TI Technology Days 2010

AC/DC Solutions for High Efficiency

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System Engineer Power Solutions

Agenda

- **General thoughts, standards and solutions**
- Quasi-resonant green mode flyback (UCC28600)
- Cascoded green mode flyback (UCC28610)
- Active clamp (UCC289x family)
- Interleaved PFCs (UCC2806x / 28070)
- LLC resonant half bridge (UCC25600)
- Green synchronous rectifier controller (UCC24610)
- Advanced green mode phase shifted full bridge (UCC28950)
- Other sources for support
- Summary

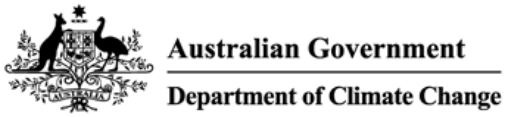
Efficiency increase – directives and legislation

- Enforcement Levels
  - Incentive Programs

  - Voluntary

EC Code of Conduct (EU)

  - Mandatory



EC EuP Eco-Directive (EU) 2005/32/EC

EuP – EPS ≤ 250W (External Power Supplies)

COMMISSION REGULATION (EC) No 278/2009 of 6 April 2009

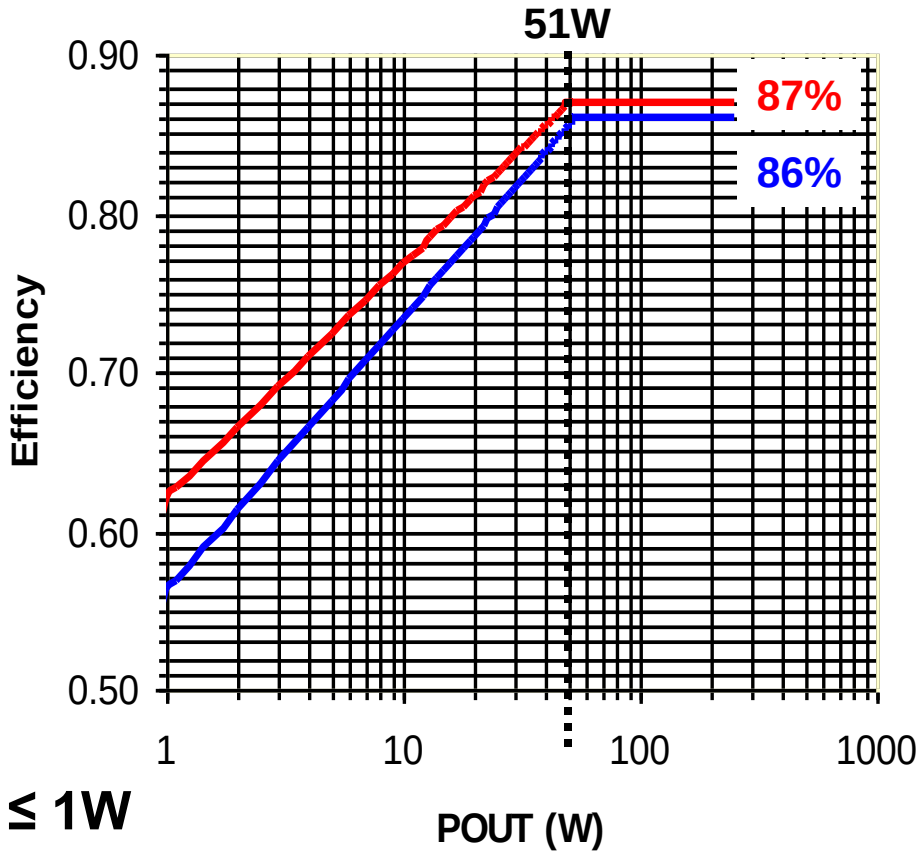
No-load power consumption

≤ 300mW for P_{OUT} ≤ 51W
≤ 500mW for P_{OUT} > 51W

Average active efficiency at 25 / 50 / 75 / 100% of rated P_{OUT} for 1W < P_{OUT} ≤ 51W

2011 EPS (Low Voltage Excluded)
0.063 x ln(P_{OUT}) + 0.622

2011 Low Voltage EPS
(V_{OUT} < 6V & I_{OUT} ≥ 550mA)
0.075 x ln(P_{OUT}) + 0.561



Additional requirements for POUT ≤ 1W (Not shown here)

EuP - Standby and off mode power consumption

COMMISSION REGULATION (EC) No 1275/2008 of 17 December 2008

- Equipment shall, … provide:
  - off mode and/or
  - standby mode, and/or
  - another condition which does not exceed … power consumption requirements for off mode and/or standby mode when the equipment is connected to the mains power source.

Power Consumption	Form January 2010 on , Power Consumption (W)	January 2013, Power Consumption (W)
OFF Mode	**1**	**0.5**
Standby Mode providing only reactivation function w/ or w/o indication of enabled reactivation function	**1**	**0.5**
Standby Mode providing only *information or status display* w/ or w/o a reactivation function	**2**	**1**
Power Management for automatic transition into OFF Mode or Standby Mode	**-**	**YES**

Ways to achieve required efficiency

- Select proper power stage topology
- Optimize components in power stage
- Utilize power saving modes & features
  - Low start-up and operation quiescent currents
  - Quasi-resonant and resonant techniques
  - ZVS (Zero Voltage Switching)
  - Phase management
  - Burst mode
  - Synchronous rectification

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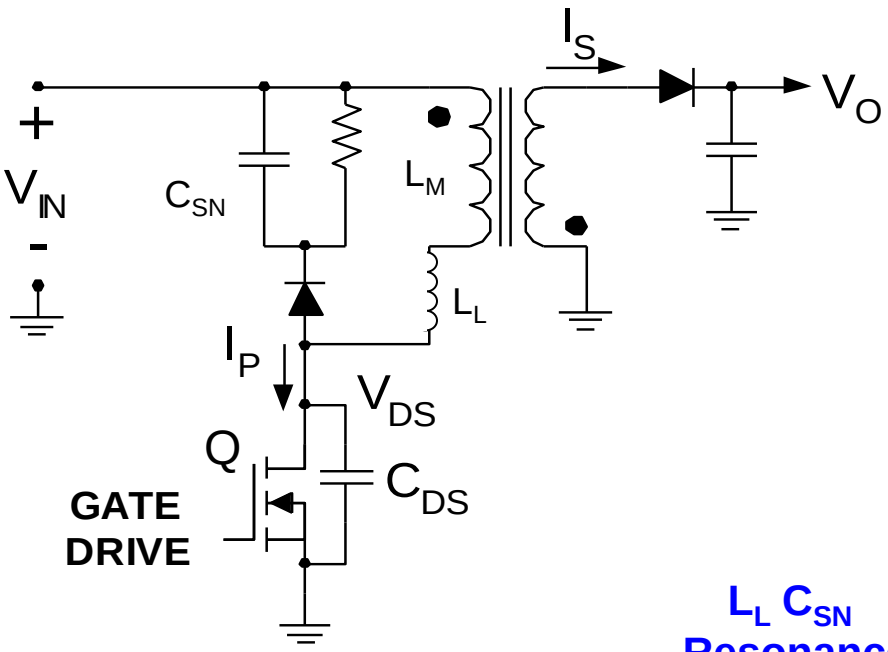
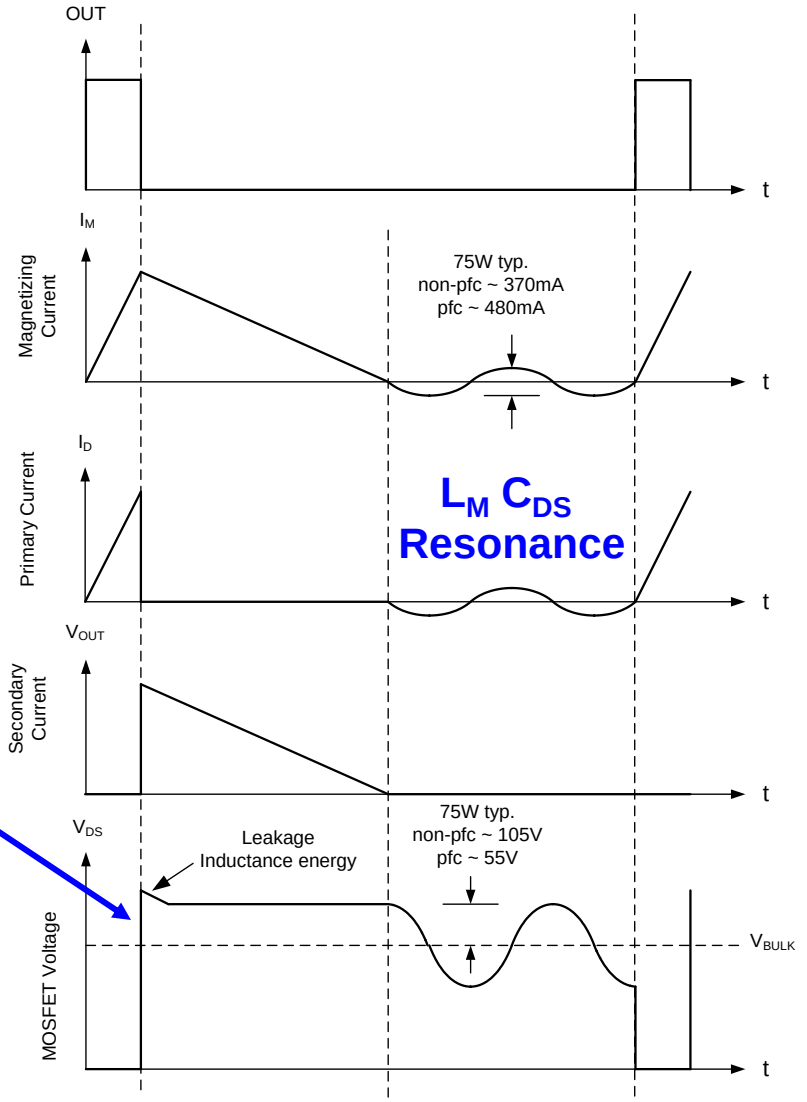
UCC28600 – Valley switching makes the difference



Energy in C_{DS} is lost each time Q is switched ON $\frac{1}{2} C_{DS} V_{DS}^{2}$



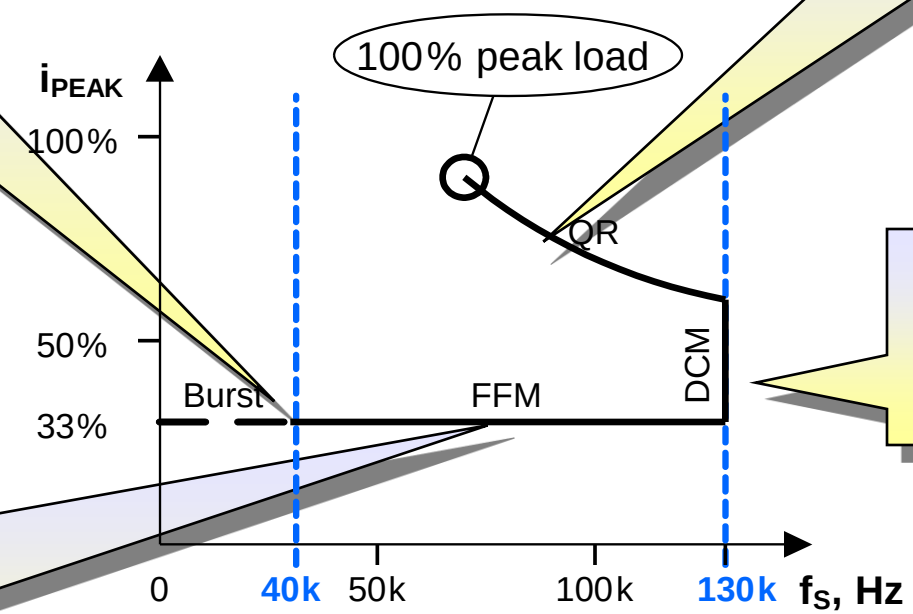
UCC28600 – Multiple operation modes make the difference

Green Mode (Burst Mode)
use bursts to reduce snubber loss and split harmonics for audio reduction

Quasi-Resonant Mode
high efficiency at full load

Discontinuous Conduction Mode
limit upper frequency for smaller EMI filter

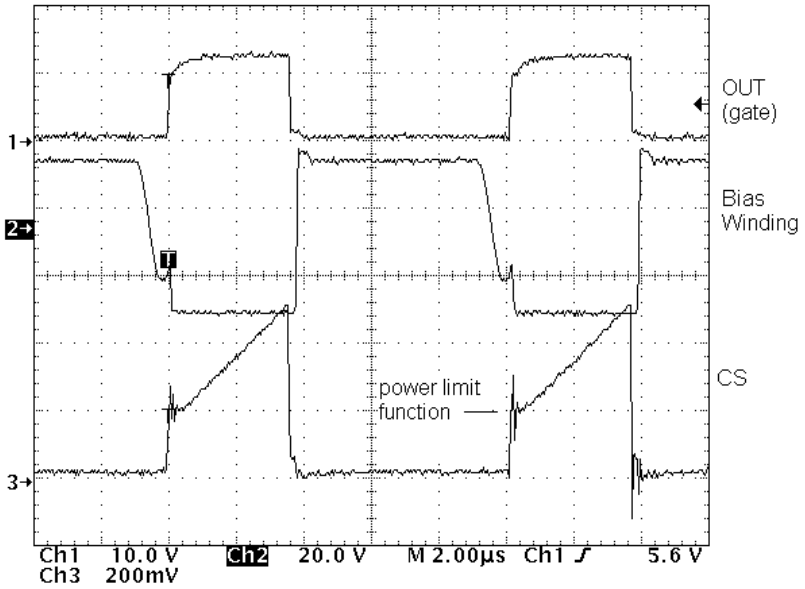
Frequency Foldback Mode
enhance light load efficiency by reduction of switching frequency



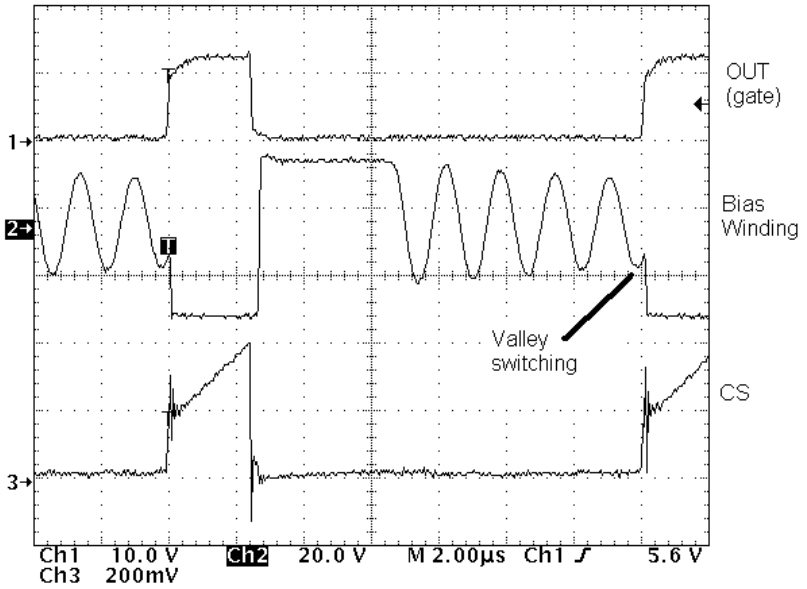
% i_{PEAK} vs f_S for loads ≤ 100% peak load

QR and FFB valley switching

36W, QR mode

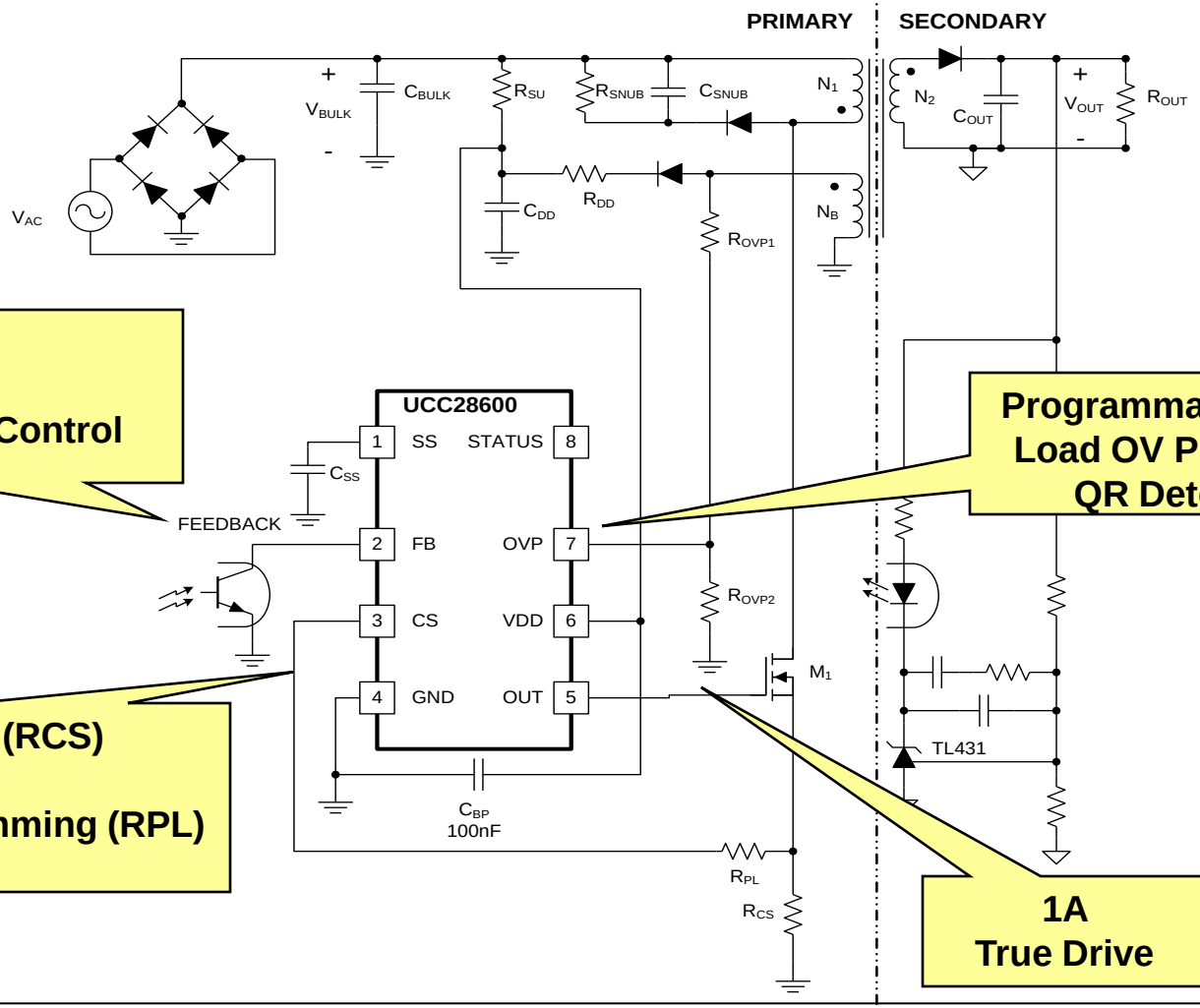


13.8W, FFB mode



UCC28600 - 8-pin QR green mode PWM controller

Multi - function pins give full features in 8-pins instead of 14 !



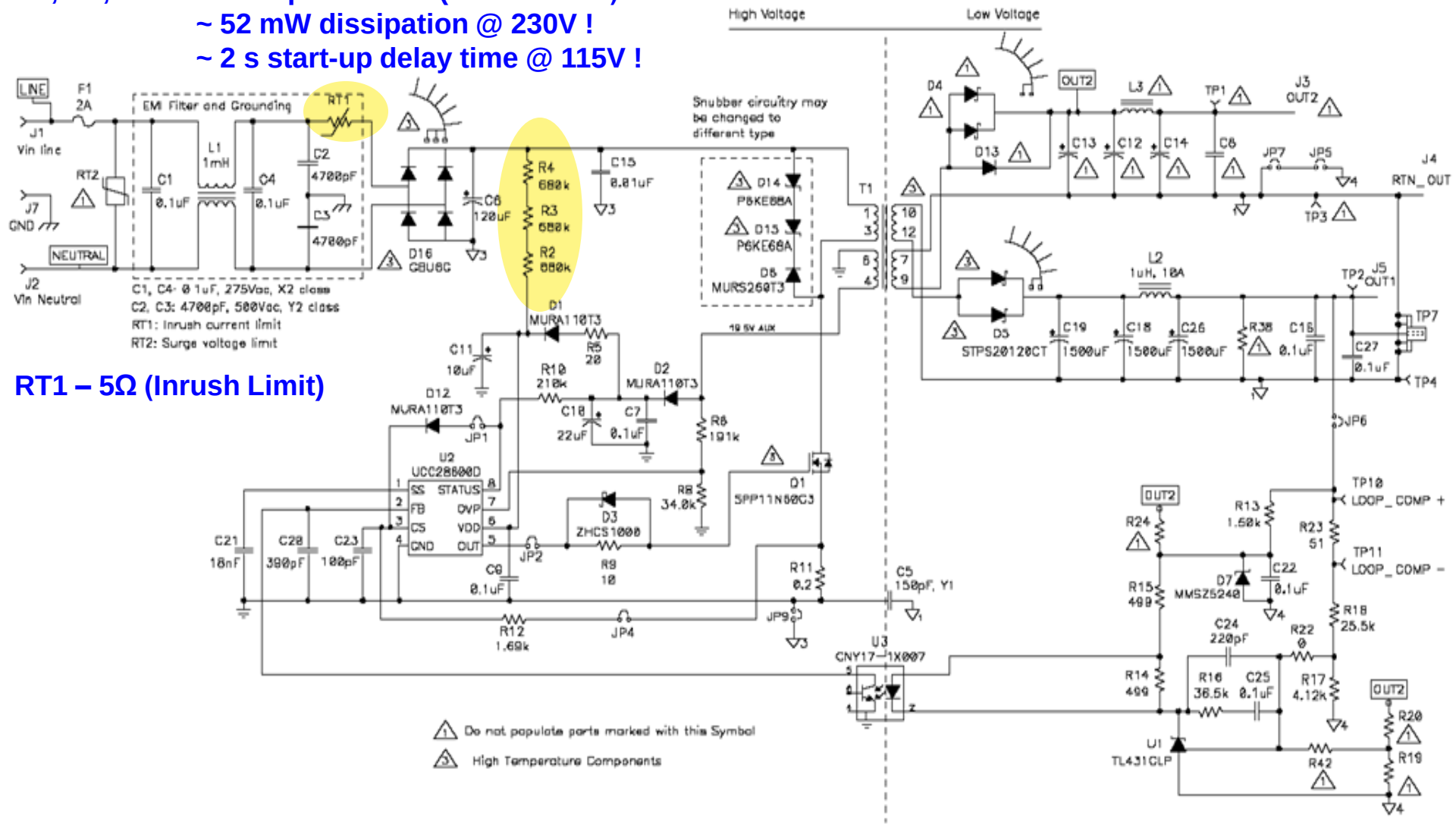
UCC28600 – Design support

- Application Notes
  - Bootstrap circuit for green mode applications (slua373)
  - Design considerations for the UCC28600 (slua399b)
  - Flyback transformer design for the UCC28600 (slua418)
- Seminar topics
  - Seminar 1700 - topic 2: Green-mode power by the milli-Watt (topic2mm)
  - 2010/2011 Seminar – topic 1: Under the Hood of Flyback SMPS Designs
- EVMs
  - 65W universal input
  - 120W universal input with PFC
- Design tools
  - UCC28600 design calculator (slvc104f)
- Reference Designs
  - More than 100 tested designs from 0.5W to 80W

