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)
- Advanced green mode phase shifted full bridge (UCC28950)
- Summary

Power density & efficiency

Main efficiency goal

Efficiency increase

Loss reduction

Driving forces

Heat reduction

Under full load

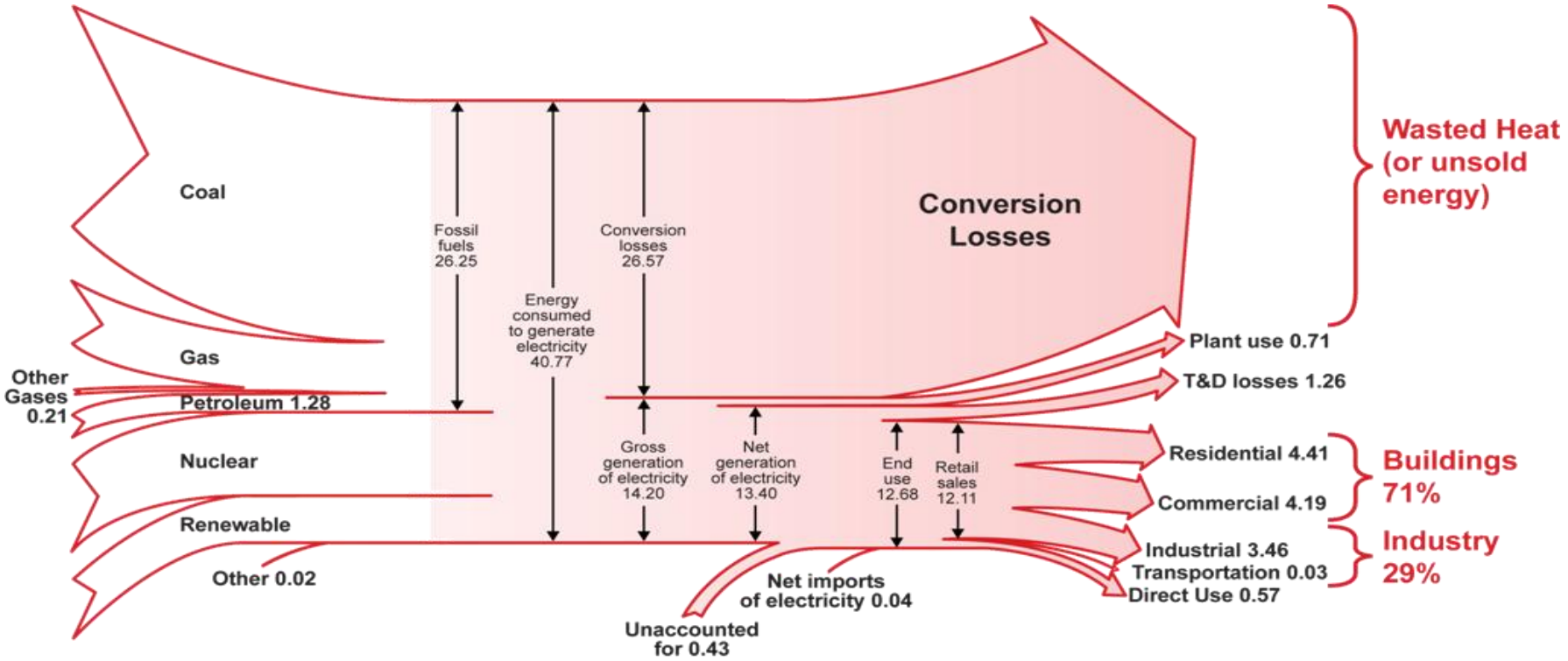
Prerequisite for **increased power density**

Legislation (Energy Star, EuP, …)

All load conditions

Efficiency Increase – The Global View

65% of all energy created is lost in the conversion & distribution process… this is why energy conservation is so important



EIA: Energy Information Administration. Official Energy Statistics from the US Government.

1kWh saved is 3.3kWh of energy source never consumed

Efficiency increase – directives and legislation

- Enforcement Levels
  - Incentive Programs

  - Voluntary

EC Code of Conduct (EU)

  - Mandatory

Australian Government
Department of Climate Change

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

EuP – EPS ≤ 250W (External Power Supplies)

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

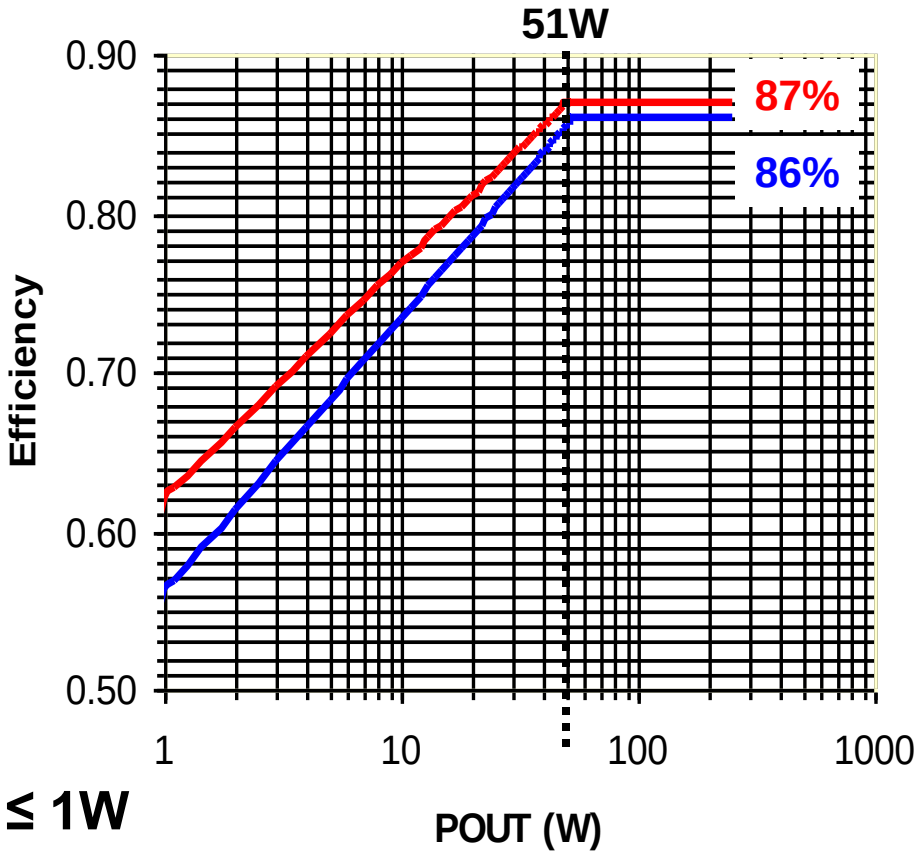
No-load power consumption

≤ 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)
$0.063 \times \ln(P_{OUT}) + 0.622$

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



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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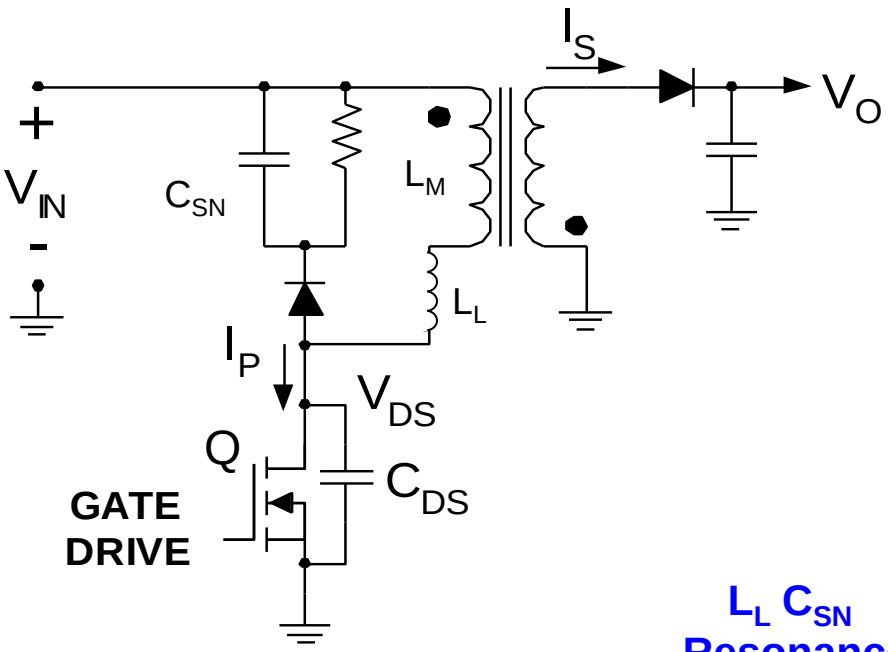
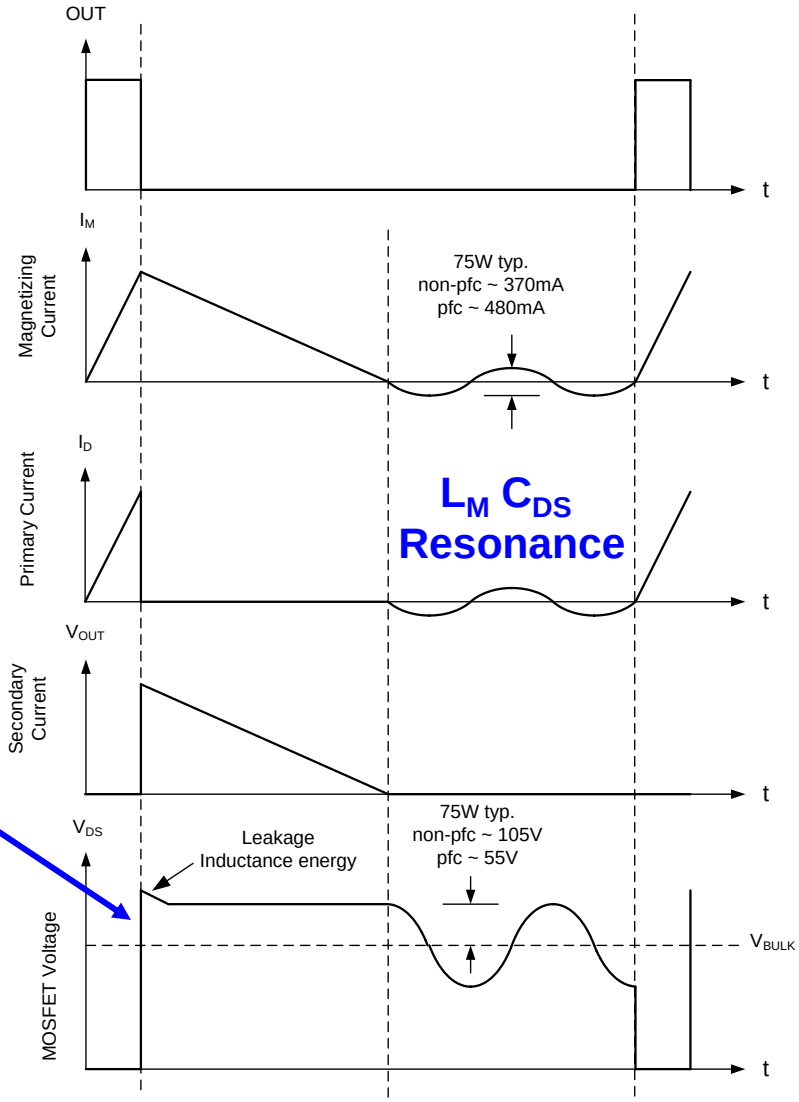
UCC28600 – Valley switching makes the difference



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



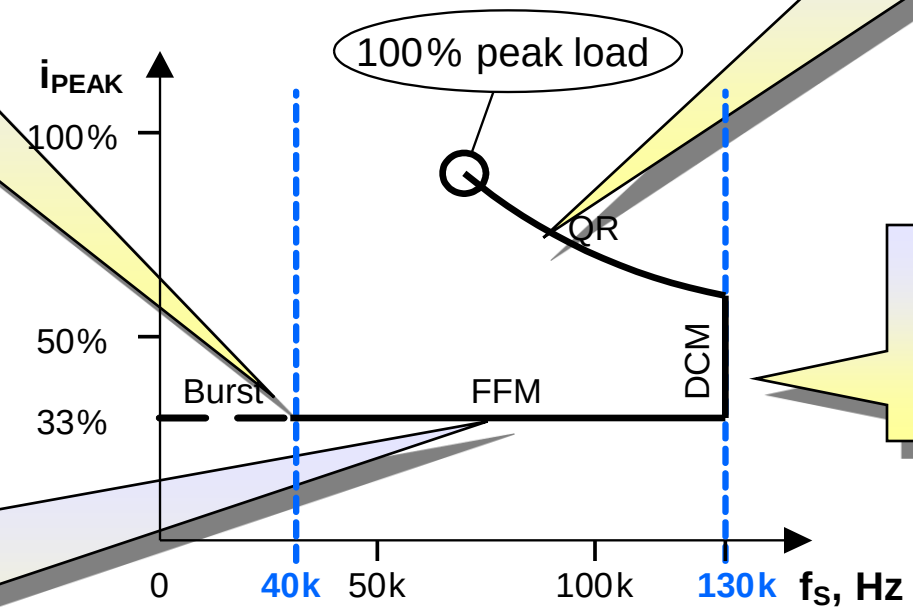
UCC28600 – Multiple operation modes make the difference

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

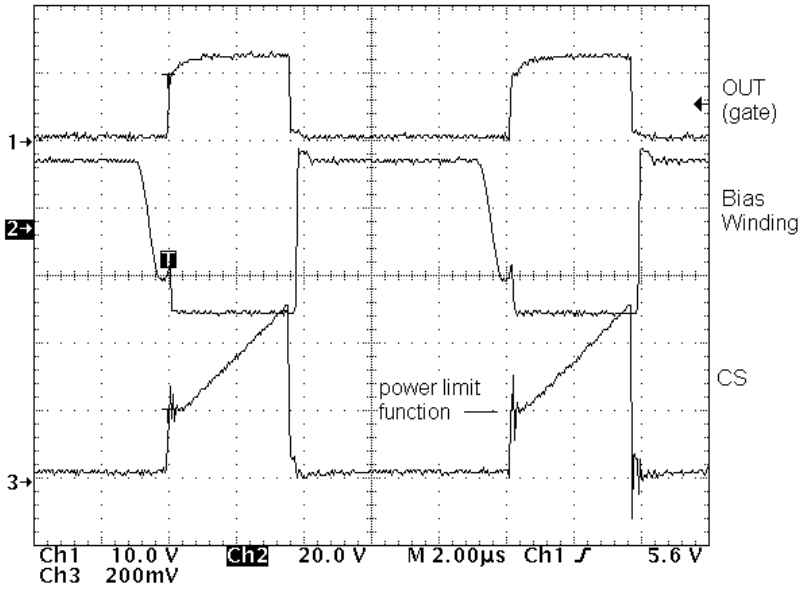
Frequency Foldback Mode
enhance light load efficiency by reduction of switching frequency



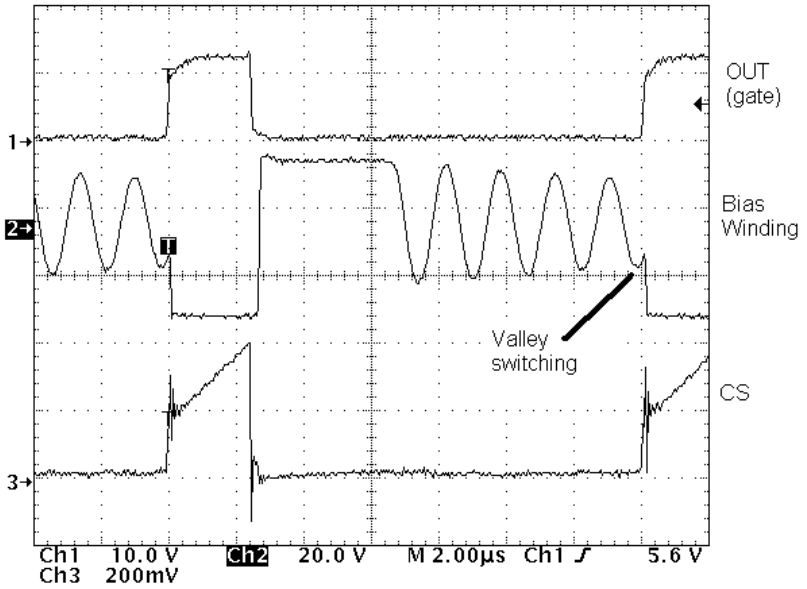
% i_{PEAK} vs f_S for loads ≤ 100% peak load

