FUTURE ELECTRONICS

A Tutorial Introduction to Power Factor Correction

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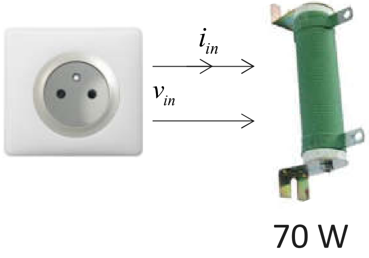
October 2024 – Rev 0.4

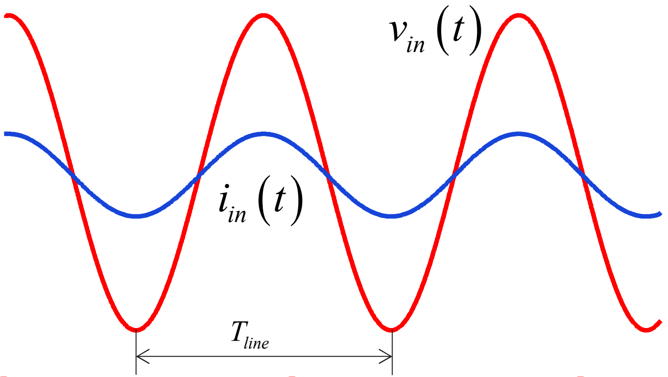
Agenda

- Notions of Power Factor
- Power Factor Correction Structures
- Processing the Power
- Loop Compensation of a PFC
- Solutions from Future Suppliers

What is Power Factor?

- The goal of any power factor correction circuit is to emulate a resistance
  - ➢ The absorbed current must be sinusoidal and in phase with the input voltage



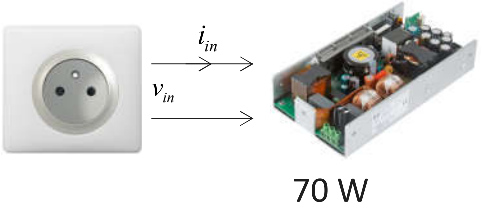


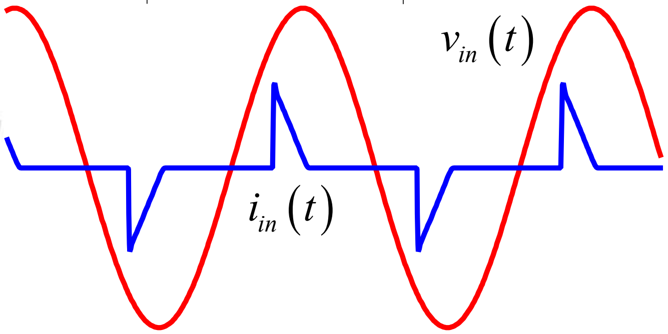
$$p_{in}(t) = i_{in}(t)\,v_{in}(t) = \frac{v_{in}(t)}{R}\,v_{in}(t)$$

$$P_{in,avg} = \frac{1}{T_{line}}\int_0^{T_{line}} p_{in}(t)\cdot dt = 70\ \text{W}$$

$$P_{in,app} = V_{in,rms}\cdot I_{in,rms} = 85\times 823m = 70\ \text{VA}$$

$$\text{PF} = \frac{\text{active power}}{\text{apparent power}} = \frac{[\text{W}]}{[\text{V}\cdot\text{A}]} = 1$$





$$P_{in,avg} = \frac{1}{T_{line}}\int_0^{T_{line}} p_{in}(t)\cdot dt = 70\ \text{W}$$

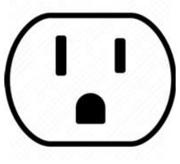
$$P_{in,app} = V_{in,rms}\cdot I_{in,rms} = 85\times 1.46 = 124\ \text{VA}$$

$$\text{PF} = \frac{\text{active power}}{\text{apparent power}} = \frac{[\text{W}]}{[\text{V}\cdot\text{A}]} = 0.56$$

What is the Impact of a Low PF?

- Assume a 250-W load absorbed by an equipment from a 110-V 15-A ac outlet
- With a PF of 0.56, the current is 250/110/0.56 ≈ 4 A rms

✓ You can safely connect a maximum of 3 devices (15/4 = 3.75)



110 V – 15 A

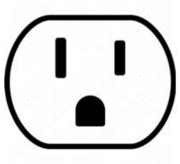
P_{max} = 1.65 kVA

$I_{in,rms}$ = 4 A

x 3

250 W – PF = 0.56

- Add a front-end power factor correction stage to bring PF close to unity



110 V – 15 A

P_{max} = 1.65 kVA

$I_{in,rms}$ = 2.3 A

x 6

PFC

250 W – PF = 0.99

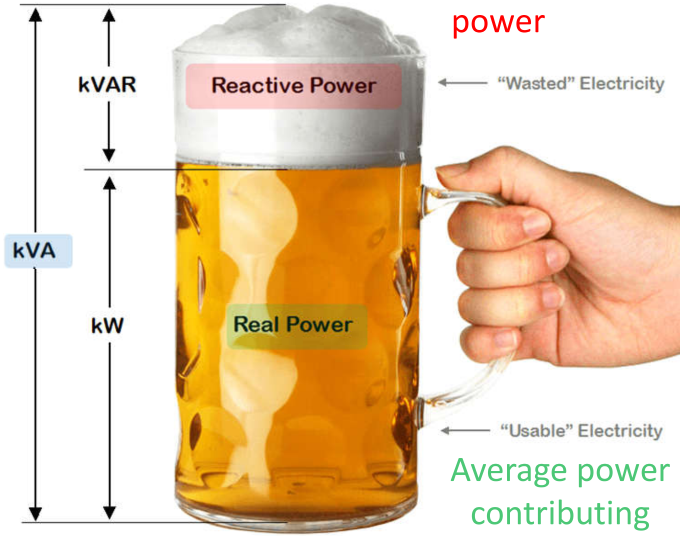
You can safely connect 6 workstations

Explaining Power Factor with Beer

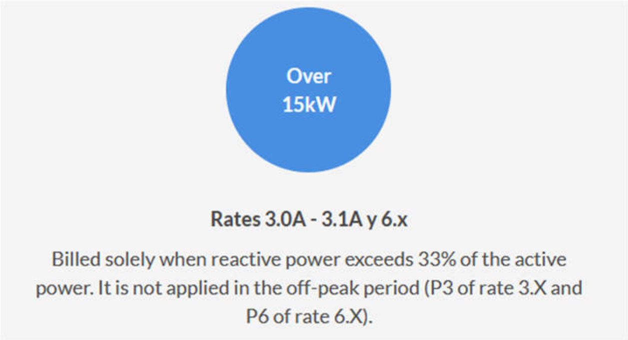
- A low power factor will force the circulation of a higher rms current
- Electric wires can overheat and utility companies push for power factor correction
- ✓ A glass of beer with an excessive foam can help appreciate the issue

Useless circulating power

Apparent power S supplied by the utility



Average power contributing the work



[VA] [W] [VAR]

$$S = P + jQ$$

$$\left|\frac{P}{PF}\right| = \sqrt{P^2 + Q^2}$$

$$Q = P\sqrt{\frac{1}{\mathrm{PF}^2} - 1}$$

If PF < 0.95

$$Q\,[\mathrm{VAR}] > 33\% \cdot P\,[\mathrm{W}]$$

https://www.iberdrola.es/en/homeowners-associations/information/reactive-power

Power Factor and Distortion

- Power factor depends on two parameters:

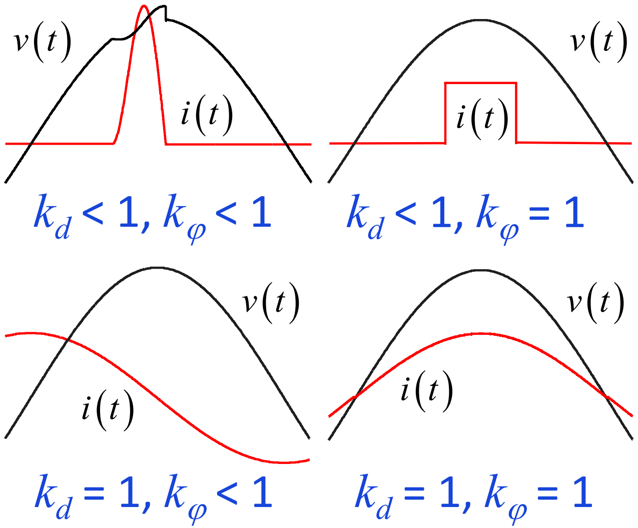
$$PF = \frac{I_{1,rms}}{I_{rms}} \cos\varphi = k_d k_\varphi$$

Fundamental rms current

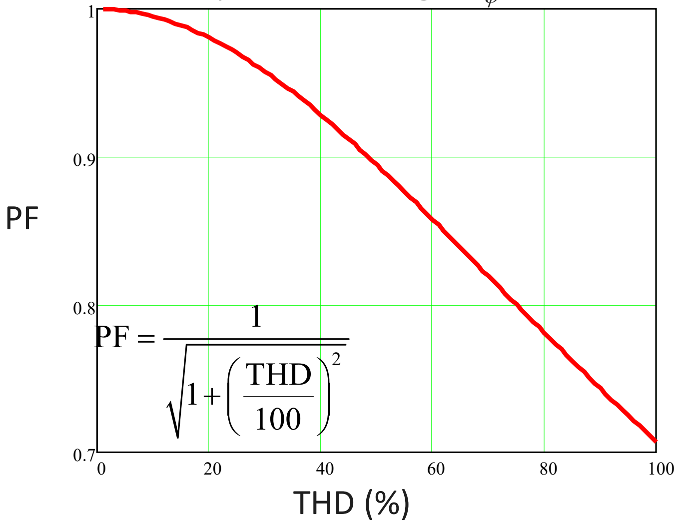
Total rms current

✓ k_d represents the distortion factor

✓ k_φ designates the displacement angle



For a displacement angle k_φ of 1:



THD = 30%, PF = 0.958

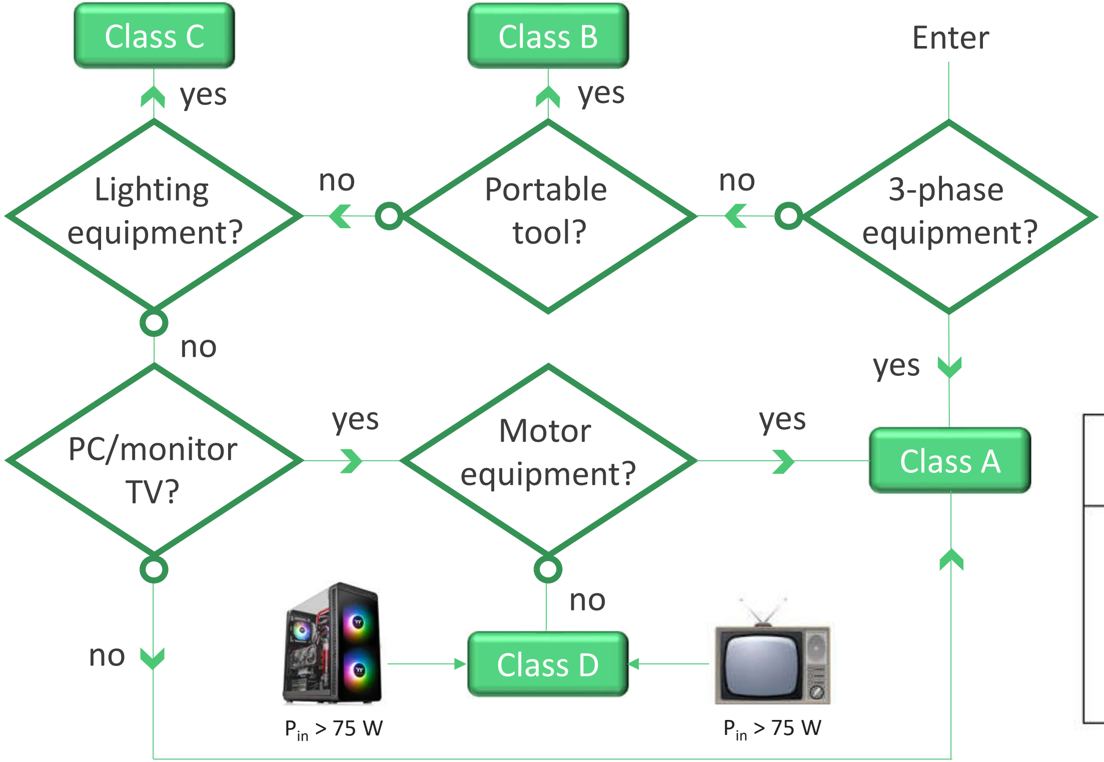
THD = 10% PF = 0.995

THD = 5% PF = 0.999

Check harmonics limits according to IEC1000-3-2

Equipment Compliance

- The standard EN61000-3-2 defines the class of equipment and associated limits



NORME INTERNATIONALE — CEI
INTERNATIONAL STANDARD — IEC

61000-3-2

Deuxième édition
Second edition
2000-08

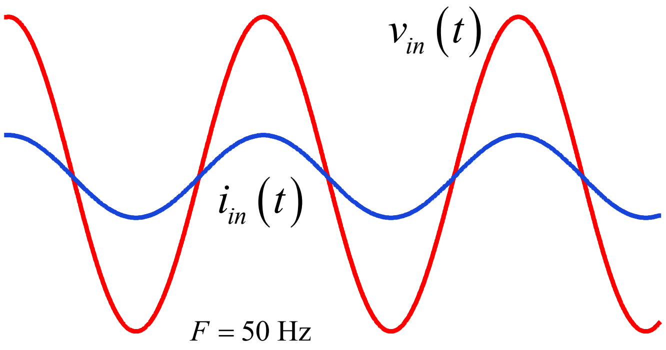
Class D limits

Rang harmonique n	Courant harmonique maximal autorisé par watt mA/W	Courant harmonique maximal autorisé A
3	3,4	2,30
5	1,9	1,14
7	1,0	0,77
9	0,5	0,40
11	0,35	0,33
$13 \leq n \leq 39$ (harmoniques impairs seulement)	$\frac{3,85}{n}$	Voir tableau 1

J. Turchi, D. Dalal, *Power Factor Correction: from Basics to Optimization*, Technical Seminar, APEC 2014

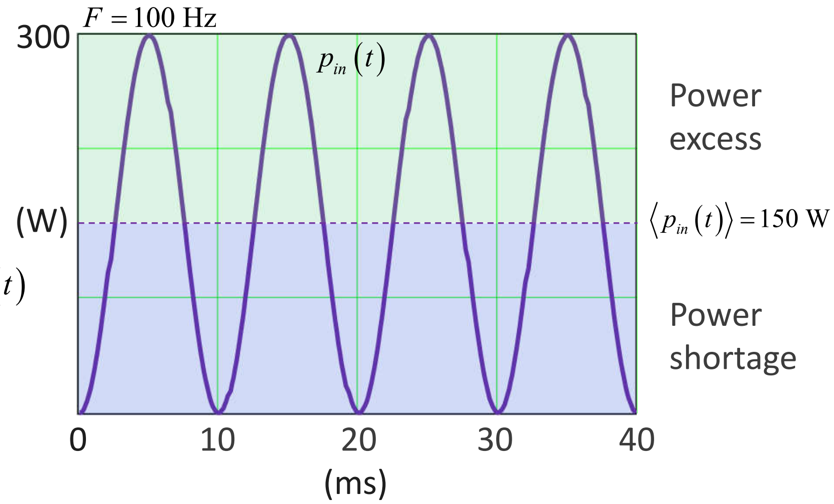
The Need for Storage

- The goal of a PFC front-end converter is to emulate a resistive load
- The power of a single-phase ac source feeding a resistance involves a squared sinewave