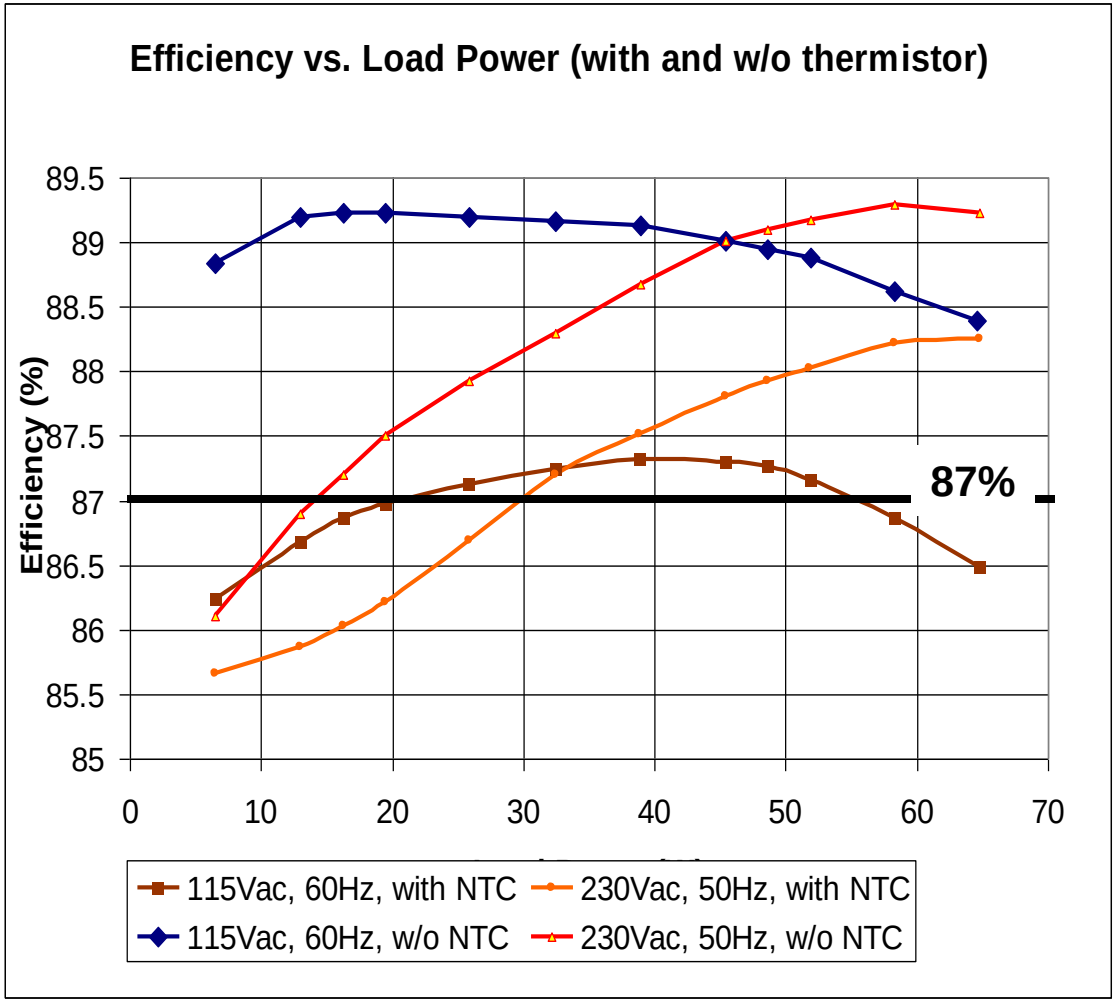
UCC28600 – 18V / 65W universal input design EVM

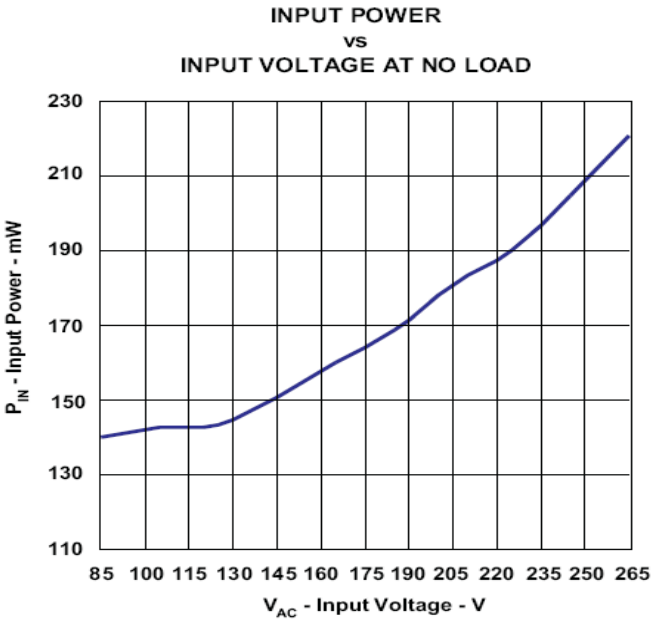
R2, R3, R4 – Start-up resistors (2MΩ in total)
~ 52 mW dissipation @ 230V !
~ 2 s start-up delay time @ 115V !

RT1 – 5Ω (Inrush Limit)



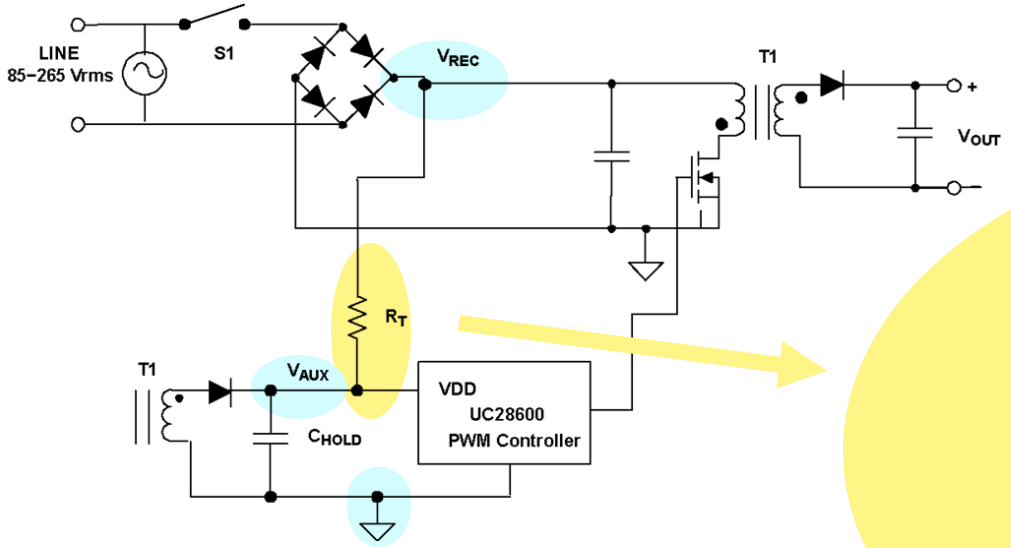
UCC28600 – 18V / 65W universal input design EVM





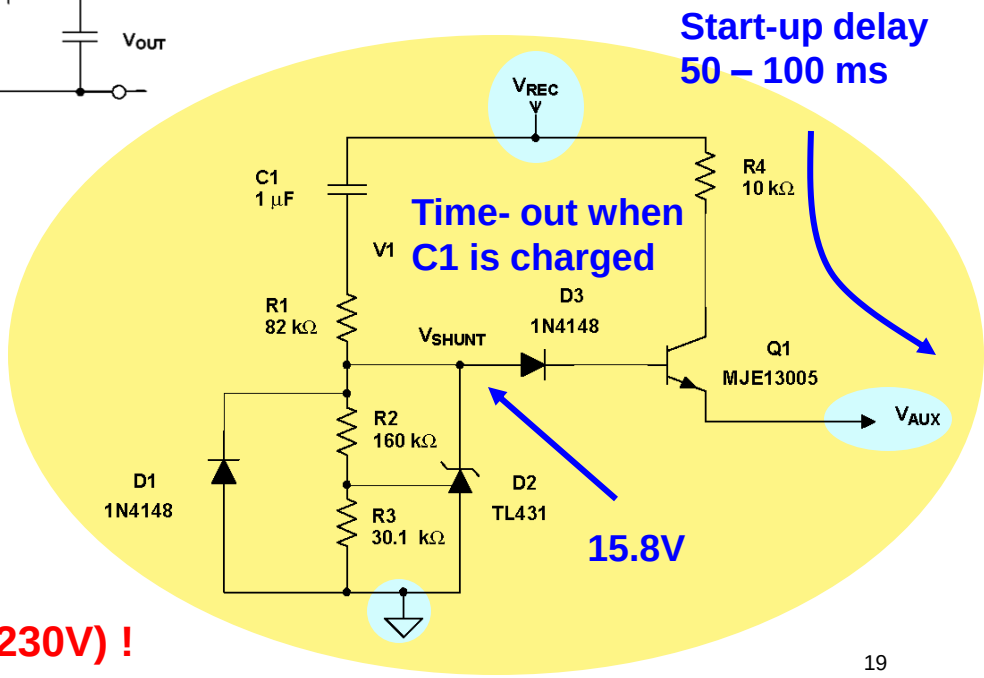
Improved start-up

- Reduce continuous dissipation in start-up resistor
  - Reduce no-load power loss caused by start-up resistor
- Reduce start-up delay time
- App Note : Bootstrap Circuit for Green Mode Applications (slua373)



Improved start-up circuit

Start-up delay 50 – 100 ms



Standard start-up circuit
82 kΩ selected for RT to reduce start-up delay to 200 – 600 ms
BUT 1.2 W *continuous* power dissipation (@230V) !

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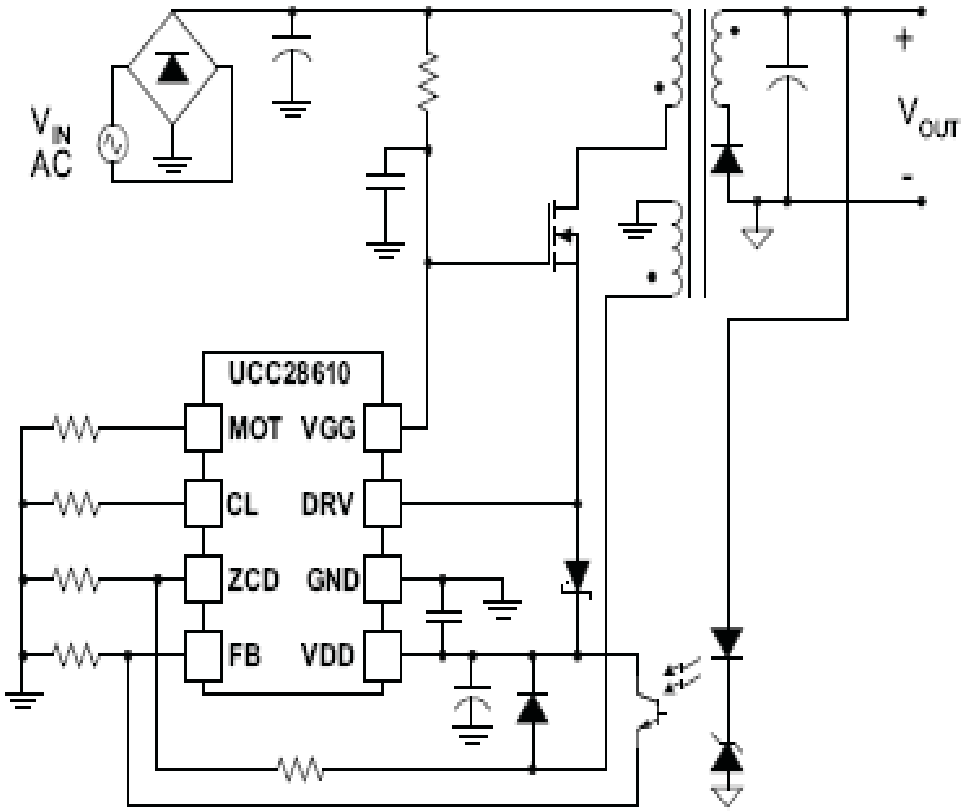
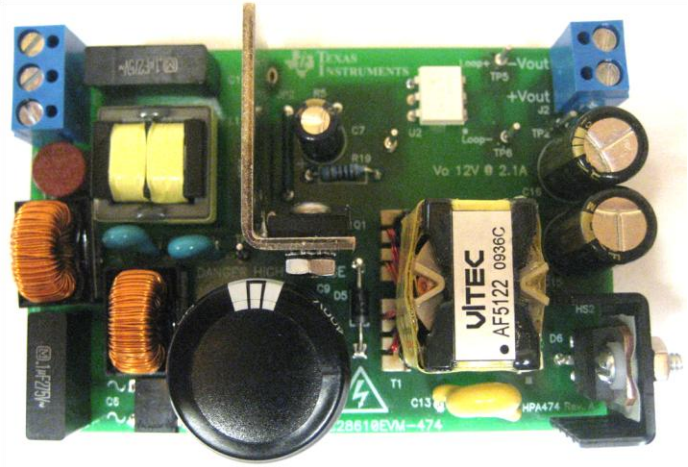
UCC28610 - Cascoded 12 - 65W Green Mode PWM Controller

- Cascoded MOSFET drive for
  - **Integrated current control (no R_{SENSE} required)**
  - **Fast start-up**
  - **Improved MOSFET drive**
  - **Ruggedized design**
- Full Green mode support
  - Frequency and amplitude modulation (FM, AM) and burst mode depending on load
  - Quasi valley switching
  - Ultra-low no-load consumption
- Full set of protection features
  - Advanced OC protection for input & output
  - Timed overload (retry or latch-off)
  - Opto-less output OV protection
  - Fastest latched fault recovery



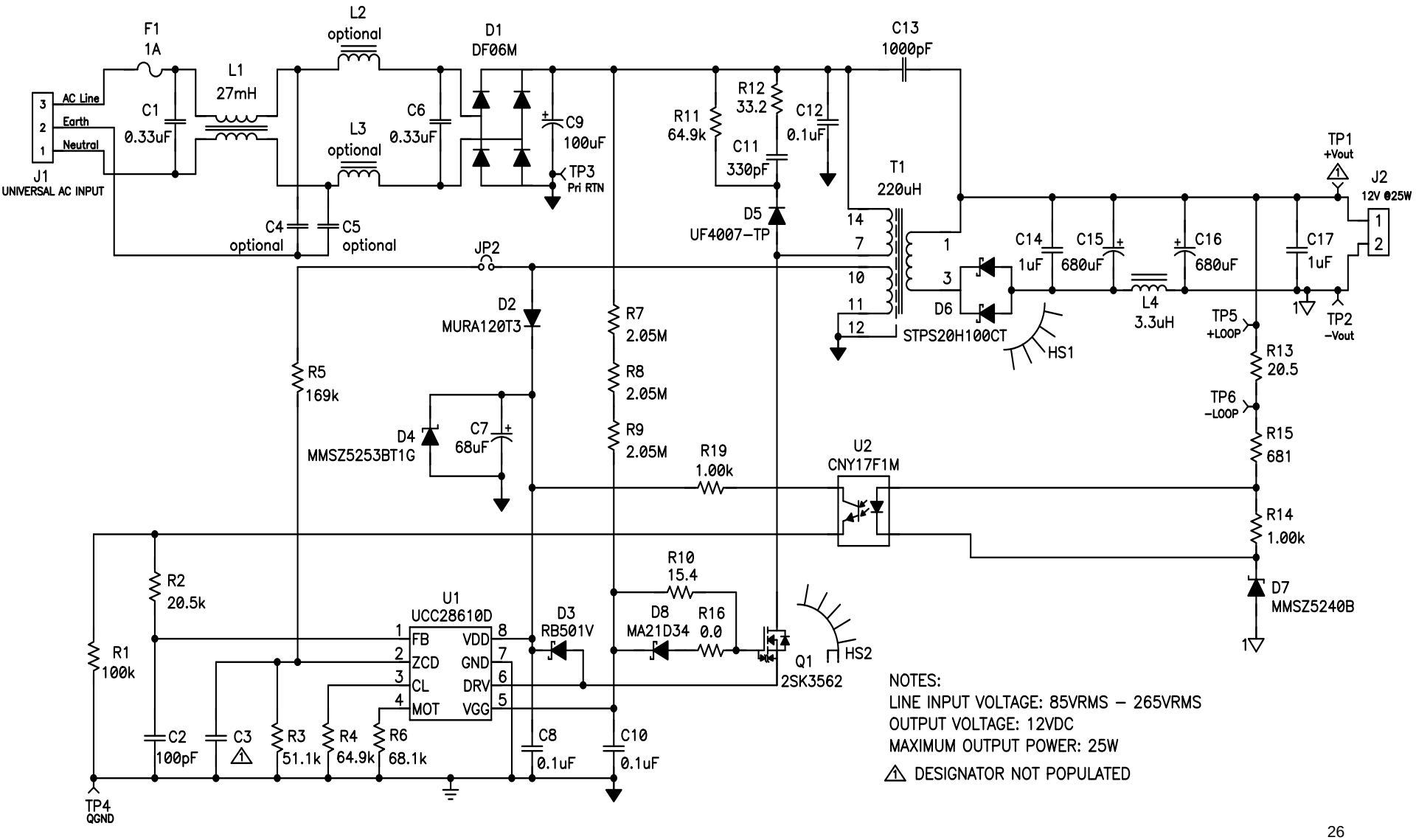
UCC28610 – Design support

- Design tools
  - UCC28610 Design Calculator (sluc113)
- EVMs
  - 25-W Universal Off-Line Flyback Converter EVM (sluu383a)

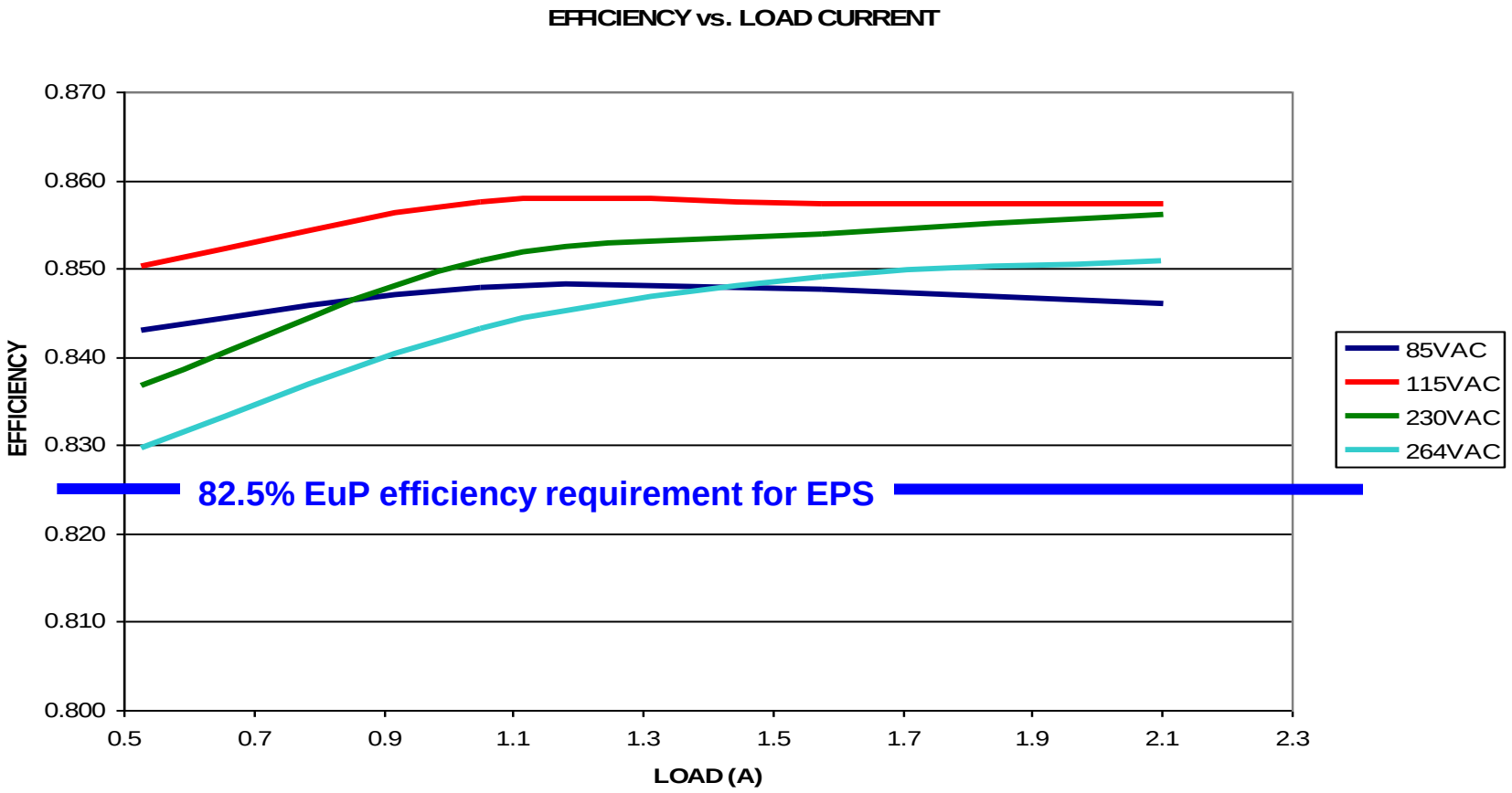


- Reference designs (15)
- 2010/2011 TI Power Supply Design Seminar
  - topic 1: Under the Hood of Flyback SMPS Designs

UCC28610 – 12V / 25W Universal Off-Line Flyback EVM



UCC28610 – 12V / 25W Universal Off-Line Flyback EVM



- **Design fulfills also no-load power consumption requirement: 115mW @ 230V achieved, 300mW allowed by standard**
- **Start-up delay reduced to roughly 150ms !!!**

