Deep Dive into PFC Topologies

September 2024

Session 1 Starts: 1 AM PDT | 4 AM EDT | 10 AM CEST
Session 2 Starts: 9 AM PDT | 12 PM EDT | 6 PM CEST

Agenda

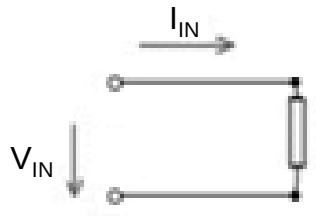
- Introduction: Power Factor Correction
- Boost PFC Control
- Boost PFC Improvements (Efficiency, PF, Distortion)
- Bridgeless PFC
- Questions and Answers

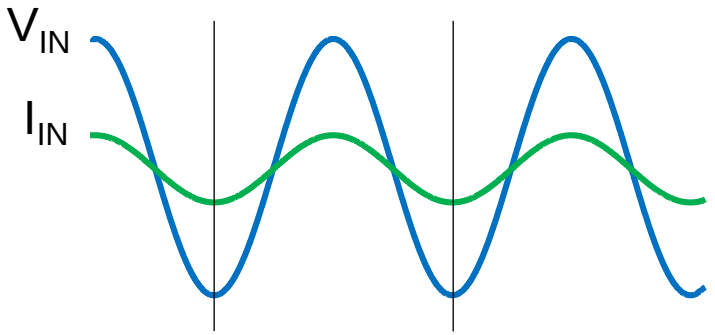
Power Factor Correction (PFC)

- 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:

$$\mathrm{PF} = \frac{\text{Active Power}}{\text{Apparent Power}} = \frac{[\mathrm{W}]}{[\mathrm{V}x\mathrm{A}]}$$

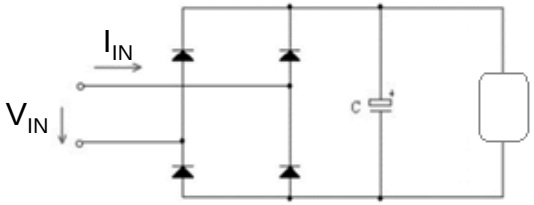
- A PF of 1 corresponds to a pure resistive load

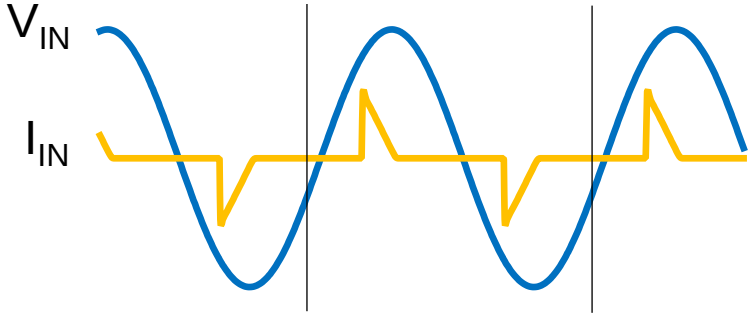




  - The current is sinusoidal and in phase with V_{IN}.

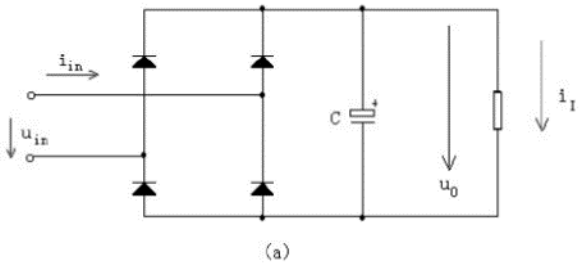
- A typical power supply has a PF below 1.



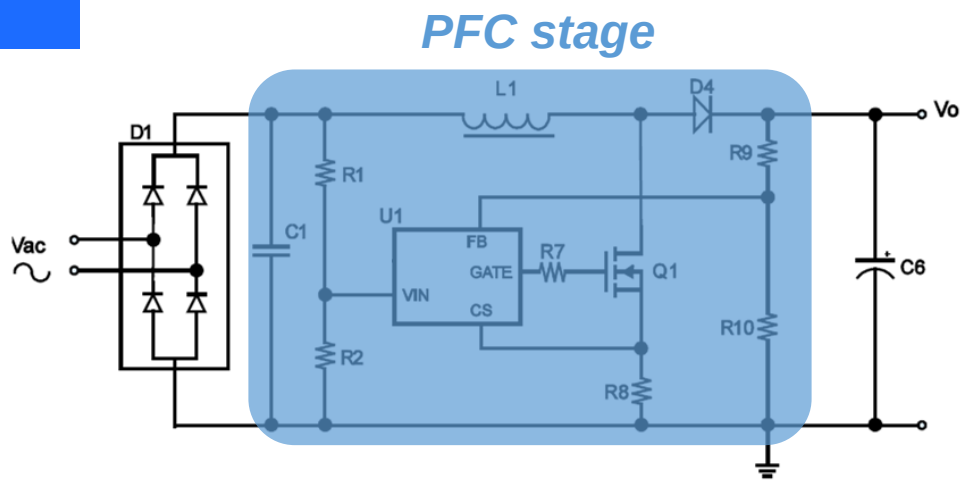


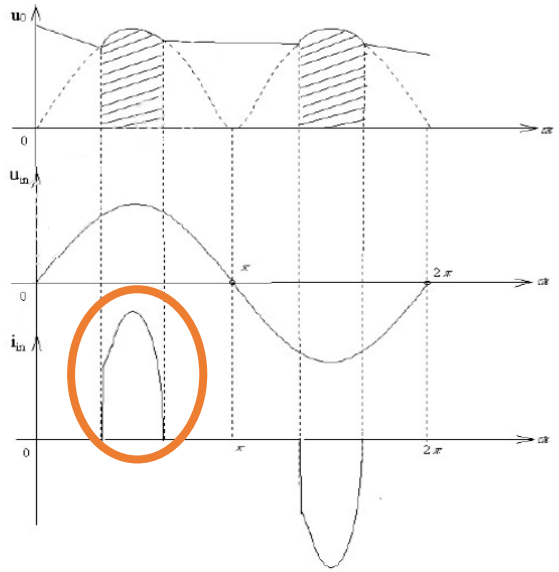
  - The current is not sinusoidal and may be out of phase with V_{IN}.
  - Larger RMS current circulates in the input (higher reactive power).

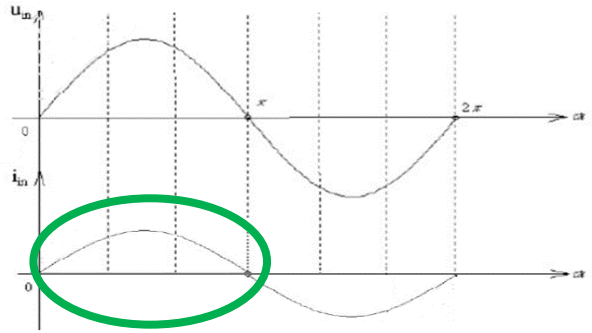
The Basic Concept of PFC



Adding PFC







The input current follows the voltage (sinusoidal).

PFC can be **passive** (e.g. inductor, 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.

