Deep Dive into PFC Solutions

November 2024

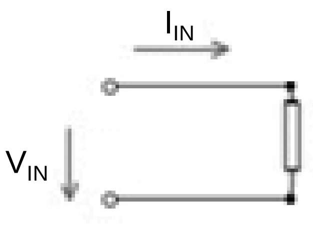
Agenda

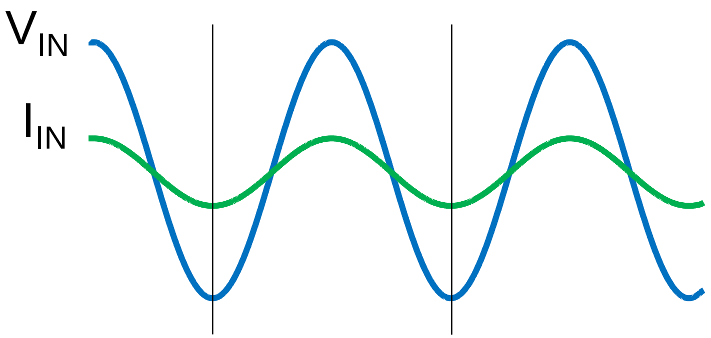
- **Introduction**
  - Power Factor Correction Basics
- **Advanced PFC Solution**
  - Improvement on Efficiency, PF, and Harmonics
- **Progressive Totem-pole PFC solution**
  - Simple and Reliable enough for Practical Uses

Power Factor Correction (PFC)

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

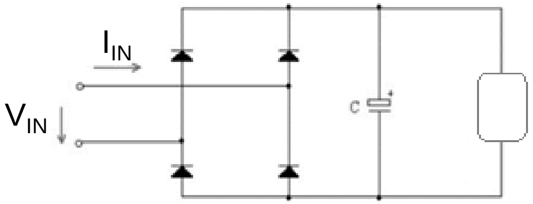
- A PF of 1 corresponds to a pure resistive load

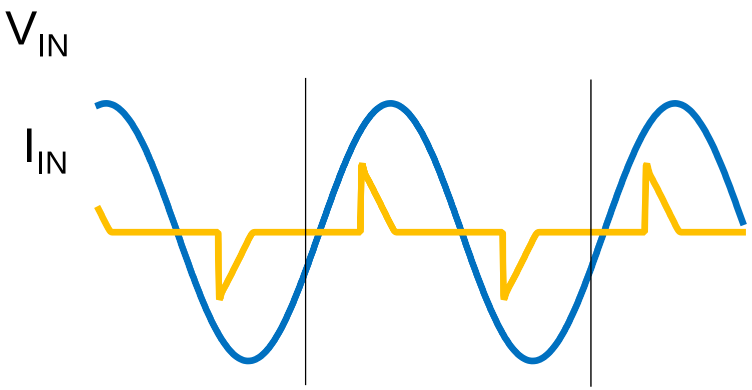




  - The current is sinusoidal and in phase with V_{IN}.

- A typical power supply has a PF below 1.

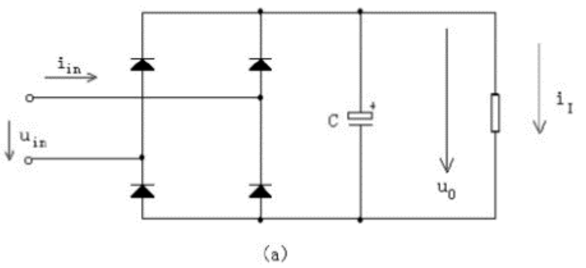




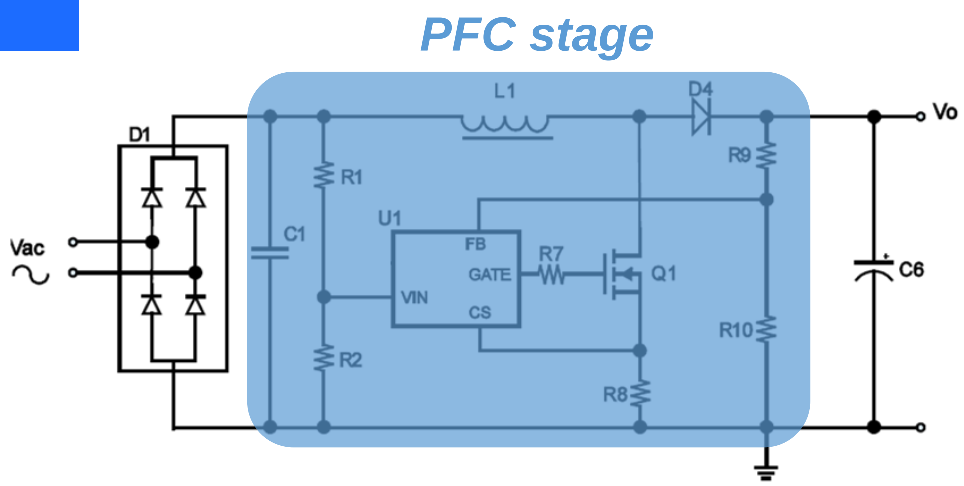
  - The current is not sinusoidal and may be out of phase with V_{IN}.
  - Larger RMS current circulates in the input (higher reactive power).

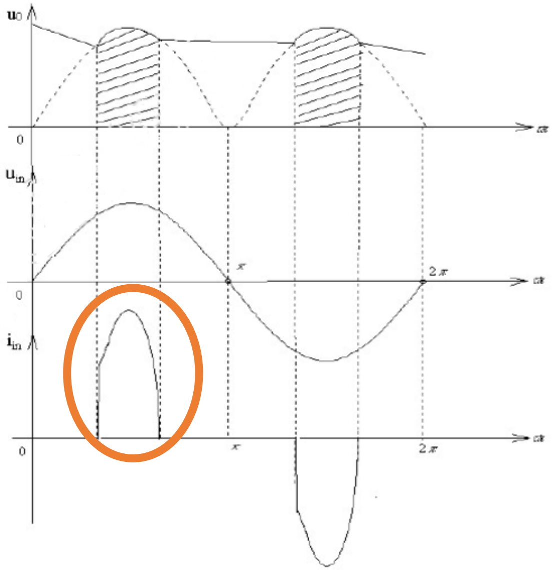
MPS

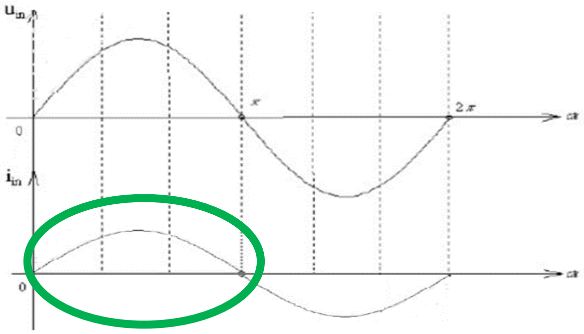
The Basic Concept of PFC



Adding PFC



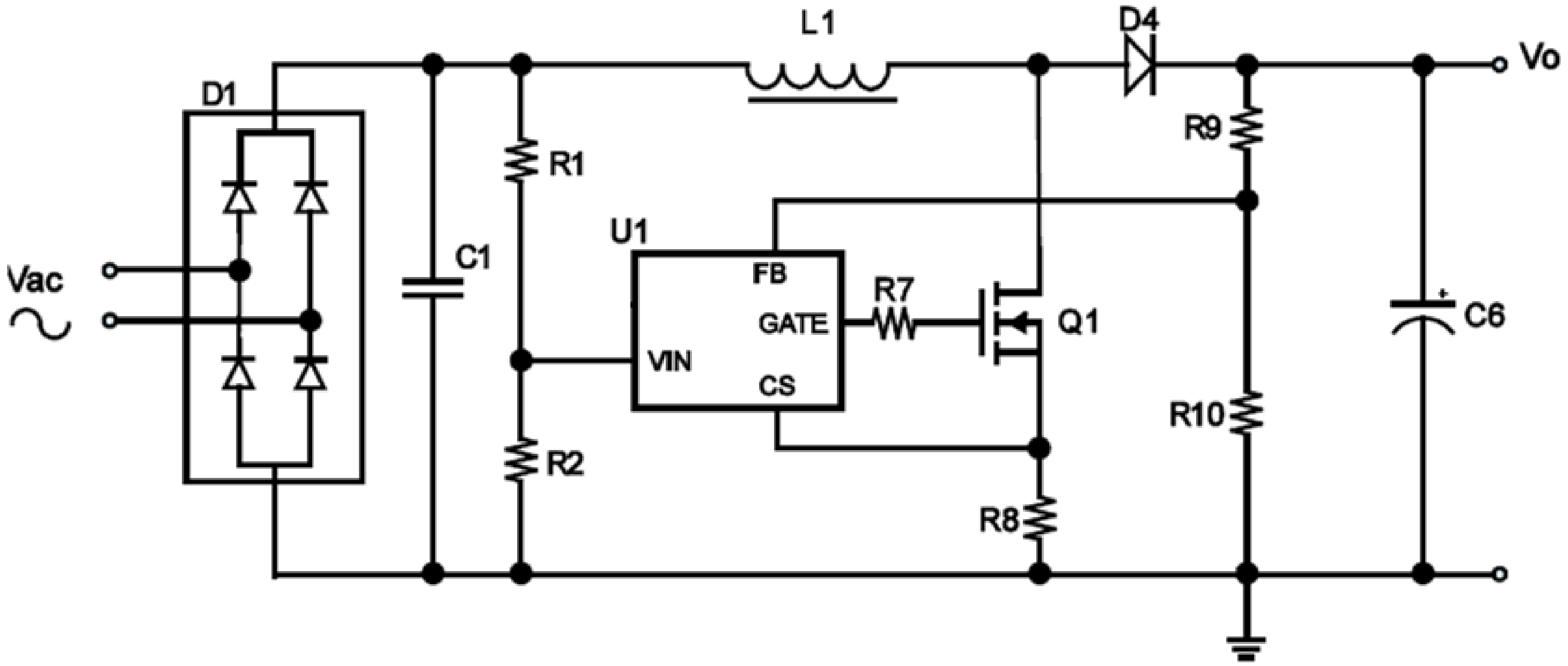




The input current follows the voltage (sinusoidal).