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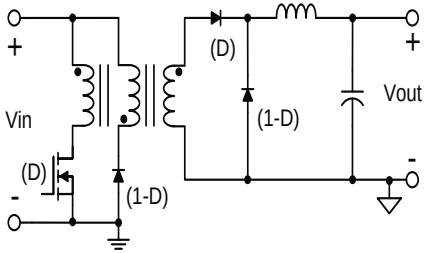
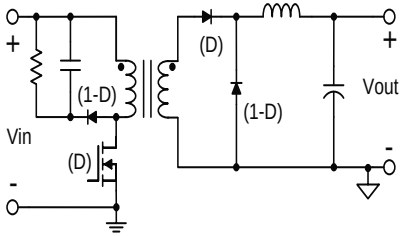
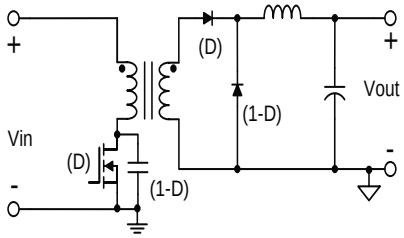
(Forward) Transformer Reset Techniques



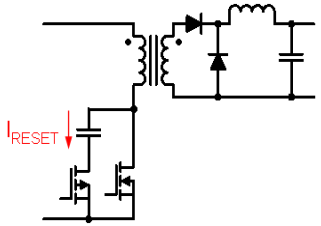
Reset Winding



RCD Clamp



Resonant Reset

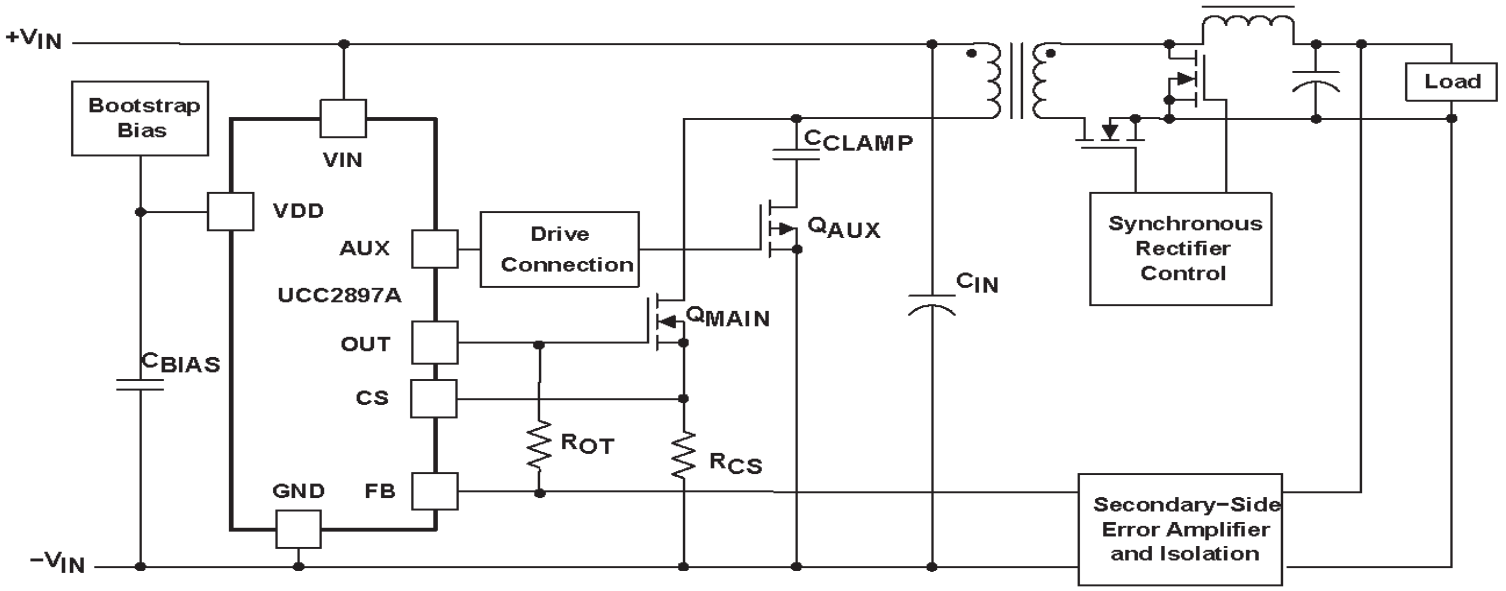


Active Clamp & Reset

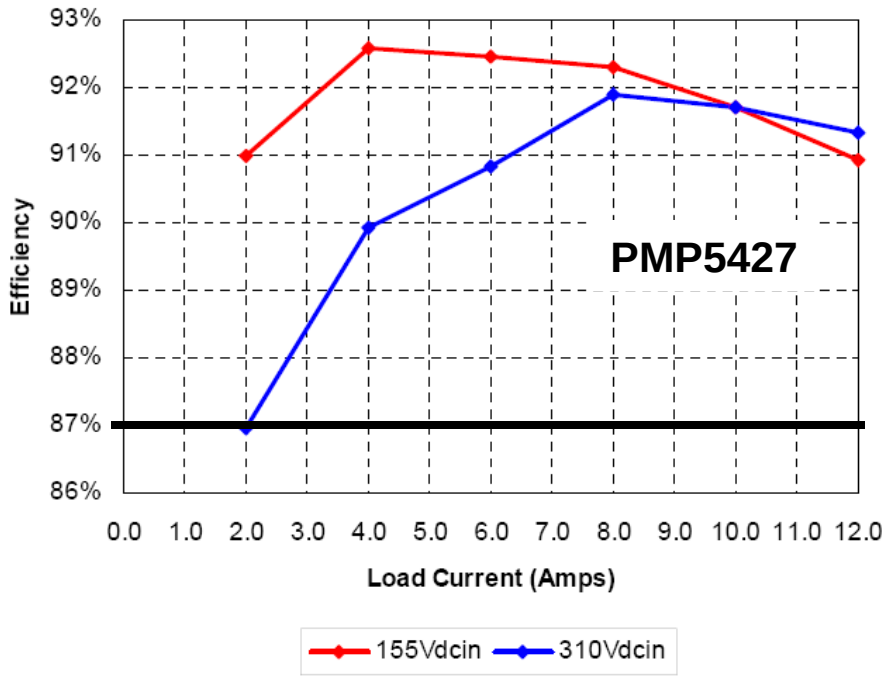
	Reset Winding	RCD Clamp	Resonant Reset	Active Clamp and Reset
Soft Switching (ZVS)	No	No	No	✓
Recycles Inductive Energy	✓	No	✓	✓
Recycles Capacitive Energy	No	No	No	✓
> 50 % Dutycycle	No	✓	✓	✓
Complexity	High	Low	**Lowest**	Highest
Efficiency		Lowest		**Highest**

UCC2891 / 92 / 93 / 94 / 97A – Active Clamp Controller

	UCC2891	UCC2892	UCC2893	UCC2894	UCC2897A
Additional 2nd level current limit					✓
P-channel Aux FET drive	✓	✓			✓
Bi-directional synchronization					✓
Line overvoltage lockout & hysteresis		✓		✓	
Internal 110V Start-up circuit	✓		✓		✓
Targeted for Off-line AC/DC				✓	



UCC2894 – Active clamp forward universal AC input 12V/150W output reference design (PMP5427)



Efficiency was measured by applying a DC input to the AC lines.

Design fulfilles easily the EuP requirements for EPS,

BUT most likely an additional PFC stage will be needed (for >75W) as front-end, lowering the total efficiency!

PFC provides a regulated output voltage, allowing to optimize the active clamp forward converter for that specific voltage as operating point.

Good PFC efficiency will be in the range of 92 – 97%, resulting in 85 – 88% average total efficiency at 25 / 50 / 75 / 100% of rated load.

UCC2891 / 92 / 93 / 94 / 97A – Design support

- Application Notes
  - Understanding and Designing an Active Clamp Current Mode Controlled Converter (slua535)
  - Designing for high efficiency with the active clamp UCC2891 PWM controller (slua303)
  - Active clamp transformer reset: high side or low side? (slua322)
  - U-138 Zero Voltage Switching Resonant Power Conversion (slua159)
- Seminar topics
  - Seminar 1000 - topic 3: active clamp and reset technique enhances forward converter performance (slup108)
  - Seminar 1100 - topic 3: - Consideration for Active Clamp and Reset (slup112)
  - 2010/2011 Seminar – topic 2: Incorporating Active-Clamp Technology to Maximize Efficiency in Flyback and Forward Designs
- EVMs
  - UCC2891EVM, UCC2897EVM (both telecom input)
- Reference Designs
  - More than 150 tested designs for industrial, automotive, telecom and AC/DC off-line applications

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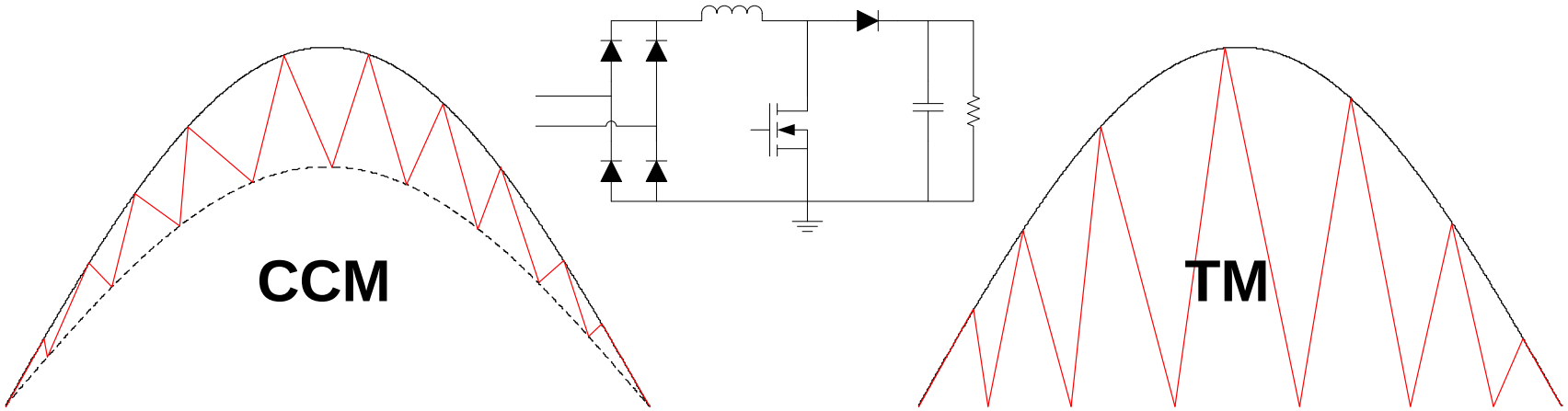
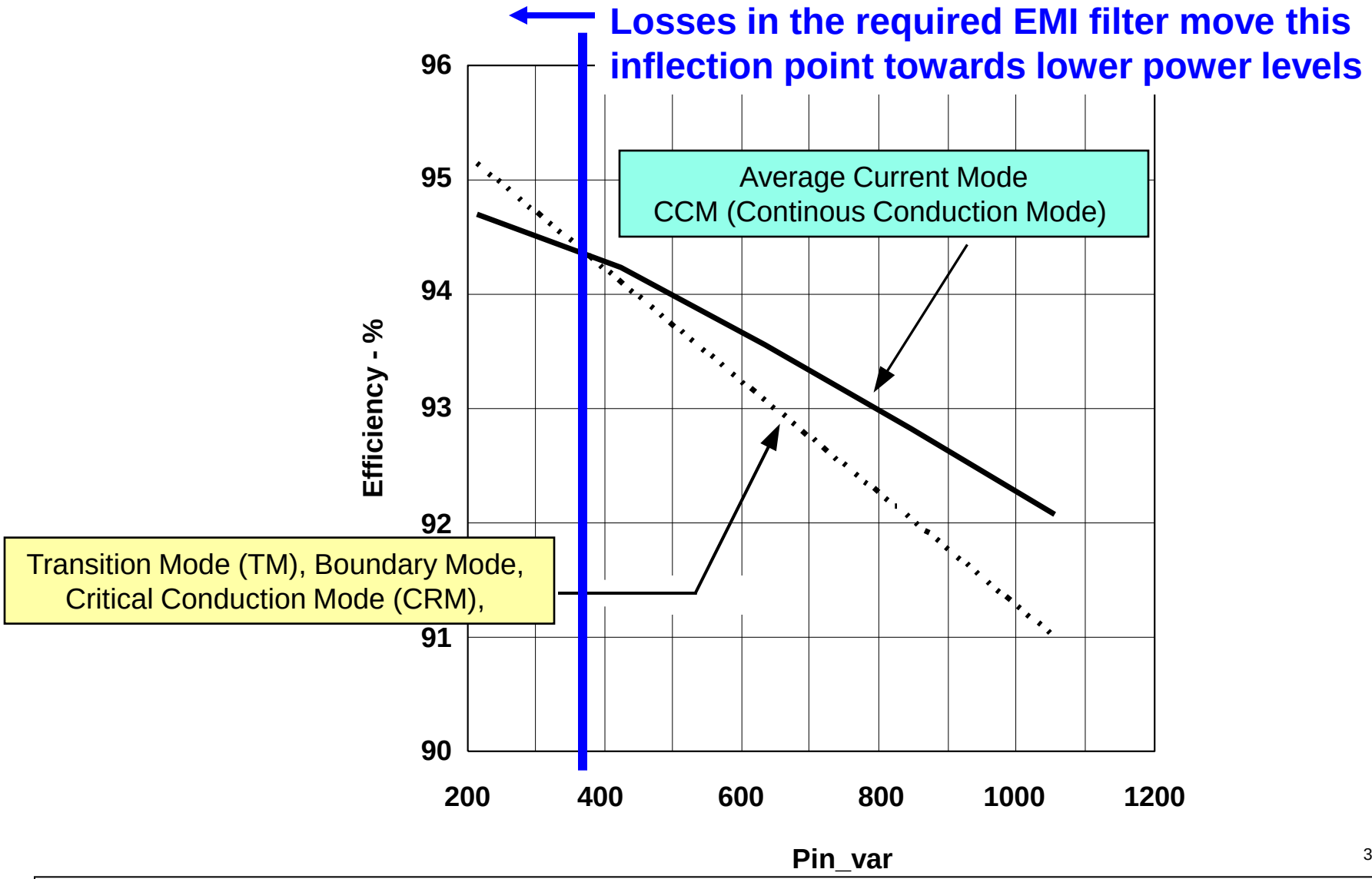
CCM - vs. TM - PFC



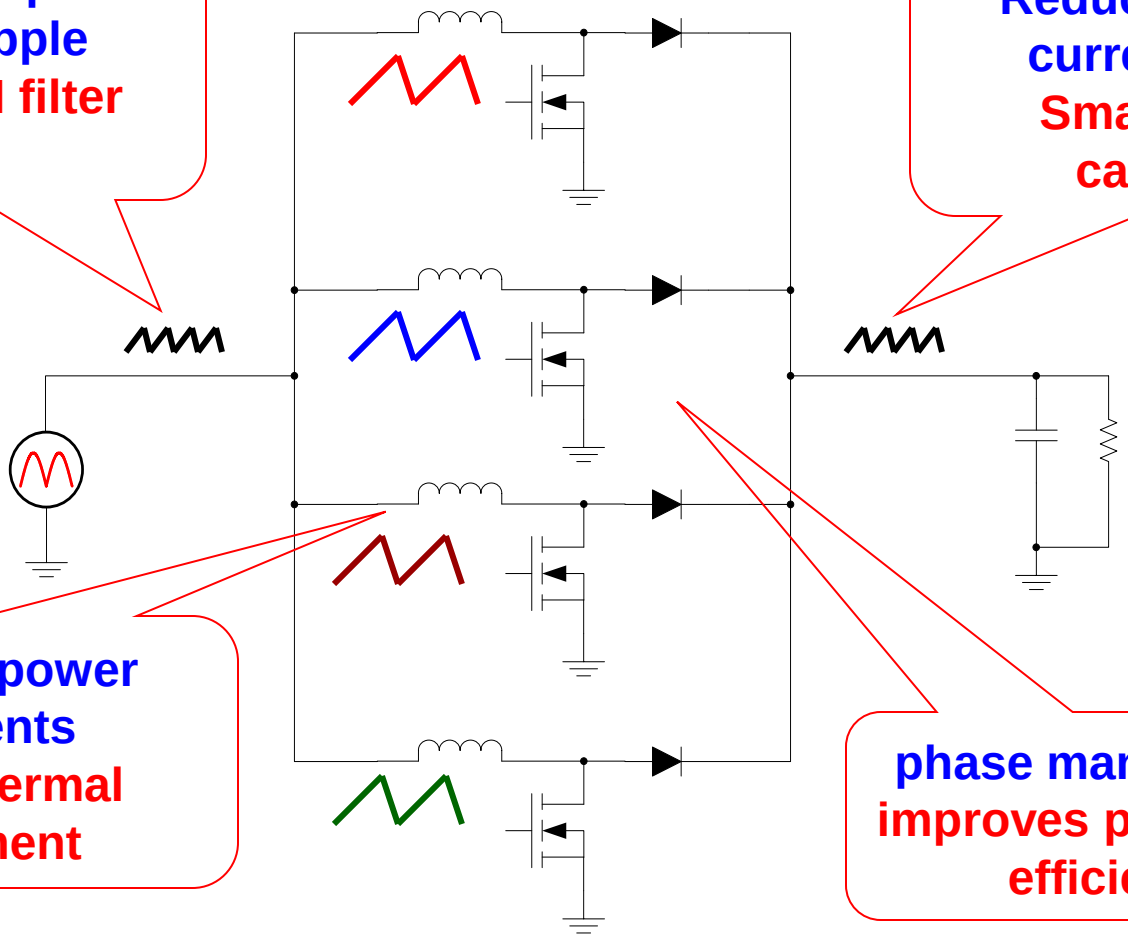
- **Smaller ripple current**
- **Smaller EMI filter**
- Constant switching frequency
- **Better for higher power**
- Switching loss may be higher due to diode reverse recovery current
- High components cost to maintain high efficiency

- **No reverse recovery loss - ZCS**
- **Lower cost solution**
- Soft switching possible
- Variable switching frequency "**Natural spread spectrum**"
- Better for lower power
- Large HF current ripple, larger conduction loss (AC resistance!)
- **Larger EMI filter**

Inflection Point TM vs. CCM w/o input EMI filter (single phase)



Interleaved PFC



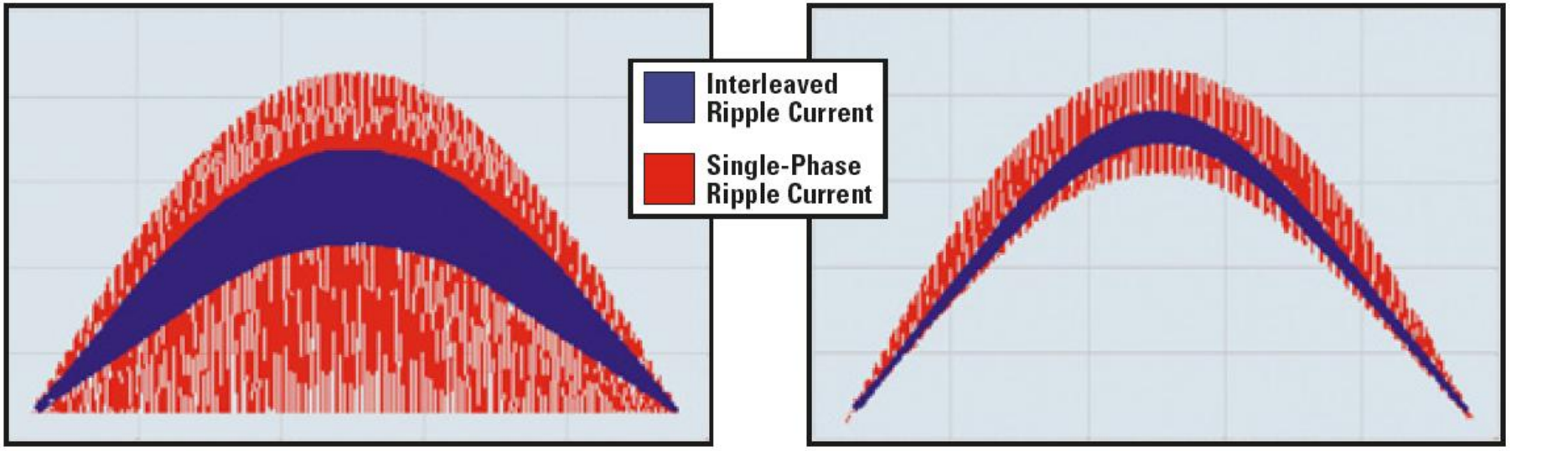
Reduced input current ripple
Smaller DM filter caps

Reduced output current ripple
Smaller bulk capacitor

Distributed power components facilitate thermal management

phase management improves partial load efficiency

Interleaved PFC – Significant input ripple current reduction



UCC28060 Transition Mode PFC with Natural Interleaving™ technique.