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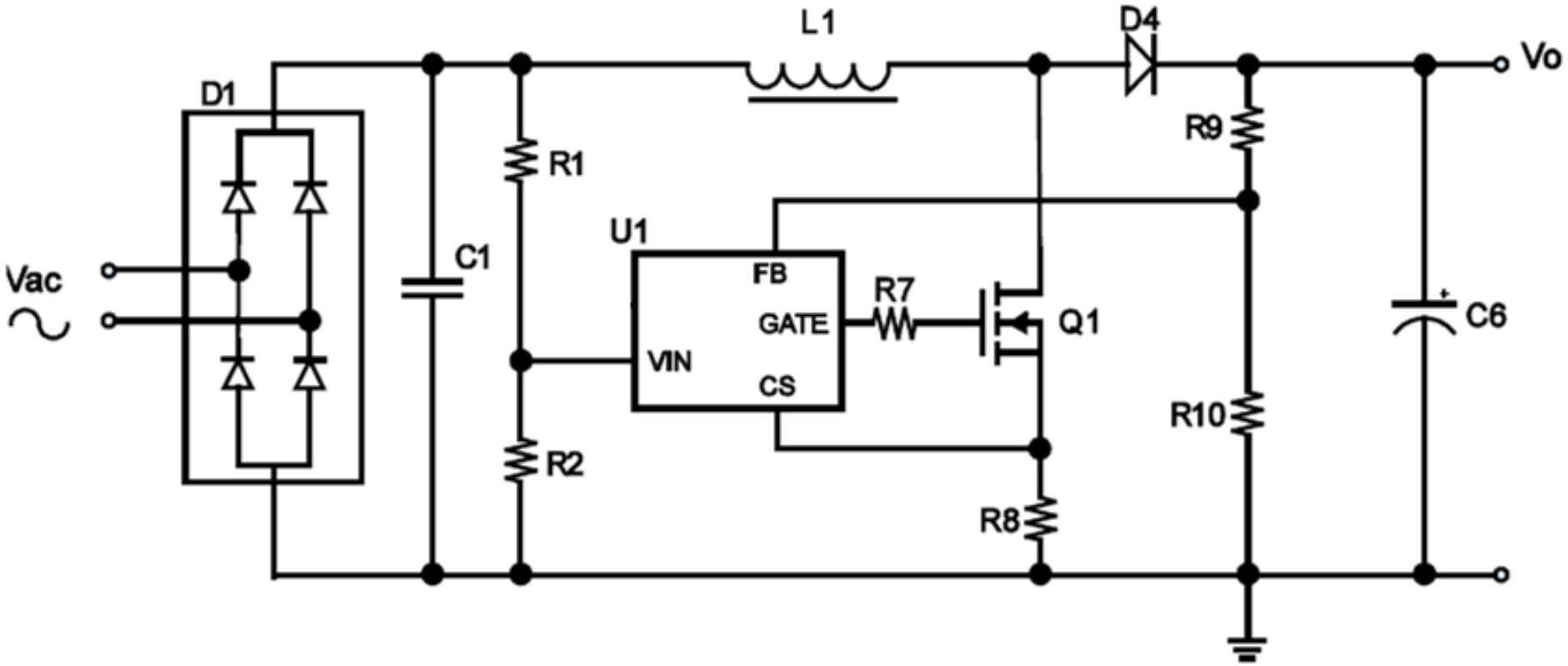
- Boost PFC Control
- Boost PFC Improvements (Efficiency, PF, Distortion)
- Bridgeless PFC
- Questions and Answers

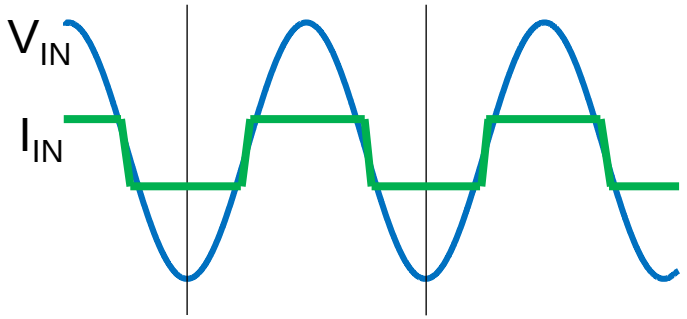
Boost PFC

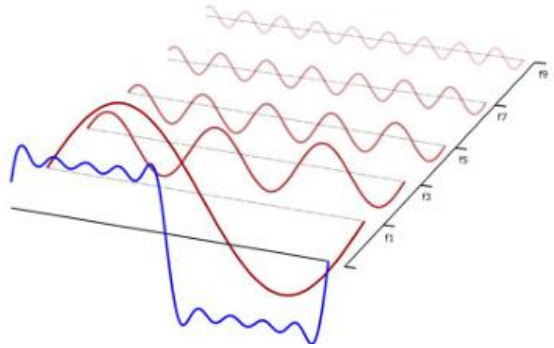


- Simple implementation (1x inductor, 1x switch, 1x diode)
- High efficiency
- Can operate at low input voltage
- Step-up

Boost PFC Control Methods

- Depending on the market, the type of converter, and the region of the world, the standard minimum PF requirements may be different, ranging from not necessary to a high value. There may also be additional requirements, such as the amount of distortion or minimum PF at different output power levels.
  Different types of PFC circuits and their various control methods are well-suited for different scenarios.
  In addition, new standards may be implemented or evolve over time, and certain methods may become obsolete.
- For example, one of the simplest control methods for an active boost PFC is to run it at a constant current.



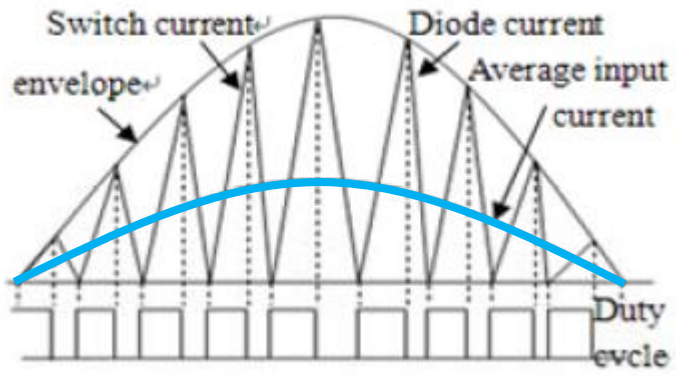


This method greatly improves the rectifier bridge's conduction time, but the average input current is far from sinusoidal (a square wave is a highly distorted sinusoid). Although the PF is not very high (about 0.7) and the distortion is high, this method is sufficient in certain cases.

- For this webinar, we will focus on the most practical and widely used control methods.