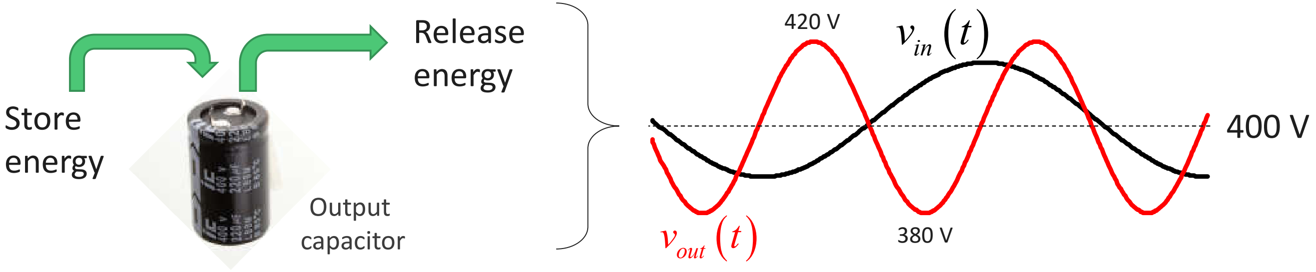


$P_{in} = 150$ W

$p_{in}(t) = v_{in}(t) \cdot i_{in}(t)$



- Active power factor stores and release energy



✓ Output voltage ripple is twice the input frequency

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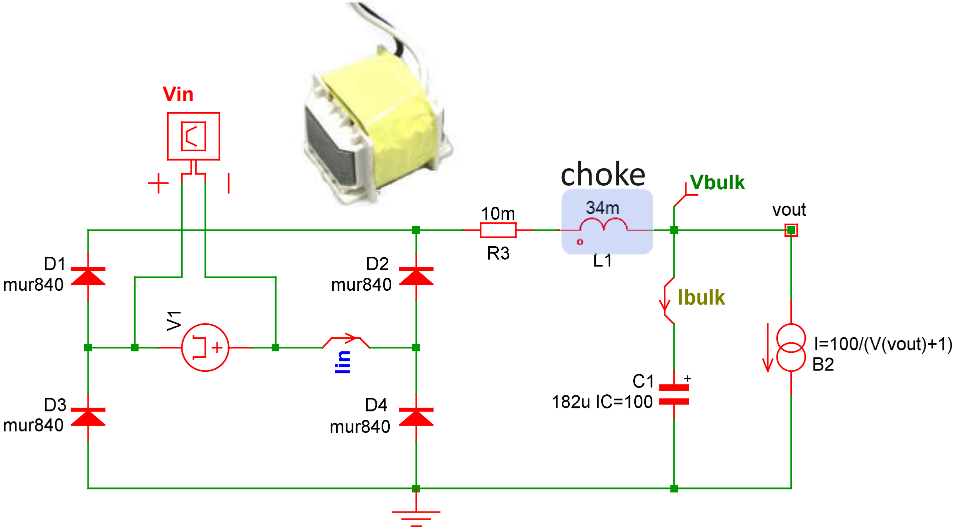
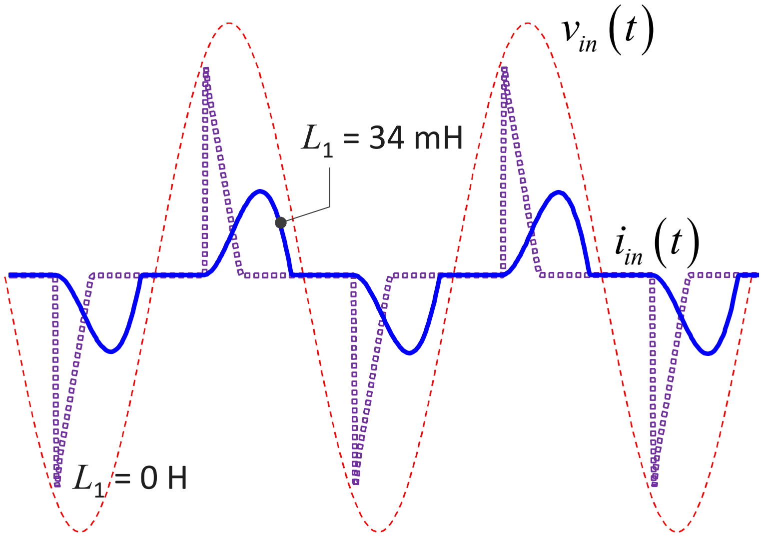
Passive Power Factor Correction

- Capacitor refueling in a full-bridge rectifier is confined at the sinewave peak
- A very narrow spike is generated, rich of numerous harmonics
- ✓ Spreading the current across the sinewave smooths the current signature



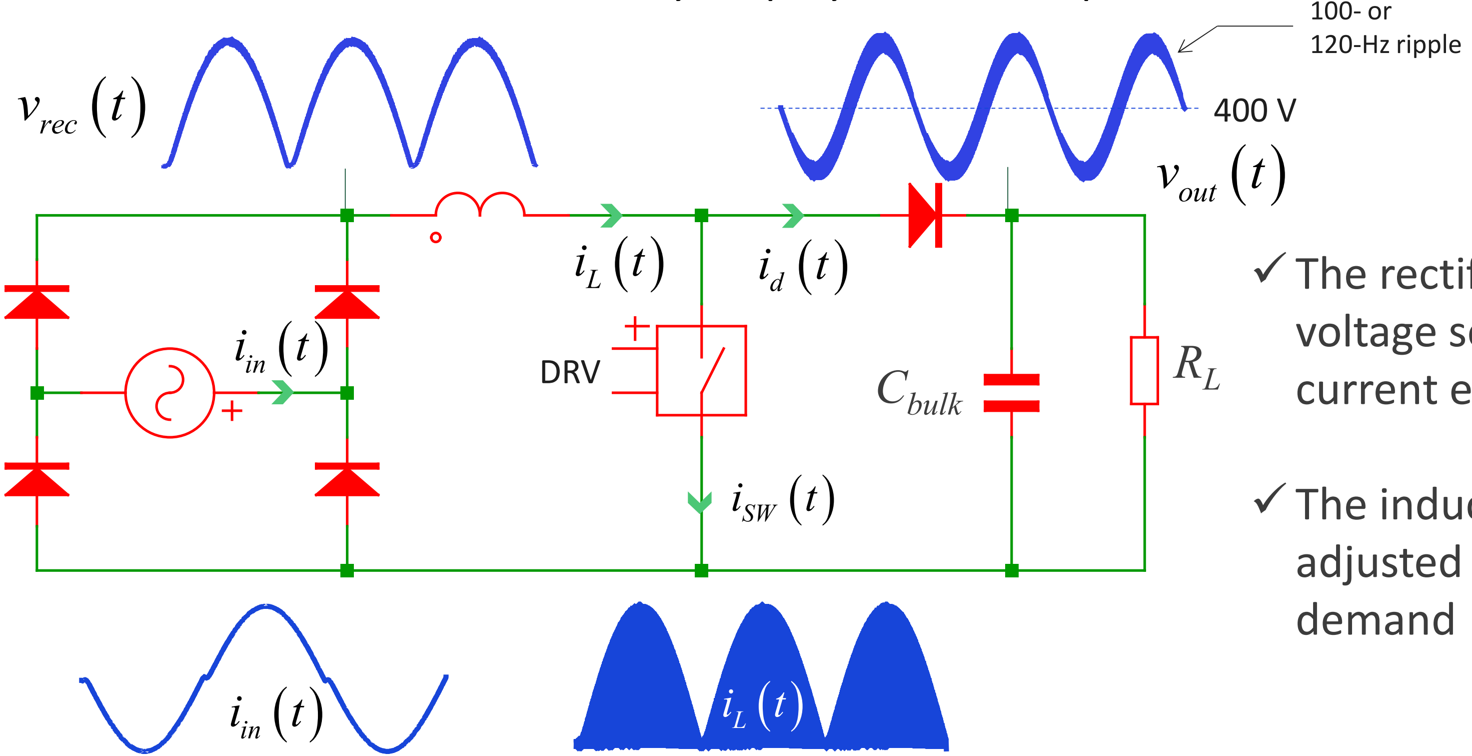


- ❖ Choke is bulky, heavy and induces mechanical stress
- ❖ Reduces rms current but marginal results harmonic-wise

P_{out} = 100 W
$I_{in,rms}$ = 1.8 A without L
$I_{in,rms}$ = 1.2 A with L = 34 mH

Active Power Factor Correction

- An active PFC forces a sinusoidal current absorption in phase with the voltage
- A boost converter is traditionally employed for this operation

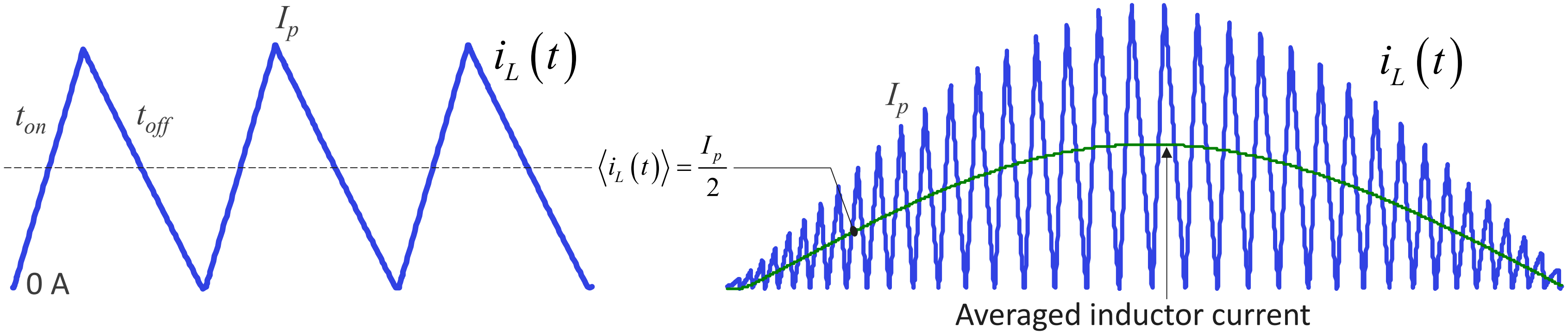


✓ The rectified input voltage sets the inductor current envelope

✓ The inductor current is adjusted to match power demand

Conduction Mode – BCM or CrM

- Inductor current reduces to 0 A before a new cycle starts in **b**orderline **c**onduction **m**ode
- ✓ Well suited for power levels up to 300 W or higher with interleaved version
- ✓ Near-zero-voltage switching in some conditions
- ✓ Discontinuous operation reduces t_{rr}-related power dissipation on the diode

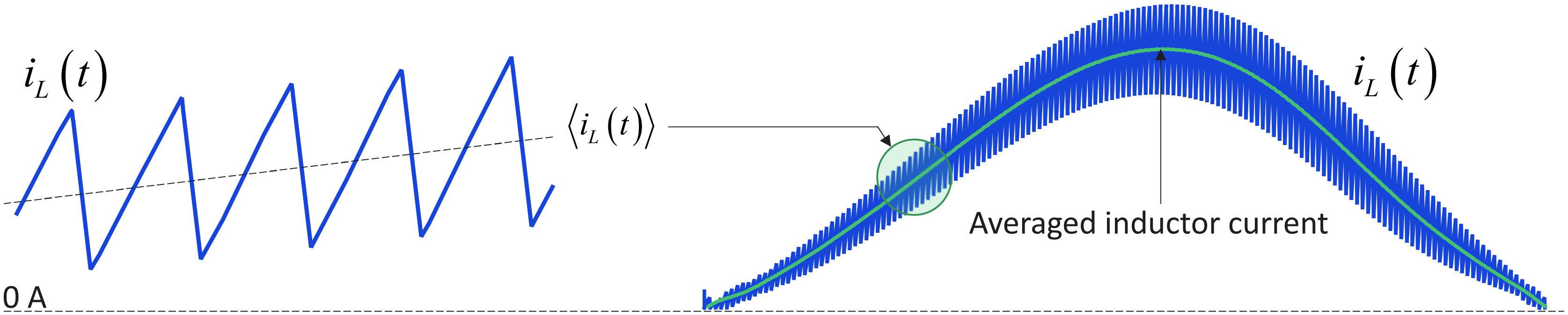


- ❖ Variable-frequency switching makes light-load operation less efficient
- ❖ Internal frequency clamp or foldback is generally implemented to reduce losses
- ❖ Large circulating currents inducing conduction (rms) and core losses (ΔI_L)

CrM: CRitical Conduction Mode

Conduction Mode - CCM

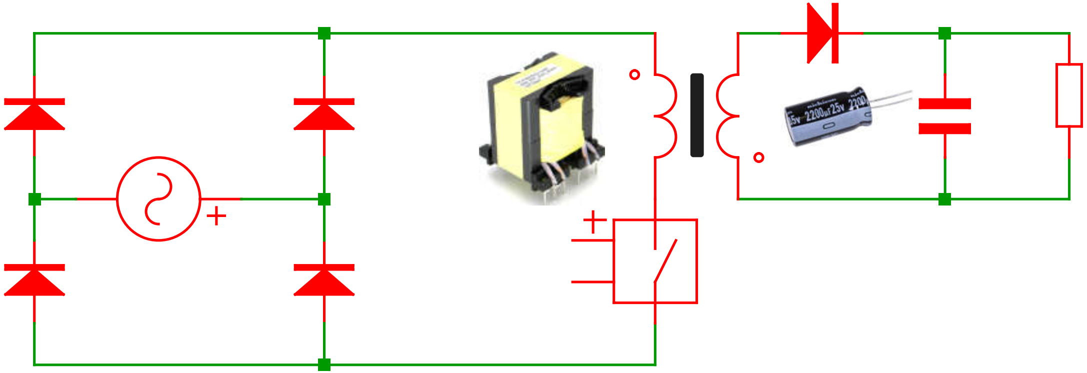
- The inductor current never touches zero within a switching cycle
- ✓ Continuous conduction mode is well suited for high-power converters > 300 W
- ✓ Current can be monitored by an independent loop for best distortion figures
- ✓ Circulating rms currents are minimized with a moderately-low ripple current

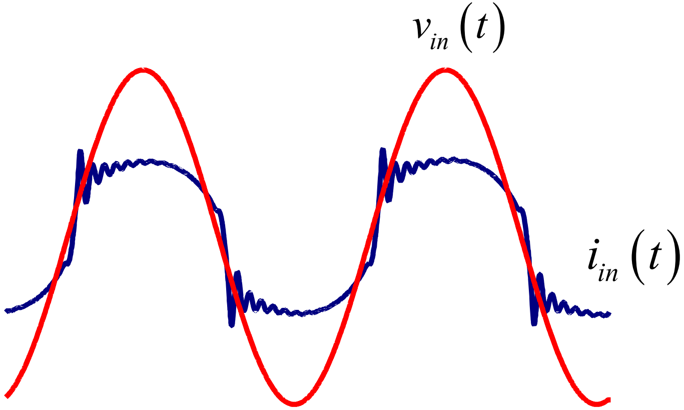


- CCM induces switching losses and low-t_{rr} diodes or SiC types are mandatory
- Larger inductance value compared to BCM operation
- Two loops to stabilize in the classical multiplier-based approach