QR and FFB valley switching

36W, QR mode

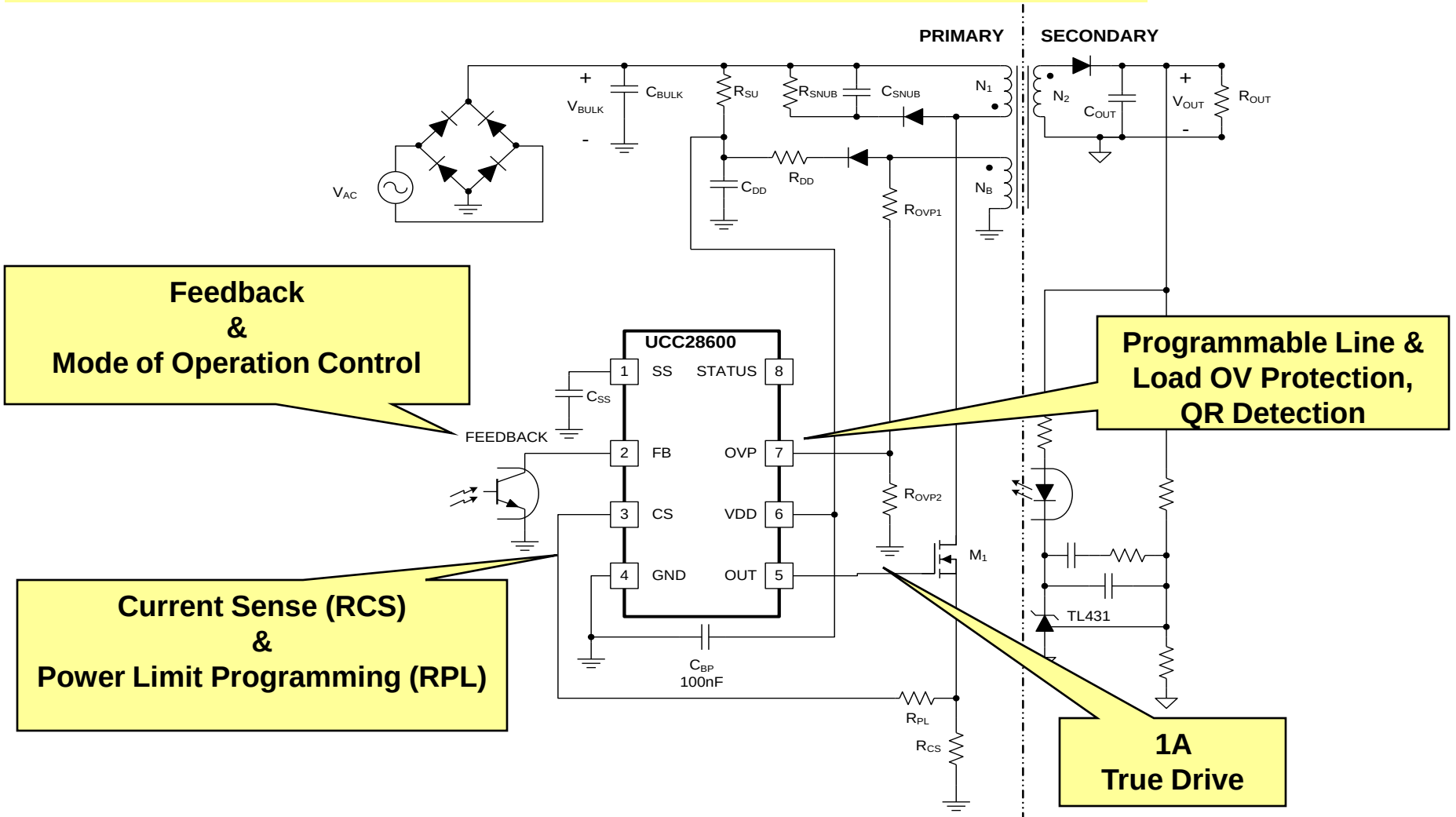


13.8W, FFB mode



UCC28600 - 8-pin QR green mode PWM controller

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

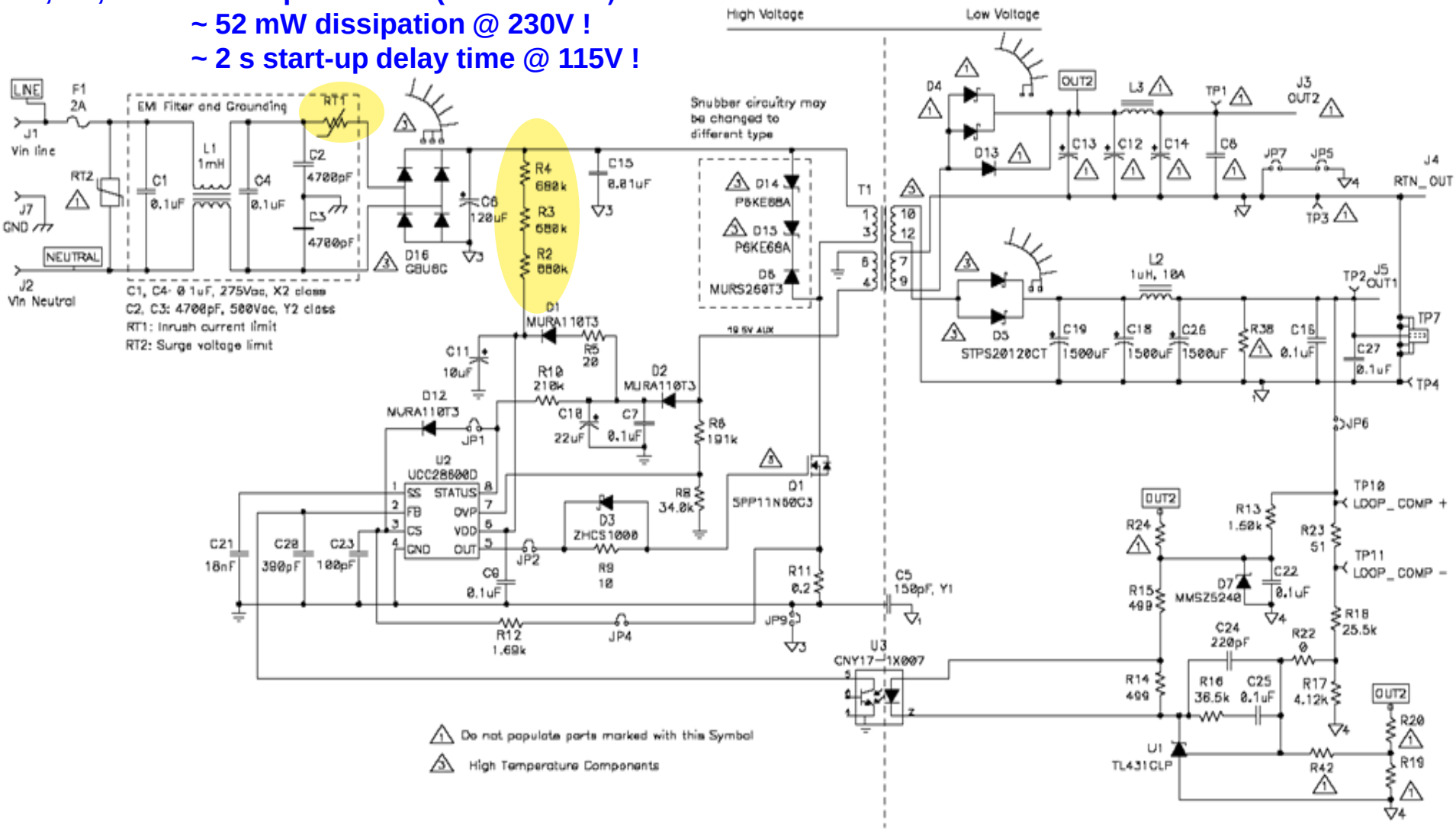


UCC28600 – Design support

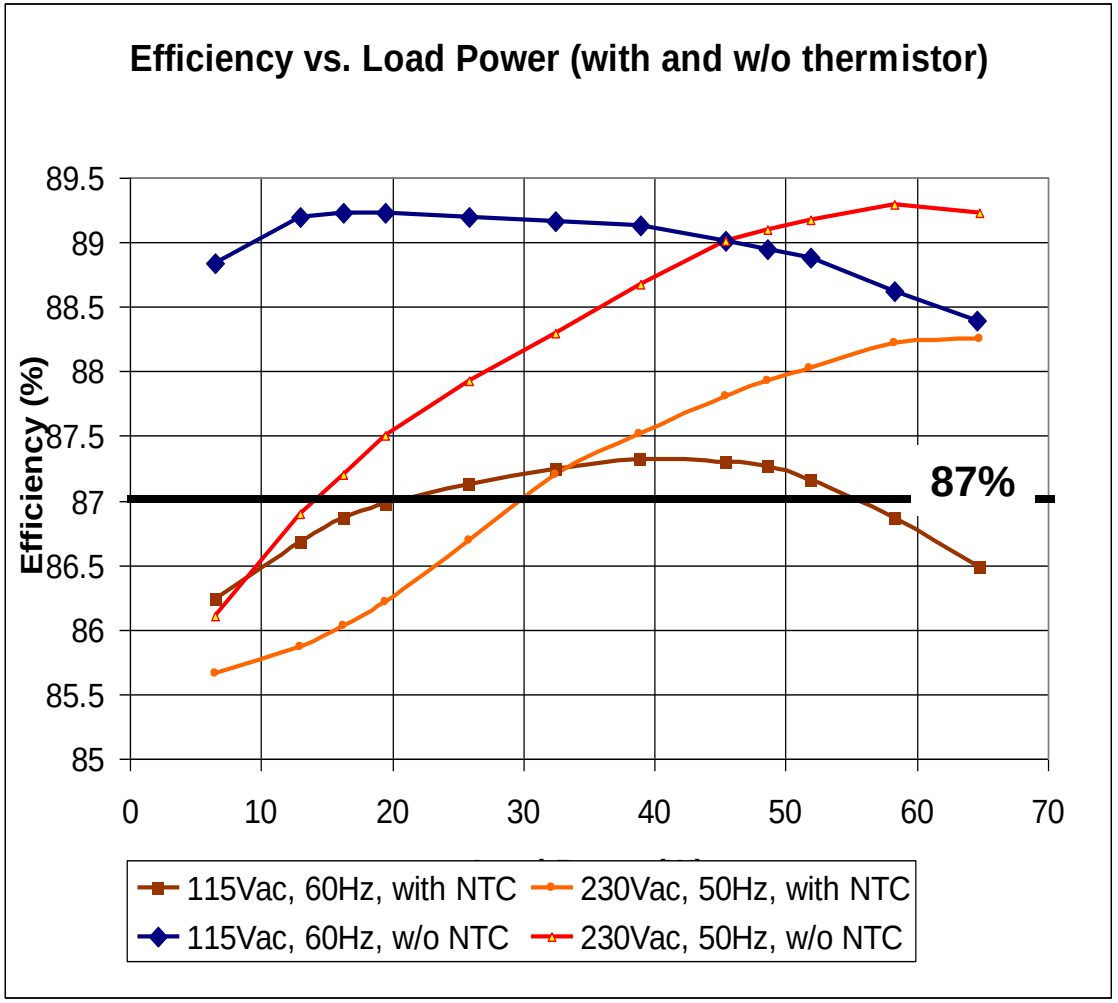
- Application Notes
  - Bootstrap circuit for green mode applications (slua373)
  - Design considerations for the UCC28600 (slua399b)
  - Flyback transformer design for the UCC28600 (slua418)
- Seminar topics
  - Seminar 1700 - topic 2: Green-mode power by the milli-Watt (topic2mm)
- EVMs
  - 65W universal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

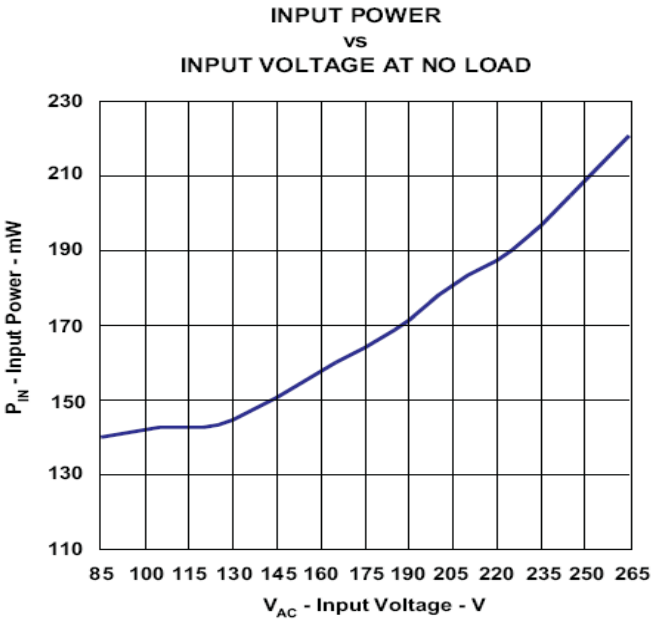
UCC28600 – 18V / 65W universal input design EVM

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



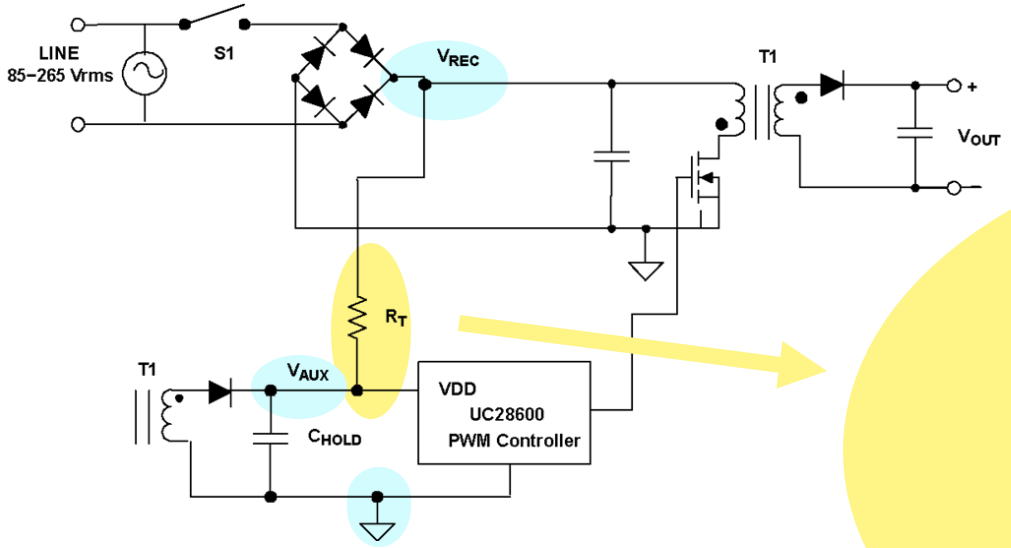
UCC28600 – 18V / 65W universal input design EVM





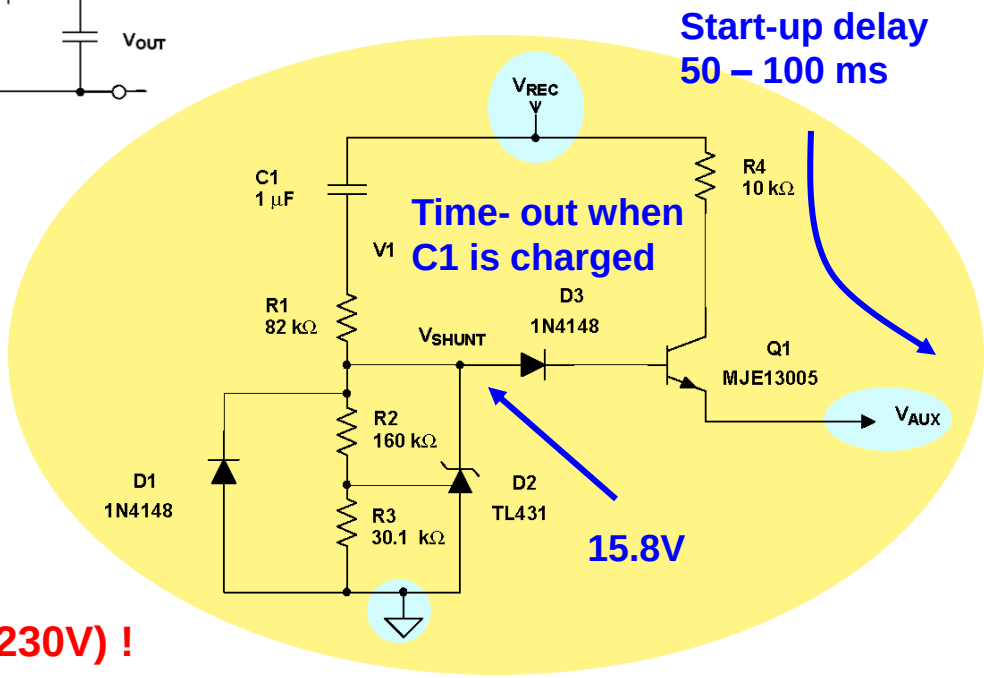
Improved start-up

- 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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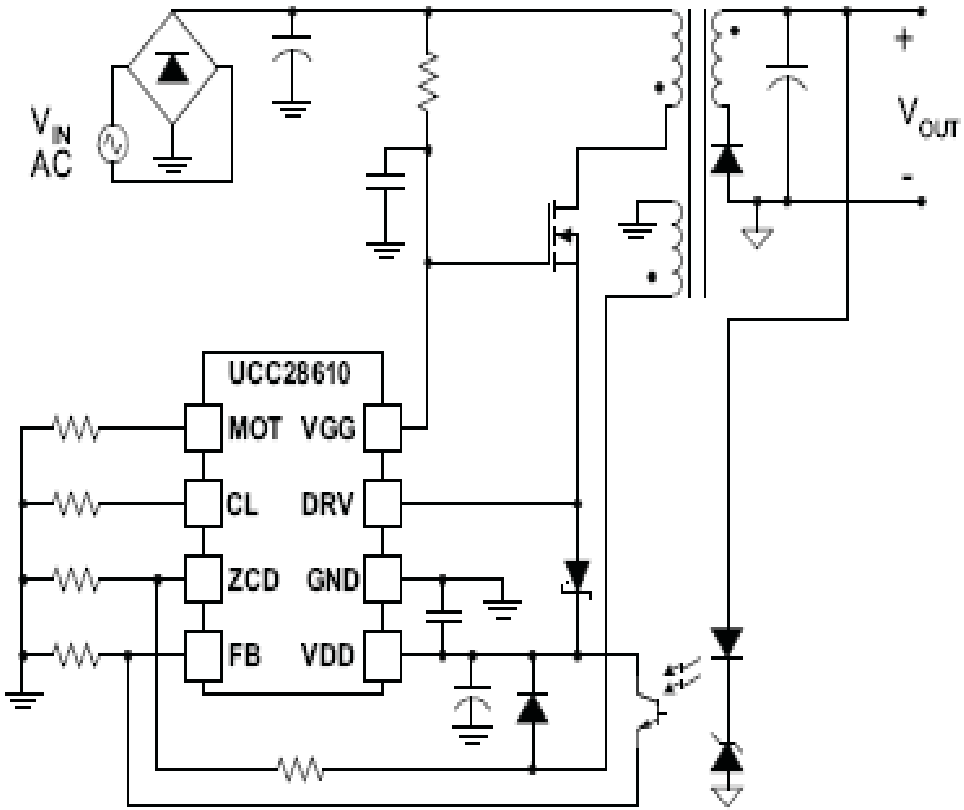
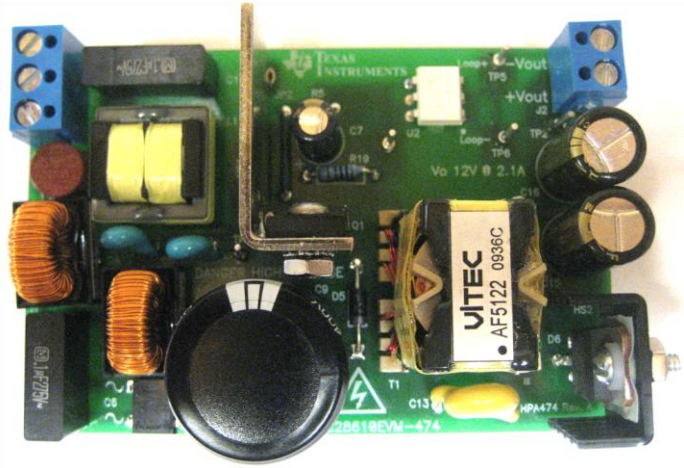
UCC28610 - Cascoded 12 - 65W Green Mode PWM Controller

