Understanding PFC and LLC Topologies

October 2023

Webinar will begin at 5:00 PM CEST | 8:00 AM PDT | 11:00 AM EDT

rev 20180504

Agenda

- Understanding Power Factor Correction
- MPS Solutions for PFCs
- Understanding Resonant Power Conversion
- MPS Solutions for LLCs
- Q&A

What Is PFC?

- PFC stands for **P**ower **F**actor **C**orrection
- **P**ower **F**actor (PF) is the ratio of active (real) power over apparent power:

$$\mathrm{PF} = \frac{\text{active power}}{\text{apparent power}} = \frac{[\mathrm{W}]}{[\mathrm{V} \cdot \mathrm{A}]}$$

- Popular analogy

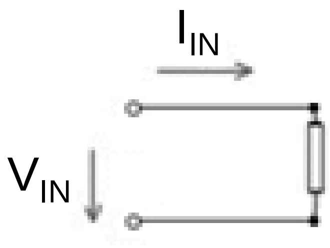
Apparent Power

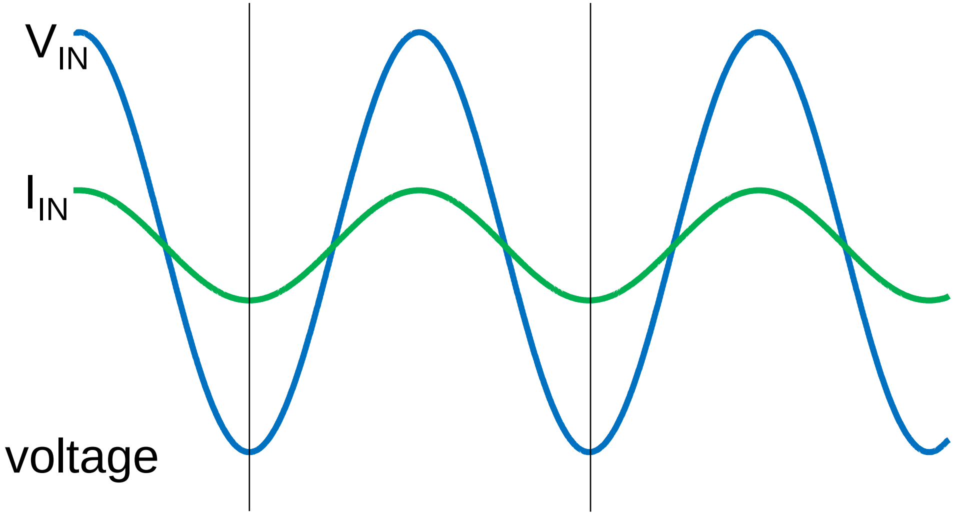
Reactive Power

Real Power

What Is PFC?

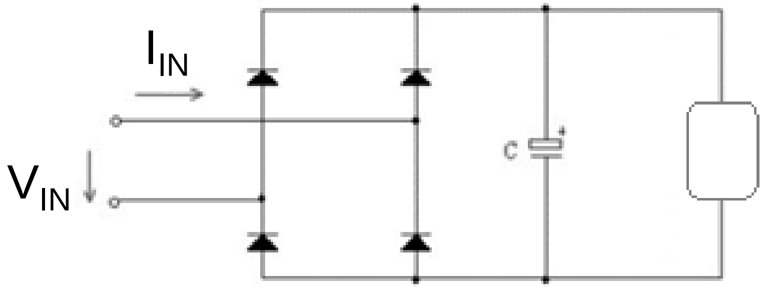
- A PF of 1 corresponds to the resistor case:

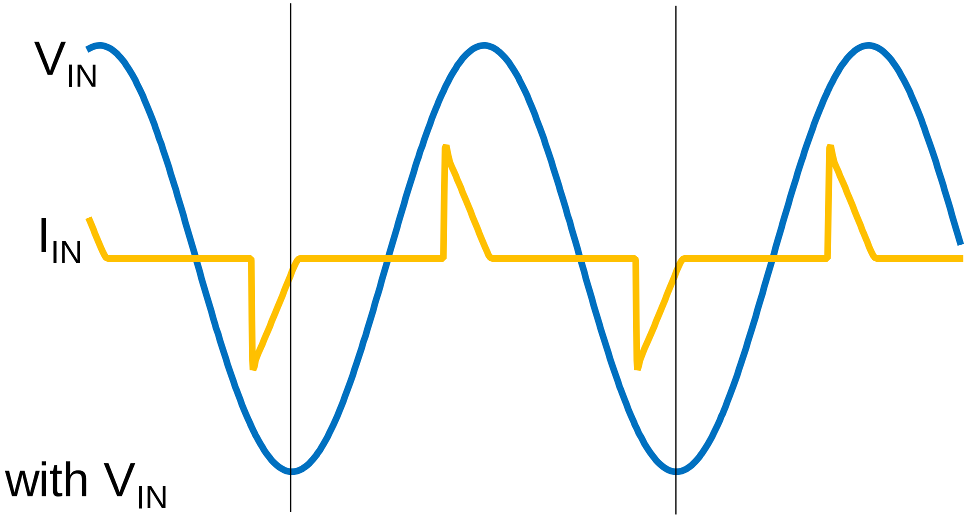




  - The current is sinusoidal and in phase with the input voltage

- A typical power supply has a PF below 1:





  - The current is not sinusoidal, and may be out of phase with V_{IN}
  - Larger RMS current circulates in input (higher reactive power)

MPS

Why Is PFC Needed?

If the PF is low, more power circulates in the input wires than is used by the actual load

➔ Risk of overheating of electrical wires

- At home:

220 Vac

3x 300W equipment with PF = 0.5 ≥ 8 A

The same with PF = 1 ≥ 4A

- On the distribution lines:

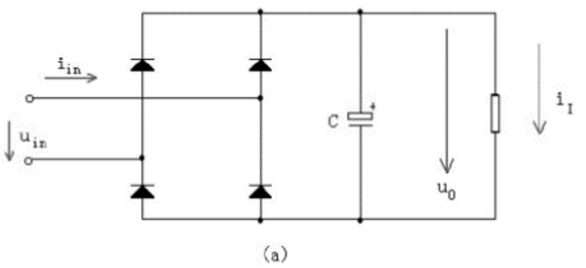
Happy birds!

➔ Utility companies push for high PF

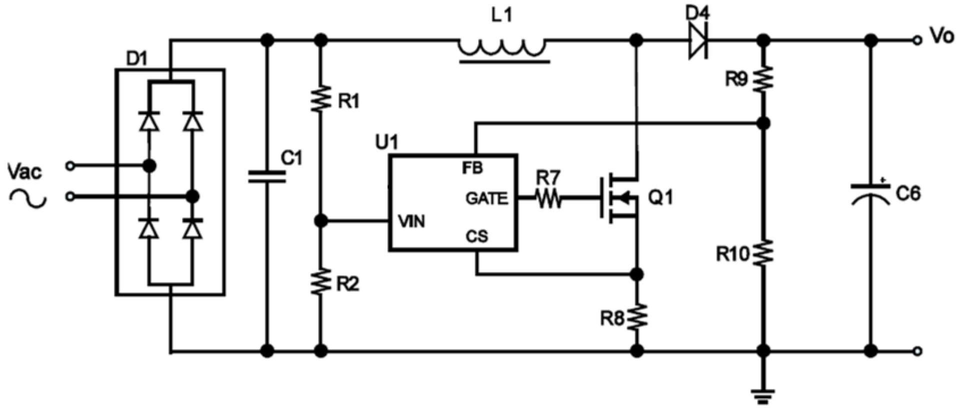
- Fewer power plants needed for the same equipment
- They can bill all the electricity generated!

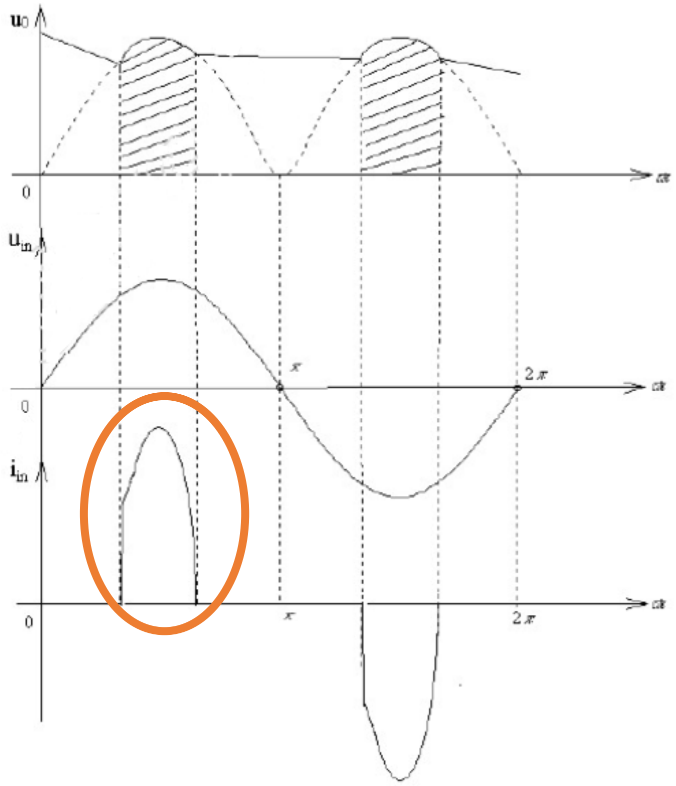
$ $

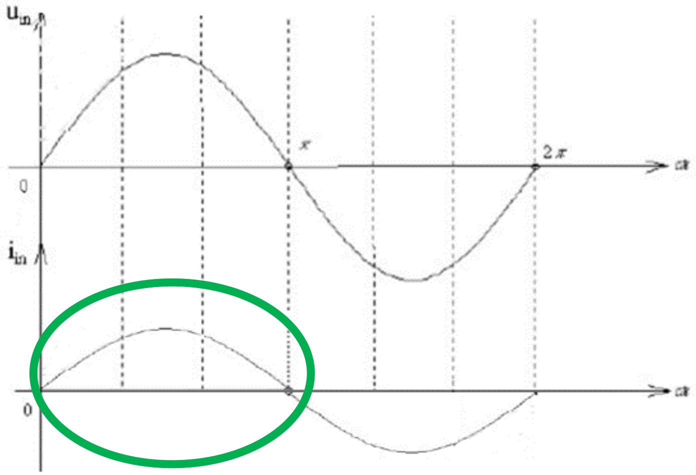
The Basic Concept of PFC



Adding PFC



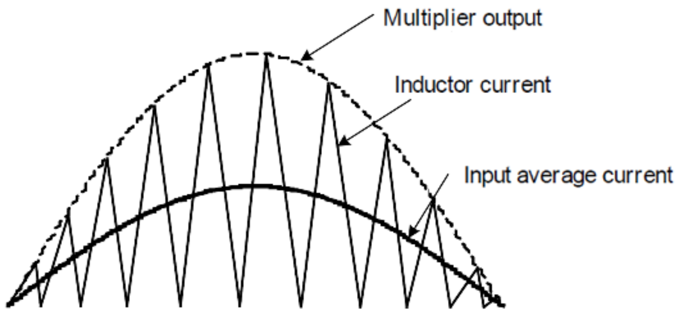




The input current follows the voltage

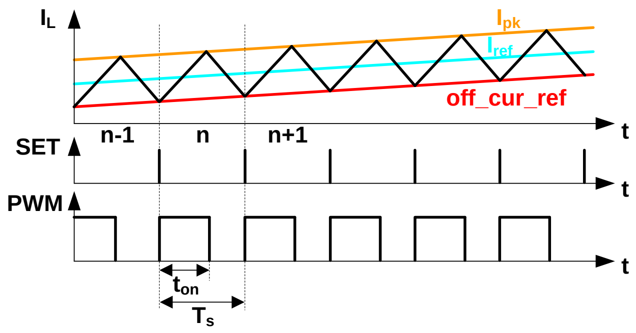
PFC Modes of Operation

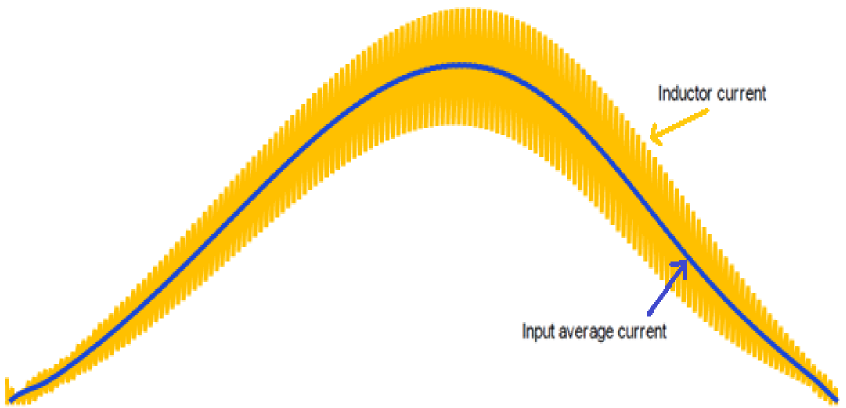
- Boundary-Conduction Mode PFC (BCM) or CrM (Critical-Conduction Mode)



Best suited for power < 300W
Simpler architecture
Zero-voltage switching
Higher RMS currents

- Continuous Conduction Mode (CCM) PFC





Best suited for power > 200W
Lower RMS currents
Hard switching
More complex regulation loop

PFC Modes of Operation

- Multi-Mode PFC

HR12xx

CCM or BCM at high loads

→ Different DCM modes (discontinuous-conduction mode) under light loads to optimize efficiency

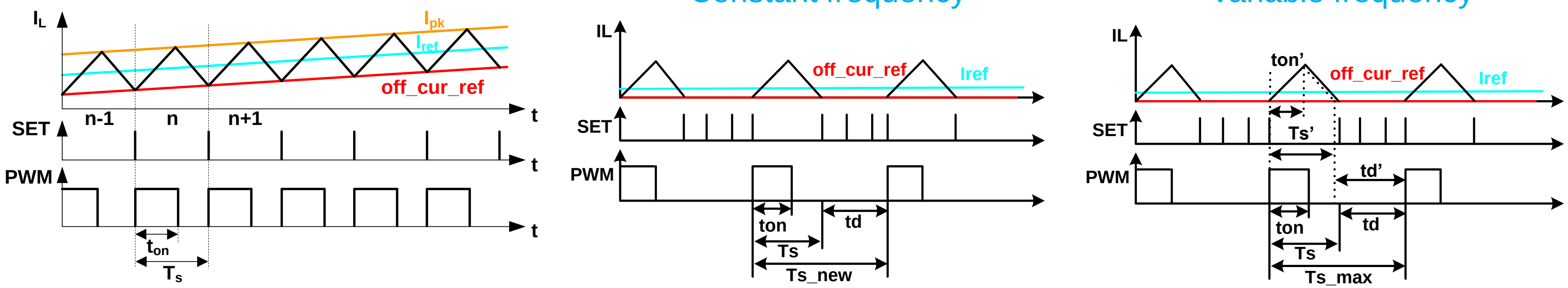
CCM

CF DCM

Constant frequency

VF DCM

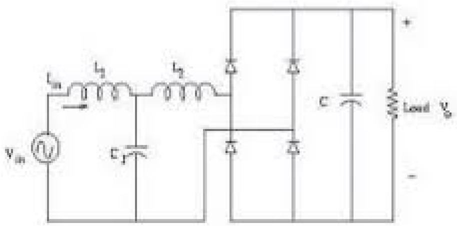
Variable frequency

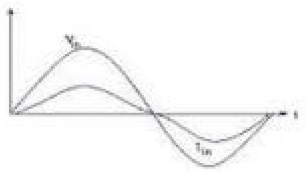


A set signal determines the CCM valley current point and DCM point.