Single-Stage Converters

- It is possible to combine a PFC stage with an isolated flyback converter
- This single-stage approach is well adapted to power levels up to 100-150 W
- ✓ The components count is reduced
- ✓ It provides galvanic isolation to the downstream load





- Large output capacitance for the storing process
- Fairly-distorted input current barely passes PF specifications
- Slow-loop operation makes it well suited for lighting systems

Bridgeless PFC

- The bridge hampers overall efficiency with two permanently-conducting diodes

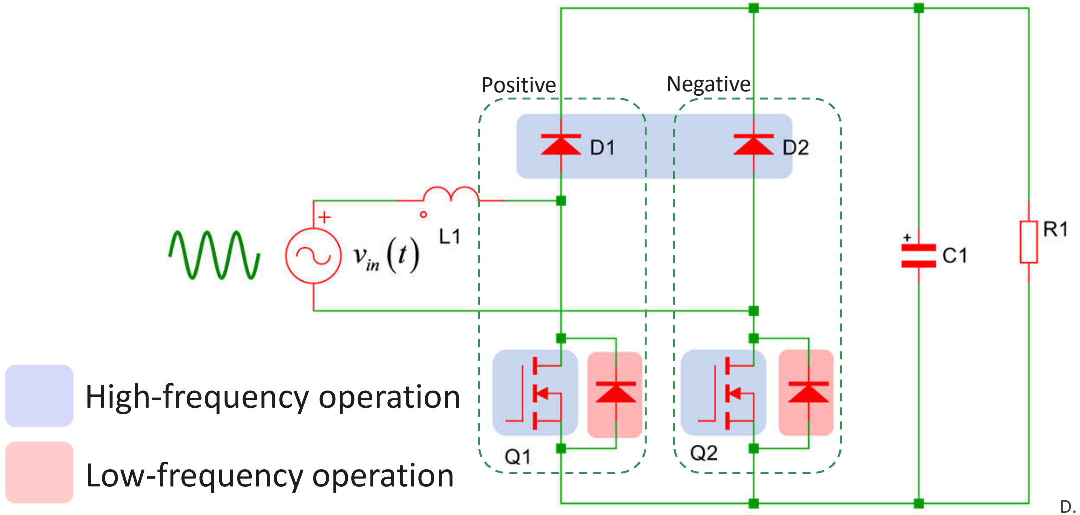
$$P_d \approx 2 V_f I_{d,avg}$$

$$I_{F,avg} = \frac{2}{\pi} \frac{\sqrt{2} P_{out}}{V_{ac,LL} \eta}$$

$P = 300$ W
$\eta = 100\%$
$V_{ac,LL} = 90$ V rms

$P_d \approx 5$ W
Eff. loss $\approx 1.7\%$

- The bridgeless PFC ensures one diode conduction via the MOSFET body



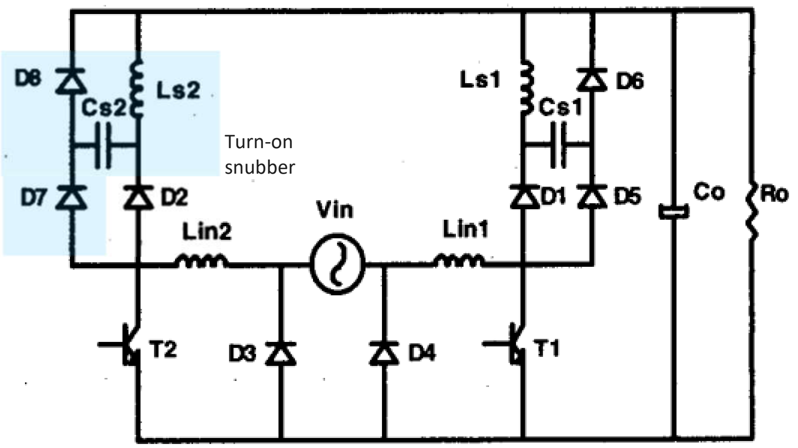
✓ Only one diode is conducting in low frequency
✓ The MOSFETs share a common drive signal without caring about line polarity

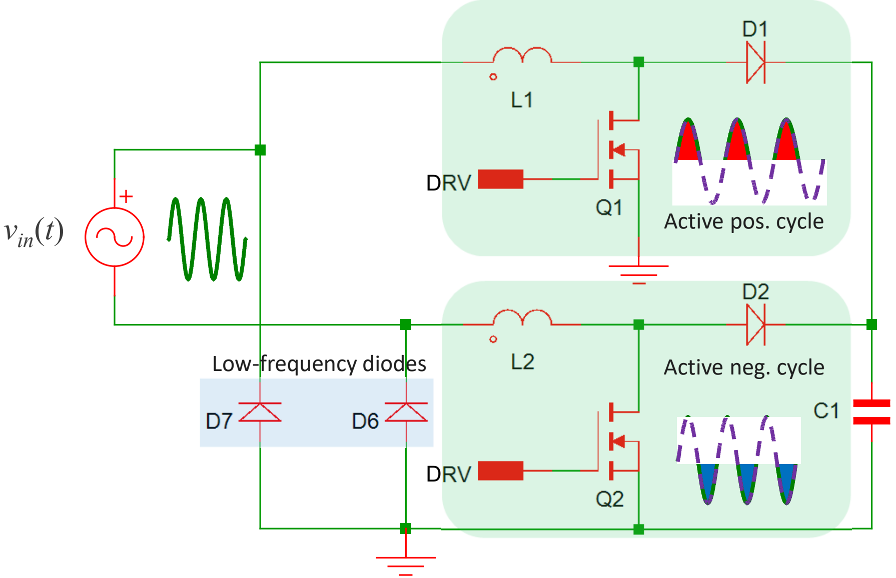
❖ Poor common-mode noise signature

D. Mitchell, *Ac-Dc Converter having Improved Power Factor*, U.S. Patent 4,412,277, Oct. 25, 1983

Variation of the Bridgeless PFC

- The original scheme suffers from a poor common-mode EMI signature
- A variation around this circuit was proposed by Ivo Barbi in 1999



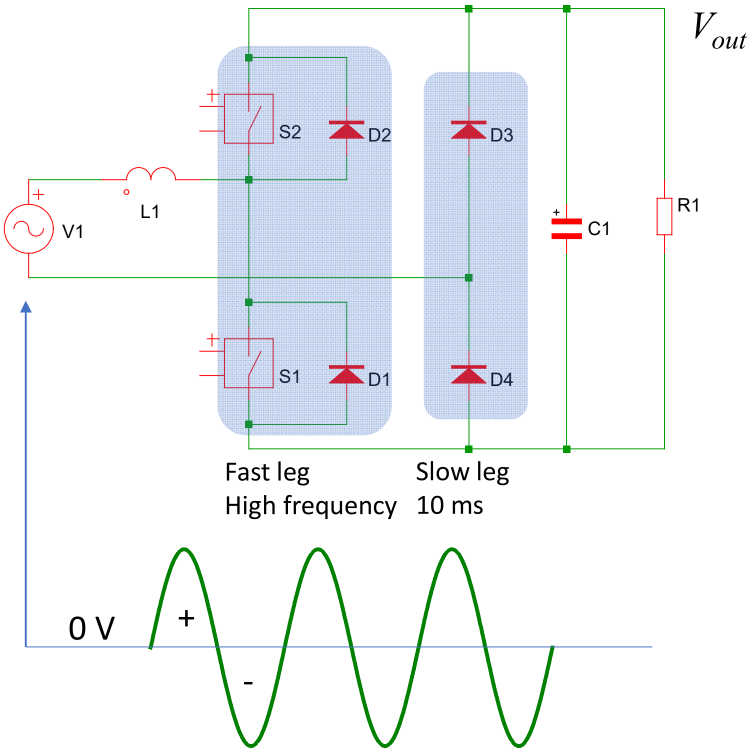


- ✓ Two PFC in parallel driven by the same pattern – easy to drive with one controller
- ✓ Conventional structure automatically activated depending on the line polarity

A. F. de Souza and I. Barbi, *High power factor rectifier with reduced conduction and commutation losses, 21st International Telecommunications Energy Conference. INTELEC '99 (Cat. No.99CH37007)*, 1999
B. J. Turchi, *A High-Efficiency 300-W Bridgeless PFC Stage*, AND8481/D, onsemi, 2014

The Totem-Pole PFC

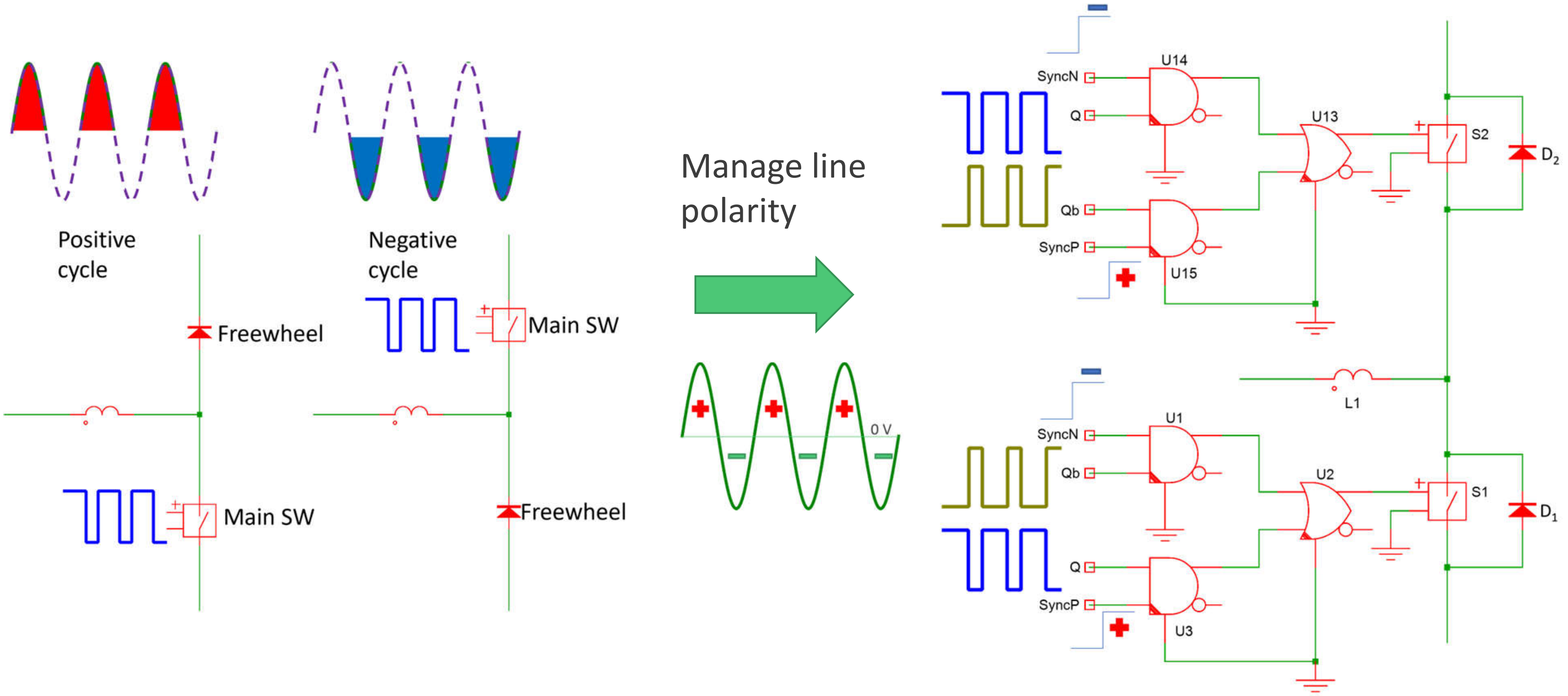
- The two high-frequency switches are connected in a half-bridge configuration
- Two diodes in the slow leg route the low-frequency portion of the input current



- ✓ The fast-leg transistors alternatively perform as power switch and catch diode
- ✓ D_2 and D_1 must be fast diodes with no recovery loss: SiC or GaN transistors are perfect for this function
- ✓ D_3 and D_4 can be controlled-switches for improved efficiency
- ✓ Common-mode noise improved compared to bridgeless PFC

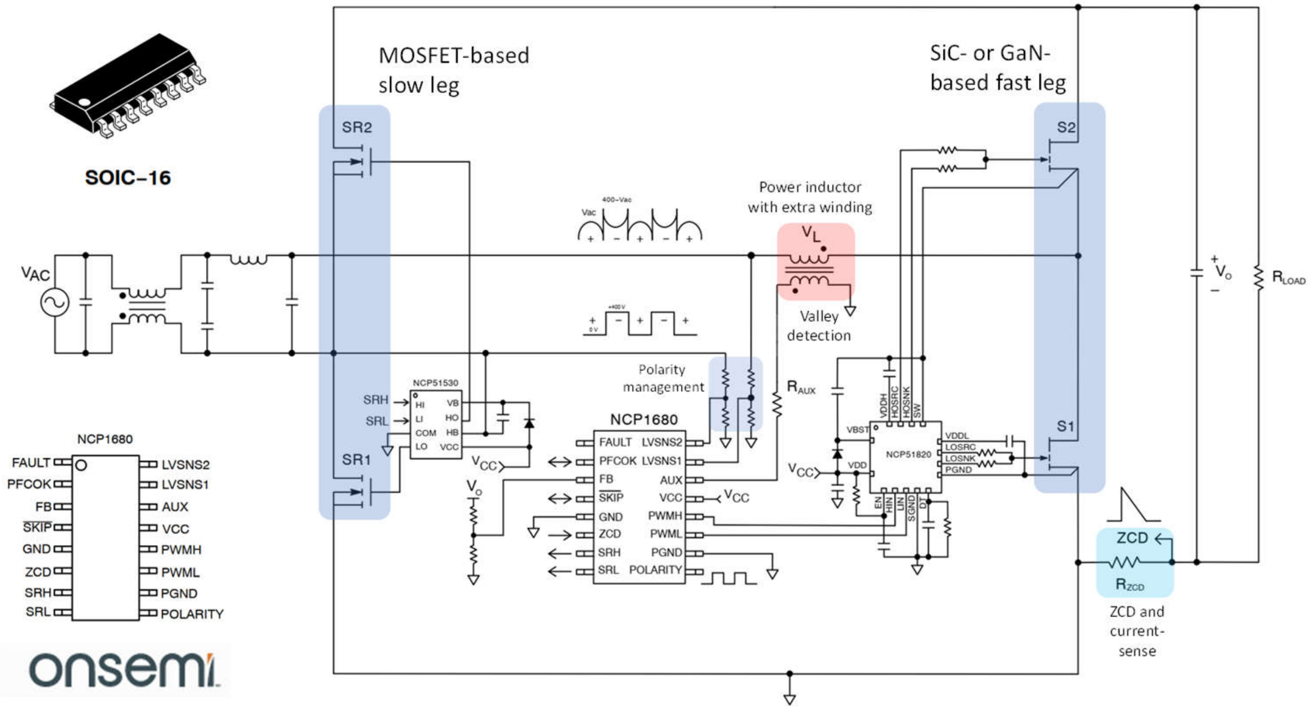
The Need to Detect the Input Line Polarity

