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Active Clamp Flyback Converters—How They Work And Tips for Design Success

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In low-power applications (typically 150 W or less), the active-clamp flyback (ACF) converter is becoming a popular choice over the quasi-resonant flyback (QRF) converter. When designed correctly, an ACF topology will have a nearly lossless leakage energy clamp and will be able to achieve zero voltage switching (ZVS) on the primary MOSFET over a wide input voltage and output load range. In low-power applications, it's possible to design an ACF for power densities as high as 39 W/in^3 and with peak efficiencies that exceed 94%.

The only problem with ACF is that the topology is fairly new; some designers may not have heard about it, and/or may be reluctant to use it. The purpose of this article is to review the benefits and operation of an ACF and give some design guidance and tips on applying it. The benefits of using a dedicated controller such as the UCC28780 to implement an ACF converter are noted and a 45-W design example based on this controller is implemented to explain and demonstrate the design tips and the resulting efficiency.

ACF's Nearly Lossless Clamp

A traditional flyback converter normally uses a resistor-capacitor-diode (RCD) clamp or a transient voltage suppression (TVS) diode clamp to dissipate the transformer's (T1) leakage inductance energy and protect the converter's main switch (Q1) from electrical overstress. See Fig. 1 where the components and connections for these clamps are denoted in red.

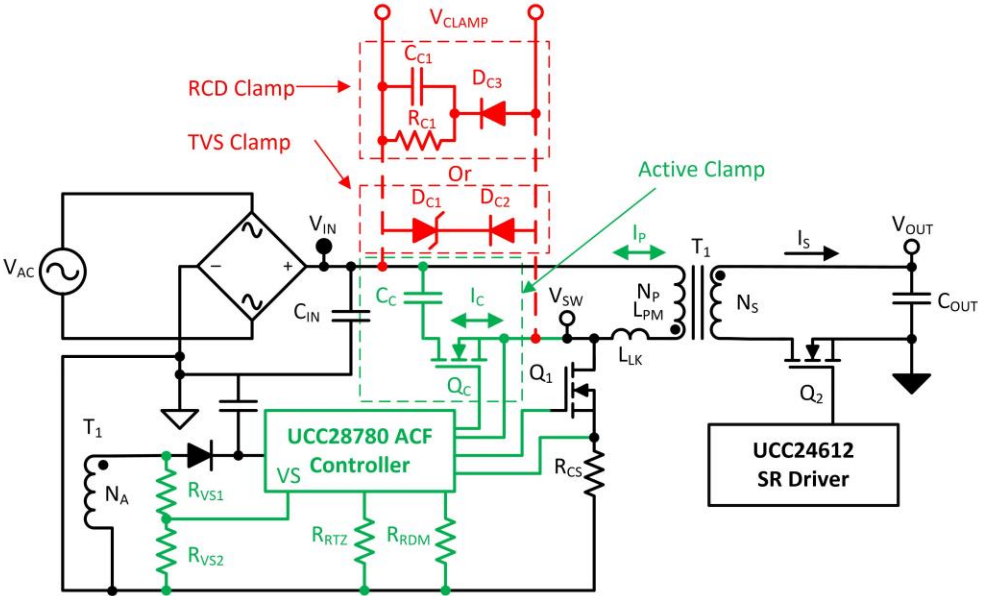

Fig. 1. Offline flyback converter showing RCD, TVS and active clamps.

These passive clamps work quite well for protecting Q1 from electrical overstress, but unfortunately dissipate power that only increases with switching frequency (f_{SW}). Equation 1 is the power dissipation equation for a passive clamp ($P_{CLAMP(QRF)}$) used in a QRF converter.

$$P_{CLAMP(QRF)} = \frac{V_{CLAMP}}{V_{CLAMP} - \frac{N_P}{N_S} \times V_{OUT}} \times \frac{1}{2} \times L_{LK} \times {I_{PK}}^2 \times f_{SW} \qquad (1)$$

where variable V_{CLAMP} is the voltage across the clamp when Q_1 is off, I_{PK} is the transformer's peak primary current, N_P/N_S is the flyback transformer's primary-to-secondary turns ratio and L_{LK} is the transformer's primary leakage inductance.