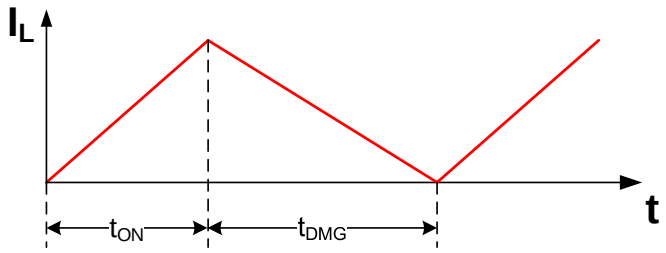
Boost PFC Control Method: CoT BCM

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



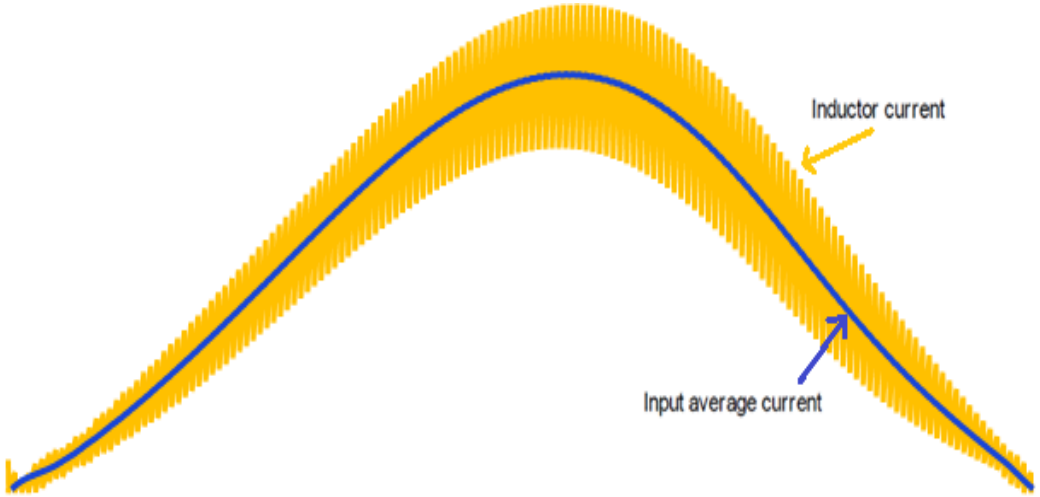
- Simple architecture (no need to measure V_{IN})
- Zero-current switching (and valley switching)
  - ➢ *Low cost, low noise*

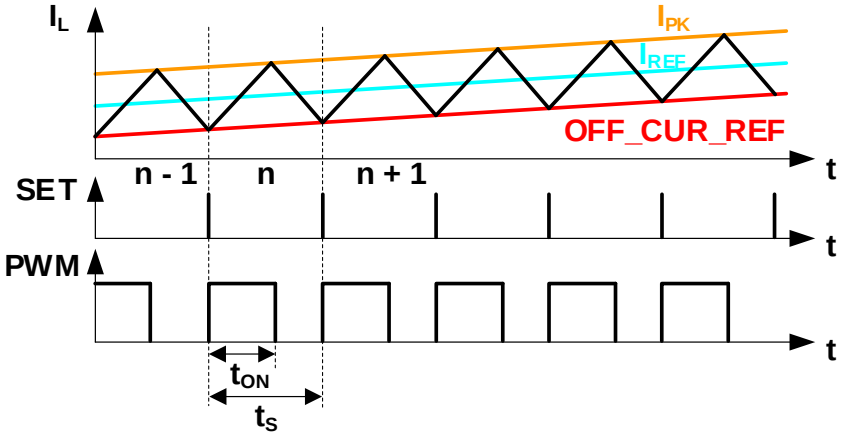
- High RMS current (I_{PK} is double the I_{IN} average)
  - ➢ *Limited to < 300W (more with interleaving)*

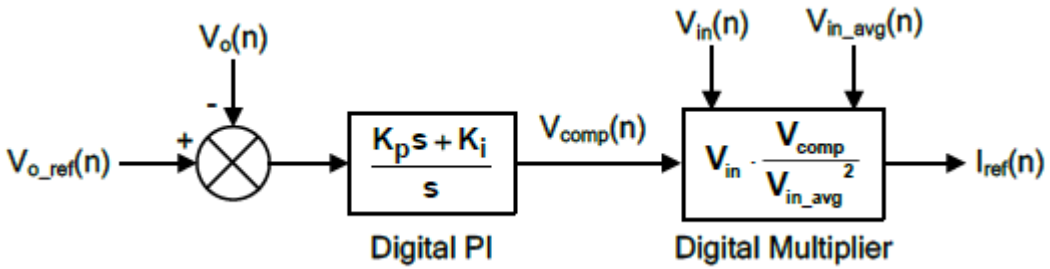
	CrM (Constant-On-Time)
Operation Mode	
Input Current	$I_{IN1}(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{2 \times L} \times t_{ON}(\theta) = \frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ1}}$
Input Equivalent Impedance	$R_{EQ1} = \frac{2 \times L}{t_{ON}(\theta)}$
Condition for PF = 1	$t_{ON}(\theta) = \text{constant}$

Boost PFC Control Method: CCM

Continuous Conduction Mode (CCM)







(from HR12xx digital PFC)

- Lower RMS current (I_{IN} average is very close to I_{PK})
  - ➢ *Can be used for higher power up to 1kW (more with interleaving)*

- More complex architecture (V_{IN} is used to set the reference for the current)
- Hard switching
  - ➢ *Higher cost, higher noise*

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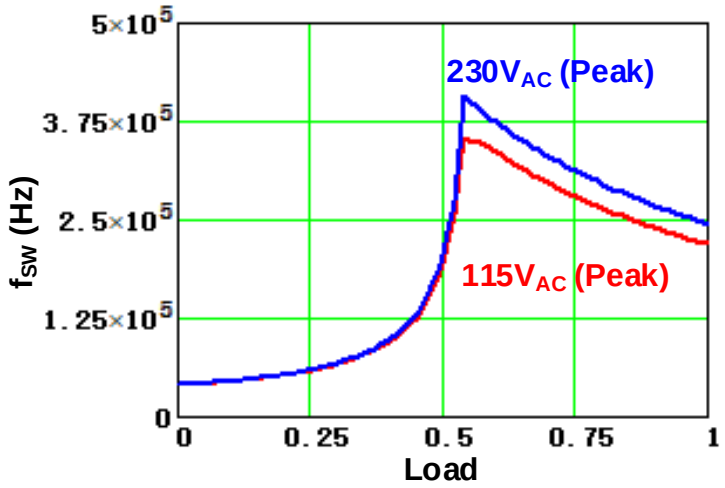
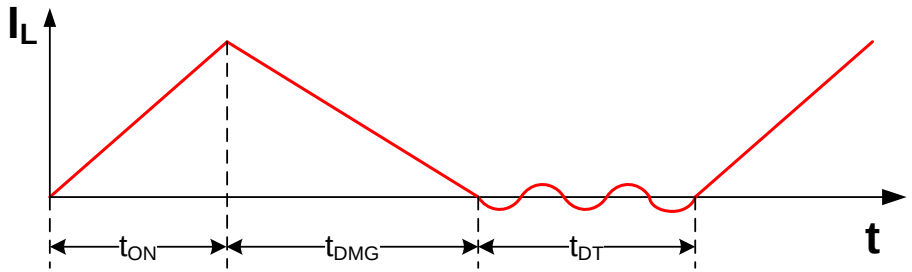
Efficiency Improvement – BCM + DCM

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.

Inserting a dead time to force it into DCM reduces f_{SW}, which results in higher light-load efficiency.