PFC Topologies

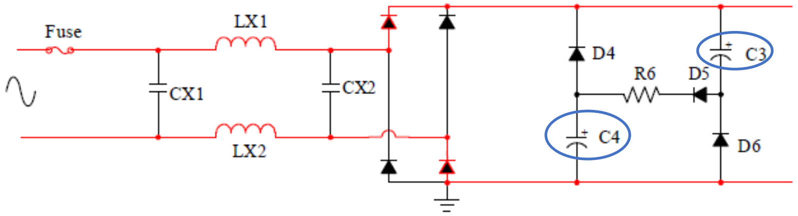
Passive: Line Filter





Large input inductor forces the current to be sinusoidal

Valley Fill

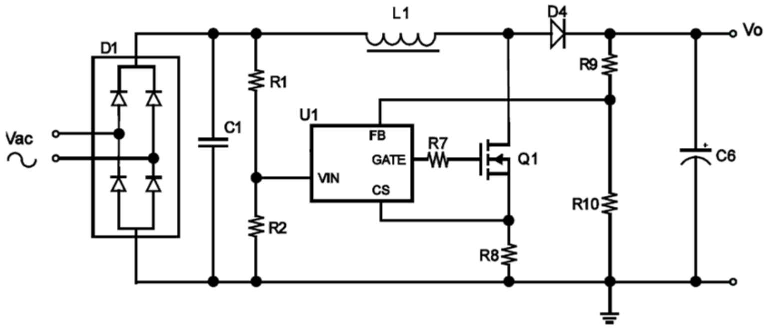


2x filtering capacitors are charged in series but discharged in parallel

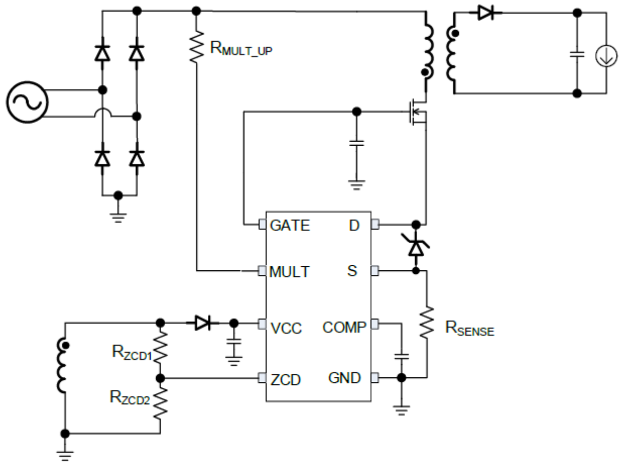
Active: Flyback (low-power, single-stage: PFC + isolated regulation)

Buck (not very common)

Boost (most common for P_{OUT} > 100W)



High Efficiency



BCM flyback with Multiplier and Small Input Filtering Capacitor

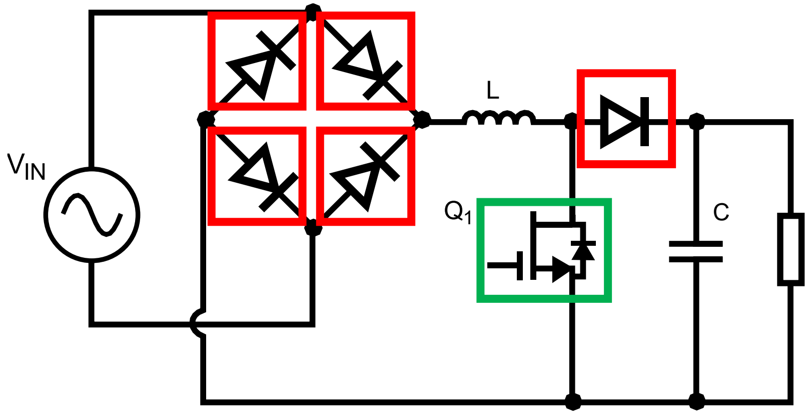
PFC Topologies

There are many more active PFC structures, most of them based on boost topology

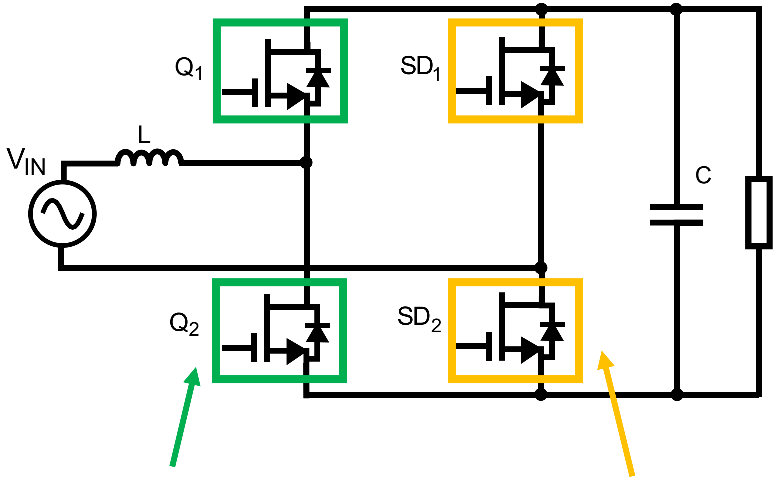
Their main purpose is to achieve the best efficiency possible for a given output power (and price point)

For example: interleaved boost, bridgeless boost, Vienna rectifier, totem-pole, etc.

Full-Bridge Rectifier + Boost



Totem-Pole Bridgeless PFC



Fast Switching

f_{SW} = 100kHz

Slow Switching

$f_{SW} = f_{GRID}$

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MPS PFC Roadmap

Combo PFC + LLC

HR1210/1/3/5
Full Digital PFC + LLC
CCM PFC

HR1280
Full Digital PFC + LLC
CCM PFC

HR1275
Full Digital PFC + LLC
BCM PFC

Totem-Pole PFC

MPF32010
Full Digital TP PFC
CCM TP PFC

MPxxxxx
BCM TP PFC

Standalone PFC

MP44010
BCM PFC
Analog

MP44014/A
BCM PFC
Analog

MP44018A
BCM PFC,
Low Standby Power

MP44060
BCM PFC,
High f_{SW}

MP44017
BCM PFC, Burst
Optimized for Lighting

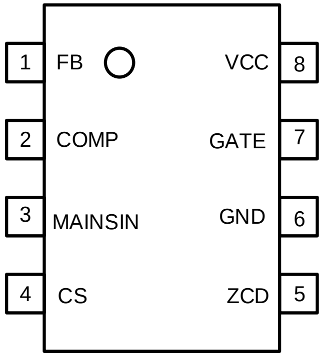
MP44019
BCM PFC
with Second OVP for TV

Released | **Sampling** | **Under Design**

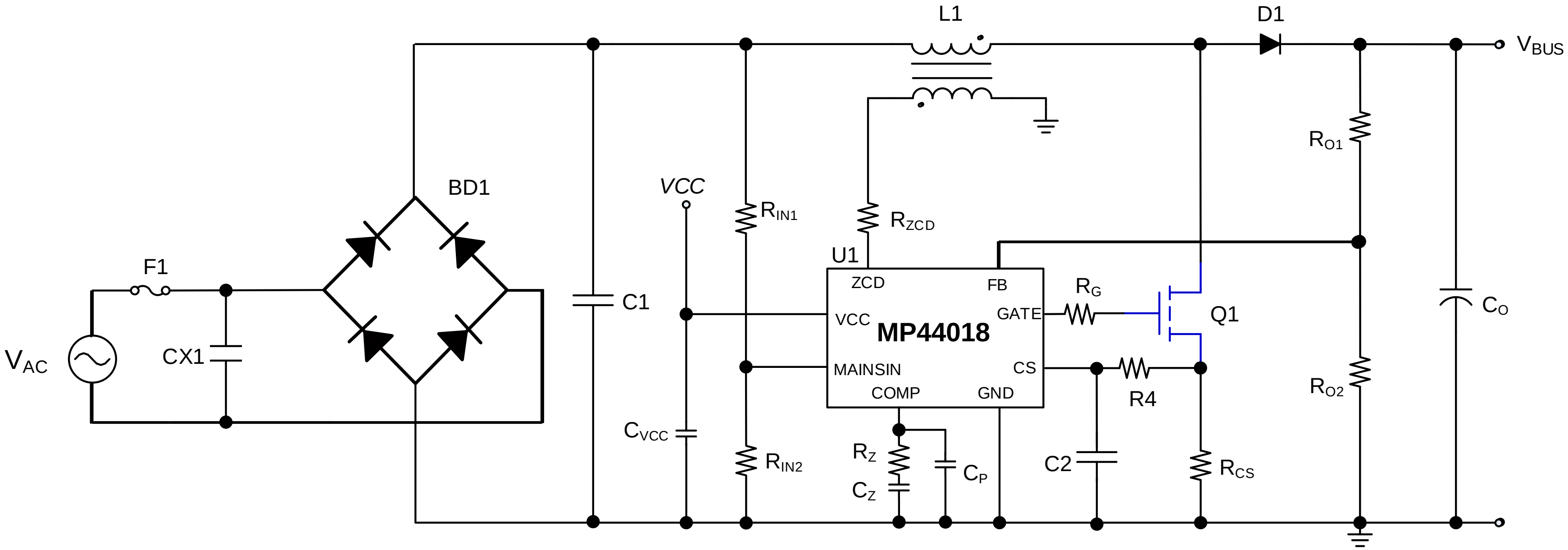
MPS

MP44018 Key Features

- Valley Turn-On for Minimum Switching Loss
- Input Feed-Forward (Mains Compensation)
- Frequency Reduction to Reduce Switching Loss under Light-Load Conditions
- Improved THD
- Enhanced Dynamic Response
- Soft-Start/Shutdown Burst for Low Audible Noise
- Soft Start
- Under-Voltage Protection (UVP)
- Over-Voltage Protection (OVP)
- Over-Current Limit (OCL)
- Over-Current Protection (OCP)
- Brown-In (BI) and Brownout (BO)
- Open/Short Pin Protection
- Over-Temperature Protection (OTP)

