >> D_{CSB}$. At light loads, the converter should operate in discontinuous conduction mode, where D_{eff} will be smaller than D_{eff} in continuous conduction mode at the same input/output voltage condition. In order to keep $D_{eff}T_S$ greater than $D_{CSB}T_S$ even at light loads, you can use frequency-reduction control or burst-mode control.

Because the C_{CL} ripple voltage affects the total voltage stress on the output rectifier, you must select a large-enough C_{CL} for a low capacitor ripple voltage. You must also select C_{CL} such that the inductor-capacitor (LC) resonant period formed by L_r and C_{CL} is much longer than the switching period [3], expressed by Equation 1:

$$2\pi\sqrt{\left(\frac{N_S}{N_p}\right) \times L_r \times C_{CL}} \gg T_S \quad (1)$$

The rectifier voltage stress will clamp to around $V_{IN}N_S/N_P$ with the active snubber, which is half of the voltage stress without any clamp circuit. Unlike the passive snubber in [1], the active snubber doesn't dissipate the ringing energy on the power resistor but circulates the energy in the LC resonant tank as a lossless snubber. Therefore, you can expect higher converter efficiency on a PSFB with an active snubber than a PSFB with a passive snubber in an identical specification.

To understand the factors that determine the ACL current level, you'll need to calculate the current flow through the ACL itself. Figure 3 illustrates waveforms around the ACL conduction period.

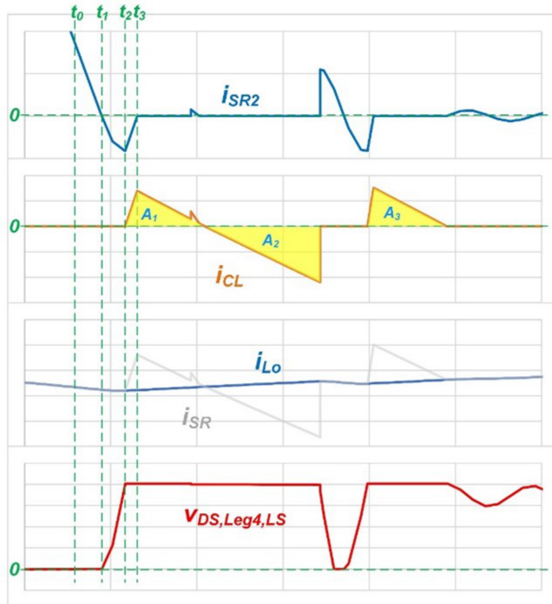

Figure 3. Waveforms during an ACL current conduction period. Source: Texas Instruments

Assuming that V_{CL} is a constant and $L_m = \infty$, Equation 2 derives the current in one side of the output rectifier (i_{SR2}) as the drain to source voltage rises as:

$$i_{SR2\,|\,t2} = \frac{V_{IN}}{\frac{N_S}{N_P}L_r}(t_2 - t_1) \quad (2)$$

By assuming i_{SR2} current decreases at a constant rate, Equation 3 derives the time duration of t_2-t_1 as:

$$(t_2 - t_1) = \sqrt{2C_{OSS}\frac{N_S V_{CL} L_r}{N_P V_{IN}}} \quad (3)$$

Since C_{CL} needs to maintain current-second balance, the sum of areas A1 and A3 will equal area A2. With all of this information, it is possible to calculate the root-mean-square (RMS) value of i_{CL}. As Equation 3 shows, the synchronous rectifier (SR) output capacitance (C_{oss}) controls the peak current on the ACL. If you select a lower C_{oss} SR FET, the ACL RMS current will be lower and thus help improve converter efficiency.

Figure 4 shows waveforms of the Texas Instruments (TI) 54-V, 3-kW phase-shifted full bridge with active clamp reference design, which is a 400V input, 54V output, 3kW PSFB converter using an active clamp realized with TI's C2000™ microcontroller. In this design, the transformer turns ratio is Np:Ns = 16:3. With the ACL FET turned on only for 300ns within the output inductor energizing period, the output rectifier voltage stress (Ch1 in Figure 4) is limited to 80V, even at a 3kW load. The lower voltage stress enables the use of SR FETs with a lower voltage rating and a better figure of merit to further improve the efficiency of the PSFB.