- Each fast-leg transistor alternatively plays the role of the switch and the diode
  - ✓ The switching element needs instruction on the input line polarity



Dedicated Controllers for TPPFC

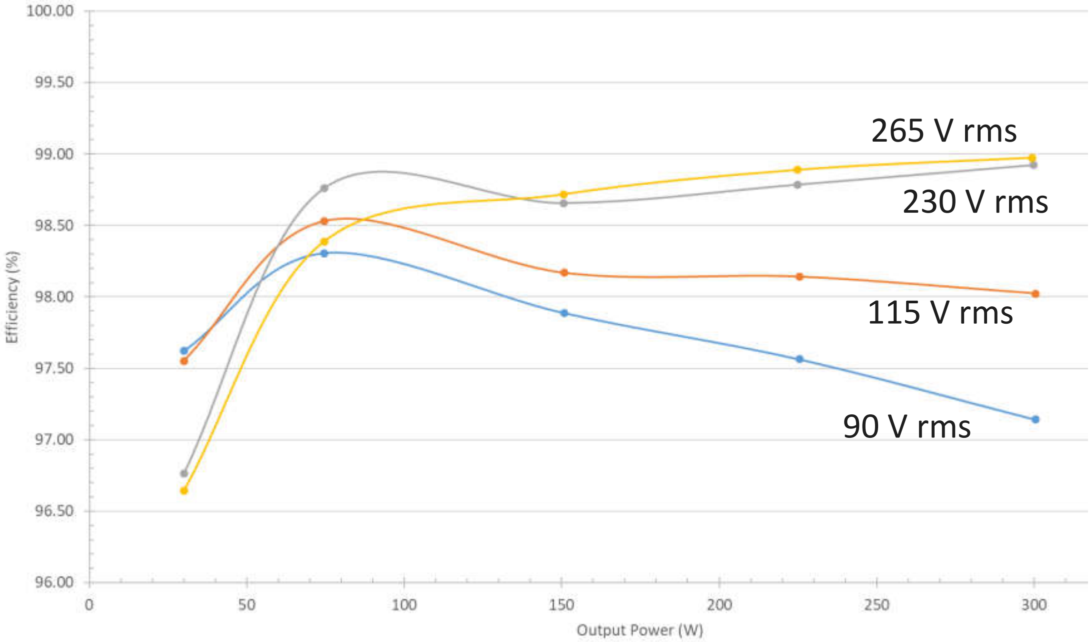
- *onsemi* has introduced two low-voltage controllers operating in BCM and CCM
- ✓ NCP1680 can implement a pre-converter up to 300 W



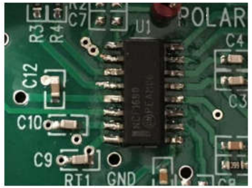
- ✓ One single inductor with auxiliary winding ensures ZVS operation
- ✓ Line management with a pair of resistive dividers
- ✓ Two external drivers dedicated to fast and slow legs: NCP51820 and NCP51530

Efficiency Performance of the BCM TPPFC

- The TPPFC efficiency is excellent compared with a classical approach
- A gain of 1.8% is brought by the all-synchronous approach at 90-V rms input voltage



300-W PFC demonstration board



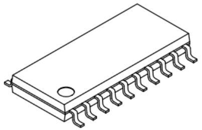
NCP1680

✓ Efficiency approaches 99% at 230 V rms and full power

TPPFC High-Power Operations

- Continuous conduction mode is selected for high-power PFC pre-converters
- The NCP1681 includes a multi-mode engine operating in CCM, BCM and DCM

✓ Mode change is inhibited for high-power applications and the part keeps CCM



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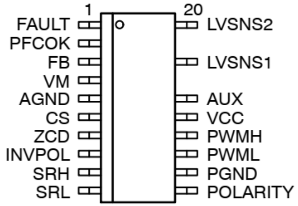
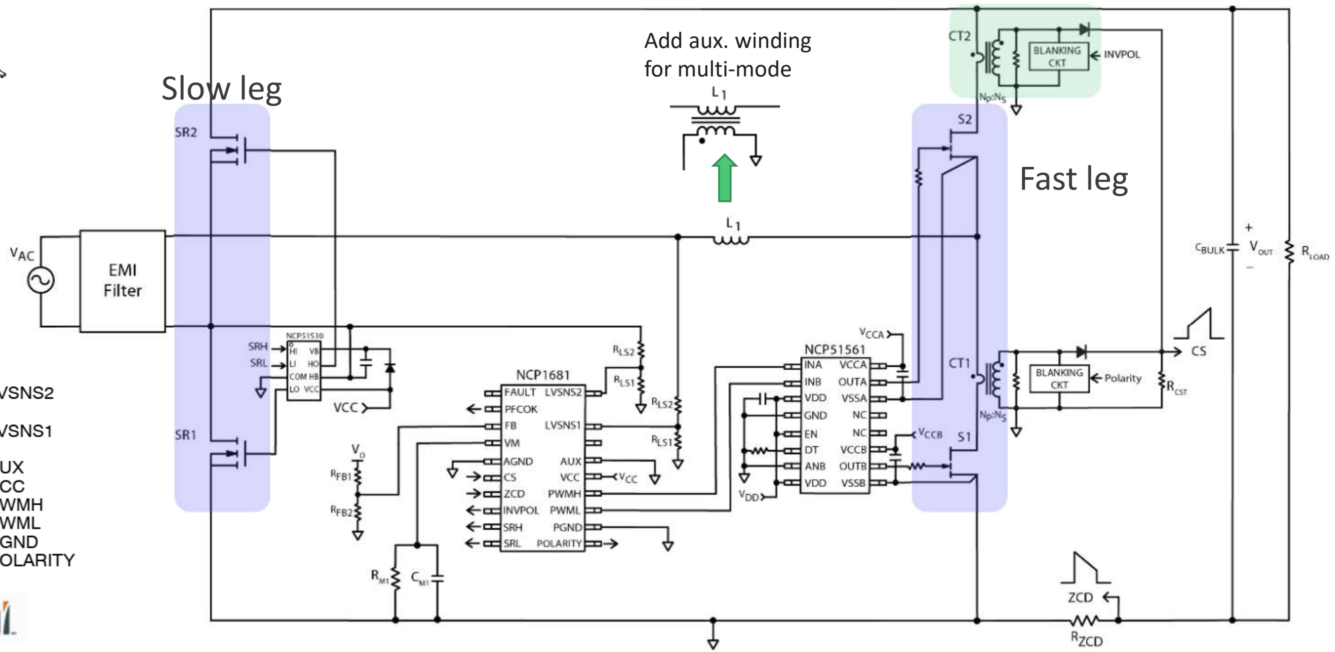
NARROW BODY

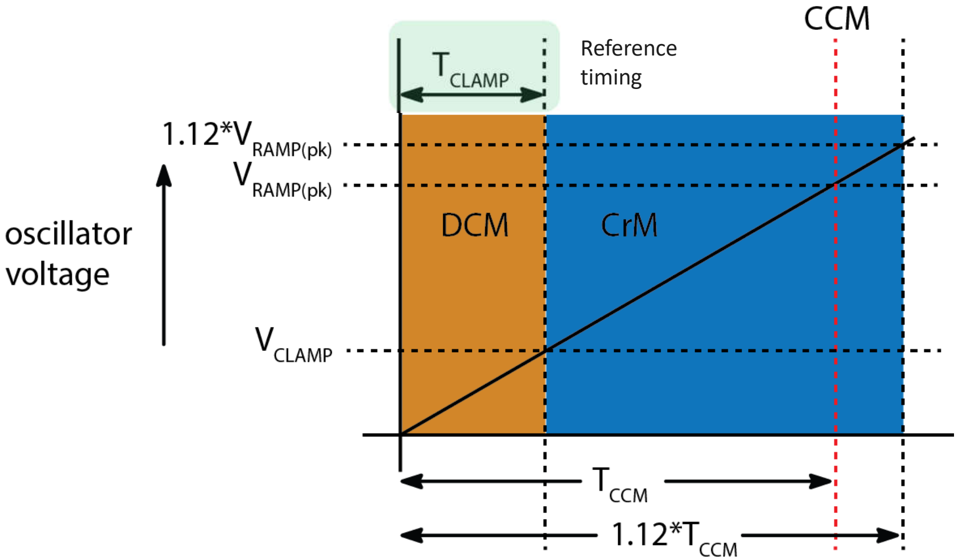


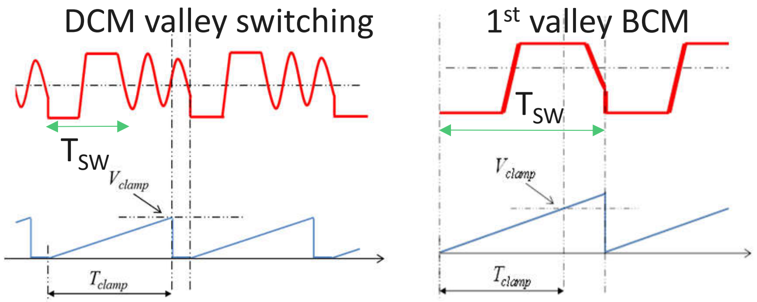


Multi-Mode Operations

- The downstream converter may operate with different load profiles, low to high current
- CCM is optimized for high power but BCM and DCM bring better efficiency at lighter loads

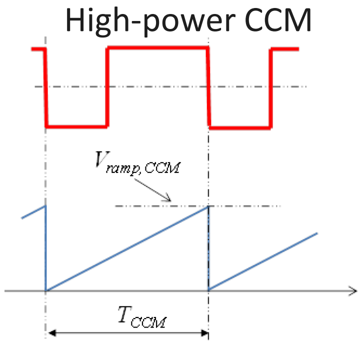
✓ NCP1681 embarks a multi-mode engine smoothly transitioning across all these modes





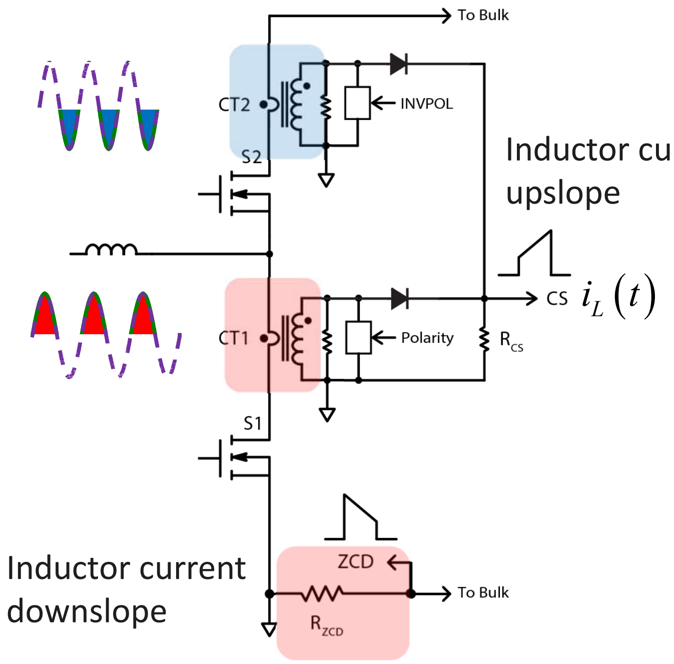
✓ The part internally compares operating timings with thresholds to determine the mode

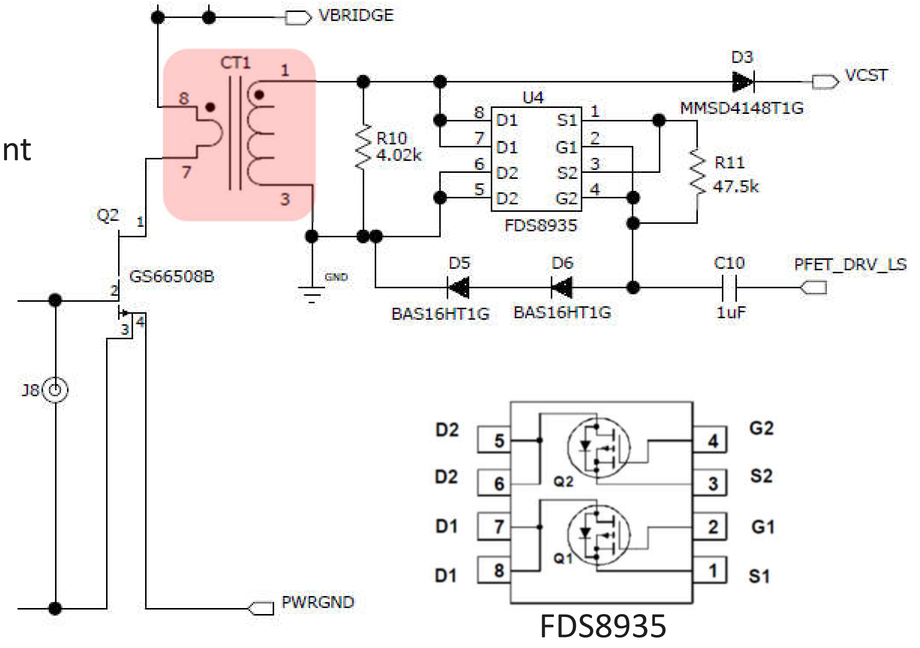
✓ The mode is kept during an entire half cycle



Managing Current Transformers

- Fast-leg switches play the main power switch or the rectifier role in a TPPFC
- Current flow in the leg depends on the input line polarity and needs specific action
- ✓ Current transformers secondaries are alternatively shorted depending on line polarity





