Demystifying active-clamp flyback loop compensation

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What will I get out of this session?

• Purpose:

1. Analyze the small-signal properties of CCM and TM operations of ACF

2. Address the benefit and stability issue of burst mode operation of ACF

3. Introduce design guides based on the analytical model and two simple ripple compensation methods to stabilize the burst control loop

• Relevant End Equipment:

1. High density AC adapter or charger

2. USB power delivery chargers

3. AC/DC or DC/DC auxiliary power supply
Content

- Small-signal model of current-mode controlled ACF
- Burst mode operation as light load operation of ACF
- Ripple compensation to stabilize burst mode control
- Serial damping for ACF with $\pi$ output filter
- Summary
Quasi-resonance (QR) vs. active clamp (ACF)

**QR**

- $V_{\text{bulk}}$
- $L_k$
- $i_m$
- $L_m$
- $V_{\text{sw}}$
- $i_{\text{sec}}$
- $i_{\text{clamp}}$

**ACF**

- $V_{\text{bulk}}$
- $L_k$
- $i_m$
- $Q_H$
- $V_{\text{sw}}$
- $i_{\text{sec}}$
- $i_{\text{clamp}}$

**Clamping loss**

**Switching loss**

**EMI**

**Recycle $L_k$ energy w/o clamping loss**

**Zero voltage switching (ZVS)**
TI active clamp flyback (ACF) vs. existing solutions

<table>
<thead>
<tr>
<th>Power level (W)</th>
<th>TI 65W QR</th>
<th>65W ACF (94% pk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 W/in³</td>
<td>15 W</td>
<td>65 W</td>
</tr>
<tr>
<td>7 W/in³</td>
<td>45 W</td>
<td>65 W</td>
</tr>
<tr>
<td>11 W/in³</td>
<td>65 W</td>
<td>65 W</td>
</tr>
<tr>
<td>19.3 W/in³ 27 W</td>
<td>45 W</td>
<td>65 W</td>
</tr>
<tr>
<td>22 W/in³ 65 W</td>
<td>27 W</td>
<td>65 W</td>
</tr>
<tr>
<td>30 W/in³ 65 W</td>
<td>30 W</td>
<td>65 W</td>
</tr>
</tbody>
</table>

*Open frame power density
Efficiency difference on 45W adapter (22W/in³)

Condition: (1) same RM8LP XFRM  
(2) same EMI filter  
(3) same output CLC filter  
(4) similar f_sw range

<table>
<thead>
<tr>
<th>Device</th>
<th>90VAC Eff. (f_sw)</th>
<th>265VAC Eff. (f_sw)</th>
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<tbody>
<tr>
<td>Si QR</td>
<td>92.12% (237kHz)</td>
<td>89.93% (413kHz)</td>
</tr>
<tr>
<td>Si ACF</td>
<td>93.12% (206kHz)</td>
<td>93.51% (285kHz)</td>
</tr>
<tr>
<td>GaN ACF</td>
<td>94.14% (227kHz)</td>
<td>94.63% (295kHz)</td>
</tr>
</tbody>
</table>

- Si ACF provides 3.6% improvement over Si QR at 265V_AC
- With same EMI filter, Si ACF is 1% lower than GaN ACF at 90V_AC
Cont. conduction mode (CCM) vs. transition mode (TM)

**CCM**
- PWMH turns off by a programmable clock
- PWML turns on after $t_{D(H-L)}$ delay
- PWML turns off by a peak current loop

*(Legacy controller: UCC289x)*

**TM**
- PWMH turns off by a separate ZVS loop (like a negative valley current loop)
- PWML turns on after $t_{D(H-L)}$ delay
- PWML turns off by a peak current loop

*(New controller: UCC28780)*
Small-signal property in CCM operation

**UCC289x**

- Need slope compensation to damp $f_{SW}/2$ double pole to stabilize the peak current loop as duty cycle > 50%
- Phase delay of RHP zero limits system bandwidth

**V_{CST} to V_{O} transfer function:**

- RHP zero (right half plane)
- $f_{SW}/2$ double pole
- ESR zero of $C_O$

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**Graph:**

- Gain (dB) vs. Frequency
- Phase (°) vs. Frequency

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**Note:**

- Graph illustrates frequency response and phase characteristics of the transfer function $V_{CST} to V_{O}$.
Small-signal property in TM operation

