High VOLT Interactive

Where power supply design meets collaboration

# Demystifying active-clamp flyback loop compensation

**Pei-Hsin Liu**

# What will I get out of this session?

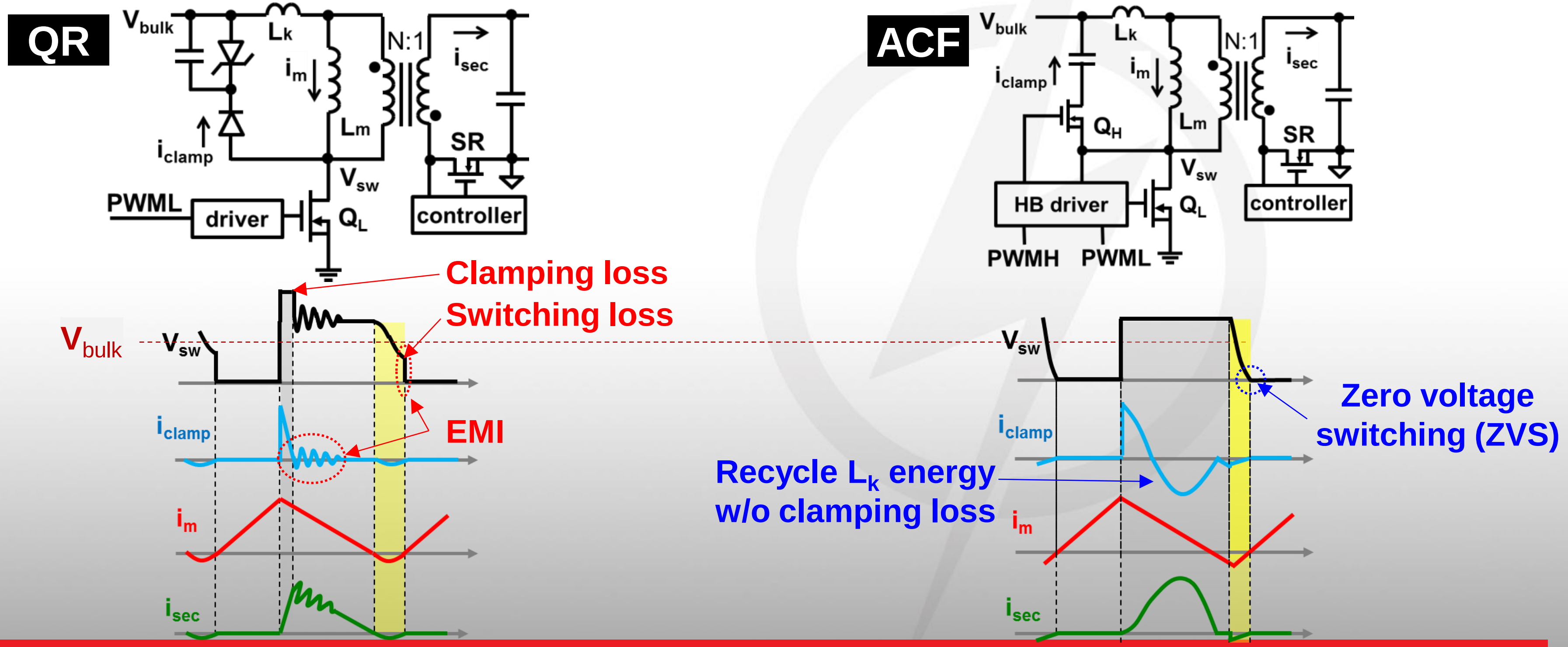
- Purpose:
  1. Analyze the small-signal properties of CCM and TM operations of ACF
  2. Address the benefit and stability issue of burst mode operation of ACF
  3. Introduce design guides based on the analytical model and two simple ripple compensation methods to stabilize the burst control loop

- 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 π output filter
- Summary

# Quasi-resonance (QR) vs. active clamp (ACF)



**Clamping loss**

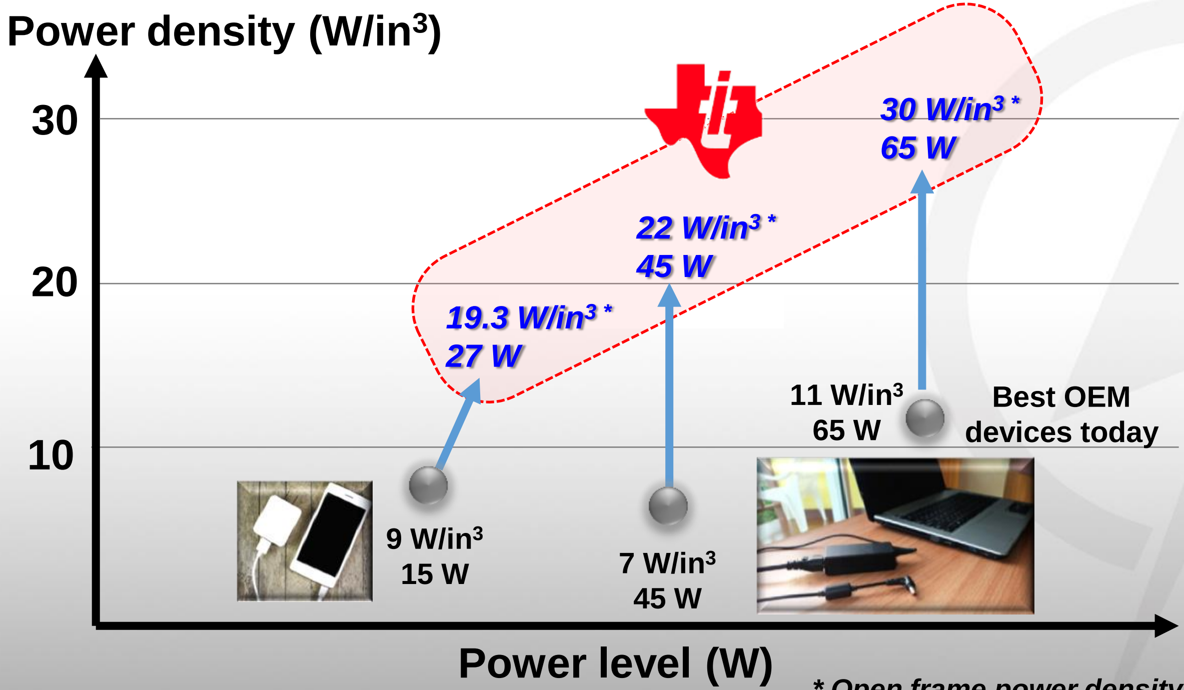
**Switching loss**

**EMI**

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

**Zero voltage switching (ZVS)**

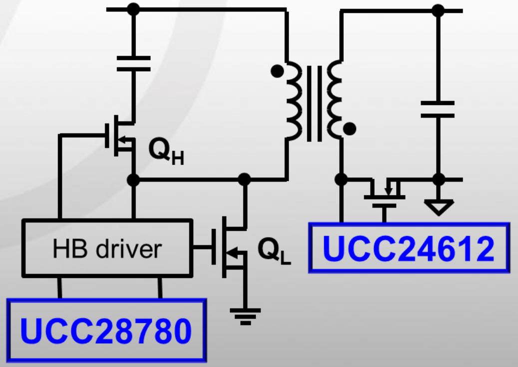
# TI active clamp flyback (ACF) vs. existing solutions