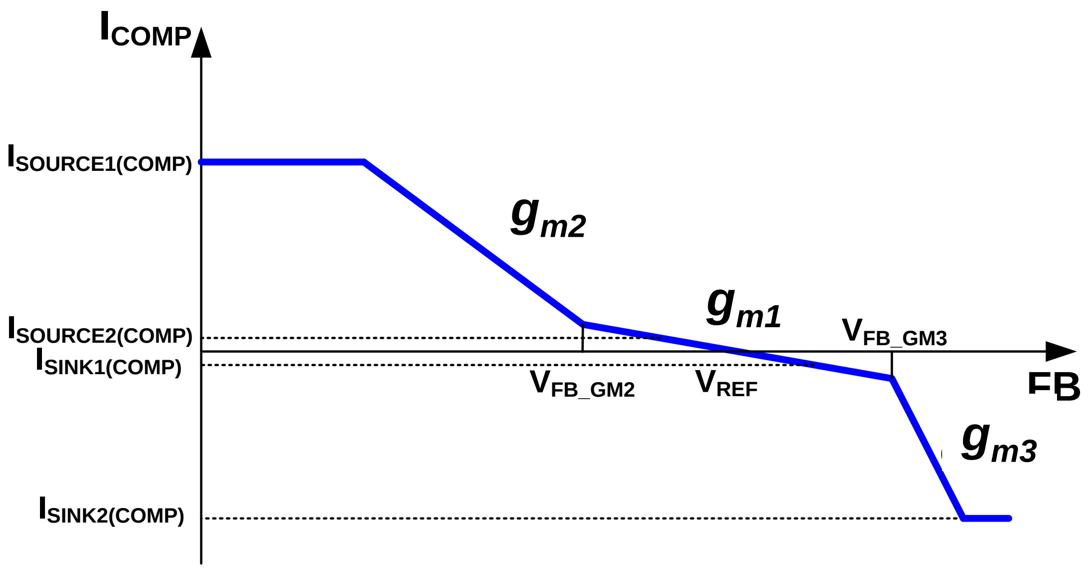


SOIC-8 (5mmx6.2mmx1.7mm) Package

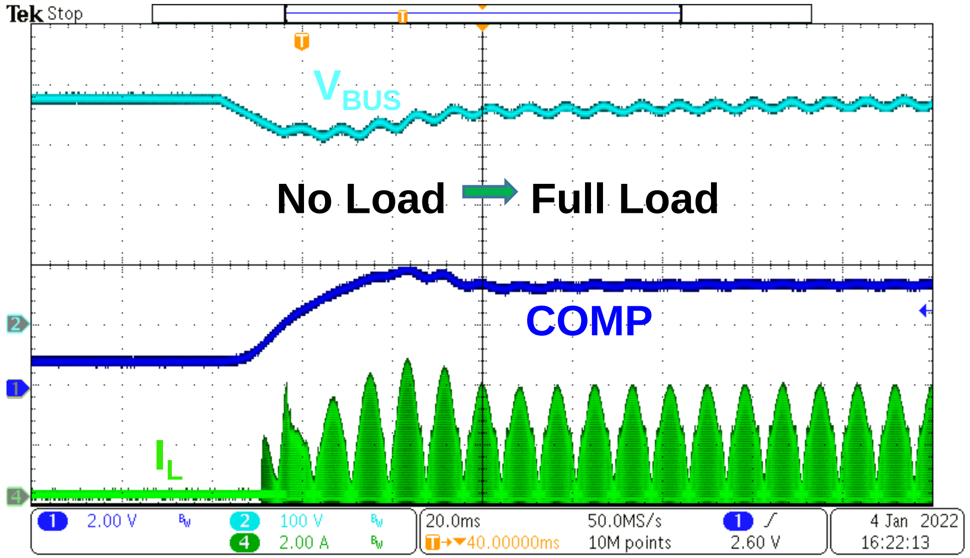


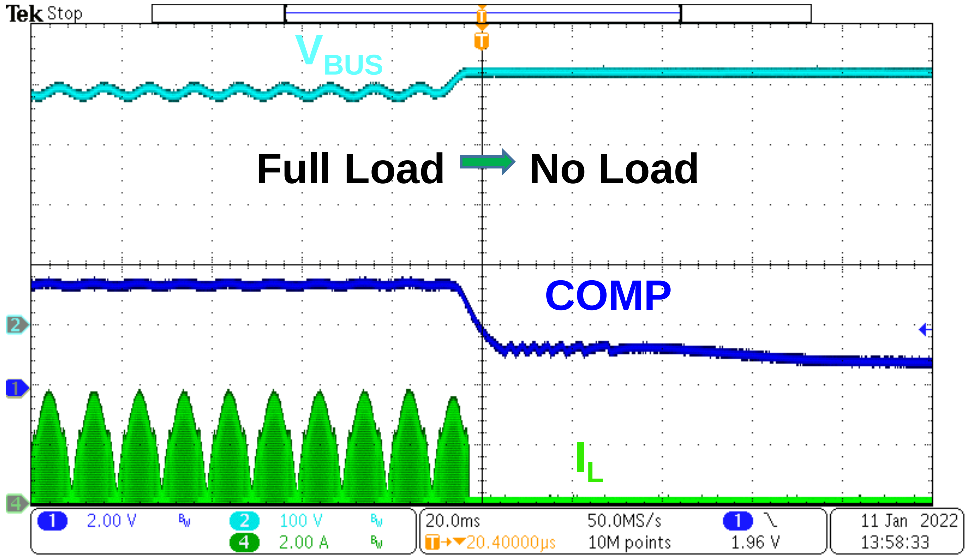
MP44018 Enhanced Dynamic Response

Enhanced Dynamic Response



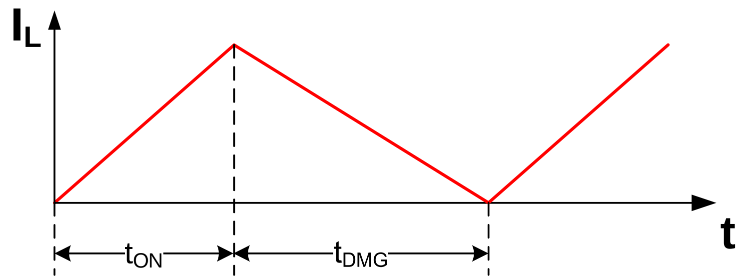
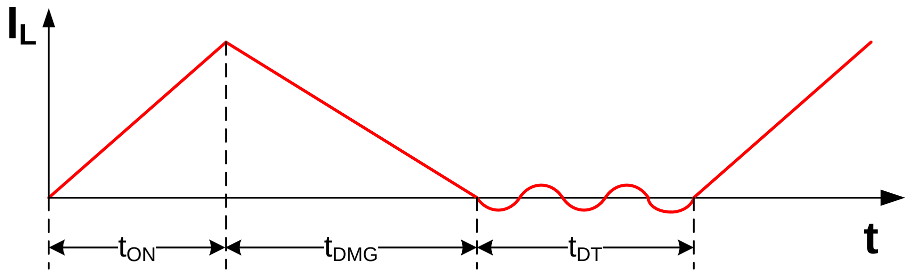
Nonlinear g_m





- Low g_m (g_{m1}) for better PF and THD in steady state
- High g_m (g_{m2} & g_{m3}) for faster transient response

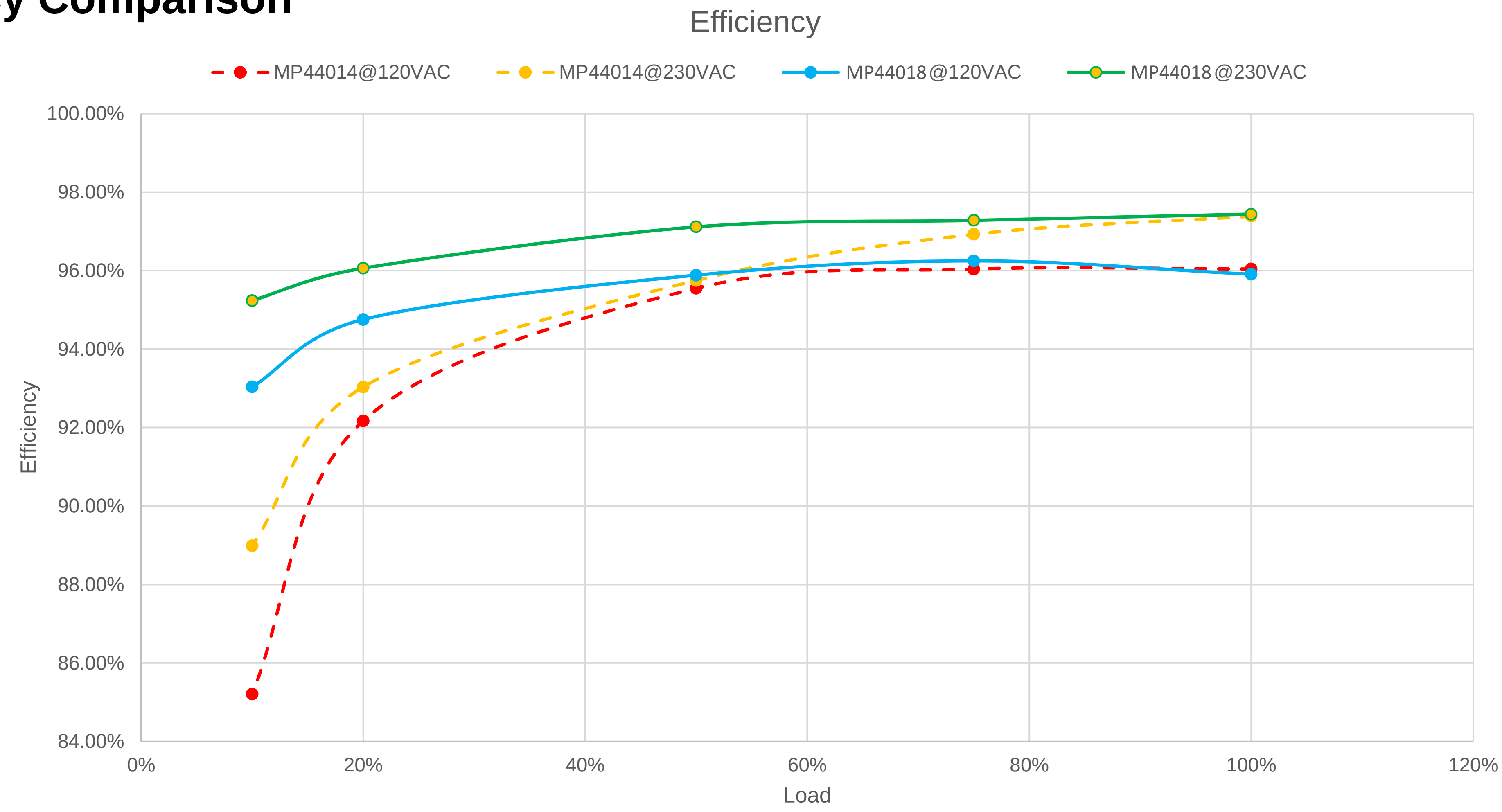
MP44018 THD Improvement

	BCM (Constant-On-Time)	DCM (Variable-On-Time)
Operation Mode		
Input Current	$I_{IN1}(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{2\times L}\times t_{ON}(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ1}}$	$I_{IN2}(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{2\times L}\times t_{ON}(\theta)\times D_C(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ2}}$ $D_C(\theta)=\frac{t_{ON}(\theta)+t_{DMG}(\theta)}{t_{ON}(\theta)+t_{DMG}(\theta)+t_{DT}}$
Input Equivalent Impedance	$R_{EQ1}=\frac{2\times L}{t_{ON}(\theta)}$	$R_{EQ2}=\frac{2\times L}{t_{ON}(\theta)\times D_C(\theta)}$
Condition for PF = 1	$t_{ON}(\theta)=\varepsilon(\text{constant})$	$t_{ON}(\theta)\times D_C(\theta)=\varepsilon(\text{constant})$

A dedicated variable-on-time (VOT) control circuit is integrated and t_{ON} is calculated

MP44018 Efficiency

Efficiency Comparison

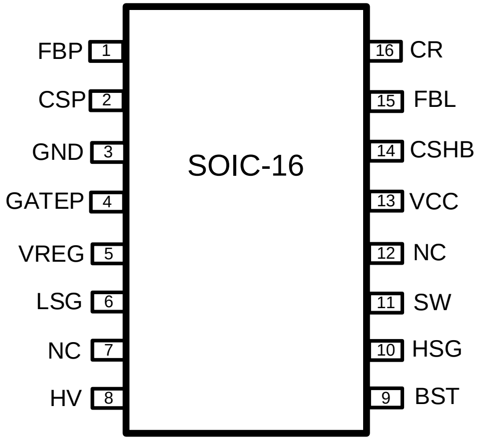


➢ Under light-load conditions, the MP44018’s efficiency is significantly higher than previous generations

HR1275 Key Features

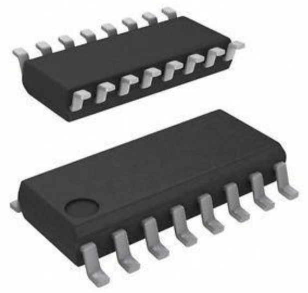
General System Features:

- Total < 85mW No-Load Power Loss (including PFC + LLC)
- HV Current Source for Start-Up
- Smart X-Capacitor Discharge when AC Dropout, Approved by IEC 62368 and IEC 60950
- Power Good (PG) Function
- External Over-Temperature Protection (OTP)
- UART Interface for Parameter Configuration
- User-Friendly GUI



PFC Controller:

- CrM/DCM Multi-Mode PFC Control with High Efficiency across Full Load Range
- Intelligent Valley Switching for Low Audible Noise
- Operates Up to 400kHz
- Input Capacitor Current Compensation
- THD Compensation
- Programmable Soft Burst-On for Higher Light-Load Efficiency with Low Audible Noise
- Programmable AC Input Brown-In/Brownout
- Cycle-by-Cycle Switching Current Limit
- Overload Protection (OLP), Over-Voltage Protection (OVP)



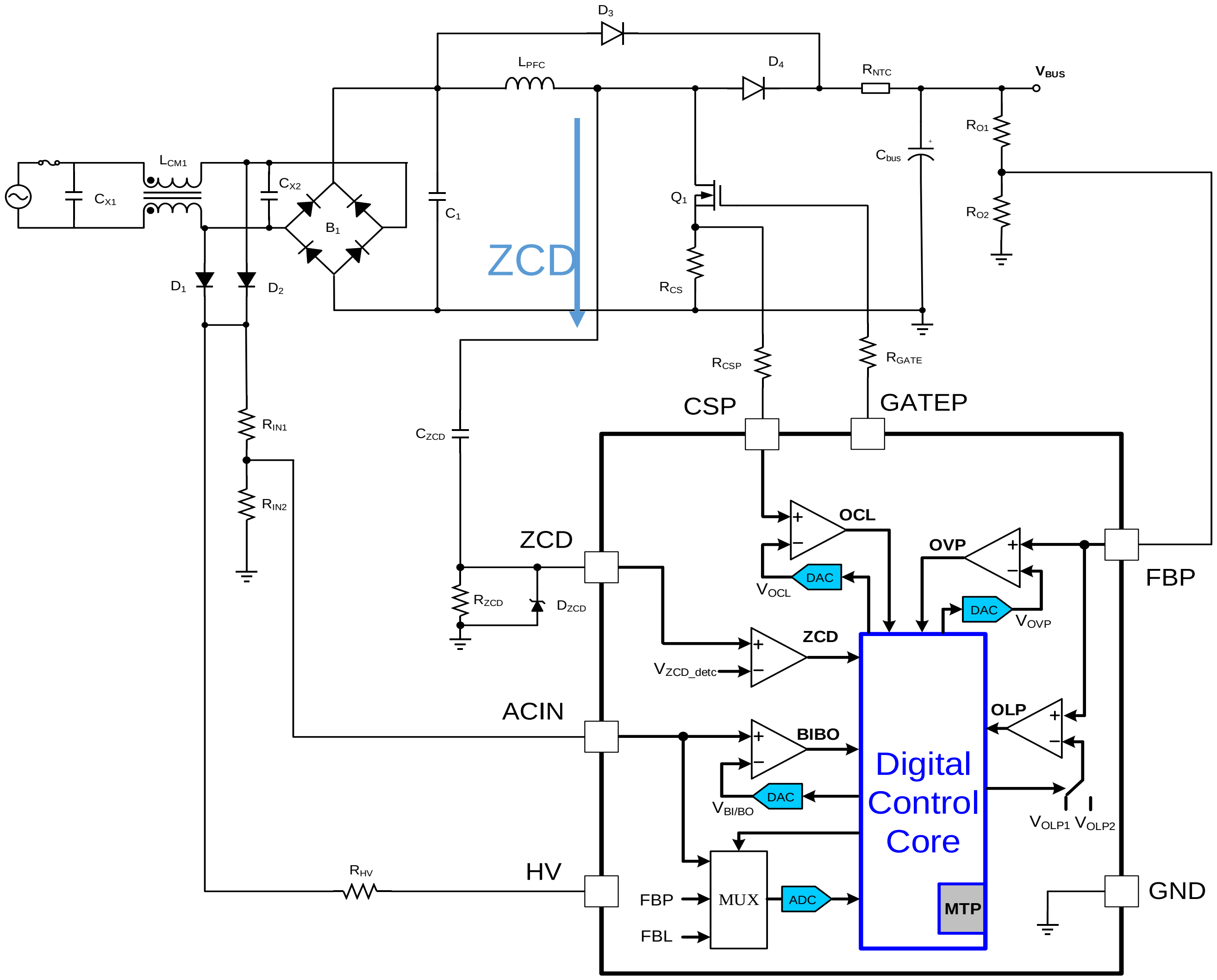
HR1275 PFC Architecture

Input Pins:

Pin	Descriptions
ACIN	AC input sense through an external divider resistor
ZCD	PFC valley & demagnetization time detect input. Connect to a PFC switch drain through a high-voltage capacitor
FBP	V_{BUS} voltage sense through an external divider resistor
CSP	Current-limit protection

Output Pins:

Pin	Descriptions
GATEP	PFC switch gate driver

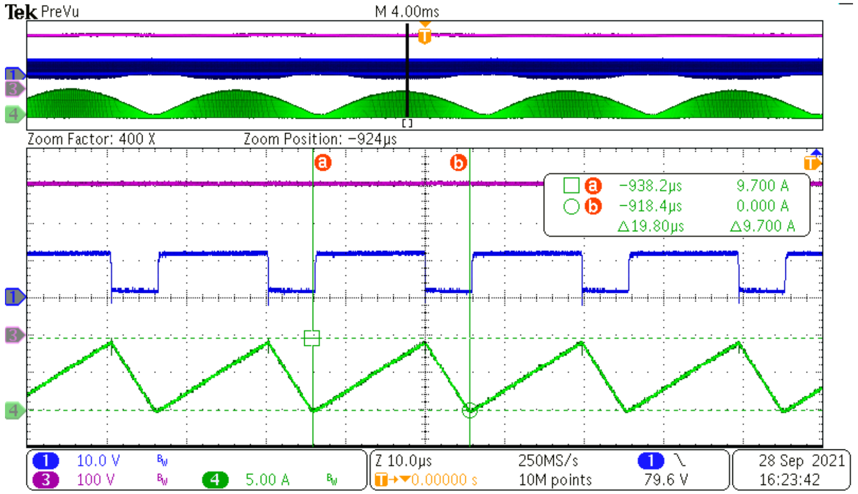


HR1275 240W Performance

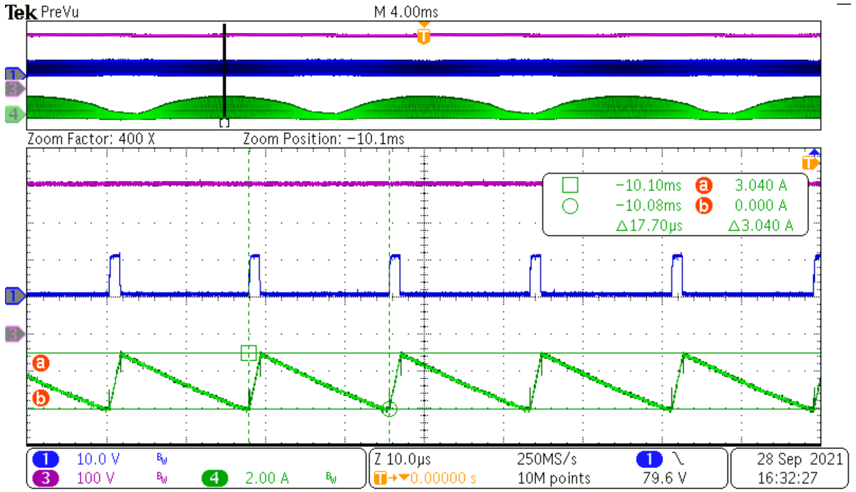
BCM

High Load

Test Conditions: V_{IN} = 85V_{AC}, I_{OUT} = 20A



Test Conditions: V_{IN} = 265V_{AC}, I_{OUT} = 20A



CH1: GATEP

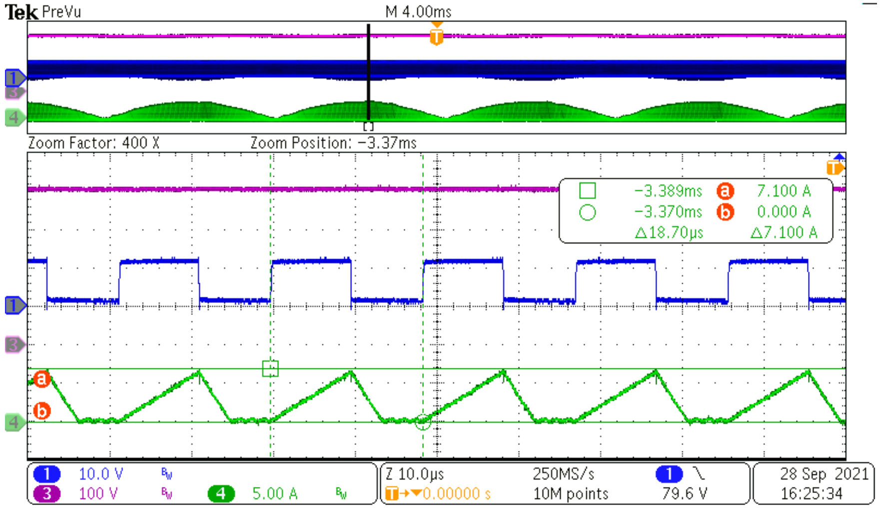
CH3: V_{BUS}

CH4: I_{PFC}

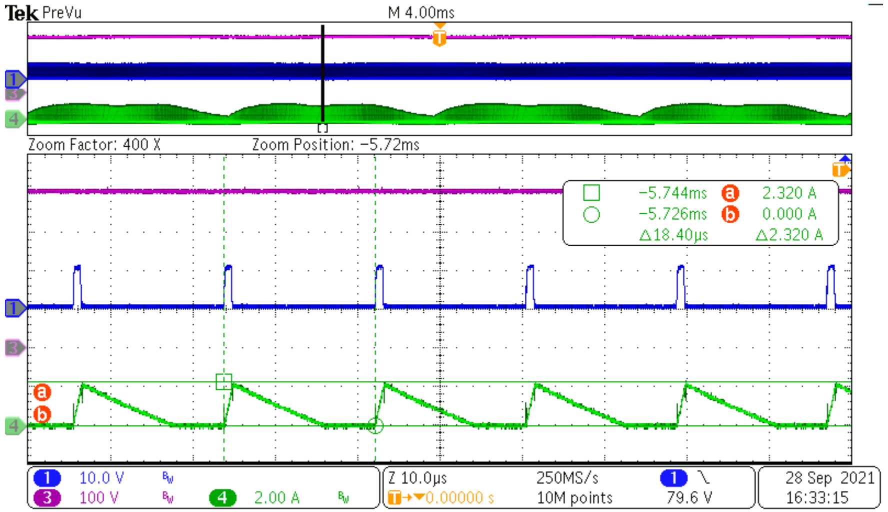
DCM

Light Load

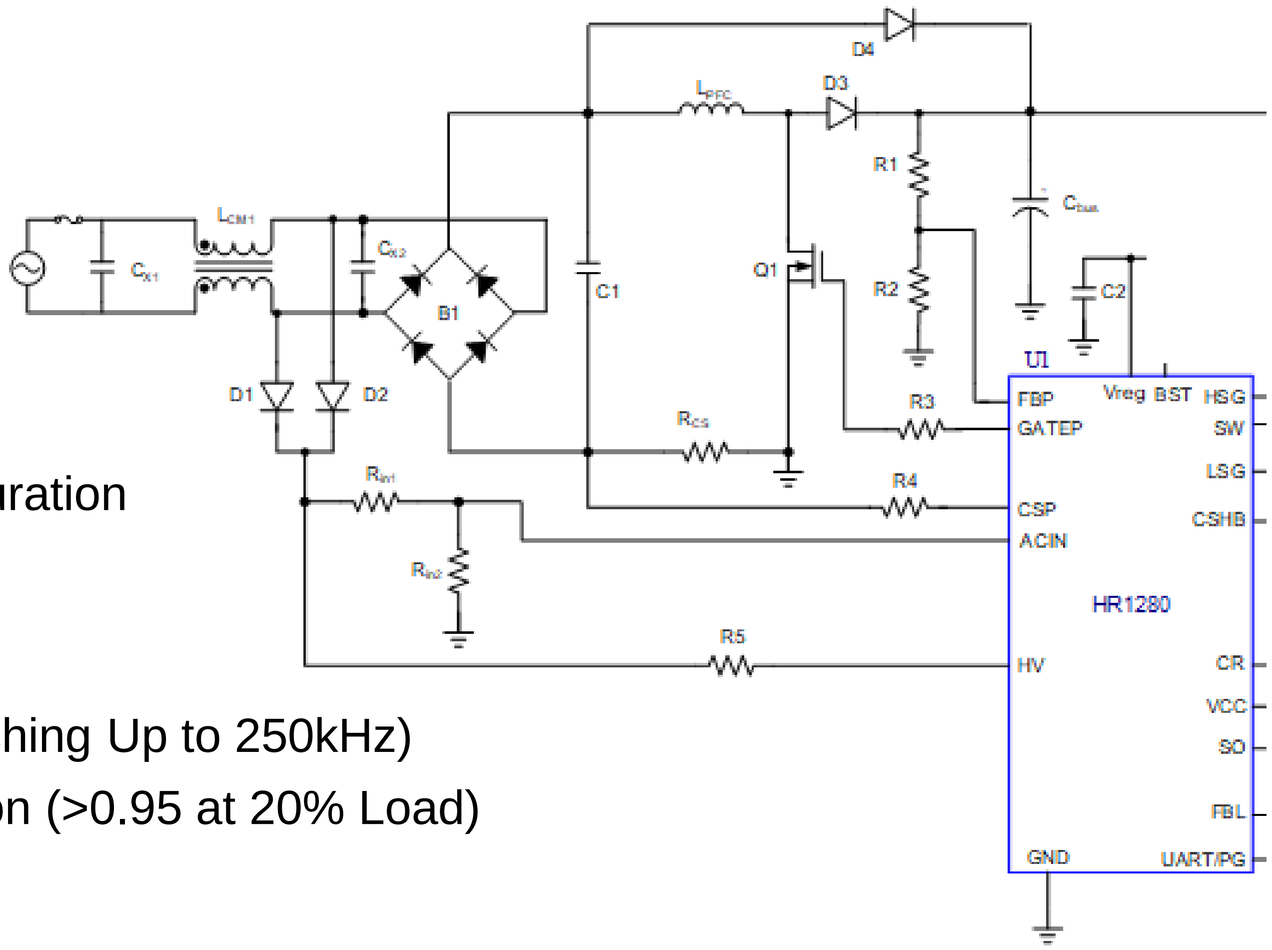
Test Conditions: V_{IN} = 85V_{AC}, I_{OUT} = 10A



Test Conditions: V_{IN} = 265V_{AC}, I_{OUT} = 10A



HR121x Key Features



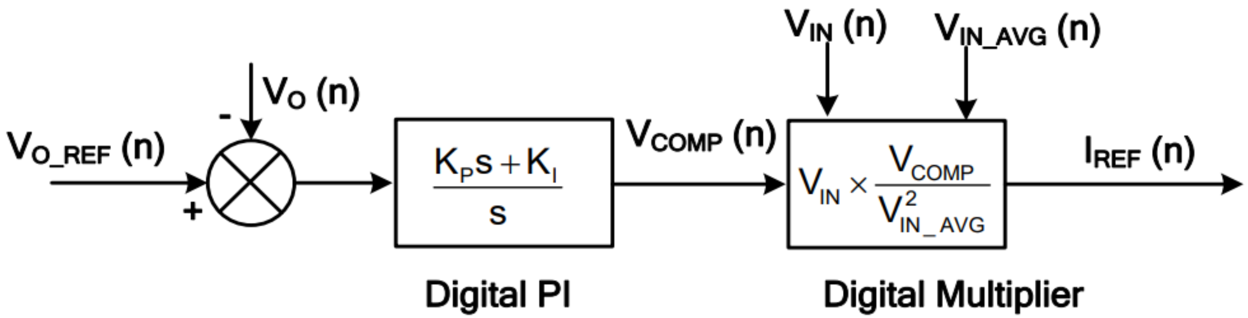
System:

- **Pin < 100mW at No Load, 12V Output**
- High-Voltage Current Source for Start-Up and Smart X-Capacitor Discharger
- **Power Good (PG) Function**
- UART Interface and GUI for Parameters Configuration

PFC:

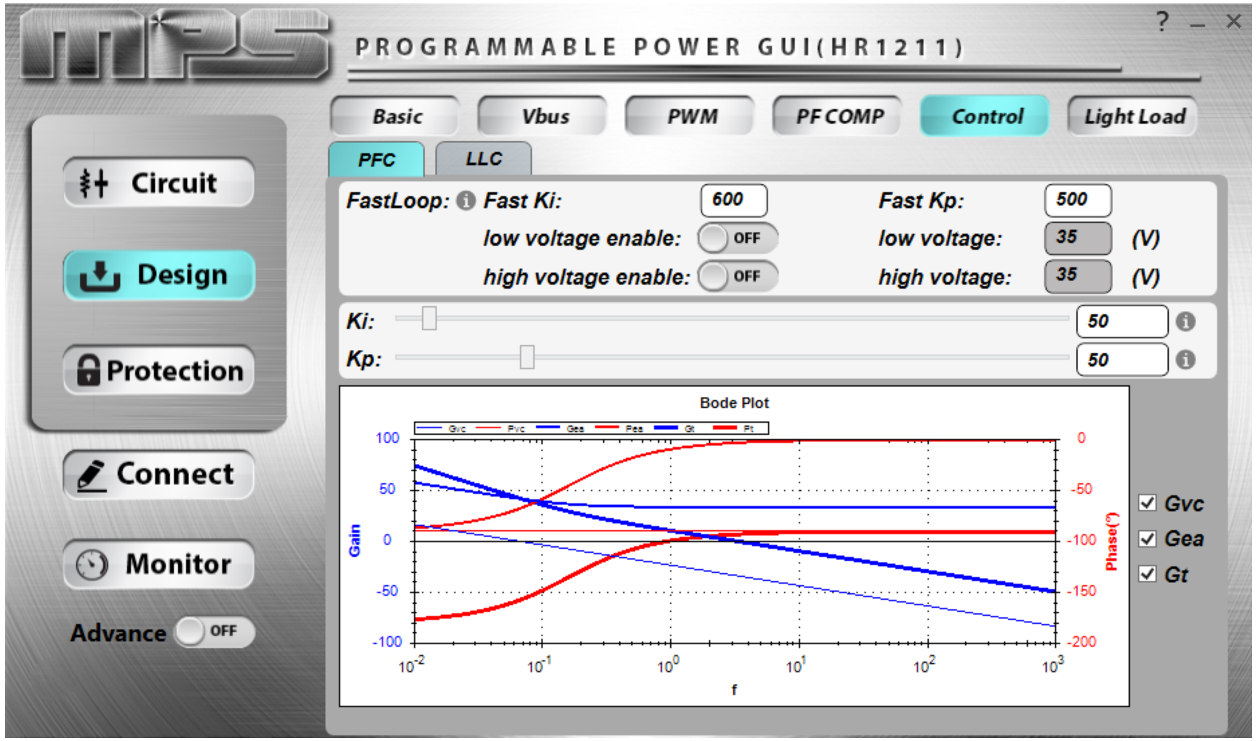
- CCM/DCM Operation of Digital PFC (Max Switching Up to 250kHz)
- High PF Due to Capacitor Current Compensation (>0.95 at 20% Load)
- Configurable Frequency Jitter to Improve EMI
- Configurable Soft Start
- Configurable Soft Burst On for Low Audible Noise
- Configurable AC Brown-In/Brownout, Overload Protection (OLP), Over-Voltage Protection (OVP), Over-Current Limit (OCL)