PFC can be **passive** (e.g. inductors, valley-fill) or **active** (e.g. Buck, Boost, Flyback).
When considering the tradeoffs between performance, efficiency, size, and cost, the **boost** PFC is the most widely used topology.

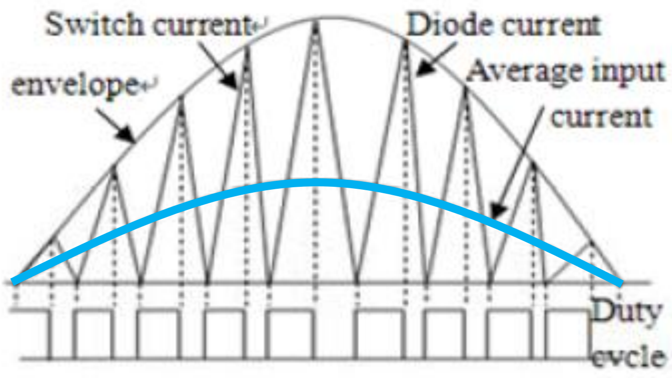
Boost PFC



- Simple implementation (1x inductor, 1x switch, 1x diode)
- Step-up with high efficiency
- Good surge immunity

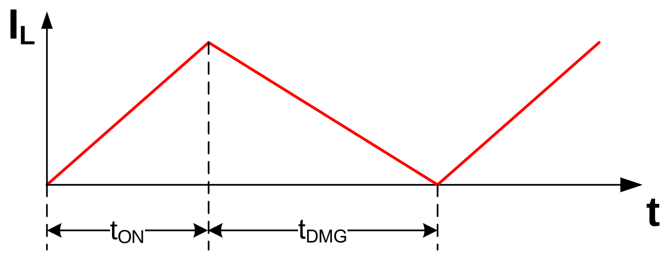
Boost PFC Control Method: CoT BCM

Constant-on-Time (COT) Boundary-Conduction Mode (BCM) / Critical-Conduction Mode (CrM)



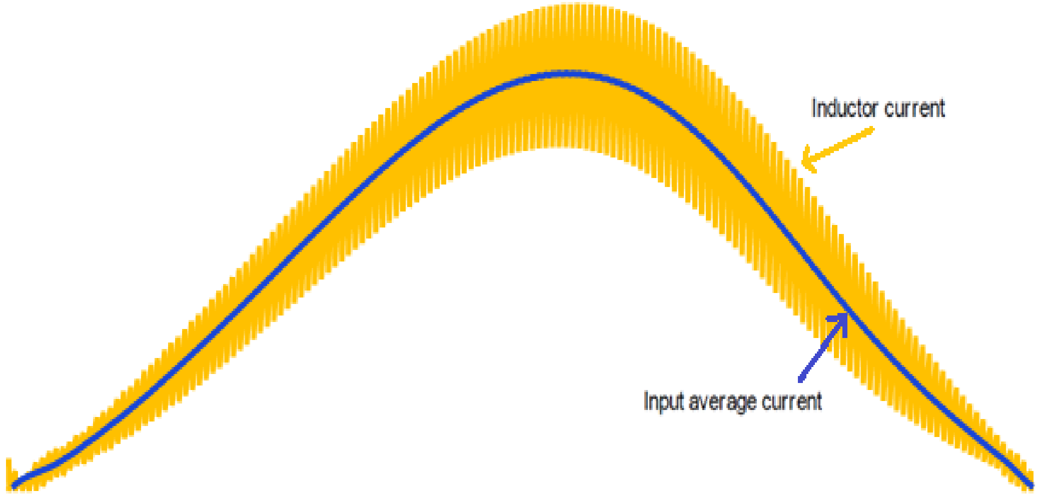
- Simple architecture (no need to measure V_{IN})
- Zero-current switching (and valley switching)
  - *Low cost, low noise*

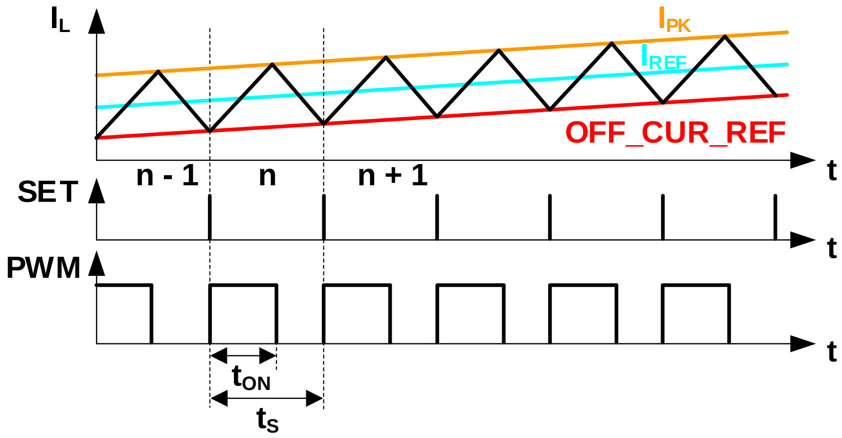
- High RMS current (I_{PK} is double the I_{IN} average)
  - *Limited to < 300W (more with interleaving)*

	CrM (Constant-On-Time)
Operation Mode	
Input Current	$I_{IN1}(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{2 \times L} \times t_{ON}(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ1}}$
Input Equivalent Impedance	$R_{EQ1} = \frac{2 \times L}{t_{ON}(\theta)}$
Condition for PF = 1	$t_{ON}(\theta) = \text{constant}$

Boost PFC Control Method: CCM

Continuous Conduction Mode (CCM)





- Lower RMS current (I_{IN} average is more close to I_{PK})
  - *Can be used for higher power*

- More complex architecture (Control based on Input voltage and inductor current sampling)
- Hard switching
  - *Higher cost, higher noise, higher switching loss*

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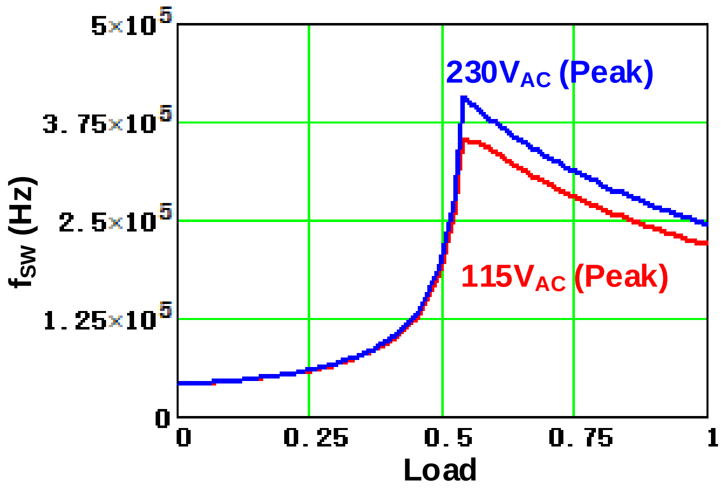
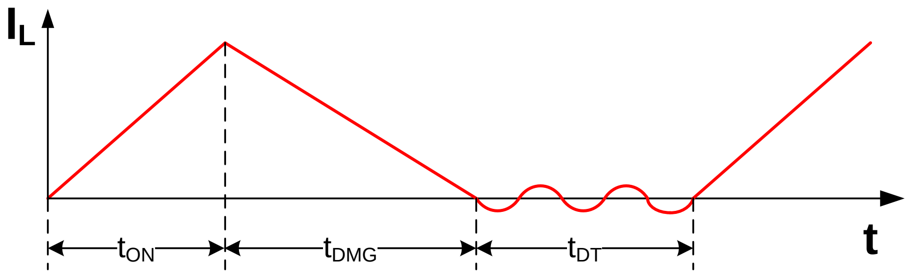
Efficiency Improvement – BCM + DCM

Allowing Discontinuous Conduction Mode (DCM) when the Output Power (P_{OUT}) Decreases

In BCM, the switching frequency (f_{SW}) goes up when P_{OUT} decreases. This results in high switching losses.

Multi-mode controllers, like HR1275 from MPS, insert a dead time to force it into DCM tp reduce f_{SW}, which results in higher light-load efficiency.