** Open frame power density*

**65W QR**

**65W ACF (94% pk)**

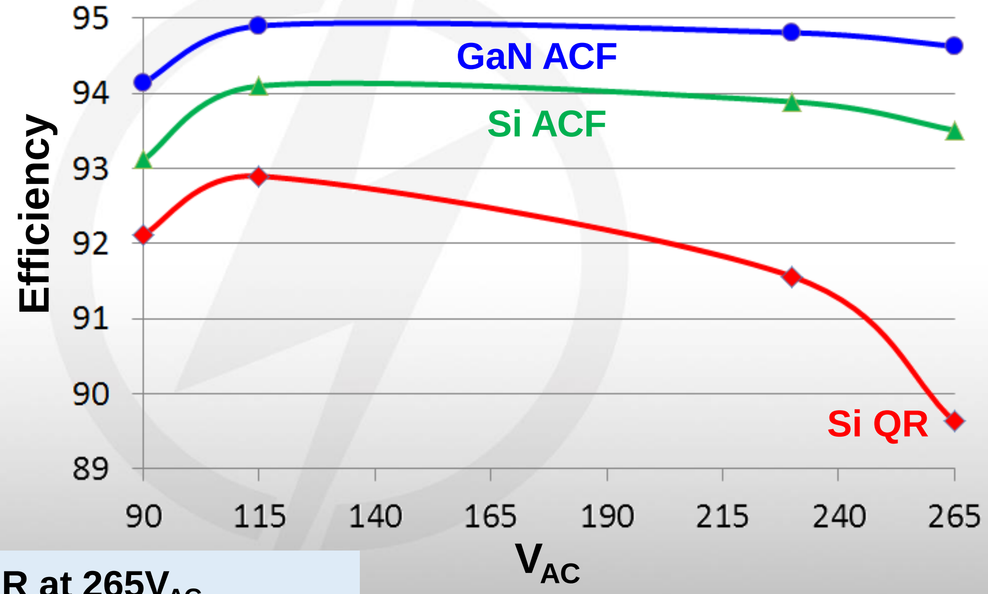


# Efficiency difference on 45W adapter (22W/in$^3$)

**Condition: (1) same RM8LP XFRM**
**(2) same EMI filter**
**(3) same output CLC filter**
**(4) similar $f_{SW}$ range**

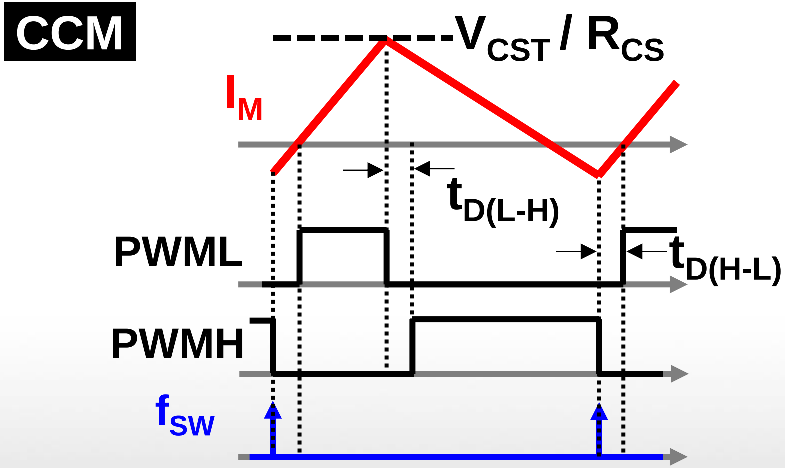
| | $90V_{AC}$ | $265V_{AC}$ |
|---|---|---|
| Si QR | 92.12%<br>($f_{sw}$=237kHz) | **89.93%**<br>($f_{sw}$=413kHz) |
| Si ACF | **93.12%**<br>($f_{sw}$=206kHz) | 93.51%<br>($f_{sw}$=285kHz) |
| GaN ACF | **94.14%**<br>($f_{sw}$=227kHz) | 94.63%<br>($f_{sw}$=295kHz) |

- **20V/45W efficiency with UCC28780:**



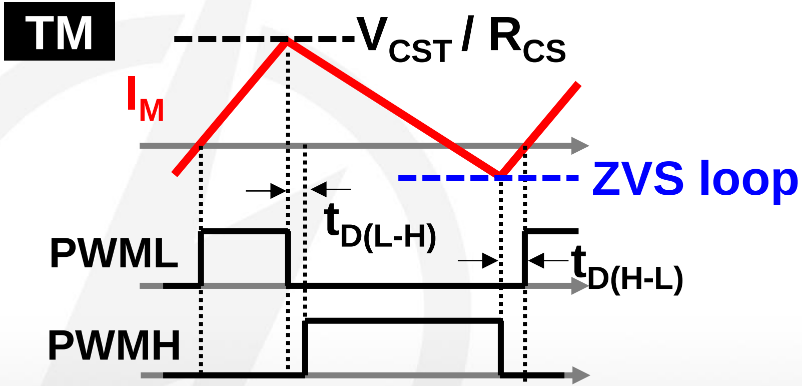
- **Si ACF provides 3.6% improvement over Si QR at $265V_{AC}$**
- **With same EMI filter, Si ACF is 1% lower than GaN ACF at $90V_{AC}$**

# Cont. conduction mode (CCM) vs. transition mode (TM)



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

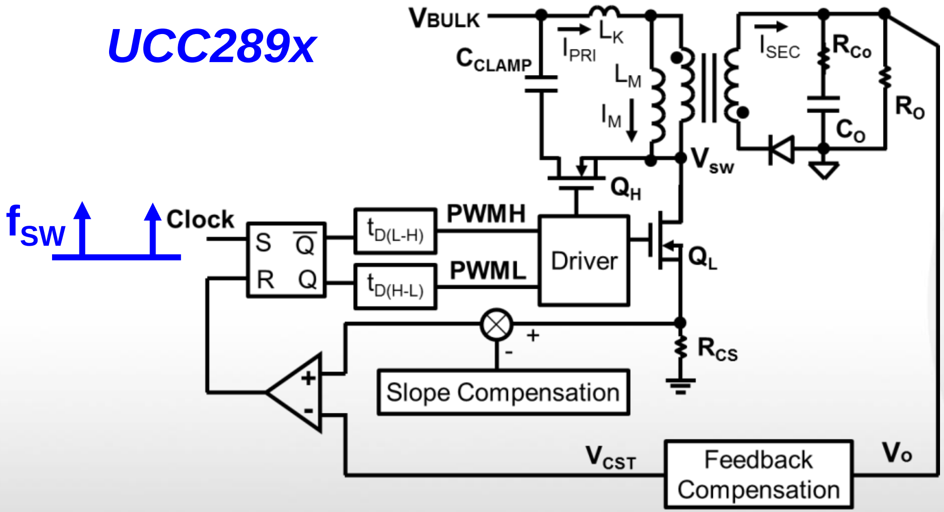
***(Legacy controller: UCC289x)***



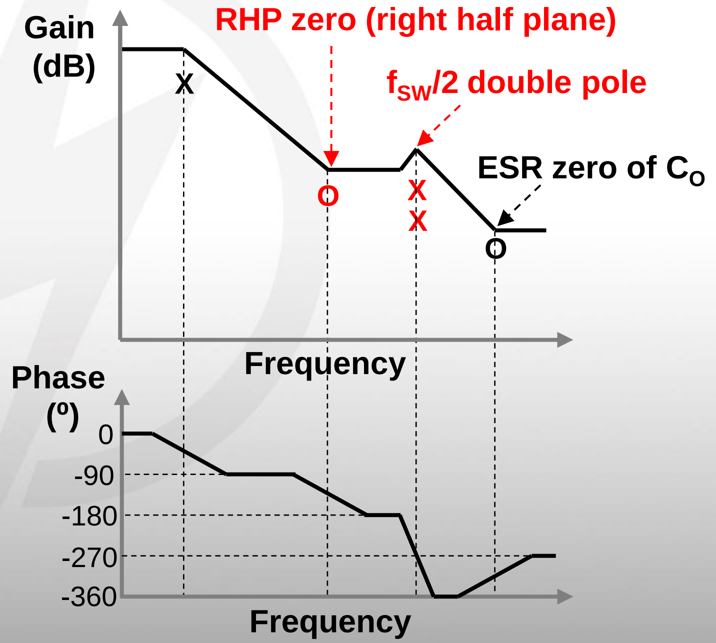
- PWMH turns off by a separate ZVS loop (like a negative valley current loop)
- PWML turns on after $t_{D(H-L)}$ delay
- PWML turns off by a peak current loop

***(New controller: UCC28780)***

# Small-signal property in CCM operation

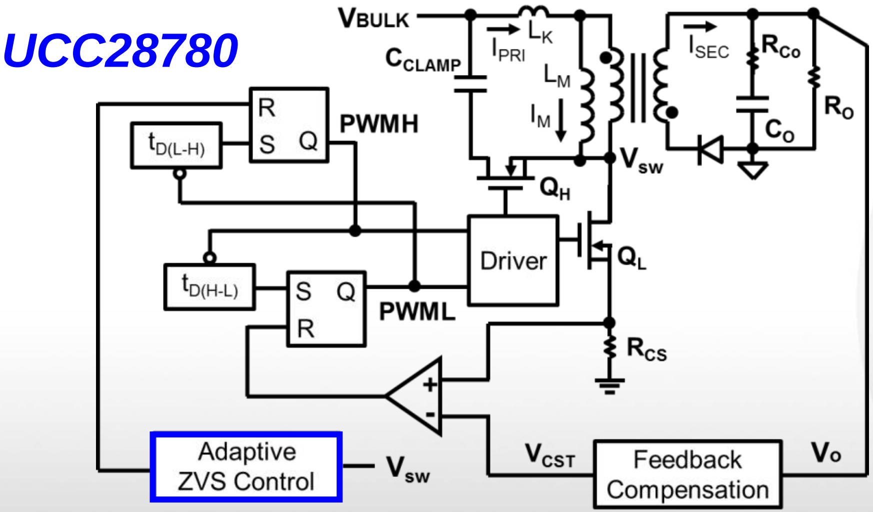


- $V_{CST}$ to $V_O$ transfer function:

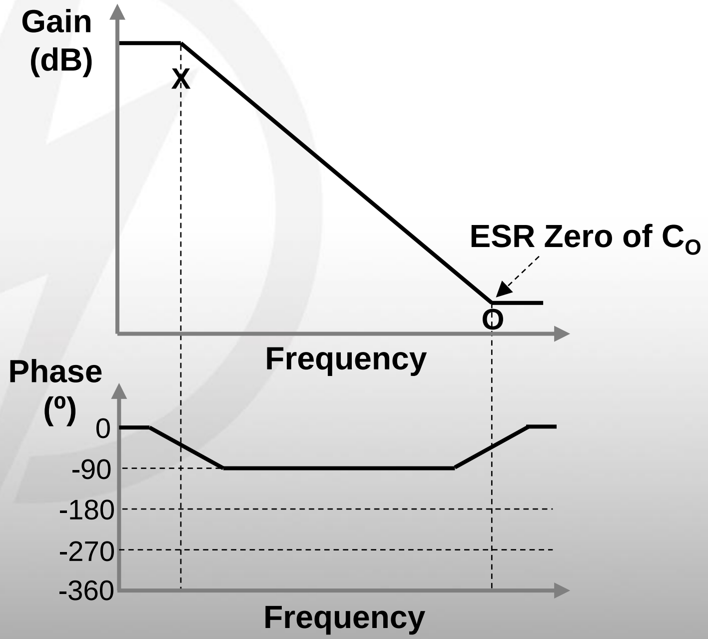


- Need slope compensation to damp $f_{SW}/2$ double pole to stabilize the peak current loop as duty cycle > 50%
- Phase delay of RHP zero limits system bandwidth

# Small-signal property in TM operation

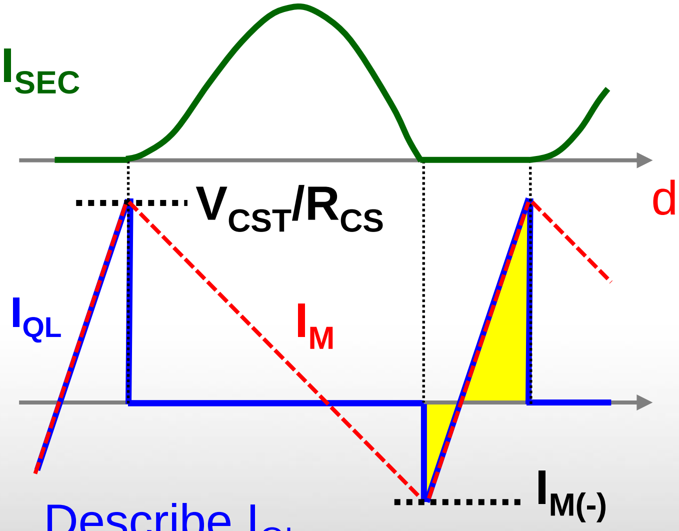


➢ $V_{CST}$ to $V_O$ transfer function:

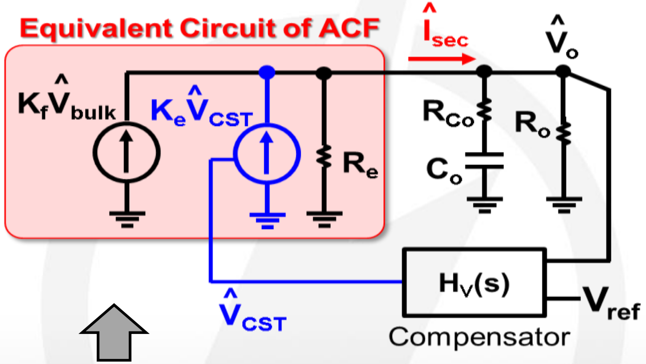


- PWML off by peak current loop; PWMH off by ZVS loop
- Inherently stable; no need slope compensation
- No RHP zero results in a higher bandwidth design

# Proposed modeling methodology for TM ACF



difficult



$$\hat{I}_{SEC} = \frac{\partial I_{SEC}}{\partial V_{CST}}\hat{V}_{CST} + \frac{\partial I_{SEC}}{\partial V_{BULK}}\hat{V}_{BULK} + \frac{\partial I_{SEC}}{\partial V_O}\hat{V}_O$$

***Small-signal perturbation***

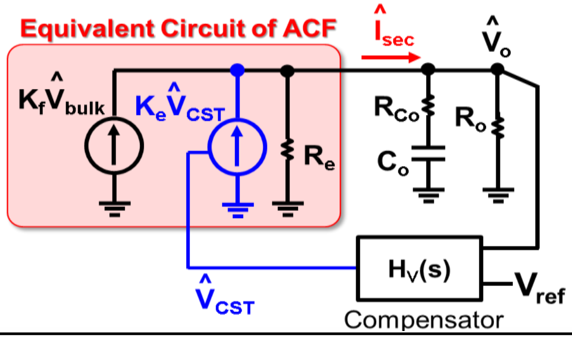
Describe $I_{QL}$ mathematically

$$I_{QL} \approx \frac{1}{2}\left(\frac{V_{CST}}{R_{CS}} + I_{M(-)}\right)\frac{N_{PS}V_O}{V_{BULK} + N_{PS}V_O}$$

$$I_{SEC} = \eta\frac{V_{BULK}I_{QL}}{V_O}$$

***From energy balance w/o describing resonance current***

# Small-signal model and simulation verification

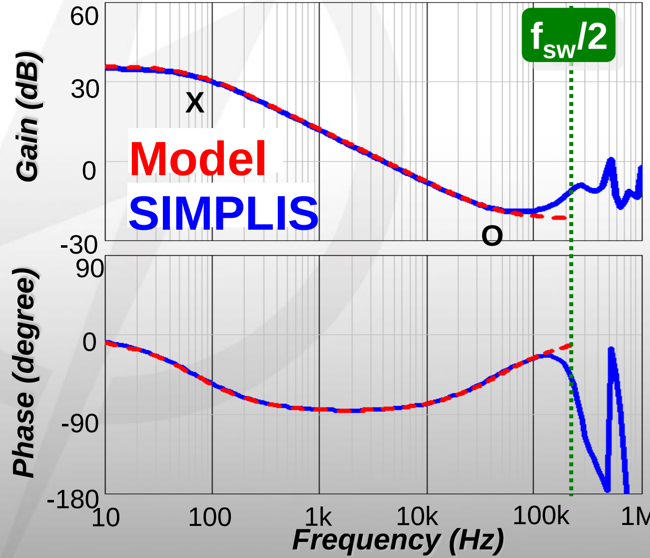


$$\frac{V_O(s)}{V_{CST}(s)} = K_e \frac{R_e R_L}{R_e + R_L} \frac{1 + sC_O R_{Co}}{1 + sC_O\left[\frac{R_e R_L}{R_e + R_L} + R_{Co}\right]}$$

-----▸ ESR zero

-----▸ LF pole

| | |
|---|---|
| $I_{M(-)}$ | $V_{BULK}\sqrt{C_{SW}/L_M}$ |
| $K_e$ | $N_{PS}V_{BULK}\ /[2R_{CS}(V_{BULK} + N_{PS}V_O)]$ |
| $R_e$ | $\frac{2R_{CS}(V_{BULK} + N_{PS}V_O)^2}{N_{PS}{}^2 V_{BULK}(V_{CST} + R_{CS}I_{M(-)})}$ |
| $V_{CST}$ | $\frac{2P_{in}(V_{BULK} + N_{PS}V_O) - N_{PS}V_O V_{BULK} I_{M(-)}}{N_{PS}V_O V_{BULK}} R_{CS}$ |



# 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 π output filter
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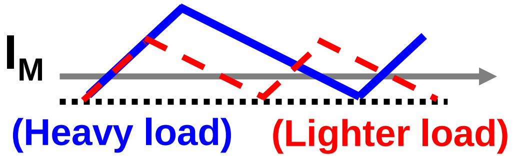
# Issue of ACF light load efficiency



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

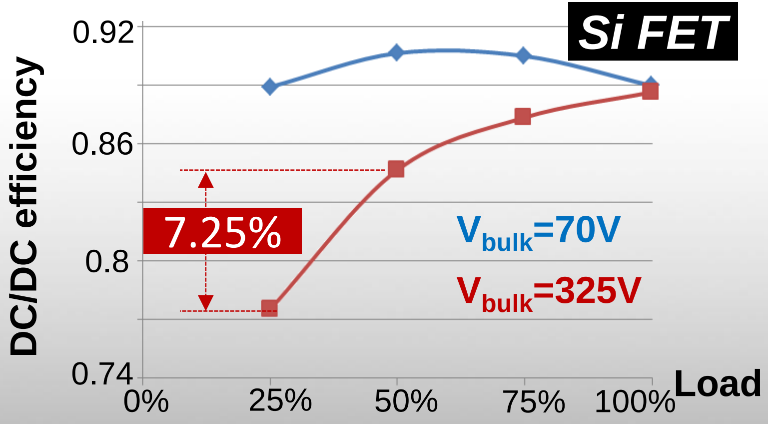
$i_{m(-)}$: Stores energy used for ZVS (no contribution to output power)