A Reliable Controller with Fault Management

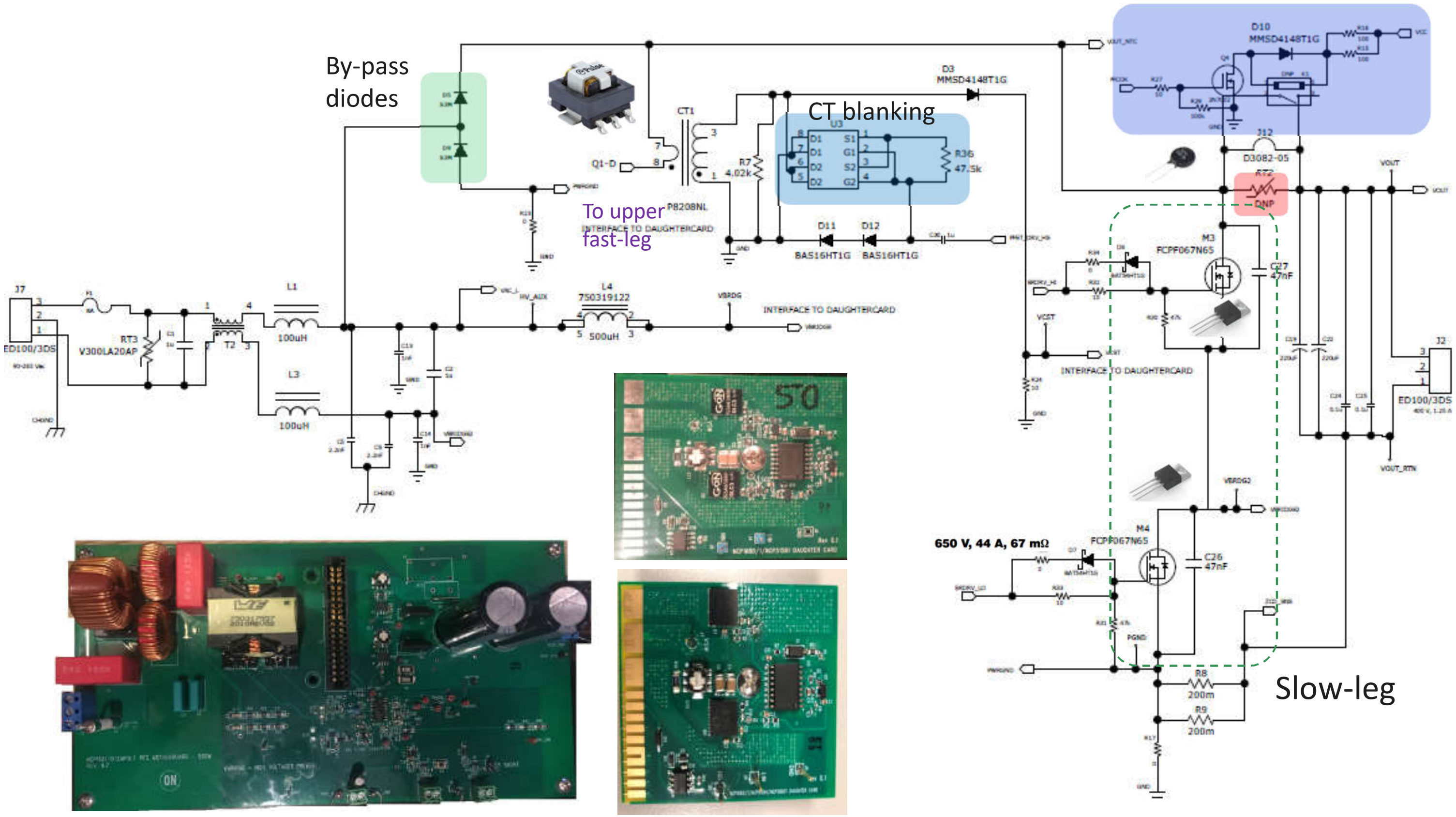
- The controller permanently monitors operating variables for maximum protection
- Some minor faults involve a quick recovery while heavier issues start a 500-ms timer

Fault	Trigger	Cleared By*	Comments / Notes
UVP	$V_{FB} < V_{UVP}$	$V_{FB} > V_{UVP} + V_{UVP(HYS)}$	• All DRV pulses are stopped • PFCOK signal pulled to GND • Polarity signal remains ON
Bulk Under-Voltage (BUV)	$V_{FB} < V_{BUV}$ + PFC_OK	T_{BUV} expires	• BUV stops DRVs (Soft-stop option) • PFCOK signal pulled to GND. • Polarity signal remains on • 500 ms restart timer
Soft OVP	$V_{FB} > V_{softOVP}$	$V_{FB} < V_{OVPrecover}$	• Fast leg DRVs disabled if soft OVP sequence completes • All other signals remain active • Soft start on recovery
Hard OVP	$V_{FB} > V_{hardOVP}$	$V_{FB} < V_{OVPrecover}$	• Fast DRV pulses are stopped immediately • Polarity remains on • Slow leg and open loop drive signals remain ON • Soft start on recovery

- ✓ UVP or under-voltage protection monitors the FB pin and checks for a bias before delivering pulses
- ✓ BUV or bulk under-voltage checks that the output voltage is above 80% of its nominal value
- ✓ Soft OVP is active when a benign overshoot is detected like a load release
- ✓ Hard OVP can be seen as more severe fault in case of stronger overshoot or loop failure

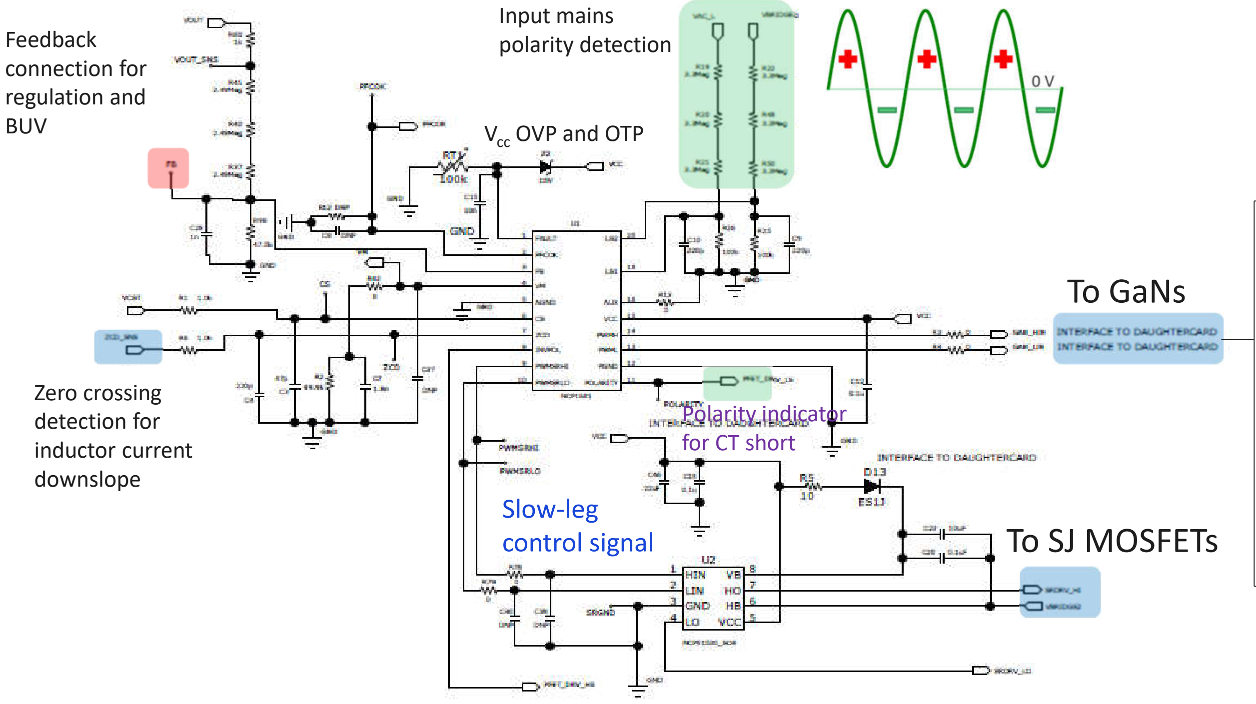
NCP1681 Evaluation Board

- A 500-W demonstration board operated in multi-mode

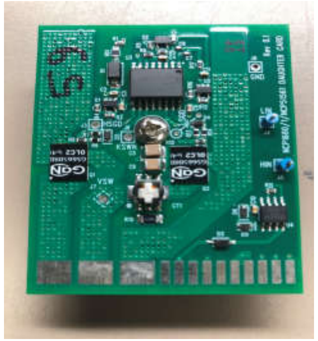


The Control Section

- The NCP1681 senses the polarity via two resistive networks
- The slow-leg requires a bootstrapped driver but of lesser speed than for GaNs



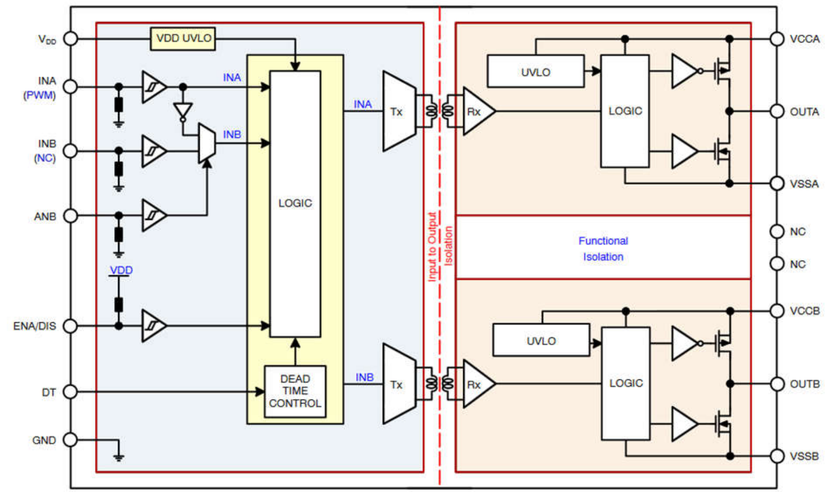
- ✓ One option with isolated gate driver NCP51561 and discrete GaNs (GS66508B)

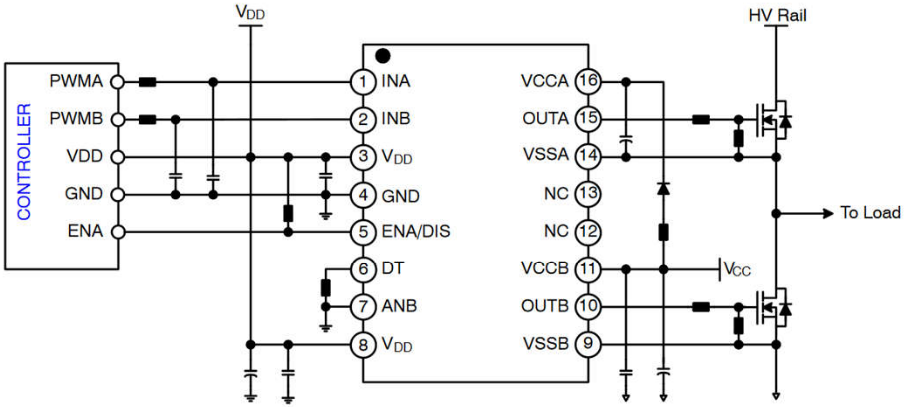


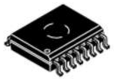
- ✓ One option with one NCP51561 and two NCP58921

NCP51561 Half-Bridge Driver

- Isolated drivers are preferred for the fast leg considering switching speed and noise
- ✓ Differential voltage up to 1.5 kV between channels
- ✓ 5-ns delay matching and pulse distortion
- ✓ Common Mode Transient Immunity grater than 200 V/ns







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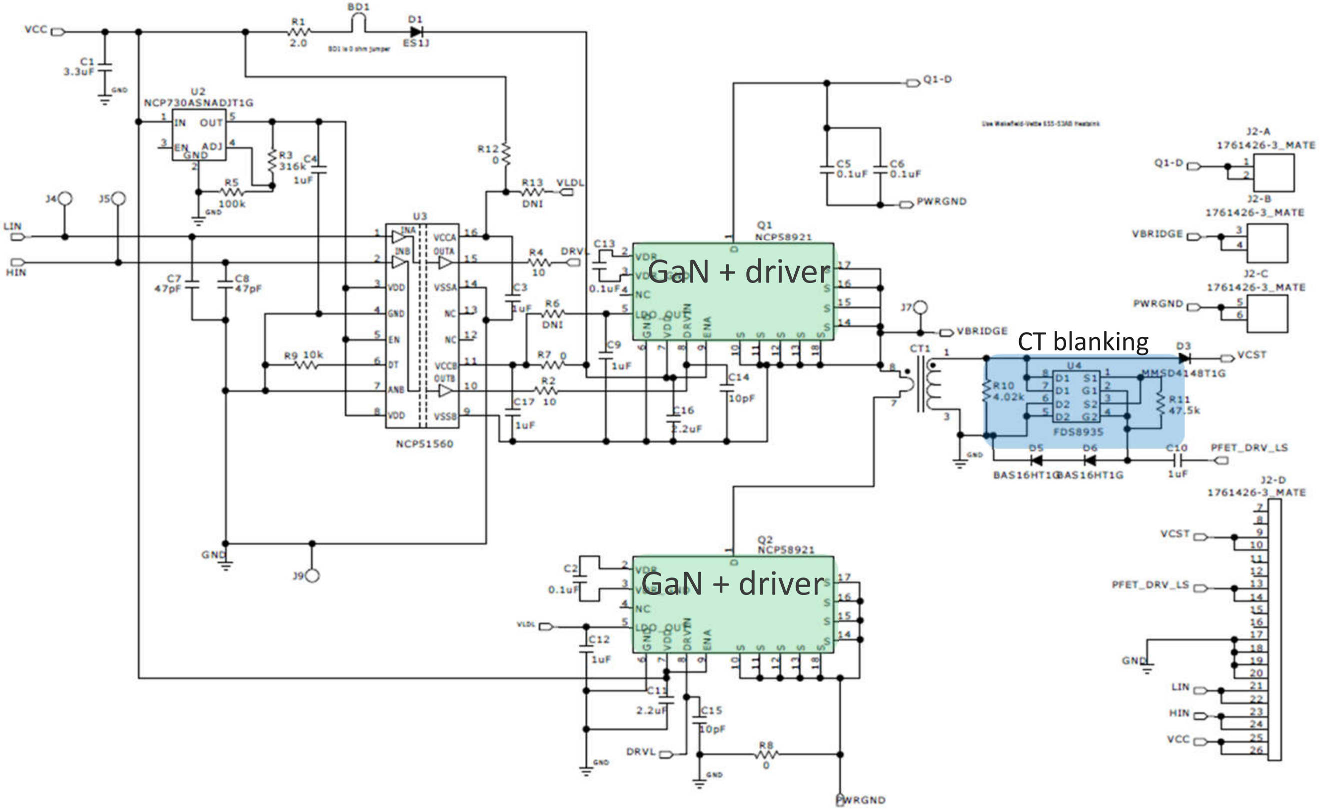
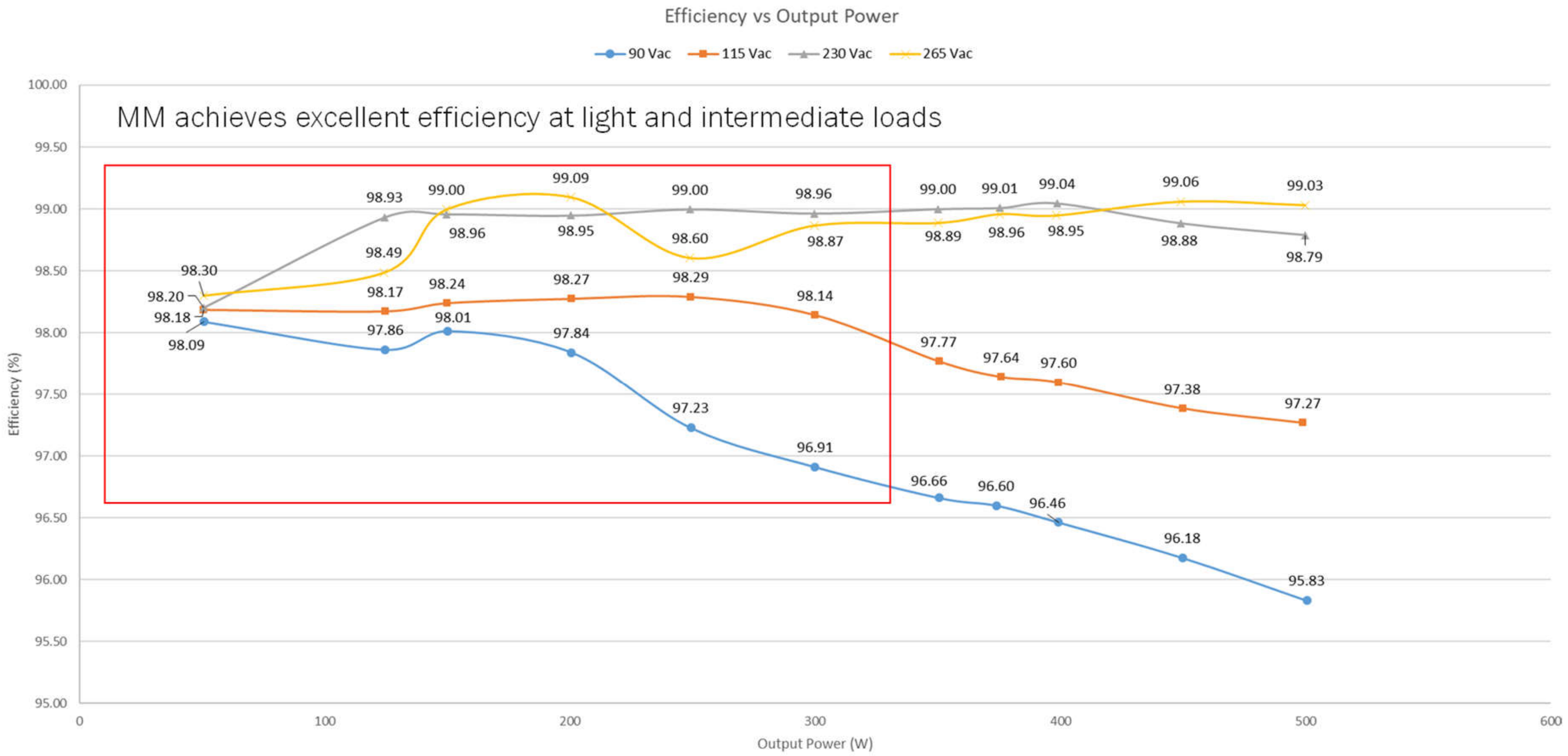
NCP58921 Integrated GaN Driver