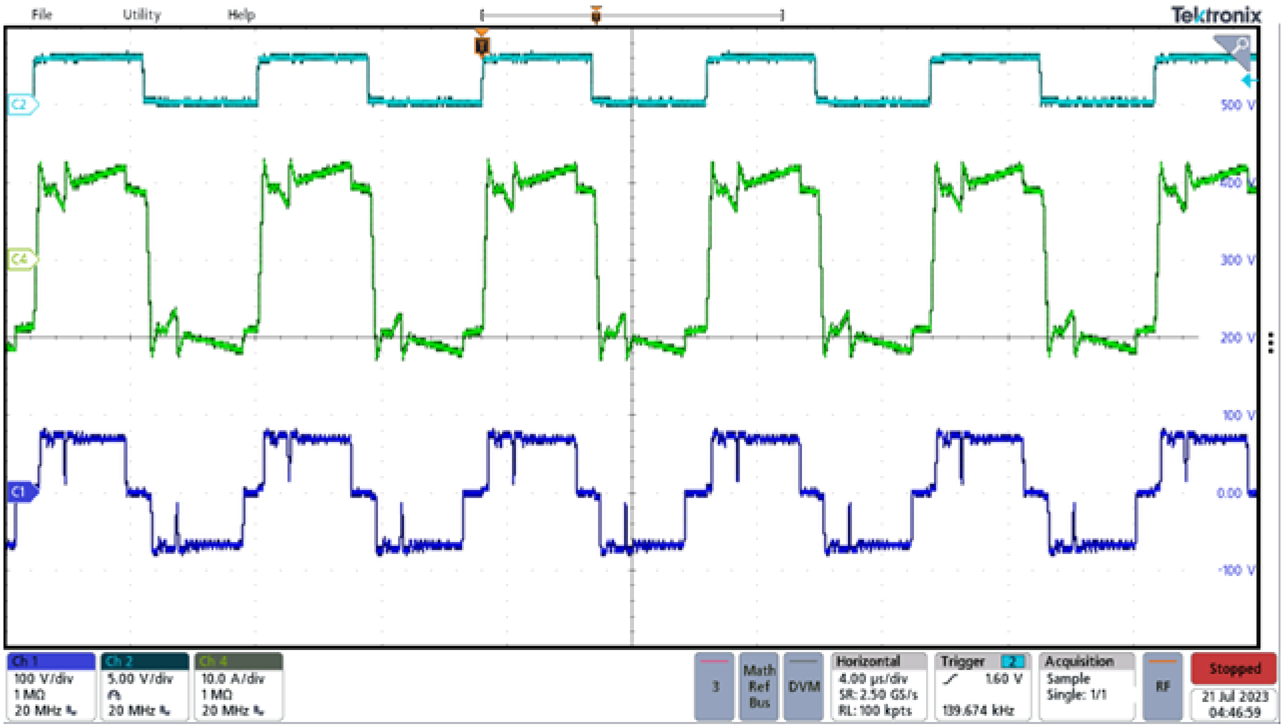

Figure 4. A 54V, 3kW phase-shifted full bridge with active clamp reference design steady-state waveforms. Source: Texas Instruments

This control method isn't limited to a full-bridge rectifier with one ACL; you can also apply it to an active snubber with other types of rectifiers such as a current doubler [4] or a center-tapped rectifier. TI's 3-kW phase-shifted full bridge with active clamp reference design with >270-W/in^3 power density has a 400V input, 12V output, 3kW PSFB converter with an active clamp where the secondary side uses a center-tapped rectifier. The output rectifier stress (Ch1 in Figure 5) is limited to 40V at a 3kW load.

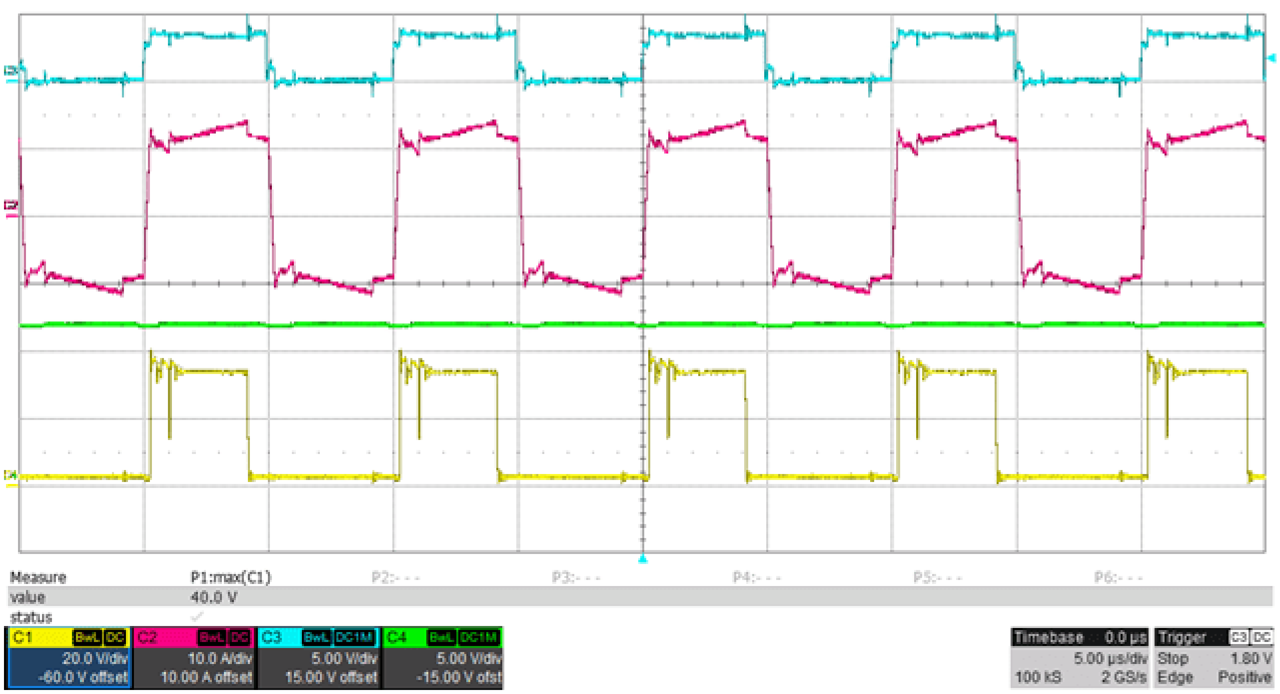

Figure 5. A 3kW phase-shifted full bridge with active clamp reference design with >270W/in^3 power density steady-state waveforms. Source: Texas Instruments

The merit of an active clamp in a PSFB converter

The implementation of an active snubber in a PSFB converter significantly reduces the maximum voltage stress on the output rectifiers. This reduction in voltage stress enables the use of an SR FET with a lower drain-to-source voltage rating, which can have a better figure of merit. While an active clamp can create challenges with the implementation of peak current-mode control, proper implementation enables the use of an active clamp and peak current-mode control in harmony. This combination achieves higher power density and higher efficiency compared to traditional PSFB implementations.

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References

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