UCC28070 Continuous Conduction Mode PFC

EMI-Filter needs to take care of Ripple Current

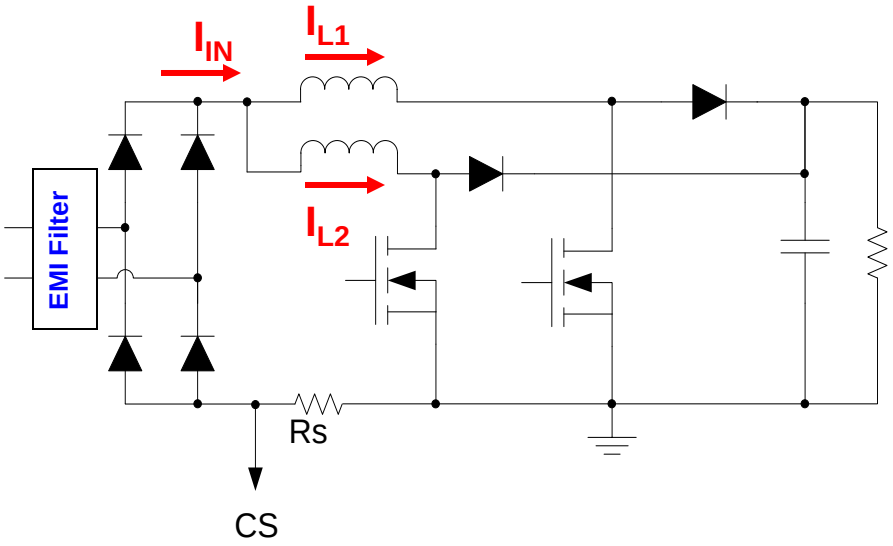
- EMI-Filtering can be drastically reduced due to drastically reduced ripple current
- Ripple of Interleaved TM is similar to Single Phase CCM

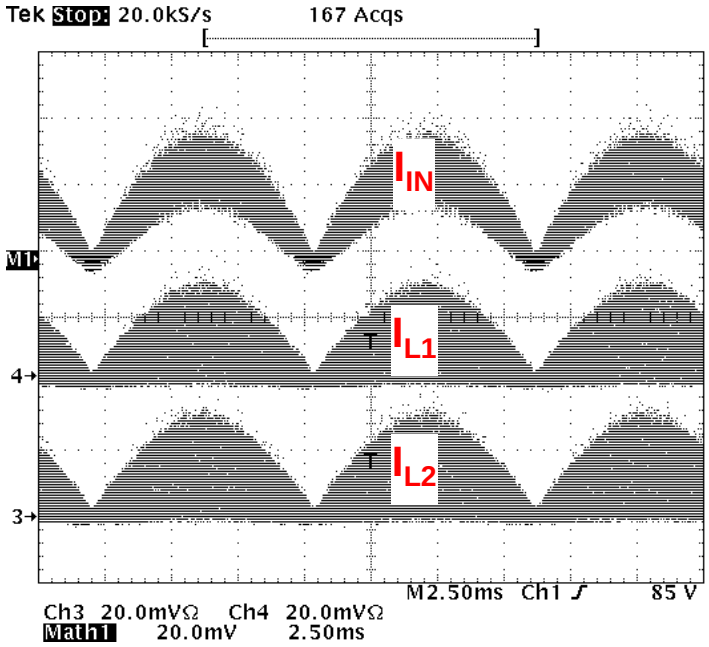
TI solves the interleaving problems for TM boost PFC

UCC28060 **Industry's First Natural Interleaving™ Transition Mode PFC**

UCC28061 **UCC28060**

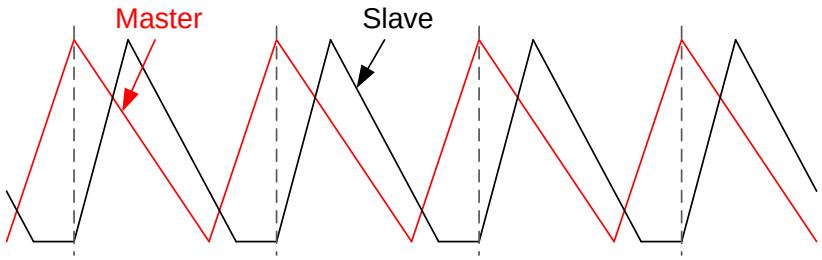
- **w/ improved audible noise performance**
- **w/ auto soft re-start after OV-Faults**
- **w/o Burstmode @ light load**





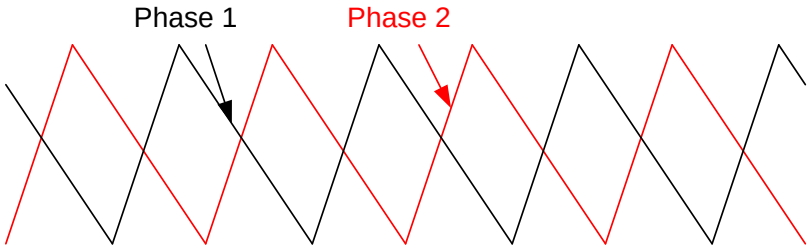
UCC 28060 / 61 uses Natural Interleaving

Master- Slave Method



- Lower Inductance in the slave phase to prevent entering CCM
- Phase shift not optimal
- Current sharing not optimal

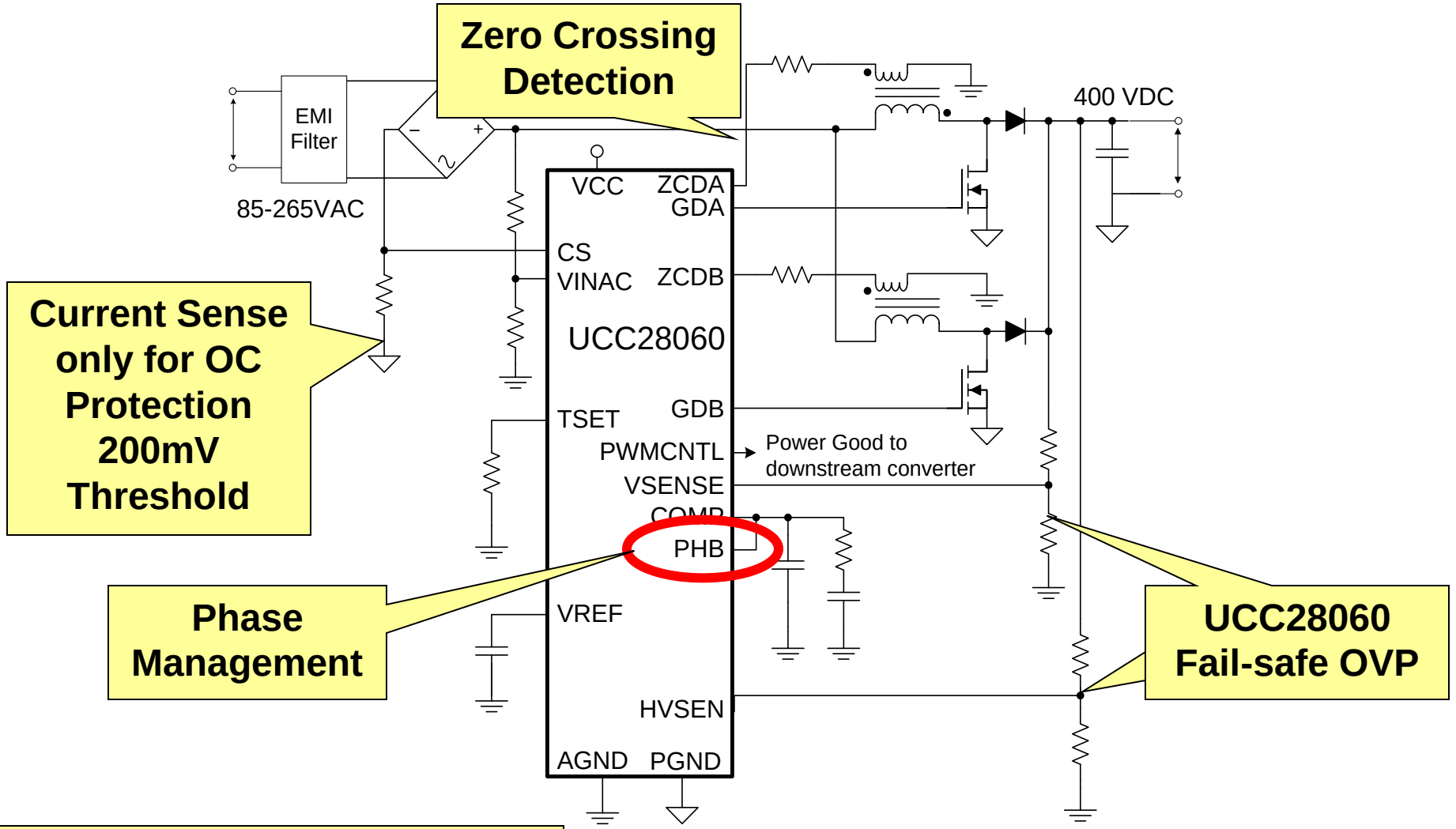
Natural Interleaving



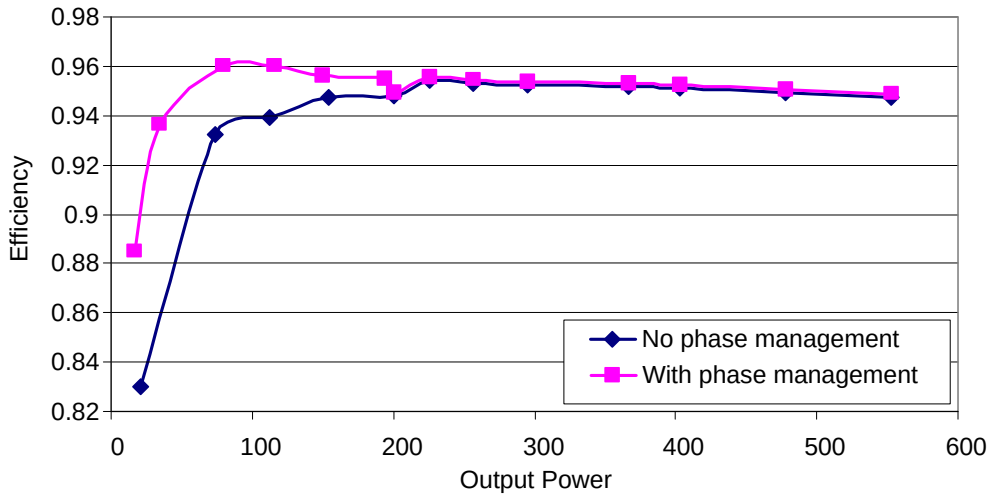
- Both channels operate in TM
- Phase shift of the phases is 180
- No Master / no Slave

Better current sharing and lower ripple current

UCC28060 / 28061 Typical circuit

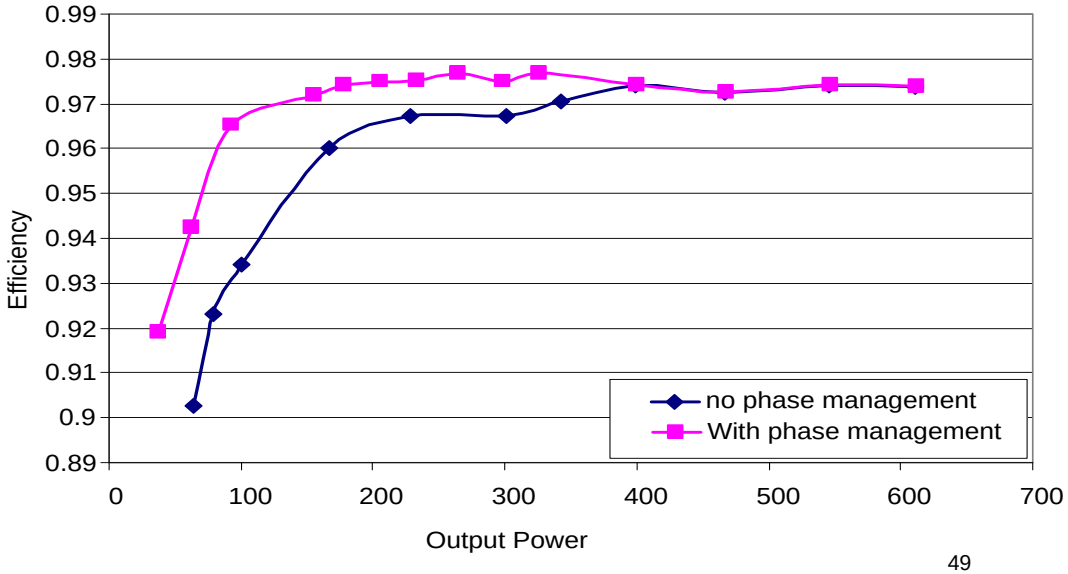


UCC28060 - Phase management improves light load efficiency



115V input

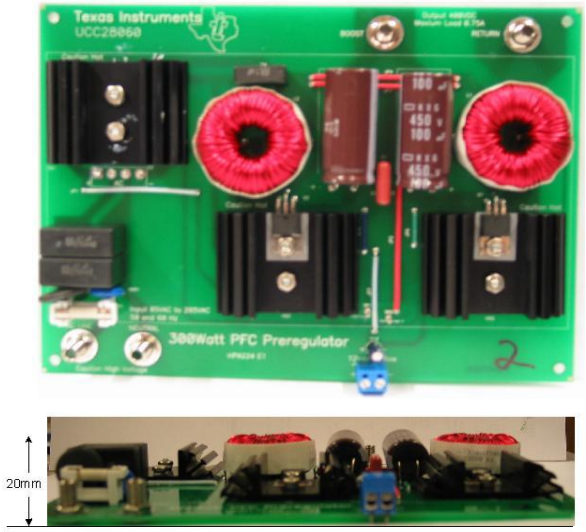
230V input



- **Single-phase operation at light load conditions improves system efficiency**
- **Phase management improves system efficiency at different line and load conditions**

UCC28060 / 61 - Design support

- 300W EVM (sluu280b , sluu316) 20mm height



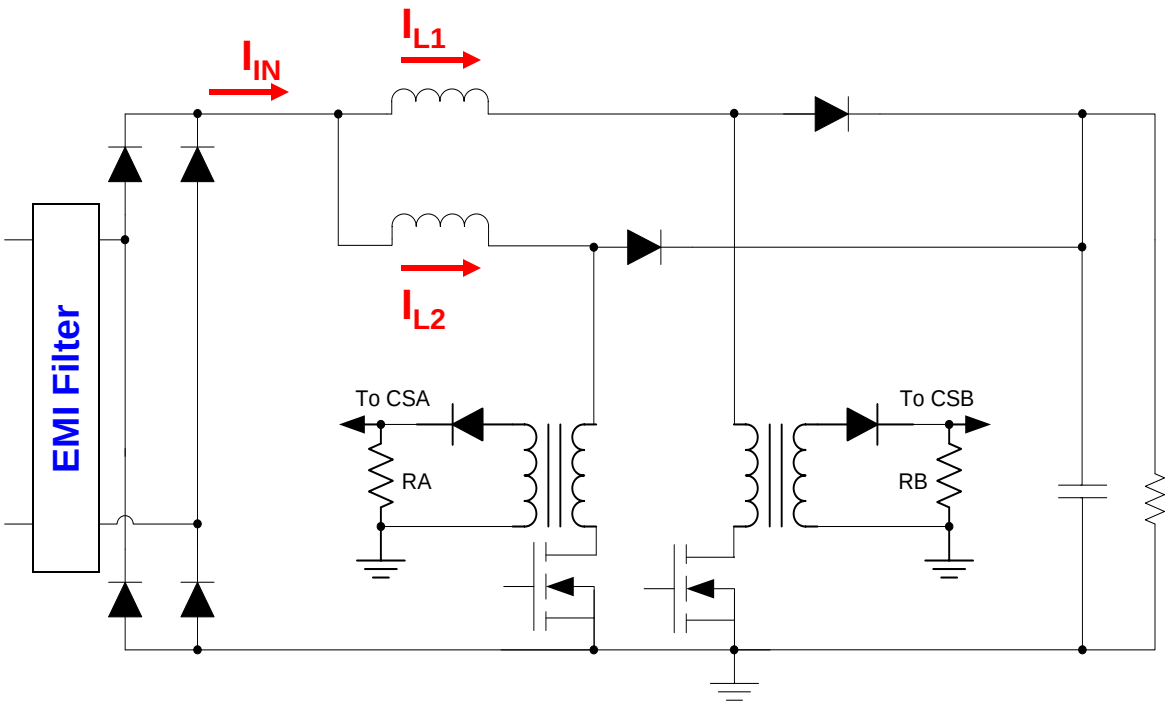
- Excel Design Tool (sluc072b)

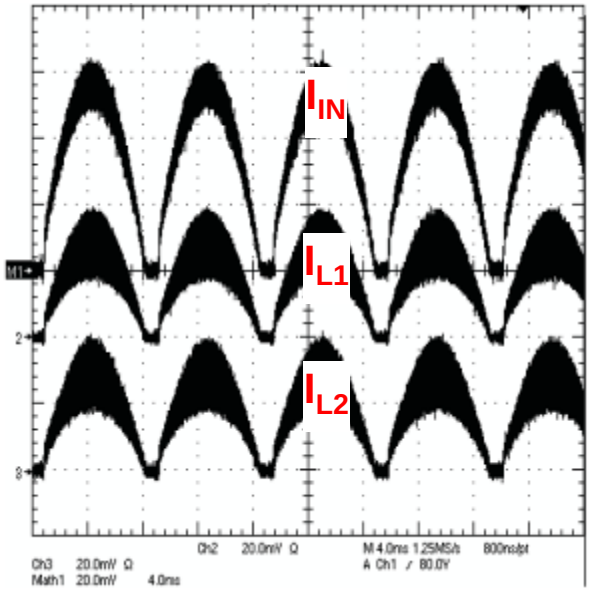
UCC28060 Controller Setup Tool		
Note this tool was designed to work with the UCC28060 data sheet design example		
Please enter design parameters into the	shaded	cells;
Calculated results will be in RED		
Design Parameters:	**Variable Names**	
Minimum RMS Input Voltage	V_{IN_MIN}	85
Maximum RMS Input Voltage	V_{IN_MAX}	265
Minimum Line Frequency	f_{LINE}	47
Maximum Line Frequency		63
Maximum Output Power	P_{OUT}	300
Full Load Efficiency (Needs to be less than 0.99)	η	0.92
Minimum Switching Frequency	f_{MIN}	4.50E+04
Output Voltage	V_{OUT}	390

- 600W Design User Guide (sluu299a)
- AppNotes:
  - A 300-W, Universal Input, Isolated PFC Power Supply for LCD TV Applications (sluu341b)
- Additional AppNotes and MathCAD Files in productfolder of UCC38050 / 51
  - UCC38050 100W Critical Conduction (PFC) Reference Design (sluu138a)
  - MathCAD Calculation Tool for UCC38050 Transition Mode PFC Controller (UCC38050-CALC)

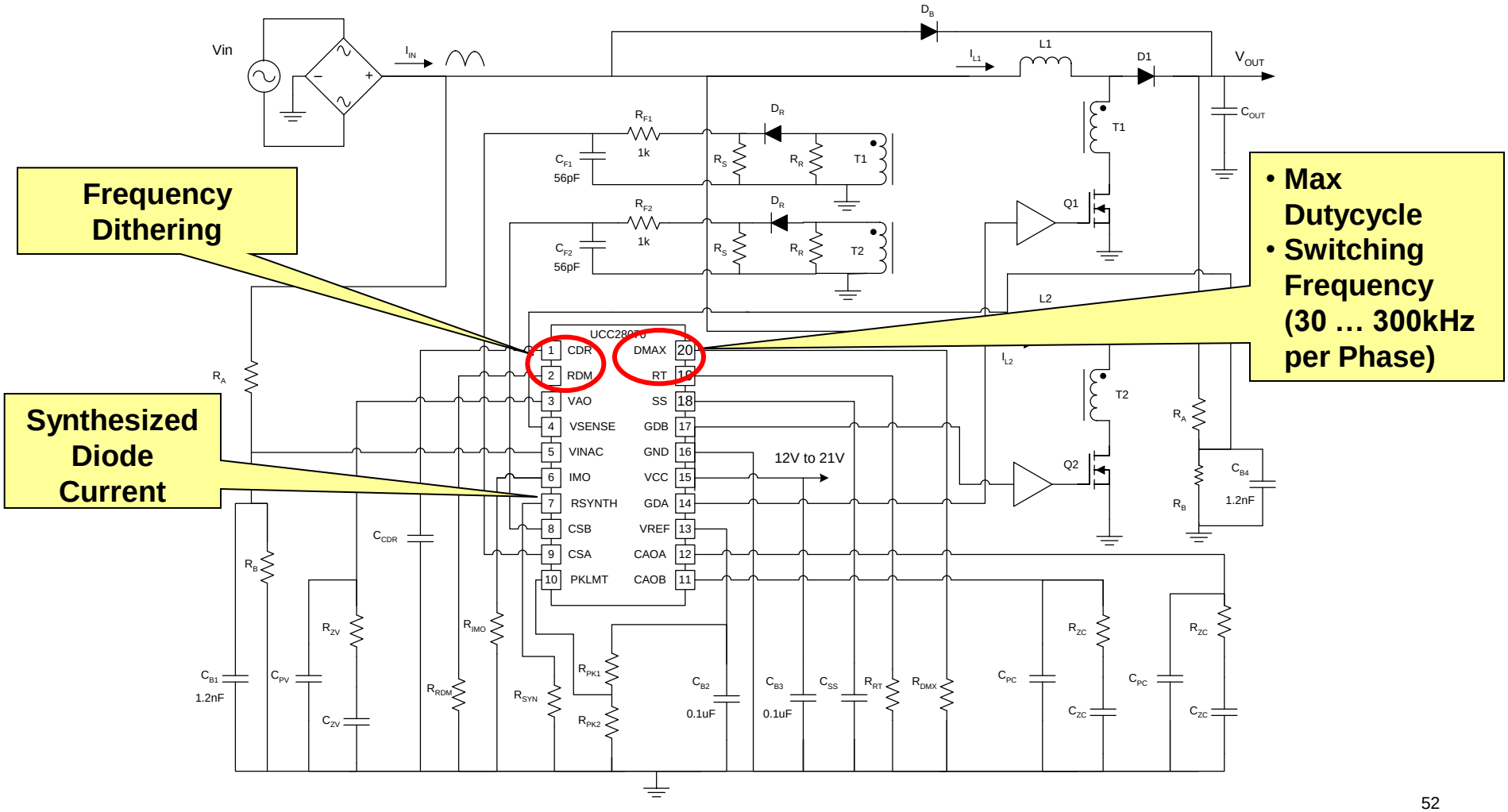
PFC - TI solves the interleaving problems for CCM Boost PFC