- Integrated GaN and driver simplifies PCB layout and reduces BOM cost



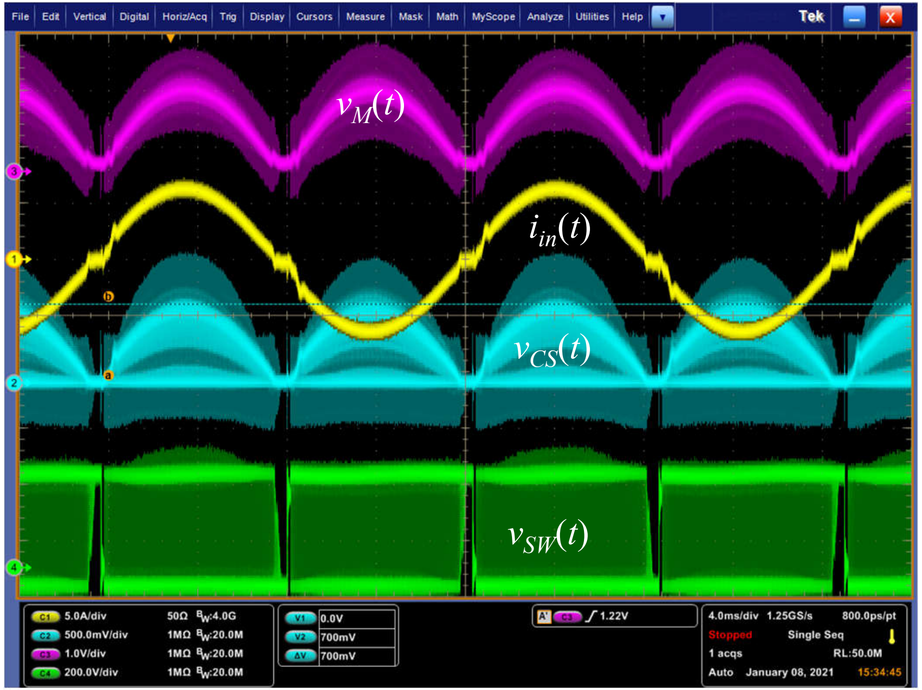
Efficiency Charts with Multi-Mode Engine

- The multi-mode engines clearly shows its positive effects in light-load conditions

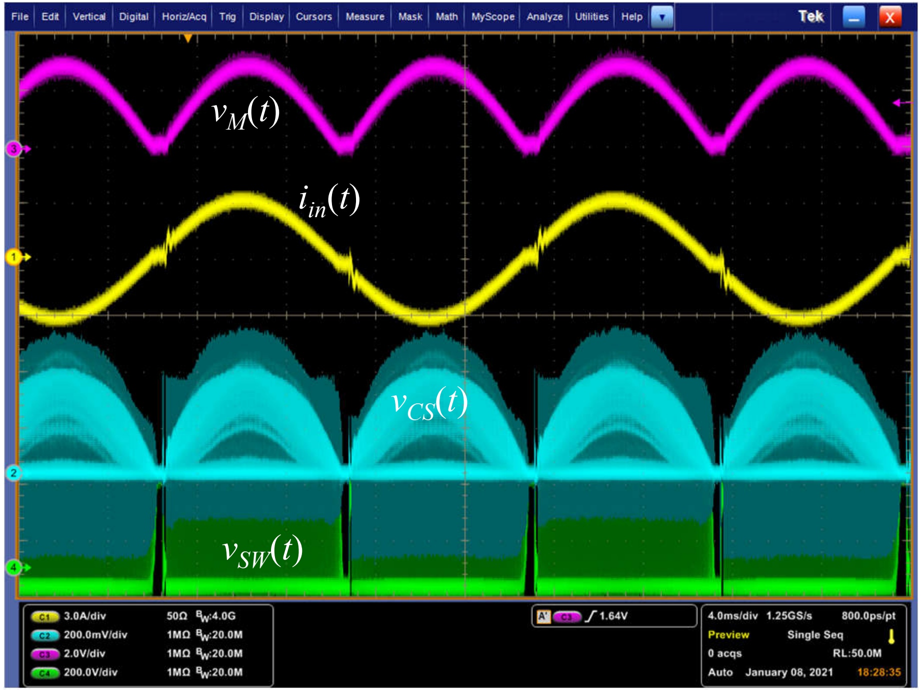


Operating Waveforms

- The part excels in distortion performance which keeps below 5% at full load



V_{in} = 115 V rms – THD = 4.2%



V_{in} = 230 V rms – THD = 2.7%

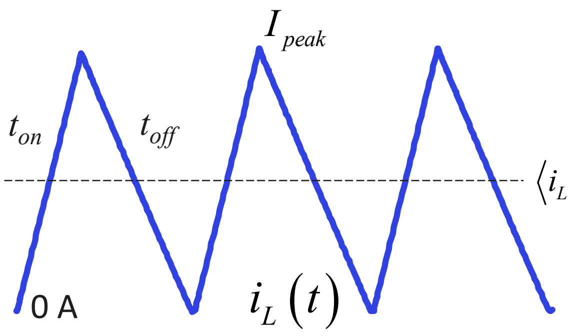
Agenda

- Notions of Power Factor
- Power Factor Correction Structures
- Processing the Power
- Loop Compensation of a PFC
- Solutions from Future Suppliers

Constant On-Time Control

- Voltage-mode control offers the easiest implementation for BCM PFCs

✓ Start with the inductor instantaneous current waveform:



$$\langle i_L(t)\rangle = \frac{I_{peak}}{2}$$

$$p_{in}(t) = v_{in}(t)\,i_{in}(t) = v_{in}(t)\frac{i_{L,peak}(t)}{2}$$

$$i_{L,peak}(t) = \frac{v_{in}(t)}{L}t_{on}(t) \quad\Rightarrow\quad p_{in}(t) = \frac{v_{in}^2(t)}{2L}t_{on}(t)$$

$$\langle i_{in}(t)\rangle = \frac{v_{in}(t)}{2L}t_{on}(t) \quad\Leftrightarrow\quad \langle i_{in}(t)\rangle = \frac{v_{in}(t)}{R_{in}} = \frac{v_{in}(t)}{\frac{V_{ac}^2}{P_{in}}}$$

Resistive input

- The power sets the on-time value in relationship with the rms input voltage

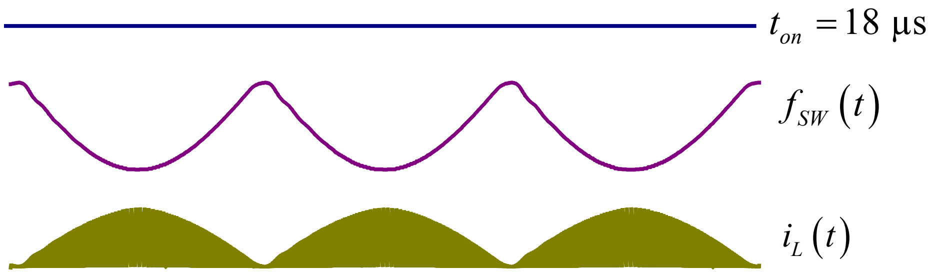
$$t_{on} = \frac{2LP_{in}}{V_{ac}^2}$$

$$\Rightarrow\quad i_{in}(t) = \frac{V_{ac}\sqrt{2}t_{on}}{2L}\sin(\omega t)$$

constant

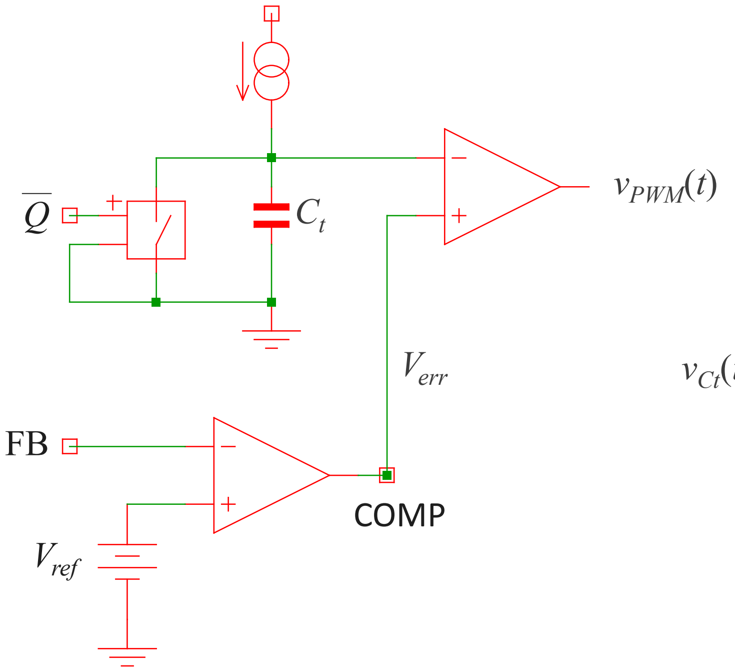
✓ On-time is constant

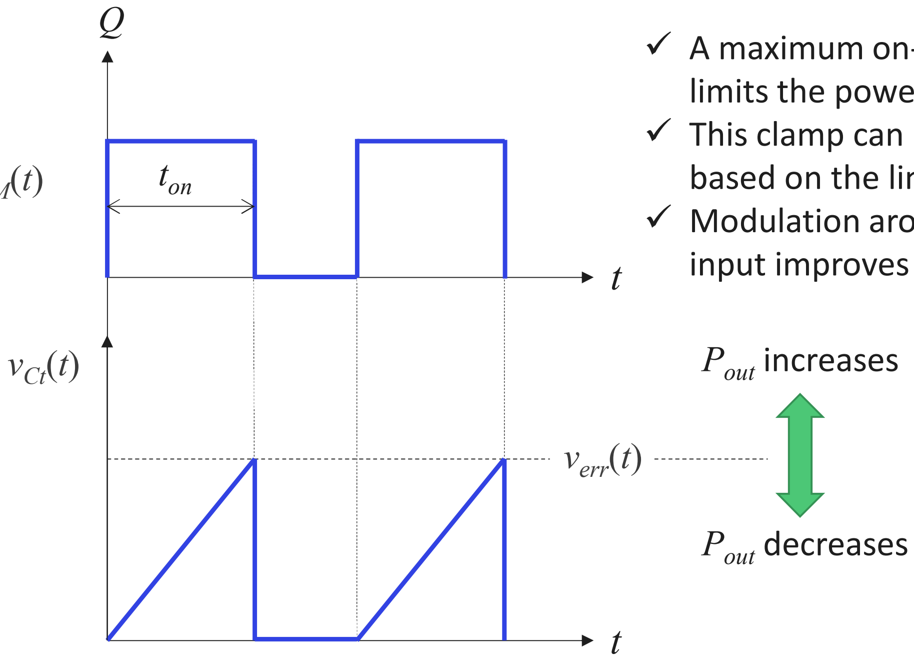
✓ Frequency is variable



Modulating the On-Time

- A capacitor is charged by a constant-current source
- ✓ The error voltage modulates the toggling threshold and adjusts t_{on}