- 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



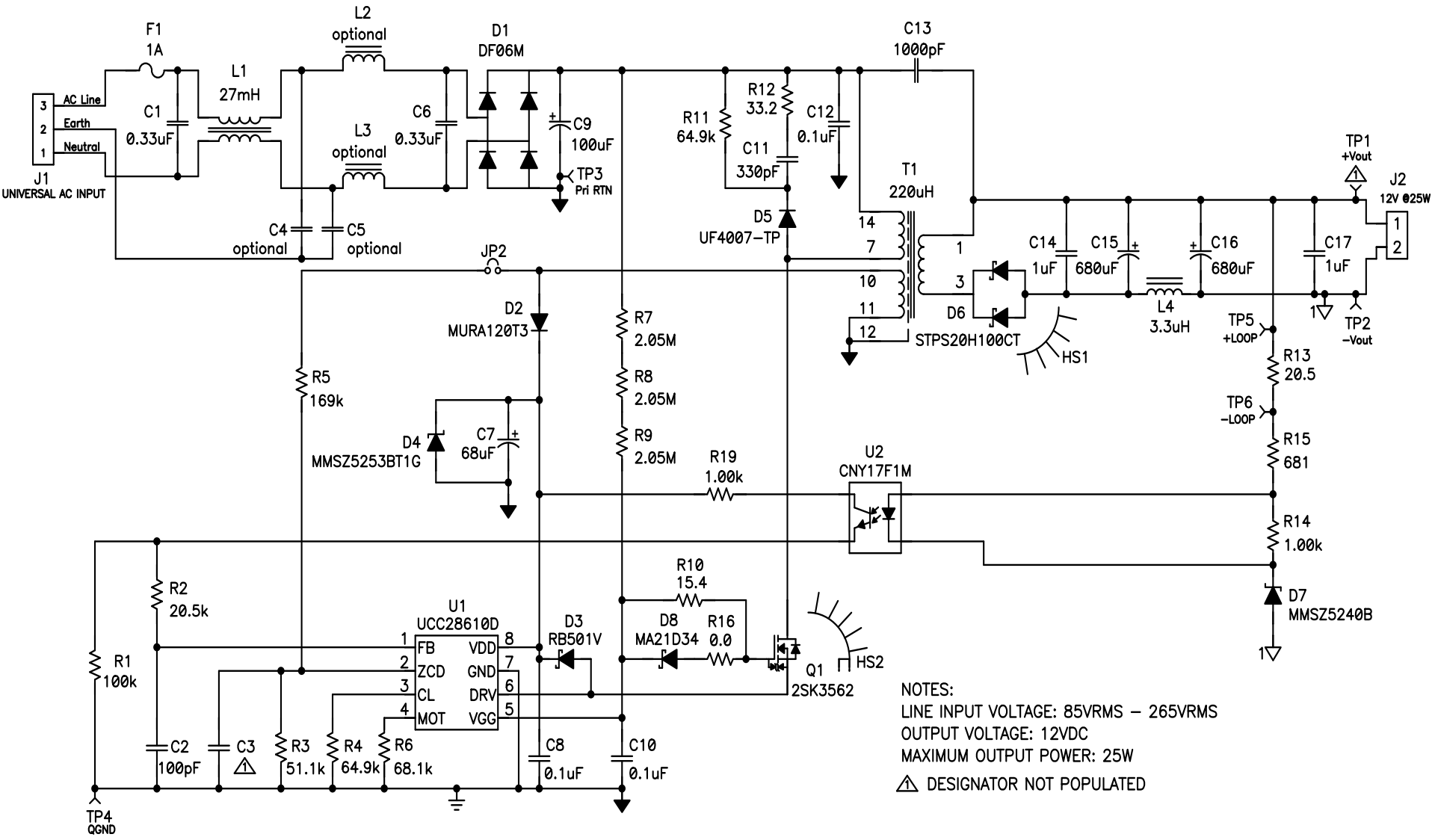
UCC28610 – Design support

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

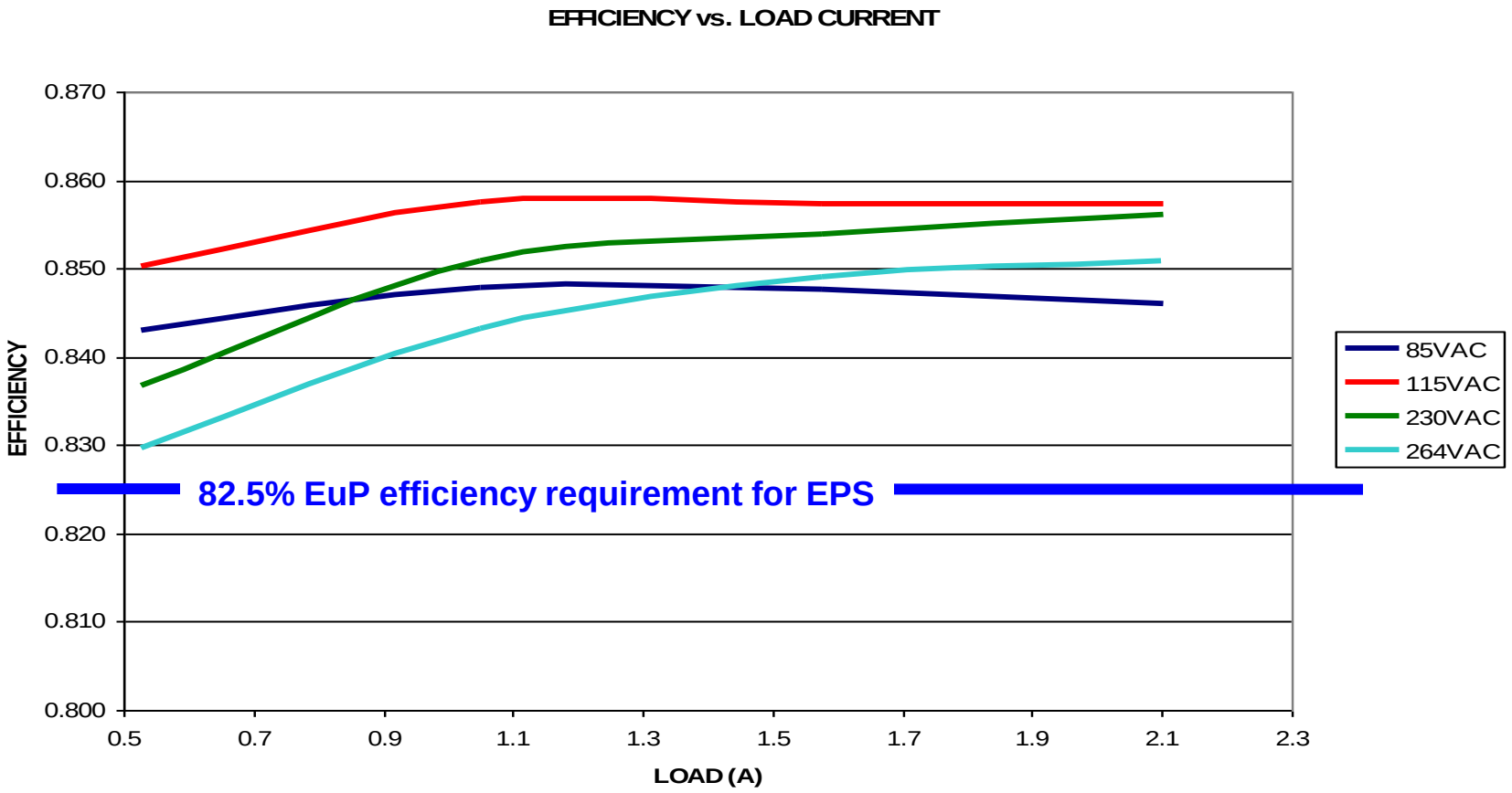


- Reference designs (15)

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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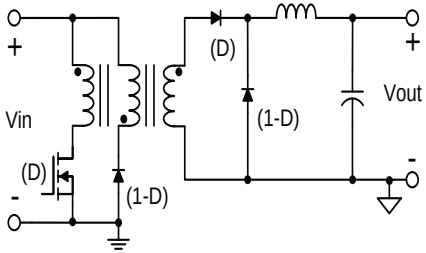
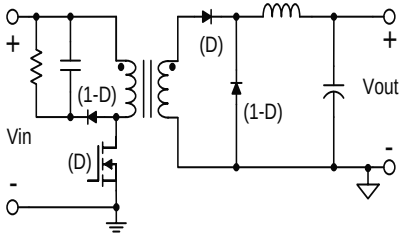
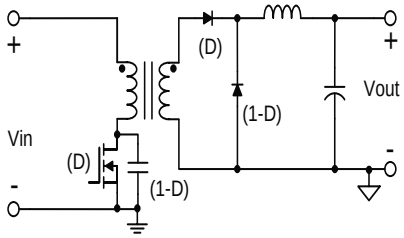
(Forward) Transformer Reset Techniques



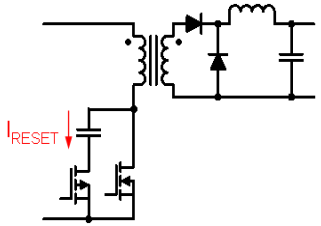
Reset Winding



RCD Clamp



Resonant Reset



Active Clamp & Reset

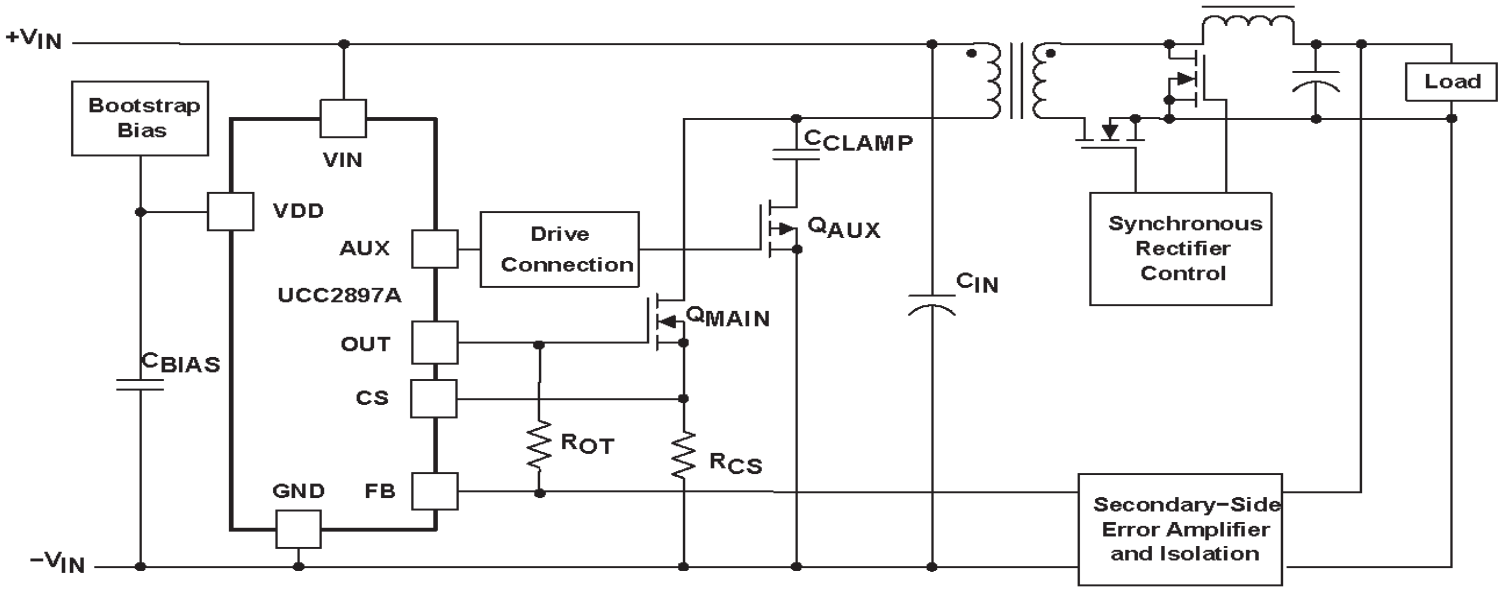
	Reset Winding	RCD Clamp	Resonant Reset	Active Clamp and Reset
Soft Switching (ZVS)	No	No	No	✓
Recycles Inductive Energy	✓	No	✓	✓
Recycles Capacitive Energy	No	No	No	✓
> 50 % Dutycycle	No	✓	✓	✓
Complexity	High	Low	**Lowest**	Highest
Efficiency		Lowest		**Highest**

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

- Active Clamp Forward / Flyback → Universal for High Efficiency & Low EMI
- Peak Current Mode Control → Cycle-by-Cycle Current Limit
  - Additional 2nd level current limit
- up to 1MHz switching → Small size
  - Programmable / (bi-directional) synchronization
- Integrated gate drivers (Main & Aux FET) → Reduced complexity
  - P-channel Aux FET drive
- Programmable
  - Delay → ZVS switching
  - Slope compensation → Simplified circuit
  - Max duty cycle (55 … 85%) → Converter protection
  - Switching frequency → Size vs. efficiency optimization
  - UVLO / OVLO & Hysteresis → System feature and protection
- Internal 110V Start-up circuit → Reduced complexity

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

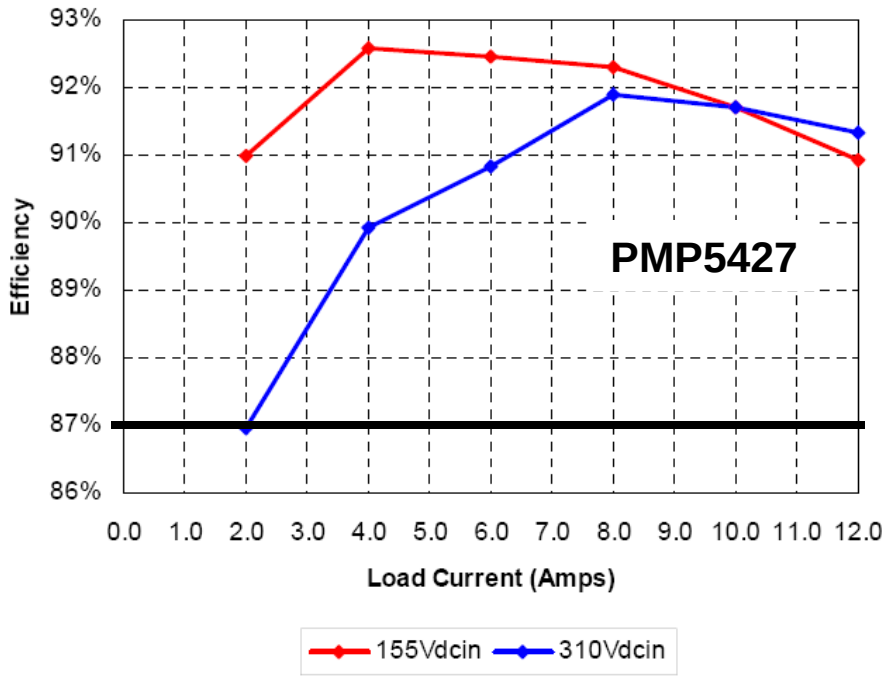
	UCC2891	UCC2892	UCC2893	UCC2894	UCC2897A
Additional 2nd level current limit					✓
P-channel Aux FET drive	✓	✓			✓
Bi-directional synchronization					✓
Line overvoltage lockout & hysteresis		✓		✓	
Internal 110V Start-up circuit	✓		✓		✓
Targeted for Off-line AC/DC				✓	



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

- Application Notes
  - 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)
- EVMs
  - UCC2891EVM, UCC2897EVM (both telecom input)
- Reference Designs
  - More than 150 tested designs for industrial, automotive, telecom and AC/DC off-line applications

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.

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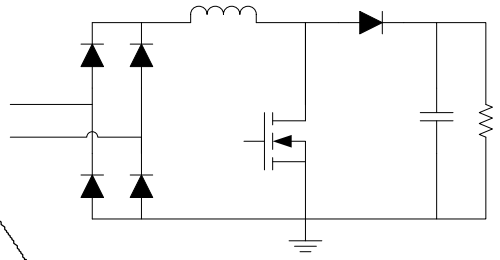
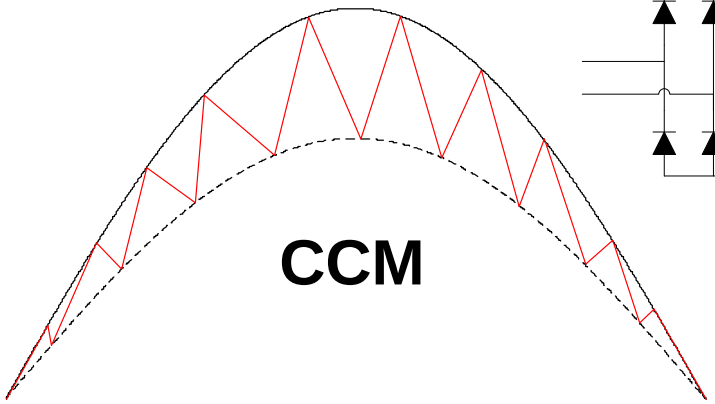
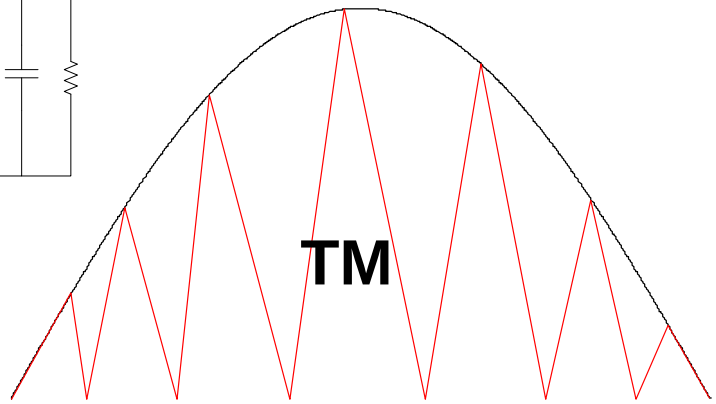
CCM - vs. TM - PFC