UCC28070 **Industry's First Interleaved CCM Boost PFC**



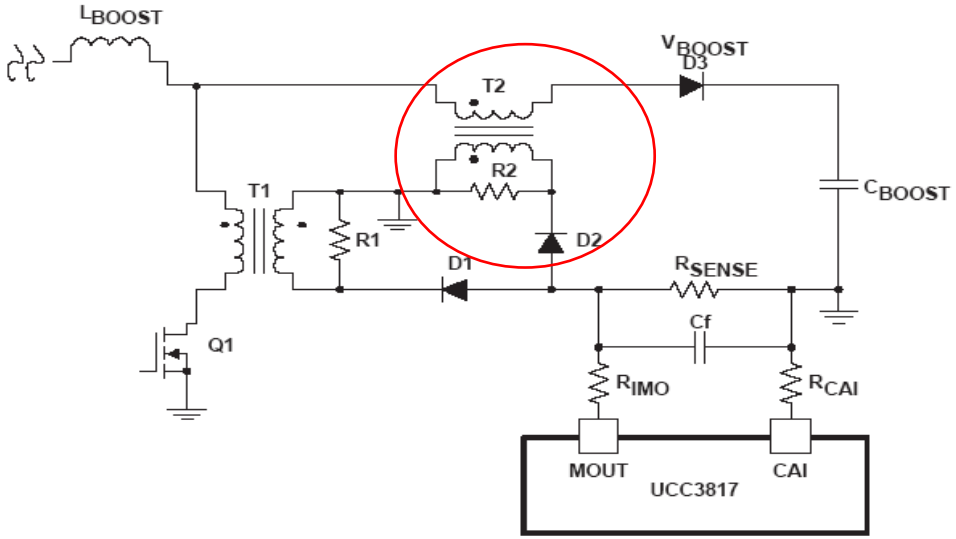


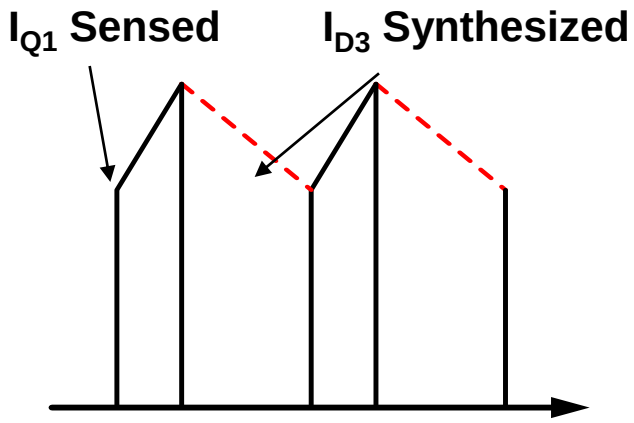
UCC28070 - Average CM interleaved PFC



UCC28070 - Current syntheses reduces component count

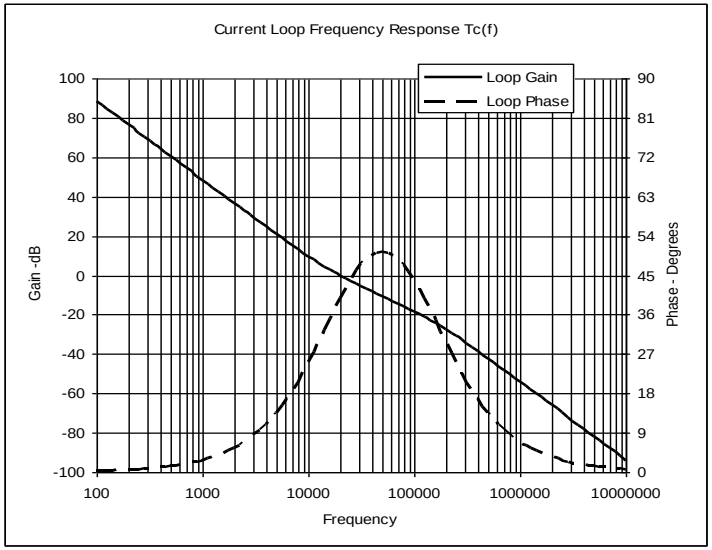
- **Traditional Current Sensing in PFC Boost**
  - ✓Requires a CT network in series with Q1
  - ✓Requires a CT network in series with D3
- **UCC28070 Synthesizes Diode Current**
  - ✓Setup with Single Resistor to Gnd (R_{SYN})
  - ✓**Removes CT network in series with D3**
  - ✓**6 components are eliminated in interleaved configuration**
    - ❖**Results in a cheaper BOM cost**

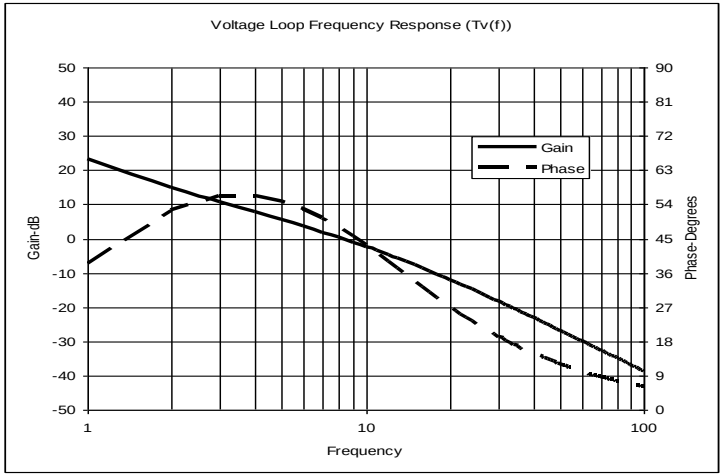




UCC28070 - Support & design tools

- Detailed Application Note
  - (Design Review) (slua479a)
  - UCC28070 Bridgeless PFC (slua517)
- 300 W Evaluation Module (sluu312b)
  - ✓ Same Power as UCC28060
- ✓ UCC28070 Video Cast SLUC083
- Excel Design Tool (sluc114)
  - ✓ Theoretical Small Signal Analysis
- ✓ PSpice Models
  - ✓ UCC28070 PSpice Average Model
  - ✓ UCC28070 PSpice Transient Model





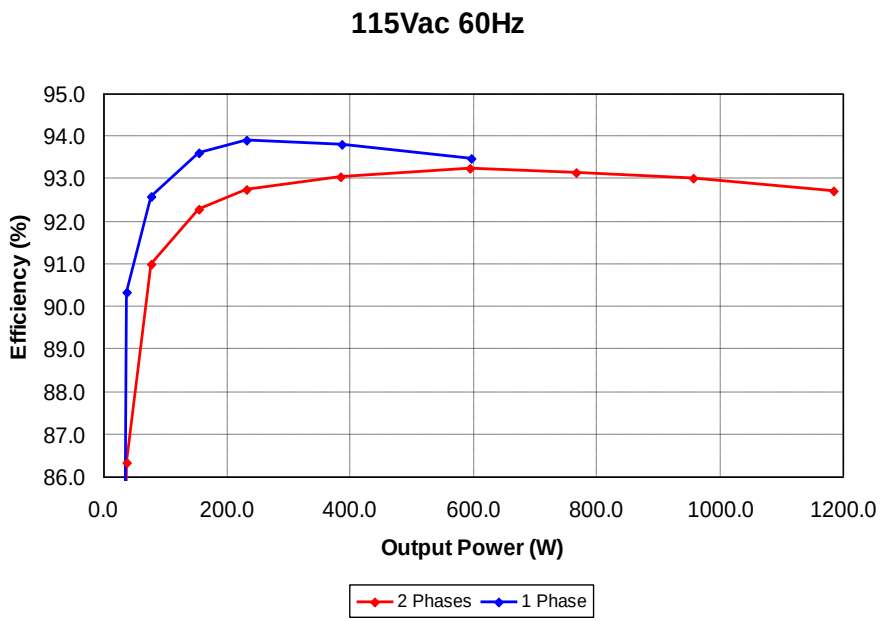
UCC28070 – 1.2kW Reference Design w/ implemented Phase Management

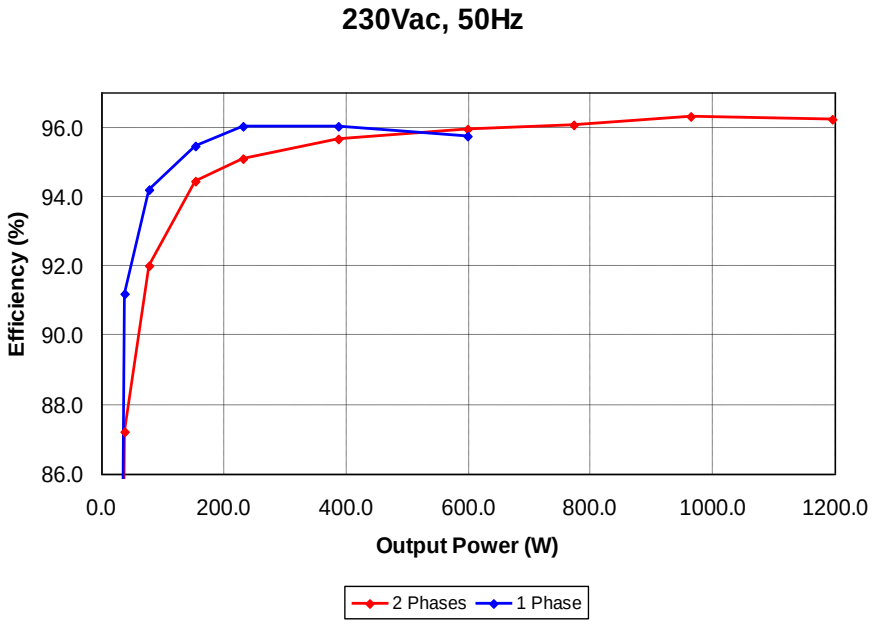
Enormous reduction in size of boost inductors by use of 2-phase interleaved approach

PR779 / 780

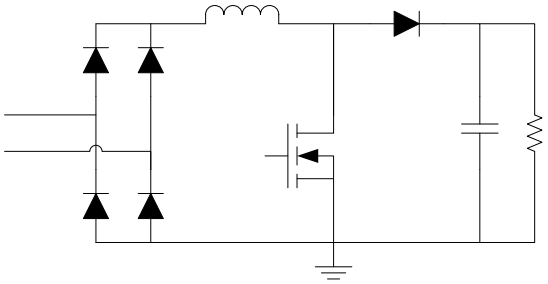
Phase Management w/ Interleaved PFCs (UCC28070 – 1.2KW Example Shown)

Phase Management Ensures
Highest Efficiency under all Load Conditions

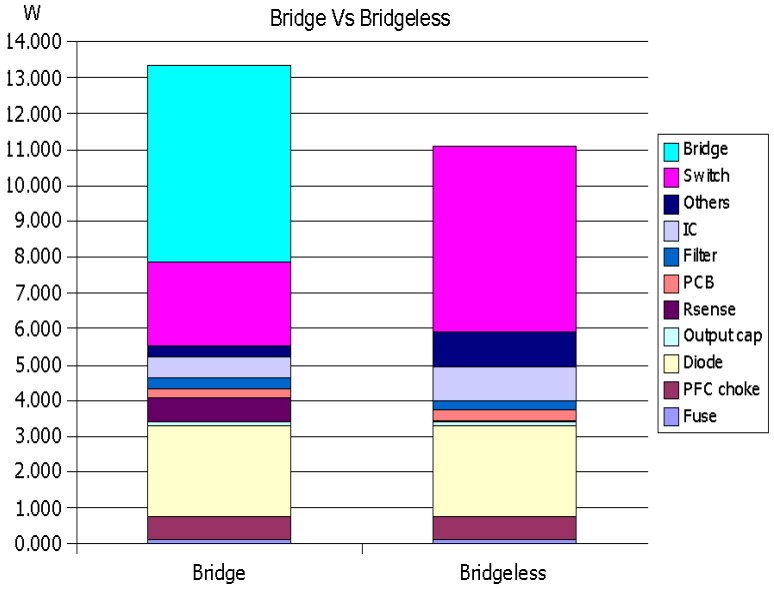




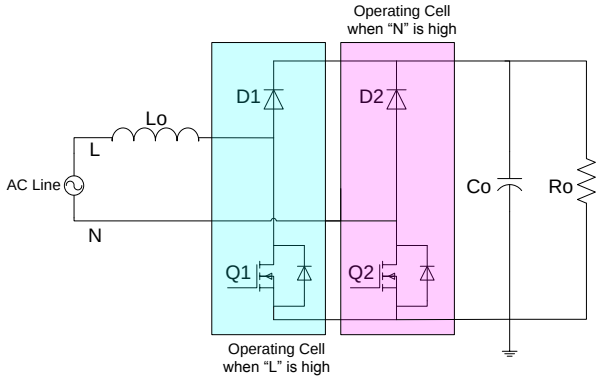
Increase PFC efficiency further?
Implementation of bridgeless PFC



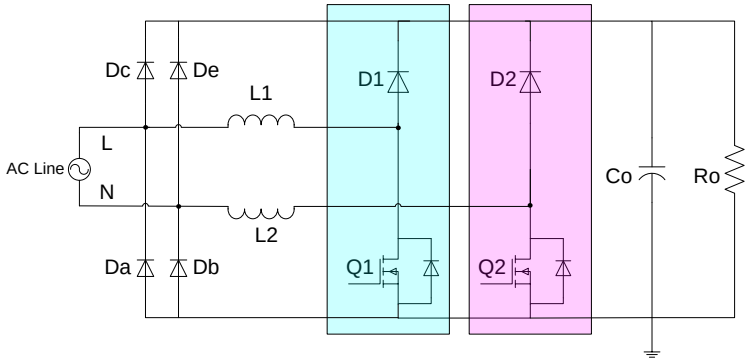
Classical PFC with bridge rectifier



Goal of bridgeless PFC:
Increase efficiency by eliminating some of the losses of the bridge rectifier



Classical bridgeless PFC implemetation

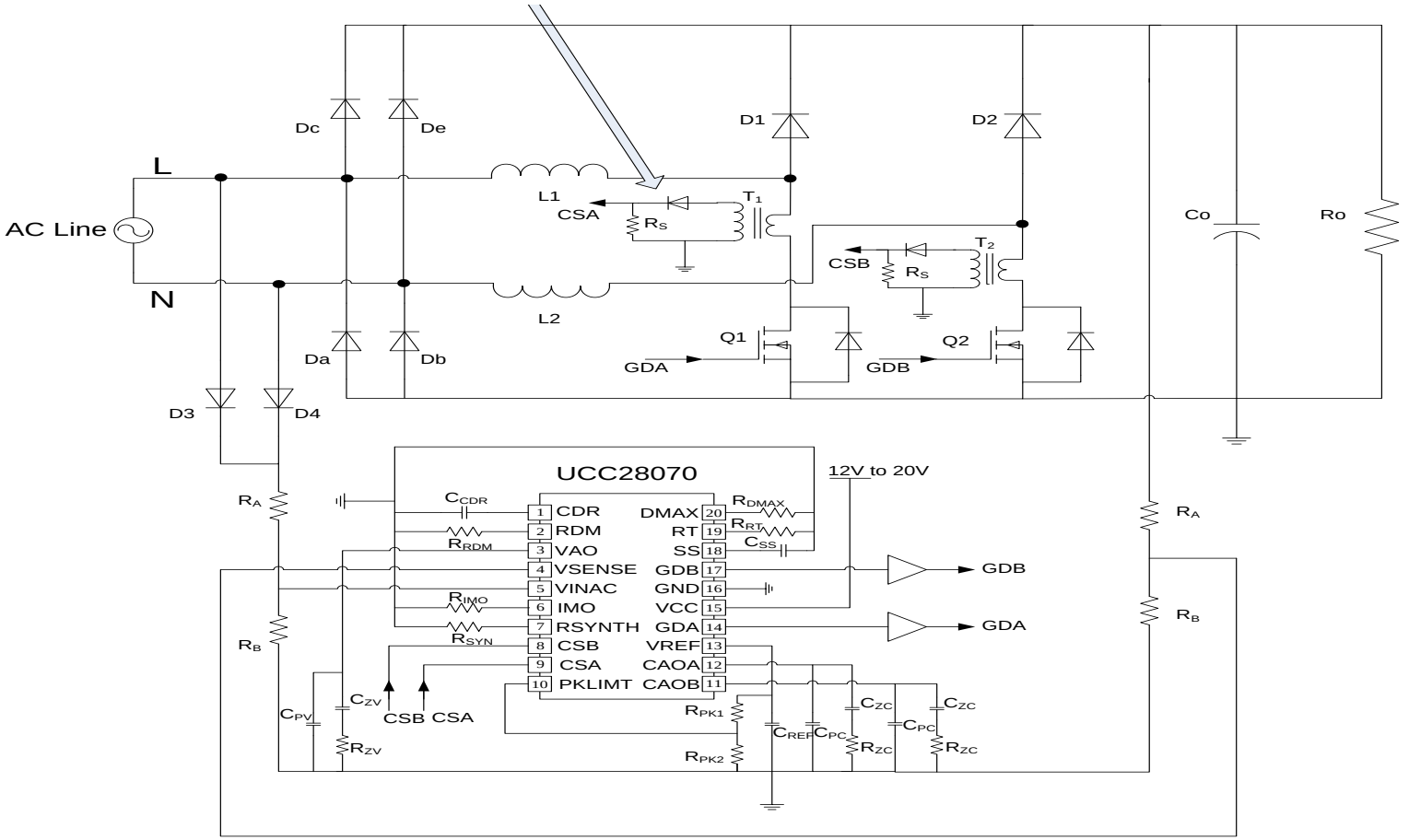


Semi-bridgeless PFC implementation

Increase PFC efficiency further? Implementation of bridgeless PFC

- UCC28070 Implement Bridgeless Power Factor Correction (PFC) Pre-Regulator Design – SLUA517

Current synthesizing of UCC28070 simplifies implementation



Increase PFC efficiency further? Implementation of bridgeless PFC

- UCC28070 Implement Bridgeless Power Factor Correction (PFC) Pre-Regulator Design – SLUA517

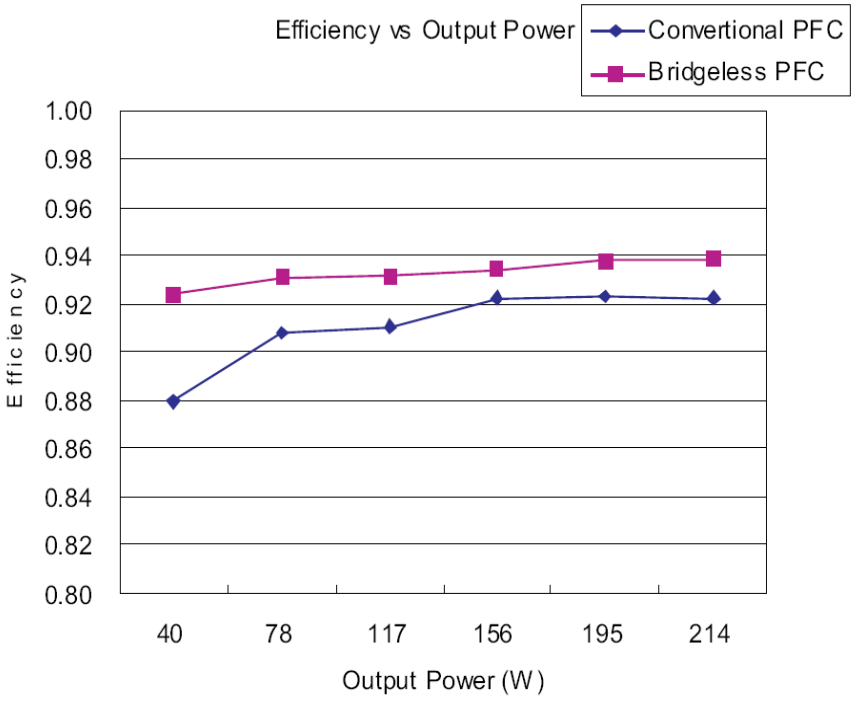


Figure 9. Efficiency at V_{IN}=110 V_{AC}

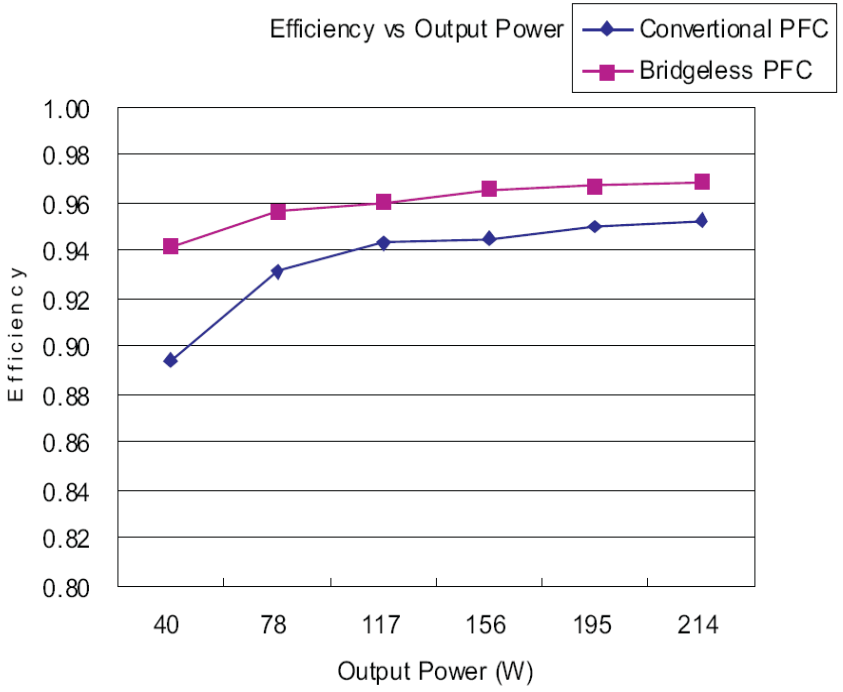
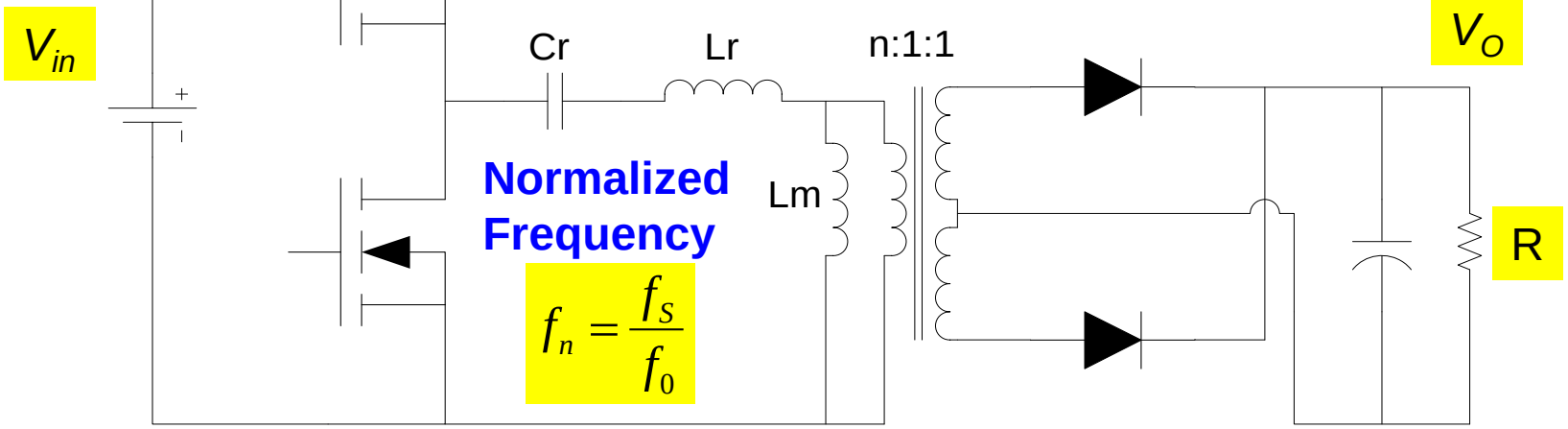


Figure 10. Efficiency at V_{IN} = 220 V_{AC}

Agenda

- General thoughts, standards and solutions
- Quasi-resonant green mode flyback (UCC28600)
- Cascoded green mode flyback (UCC28610)
- Active clamp (UCC289x family)
- Interleaved PFCs (UCC2806x / 28070)
- **LLC resonant half bridge (UCC25600)**
- Green synchronous rectifier controller (UCC24610)
- Advanced green mode phase shifted full bridge (UCC28950)
- Other sources for support
- Summary