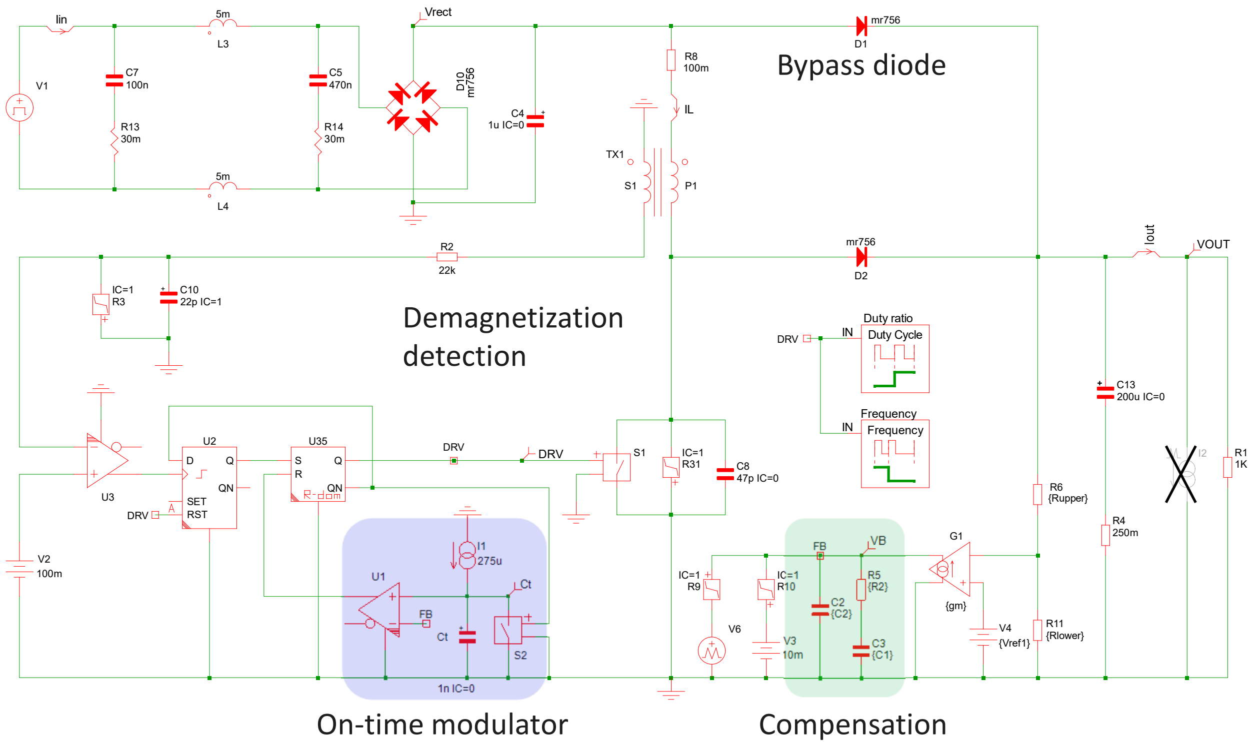


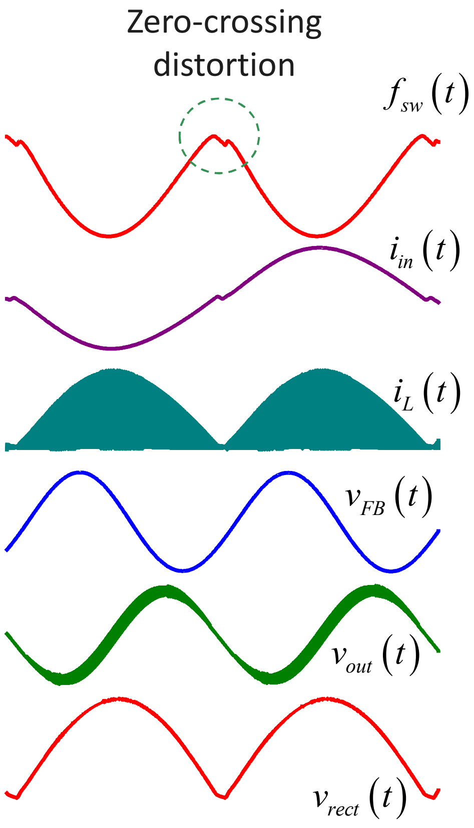


- ✓ A maximum on-time clamp limits the power
- ✓ This clamp can be adjusted based on the line level
- ✓ Modulation around the 0-V input improves distortion

Voltage-Mode Operation

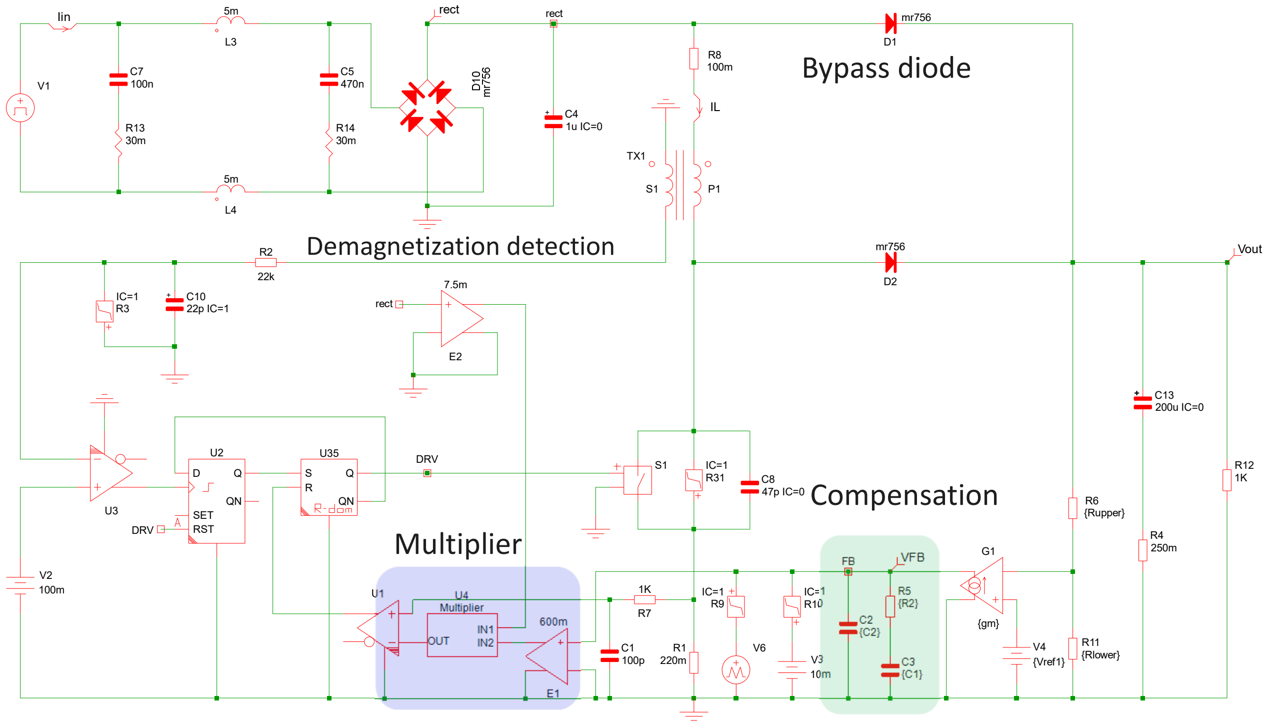
- Constant on-time can be implemented in voltage-mode control
- ✓ No need to sense the input voltage!

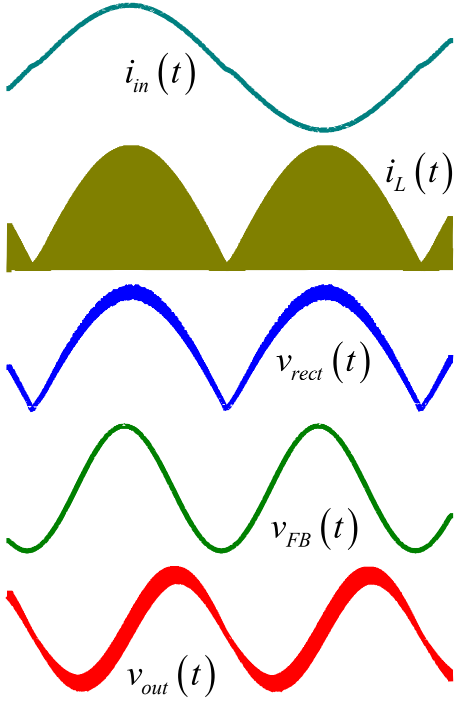




Peak-Current-Mode Operation

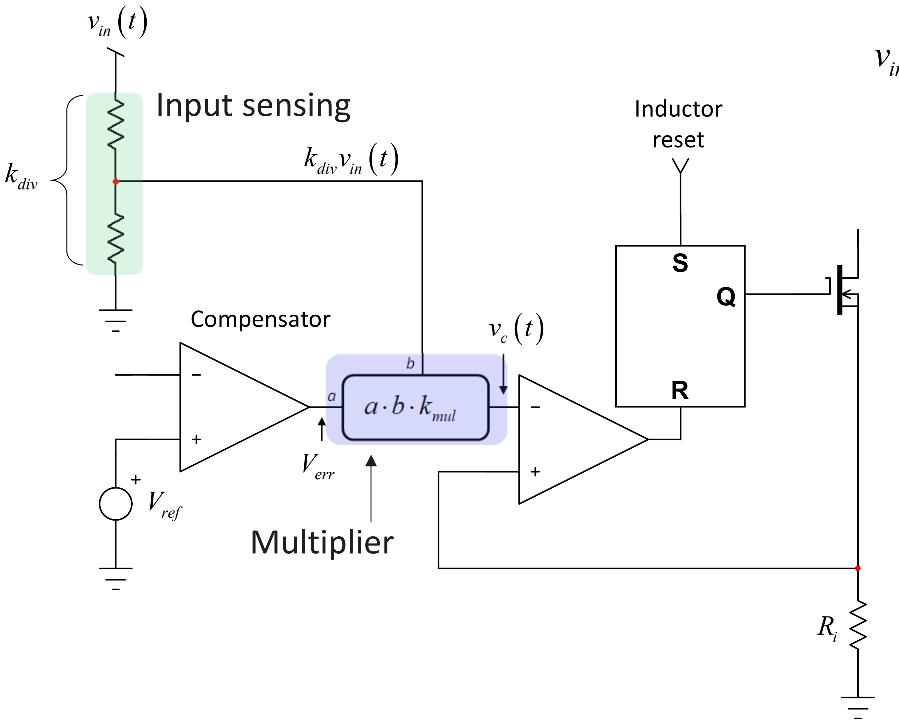
- The inductor *peak current* follows the rectified voltage for a sinusoidal envelope
  - A multiplier is needed to sense the input voltage: increased power consumption

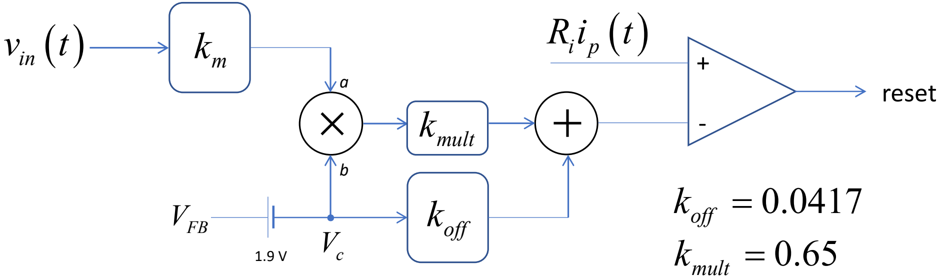




A Multiplier in the Chip

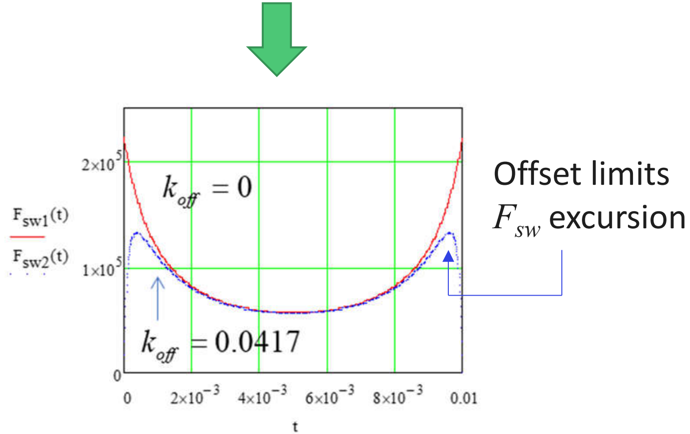
- The inductor current is scaled by the rectified voltage and follows the envelope
- A small offset is added to the multiplier and effectively reduces F_{sw} near 0 V





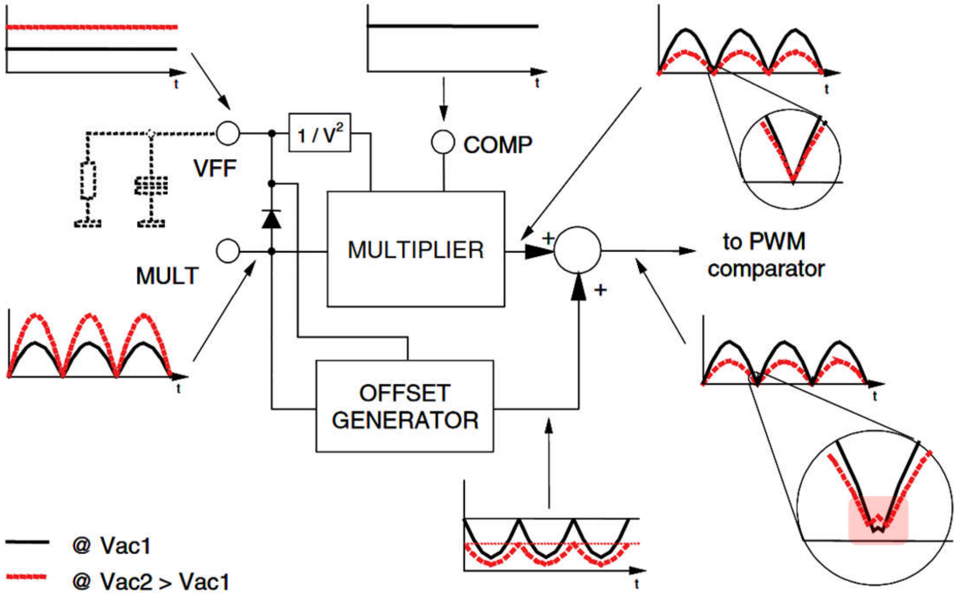
$k_{off} = 0.0417$

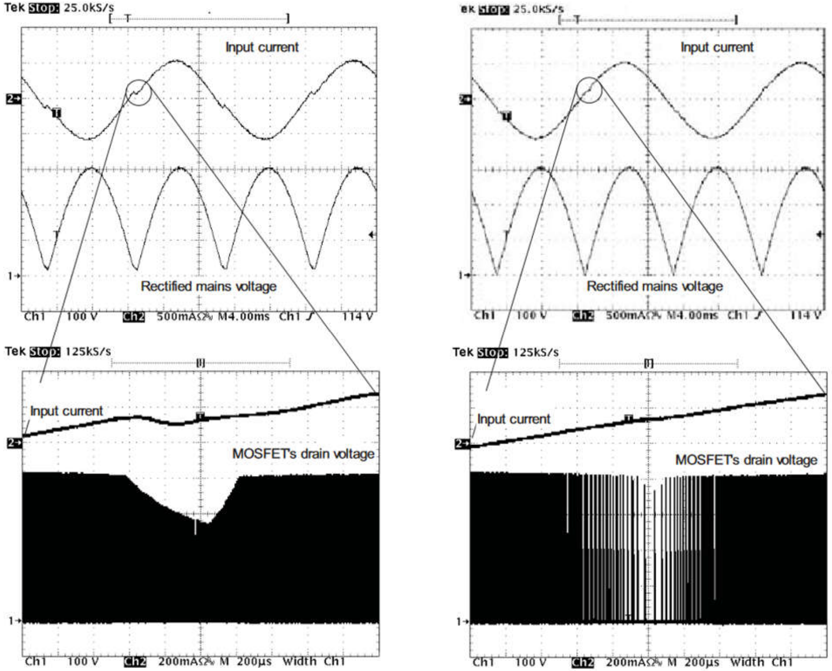
$k_{mult} = 0.65$



Harmonic Distortion Enhancer

- The front-end capacitor holds some residual voltage near zero crossing
- A THD enhancer typically forces a higher on-time at low input voltage