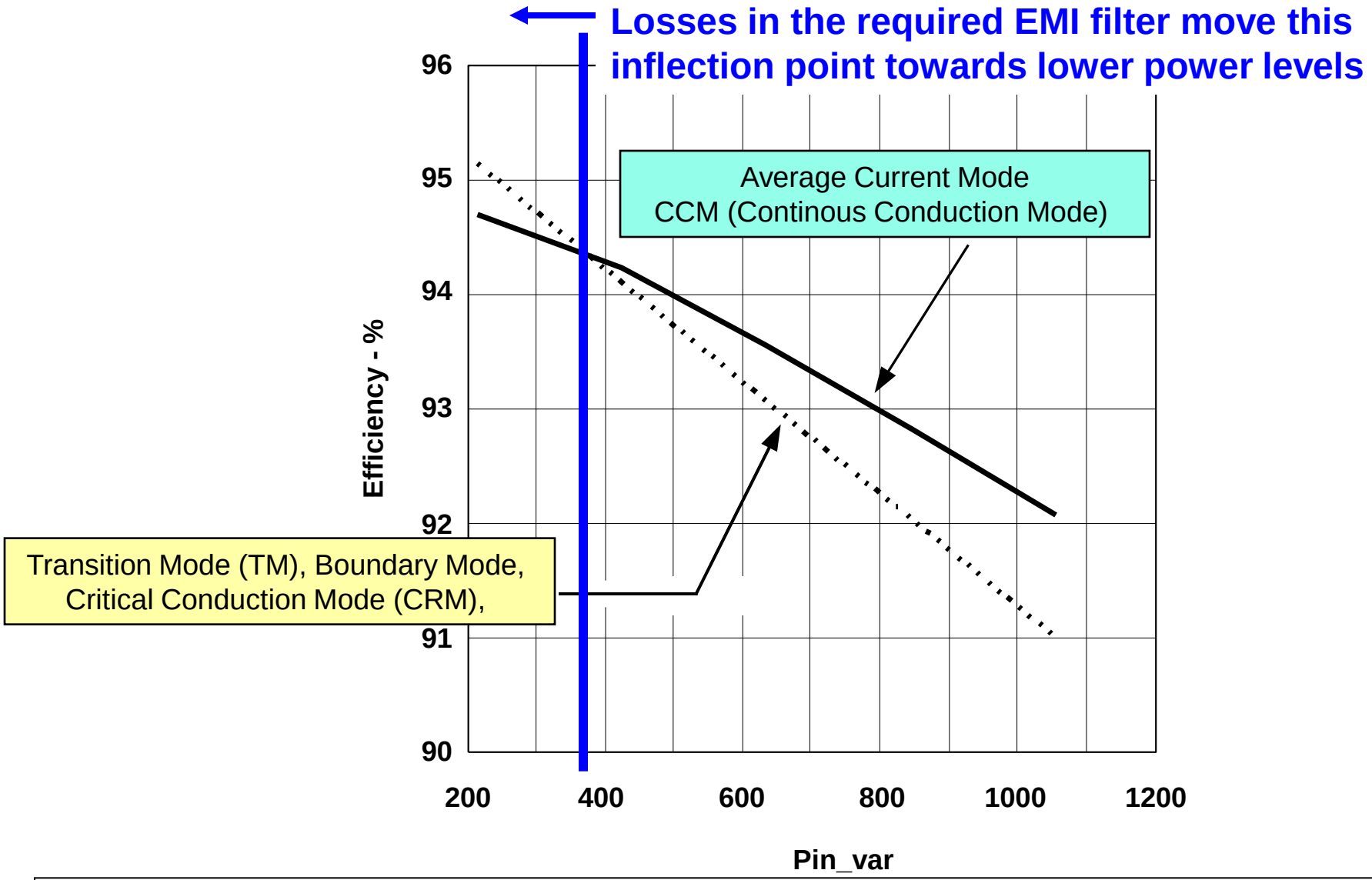




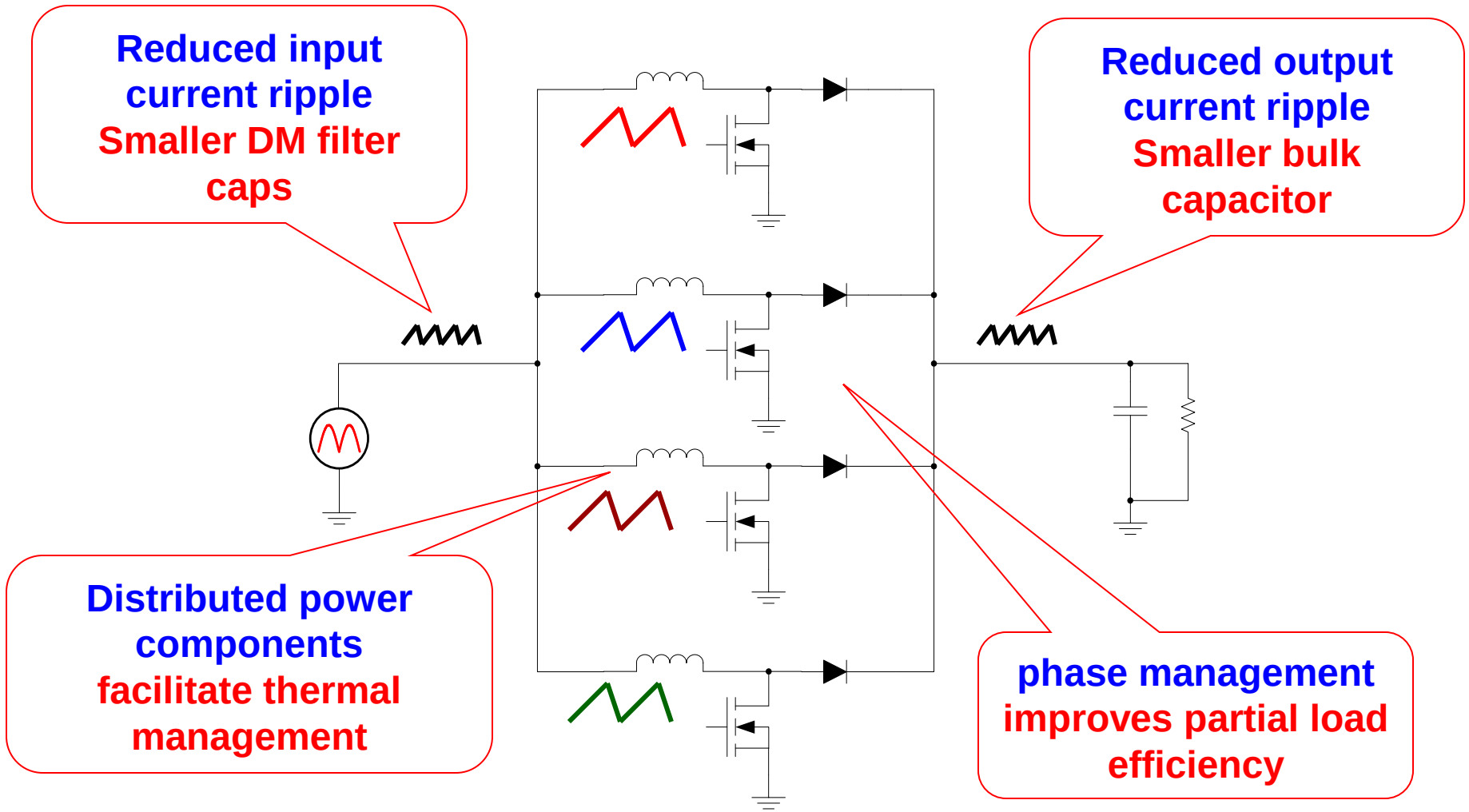
- **Smaller ripple current**
- **Smaller EMI filter**
- Constant switching frequency
- **Better for higher power**
- Switching loss may be higher due to diode reverse recovery current
- High components cost to maintain high efficiency

- **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**

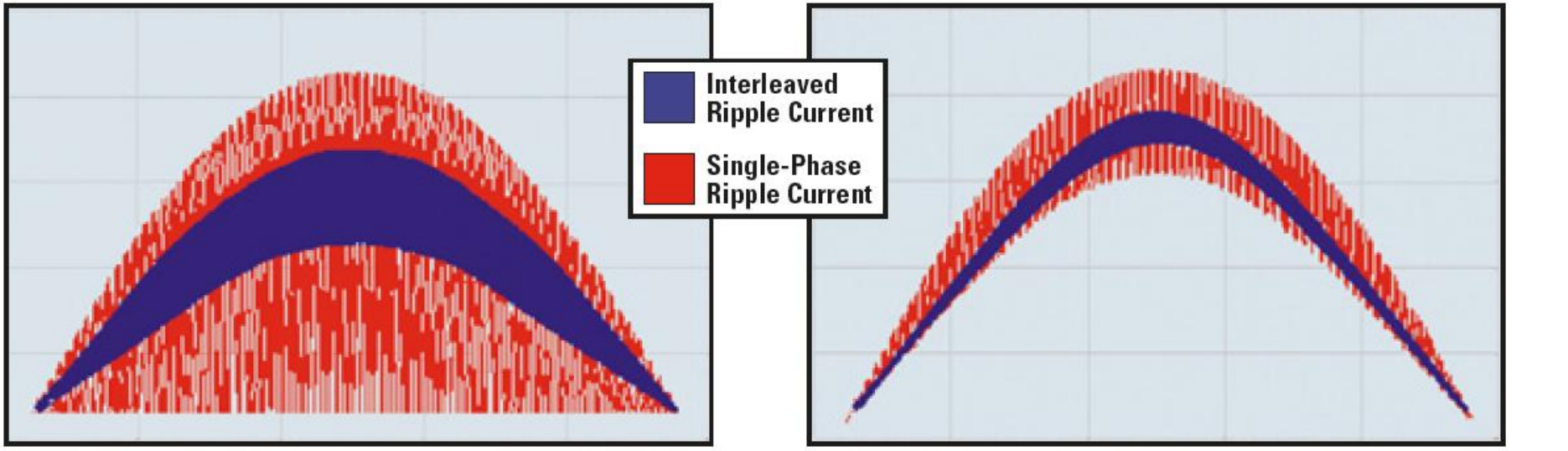
Inflection Point TM vs. CCM w/o input EMI filter (single phase)



Interleaved PFC



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

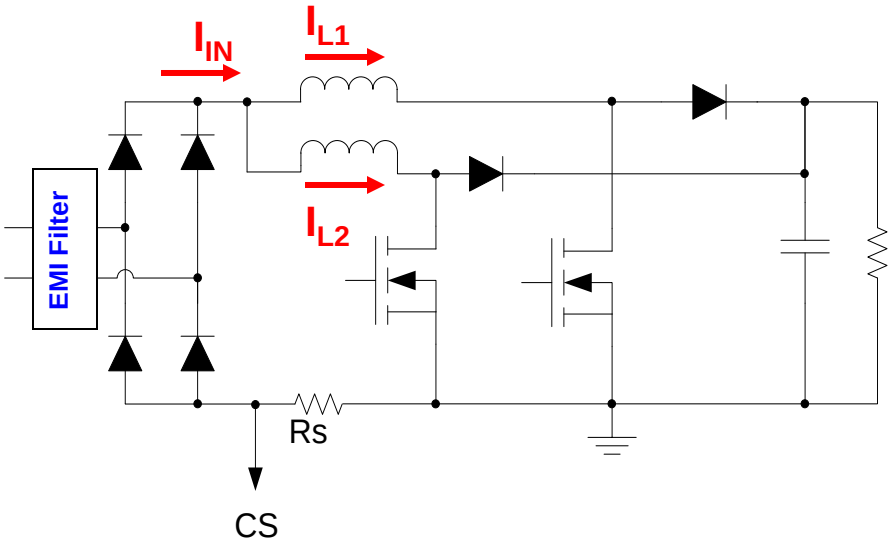
- EMI-Filtering can be drastically reduced due to drastically reduced ripple current
- Ripple of Interleaved TM is similar to Single Phase CCM

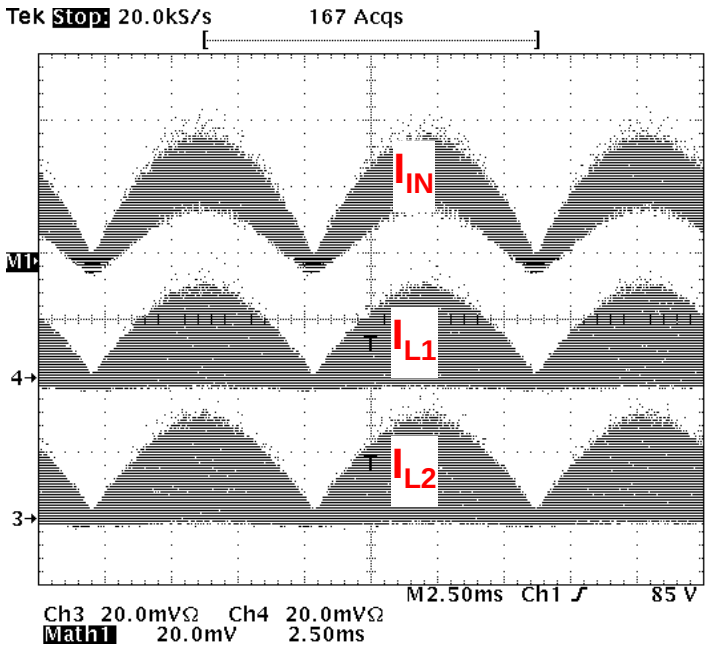
TI solves the interleaving problems for TM boost PFC

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

UCC28061 **UCC28060**

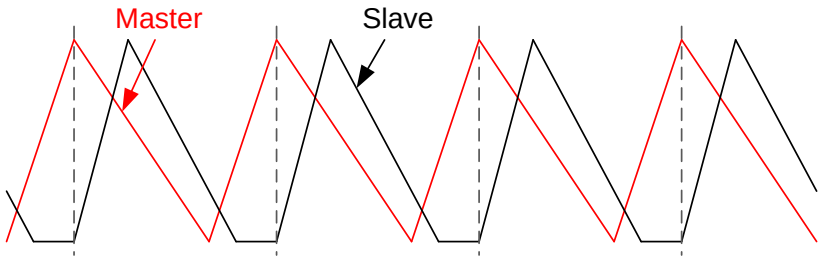
- w/ improved audible noise performance
- w/ auto soft re-start after OV-Faults
- w/o Burstmode @ light load





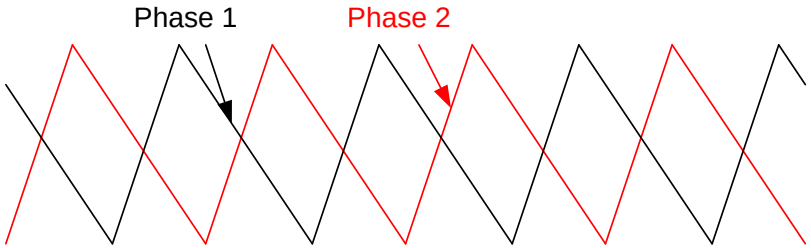
UCC 28060 / 61 uses Natural Interleaving

Master- Slave Method



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

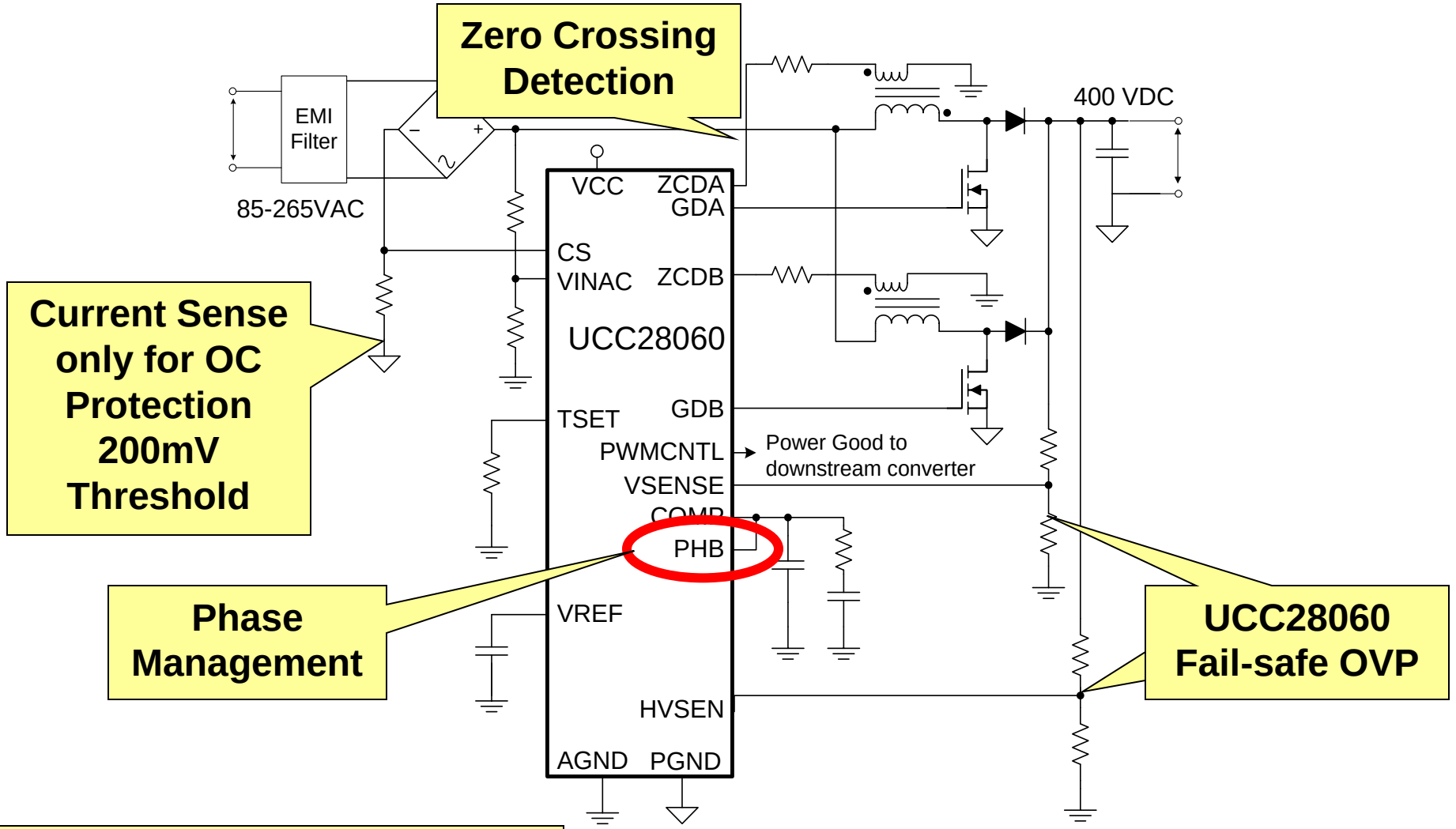
Natural Interleaving



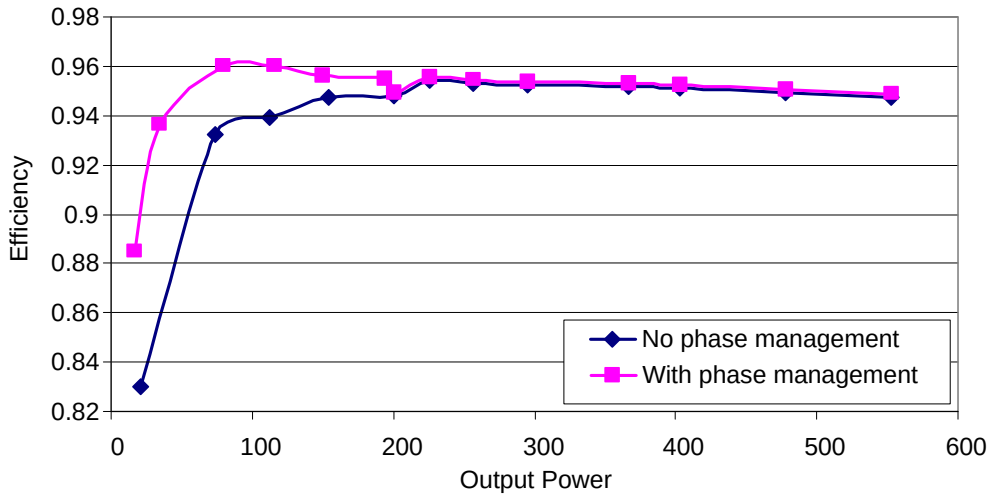
- Both channels operate in TM
- Phase shift of the phases is 180
- No Master / no Slave