The active clamp, shown in green in Fig. 1, replaces the passive clamp with a switch (Q_C) and a clamp capacitor (C_C). This gives a place for the discharging and storage of T_1's leakage inductance (L_{LK}) energy to protect Q_1 from electrical overstress. Since Q_C allows a bidirectional clamp current (I_C), the leakage energy can be returned to the output through the flyback converter's N_P/N_S every switching cycle, making the active clamp nearly lossless and a better choice for higher-frequency designs.

How ACF Achieves ZVS

The QRF flyback converter is a very efficient topology. Its ability to do valley switching (VS) means it has lower switching losses compared to traditional hard-switched flyback converters. However, QRF converters still have switching losses that increase with switching frequency. Equation 2 describes the switching losses ($P_{SW(QRF)}$) of the QRF switch-node voltage (V_{SW}).

$$P_{SW(QRF)} = \frac{1}{2} \times C_{SW} \times \left(V_{IN} - \frac{N_P}{N_S} \times V_{OUT}\right)^2 \times f_{SW} \qquad (2)$$

where the variable C_{SW} is the flyback converter's V_{SW} capacitance.

An ACF can achieve ZVS by delaying the turn-off of Q_C and delaying the turn-on of Q1. Q_C has to be left on long enough so that some of the energy stored in C_c can be transferred to the transformer's primary magnetizing inductance (L_{PM}) to achieve ZVS. To accomplish this efficiently, Q_C only needs to be on long enough to develop a minimum peak negative current ($-I_P$) in the transformer's primary, ensuring that L_{PM} has sufficient energy to resonate with C_{SW} to achieve ZVS.

This does take some work in the lab, but removing the switching losses is well worth the effort: It's possible to design the ACF converter for two to three times the switching frequency compared to a traditional QRF. See Fig. 2 for a switching waveform comparison.

Please note to achieve ZVS the energy in L_{PM} needs to equal the energy stored in the switch-node capacitance, (Equation 3).

$$\frac{1}{2} \times L_{PM} \times (-I_P)^2 \approx \frac{1}{2} \times C_{SW} \times V_{SW}{}^2 = \frac{1}{2} \times C_{SW} \times \left(V_{IN} - \frac{N_P}{N_S} \times V_{OUT}\right)^2 \qquad (3)$$

TI's UCC28780 active-clamp flyback controller monitors the switch node and will adjust Q_C turn-off delay and Q_1 turn-on delay in order to achieve ZVS. This controller continuously monitors the switch node, V_{IN} and V_{OUT}, and will adjust the delays within a few switching cycles to ensure that the design still achieves ZVS over line voltage and load changes. The UCC28780 removes the fine tuning generally required to achieve ZVS and should reduce the ACF design cycle time, reducing development costs.

To show how efficient an ACF can be, TI constructed a 45-W offline evaluation model with these specifications:

- Vac = 90 to 264 Vrms ac input
- $V_{IN(MIN)}$ = 80 V, minimum flyback dc input voltage
- $V_{IN(MAX)}$ = 375 V, maximum flyback dc input voltage
- V_{OUT} = 20 V output voltage.

- P_{OUT} = 45 W, maximum rated output power.
- $f_{SW(MIN)}$ = 175 kHz, minimum switching frequency.
- D_{MAX} = 57.5%, maximum duty cycle (initial target; may need modifying to optimize design).