- PWML off by peak current loop; PWMH off by ZVS loop
- Inherently stable; no need slope compensation
- No RHP zero results in a higher bandwidth design

UCC28780

V_{CST} to V_{O} transfer function:

- ESR Zero of C_{O}

[Graph showing gain and phase as a function of frequency]
Proposed modeling methodology for TM ACF

Small-signal perturbation

From energy balance w/o describing resonance current
Small-signal model and simulation verification

\[
\frac{V_o(s)}{V_{CST}(s)} = K_e \frac{R_e R_L}{R_e + R_L} \frac{1 + sC_o R_{Co}}{1 + sC_o \left[ \frac{R_e R_L}{R_e + R_L} + R_{Co} \right]} \quad \text{----- ESR zero}
\]

\[
\text{----- LF pole}
\]

\[
V_{BULK} \sqrt{C_{SW}/L_M}
\]

\[
N_{PS} V_{BULK} / \left[ 2R_{CS} \left( V_{BULK} + N_{PS} V_O \right) \right]
\]

\[
\frac{2R_{CS} \left( V_{BULK} + N_{PS} V_O \right)^2}{N_{PS}^2 V_{BULK} \left( V_{CST} + R_{CS} I_{M(-)} \right)}
\]

\[
2P_{in} (V_{BULK} + N_{PS} V_O) - N_{PS} V_O V_{BULK} I_{M(-)} R_{CS}
\]

\[
N_{PS} V_O V_{BULK}
\]
Small-signal model of current-mode controlled ACF

Burst mode operation as light load operation of ACF

Ripple compensation to stabilize burst mode control

Serial damping for ACF with π output filter

Summary
Issue of ACF light load efficiency

Condition: $P_{o(\text{max})}=30\text{W}$, $V_o=20\text{V}$, sec. Schottky

$i_{m(+)}$: Delivers energy to output

$i_{m(-)}$: Stores energy used for ZVS (no contribution to output power)

High ratio is good

Lower ratio results in lower eff!

Current mode control only can not maintain light load efficiency
Optimize avg. eff. with burst setting of UCC28780

\[ V_{BUR} = 5V \frac{R_{BUR2}}{R_{BUR1} + R_{BUR2}} \]

\[ = (I_{m(BUR)} R_{CS}) K_{CST-BUR} \]

where \( V_{REF} = 5V \), \( K_{CST-BUR} = 4 \text{ V/V} \)

The programmable burst mode is simple to optimize the efficiency
Adaptive burst mode (ABM) of UCC28780

Condition: $P_{\text{OUT(MAX)}} = 45\, \text{W}$, $V_O = 20\, \text{V}$, RM8LP, $Q_L$ & $Q_H$ (650V/500mΩ/GaN), SR (150V/9.3mΩ/Si)

Avg. eff.
- 115V: 94.2%
- 230V: 93.6%

(A)

10% load
- $V_{\text{sw}}$
- $I_{\text{pri}}$

25% load
- $V_{\text{sw}}$
- $I_{\text{pri}}$

50% load
- $V_{\text{sw}}$
- $I_{\text{pri}}$

COC

DOE

94.2% at 115V
93.6% at 230V
- Feedback loop filters part of the switching-ripple and retains burst ripple for regulation
- Down slope of output voltage ripple generated by the output load discharging the output capacitor
- The down slope of feedback signal ($I_{FB}$) intersecting with $I_{REF}$ to trigger next burst packet
Content

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Stability issue from phase delay of feedback signal

- **Regulation method:**

  ![Diagram of regulation method](image)

  - **Compensation principle:**
    - Make $I_{FB}$ in-phase with $V_O$ “burst” ripple
    - Note: not switching ripple

- **Consequence of large phase delay between $I_{FB}$ and $V_O$:**

  ![Diagram of consequence](image)