Better current sharing and lower ripple current

UCC28060 / 28061 Typical circuit



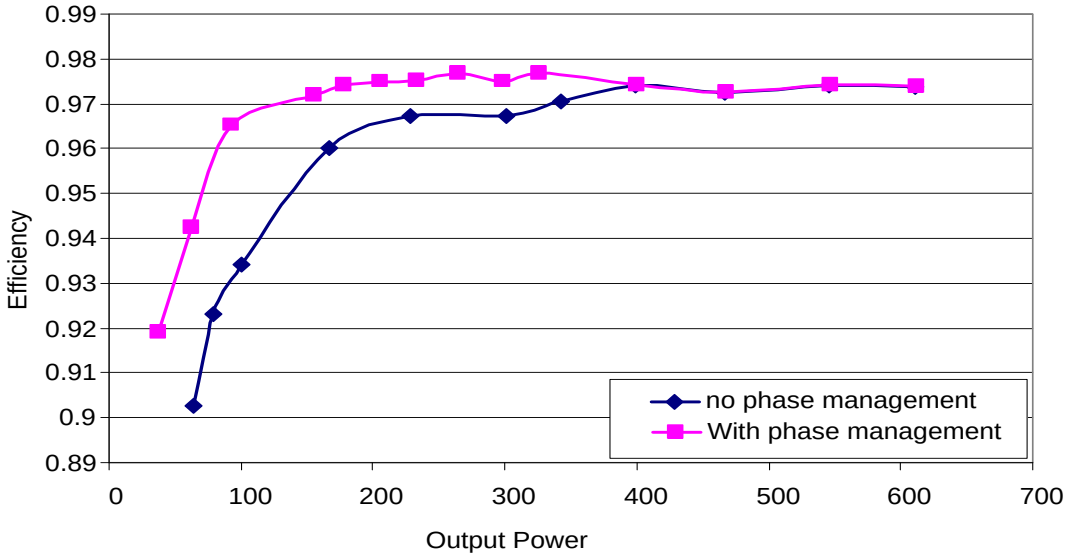
UCC28060 - Phase management improves light load efficiency



115V input

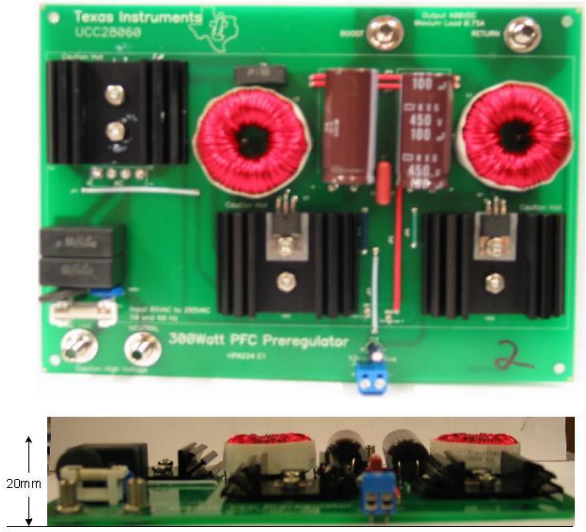
- **Single-phase operation at light load conditions improves system efficiency**
- **Phase management improves system efficiency at different line and load conditions**

230V input



UCC28060 / 61 - Design support

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



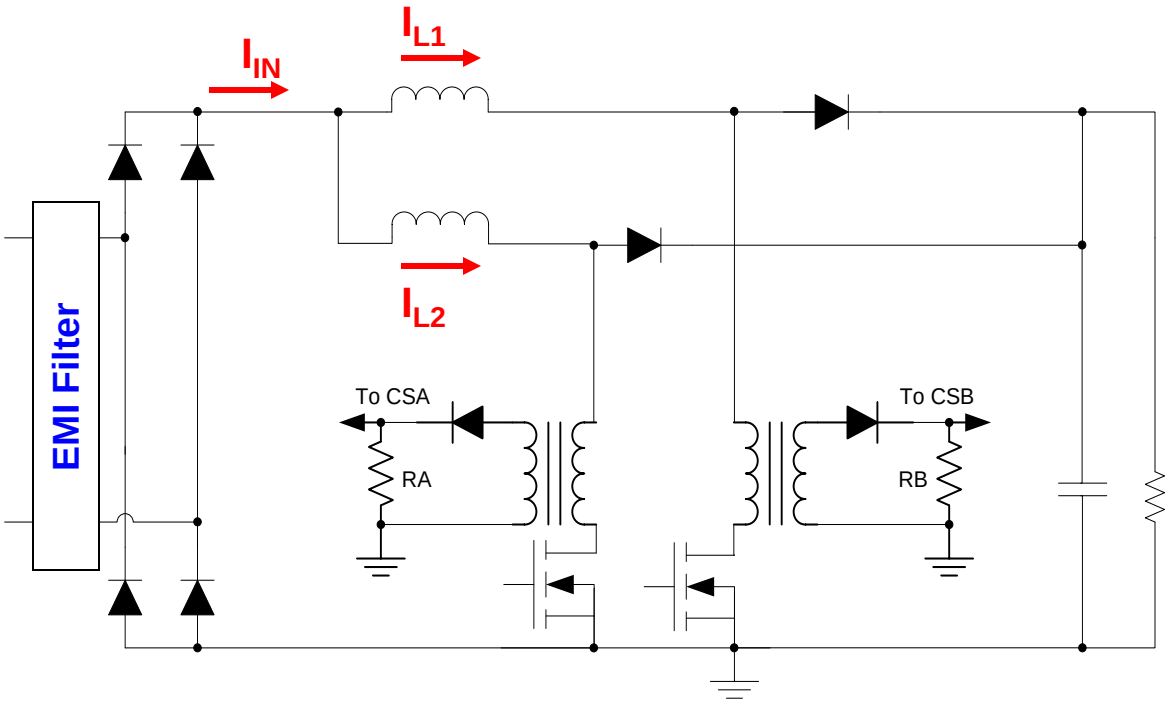
- Excel Design Tool (sluc072b)

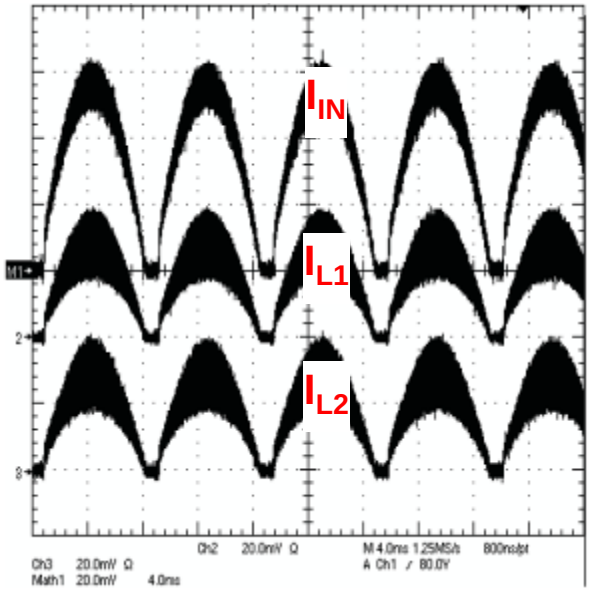
UCC28060 Controller Setup Tool		
Note this tool was designed to work with the UCC28060 data sheet design example		
Please enter design parameters into the	shaded	cells;
Calculated results will be in RED		
Design Parameters:	**Variable Names**	
Minimum RMS Input Voltage	V_{IN_MIN}	85
Maximum RMS Input 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)

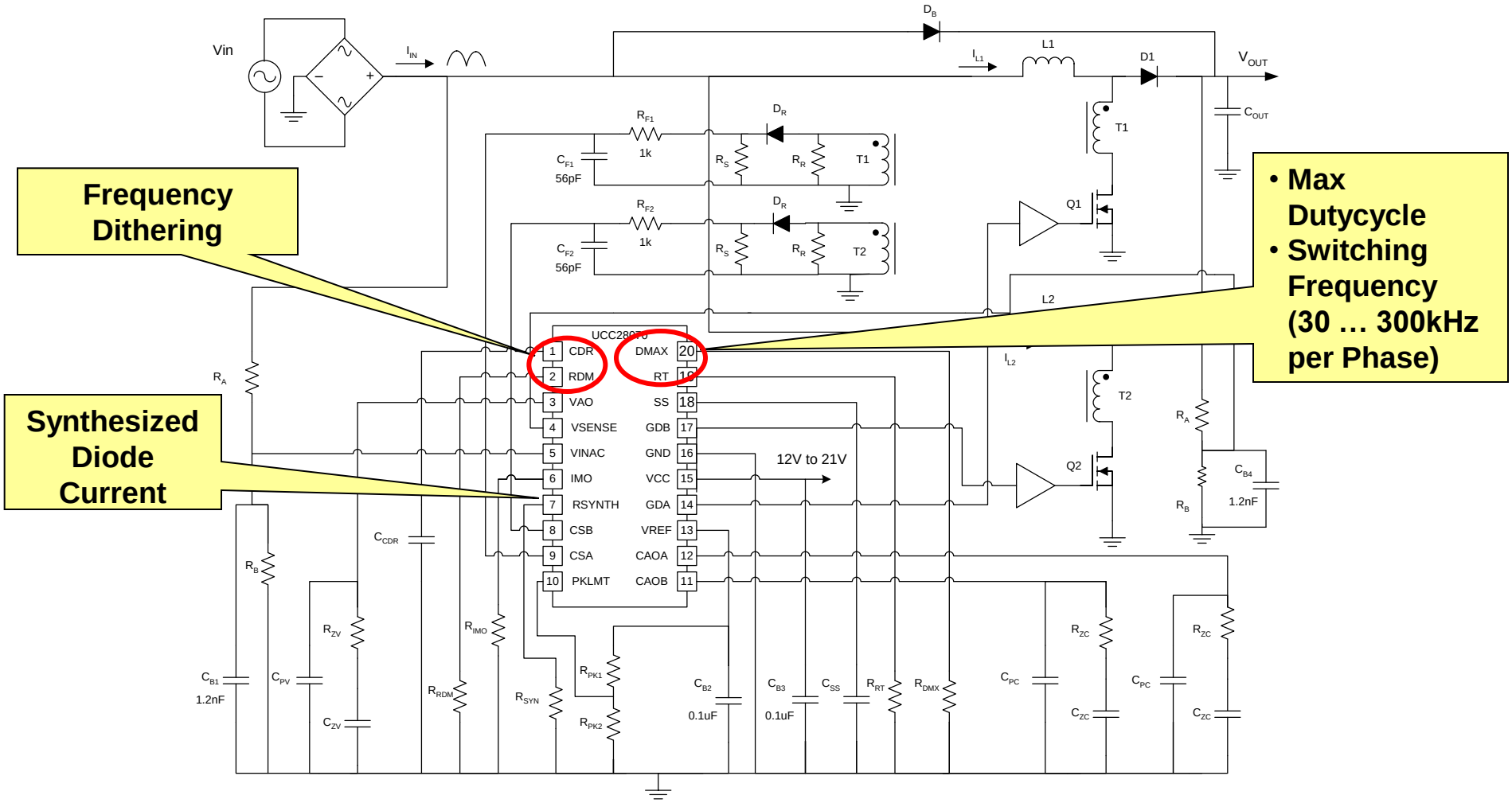
PFC - TI solves the interleaving problems for CCM Boost PFC

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



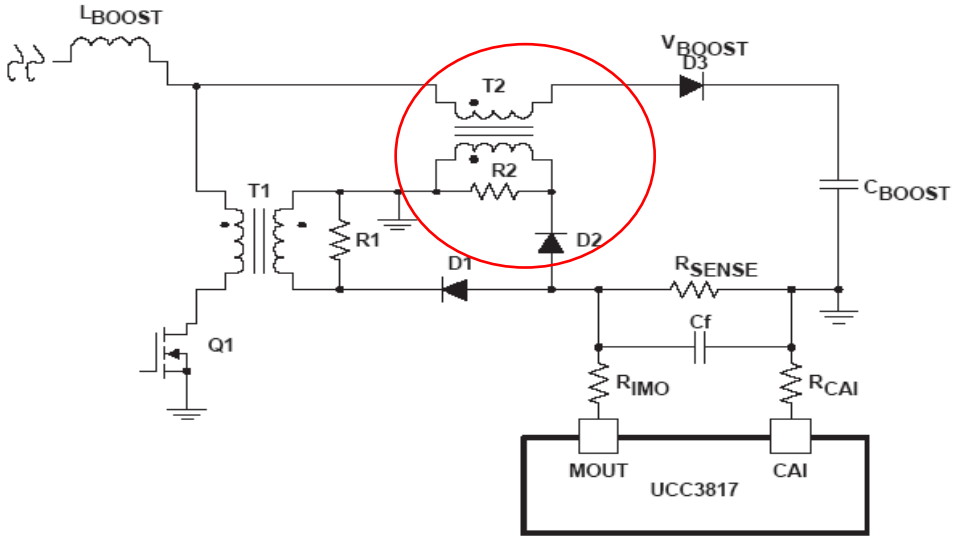


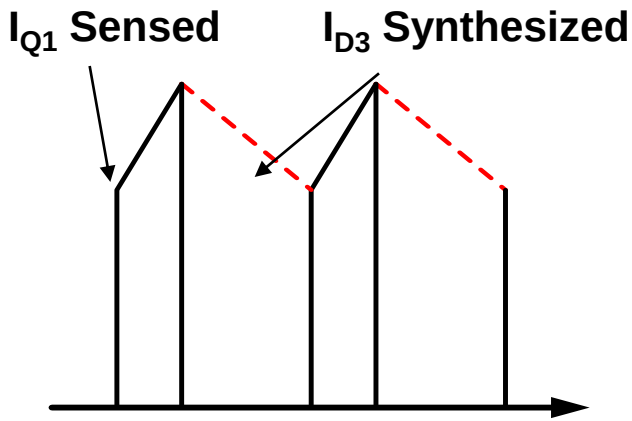
UCC28070 - Average CM interleaved PFC



UCC28070 - Current syntheses reduces component count

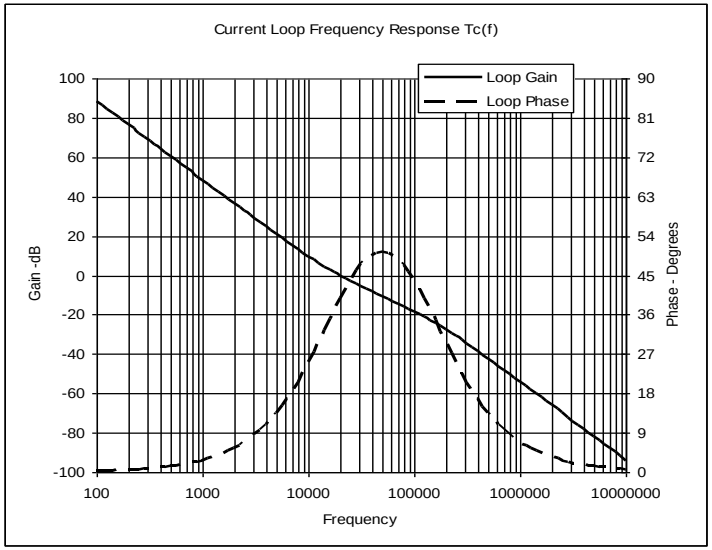
- **Traditional Current Sensing in PFC Boost**
  - ✓Requires a CT network in series with Q1
  - ✓Requires a CT network in series with D3
- **UCC28070 Synthesizes Diode Current**
  - ✓Setup with Single Resistor to Gnd (R_{SYN})
  - ✓**Removes CT network in series with D3**
  - ✓**6 components are eliminated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