HR121x PFC Control



PFC Patented Average Current Control:

- CCM for Heavy Loads
- DCM for Light Loads (Improved Efficiency)
- Digital PI Compensator
- PI Parameters Can Be Configured via the GUI
  - Directly on the Board
  - In Real Time



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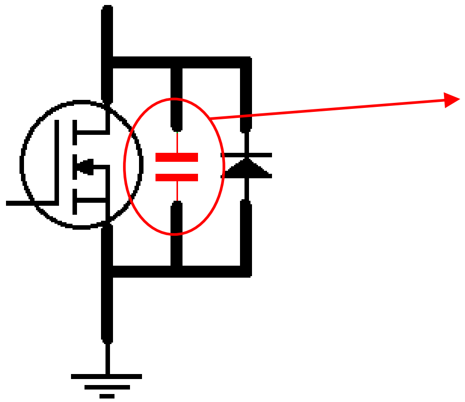
Why Resonant Converters?

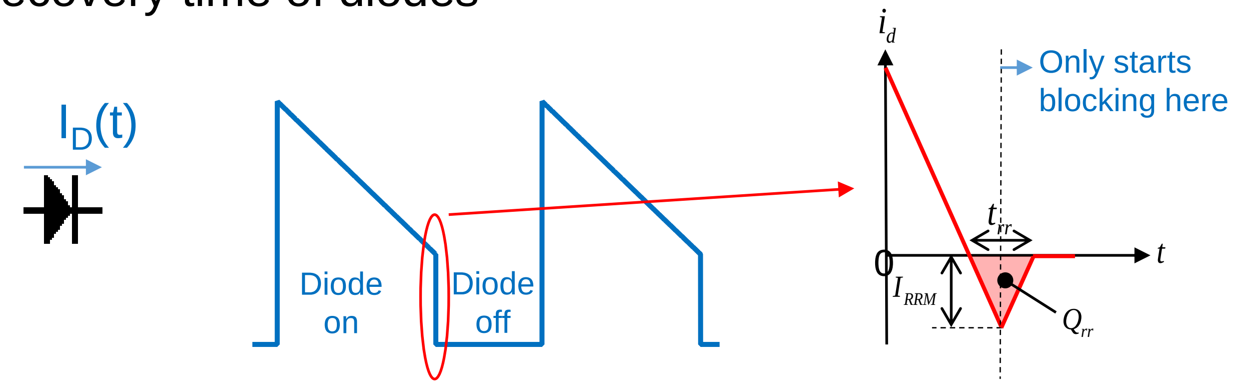
- When output power increases, classical and simpler structures become too inefficient
  - Hard switching of power switches



When the switch is turned on while the parasitic capacitor is charged, losses can be high (scale up with switching frequency)

→ Zero-Voltage Switching (ZVS)

  - Reverse recovery time of diodes



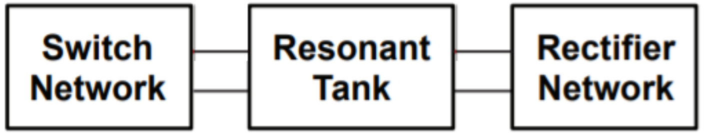
Diodes do not start blocking voltage instantaneously when reversed

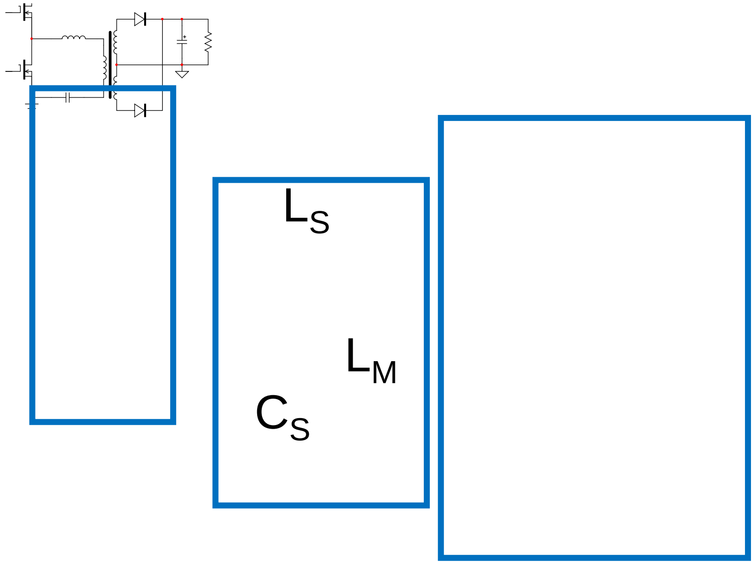
→ Zero-current Switching (ZCS)

  - Energy stored in transformers

What Is an LLC Resonant Converter?

- The LLC is a series resonant converter:
  - The magnetizing inductance (L_M) of the transformer is one of the resonating elements
  - The leakage inductance (L_S) of the transformer also participates in the resonance
  - Series capacitance (C_S) is added to ensure the resonance
  - The transformer turns ratio scales the voltage down





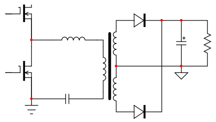
The switching frequency controls the power transmitted to the output

What Is an LLC Resonant Converter?

The LLC converter ensures soft switching under normal-load conditions:

- Zero-voltage switching (ZVS) for the power switches (primary side)
- Zero-current switching (ZCS) for the rectifying diodes (secondary side)

It can operate at a high switching frequency to build compact converters



D_1

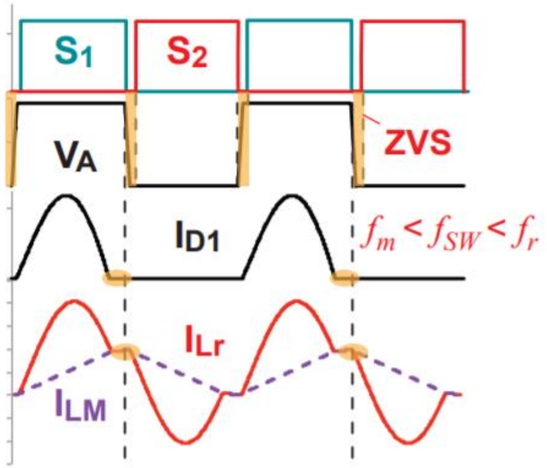
S_1

L_R

S_2

L_M

C_S



Limited component count + magnetics can be made compact (especially at high switching frequencies)

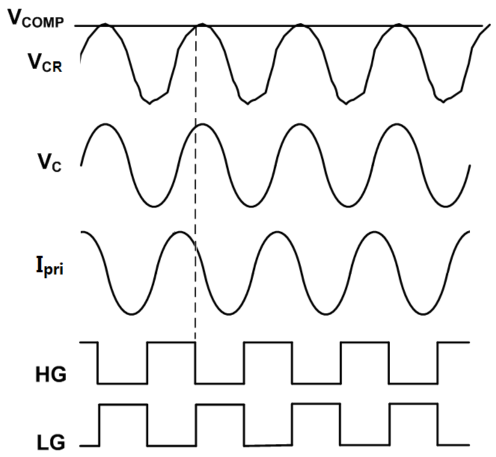
→ high power density

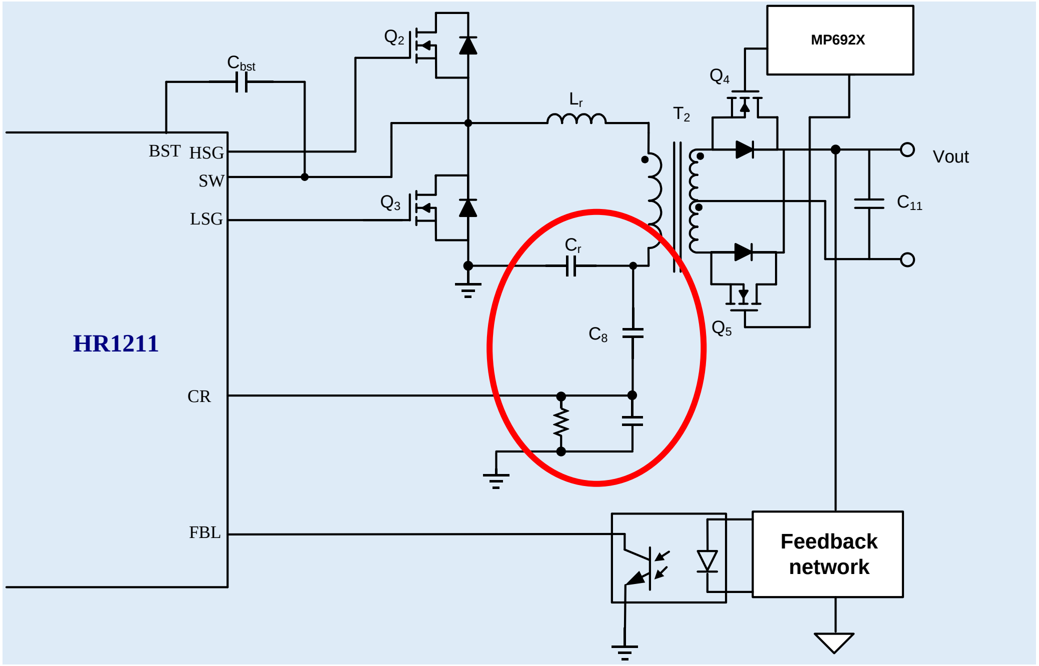
Current-Mode LLC

- Controlling the frequency of the LLC to regulate the output leads to complicated loop compensation
- It can be made simpler by controlling the primary peak current cycle-by-cycle
  → current-mode control

- By monitoring the voltage across the resonant capacitor, the controller has access to the current information

$$\Delta V_{C_r} = \frac{1}{C_r} \int i_{C_r}(t) \cdot dt$$





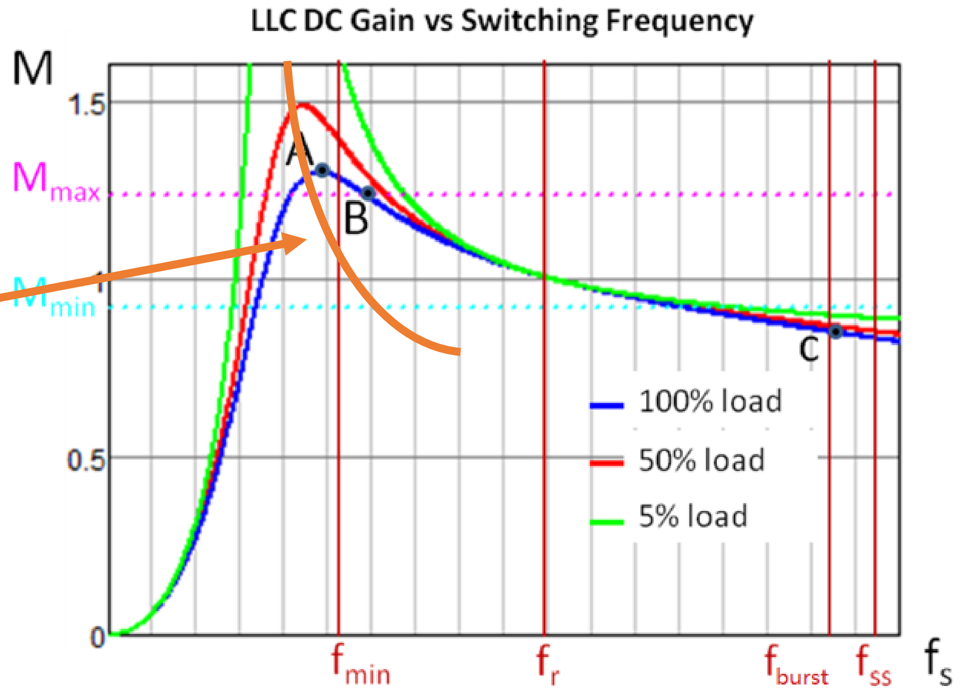
Current-Mode LLC with Frequency Control

Based on first-harmonic approximation (FHA), the DC gain can be controlled by adjusting the switching frequency

The control law inverts itself below a certain frequency

→ Avoid changing regions

(capacitive vs. inductive regions)



Due to its limited DC gain range, the LLC converter does not easily accommodate large input and output voltage variations:

- Fits well with the PFC front-end stage (stable, constant input voltage for the LLC stage)
- Not adapted to all applications (better for constant voltage outputs)