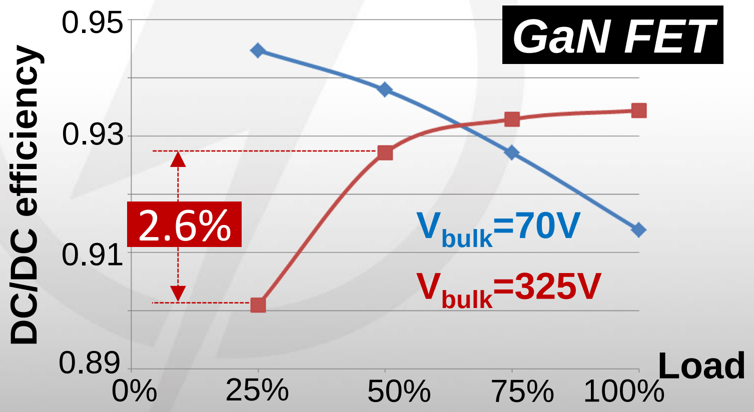
$$\frac{i_{m(+)}}{i_{m(-)}}$$

***High ratio is good***

***Lower ratio results in lower eff!***

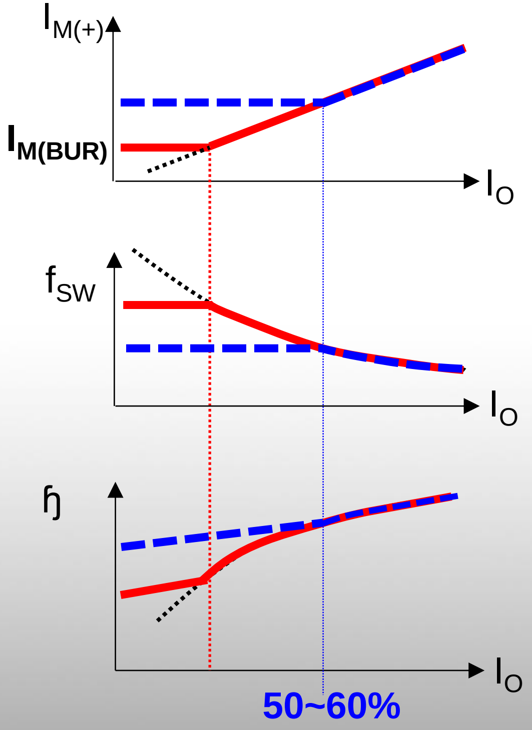
Condition: $P_{o(max)}$=30W, $V_o$=20V, ***sec. Schottky***

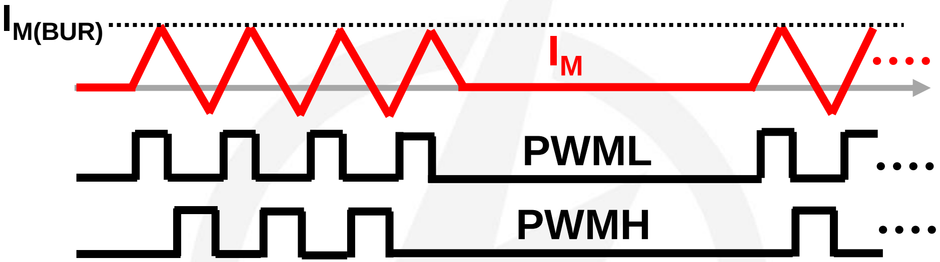




**Current mode control only can not maintain light load efficiency**

# Optimize avg. eff. with burst setting of UCC28780

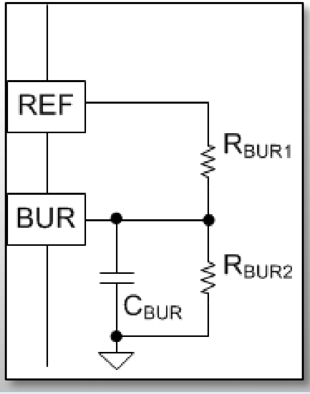




$$V_{BUR} = 5V \frac{R_{BUR2}}{R_{BUR1} + R_{BUR2}}$$

$$= (I_{m(BUR)} R_{CS}) K_{CST-BUR}$$

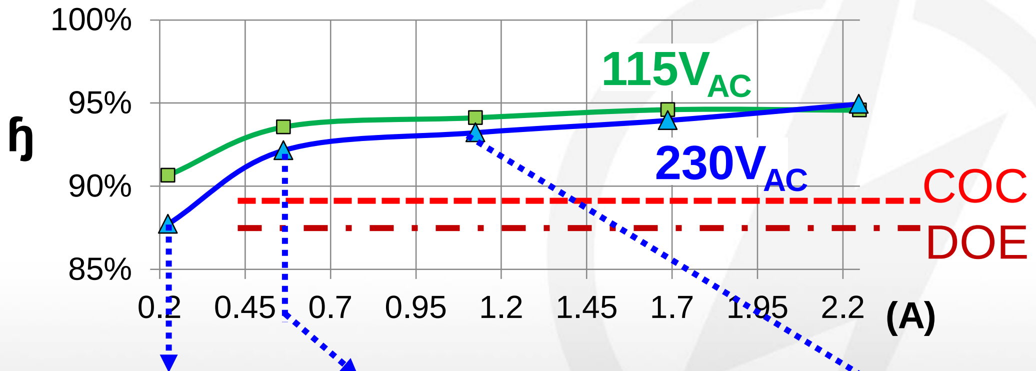
where $V_{REF}$ = 5V, $K_{CST-BUR}$ = 4 V/V



**The programmable burst mode is simple to optimize the efficiency**

# Adaptive burst mode (ABM) of UCC28780

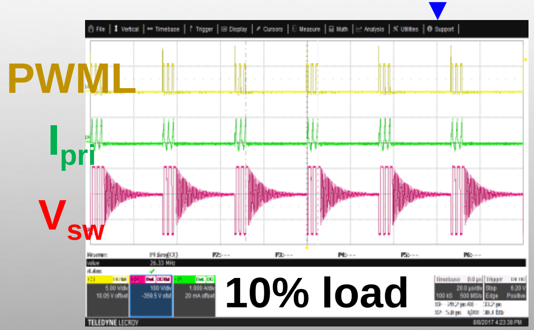
Condition: $P_{OUT(MAX)}$ = 45 W, $V_O$ = 20 V, RM8LP, $Q_L$ & $Q_H$ (650V/500mΩ/GaN), SR (150V/9.3mΩ/Si)