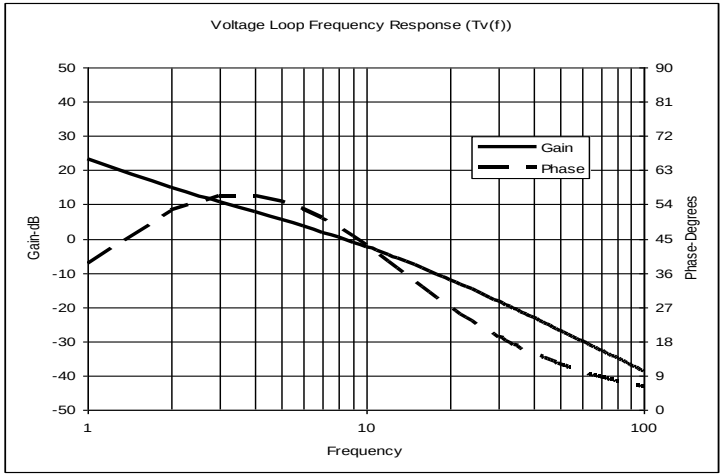




UCC28070 - Support & design tools

- 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





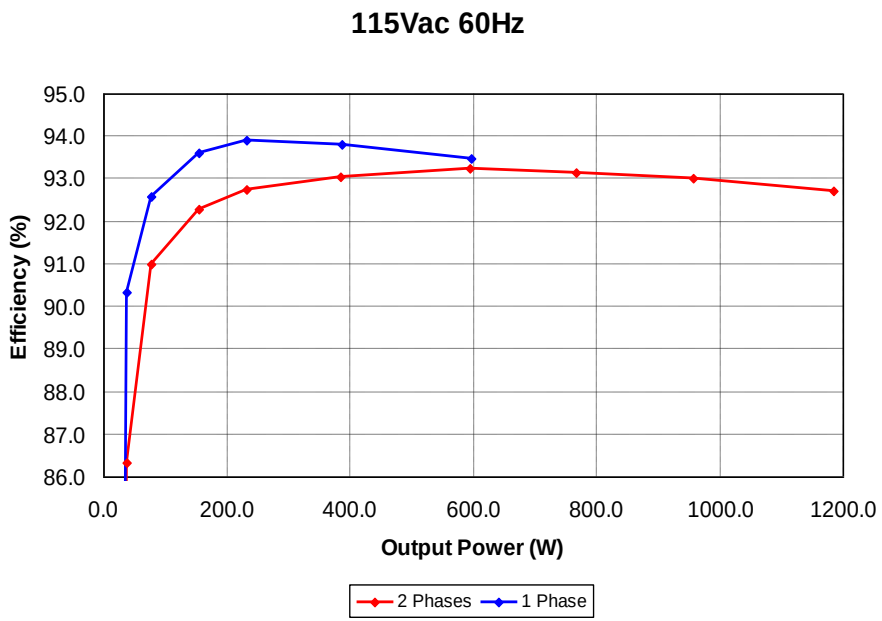
UCC28070 – 1.2kW Reference Design w/ implemented Phase Management

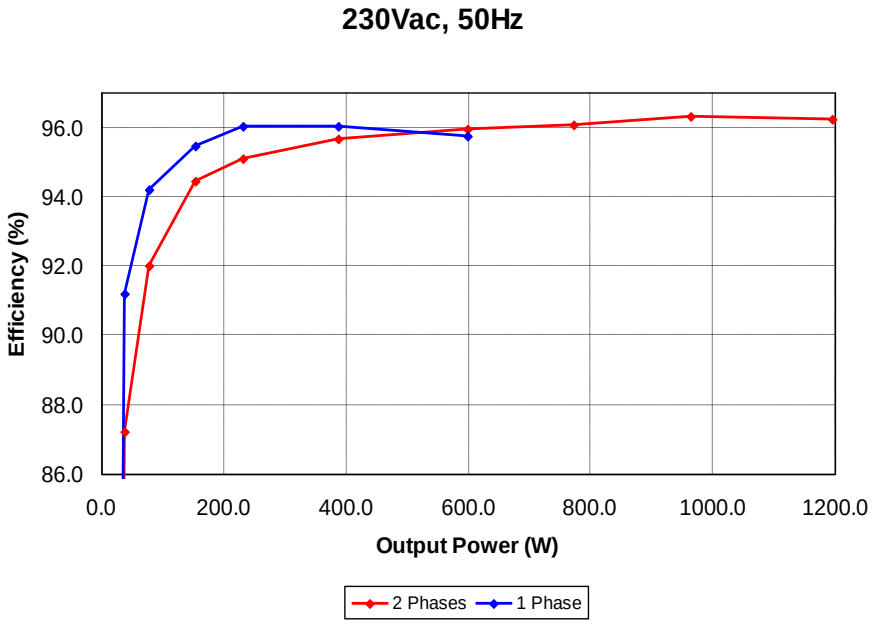
Enormous reduction in size of boost inductors by use of 2-phase interleaved approach

PR779 / 780

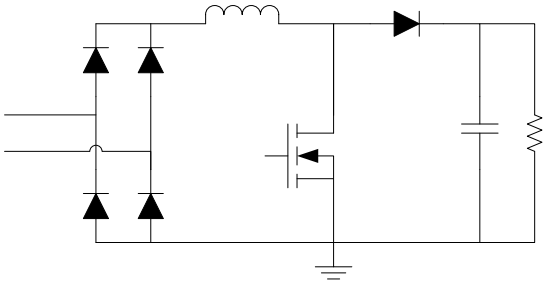
Phase Management w/ Interleaved PFCs (UCC28070 – 1.2KW Example Shown)

Phase Management Ensures
Highest Efficiency under all Load Conditions

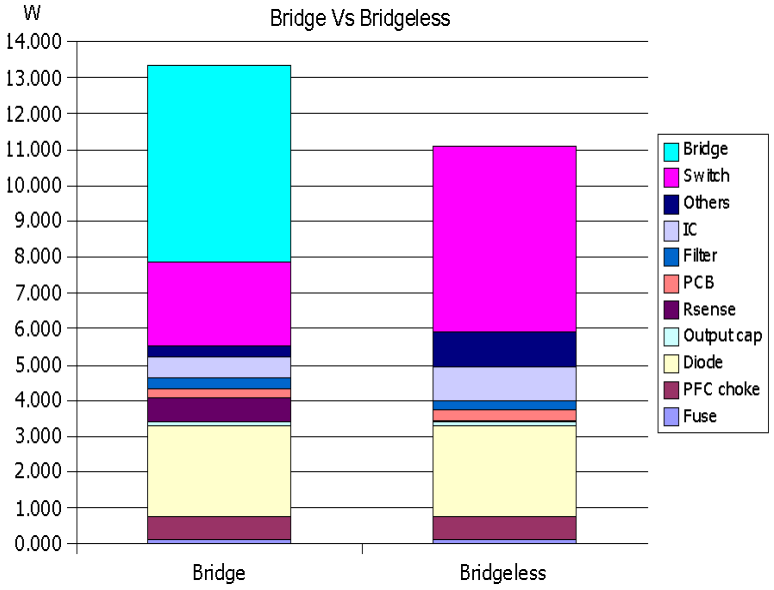




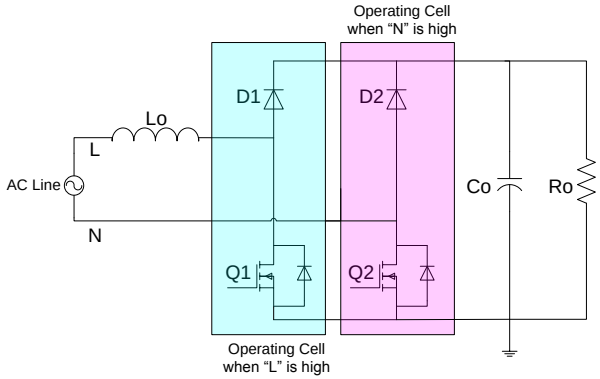
Increase PFC efficiency further?
Implementation of bridgeless PFC



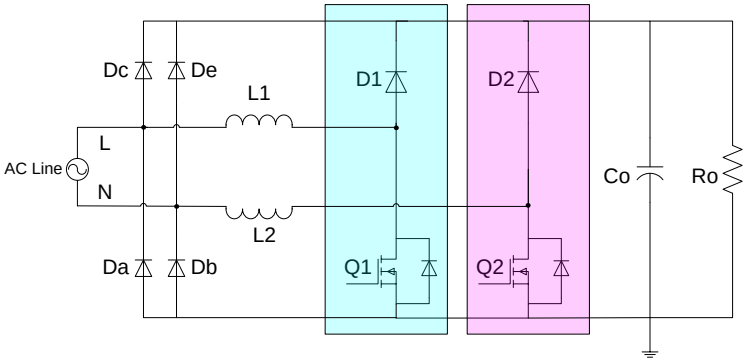
Classical PFC with bridge rectifier



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



Classical bridgeless PFC implemetation

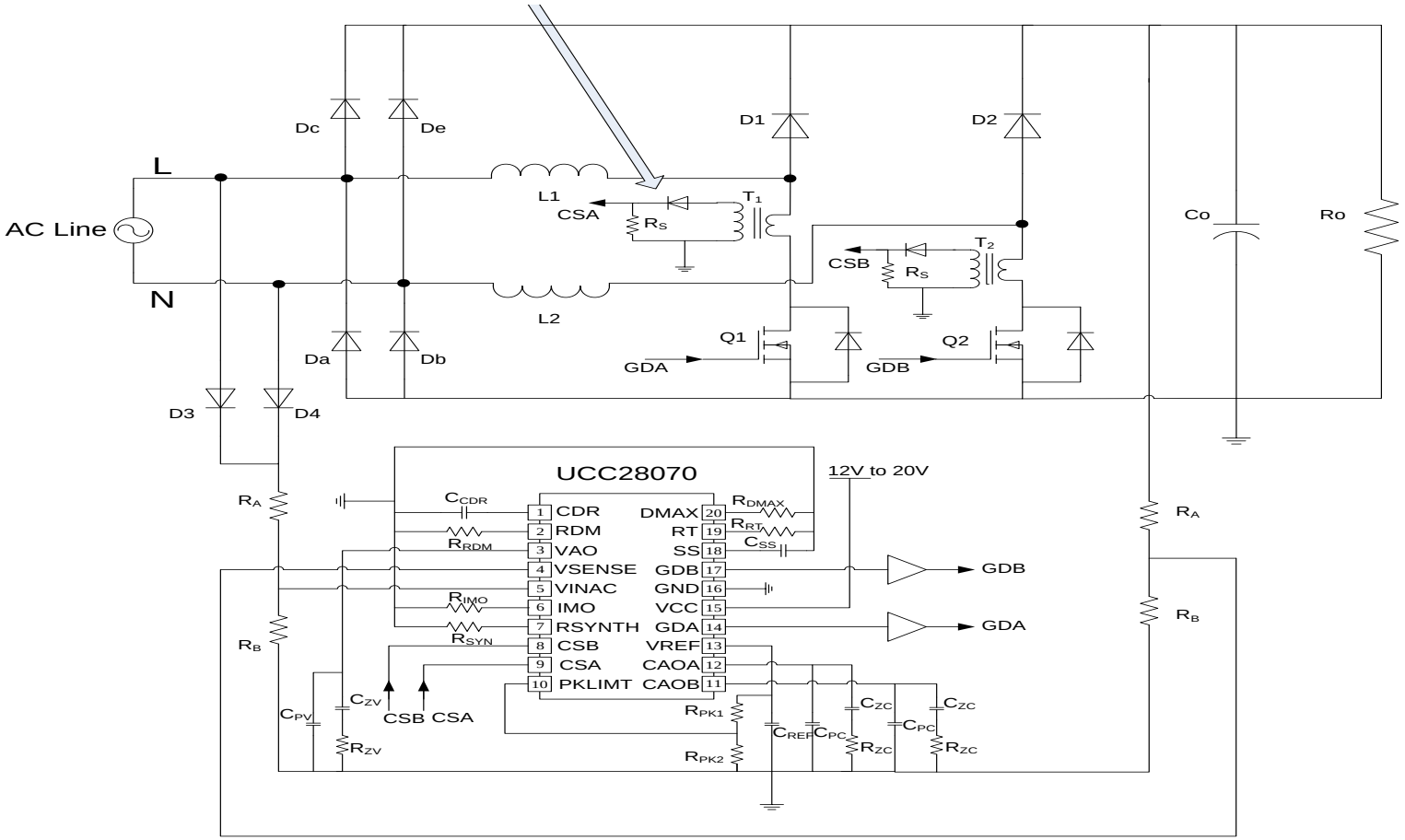


Semi-bridgeless PFC implementation

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

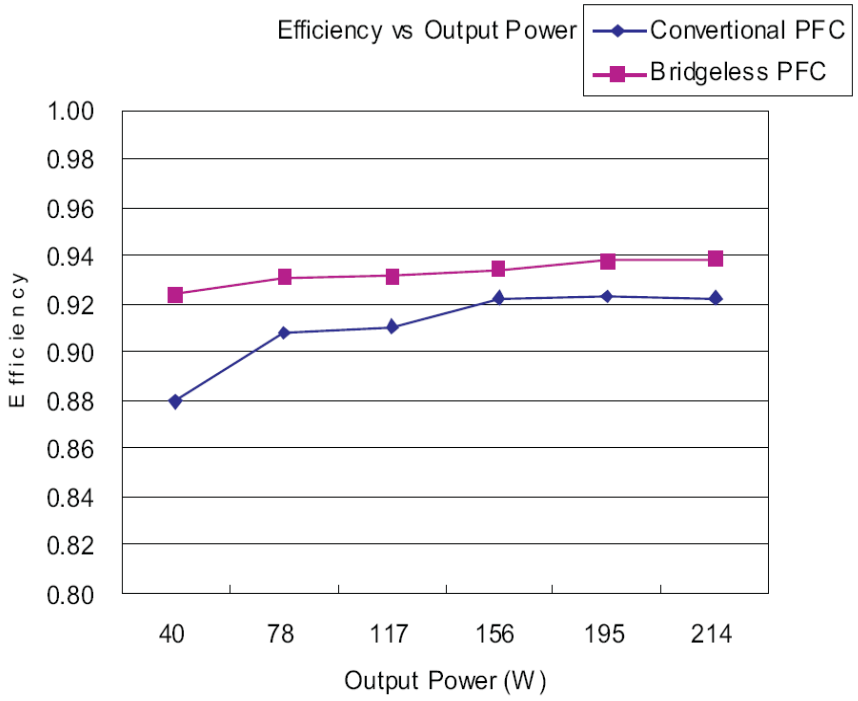


Figure 9. Efficiency at V_{IN}=110 V_{AC}

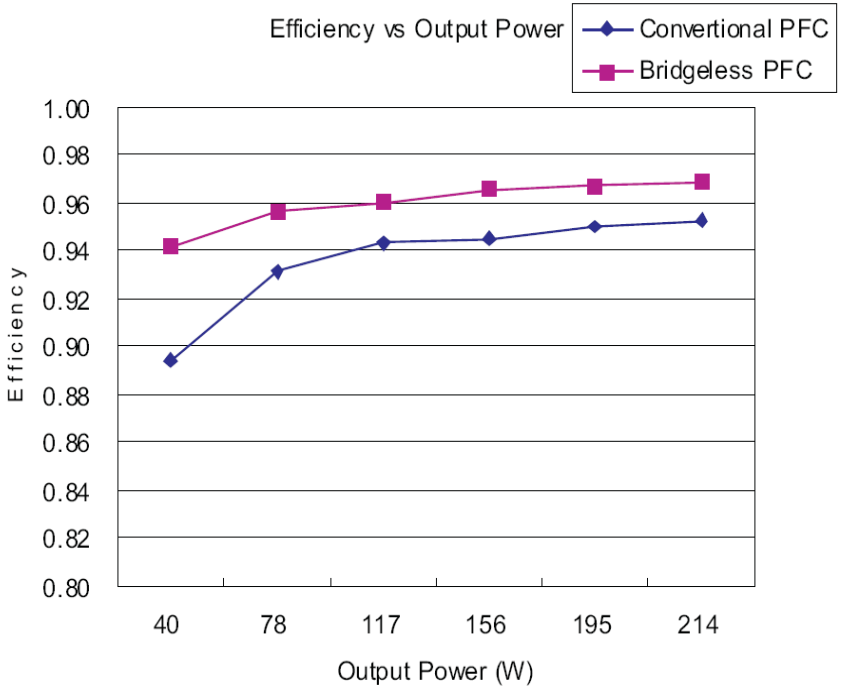


Figure 10. Efficiency at V_{IN} = 220 V_{AC}

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)**
- Advanced green mode phase shifted full bridge (UCC28950)
- Summary