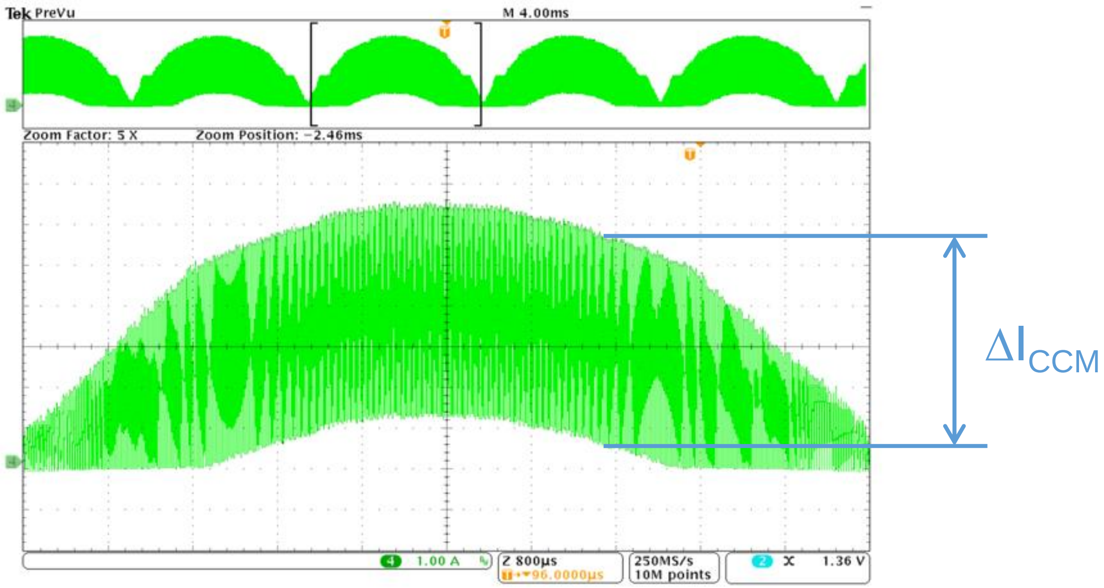


	DCM (Variable-On-Time)
Operation Mode	
Input Current	$I_{IN2}(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{2\times L}\times t_{ON}(\theta)\times D_C(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ2}}$ $D_C(\theta) = \frac{t_{ON}(\theta)+t_{DMG}(\theta)}{t_{ON}(\theta)+t_{DMG}(\theta)+t_{DT}}$
Input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

Efficiency Improvement – CCM + BCM + DCM

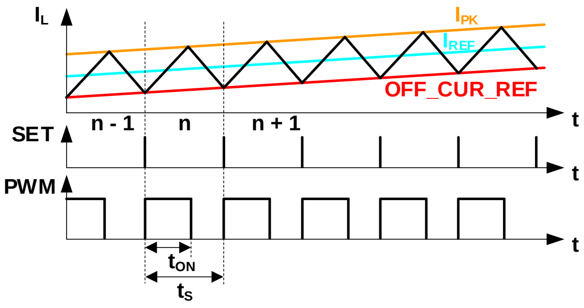
Enhanced Multi-Mode (EMM) control with all 3 modes, i.e. CCM, BCM, and DCM, is implemented by advance PFC controllers, like HR1230, HR1211 from MPS.

- CCM at high current
- BCM at medium current.
- Variable DCM modes at low current or light loads



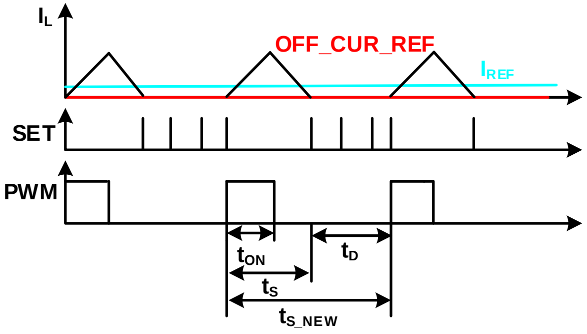
DCM……CrM…...CCM......CrM......DCM

CCM



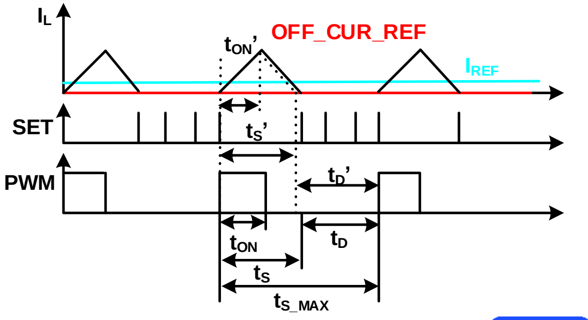
CF-DCM

Constant Frequency



VF-DCM

Variable Frequency

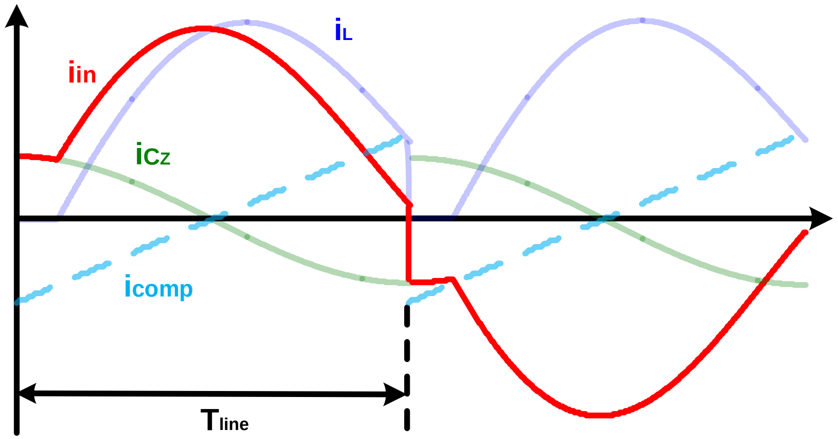


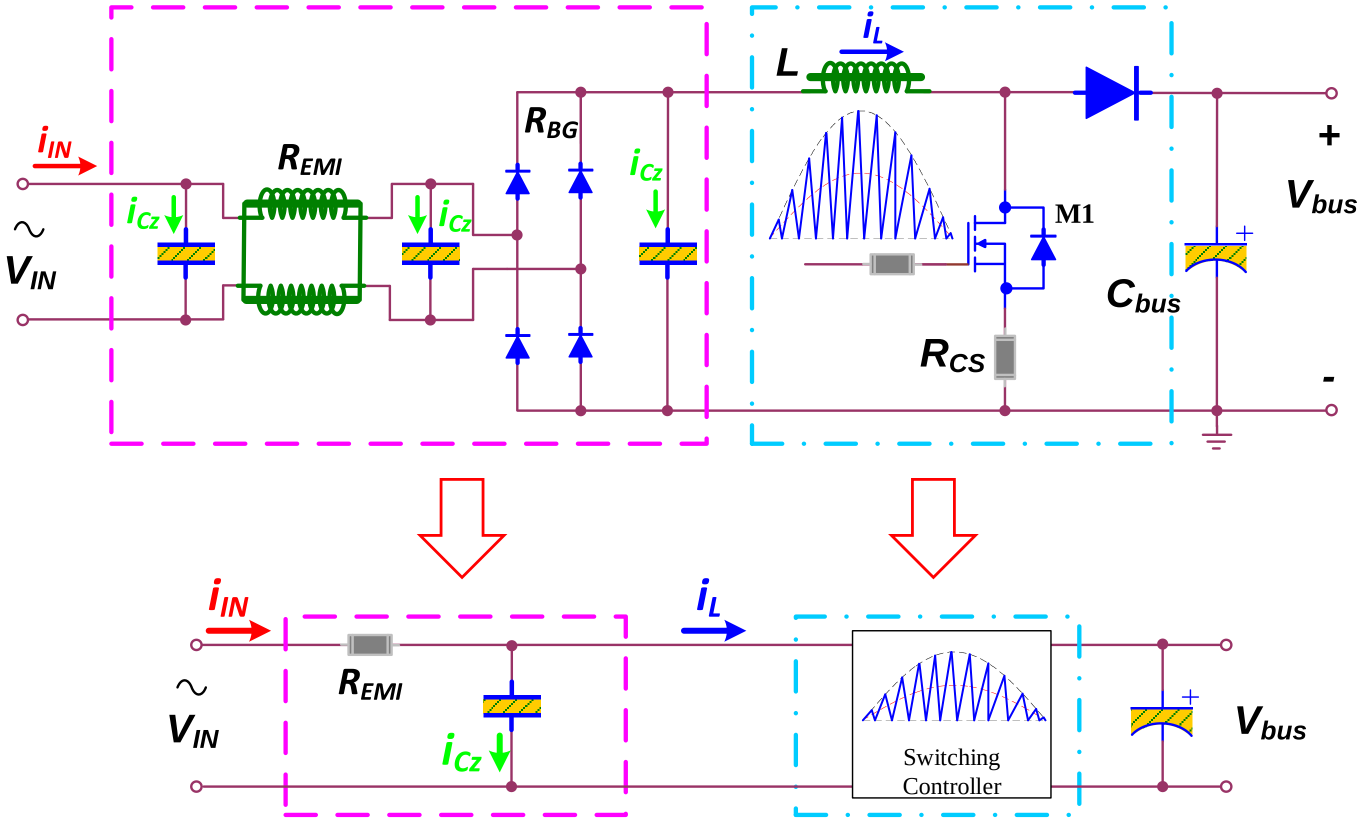
PF Enhancement with Input Capacitor Current Compensation

A boost PFC shapes its input current to be sinusoidal, but the input filter placed in front of the PFC can degrade the Power Factor by introducing a phase shift.

- Compensating for the input capacitor current can improve the PF

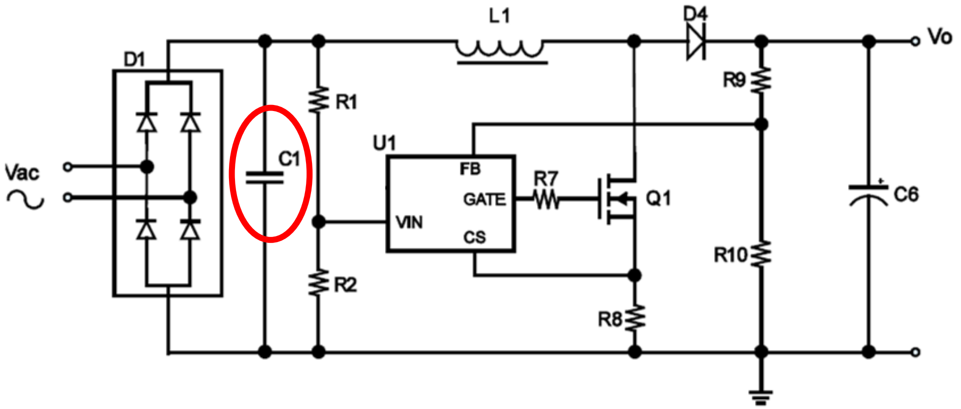
<u>Example of compensation</u>:
Add a triangular wave in the PFC control law.