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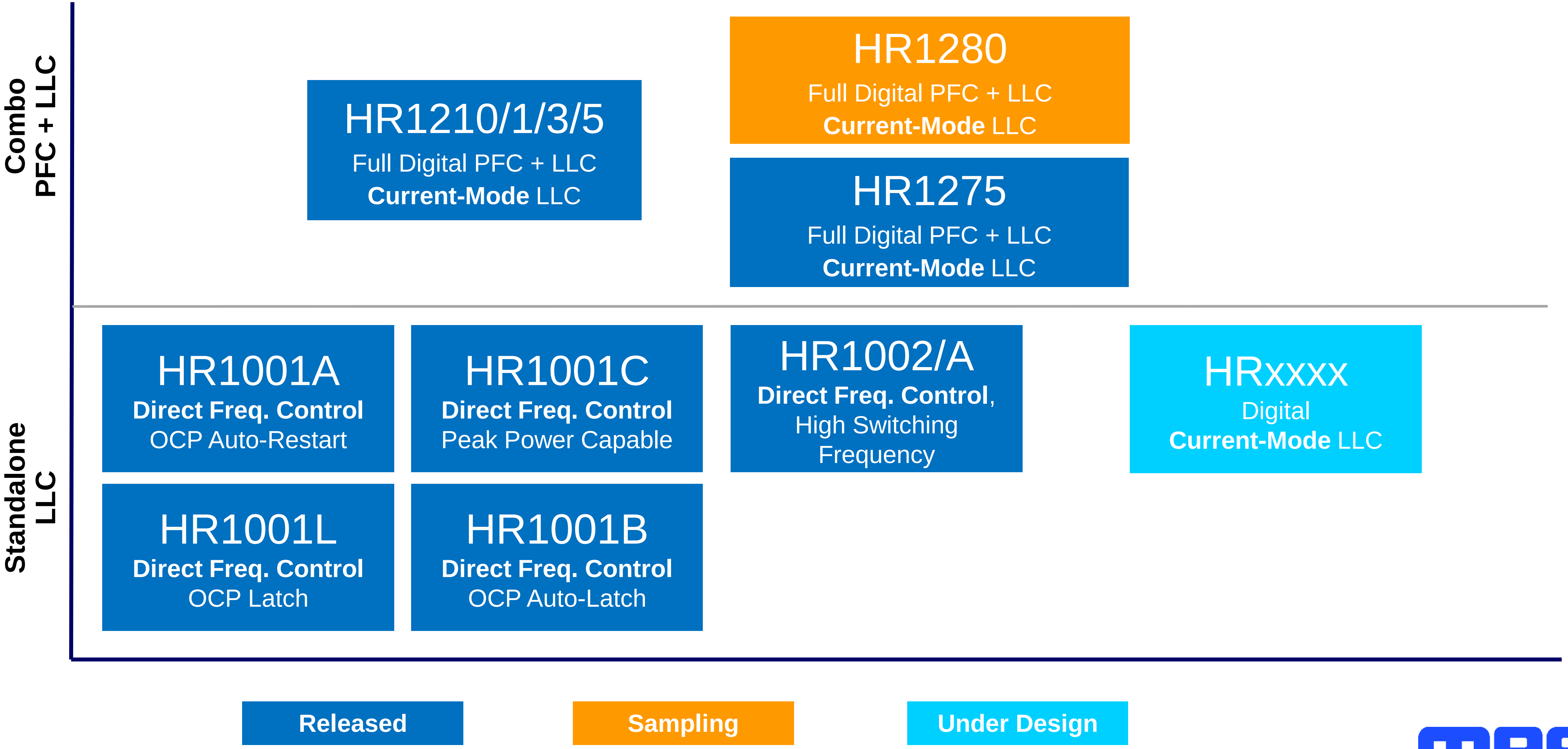
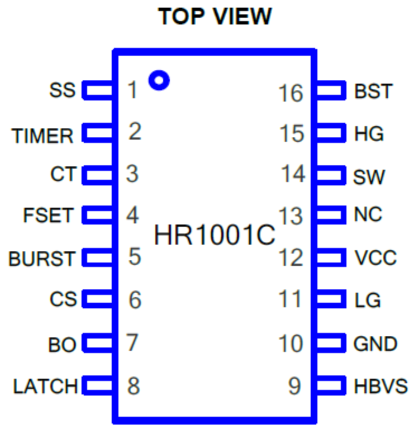
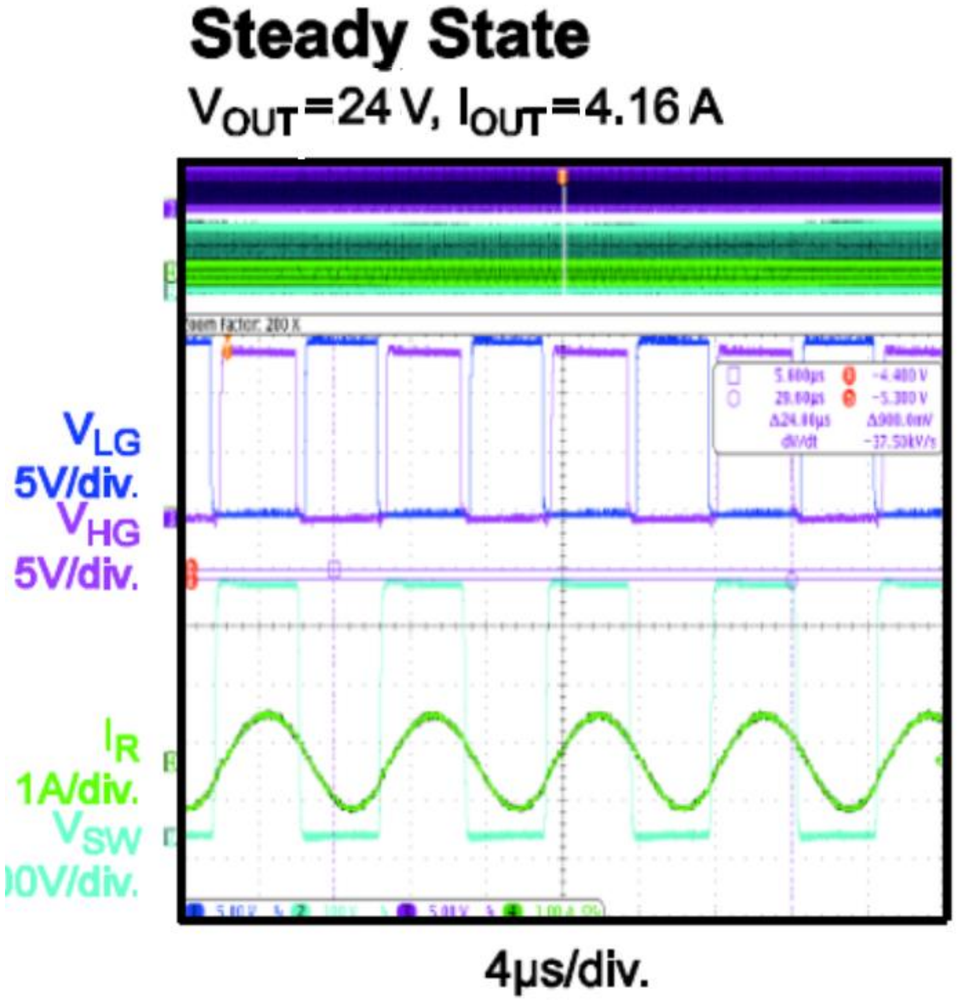
MPS LLC Controllers Roadmap



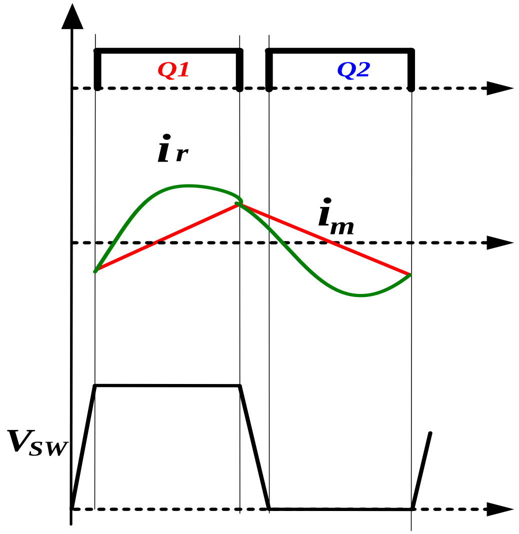
HR1001C Key Features

- Adaptive Dead-Time Adjustment (ADTA)
- Over-Current Protection (OCP) with Configurable Delay Time for Enhanced Surge Performance
- Capacitive Mode Protection (CMP)
- 50% Duty Cycle, Variable Frequency Control for Resonant Half-Bridge Converter
- 600V High-Side Gate Driver with Integrated Bootstrap Diode

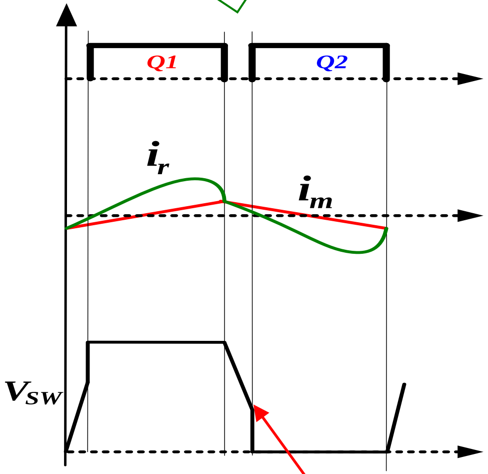




HR1001C Adaptive Dead Time



Soft switching at normal



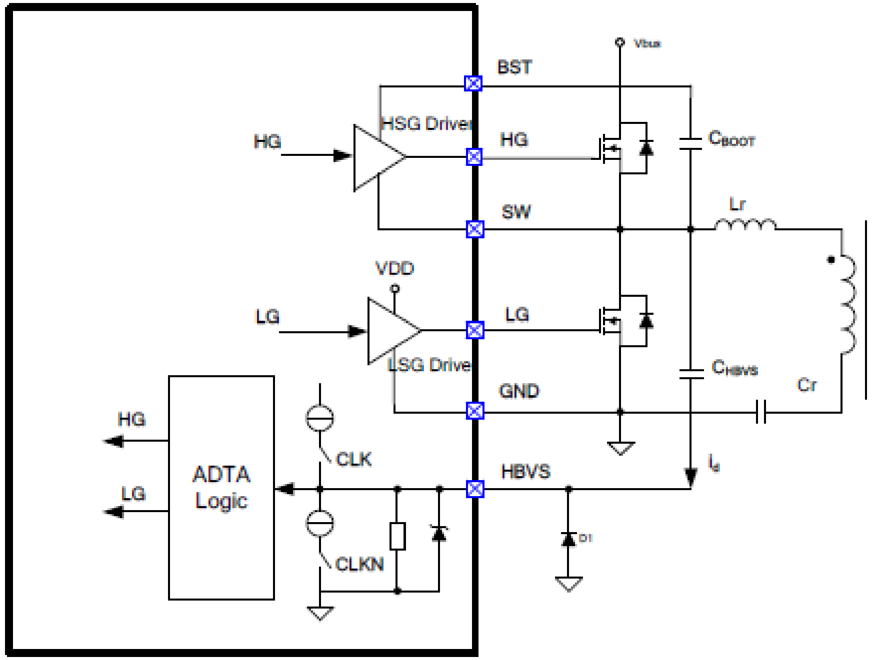
f_{SW} increases at light loads

L_M Tolerance

Hard Switching!

- Low Efficiency
- Thermal Problems
- Higher Cost

ADTA Block Diagram



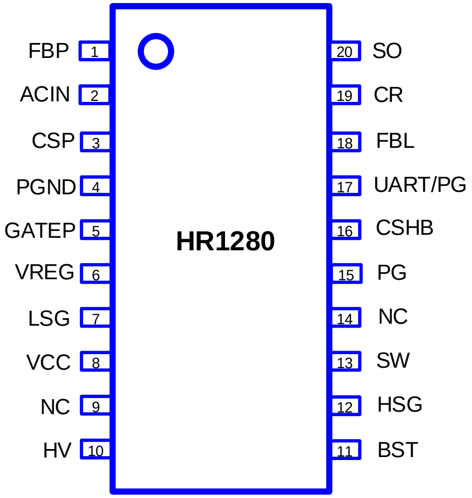
Adaptive dead time adjustment automatically ensures ZVS even under light-load conditions

→ High efficiency and low cost can be achieved with any MOSFET

HR1275 LLC Key Features

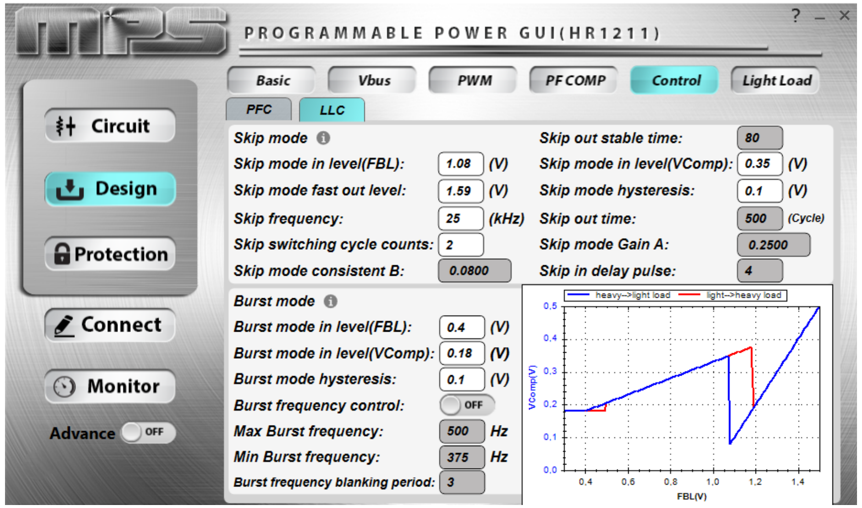
General System Features

- Total <85mW No-Load Power Loss
- HV Current Source for Start-Up
- Smart X-Capacitor Discharge during AC Dropout, Approved by IEC 62368 and IEC 60950
- Power Good (PG) Function
- External Over-Temperature Protection (OTP)
- UART Interface for Parameter Configuration
- User-Friendly GUI