LLC Resonant half bridge – the details



Inductor Ratio

$$L_n = \frac{L_m}{L_r}$$

Resonant Frequency

$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}}$$

Transformer Turns-Ratio

$$n = \frac{V_{in}/2}{V_o}$$

Normalized Frequency

$$f_n = \frac{f_S}{f_0}$$

Quality Factor

$$Q = \frac{\sqrt{Lr/Cr}}{n^2 R}$$

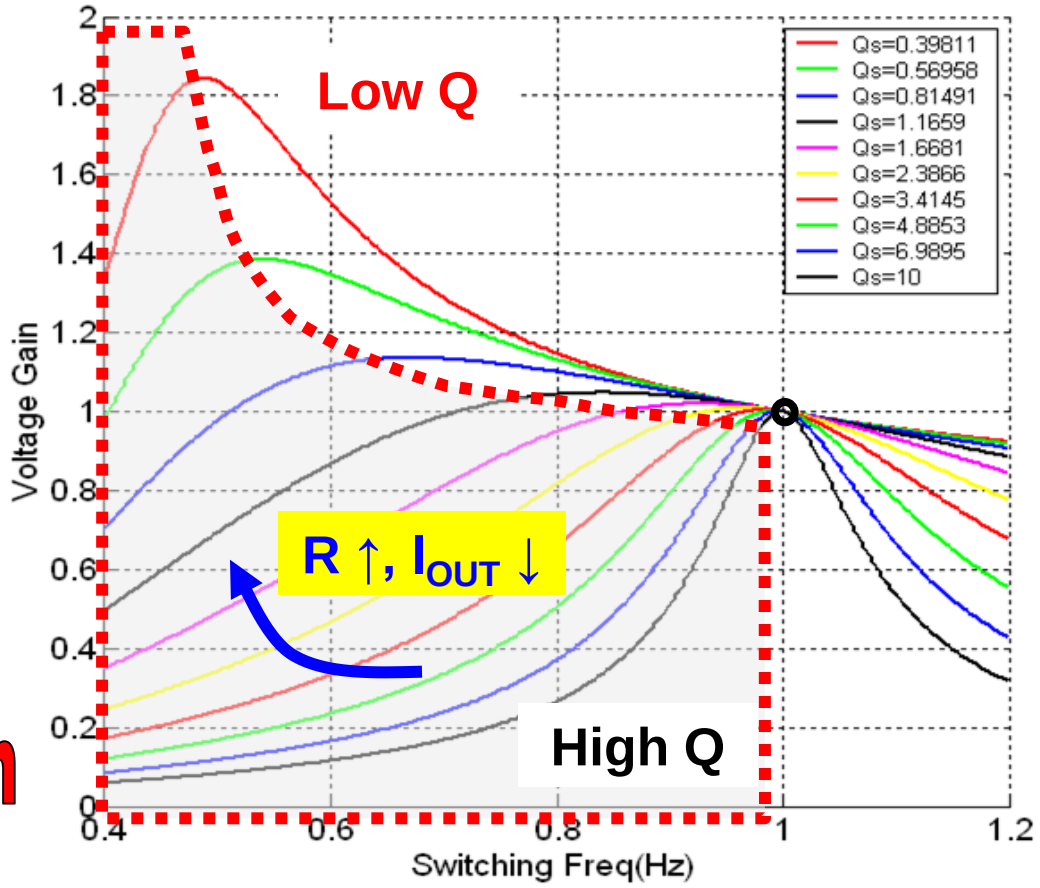
Voltage Gain

$$g = \frac{n \cdot V_O}{V_{in}}$$

LLC Resonant half bridge

UCC25600 8-Pin Optimized High Performance

LLC HB Resonant Mode Controller

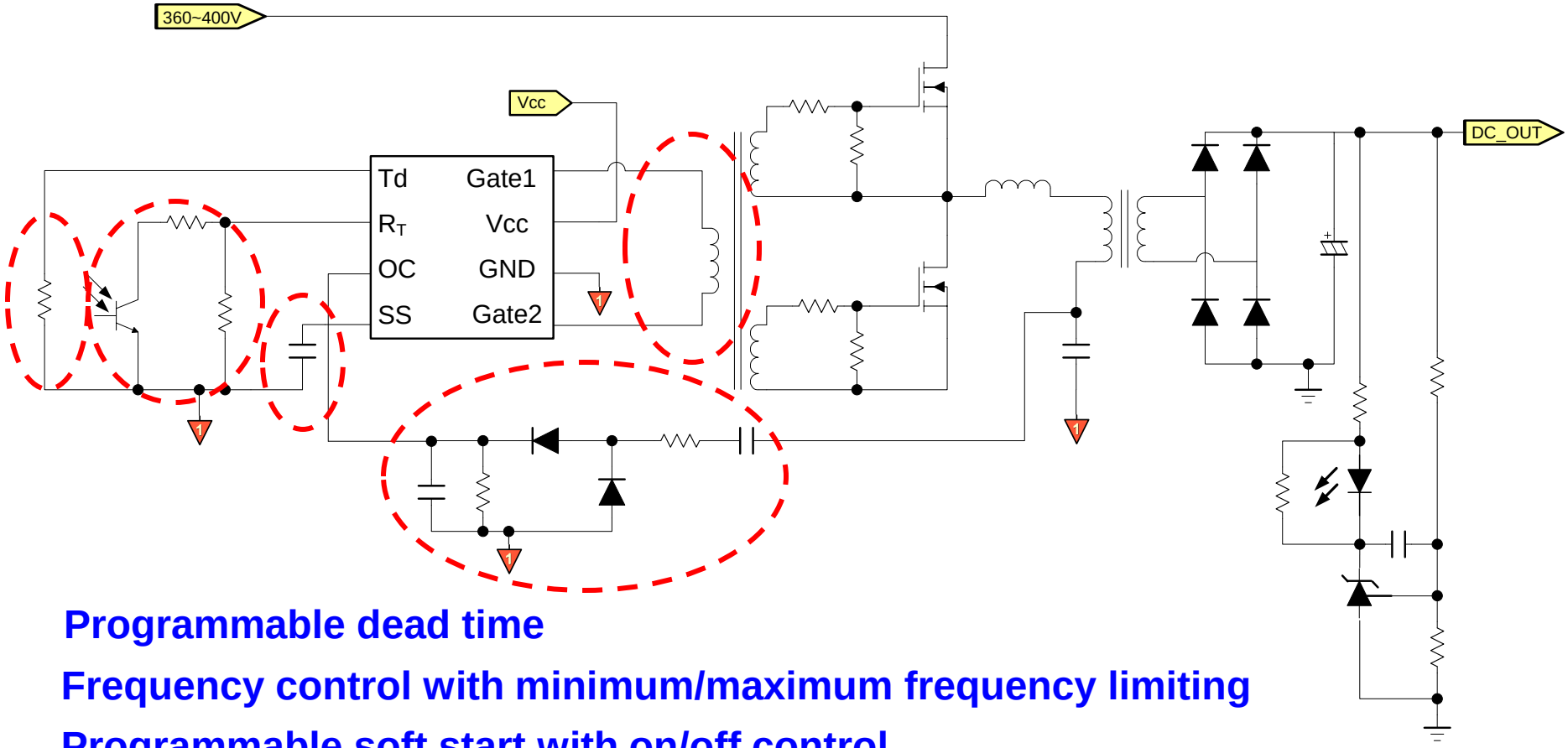


ZVS region

$$Q = \frac{\sqrt{Lr/Cr}}{n^2 R}$$

ZCS region

UCC25600 Application Circuit



Programmable dead time

Frequency control with minimum/maximum frequency limiting

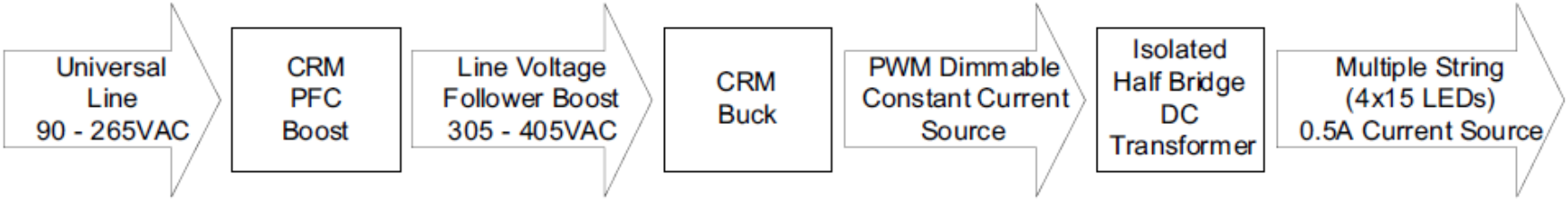
Programmable soft start with on/off control

Two level over current protection, auto-recovery and latch up

Matching output with 50ns tolerance

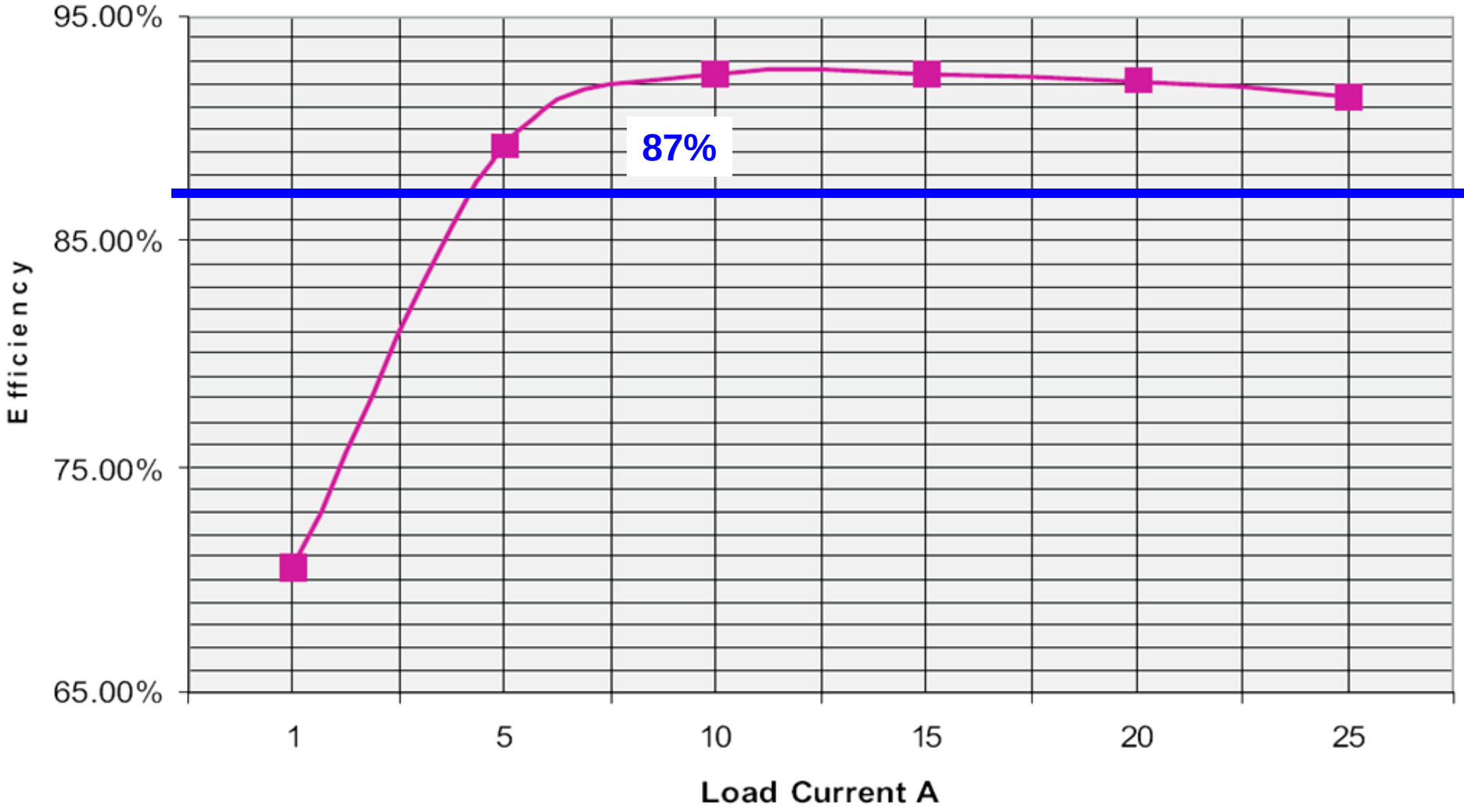
UCC25600 - Support & design tools

- **App Note**
  - A 300-W, Universal Input, Isolated PFC Power Supply for LCD TV Applications (sluu341b)
  - U-138 Zero Voltage Switching Resonant Power Conversion (slua159)
- **Evaluation Module**
  - LLC Resonant Half Bridge Converter 300 W Evaluation Module (sluu361)
  - UCC28810EVM-003 110W Multiple String LED Driver with Universal Line Input and PF (sluu380a)

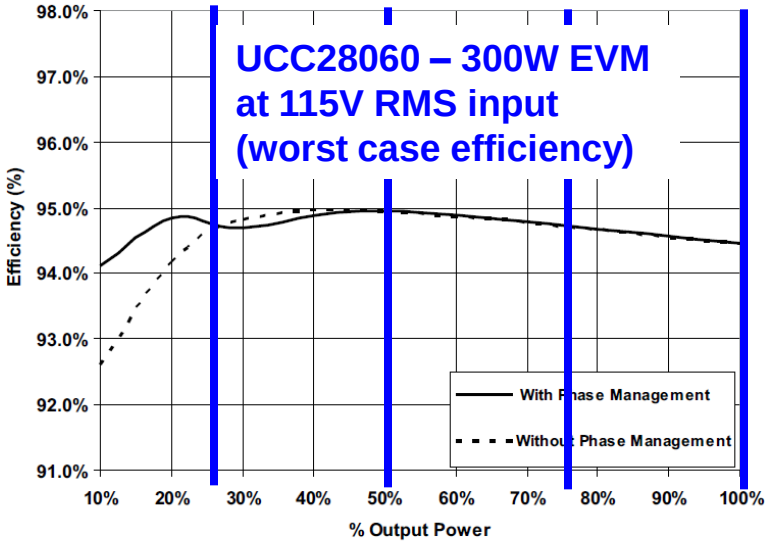


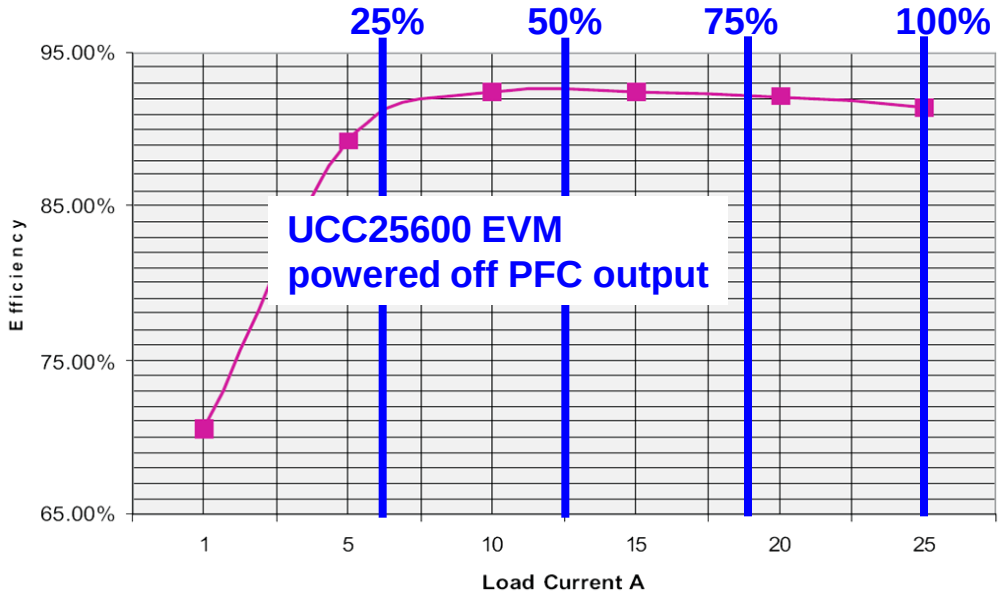
- **Excel Design Tool (sluc146)**
- **Seminar Topics**
  - Seminar 700 Topic 6: Resonant Mode Converter Topologies -Additional Topics (slup092)
  - Seminar 600 Topic 1: Resonant Mode Converter Topologies (slup085)
  - 2010/2011 Seminar – topic 3: Designing an LLC Resonant Half-Bridge Power Converter

UCC25600 – 300W EVM Performance VIN: 390VDC, VOUT:12V



UCC25600 – 300W EVM: total efficiency together w/ UCC28060 EVM





% of rated POUT	η of PFC (%)	η of LLC HB (%)	Total Efficiency (%)
25	94.7	91.0	86.2
50	94.9	92.7	88.0
75	94.7	92.2	87.3
100	94.4	91.5	86.4
Average			**87.0**

UCC25600 + UCC28060 fulfill 87% efficiency requirements for EPS as requested by EuP directive

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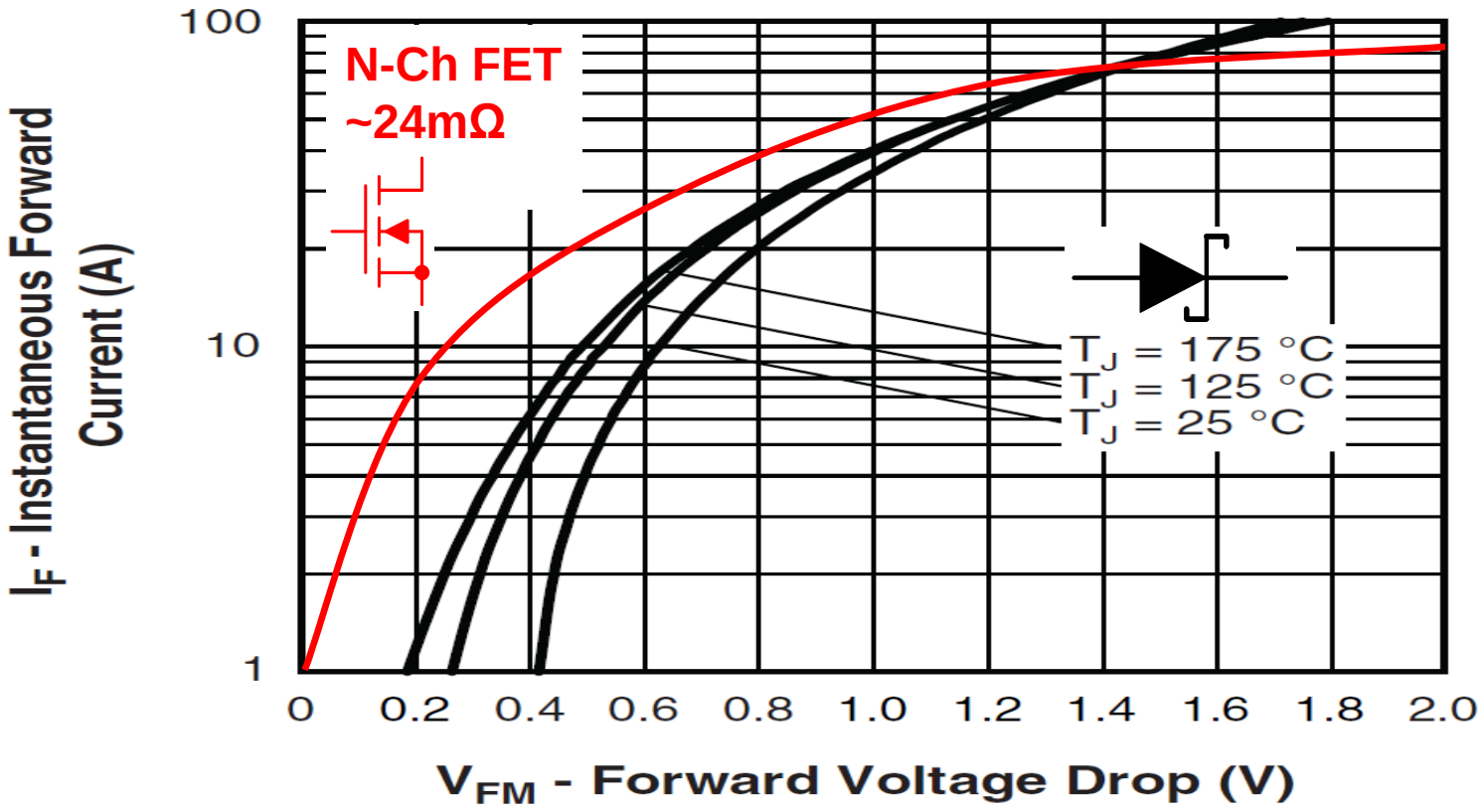
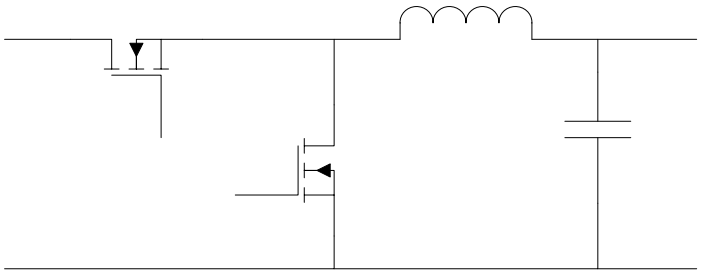
- LLC resonant half bridge (UCC25600)
- **Green synchronous rectifier controller (UCC24610)**
- Advanced green mode phase shifted full bridge (UCC28950)
- Other sources for support
- Summary

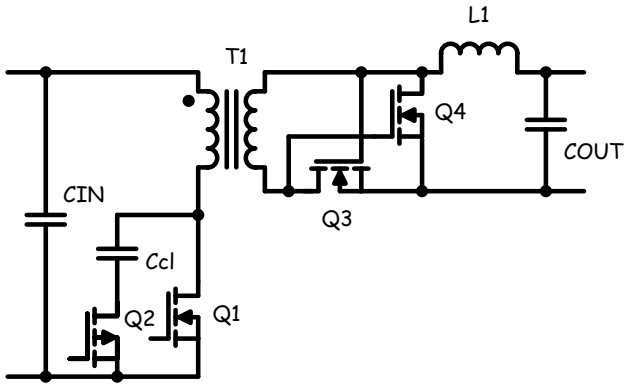
Schottky Diode vs. Synchronous Rectifier



- Syncronous rectification reduces the conduction loss significantly
- Higher efficiency can be expected for low-voltage applications
- BUT: Dominance of switching and gate drive losses under no or low load condition

SR Control in Different Applications (I)





Synchronous Buck

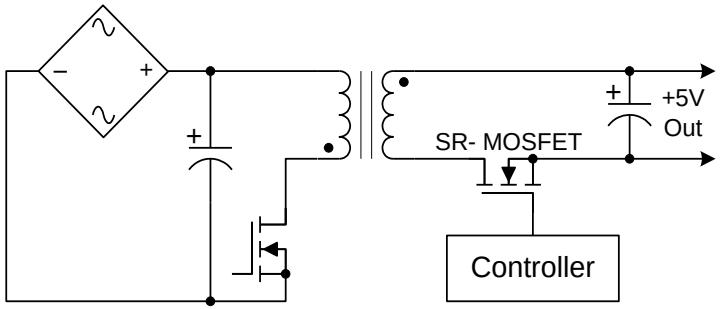
- Complementary conduction
- Adaptive turn-on to reduce body-diode loss