LLC Resonant half bridge – the details

Inductor Ratio

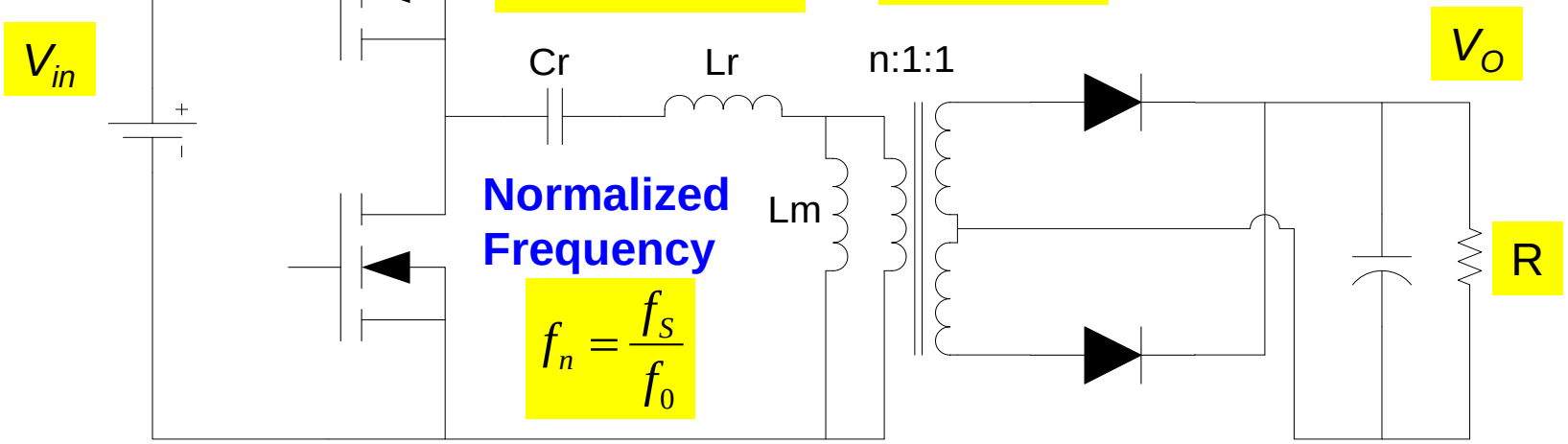
$$L_n = \frac{L_m}{L_r}$$

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

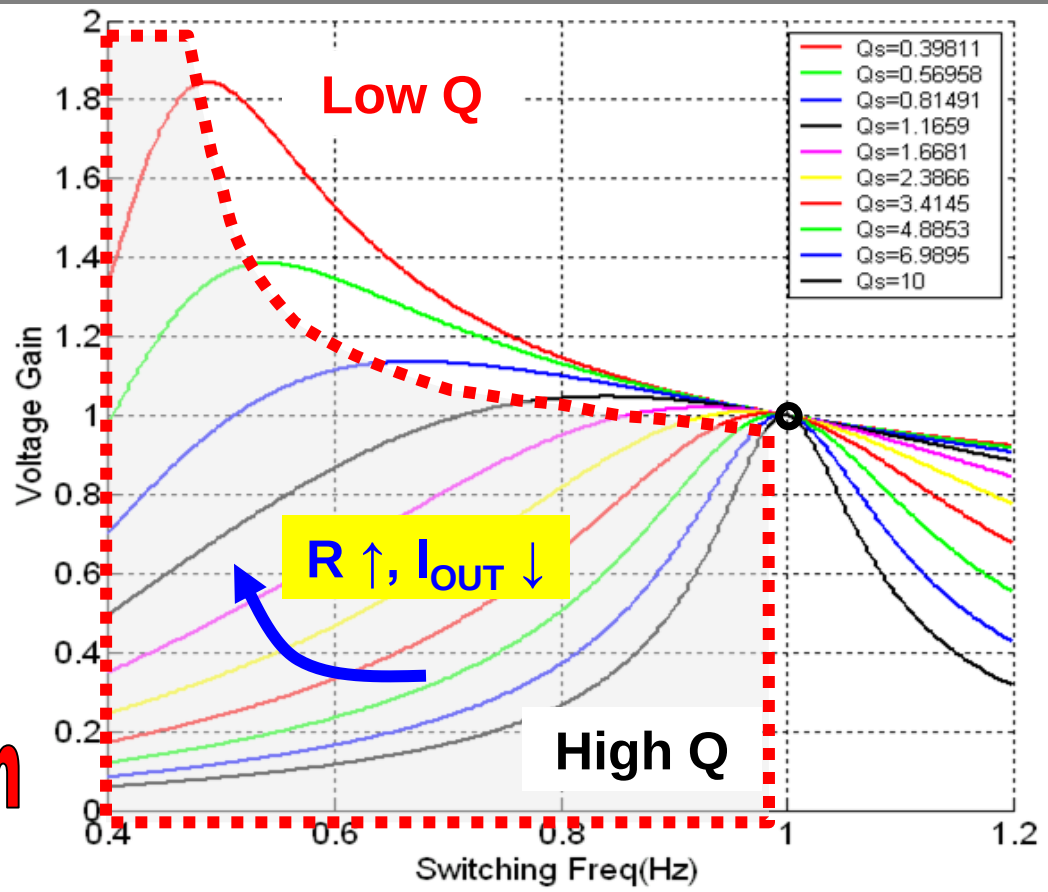
$$Q = \frac{\sqrt{Lr/Cr}}{n^2 R}$$

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

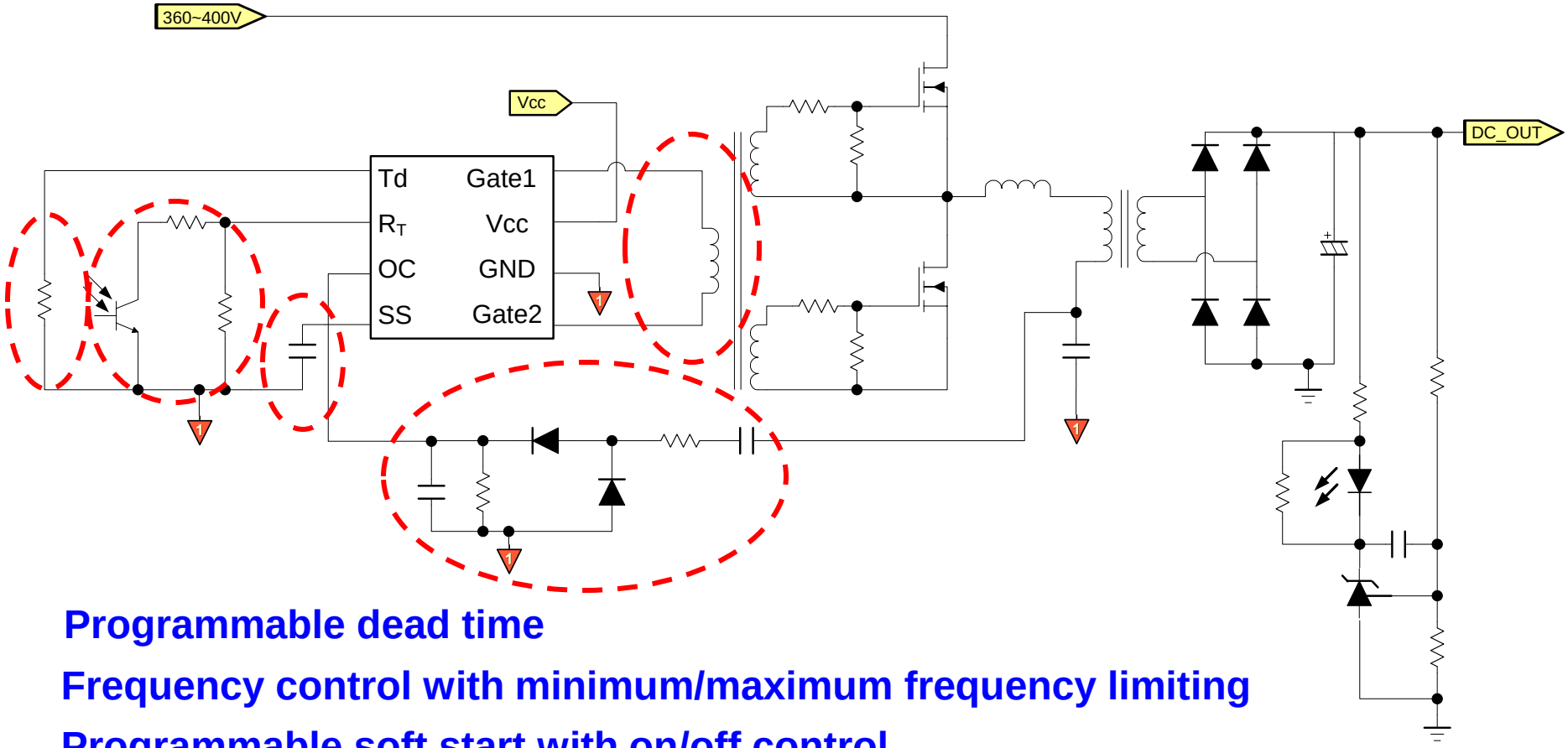


ZVS region

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

ZCS region

UCC25600 Application Circuit



Programmable dead time

Frequency control with minimum/maximum frequency limiting

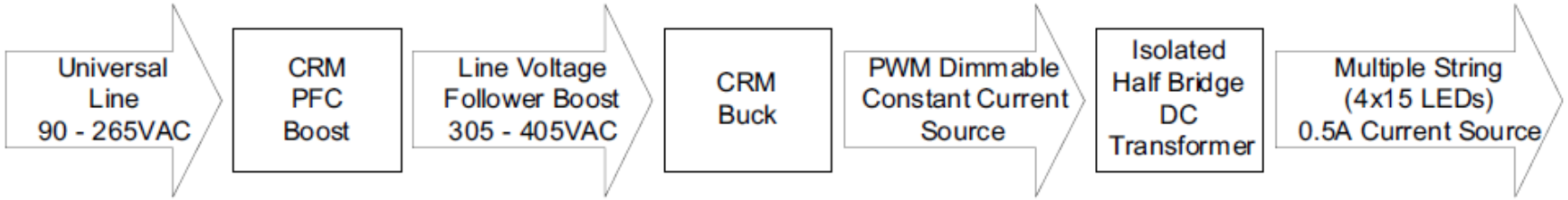
Programmable soft start with on/off control

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

Matching output with 50ns tolerance

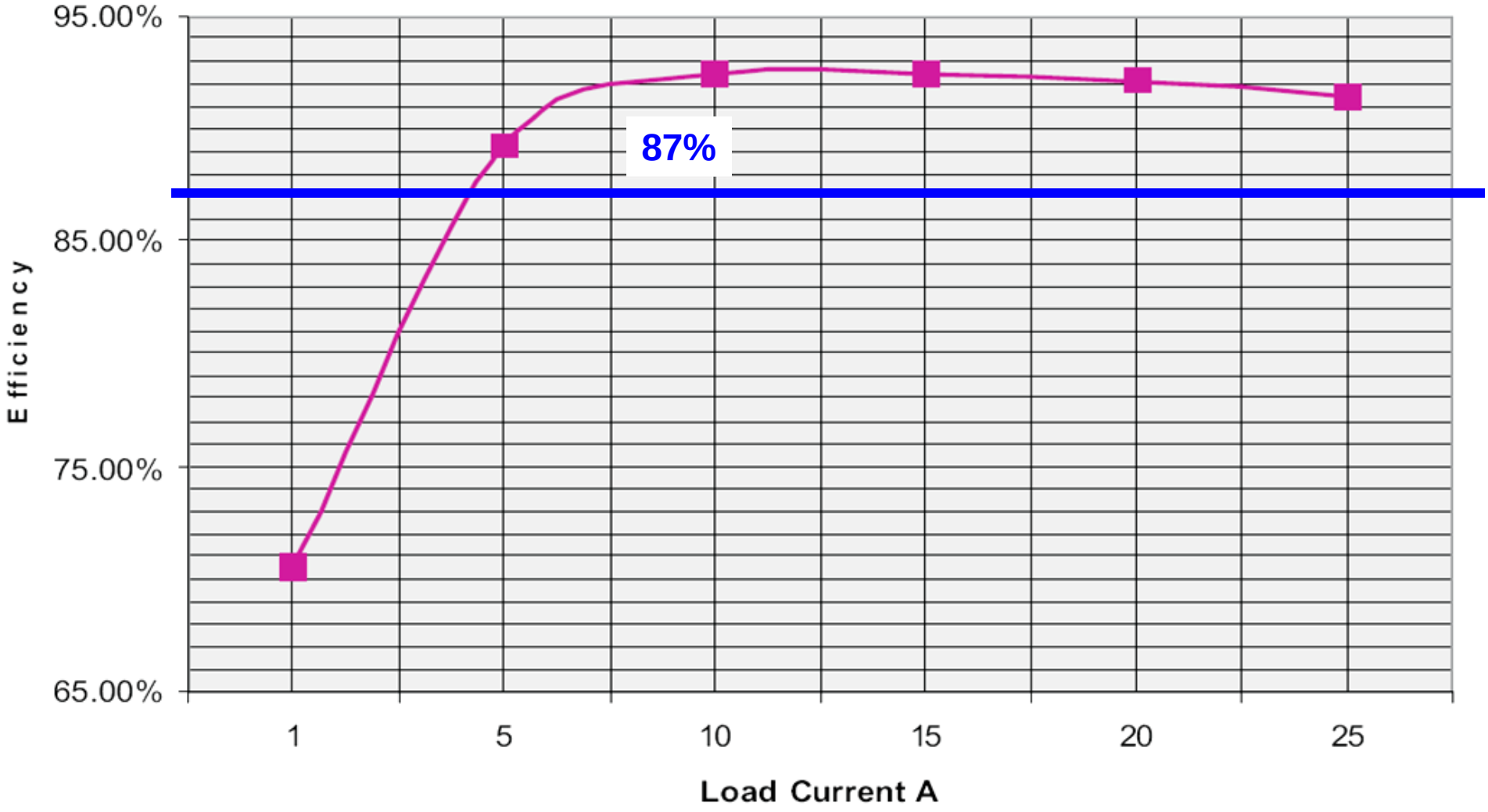
UCC25600 - Support & design tools

- **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)

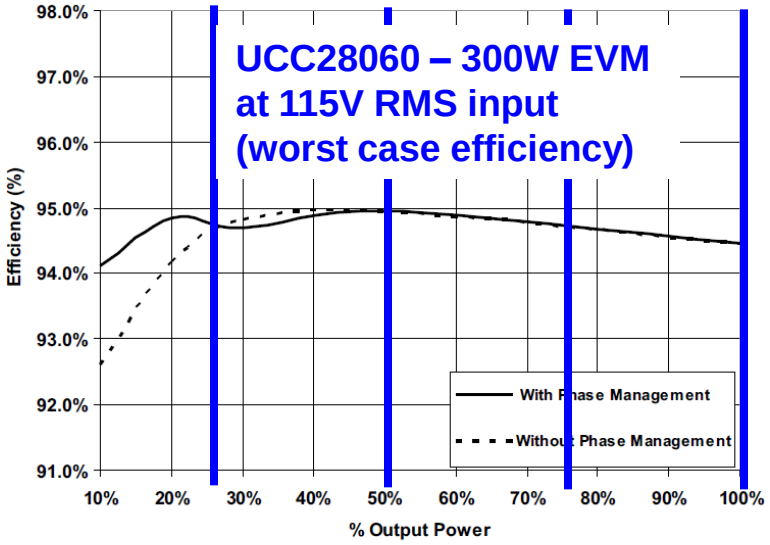


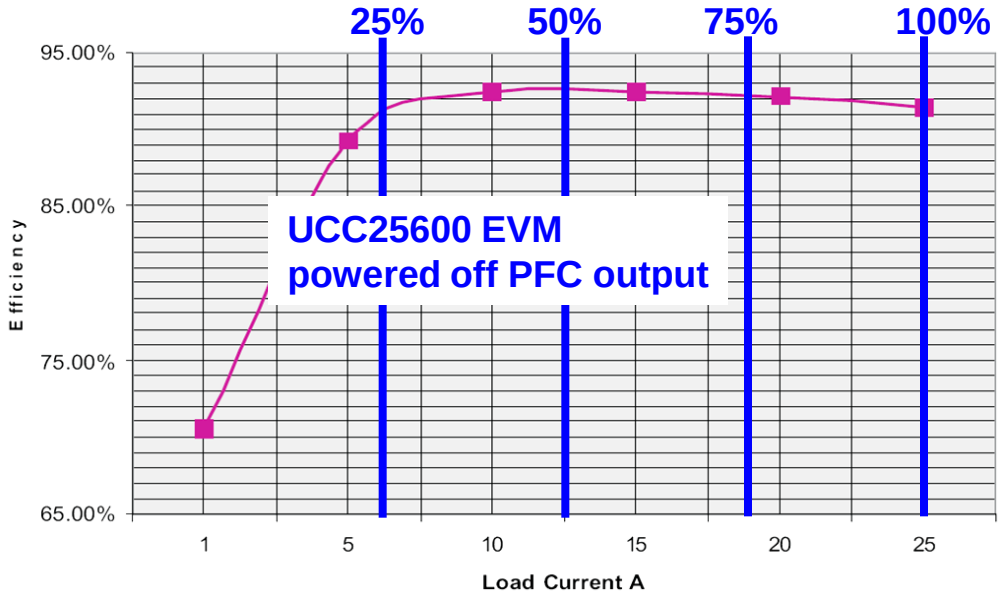
- **Seminar Topics**
  - Seminar 700 Topic 6: Resonant Mode Converter Topologies -Additional Topics (slup092)
  - Seminar 600 Topic 1: Resonant Mode Converter Topologies (slup085)

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



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





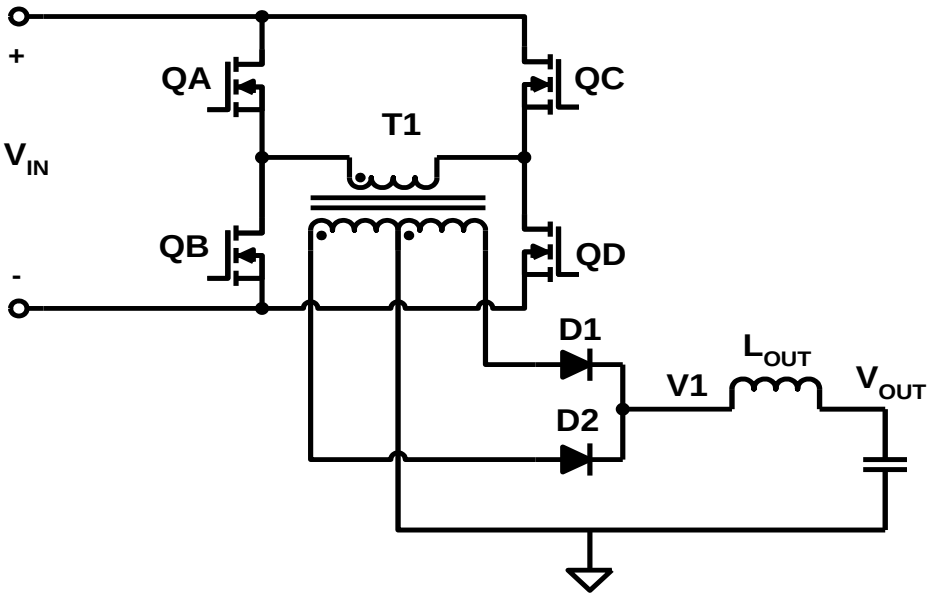
% of rated POUT	η of PFC (%)	η of LLC HB (%)	Total Efficiency (%)
25	94.7	91.0	86.2
50	94.9	92.7	88.0
75	94.7	92.2	87.3
100	94.4	91.5	86.4
Average			**87.0**

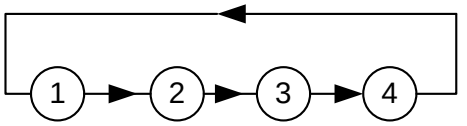
UCC25600 + UCC28060 fulfill 87% efficiency requirements for EPS as requested by EuP directive

Agenda

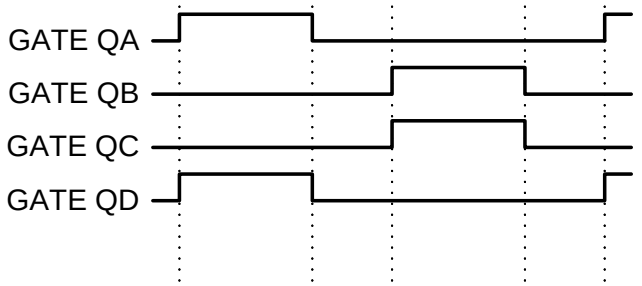
- General thoughts, standards and solutions
- Quasi-resonant green mode flyback (UCC28600)
- Cascoded green mode flyback (UCC28610)
- Active clamp (UCC289x family)
- Interleaved PFCs (UCC2806x / 28070)
- LLC resonant half bridge (UCC25600)
- **Advanced green mode phase shifted full bridge (UCC28950)**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