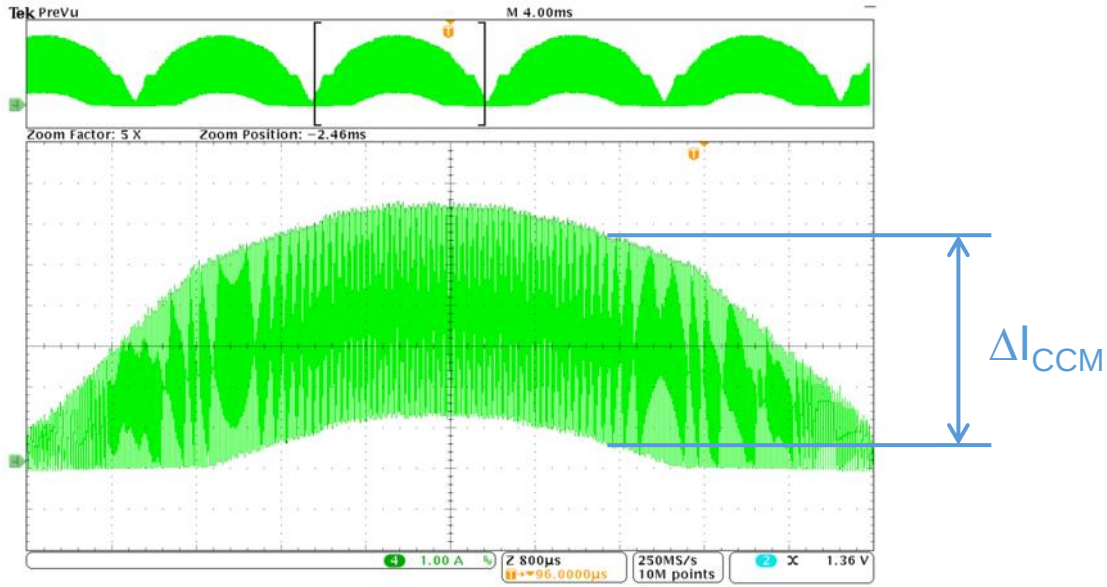


	DCM (Variable-On-Time)
Operation Mode	
Input Current	$I_{IN2}(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{2\times L}\times t_{ON}(\theta)\times D_C(\theta)=\frac{\lvert V_{AC}(\theta)\rvert}{R_{EQ2}}$ $D_C(\theta)=\frac{t_{ON}(\theta)+t_{DMG}(\theta)}{t_{ON}(\theta)+t_{DMG}(\theta)+t_{DT}}$
Input Equivalent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

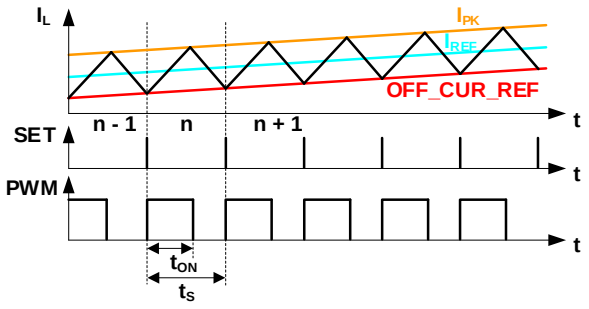
Multi-mode control: all 3 modes (CCM, BCM, and DCM) are used by the PFC controller under different output load conditions, depending on the instantaneous input voltage level

- CCM or BCM at high loads.
- Different DCM modes at light loads to optimize efficiency.



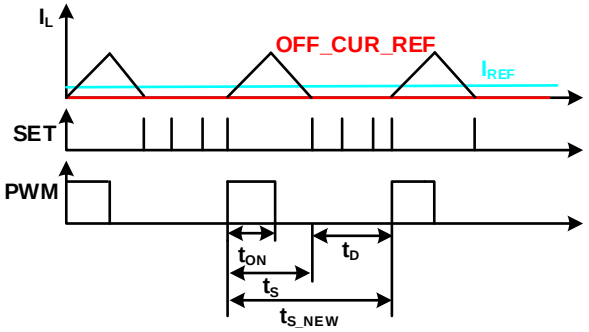
DCM……CrM……CCM……CrM……DCM

CCM



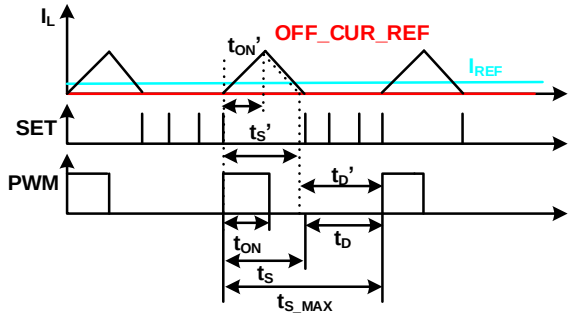
CF-DCM

Constant Frequency



VF-DCM

Variable Frequency



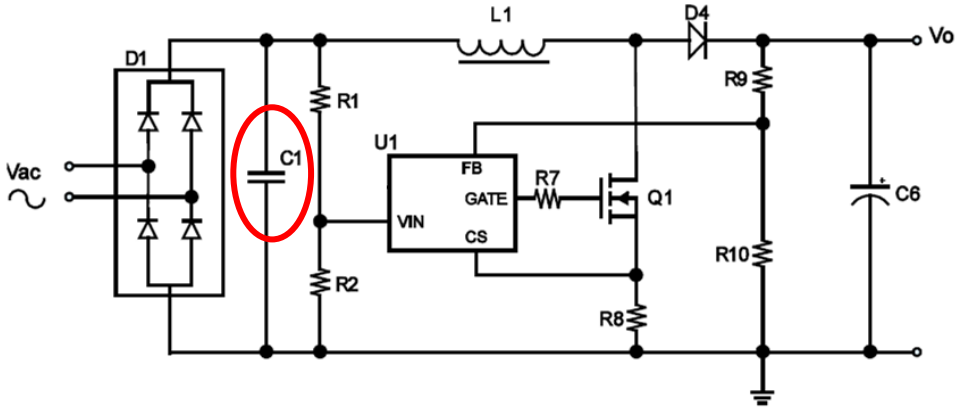
A set signal determines the CCM valley current point and DCM point.

THD Performance Improvement with Variable-On-Time

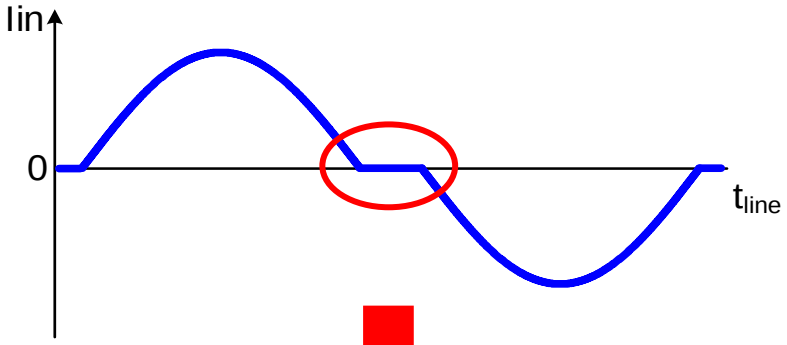
At light loads, the input filtering capacitor does not fully discharge around the zero crossing of the input AC.