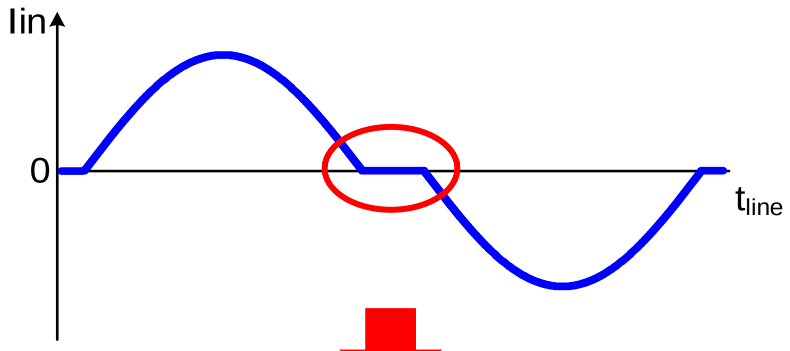


Harmonic Improvement with Extension on Zero-Crossing

At light loads, the input filtering capacitor does not fully discharge around the zero crossing of the input AC.
A constant-on-time (COT) controller may also reach the max frequency limit around zero-crossing
This is the cause of high distortion (high THD).

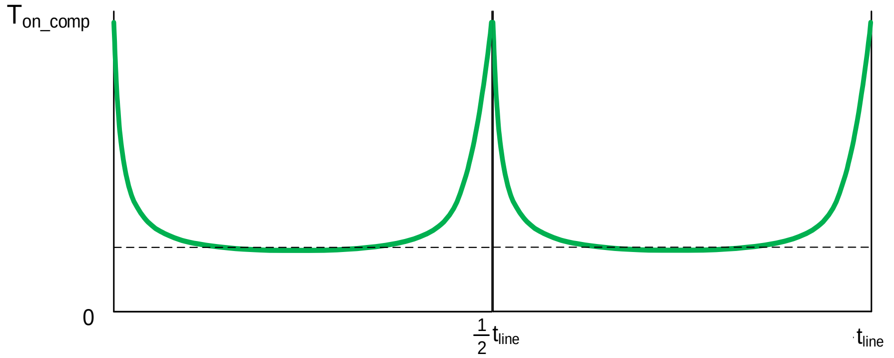


Constant-On-Time



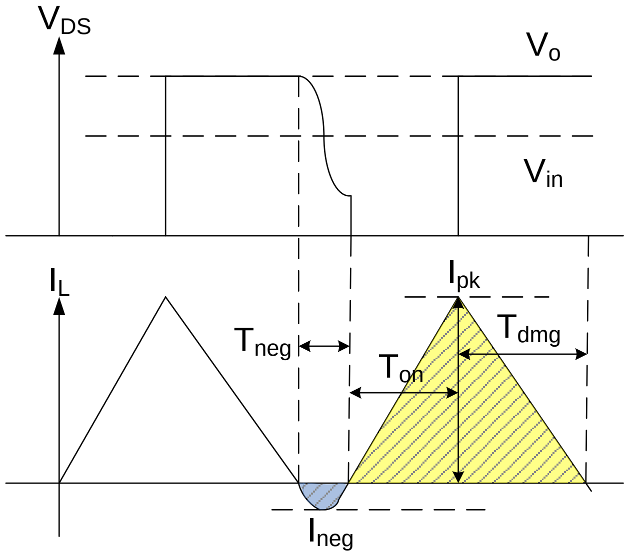
Improved Constant On-Time

- Lower total harmonic current distortion (THD) due to **extension at zero-crossing** compared to conventional constant-on-time control.

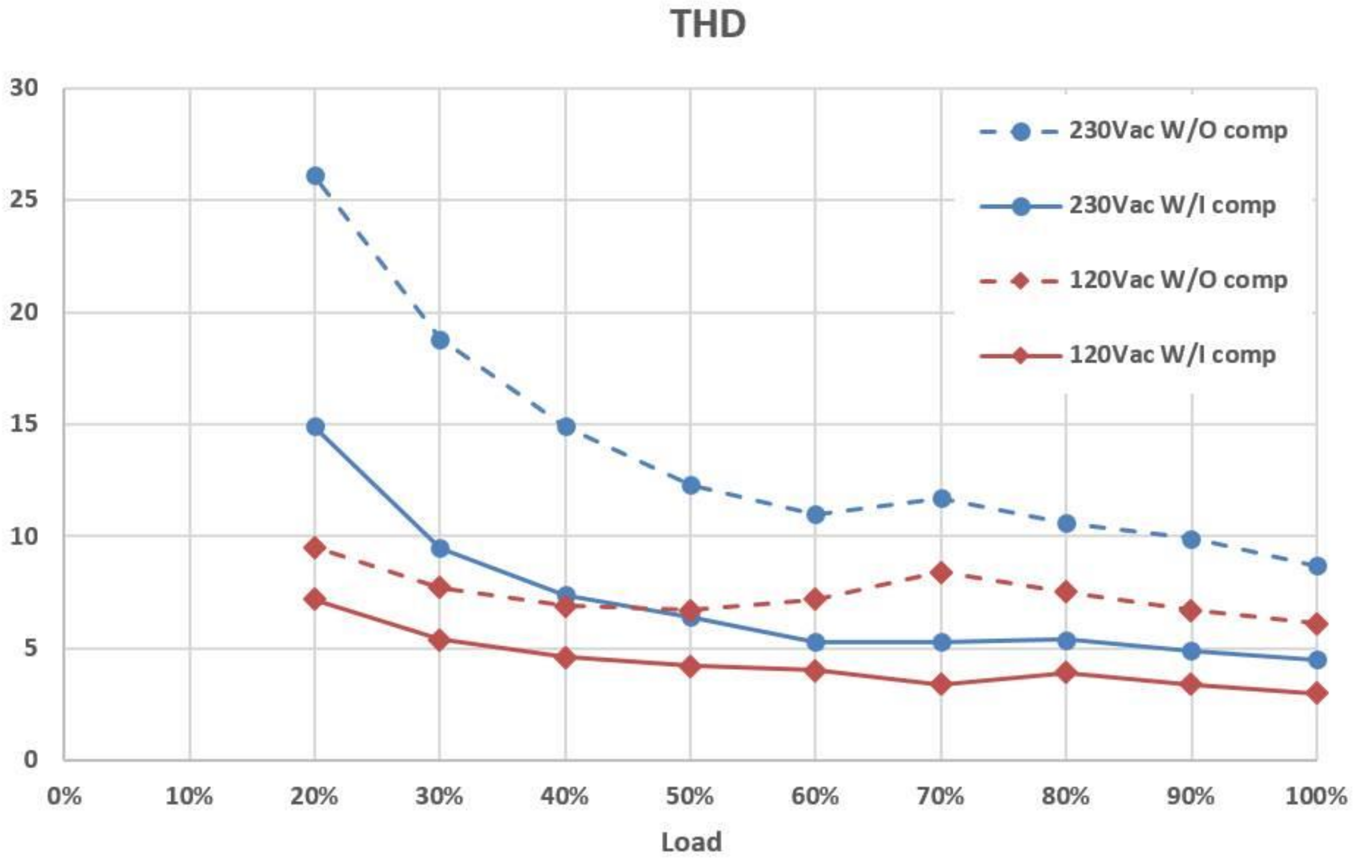


Harmonic Improvement with Oscillation Current Compensation

The oscillation current at DCM is another essential factor that cause distortion. Therefore, advanced PFC controllers, like HR1275 and HR1230 implement both extension at zero-crossing and oscillation current compensation to be able to meet all kinds of THD requirement.



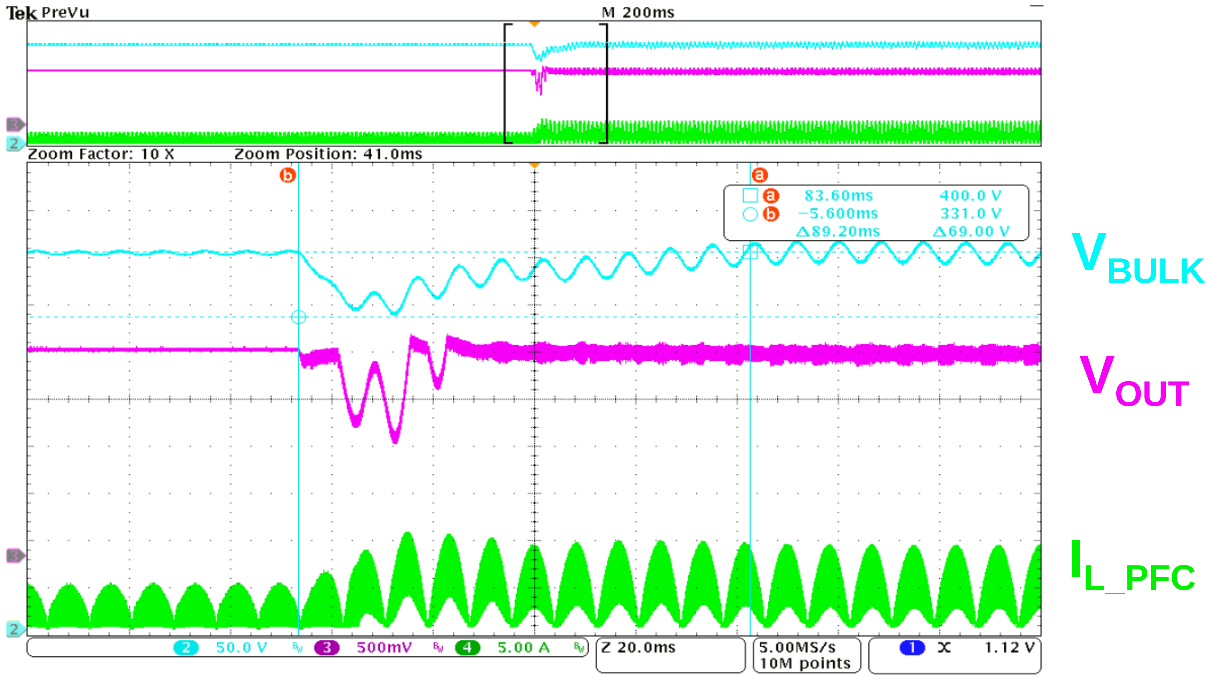
$$I_{in} = \frac{(T_{on} + T_{dmg}) \cdot \frac{I_{pk}}{2} - \int_0^{T_{neg}} I_{neg}(t)dt}{T_{on} + T_{dmg} + T_{neg}}$$