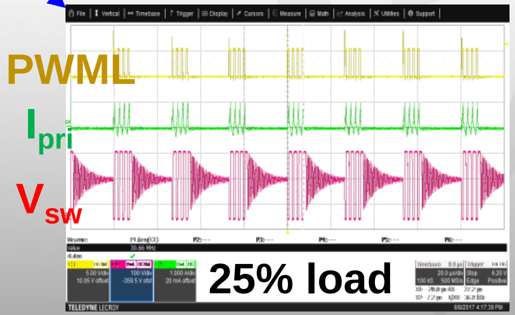
**Avg. eff.**

**94.2% at 115V**

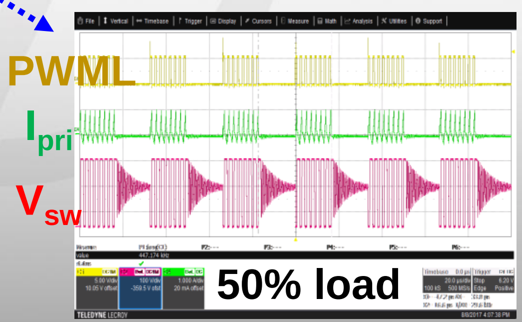
**93.6% at 230V**



10% load

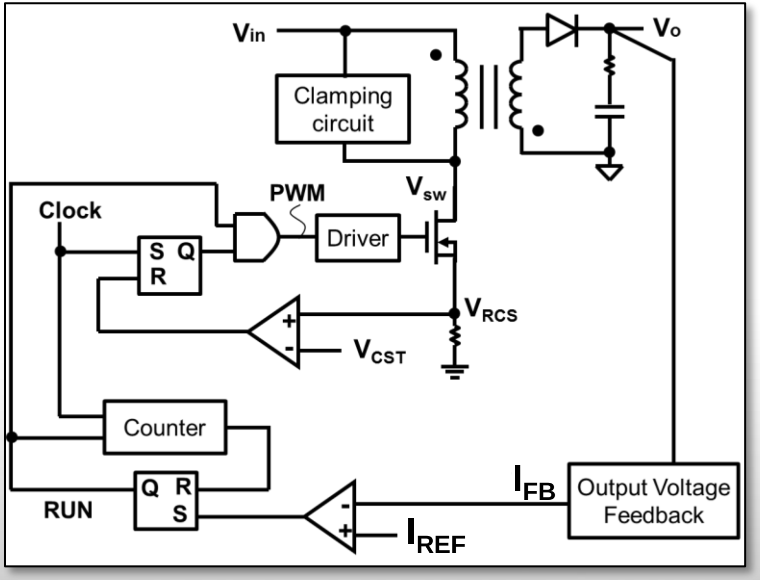


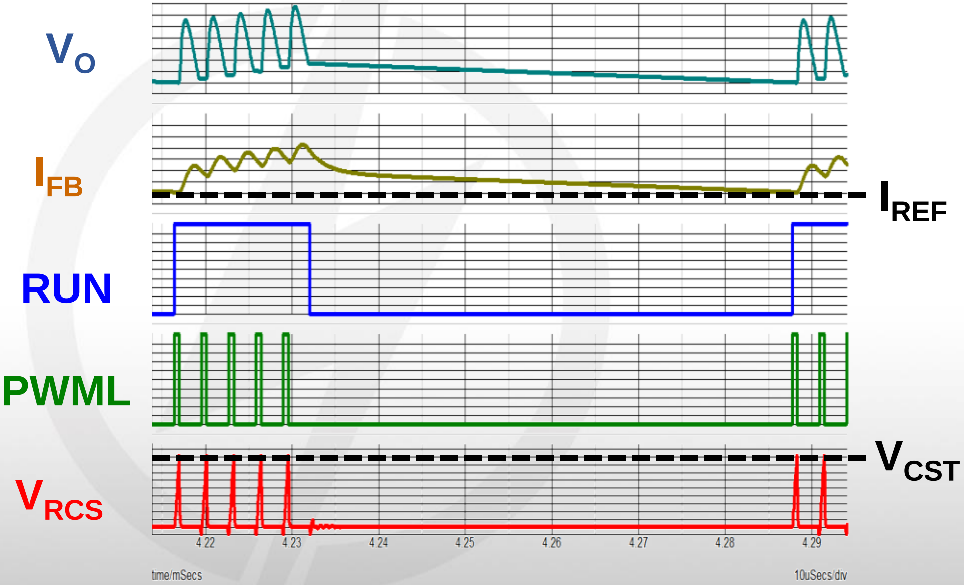
25% load



50% load

# Simplified ABM loop with ripple regulator





- 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

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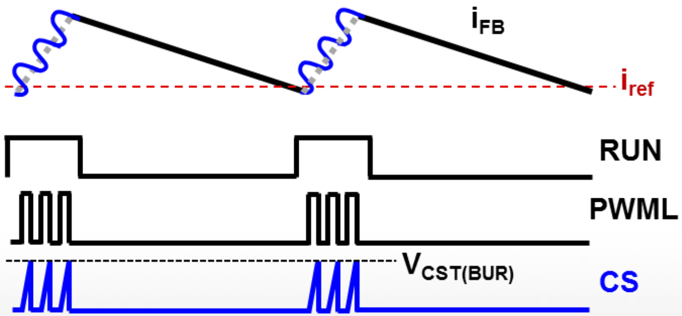
# Stability issue from phase delay of feedback signal

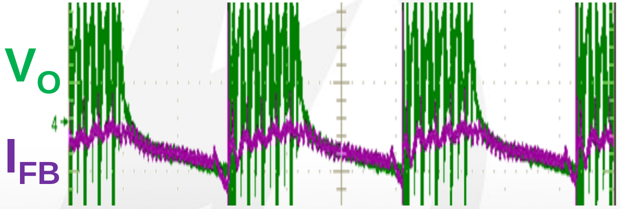
- **Regulation method:**



- **Compensation principle:**

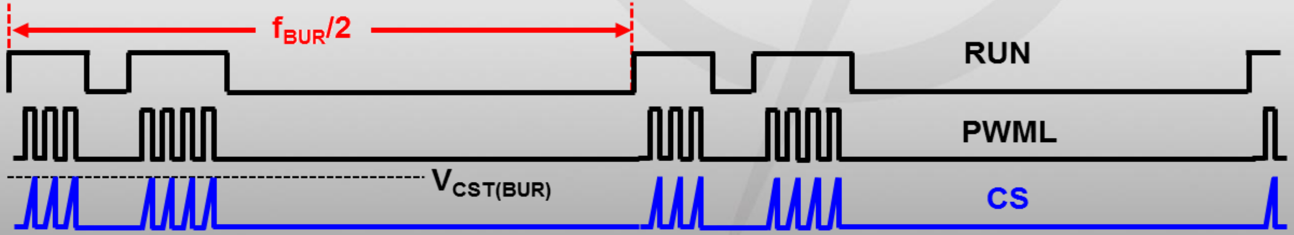
**Make $I_{FB}$ in-phase with $V_O$ "burst" ripple**

Note: not switching ripple

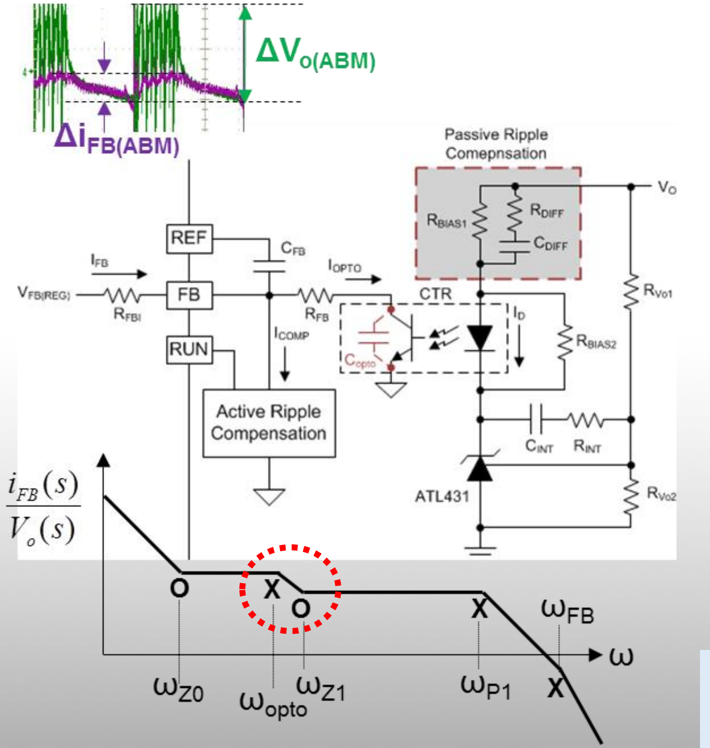


- **Consequence of large phase delay between $I_{FB}$ and $V_O$:**

**Subharmonic oscillation**



# Solution: passive ripple compensation



$$\frac{I_{FB}(s)}{V_O(s)} = \frac{CTR}{R_{BIAS1}}\,\frac{\omega_{Z0}+s}{s}\,\frac{1+(s/\omega_{Z1})}{1+(s/\omega_{P1})}\,\frac{1}{1+(s/\omega_{opto})}\,\frac{1}{1+(s/\omega_{FB})}$$

**(1)** $R_{BIAS1} = \frac{CTR}{\Delta I_{FB(ABM)}}\Delta V_{O(ABM)}$ ($\Delta I_{FB(ABM)}$=10~20μA)

**(2)** $\omega_{P1} = \frac{1}{R_{DIFF}C_{DIFF}}$ **>** Max burst frequency (35kHz) x 2

**(3)** $\omega_{opto} = \frac{1}{(R_{FB}+R_{FBI})C_{opto}}$ **≈** $\omega_{Z1} = \frac{1}{(R_{DIFF}+R_{BIAS1})C_{DIFF}}$

**(4)** $\omega_{FB} = \frac{1}{(R_{FB}//R_{FBI})C_{FB}}$ with 100~220pF of $C_{FB}$

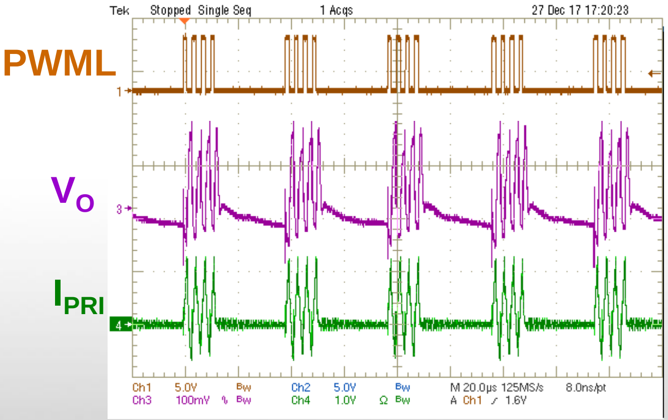
**(5)** $\omega_{Z0} = \frac{1}{(R_{Vo1}+R_{INT})C_{INT}}$ << crossover frequency of AAM