A constant-on-time (COT) controller may also reach the max frequency limit around zero-crossing

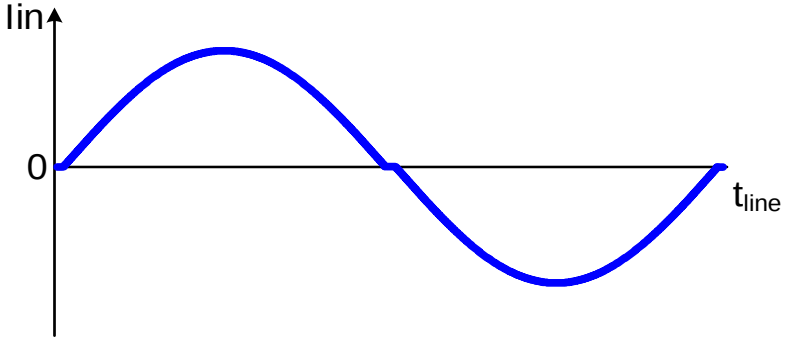
This is the cause of high distortion (high THD).



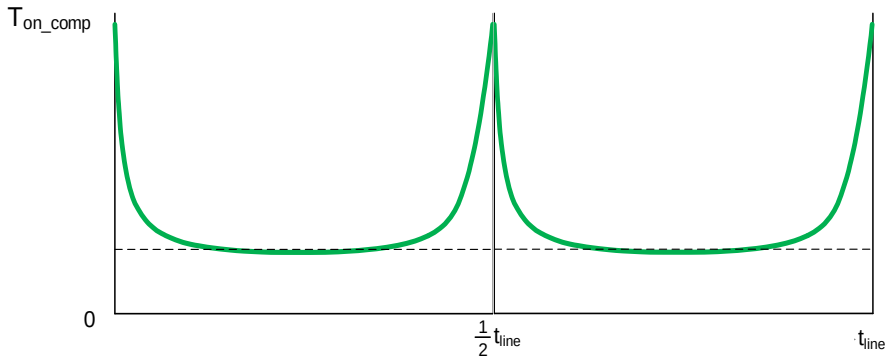
Constant-On-Time



Variable-On-Time



- Lower total harmonic current distortion (THD) due to **variable-on-time control** compared to conventional constant-on-time control.

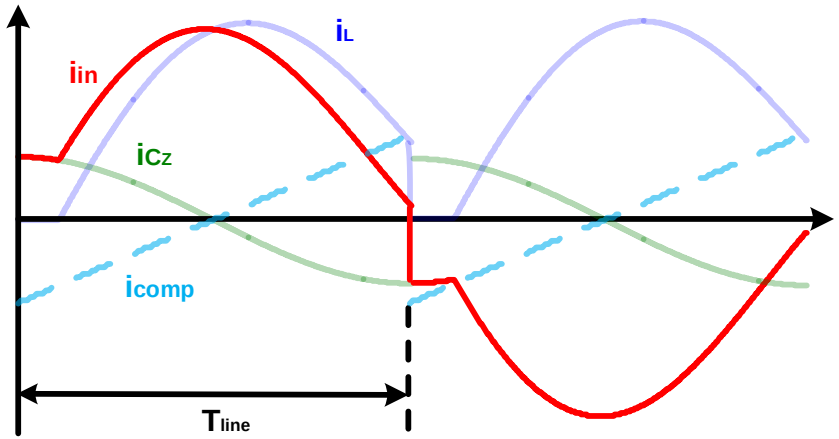


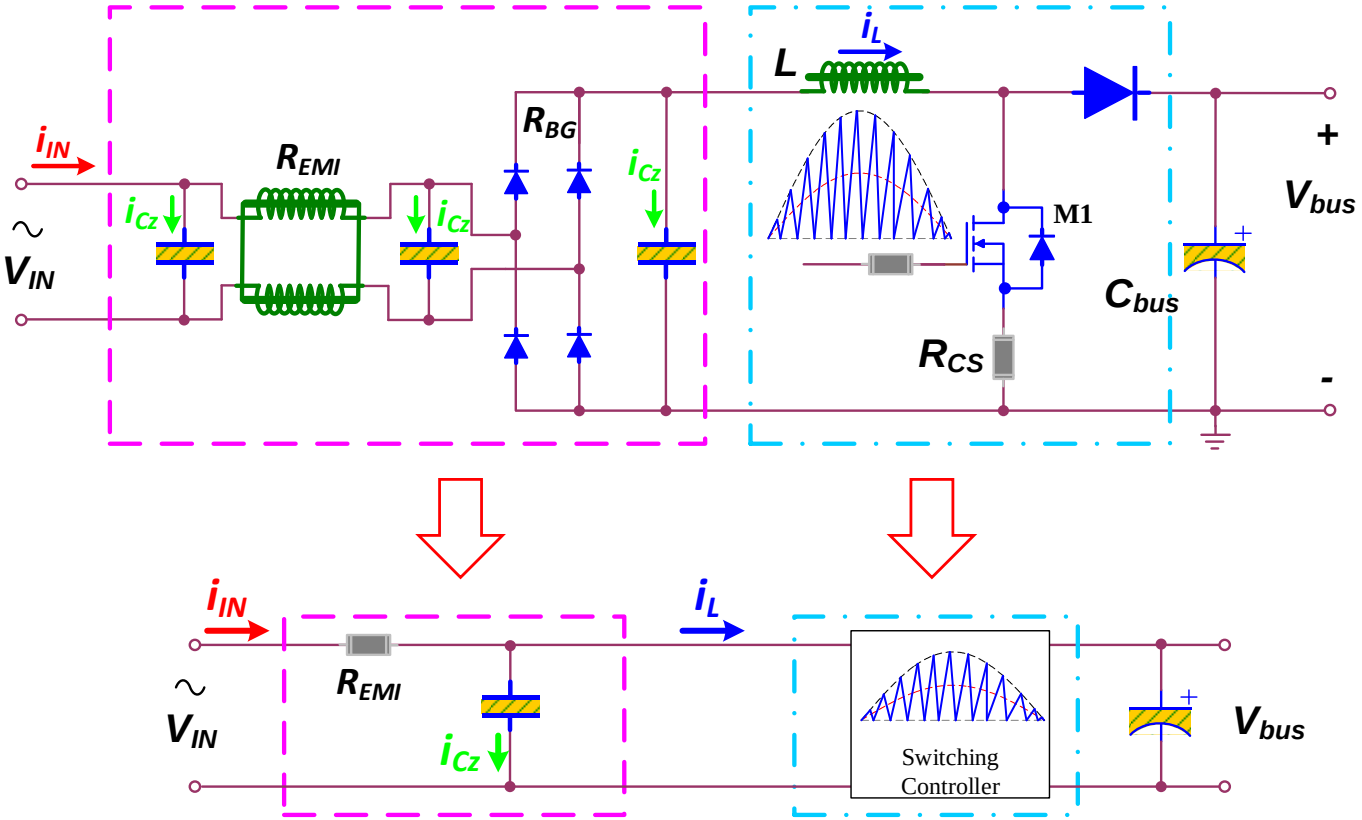
PF Enhancement with Input Capacitor Current Compensation

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.