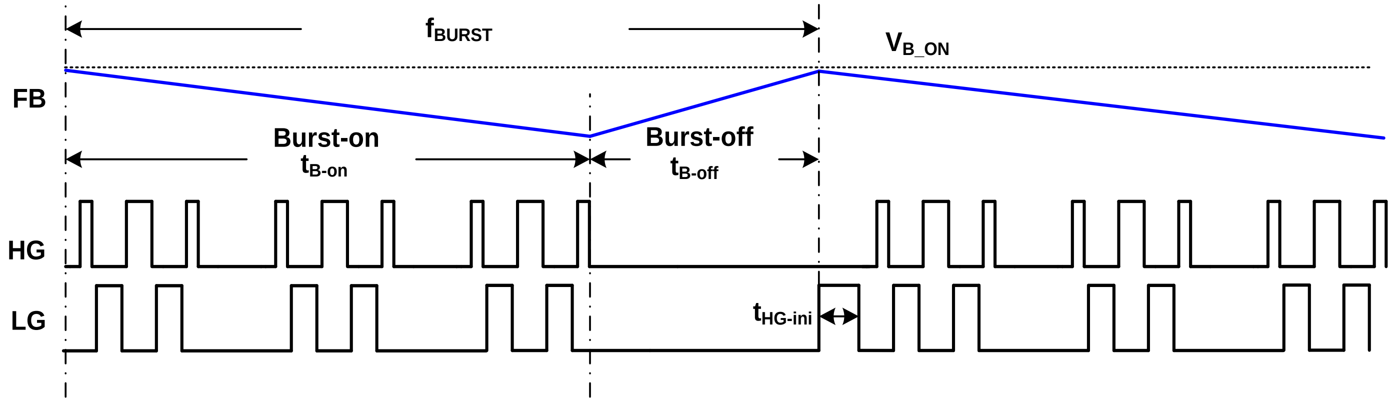
LLC Controller

- Current Mode Control
- Precise Entry/Exit Skip/Burst Mode Control
- Adaptive Dead-Time Adjustment (ADTA) of HB LLC with Minimum and Maximum Limit
- Capacitive Mode Protection
- Operates Up to 500kHz
- Over-Current Protection (OCP) and Over-Power Protection (OPP) with Configurable Protection Behaviors



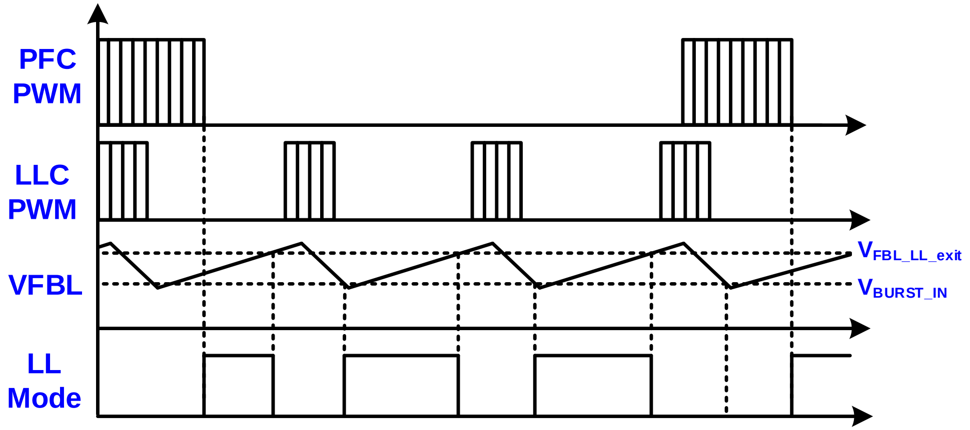
HR1275 LLC Light-Load Burst Mode

- Configurable Fixed V_{COMP}
- Configurable t_{H1} and t_{L1}
- Configurable Skip Frequency
- PWM On/Off Based on the FBL Voltage:
  Burst-On/Off Level
- Burst Frequency Control
- FBL Pull-Up Resistor Control for Power Saving



Operation Current in Burst Mode:

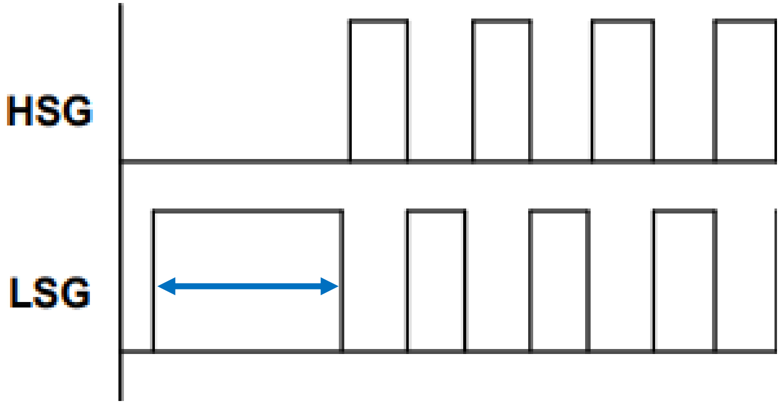
PN	HR1275	HR1280	HR1211
IC Consumption	1.2mA	1.3mA	2.2mA



HR1275 No-Load Standby Power:

V_{IN}	$85V_{AC}$	$115V_{AC}$	$230V_{AC}$	$265V_{AC}$
No Load Consumption (mW)	73.9	75.1	82.2	84.8

HR12xx Start-Up Strategy



- During start-up, there is an imbalance in the resonant capacitor voltage, which can induce hard switching

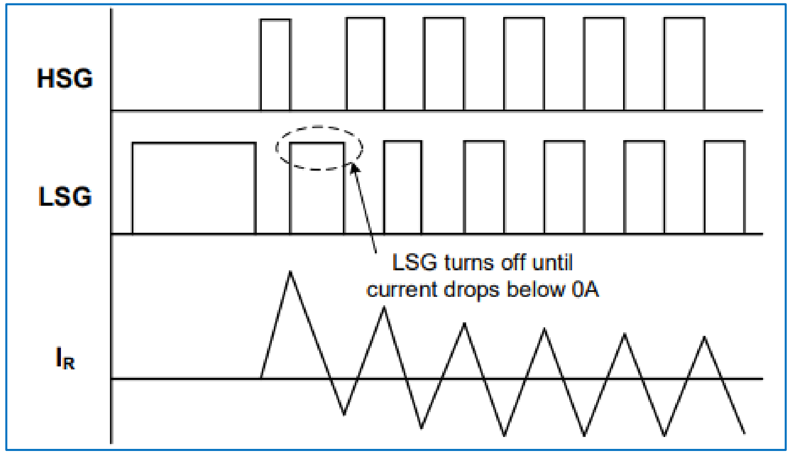
- To avoid hard switching, the LSG driver does not turn off until the resonant tank current drops below zero ($V_{CSHB} < V_{CSNR}$)

Start-Up:

- The low-side gate (LSG) turns on first to charge the BST capacitor

- Then, the high-side gate (HSG) and LSG turn on and off alternatively

- Soft start is achieved by starting with a high switching frequency, then reducing it until the feedback (FB) loop takes over



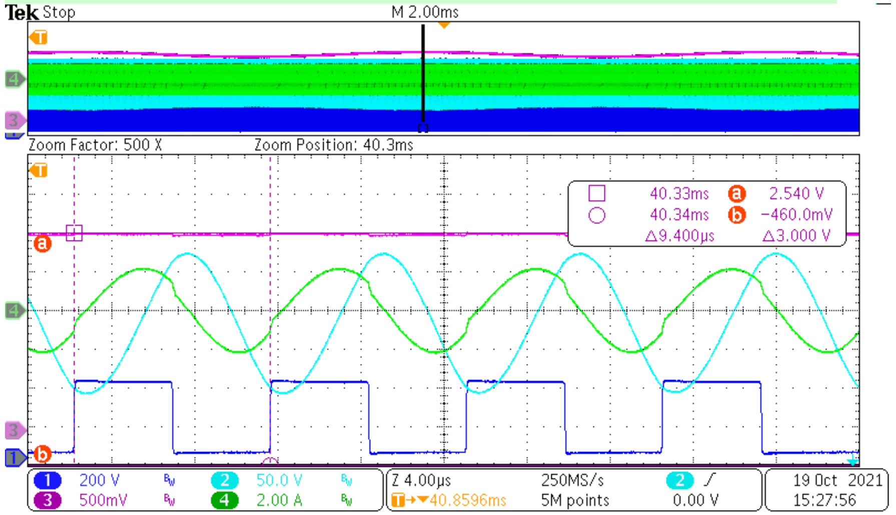
Note:

- The first LSG pulse duration can be configured by the GUI

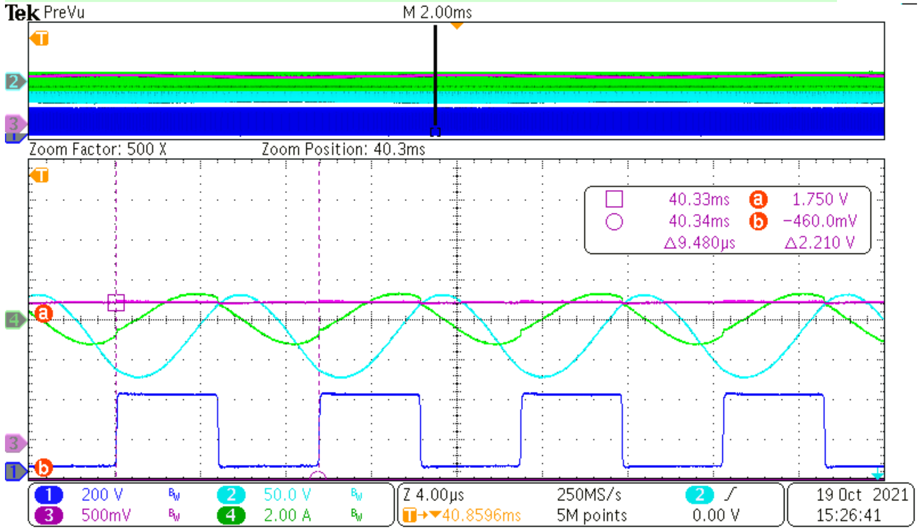
HR1275 LLC Waveforms

High Load

Test Conditions: V_{IN} = 220V_{AC}, I_{OUT} = 20A



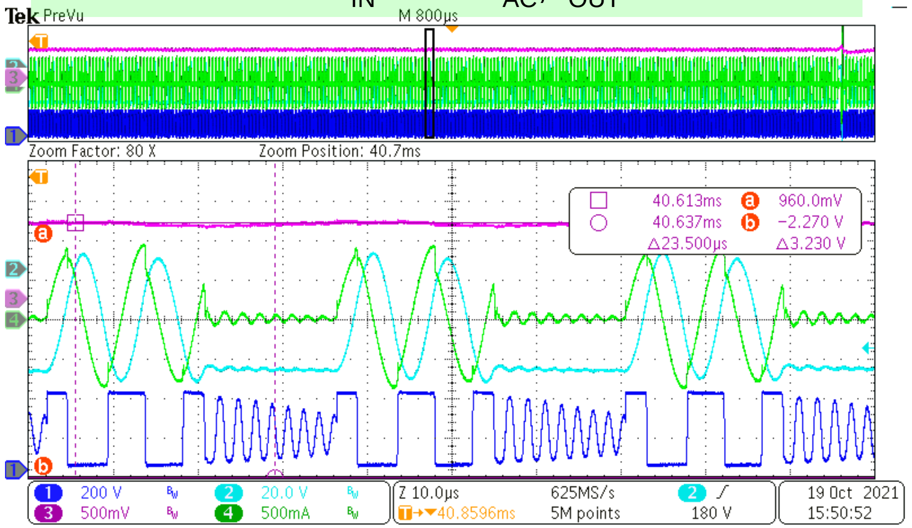
Test Conditions: V_{IN} = 220V_{AC}, I_{OUT} = 10A