**- $R_{BIAS1}$ and $C_{DIFF}$ compensate phase delay from optocoupler**
**- $\omega_{P1}$ and $\omega_{FB}$ attenuate switching ripple but not burst ripple**

# Stability issue with low-ESR cap

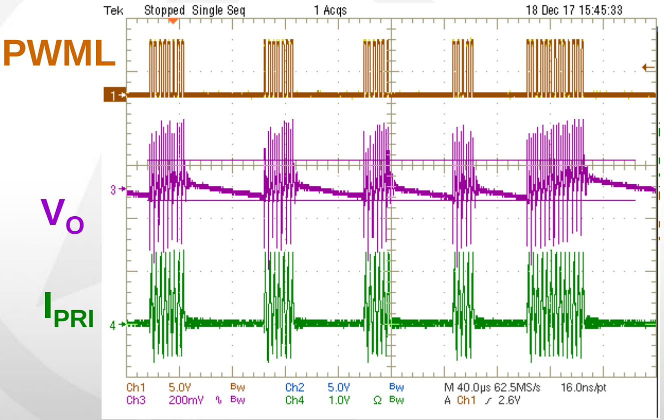
- Power stage: primary resonance ACF in ABM of UCC28780
- Condition: $V_{BULK}$=120V, $V_O$=20V, $I_O$=0.5A, $C_O$=680µF

## ➢ Closed loop with electrolytic cap



Always 4 PWML pulses per burst packet

## ➢ Closed loop with polymer cap



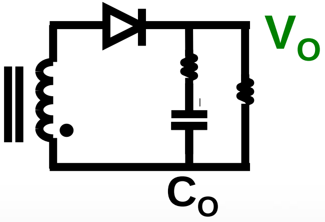
4~14 PWML pulses in different burst packets

**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**

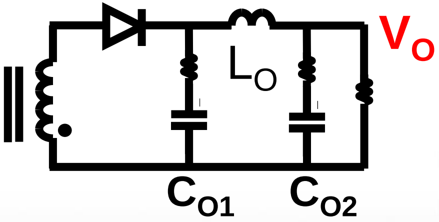
# Stability issue with 2nd-order filter

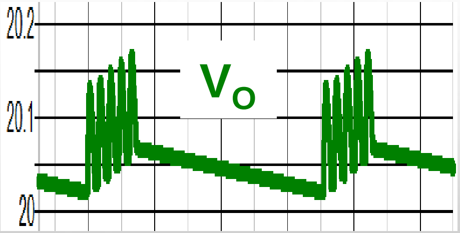
## ➢ Filter effect on burst ripple

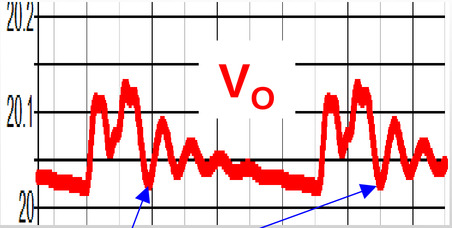
-Single cap



-With CLC filter (π filter)

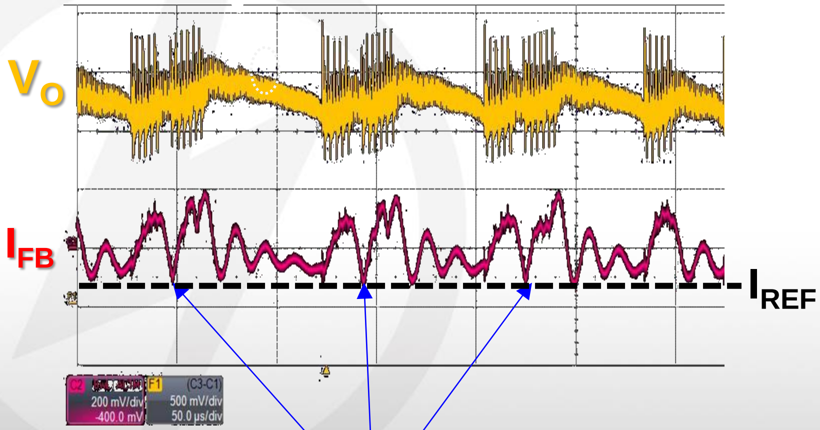






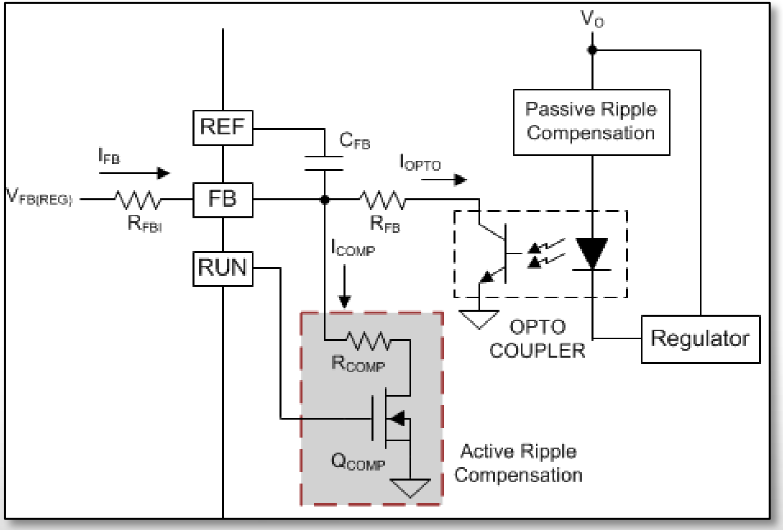
$L_O$ & $C_{O1}$ resonance creates ringing on output ripple, which may trigger next burst package prematurely

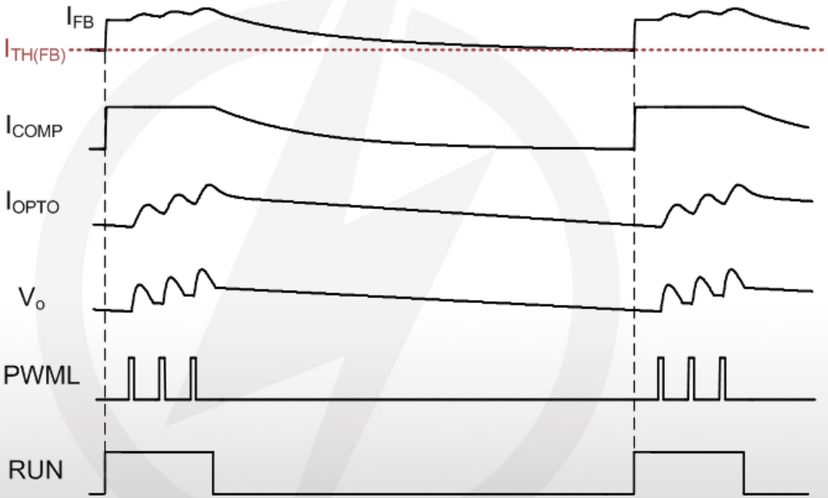
## ➢ Close loop test with π filter



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)



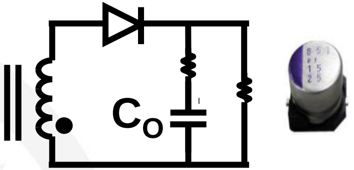


$Q_{COMP}$: 2N7002 (SOT-323); $R_{COMP}$=1~2MΩ

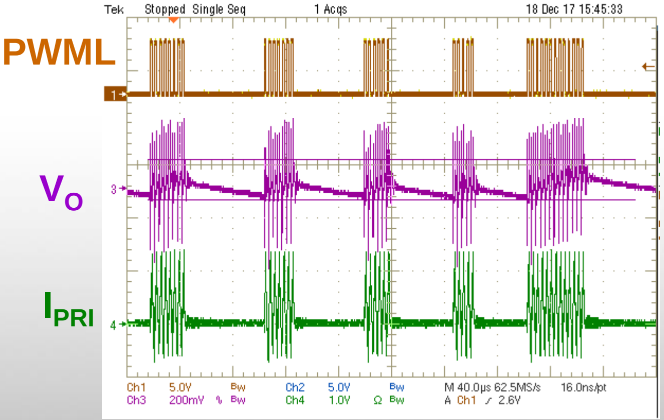
- **Used for ACF with low-ESR output capacitor or 2nd-order output filter**
- **$I_{COMP}$ to push the undesirable ripple and switching noise away from intersection point with $I_{REF}$, so consistent burst packets can be obtained**