Full bridge topology for high power converters

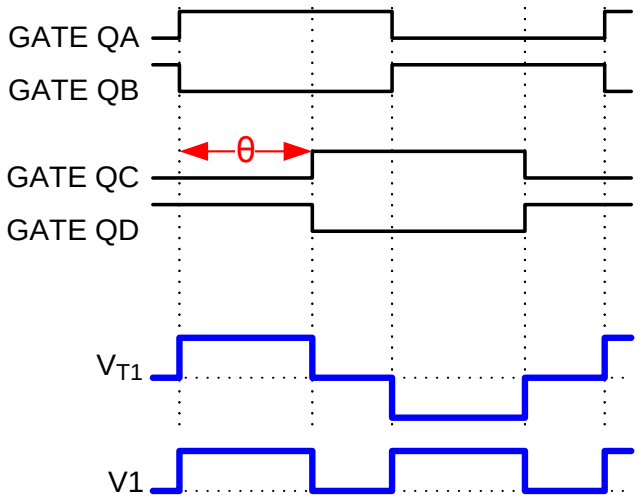




Conventional full bridge

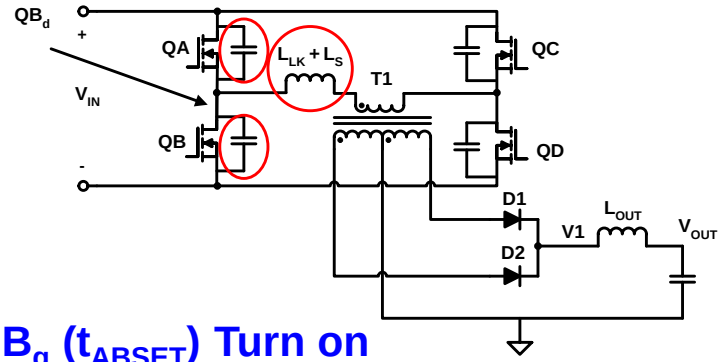


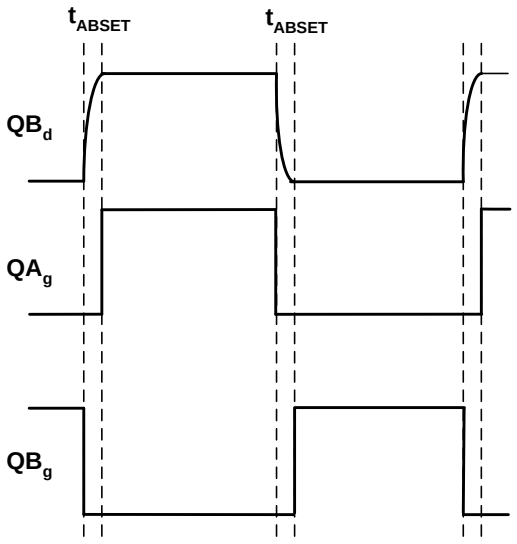
Phase shifted full bridge



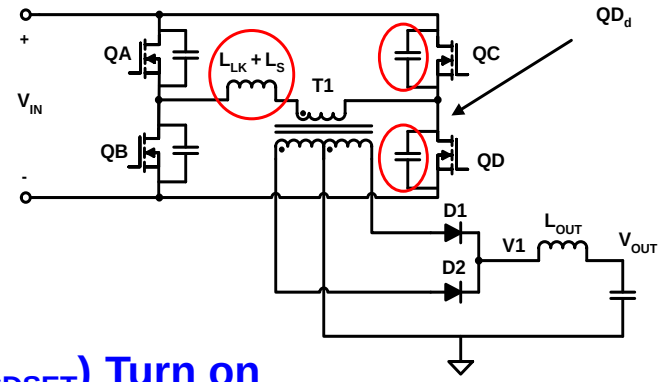
- Control signals for QA … QD make the difference
  - **Conventional full bridge:**
    - duty cycle controlled
  - **Phase shifted full bridge:**
    - controlled by phase shift θ b/w QA (QB) and QC (QD)
    - each leg is operating w/ 50% dutycycle
    - QA (QC) and QB (QD) are 180º out of phase

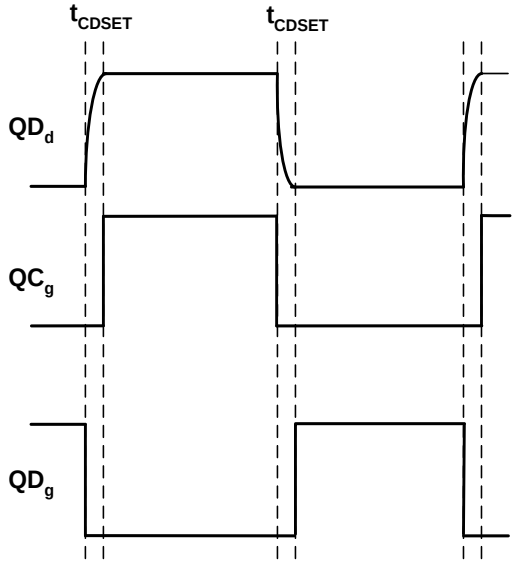
Phase shifted full bridge enables ZVS of switches on primary side





- **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**

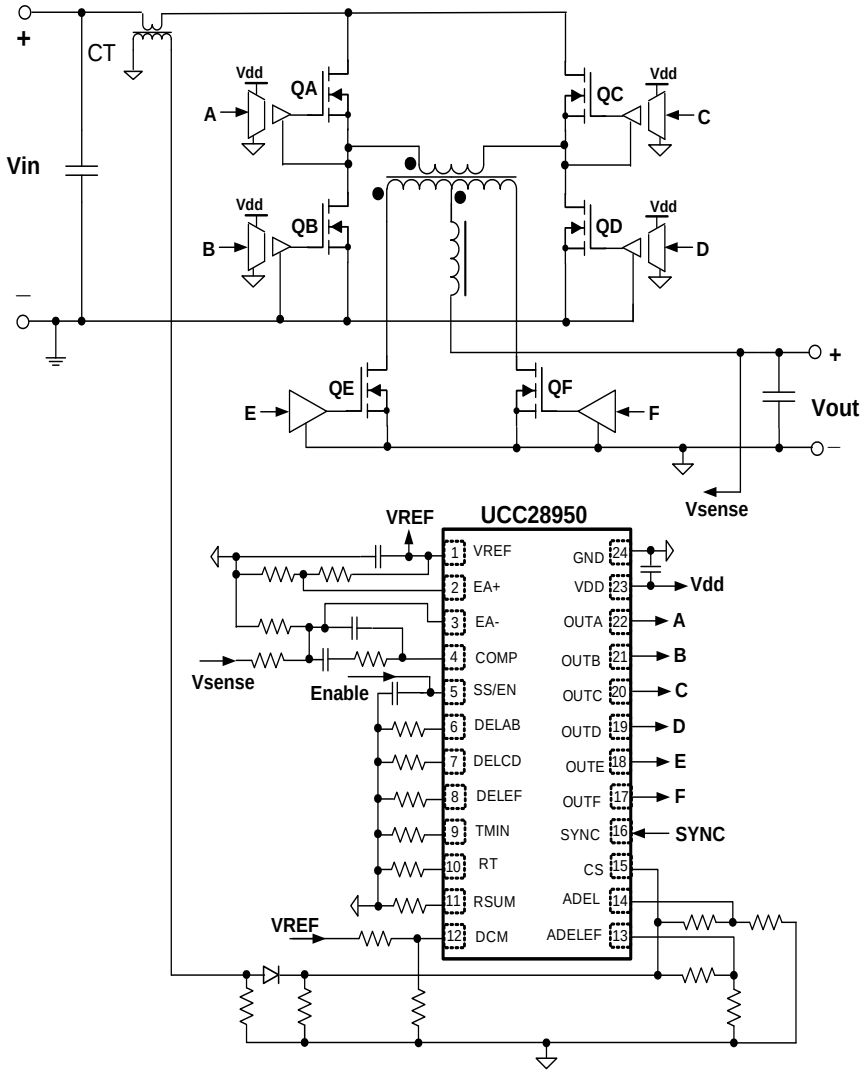




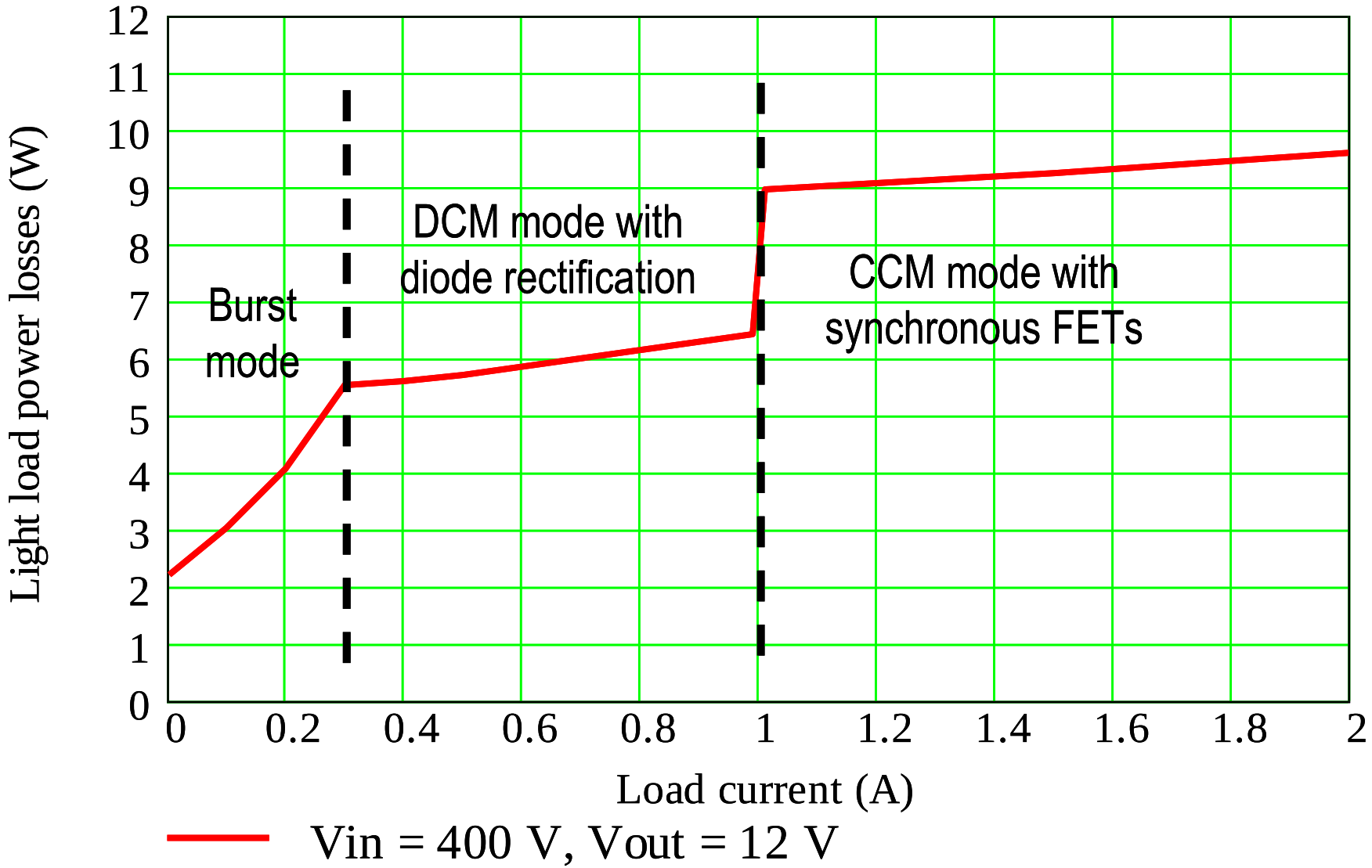
- **Add Delay QC_g and QD_g (t_{CDSET}) Turn on**
- L_{LK}+ L_S Tanking with Capacitance at Switch Node (QD_d)
- **Allows for ZVS at switch node QDd**

UCC28950 – Successor of the industry standard UCC2895

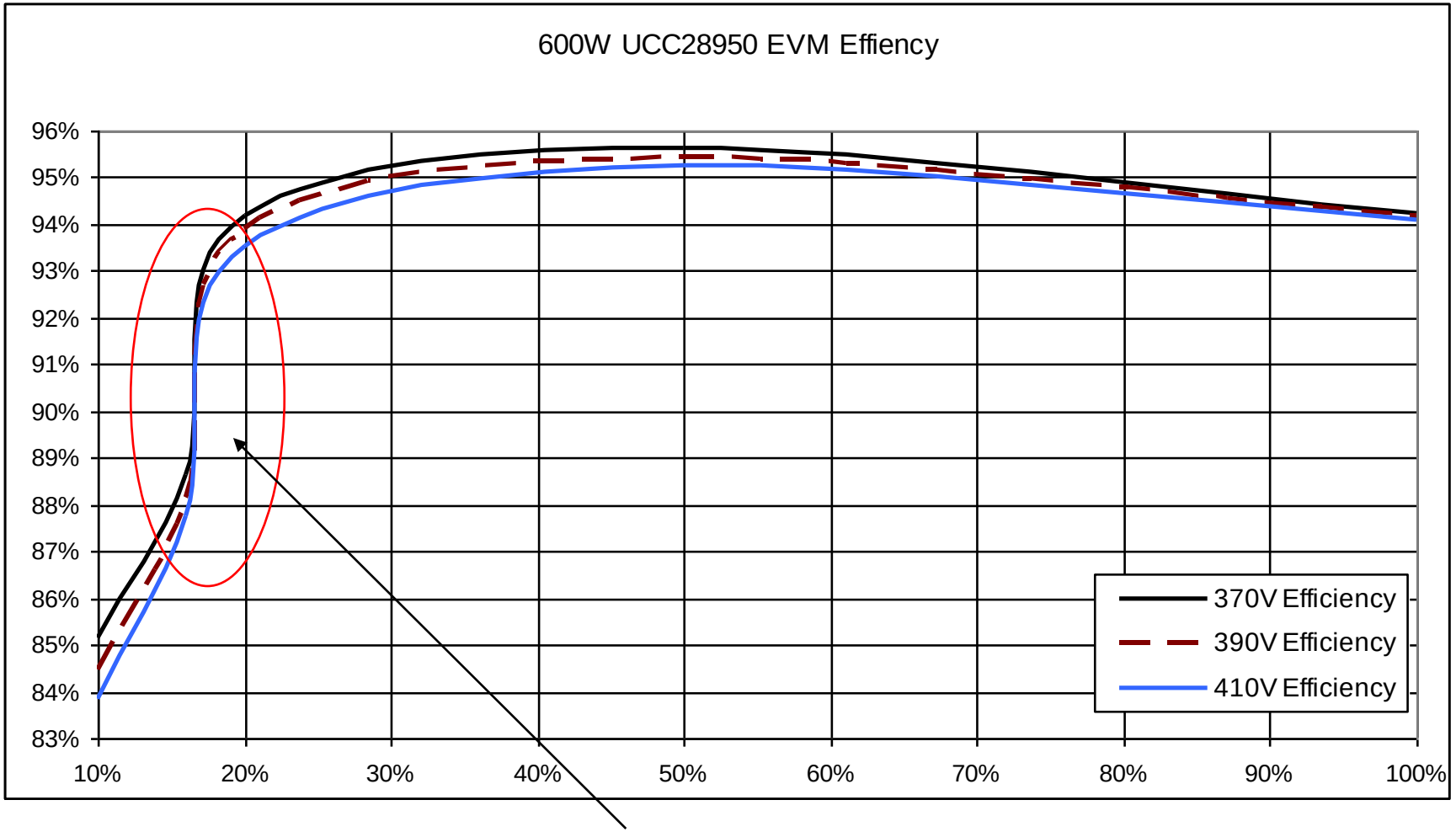
- More Advanced
  - Control outputs for primary FETs **and for synchronous rectifiers (SR)**
  - Selectable VM, avg. or peak CM
    - Programmable slope compensation
  - Phase shifted SYNC_IN/OUT for easy interleaving
  - Optimized SR drive by adaptive delay and SR drive overlap
  - Improved:
    - ZVS 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

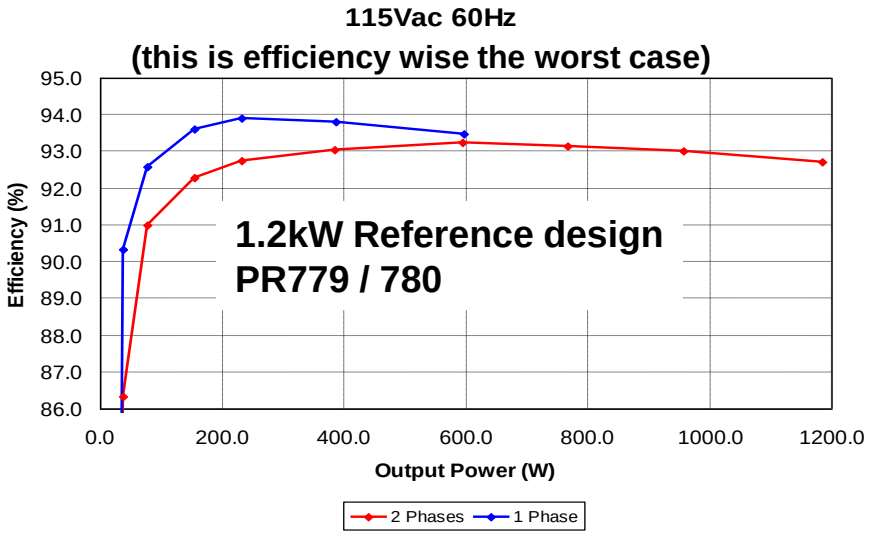


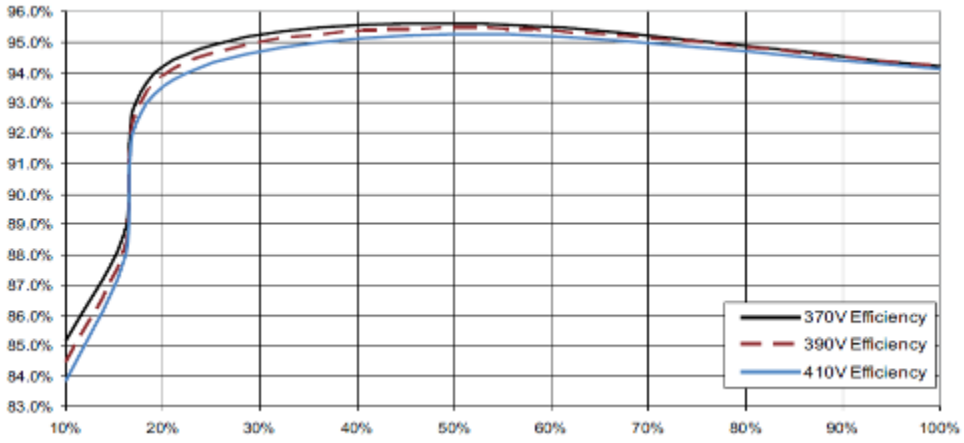
UCC28950EVM - 370 … 410VDC IN / 12V / 600W OUT



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
  - Should be available end of May
- 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)

Summary

- 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)
- Advanced green mode phase shifted full bridge (UCC28950)

The shown solutions will help you to fulfill the stringent efficiency requirements of the different standards.
TI will continue to provide green solutions for future requirements too.