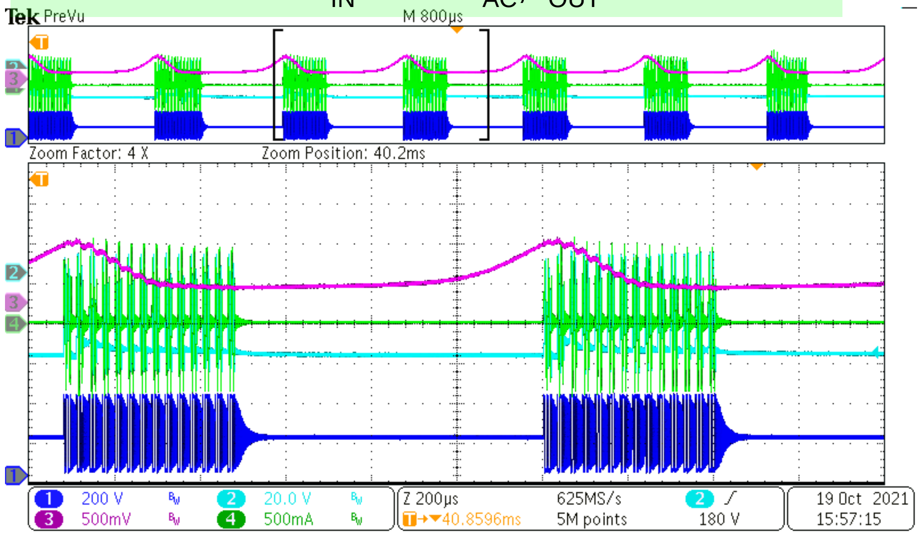
Burst

Light Load

Test Conditions: V_{IN} = 220V_{AC}, I_{OUT} = 2A



Test Conditions: V_{IN} = 220V_{AC}, I_{OUT} = 1A



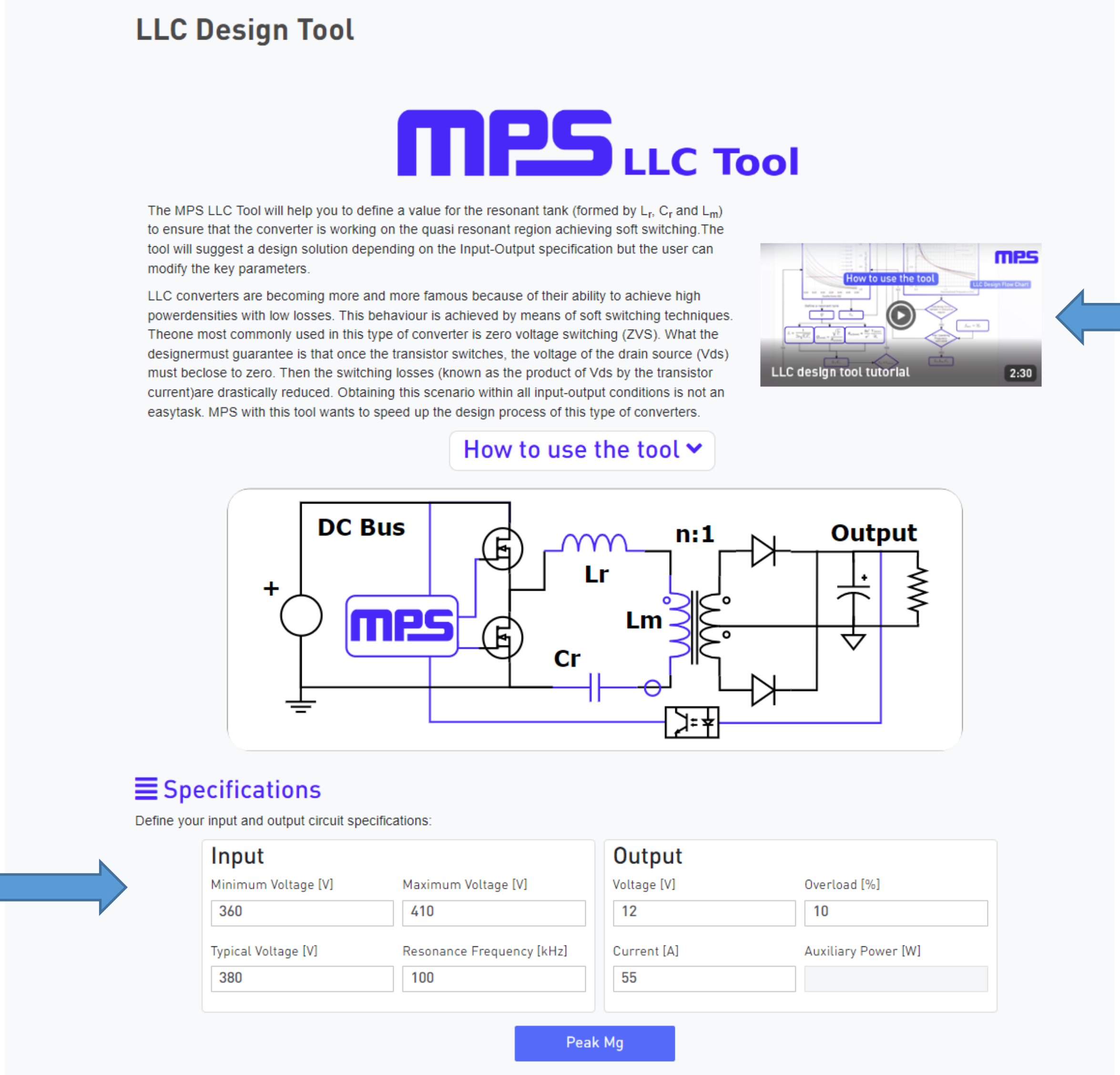
CH1: SW

CH2: V_{CR}

CH3: FBL

CH4: I_R

MPS LLC Design Tool



Tutorial

Specifications

https://www.monolithicpower.com/en/design-tools/design-tools/llc-design-tool.html

MPS LLC SR Controllers Roadmap

LLC SR Driver

Dual Synchronous Rectification (SR) Controllers for LLC

MP6925/A
High-Efficiency Dual SR

MP6926
High-Frequency
LLC SR

- Target to high power density PD markets

MP6928A
Fast Turn-Off, Intelligent
Dual SR

MP6922A
30mV V_{DS}
Dual SR

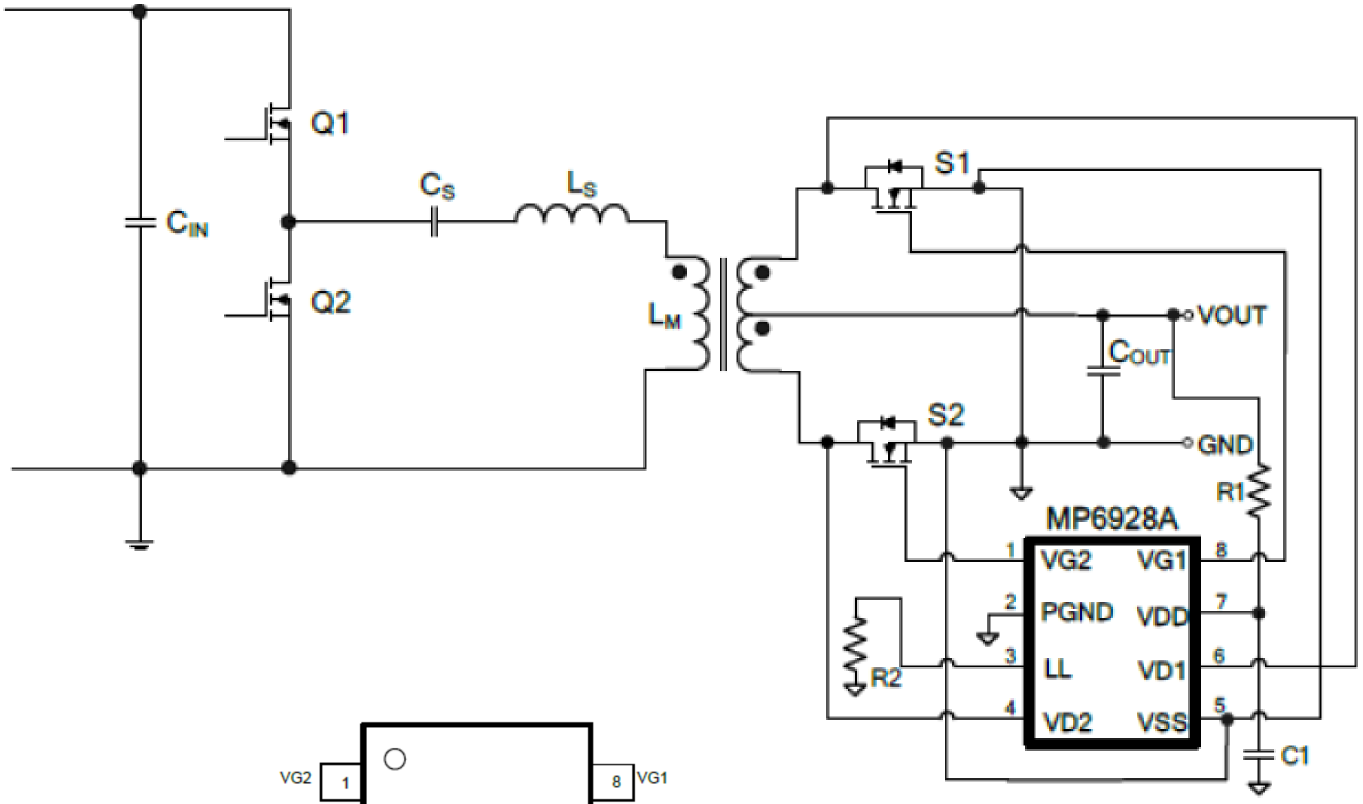
MP6923
15mV V_{DS}
Dual SR

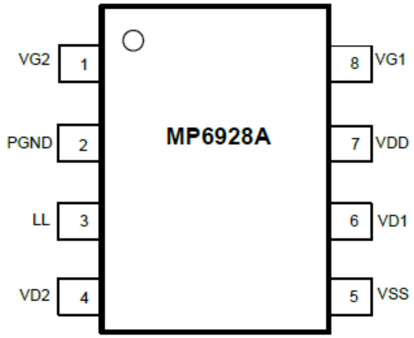
MP6922
70mV V_{DS}
Dual SR

Released **Sampling**

MP6928A Key Features

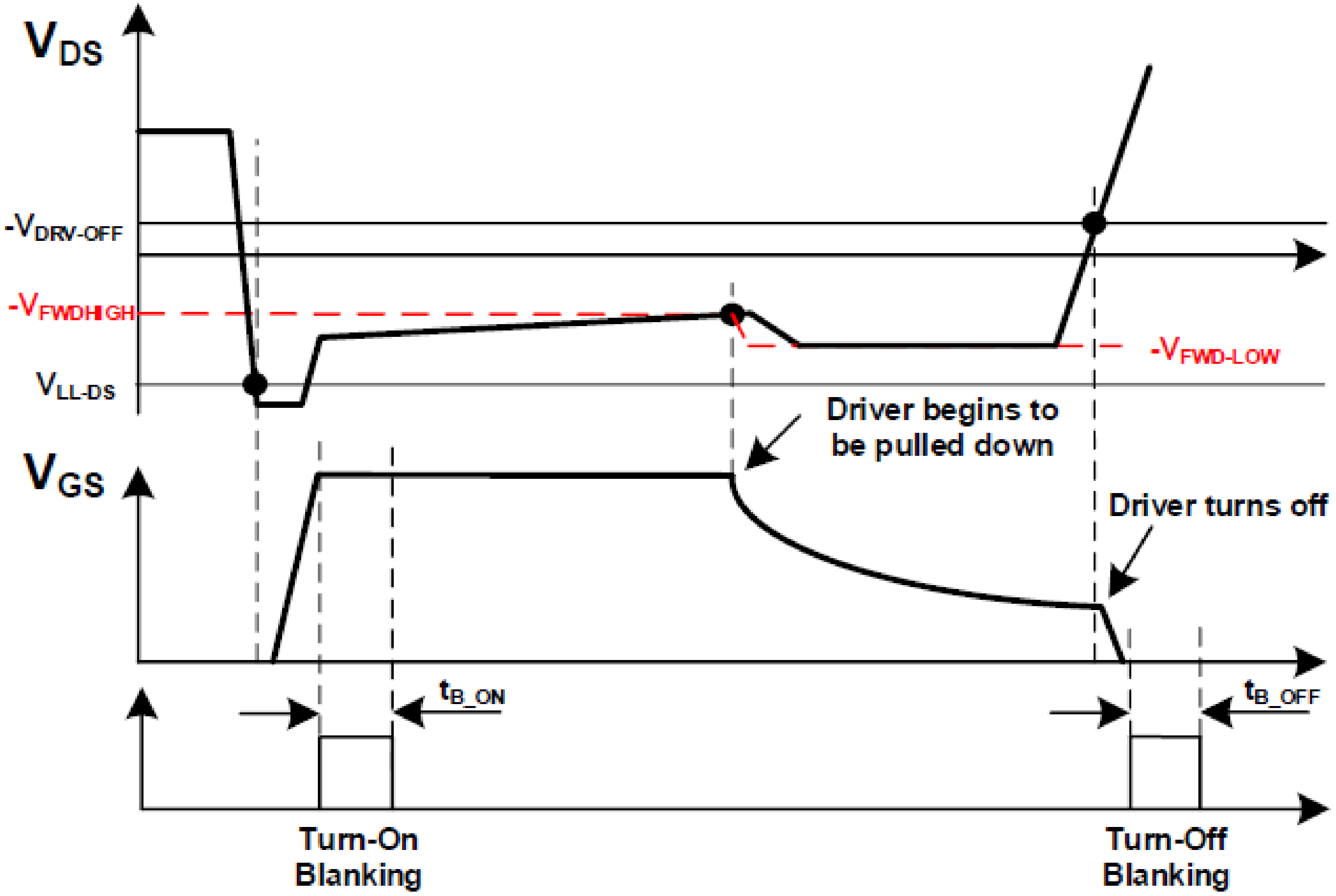
- **Works with 12V Standard and 5V Logic-Level FETS**
- Fast Turn-Off Total Delay
- 4.3V to 35V Wide V_{DD} Operating Range
- **Tolerant to 200V Drain-to-Source Voltage**
- <150µA Quiescent Current (I_Q)
- Supports High-Side and Low-Side Rectification





MP6928A Adaptive Forward Voltage

- Fast Turn-Off Speed (About 35ns)
- Supports CCM, DCM, and BCM Modes
- Light-Load Function to Latch Off the Gate Driver under Light-load Conditions, Limiting the Current to 85µA
- Drives two N-channel MOSFETs, Adaptive Forward Voltage Drop Regulation

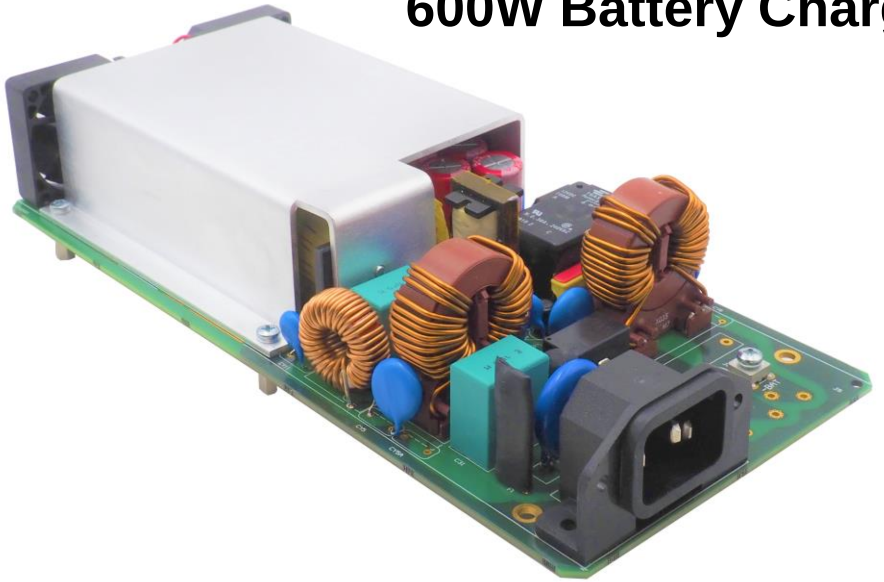


HR1211 Reference Design Examples

USB PD 3.1 240W

Parameter	Specifications
Input Voltage Range	$100V_{AC}$ to $265V_{AC}$
Output Voltage Range	$3.3V_{DC}$ to $48V_{DC}$
Output Current	Up to 5A
Efficiency	>94%
Power Factor	>98%
Conducted Emissions	Meets Class-B EN55032 Standards

600W Battery Charger



Parameter	Specifications
Input Voltage Range	$85V_{AC}$ to $265V_{AC}$
Output Voltage Range	$35V_{DC}$ to $58.8V_{DC}$ (±1.5%)
Output Current	10A (±1.5%)
Efficiency	>92%
Power Factor	>98%
Conducted Emissions	Meets Class-B EN55032 Standards

Agenda

- Understanding Power Factor Correction
- MPS Solutions for PFCs
- Understanding Resonant Power Conversion
- MPS Solutions for LLCs
- Q&A

Thank you!

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