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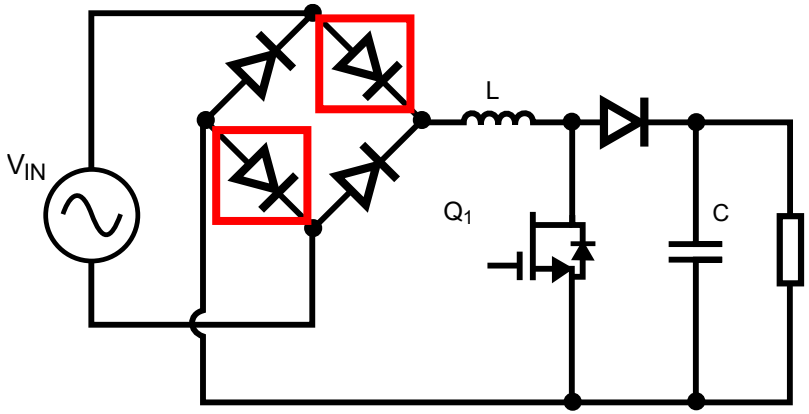
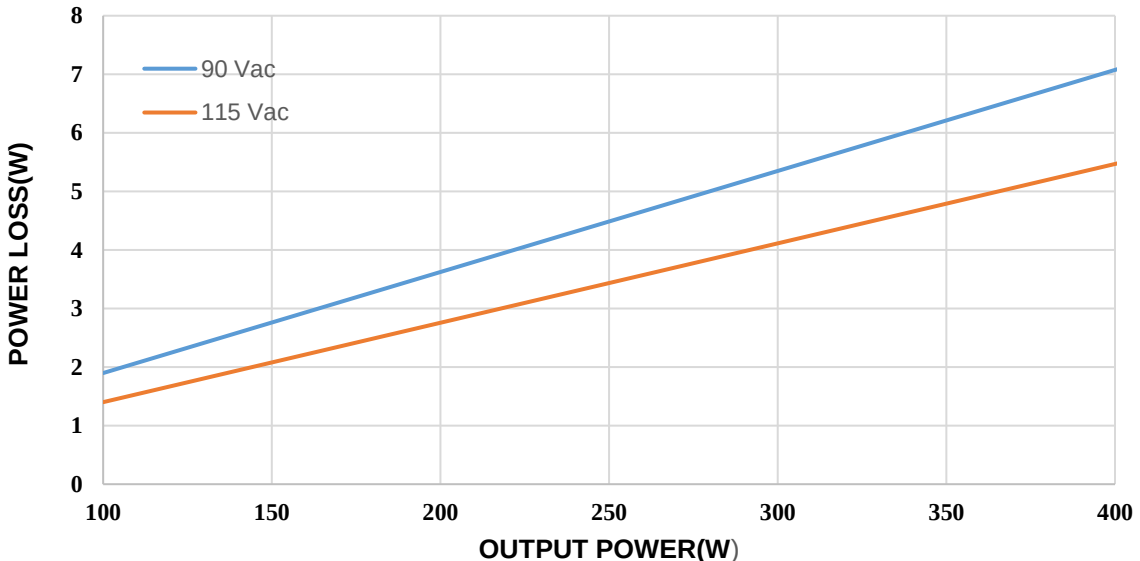
Rectifier Bridge Losses

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

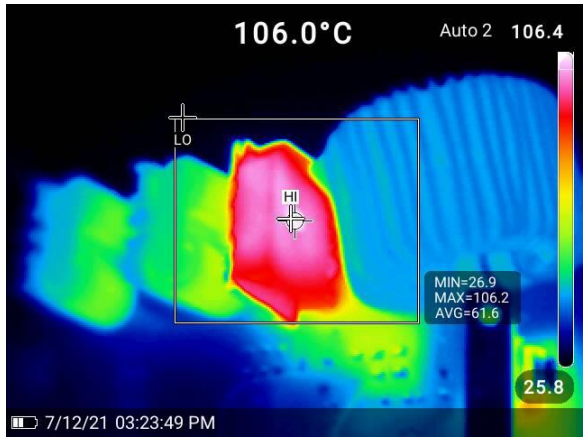


$$P_{D\ COND} = V_F\ x\ I_{RMS}$$

With the use of GaN switches and control optimization, the boost PFC's efficiency alone has increased greatly, such that the rectifier bridge has become a major contributor to efficiency loss by up to several % of loss.

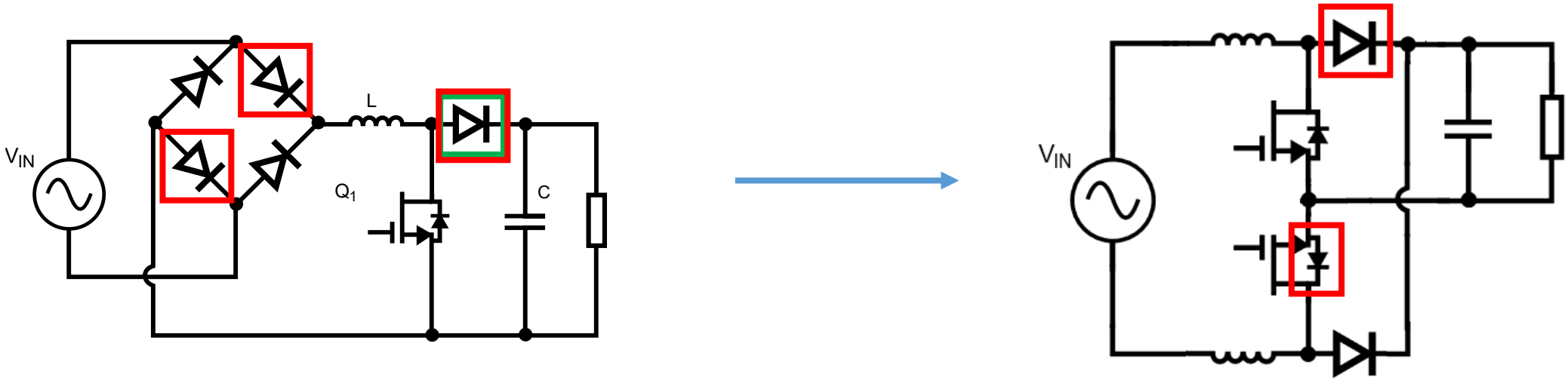


The heat generated by the bridge becomes the main factor limiting power density.



Bridgeless PFC – Concept

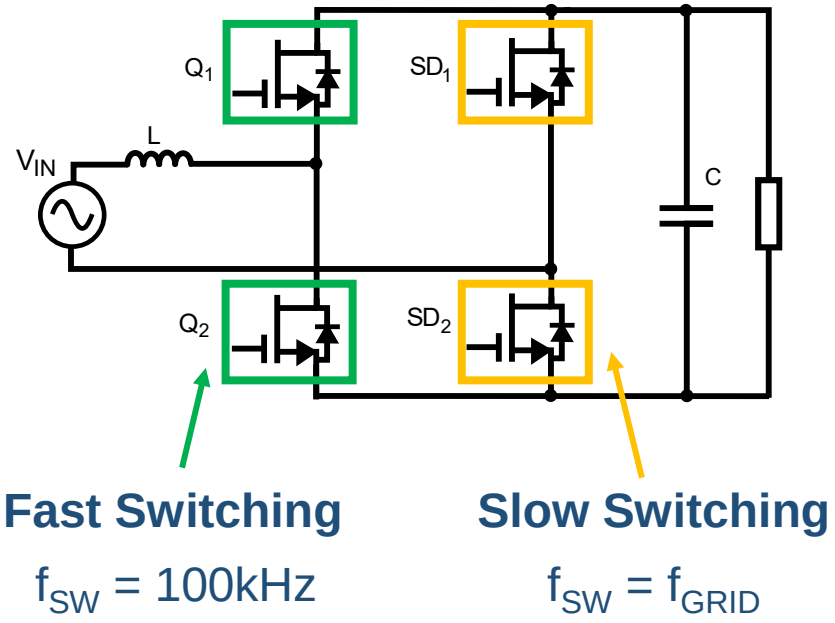
In a conventional boost PFC, there is already a diode blocking the reverse conduction — why not utilize this diode to remove the diode bridge rectifier?
When using one boost PFC on each AC line, they work in turns, one for each alternance of the sinusoidal input voltage.