# 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, $C_O$=680µF using polymer capacitor

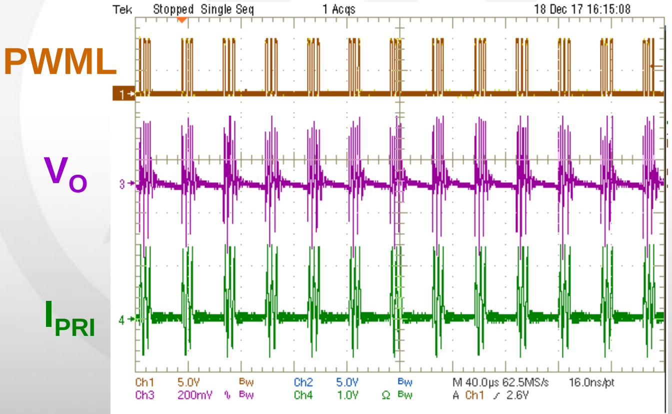


- ➢ **No ARC:**



4~14 PWML pulses in different burst packets

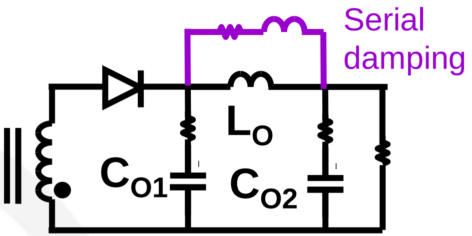
- ➢ **With ARC:**



Always 3 PWML pulses per burst packet

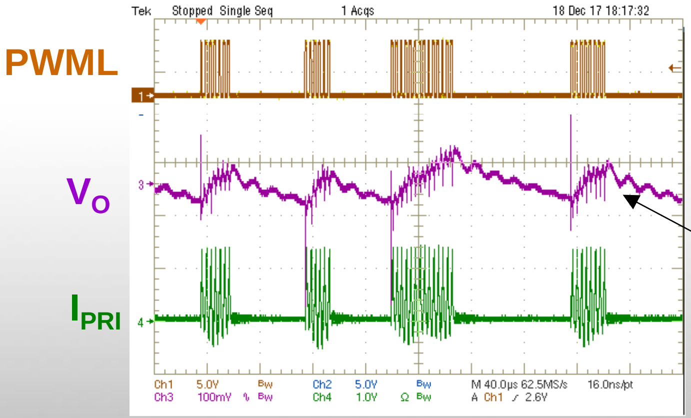
**ARC is effective on ABM with low-ESR output capacitor**

# 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, $C_{O1}$=66µF (ceramic), $L_O$=1µH, $C_{O2}$=680µF (polymer)

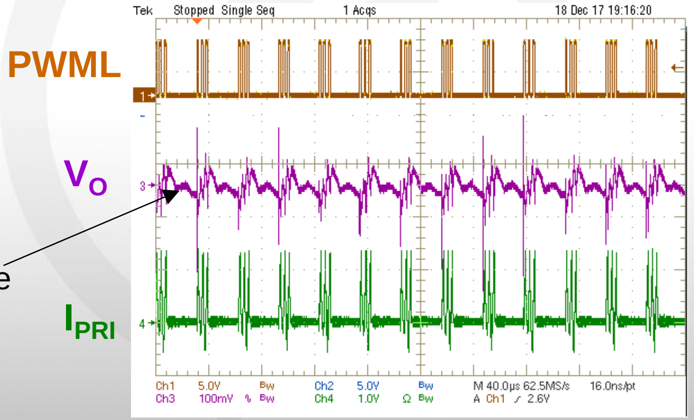
## ➢ No ARC:



4~14 PWML pulses in different burst packets

$L_O$ & $C_{O1}$ resonance

## ➢ With ARC & serial damping:



Always 3 PWML pulses per burst packet

**ARC + weak serial damping stabilizes ABM with 2nd-order output filter**

# Content

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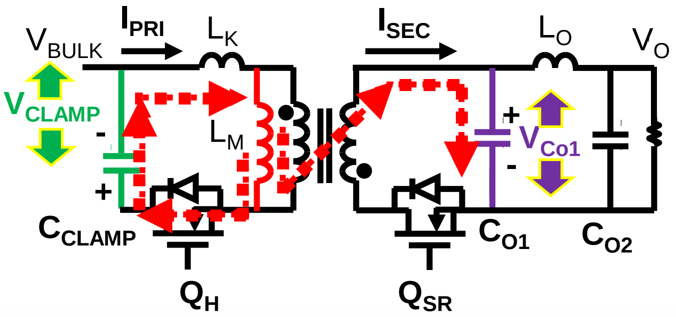
- Ripple compensation to stabilize burst mode control
- **Serial damping for ACF with π output filter**
- **Summary**

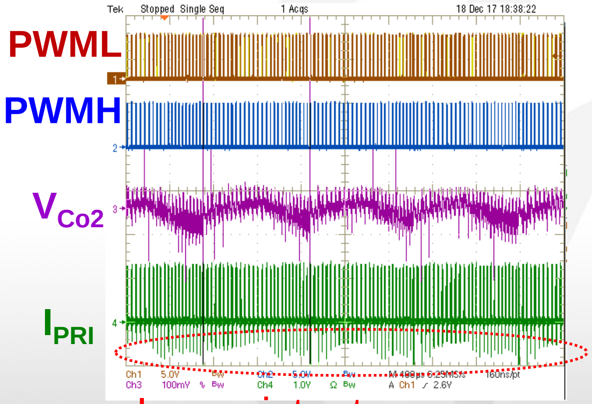
# Issues of 2nd-order filter w/o damping for ACF



*$I_M$ flows to the low-volt. side first*

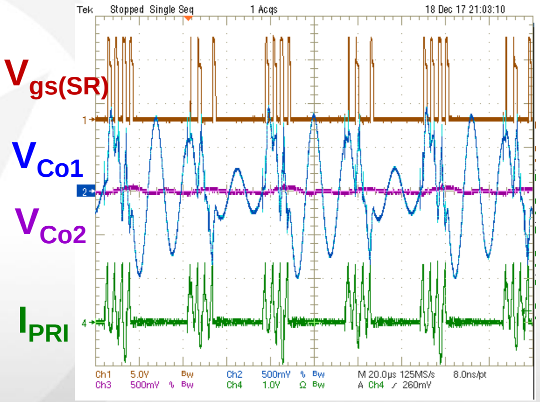
$$\begin{cases} N_{PS}V_{Co1} > V_{CLAMP}: N_{PS}I_{PRI} > I_{SEC} \\ N_{PS}V_{Co1} < V_{CLAMP}: N_{PS}I_{PRI} < I_{SEC} \end{cases}$$

## (1) 1kHz audible noise



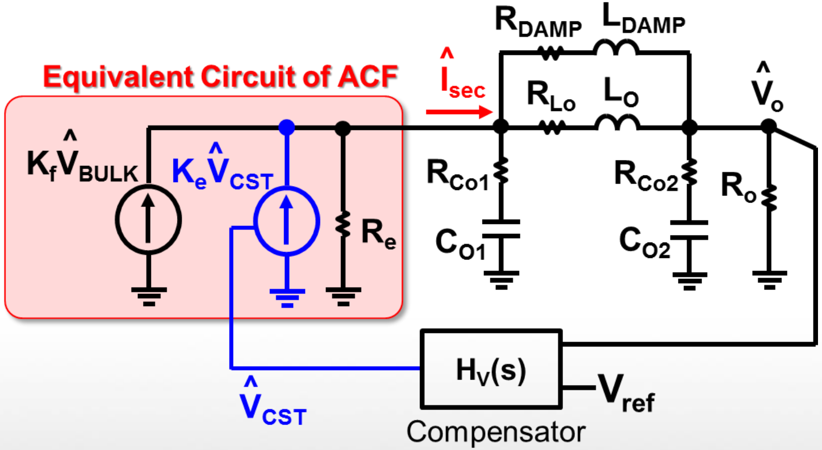
Inconsistent resonance current every switching cycle

## (2) Erratic SR operation



**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

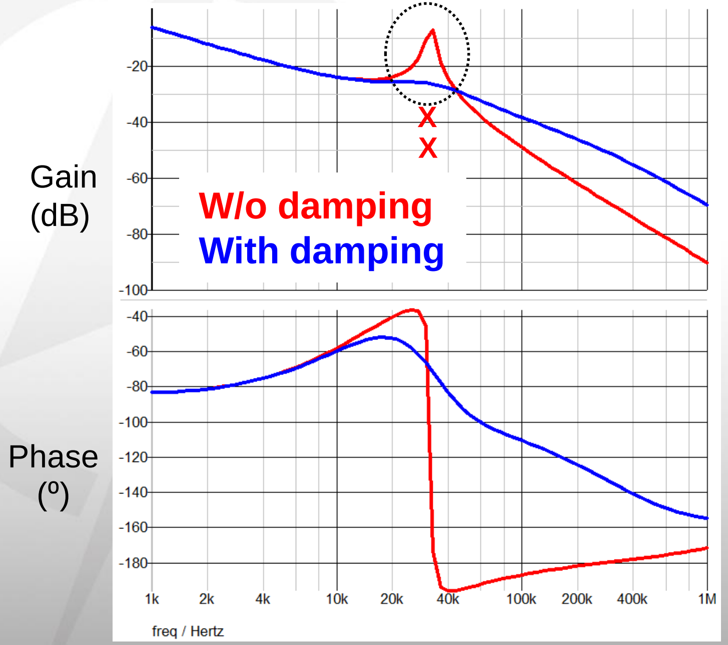


Damping ratio of $L_O$ $C_{O1}$ double pole:

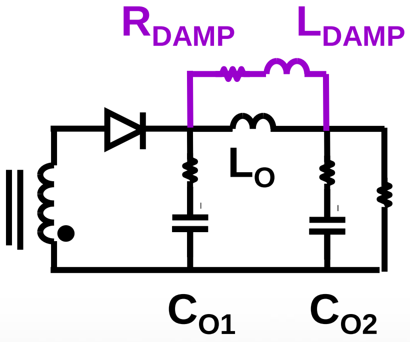
$$\boxed{\zeta\uparrow \approx \frac{1}{2}\frac{R_{DAMP}}{1+(L_{DAMP}\downarrow/L_O)}\sqrt{\frac{C_{O1}}{L_O}}}$$

**Serial damping can effectively reduce peaking of $L_OC_{O1}$ double pole**

- **Bode plot of $V_O(s)$ / $I_{SEC}(s)$:**



# Design and trade-off of damping strength



Design example:

$V_{AC}$=90V, $V_O$=20V, $P_O$=45W,

Secondary-resonance ACF,

$C_{O1}$=66µF ceramic,

$C_{O2}$=680µF polymer

$L_O$=1µH

- **Strong damping:**

$$L_{DAMP} \approx 0.13 \cdot L_O \qquad R_{DAMP} \approx \sqrt{\frac{L_O}{C_{O1}}}$$

**$L_{DAMP}$ = 150nH results in 0.5% eff drop at $90V_{AC}$**

- **Weak damping:**

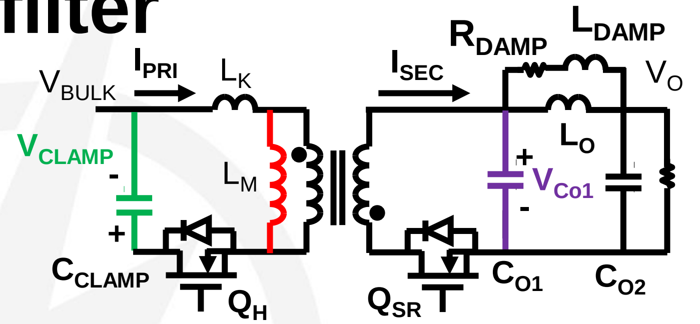
$$L_{DAMP} > 0.13 \cdot L_O \qquad R_{DAMP} > \sqrt{\frac{L_O}{C_{O1}}}$$

**$L_{DAMP}$ = 680nH results in 0.15% eff drop at $90V_{AC}$**

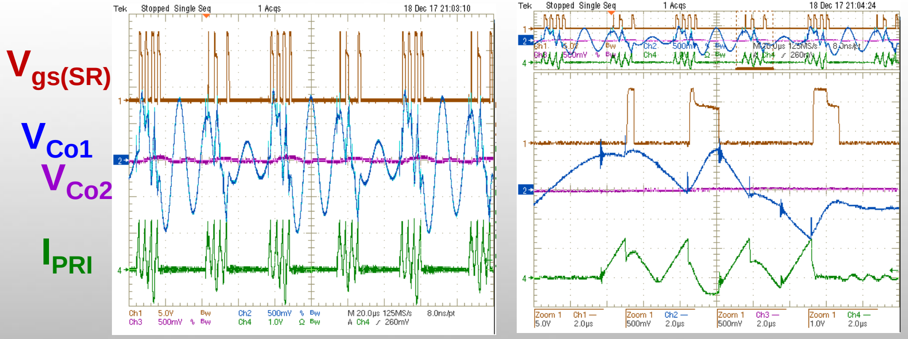
**Too strong damping traps AC current in the damping circuit and affects full load efficiency**

# ACF with weak damped output π filter

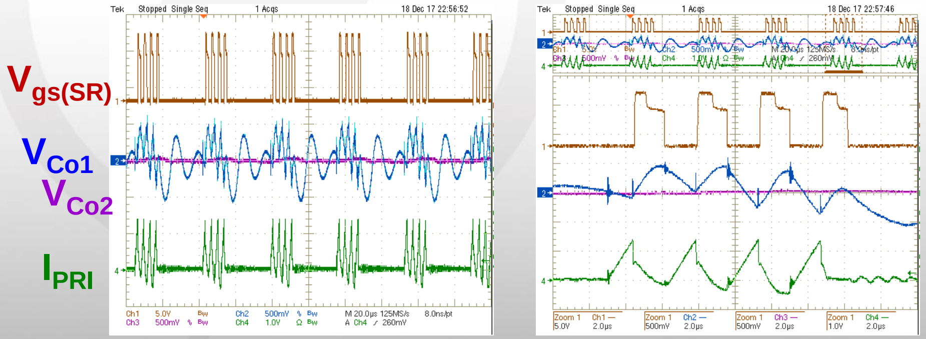
- Power stage: secondary-resonance ACF in ABM of UCC28780
- Condition: $V_{BULK}$=120V, $V_O$=20V, $I_O$=0.5A, $C_{O1}$=66µF (ceramic), $L_O$=1µH, $C_{O2}$=680µF (polymer)
- Weak damping: $L_{DAMP}$=680nH, $R_{DAMP}$=0.68Ω



## ➢ Without serial damping (ARC only):



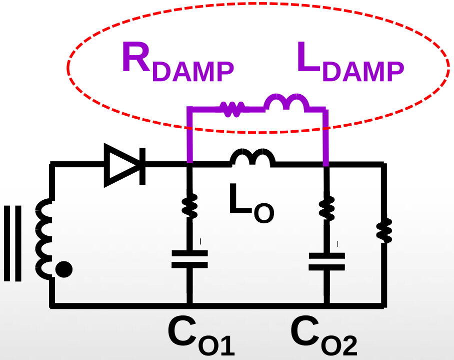
## ➢ With weak serial damping :



**Weak seral damping ensures consistent SR driving pulse and ABM operation**

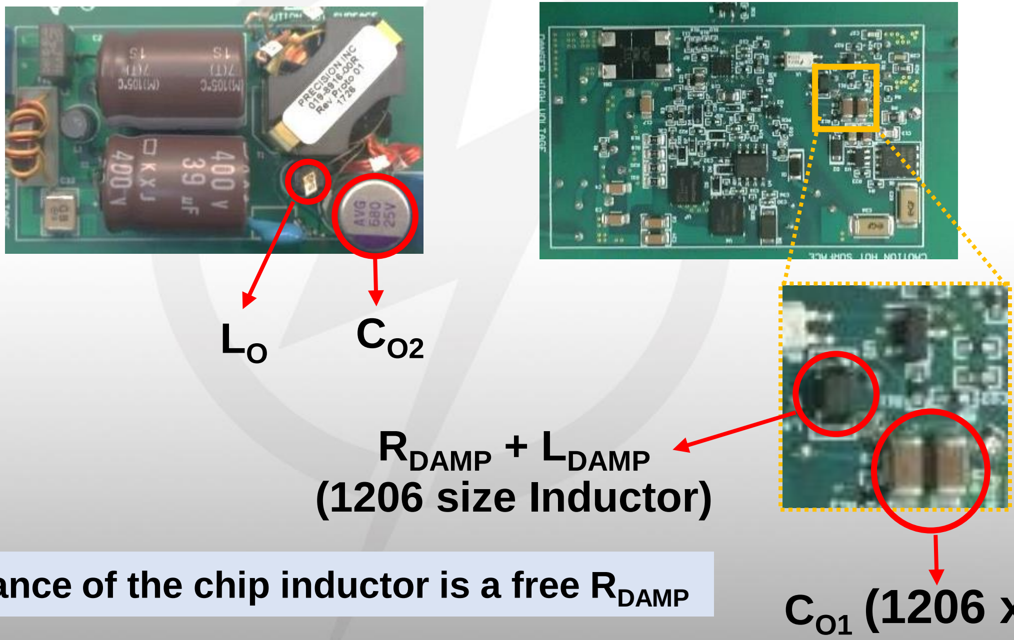
# Component selection on the weak damping

*One small SMD inductor*



$L_{DAMP}$=680nH, $R_{DAMP}$=0.68Ω

***UCC28780 45W EVM***



**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

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