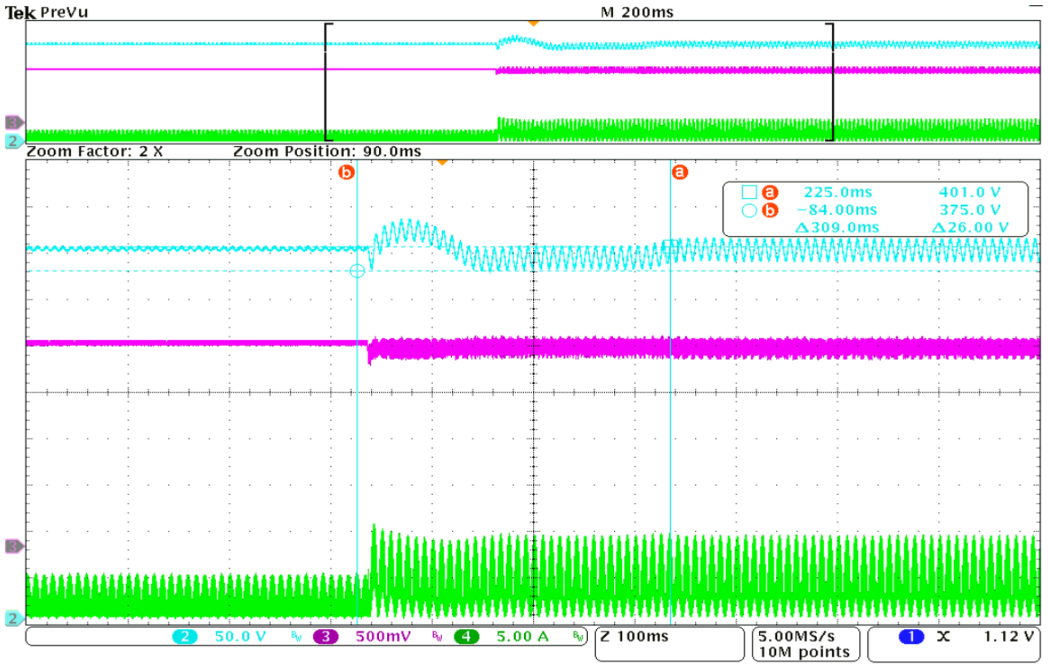
Fast Regulation Achieved by Nonlinear Control

Test condition： 230Vac 50% load → 200% load

Without PFC fast response function



With PFC fast response function



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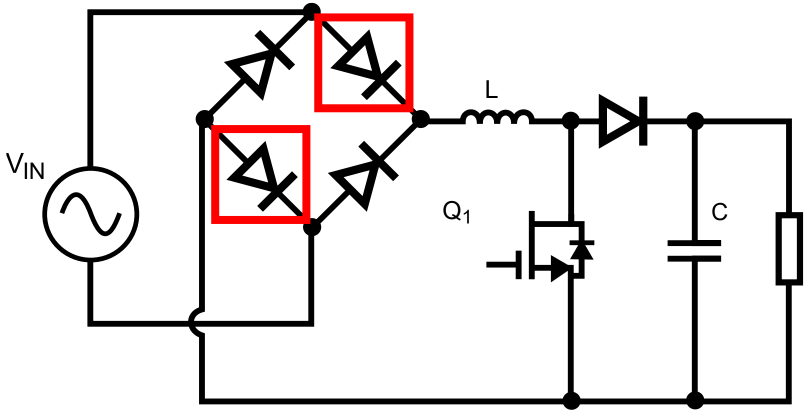
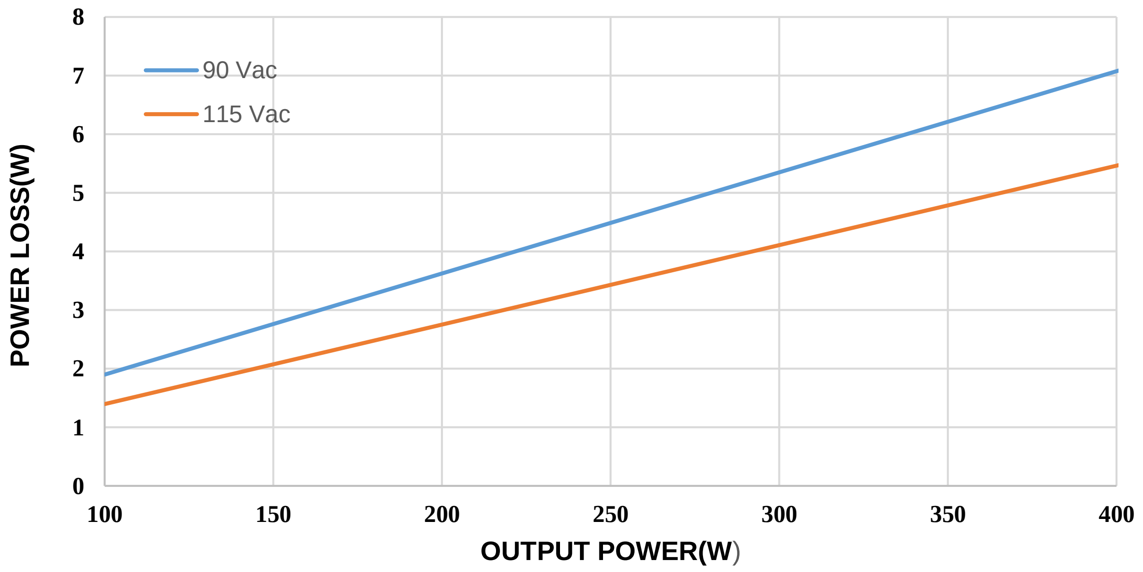
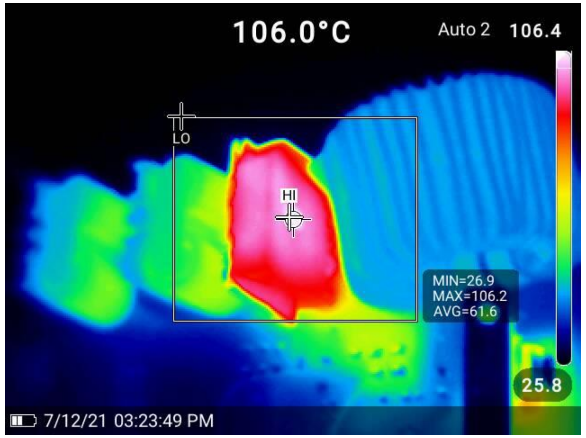
Rectifier Bridge Losses

The bridge rectifier adds 2 diodes in series with the boost PFC at all times, => conduction losses



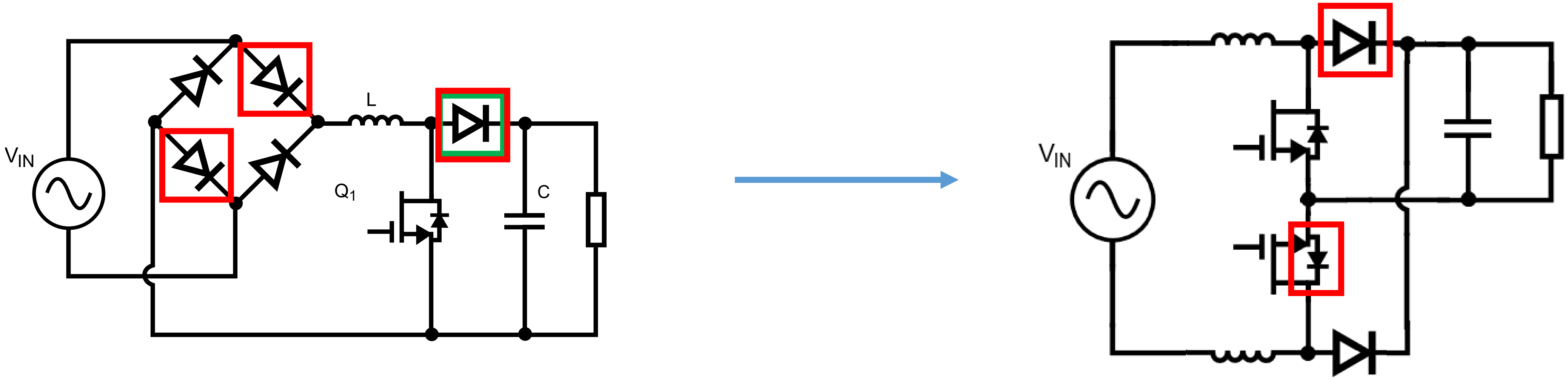
The heat generated by the bridge becomes the main factor limiting power density.