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.

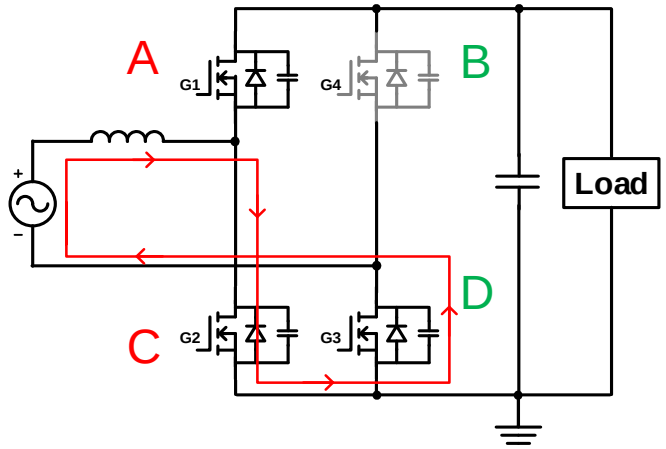
Totem-Pole PFC

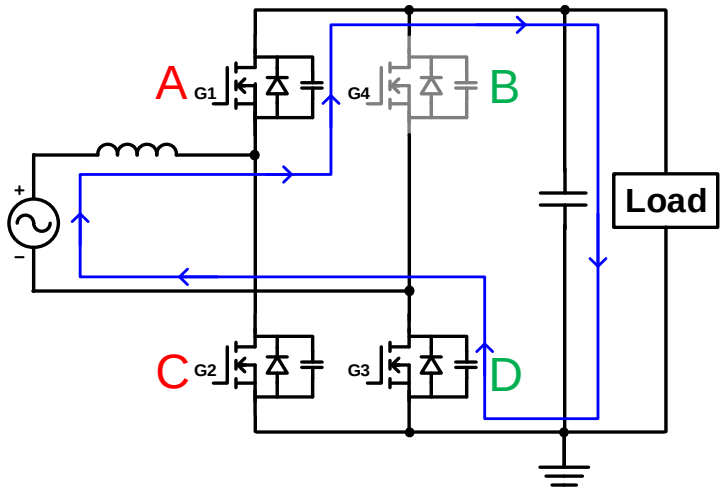
The evolution of the bridgeless dual-boost PFC is the totem-pole PFC.

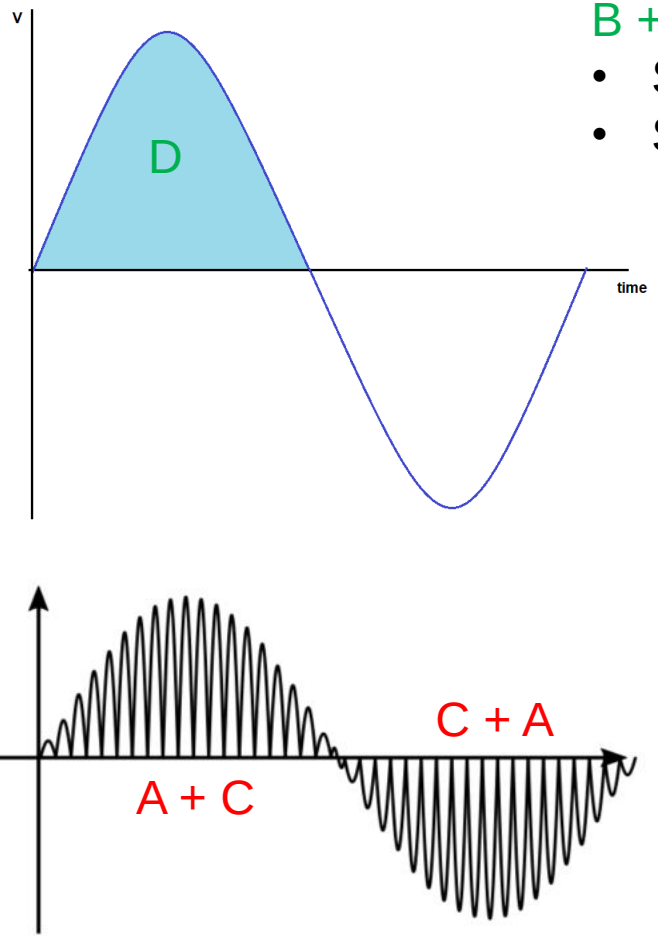


- Reduced to one inductor.
- Diodes replaced by MOSFETs.
- Rearranged to work as a synchronous boost (fast switching leg) with polarity-selection switches (slow switching leg).

Totem Pole PFC – Operation





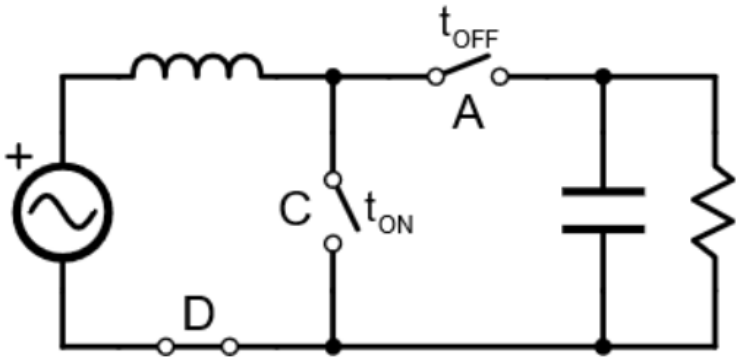


A + C

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

B + D

- Slow switches
- Select input polarity



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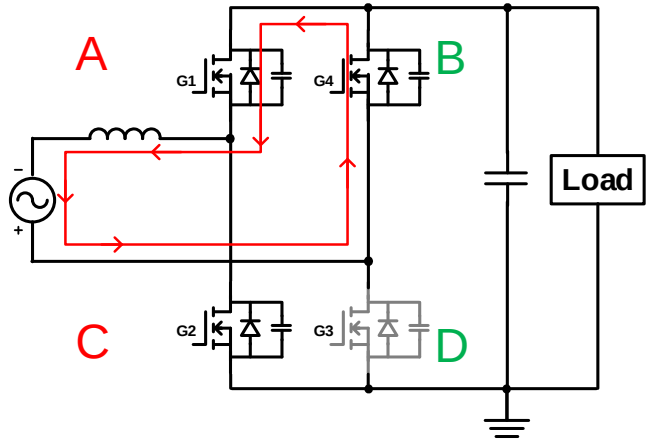