Active Clamp Forward Converter

- Self-driven based on transformer voltage

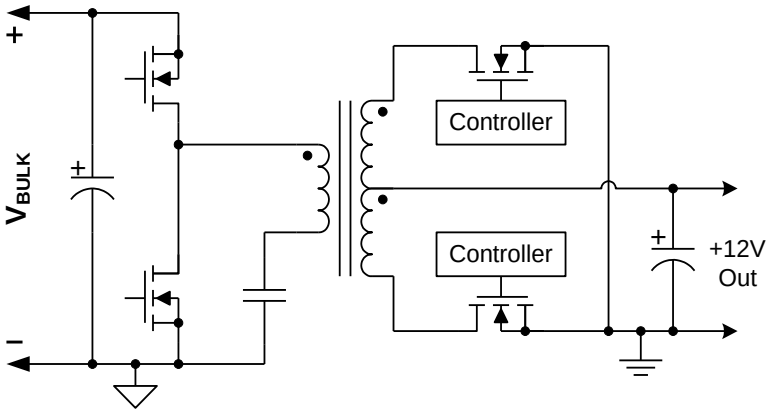
- Most power-conversion topologies can easily implement synchronous rectifier control without dedicated SR-controller IC
- Because of complicated operation modes, timing, and efficiency requirements, Flyback and LLC applications need dedicated SR-controller

SR Control in Different Applications (II)



Flyback Converter

- Ground-referenced MOSFET source
- CCM operation may need synchronization signal from primary



LLC Resonant Converter

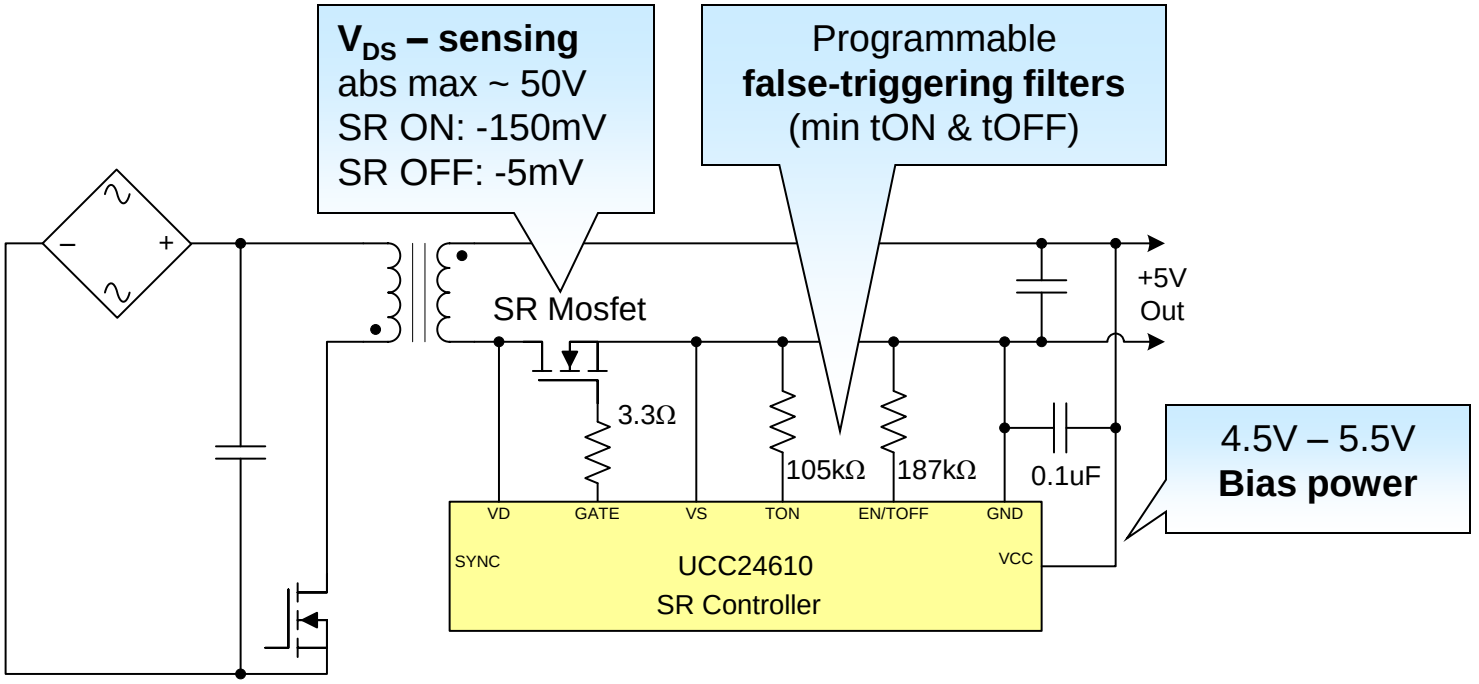
- Synchronization may be based on primary-side gate-drive signals

- SR may be required to operate in DCM or CCM, depending on topology and load and line conditions
- Intelligent control is necessary to prevent reverse current or cross-conduction in SR-MOSFET

Major Challenges for SR Control

- **Noise associated with turning on and off SR**
  - False trigger might happen due to parasitic ringing
  - Wrong action makes the ringing worse and the false triggering never ends
- **CCM operation**
  - Difficult to detect proper point in time to turn SR OFF
- **Special waveforms**
  - LLC converter has special current waveform that needs special treatment
- **Light-load efficiency**
  - At very light load, the conduction loss is very small, gate-driver loss might be significant

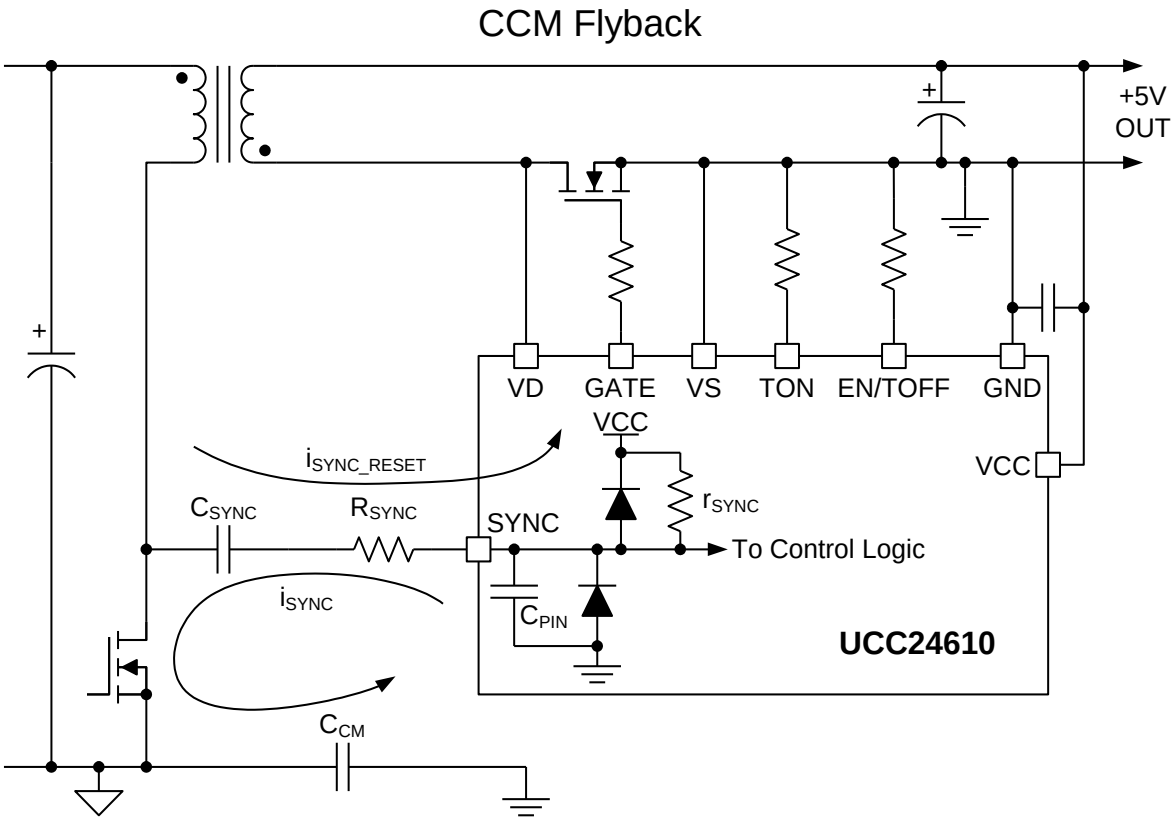
UCC24610 - TI Synchronous Rectifier Solution



- Self – synchronizing
- Up to 600kHz operation
- Automatic Light-Load Mode
- 1.6Ω sink, 2.0Ω source gate - drive

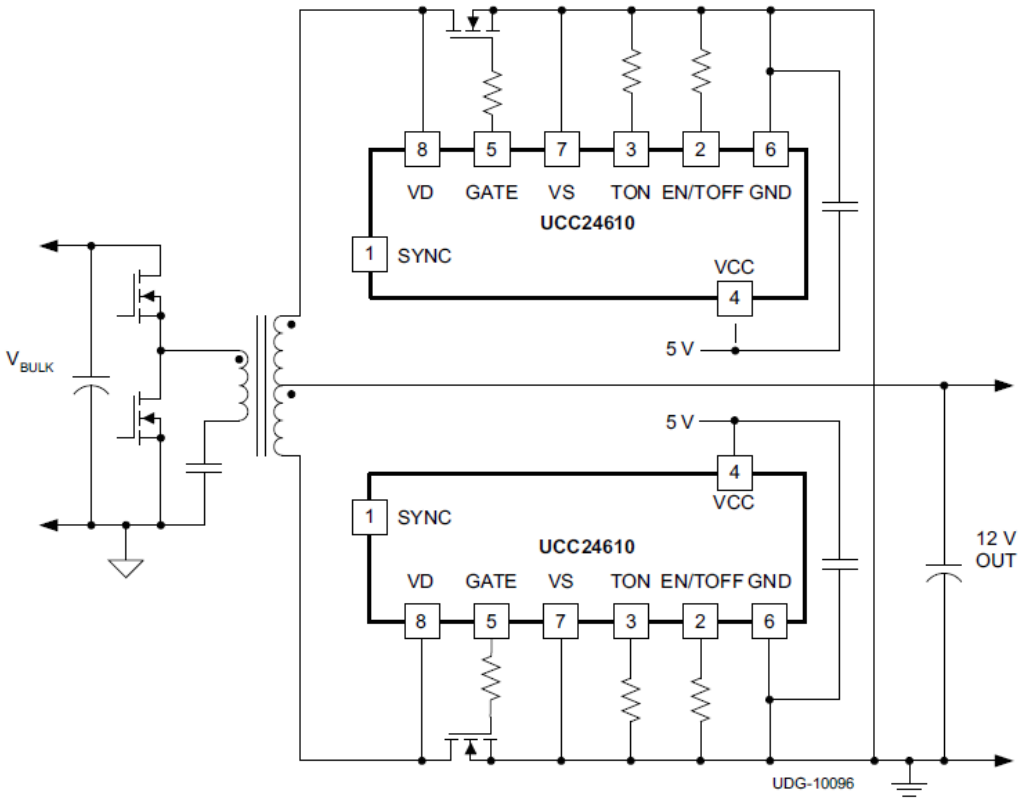
- Micro-power Sleep current for 90+ efficiency
- Synchronous wake-up from Sleep and Light-Load modes
- Protection features on programming inputs
- 8-pin SOIC and QFN packages

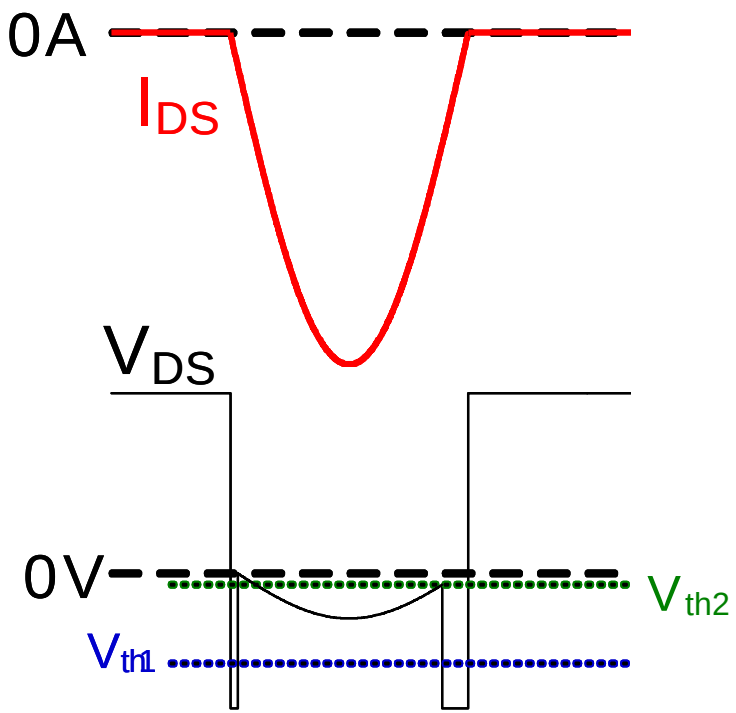
UCC24610 - CCM Implementation with SYNC



The SYNC function allows the SR to turn off before its current becomes negative, which improves system efficiency and avoids cross-conduction stress

UCC24610 – (12V) LLC Implementation





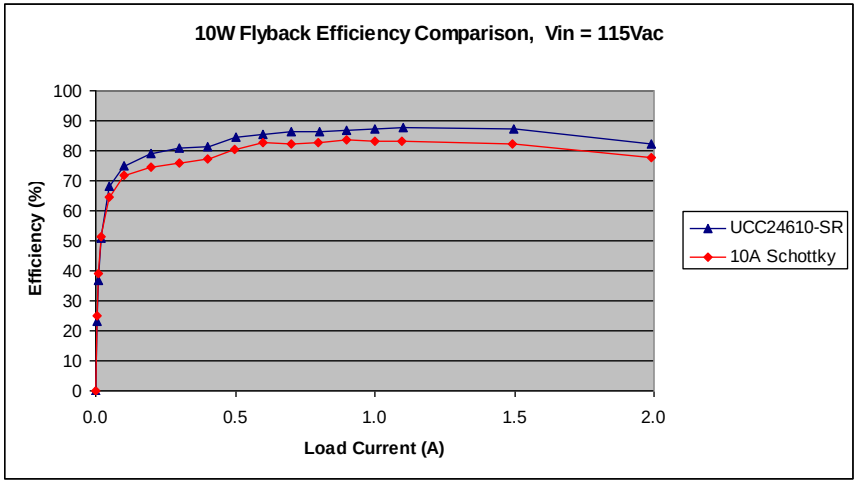
SR voltage and current

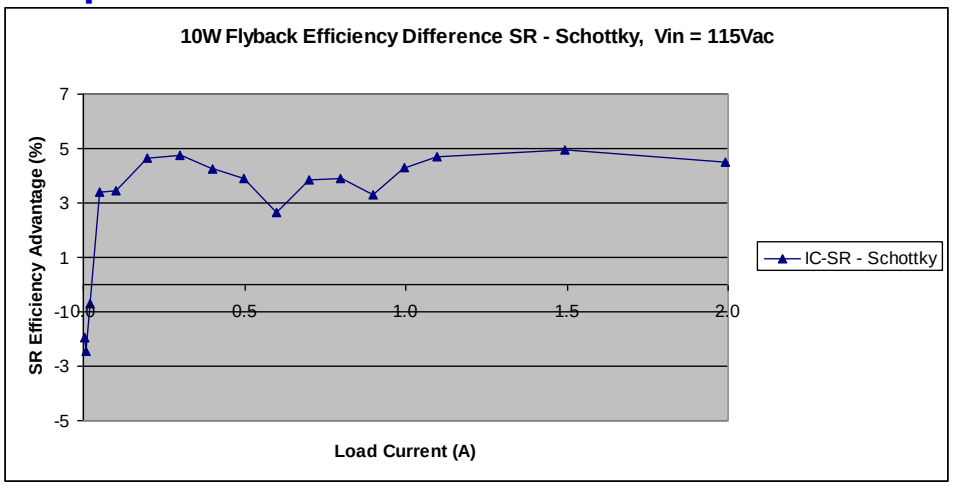
- 5V VCC needs to be generated by LDO or low power buck off the 12V output voltage
- Programmable min tON forces SR to stay ON until current rises above the turn-off threshold.

UCC24610 – 10W Quasi-Resonant Flyback

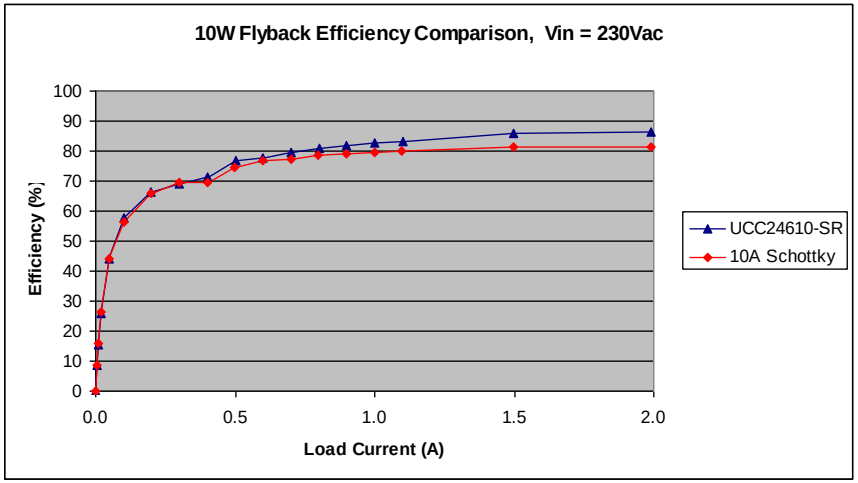
Efficiency Comparison: ~3 … 5% Improvement

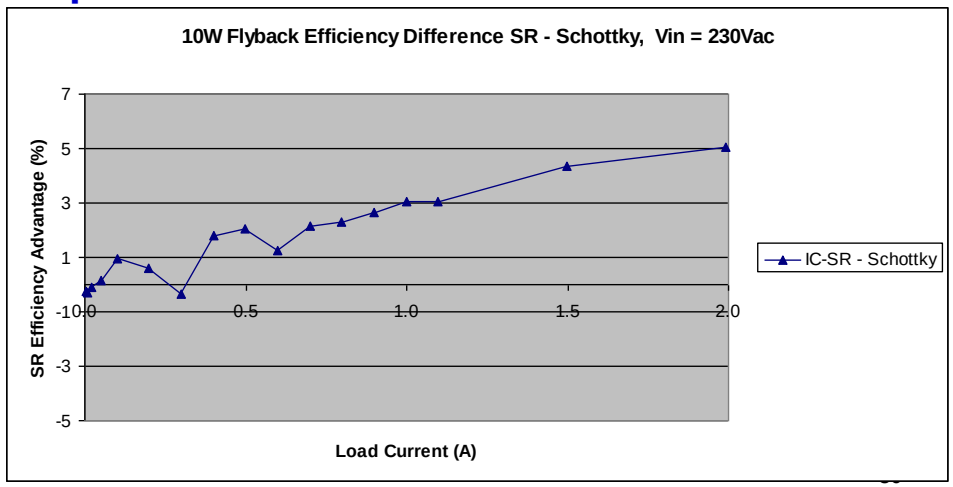
115 VAC Input





230 VAC Input





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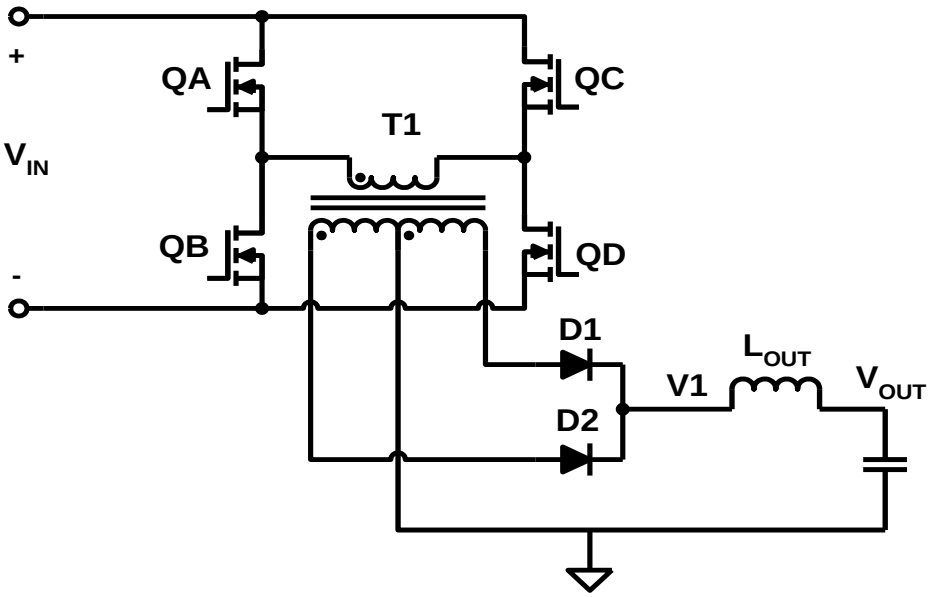
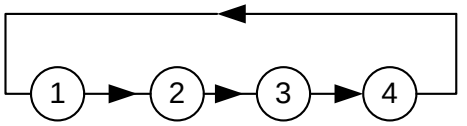
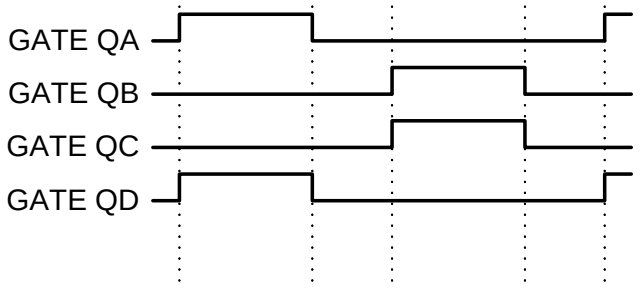
Full bridge topology for high power converters