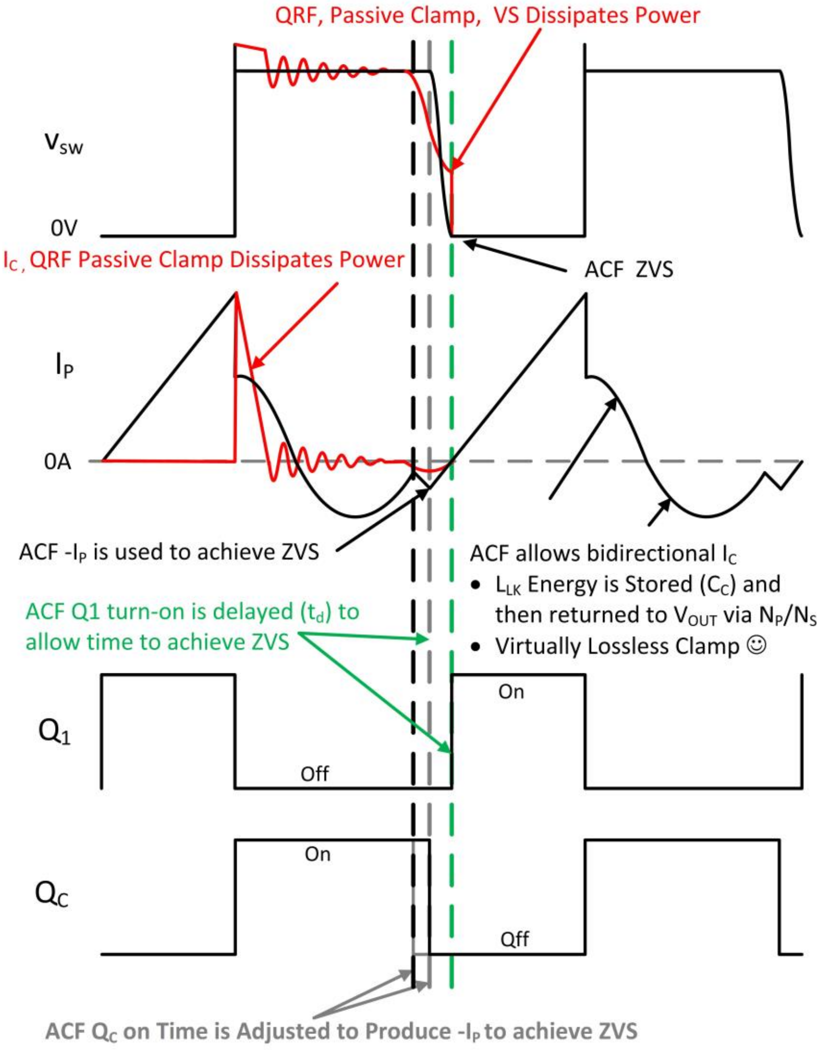

Fig. 2. ACF ZVS and active clamping vs. QRF and passive clamping.

Tip No. 1: Transformer Design

Designing the transformer for an ACF is similar to a QRF. Select L_{PM} based on f_{SW} at the maximum output power (P_{OUT}), maximum duty cycle (D_{MAX}) and minimum input voltage ($V_{IN(MIN)}$). First, calculate transformer T1's primary peak current (I_{PPK}):

$$I_{PPK} = \frac{2 \times P_{OUT}}{V_{IN(MIN)} \times D_{MAX}} \approx 1.957\ A \qquad (4)$$

Then

$$L_{PM} = \frac{2 \times P_{OUT}}{{I_{PPK}}^{2} \times f_{SW(MIN)}} \approx 134\ \mu H \qquad (5)$$

Select N_P/N_S based on a volt-second balance across the transformer at the minimum flyback input voltage and D_{MAX}.

$$\frac{N_P}{N_S} = \frac{D_{MAX} \times \left(V_{IN(MIN)}\right)}{(1 - D_{MAX}) \times (V_{OUT})} \approx 5.412 \qquad (6)$$

The actual transformer used in the design had a primary L_{PM} of 115 µH and an N_{PS} ratio of 5.26, with an L_{LK} of 2.5 µH.

Tip No. 2: Selecting C_{IN} And C_{OUT}

Select the input and output filter capacitors like you would for a QRF, based on root-mean-square currents, ripple voltage, voltage stress, ambient temperature and expected life.

Tip No. 3: Setting Up The UCC28780 To Achieve ZVS

The UCC28780 operates an ACF in peak-current-mode control. Setting up the UCC28780 in an ACF requires a basic understanding of the timing of a single ACF switching cycle, as shown in Fig. 3.