Subharmonic oscillation
Solution: passive ripple compensation

\[
I_{FB}(s) = \frac{CTR \Delta V_{O(ABM)}}{I_{FB(ABM)}}\Delta I_{FB(ABM)}
\]

\[
V_O(s) = R_{BIAS1} \frac{CTR}{s + \frac{1}{s / \omega_{p1}}} + \frac{1}{s / \omega_{o}} + \frac{1}{s / \omega_{FB}}
\]

1. \[R_{BIAS1} = \frac{CTR \Delta V_{O(ABM)}}{\Delta I_{FB(ABM)}}\Delta I_{FB(ABM)} = 10\text{~to~}20\mu\text{A}\]

2. \[\omega_{p1} = \frac{1}{R_{DIFF} C_{DIFF}} > \text{Max burst frequency (35kHz) } \times 2\]

3. \[\omega_{o} = \frac{1}{(R_{FB} + R_{FB1})C_{opto}} \approx \omega_{z1} = \frac{1}{(R_{DIFF} + R_{BIAS1})C_{DIFF}}\]

4. \[\omega_{FB} = \frac{1}{(R_{FB} / / R_{FB1})C_{FB}} \text{ with } 100\text{~to~}220pF \text{ of } C_{FB}\]

5. \[\omega_{Z0} = \frac{1}{(R_{VO1} + R_{INT})C_{INT}} << \text{crossover frequency of AAM}\]

- \(R_{BIAS1}\) and \(C_{DIFF}\) compensate phase delay from optocoupler
- \(\omega_{p1}\) and \(\omega_{FB}\) attenuate switching switching ripple but not burst ripple
Stability issue with low-ESR cap

- Power stage: primary resonance ACF in ABM of UCC28780
- Condition: \( V_{\text{BULK}} = 120 \text{V}, \ V_O = 20 \text{V}, \ I_O = 0.5 \text{A}, \ C_O = 680 \mu \text{F} \)

- Closed loop with electrolytic cap
  - Always 4 PWML pulses per burst packet

- Closed loop with polymer cap
  - 4~14 PWML pulses in different burst packets

Burst-ripple magnitude with low-ESR cap is too small to maintain consistent burst package, so the noise-sensitive burst loop impairs output ripple and aggravates audible noise.
Stability issue with 2\textsuperscript{nd}-order filter

- Filter effect on burst ripple
  - Single cap
  - With CLC filter (\(\pi\) filter)

\(L_O\) & \(C_{O1}\) resonance creates ringing on output ripple, which may trigger next burst package prematurely.

- Close loop test with \(\pi\) filter

Every first \(L_O\) & \(C_{O1}\) ringing reaches \(I_{REF}\), so the adjacent burst bundles together and results in higher voltage ripple, amplified low-frequency audible noise.
Solution: active ripple compensation (ARC)

$Q_{COMP}: 2N7002 \text{ (SOT-323)}; R_{COMP}=1\sim2\text{MΩ}$

- Used for ACF with low-ESR output capacitor or 2$^{nd}$-order output filter
- $I_{COMP}$ to push the undesirable ripple and switching noise away from intersection point with $I_{REF}$, so consistent burst packets can be obtained
ARC performance with low-ESR output cap

- Power stage: primary-resonance ACF in ABM of UCC28780
- Condition: $V_{BULK}=120V$, $V_O=20V$, $I_O=0.5A$, $C_O=680\mu F$ using polymer capacitor

**No ARC:**

- $4\sim14$ PWML pulses in different burst packets

**With ARC:**

- Always 3 PWML pulses per burst packet

**ARC is effective on ABM with low-ESR output capacitor**
ARC performance with output π filter

- Power stage: secondary-resonance ACF in ABM of UCC28780
- Condition: \( V_{BULK} = 120V, V_O = 20V, I_O = 0.5A, C_{O1} = 66\mu F, L_O = 1\mu H, C_{O2} = 680\mu F \) (ceramic)

- No ARC:
  - Power stage: secondary
  - Resonance ACF in ABM of UCC28780
  - Condition: \( V_{BULK} = 120V, V_O = 20V, I_O = 0.5A, C_{O1} = 66\mu F, L_O = 1\mu H, C_{O2} = 680\mu F \) (ceramic)