Bridgeless PFC – Concept

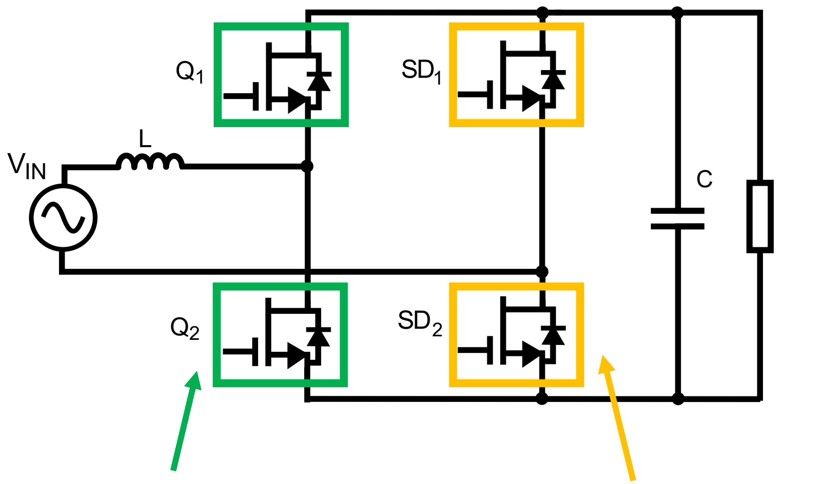
In a conventional boost PFC, there is already a diode blocking the reverse conduction — why not utilize this diode to remove the diode bridge rectifier?
When using one boost PFC on each AC line, they work in turns, one for each alternance of the sinusoidal input voltage.



With one PFC boost on each input line, one series diode can be effectively removed from the direct path, which reduces rectifying losses and improves efficiency.

Totem-Pole PFC

A variant of the bridgeless dual-boost PFC is the totem-pole PFC.



Fast Switching

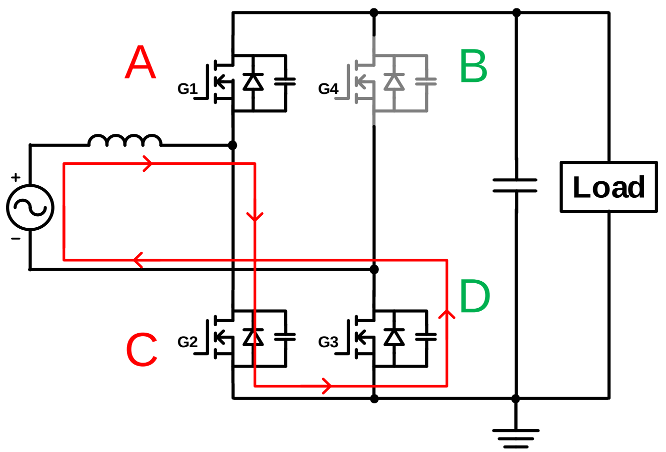
$f_{SW} = 100kHz$

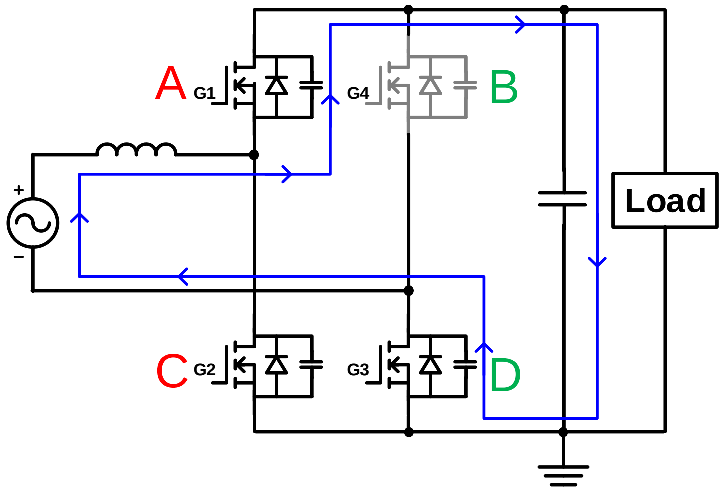
Slow Switching

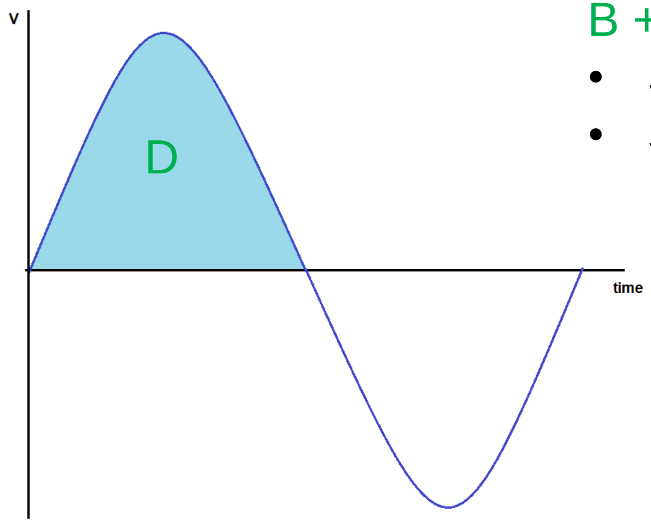
$f_{SW} = f_{GRID}$

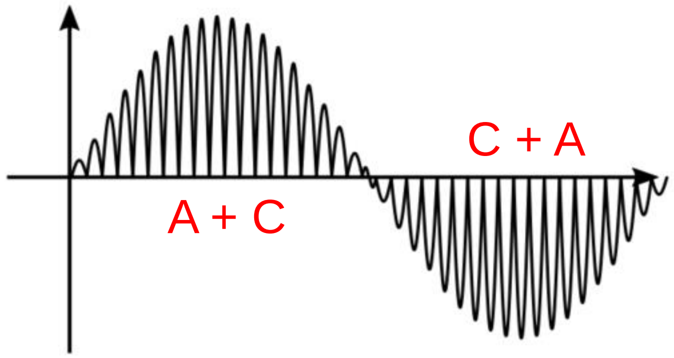
- Reduced to one inductor.
- Diodes replaced by MOSFETs.
- Rearranged to work as a synchronous boost (fast switching leg) with polarity-selection switches (slow switching leg).

Totem Pole PFC – Operation







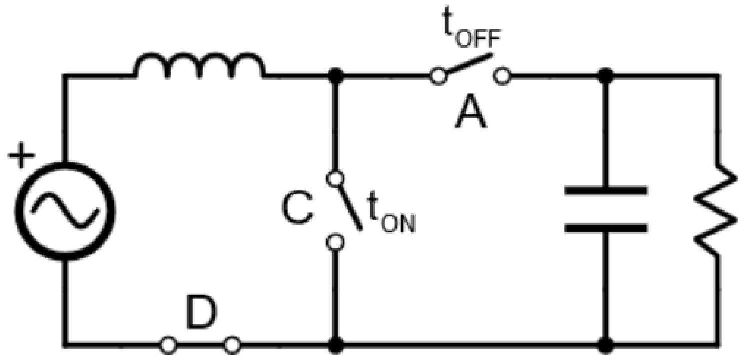


A + C

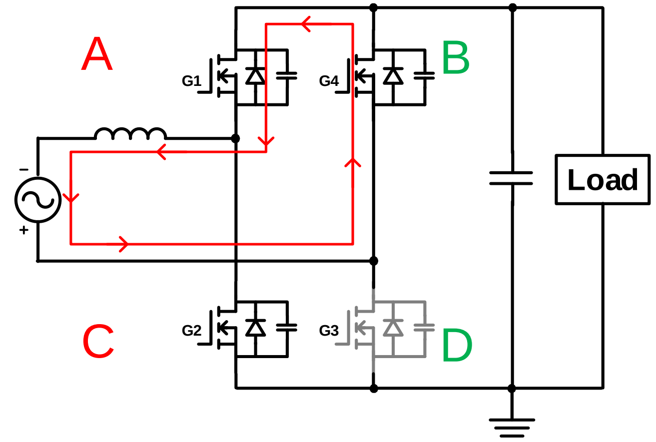
- Fast switches connected to inductor
- Work as a synchronous boost