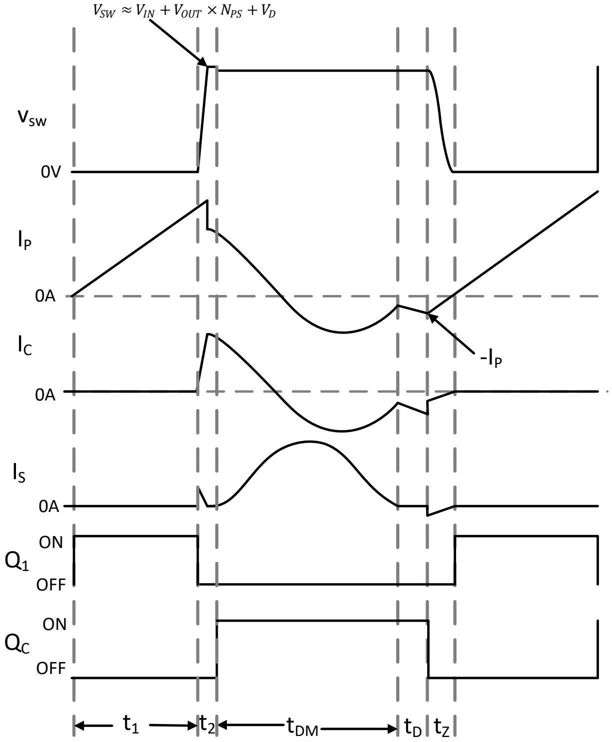

Fig. 3. ACF timing.

Time interval t_1 switch Q_1 is on; during this time, the ACF transformer's (T_1) L_{PM} is energized. At the end of interval t_1, FET Q_1 turns off to deliver the energy that was stored in L_{PM} to the secondary of the power converter (V_{OUT}).

During time interval t_2, I_P will charge the switch-node capacitance, transiting the converter's V_{SW} from 0 V to the input voltage plus the reflected output voltage across the transformer plus the body diode (V_D) of Q_C. The energy in the leakage inductance is transferred into the C_c during this time as well.

$$V_{SW} \approx V_{IN} + V_{OUT} \times N_{PS} + V_D \qquad (7)$$

During the demagnetizing time interval (t_{DM}), the transformer's stored energy is delivered to the converter's secondary (V_{OUT}). Also during this time, C_C and Q_C are clamping the switch node. Since Q_C allows I_C, the leakage energy stored in C_C returns to the system through N_P/N_S, making for a nearly lossless clamp.

After the transformer energy that was stored during t_1 is delivered to the secondary, the UCC28780 will delay the turnoff of Q_C (t_D), allowing energy that was stored in C_C to develop $-I_P$ in the primary of the transformer that will energize L_{PM} to achieve ZVS. Please note that for $-I_P$ to achieve ZVS, it needs to be large enough so that the energy stored in L_{PM} is equivalent to the energy stored in the switch-node capacitance ($C_{O(TR)Q1}$) when it is at its maximum energy storage. In our example, $C_{O(TR)}$, the main switch (Q1) effective capacitance related to time is 135 pF, so we can calculate $-I_P$ as follows.

$$\frac{L_{PM} \times (-I_P)^2}{2} = \frac{C_{O(TR)Q1} \times (V_{IN} + V_{OUT} \times N_{PS})^2}{2} \qquad (8)$$

$$-I_P = -\frac{\sqrt{C_{O(TR)Q1}} \times (V_{IN} + V_{OUT} \times N_{PS})}{\sqrt{L_{PM}}} = -0.192\ A \qquad (9)$$

Time interval t_Z is the delay time added between the turnoff of Q_C and the turn-on of Q_1 to allow time for the energy stored in L_{PM} to swing $C_{O(TR)Q1}$ to 0 V, enabling ZVS. The UCC28780 will monitor V_{SW} and vary t_Z if needed to maintain ZVS and avoid hard switching.