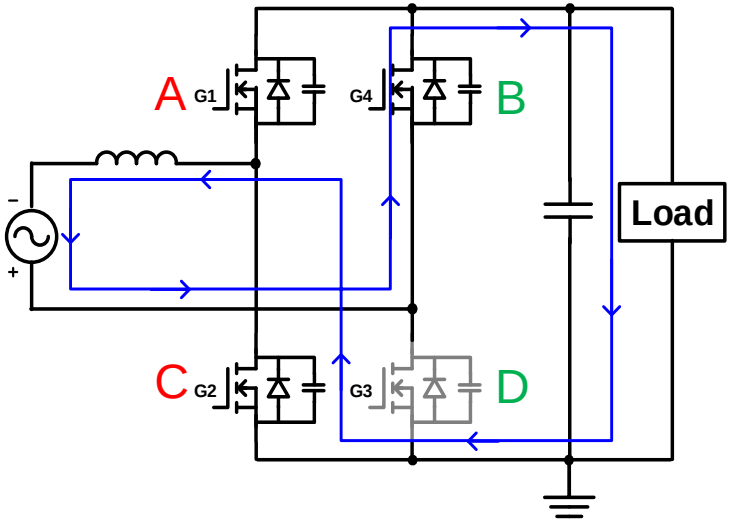

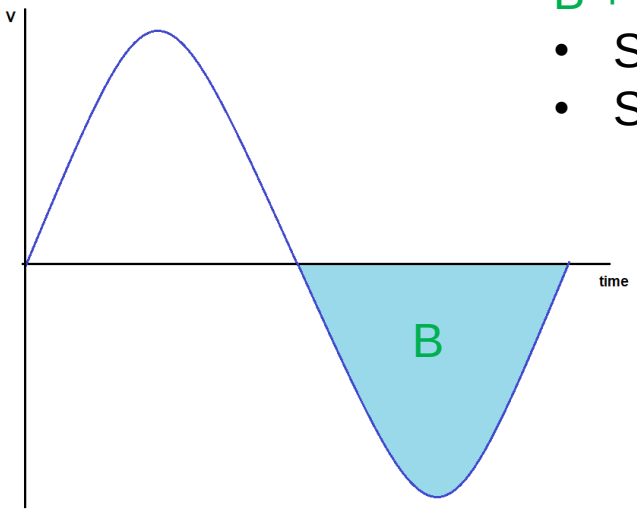

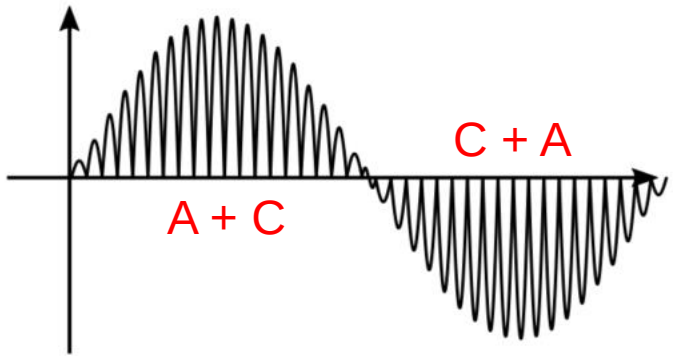

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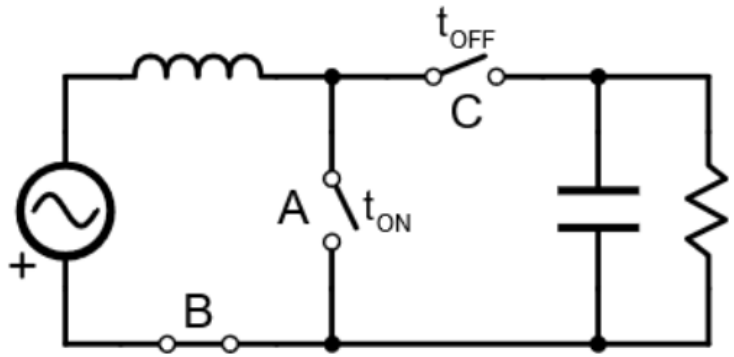
B + D

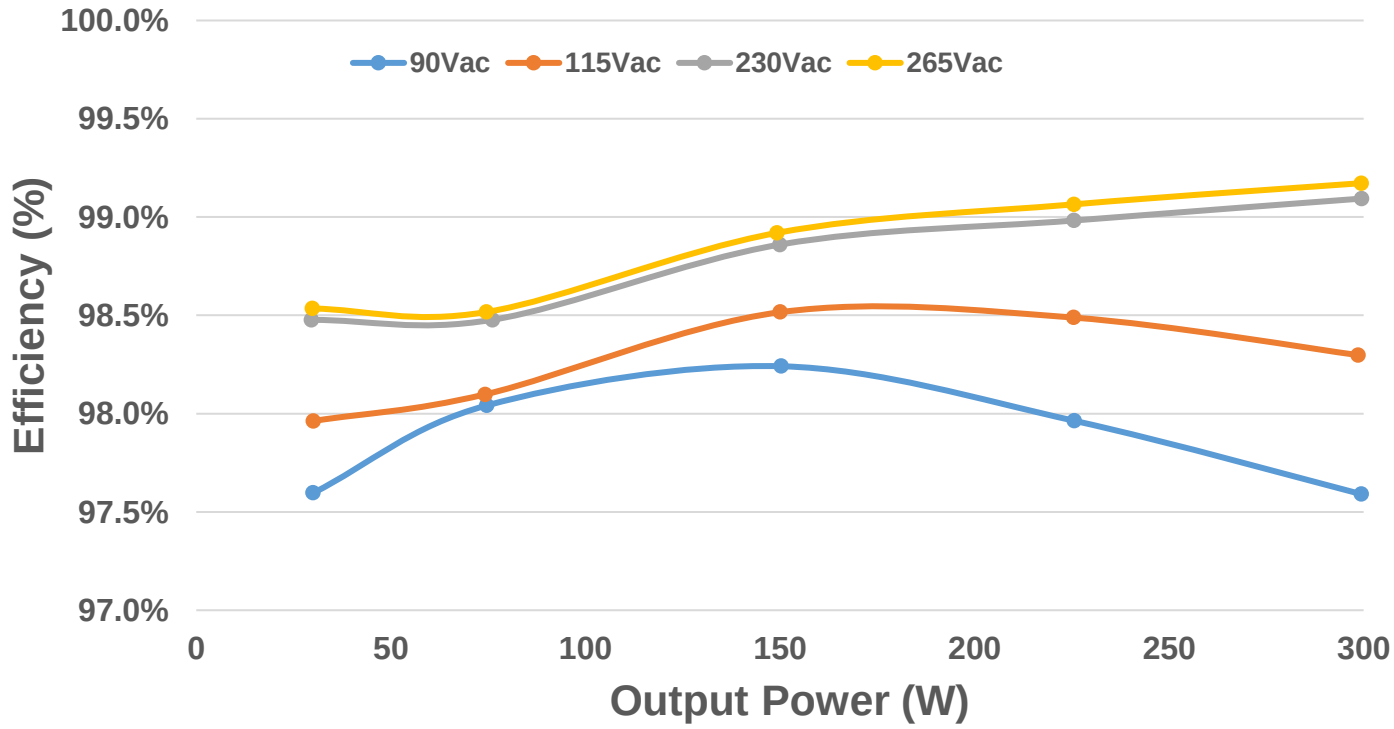
- Slow switches
- Select input polarity



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)



Agenda

- Introduction: Power Factor Correction
- Boost PFC Control
- Boost PFC Improvements (Efficiency, PF, Distortion)
- Bridgeless PFC
- Questions and Answers

Thank you!

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