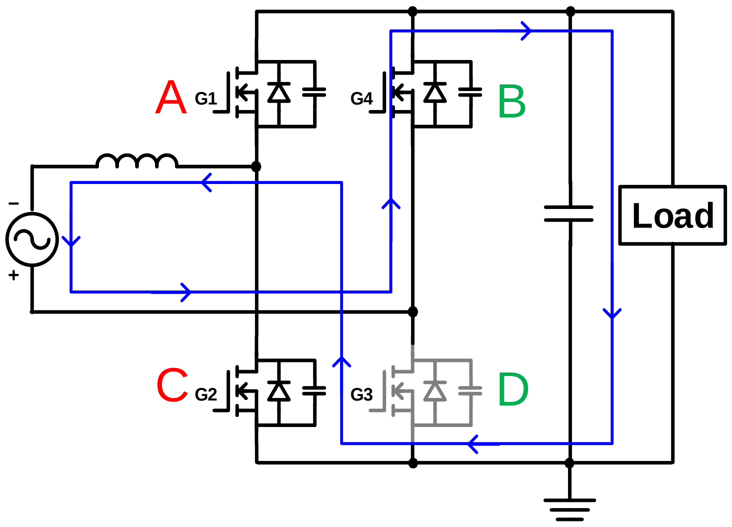
B + D

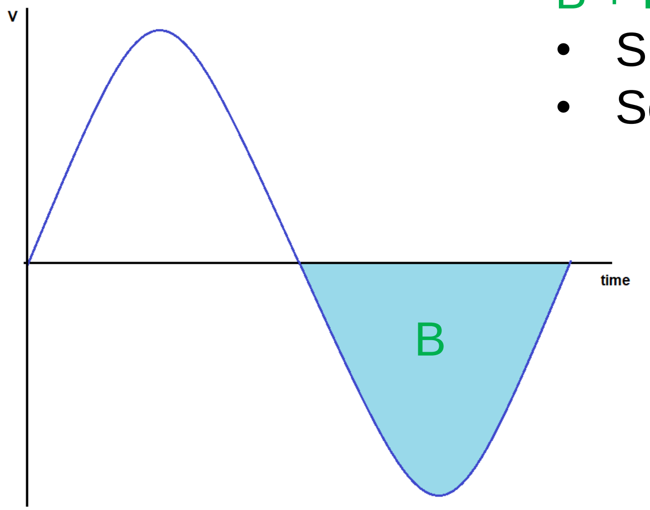
- Slow switches
- Select input polarity

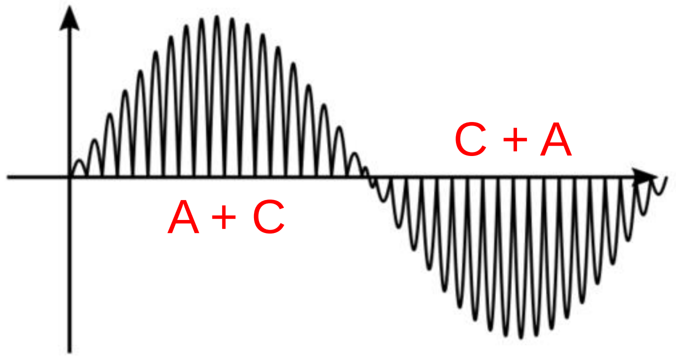


Totem Pole PFC – Operation









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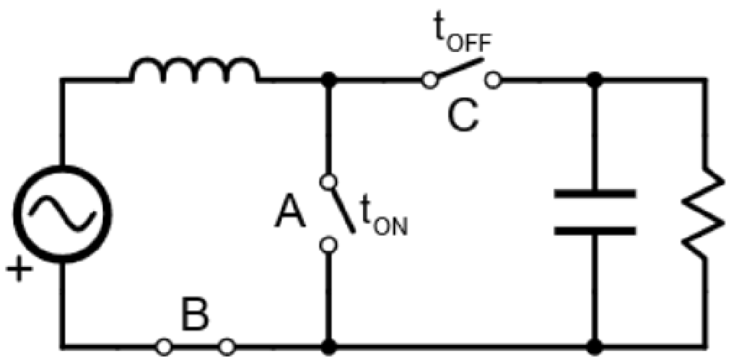
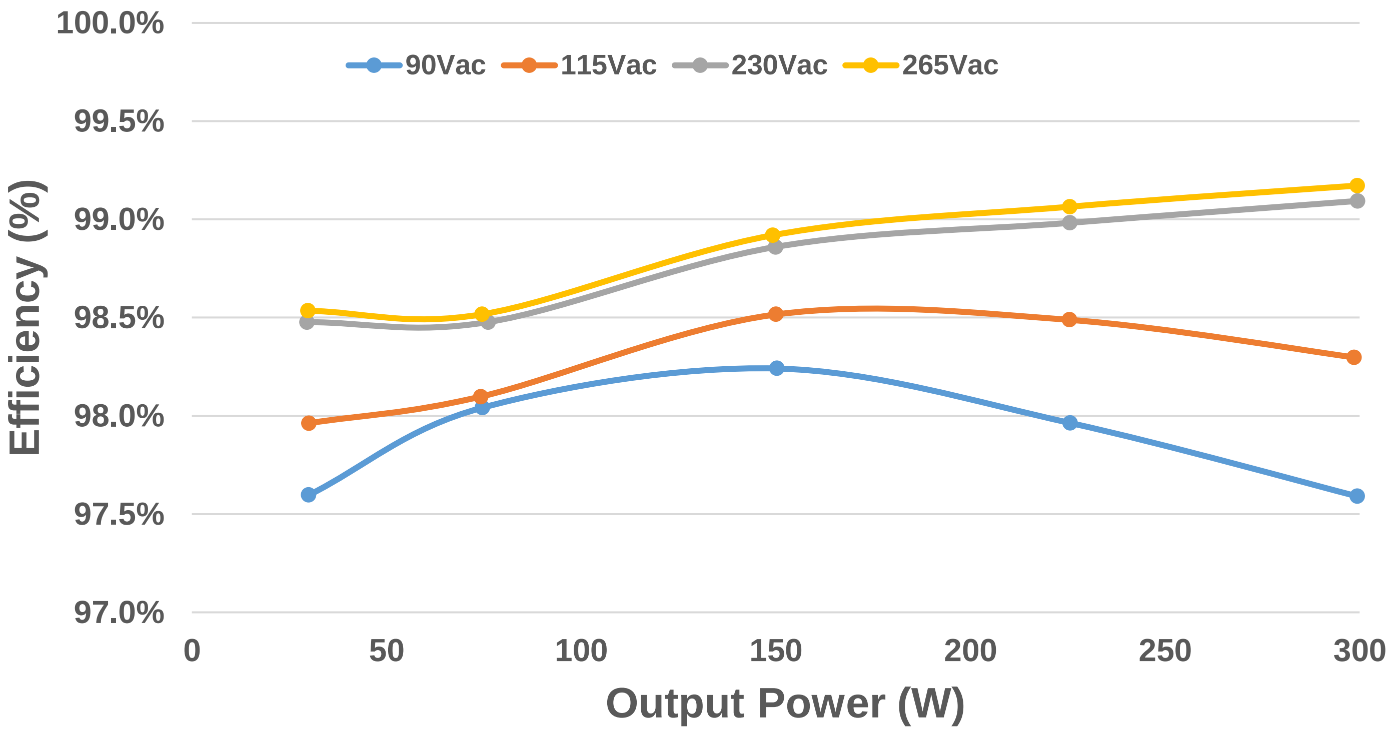


Totem Pole PFC results

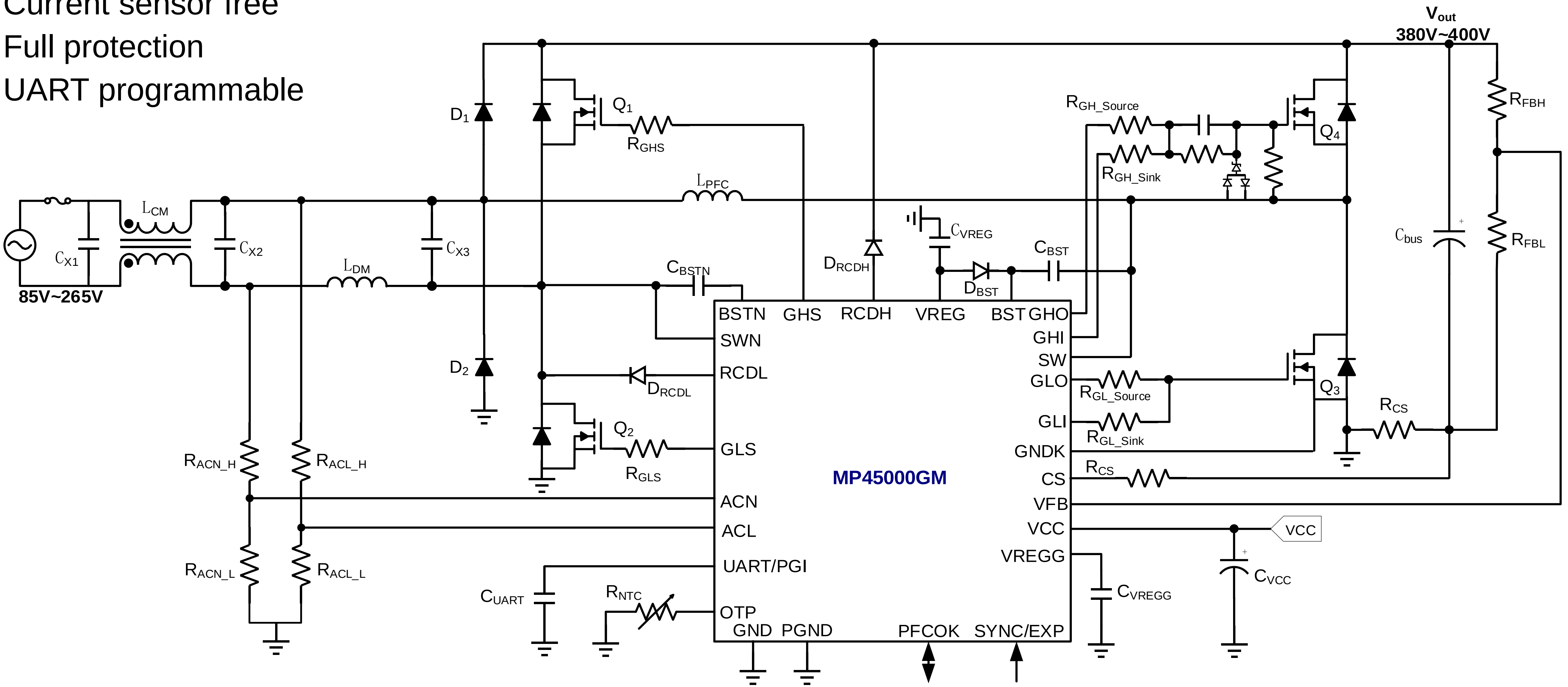
Topology	Totem Pole PFC	Normal PFC
Freewheeling diode	-	1x fast recovery
Fast MOSFET/SiC MOSFET/GaN	2x GaN FET * 2	1x GaN FET
Rectifier bridge	-	1x
Slow MOSFET/Diode	2x Si MOSFET	-
Efficiency@90V/300W	**97.6%**	**95.8%**

Measured on a 300W CrM Totem-Pole using 2x GaN FETs and 2x Si MOSFETs (MP45000 controller)