The UCC28780 does require programming an initial t_{DM} and minimum estimated t_Z through timing resistors R_{RDM} and R_{RTZ}. In this design example, t_{DM} was calculated to be roughly 2.43 µs and t_Z was 336 ns.

$$t_{DM} \approx \frac{1 - D_{MAX}}{f_{SW}} = 2.43\ \mu s \qquad (10)$$

$$t_Z \approx -\frac{2 \times \pi \times C_{O(TR)} \times L_{PM}}{2\sqrt{C_{O(TR)} \times L_{PM}}} = 409\ ns \qquad (11)$$

Tip No. 4: Designing For ACF Frequency Variations

For a given load, t_{DM} will remain fixed; the on-time (t_1) and duty cycle will vary with changes in V_{IN}. In this design example, the theoretical switching frequency can vary from 175 kHz minimum ($f_{SW(MIN)}$) to 322 kHz maximum ($f_{SW(MIN)}$) with changes in load current. Please refer to equations 12 through 15 for frequency calculations. I recommend selecting $f_{SW(MIN)}$ to be less than 200 kHz when designing the ACF power stage. This is because the ACF controller has a maximum switching frequency of 1 MHz, and a higher switching frequency may be required to control the duty cycle at lighter loads.

Assuming $f_{SW(MIN)}$ = 175 kHz, we start by calculating, D_{MIN}, the minimum duty cycle at $V_{IN(MAX)}$:

$$D_{MIN} \approx \frac{\frac{N_P}{N_S} \times V_{OUT}}{V_{IN(MAX)} + \frac{N_P}{N_S} \times V_{OUT}} = 0.219 \qquad (12)$$

Then

$$t_{1(MIN)} = \frac{D_{MIN} \times t_{DM}}{D_{MIN} - 1} \approx 682\ ns \qquad (13)$$

$$f_{SW(MAX)} = \frac{1}{t_{1(MIN)} + t_{DM}} \approx 322\ kHz \qquad (14)$$

$$f_{SW(MIN)} \leq 200\ kHz \qquad (15)$$

Tip No. 5: Designing Power Supplies Is An Iterative process

This article gave some initial recommendations and approximations to help with the ACF design process. When designing a power supply, you also need to consider component selection, thermal and electrical component stresses, ambient operating temperature, copper losses, and physical transformer design.

Reaching peak efficiency targets greater than 94% may require several paper designs and custom magnetics. Achieving overall design goals may require swapping out different electrical components, changing D_{MAX} and perhaps modifying the transformer design.

When going to production, the design will have to be prototyped and evaluated, and perhaps modified based on actual design performance. Designing a power supply is an iterative process, but I hope that the tips provided in this article can help speed up your design process.

45-W Evaluation Module Performance

The aforementioned 45-W ACF evaluation module pictured in Fig. 4 is available for order and evaluation. For schematics, bill of materials and performance data, see the evaluation module user's guide.[1]

Fig. 4. 45-W ACF reference design.

With an ac input of either 115 V or 230 V rms, the evaluation module has peak efficiencies of roughly 94% (see the table).

If you used a QRF instead of an ACF in this 45-W design, the maximum load efficiency would have been 0.8% to 1.6% less at full load and the design efficiency goals would not have been met. Note that the estimated QRF efficiency is between the ACF efficiency and the estimated efficiency of QRF with the same peak and RMS currents as the ACF. In reality, the ACF has slightly higher transformer peak and RMS currents than the QRF, and slightly greater conduction losses. Refer to Fig. 5 for efficiency curves.

Table. Efficiency performance of a 45-W ACF reference design.

V_{IN} RMS	P_{IN}	V_{OUT}	I_{OUT}	P_{OUT}(%)	EFFICIENCY	EFFICIENCY 4pt-AVERAGE	Switching Frequency @ Full Load
90	48.210	19.927	2.252	100%	93.08%	92.57%	179kHz
90	35.875	19.930	1.680	75%	93.33%		
90	24.240	19.932	1.123	50%	92.34%		
90	12.720	19.935	0.584	25%	91.53%		
115	47.670	19.928	2.250	100%	94.06%	92.82%	224kHz
115	35.760	19.930	1.680	75%	93.63%		
115	24.290	19.931	1.123	50%	92.15%		
115	12.710	19.935	0.583	25%	91.44%		
230	47.780	19.924	2.250	100%	93.82%	91.71%	288kHz
230	36.130	19.925	1.681	75%	92.70%		
230	24.970	19.926	1.131	50%	90.25%		
230	12.950	19.933	0.585	25%	90.04%		
264	47.930	19.923	2.249	100%	93.48%	91.47%	291kHz
264	36.310	19.924	1.683	75%	92.35%		
264	24.870	19.93	1.131	50%	90.63%		
264	13.060	19.93	0.586	25%	89.44%		