- With ARC & serial damping:
  - Always 3 PWML pulses per burst packet

- ARC + weak serial damping stabilizes ABM with 2nd-order output filter
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Issues of 2\textsuperscript{nd}-order filter w/o damping for ACF

\[ V_{CLAMP} \]
\[ I_{PRI} \]
\[ L_K \]
\[ I_{SEC} \]
\[ L_O \]
\[ V_O \]
\[ V_{BULK} \]
\( C_{CLAMP} \)
\( Q_H \)
\( Q_{SR} \)
\( C_{O1} \)
\( C_{O2} \)

1) 1kHz audible noise
2) Erratic SR operation

\( I_{PRI} \)
\( V_{Co2} \)
\( V_{gs(SR)} \)
\( V_{Co1} \)

Inconsistent resonance current every switching cycle

\[ I_M \text{ flows to the low-volt. side first} \]

\[ \begin{align*}
N_{PS} V_{Co1} > V_{CLAMP}: & \quad N_{PS} I_{PRI} > I_{SEC} \\
N_{PS} V_{Co1} < V_{CLAMP}: & \quad N_{PS} I_{PRI} < I_{SEC}
\end{align*} \]

Cause: large \( L_O \) & \( C_{O1} \) resonance ripple changes \( V_{Co1} \) every cycle, so the resonance current on \( I_{PRI} \) is not consistent
Concept serial damping technique

Damping ratio of $L_O C_{O1}$ double pole:

$$\zeta \approx \frac{1}{2} \frac{R_{DAMP}}{1 + \frac{C_{O1}}{L_O} \sqrt{\frac{C_{O1}}{L_O}}}$$

Serial damping can effectively reduce peaking of $L_O C_{O1}$ double pole.

Bode plot of $V_O(s) / I_{SEC}(s)$:
- W/o damping
- With damping

Gain (dB)
Phase (°)
Design and trade-off of damping strength

- **Strong damping:**
  \[
  L_{DAMP} \approx 0.13 \cdot L_O \quad R_{DAMP} \approx \sqrt{\frac{L_O}{C_{O1}}}
  \]
  \[L_{DAMP} = 150\text{nH results in 0.5\% eff drop at } 90\text{V}_{\text{AC}}\]

- **Weak damping:**
  \[
  L_{DAMP} > 0.13 \cdot L_O \quad R_{DAMP} > \sqrt{\frac{L_O}{C_{O1}}}
  \]
  \[L_{DAMP} = 680\text{nH results in 0.15\% eff drop at } 90\text{V}_{\text{AC}}\]

Design example:
\[V_{\text{AC}}=90\text{V}, \quad V_O=20\text{V}, \quad P_O=45\text{W},\]
Secondary-resonance ACF,
\[C_{O1}=66\mu\text{F ceramic},\]
\[C_{O2}=680\mu\text{F polymer}\]
\[L_O=1\mu\text{H}\]

Too strong damping traps AC current in the damping circuit and affects full load efficiency.
ACF with weak damped output π filter

- Power stage: secondary-resonance ACF in ABM of UCC28780
- Condition: $V_{BULK}=120V$, $V_O=20V$, $I_O=0.5A$, $C_{O1}=66\mu F$ (ceramic), $L_O=1\mu H$, $C_{O2}=680\mu F$ (polymer)
- Weak damping: $L_{DAMP}=680nH$, $R_{DAMP}=0.68\Omega$

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**Without serial damping (ARC only):**

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**With weak serial damping:**

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Weak serial damping ensures consistent SR driving pulse and ABM operation
One small SMD inductor

$L_{DAMP} = 680\, \text{nH}, \quad R_{DAMP} = 0.68\, \Omega$

The intrinsic resistance of the chip inductor is a free $R_{DAMP}$
Summary

• The efficiency advantage of ACF with TI’s new ACF chipsets is demonstrated and compared with QR on a high-density 45W adapter operating > 130kHz

• A unique small-signal modeling technique for ACF is proposed and the distinctive plant characteristic under CCM and TM operations are compared

• The light load efficiency advantage of ACF in burst mode is demonstrated and the stability and SR operation issues are highlighted

• Two ripple compensation techniques and a serial damping method are described that effectively stabilize both burst control loop and SR operation