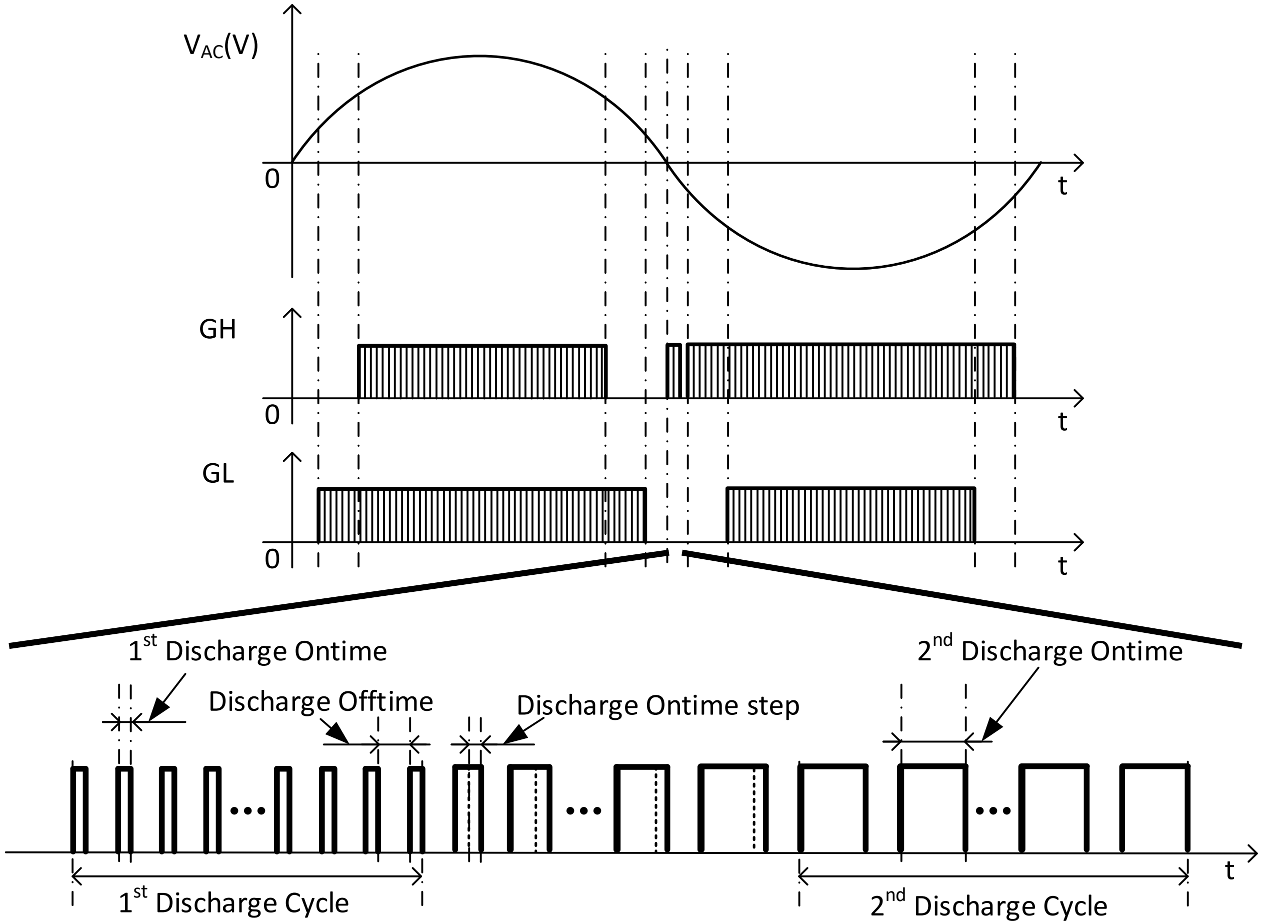


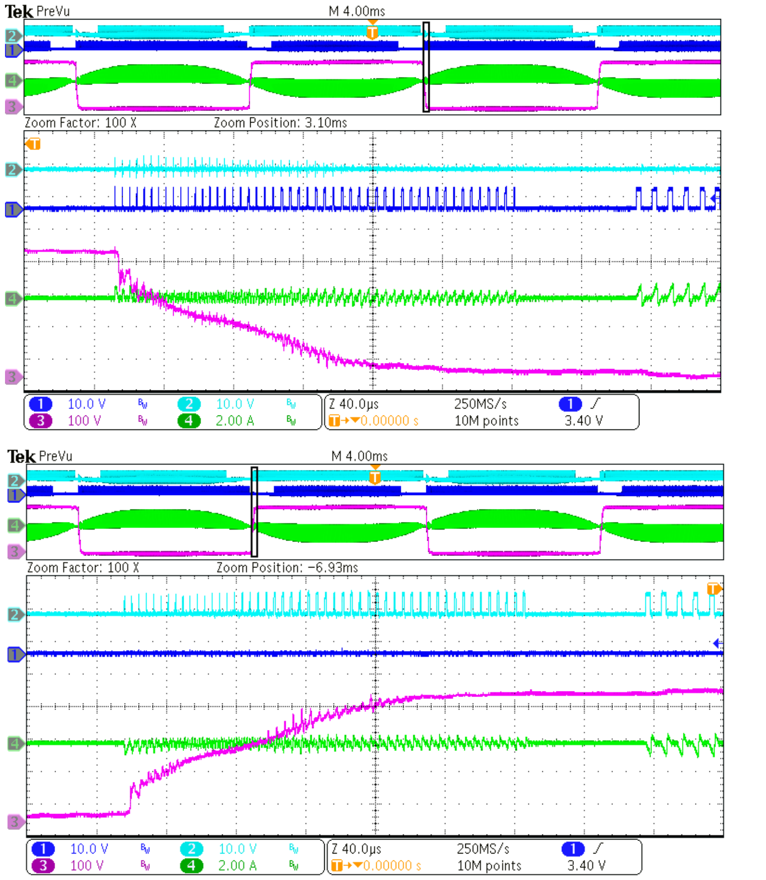
Solution to the Challenge of System Complexity and Cost

- Digital controller with all drivers integrated in TSSOP28
- Current sensor free
- Full protection
- UART programmable



Solution to the Challenge of EMI



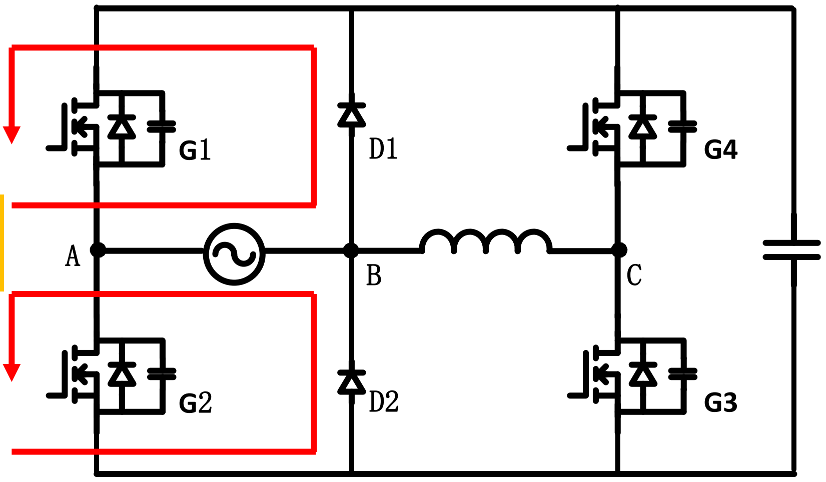


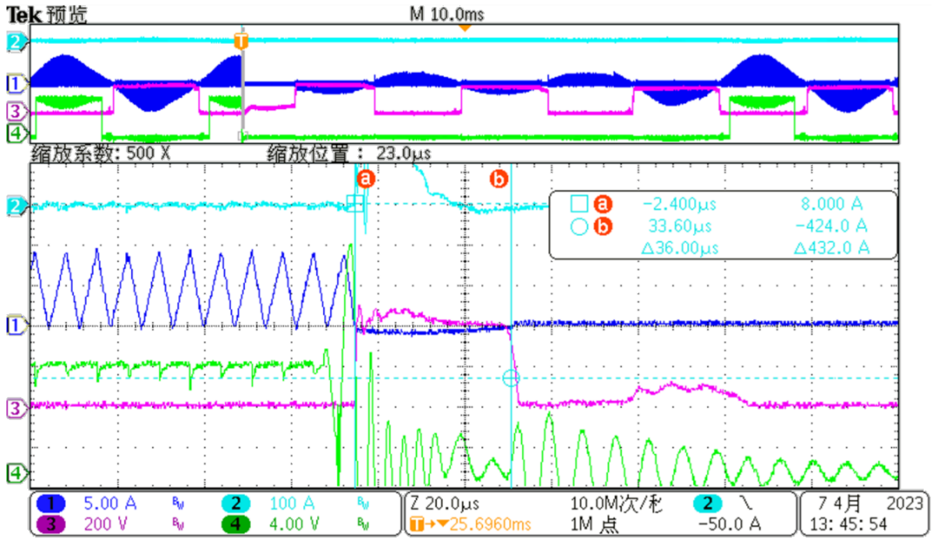
CH1:GL **CH2:GH** **CH3:AC_N** **CH4:I_L**

- When AC crossover, MP45000 use a soft switch function to slow down the voltage change speed on N line. This will help increase the EMI performance.

Solution to the Challenge of Surge Immunity

Potential short-circuit paths





CH1: I_L CH2: I_{in} CH3: V_{SWN} CH4: V_{gs_G2}

- MP45000 detect the current direction of slow bridge MOSFETs (G1&G2). All drivers will be stopped if the current flow from drain to source.
- **Current limit of slow bridge could cut off the short-circuit path and protect the power devices.**

Thank you!

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