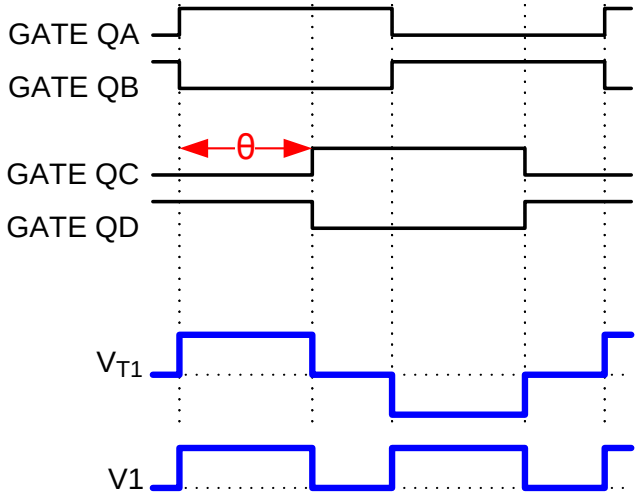




Conventional full bridge

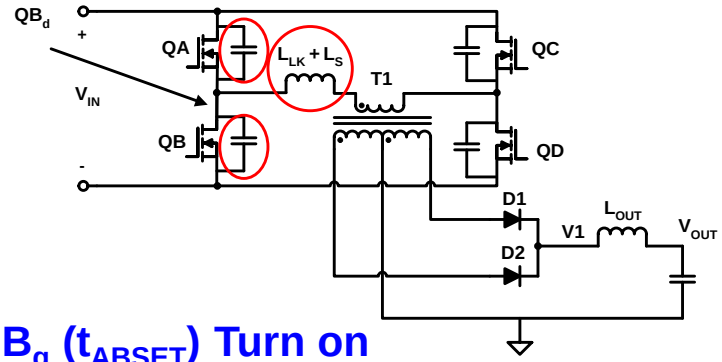


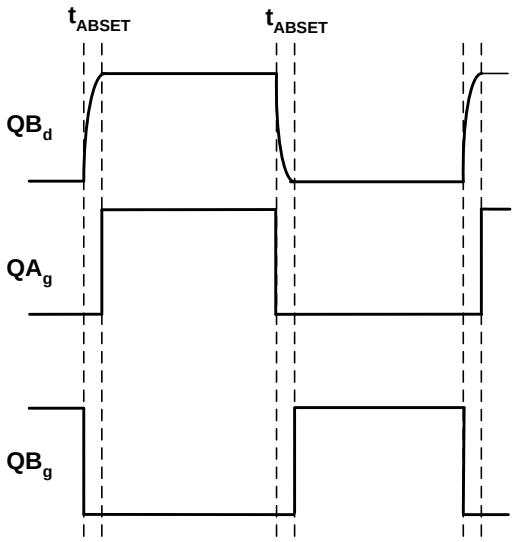
Phase shifted full bridge



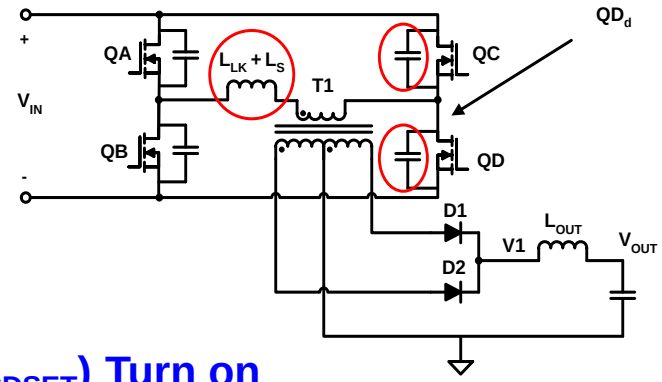
- Control signals for QA … QD make the difference
  - **Conventional full bridge:**
    - duty cycle controlled
  - **Phase shifted full bridge:**
    - controlled by phase shift θ b/w QA (QB) and QC (QD)
    - each leg is operating w/ 50% dutycycle
    - QA (QC) and QB (QD) are 180º out of phase

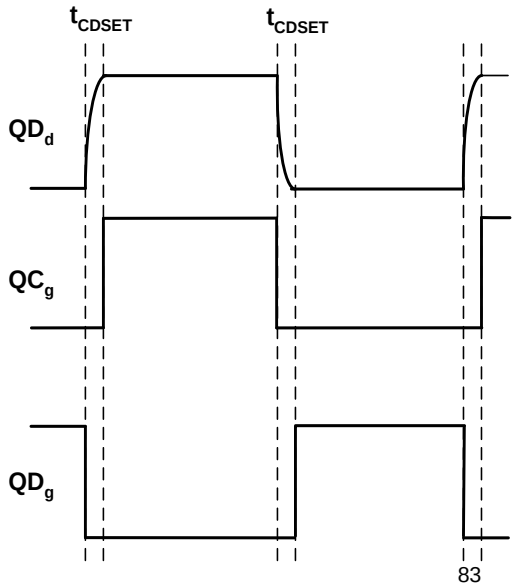
Phase shifted full bridge enables ZVS of switches on primary side





- **Add Delay QA_g and QB_g (t_{ABSET}) Turn on**
- L_{LK} + L_S Tanking with Capacitance at Switch Node (QB_d)
- **Allows for ZVS at switch node QBd**

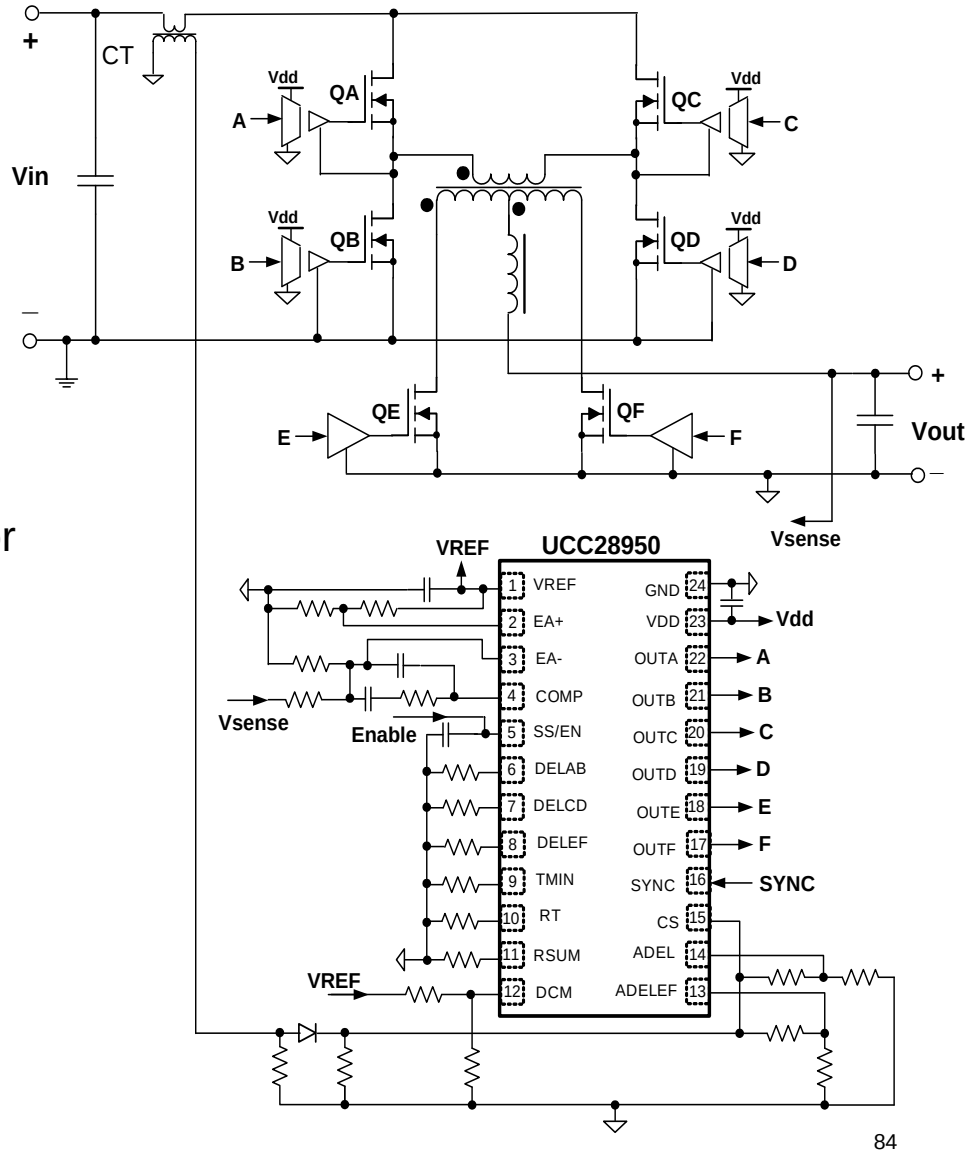




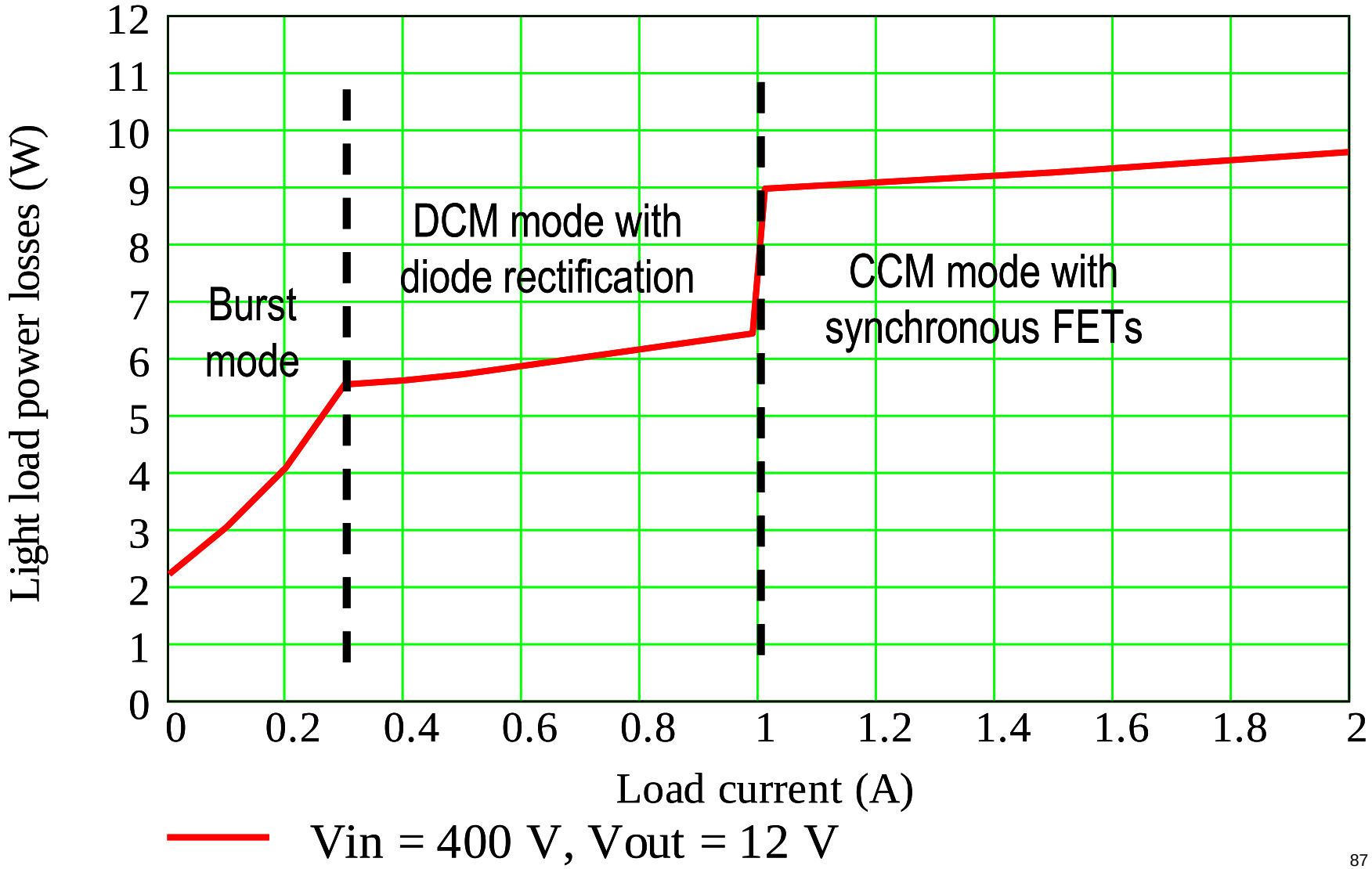
- **Add Delay QC_g and QD_g (t_{CDSET}) Turn on**
- L_{LK}+ L_S Tanking with Capacitance at Switch Node (QD_d)
- **Allows for ZVS at switch node QDd**

UCC28950 – Successor of the industry standard UCC2895

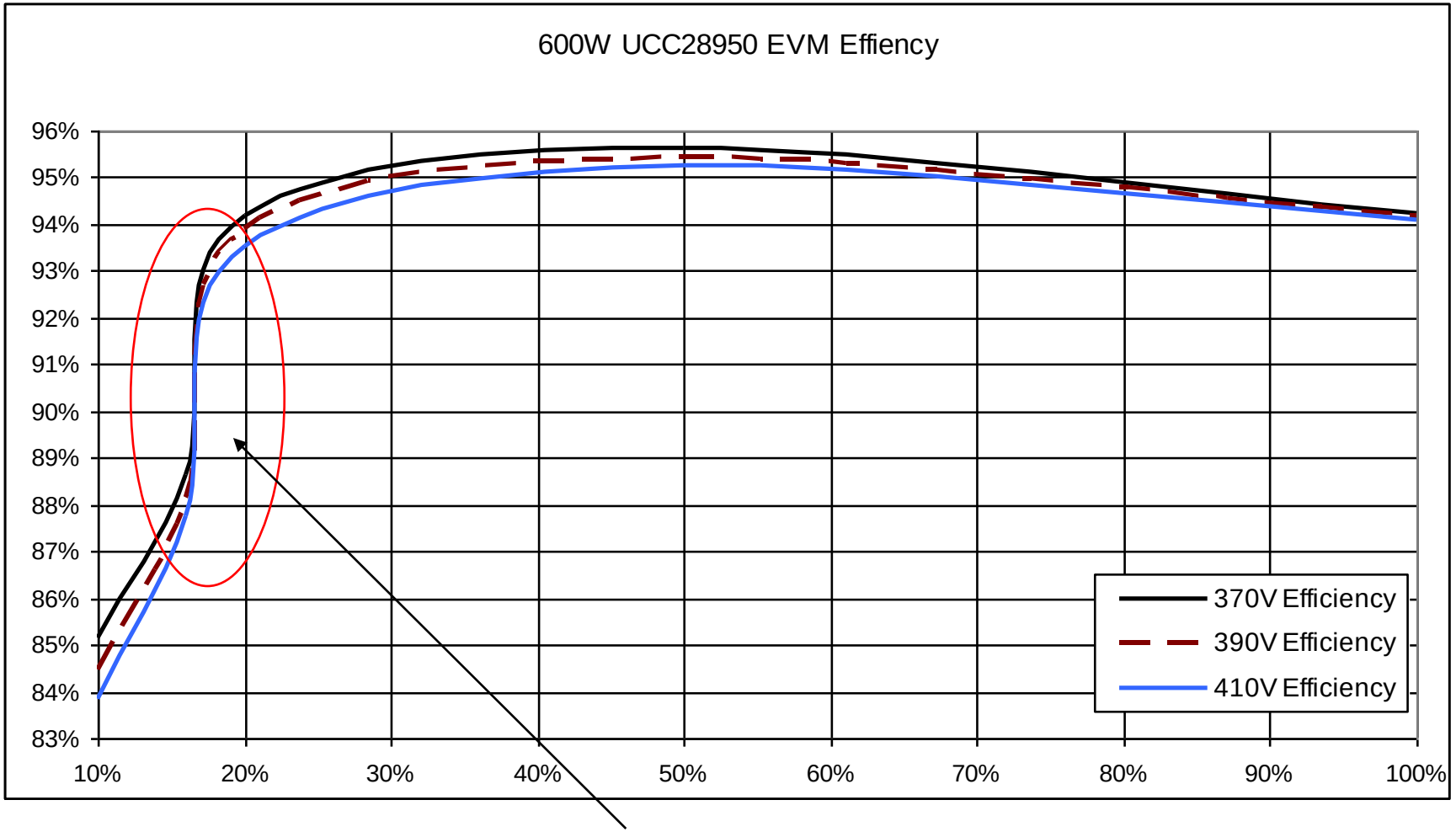
- **More Advanced**
  - Control outputs for primary FETs **and for synchronous rectifiers (SR)**
  - Selectable VM, avg. or peak CM
    - Programmable slope compensation
  - Phase shifted SYNC_IN/OUT for easy interleaving
  - Optimized SR drive by adaptive delay and SR drive overlap
  - Possible location on secondary side improves accuracy and dynamic behavior
  - Improved:
    - ZVS by increased adaptive delay range (10:1) for primary FETs
    - VREF accuracy (1.5%)
    - Current Limit (3%)
- **More green**
  - Optimized for 90+ Efficiency (Platinum)
  - Light load efficiency management by
    - Burst Mode
    - DCM mode, programmable SR On/Off



UCC28950 - Power Losses Reduction at Light Load

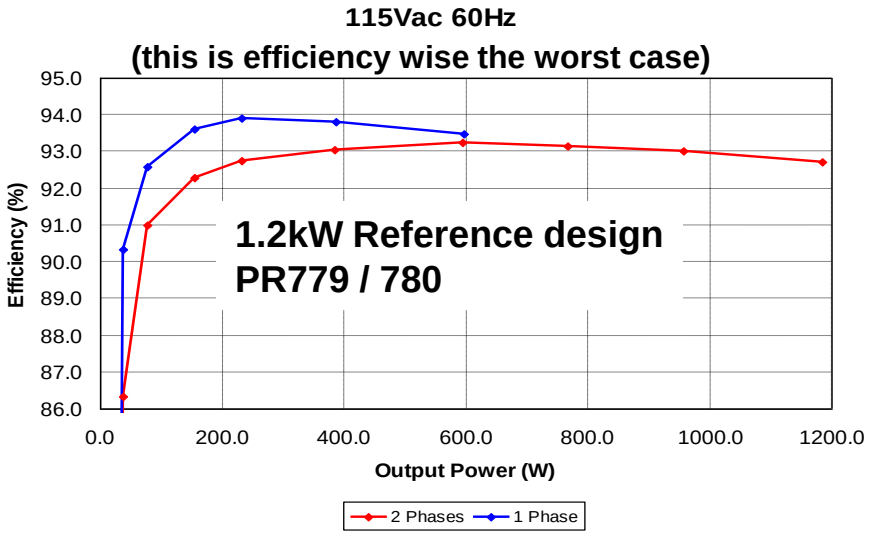


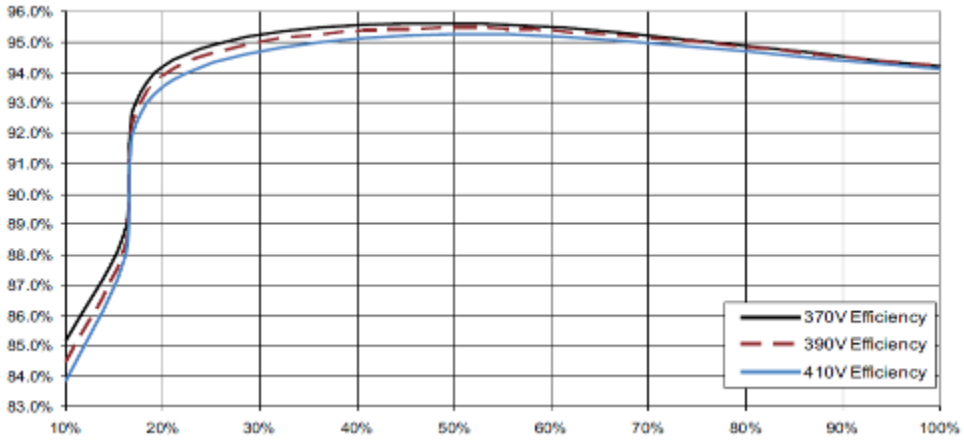
UCC28950EVM - 370 … 410VDC IN / 12V / 600W OUT



Note step in efficiency is due to FETs Turned Off

UCC28950 – 600W EVM: total efficiency w/ UCC28070 EVM





Energy Star® requirements for server power supplies

Power Supply Type	Rated Output Power	10% Load	20% Load	50% Load	100% Load
Single-Output (AC-DC & DC-DC)	> 500 – 1000 W	75.00%	85.00%	89.00%	85.00%

UCC28070 + UCC28950

PFC (UCC28070)	scaling down to 600W	92.8%	93.8%	93.5%	92.7%
Phase shifted full bridge (UCC28950)	600W	84.5%	94.0%	95.4%	94.1%
Total efficiency	600W	**78.4%**	**88.2%**	**89.2%**	**87.2%**

UCC28950 + UCC28070 fulfill stringent Energy Star® efficiency requirements for server power supplies

UCC28950 – Design support

- EVM
  - 370 … 410VDC input / 12V / 600W output
  - User Guide (SLUU421A)
- Application Note
  - Should release to web shortly
- MathCAD Design Tool
  - Should post to the web shortly
- Related App Notes
  - U-136A Phase shifted, zero voltage transition design considerations (slua107)
  - U-138 Zero voltage switching resonant power conversion (slua159)
  - DN-63 The current-doubler rectifier: An alternative rectification technique (slua121)
  - Current doubler rectifier offers ripple current cancellation (slua323)
  - Synchronous rectifiers of a current doubler (slua287)
- Related Seminar Topics
  - Seminar 700 Topic 6: Resonant mode converter topologies -Additional topics (slup092)
  - Seminar 600 Topic 1: Resonant mode converter topologies (slup085)
  - SEM800 – Fixed-frequency, resonant switched PWM with phase shifted control (slup096)
  - SEM900 - Designing a phase shifted Zero Voltage Transition power converter (slup101)
  - SEM900 – Design review: 500 Watt, 40W/in^3 phase shifted ZVT power converter (slup102)

Agenda

- General thoughts, standards and solutions
- Quasi-resonant green mode flyback (UCC28600)
- Cascoded green mode flyback (UCC28610)
- Active clamp (UCC289x family)
- Interleaved PFCs (UCC2806x / 28070)
- LLC resonant half bridge (UCC25600)
- Green synchronous rectifier controller (UCC24610)
- Advanced green mode phase shifted full bridge (UCC28950)
- **Other sources for support**
- Summary

Other sources for support

- TI E2E™ Community - http://e2e.ti.com
  - Support, videos, blogs, groups
  - Specific support for PFC and PWM controllers under: Support / Power Management / Isolated Controllers, Motor Controllers

- On demand online training under:
  - Training & Events / Analog, Online Training

- TI Power Supply Design Seminar (2010 / 2011 series)

- All former UNITRODE and TI Power Design Seminars on ti.com under:
  - Training & Events / Analog, Archived Seminars

Summary

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- Other sources for support

The shown solutions will help you to fulfill the stringent efficiency requirements now and in the future.

Thank You