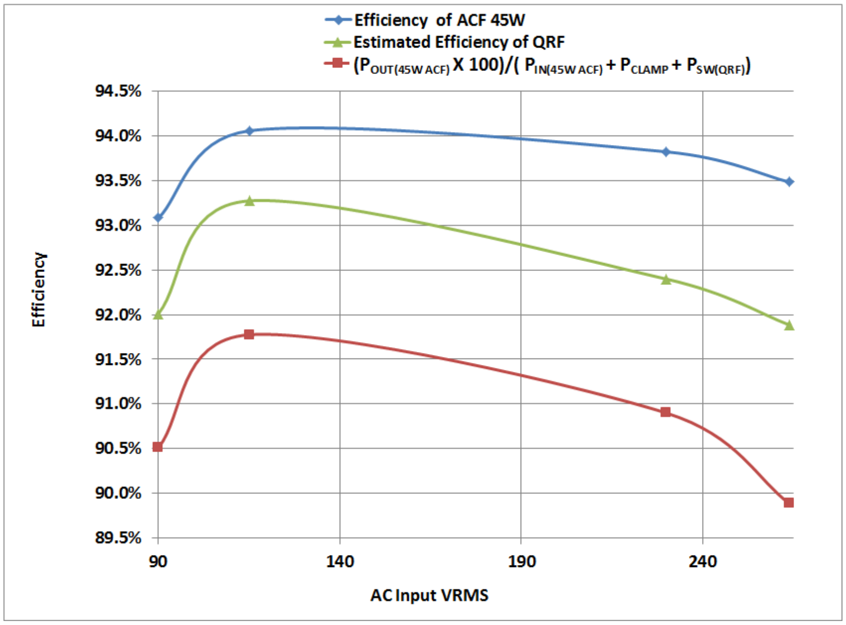

Fig. 5. 45-W ACF and estimated QRF efficiency curves.

Summary

Many applications could benefit by using an ACF, including notebook adapters, tablets, TVs, set-top boxes, printers, USB Power Delivery/wall outlets, direct and fast mobile chargers, and ac-dc or dc-dc auxiliary power supplies. When designed correctly in low-power applications (150 W or less), an ACF will achieve ZVS and have a nearly lossless clamp, resulting in flyback converter designs with peak efficiencies greater than 94%.

An understanding of the basic operation and timing of the ACF makes the design process easier. A 45-W ACF power supply would be approximately 0.8% to 1.6% more efficient than a QRF using the same power stage. Also remember that power supply design is an iterative process, and it may take several passes to reach your design goals.

References

1. "Using the UCC28780EVM-021, 45-W, 20-V High Density Silicon (Si) Based, Active-Clamp Flyback Converter/Evaluation Module" User's Guide, SLUUBV6, Aug. 2018.
2. "What is active clamp flyback?" by Eric Faraci, TI Training video, Feb. 21, 2018.
3. "The Active Clamp Flyback: Part 1" by Pei-Hsin Liu, TI Training video, Oct. 6, 2017.
4. "The Active Clamp Flyback: Part 2" by Pei-Hsin Liu and Bing Lu, TI Training video, Oct. 6, 2017.
5. UCC28780 high-frequency active clamp flyback controller data sheet.

About The Author

Michael O'Loughlin is a systems application engineer with the High Voltage Pulse Width Modulation Controller Product Group at Texas Instruments. He specializes in offline and isolated power supply design and has authored numerous articles and application notes on power factor correction, soft switching and overall power supply design topics. Michael has a bachelor's degree in electrical engineering from the University of Massachusetts Lowell.

For more information on flyback designs, see How2Power's Design Guide, locate the Topology category and click on "Flyback".