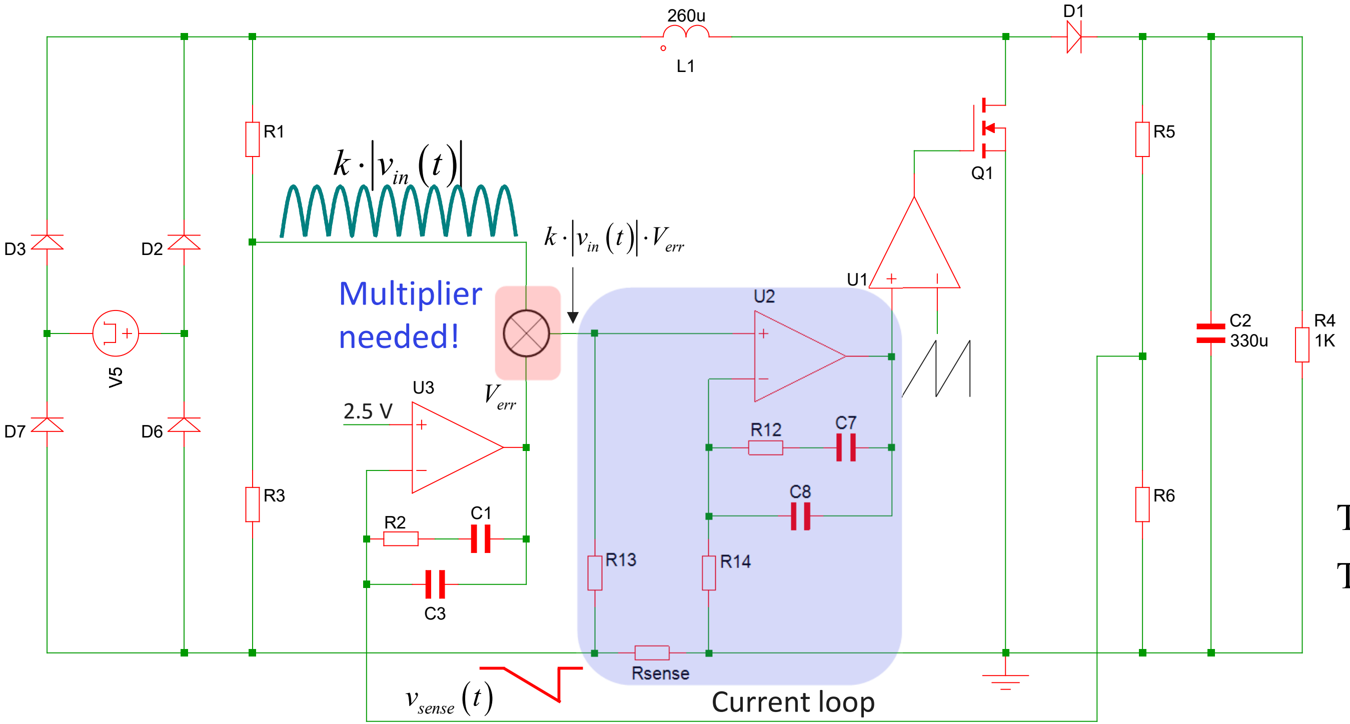


Front-end capacitor does not discharge to 0 V

L6564H data-sheet

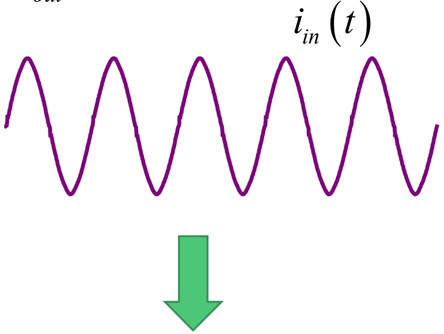
Average Mode Current

- The inductor current is shaped by a dedicated high-bandwidth loop
- ✓ Error between the inductor current and setpoint is minimized for best distortion



$V_{in} = 100$ V rms

$P_{out} = 1$ kW

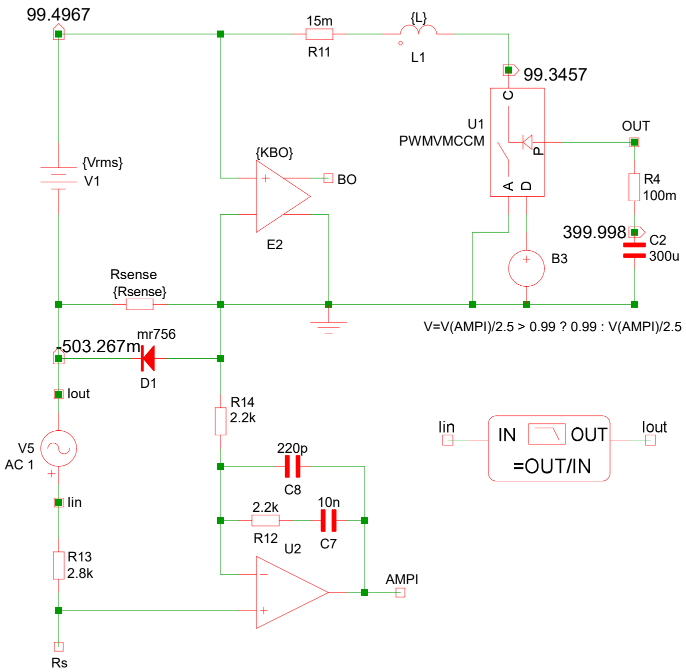


THD = 2.3% $V_{in} = 100$ V rms

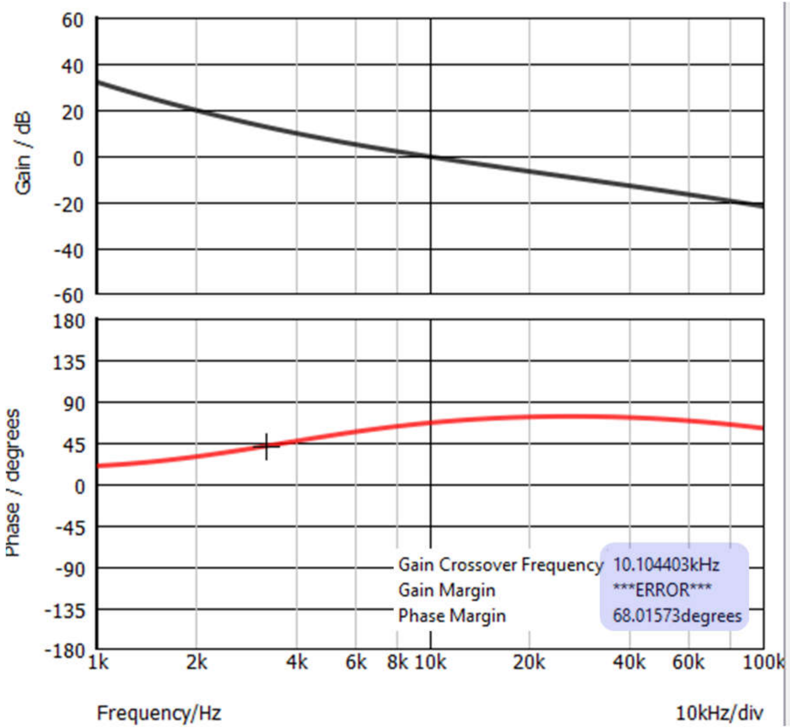
THD = 2.9% $V_{in} = 230$ V rms

A High-Speed Current Loop

- It is important to ensure the fast and precise tracking of the current envelope
- ✓ The current loop must exhibit a wide bandwidth, e.g. 10 kHz typically

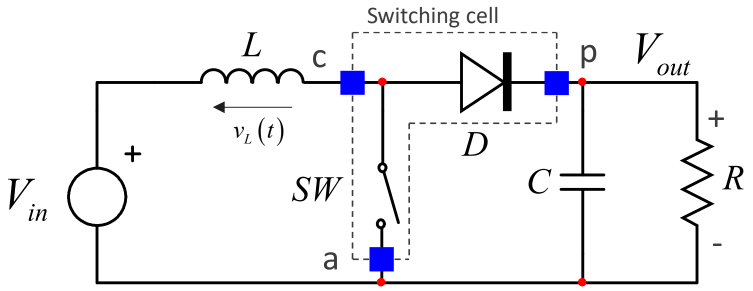


From control circuitry



Predictive Power Factor

- Most of the PFC circuits do sense the input voltage to build the control law
- ✓ Predictive timing generates PWM control without high-voltage sensing



$$\langle v_L(t)\rangle = 0 \Rightarrow \langle v_c(t)\rangle = V_{in}$$

$$\langle v_c(t)\rangle = V_{out}(1-D) = V_{out}D_{off}$$

$$\Rightarrow V_{in} = V_{out}D_{off}$$

- The input current is the inductor current

$$i_{in}(t) = i_L(t) \Rightarrow \langle i_{in}(t)\rangle = \langle i_L(t)\rangle$$

$$\frac{\langle v_{in}(t)\rangle}{\langle i_{in}(t)\rangle} = \frac{V_{out}}{\langle i_L(t)\rangle}D_{off} \Rightarrow D_{off} = \frac{R_e}{V_{out}}\langle i_L(t)\rangle$$

Input resistance R_e

Depends on power (R_e)

Regulated output (V_{out})

- Set the control law to program $D_{off}(t)$

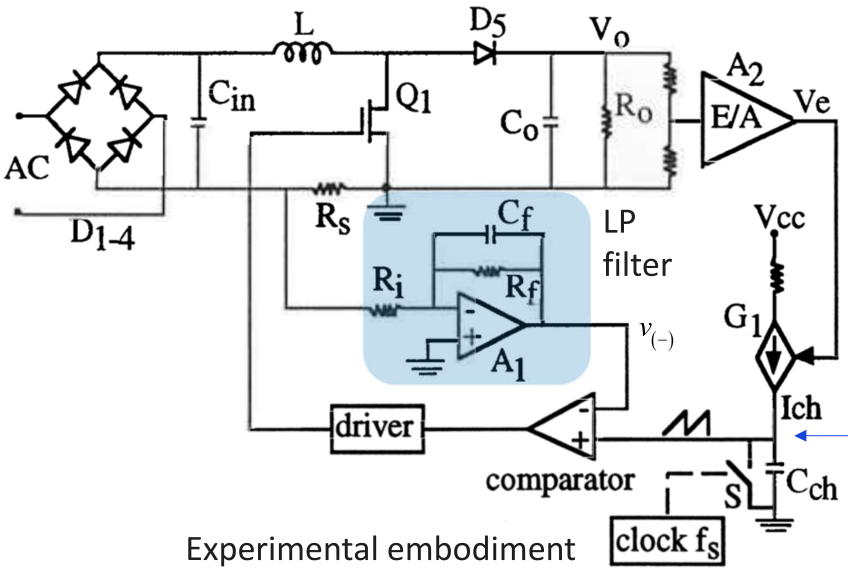
$$D_{off}(t) = \frac{R_e}{V_{out}}\langle i_{in}(t)\rangle \qquad d_{off}(t) = \left(\frac{R_e}{V_{out}}\right)\frac{|v_{in}(t)|}{R_e}$$

Average values — Instantaneous variables

Sam Ben-Yaakov and Ilya Zeltser, *PWM Converters with Resistive Input*, IEEE Transactions on Industrial Electronics, vol. 45, Issue: 3, June 1998)

No Input Voltage Sensing

- By modulating the off-time duration across the input line, resistive input is ensured
- The input current is sensed via a shunt and averaged through a low-pass filter
- ✓ The error voltage adjusts the capacitor charging current and hence off-time duration



Experimental embodiment

$$I_{ch} = g_m V_e$$

$$v_{(+)}(t) = \frac{I_{ch}}{C_{ch}} t = \frac{g_m V_e}{C_{ch}} t$$

$$v_{(-)}(t) = \langle i_L(t) \rangle R_s$$

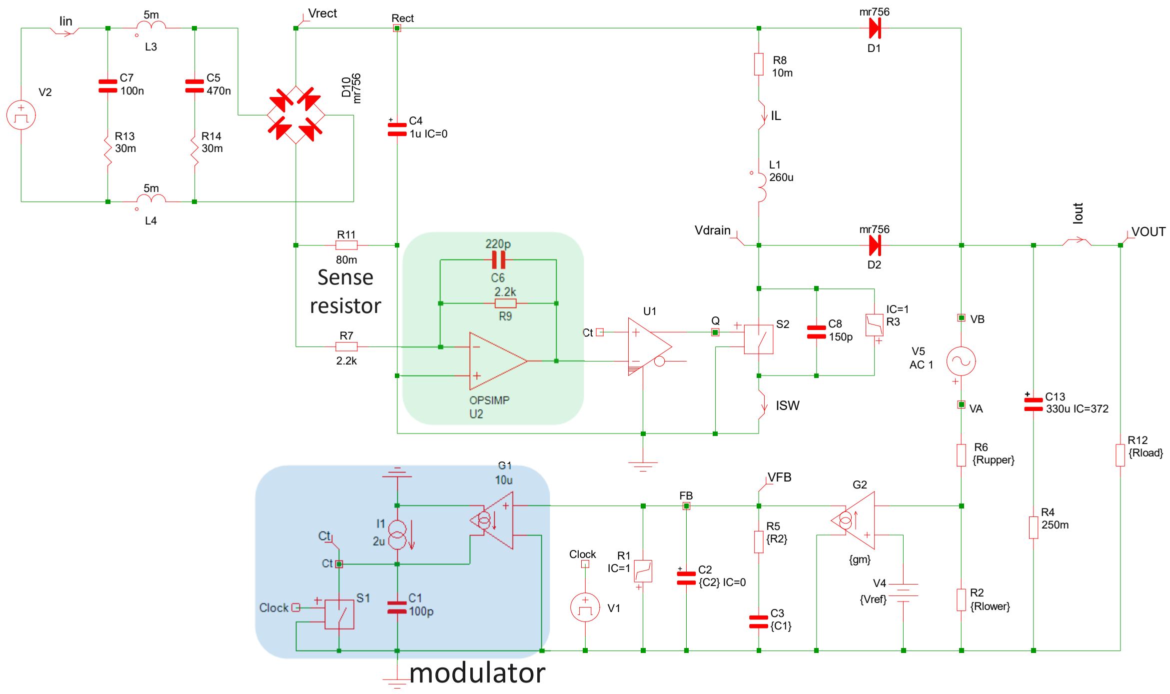
$$v_{(+)} = v_{(-)} \quad \xleftrightarrow{\text{toggling}} \quad \frac{g_m V_e}{C_{ch}} T_{off} = \langle i_L(t) \rangle R_s$$

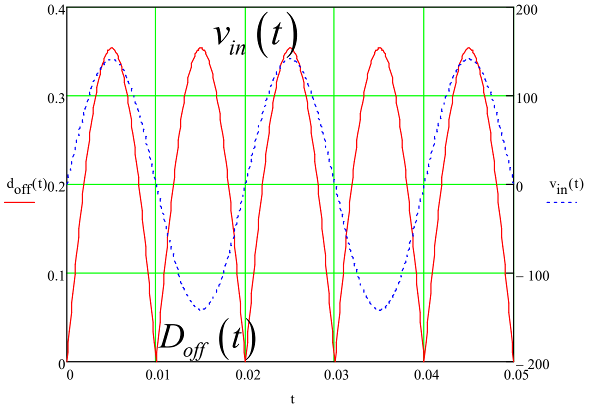
$$\Rightarrow \quad D_{off}(t) = \frac{\langle i_L(t) \rangle}{V_e} \frac{R_s}{g_m} \frac{C_{ch}}{T_{sw}}$$

Method and Apparatus for Regulating the Input Impedance of PWM Converters, S. Ben-Yaakov, M. Hadar, Green Power Technologies, US 6,307,361B1

Simulation Example

- The application circuit is simple and requires a specific off-time modulator
- A dedicated amplifier shapes the negative input current via a shunt





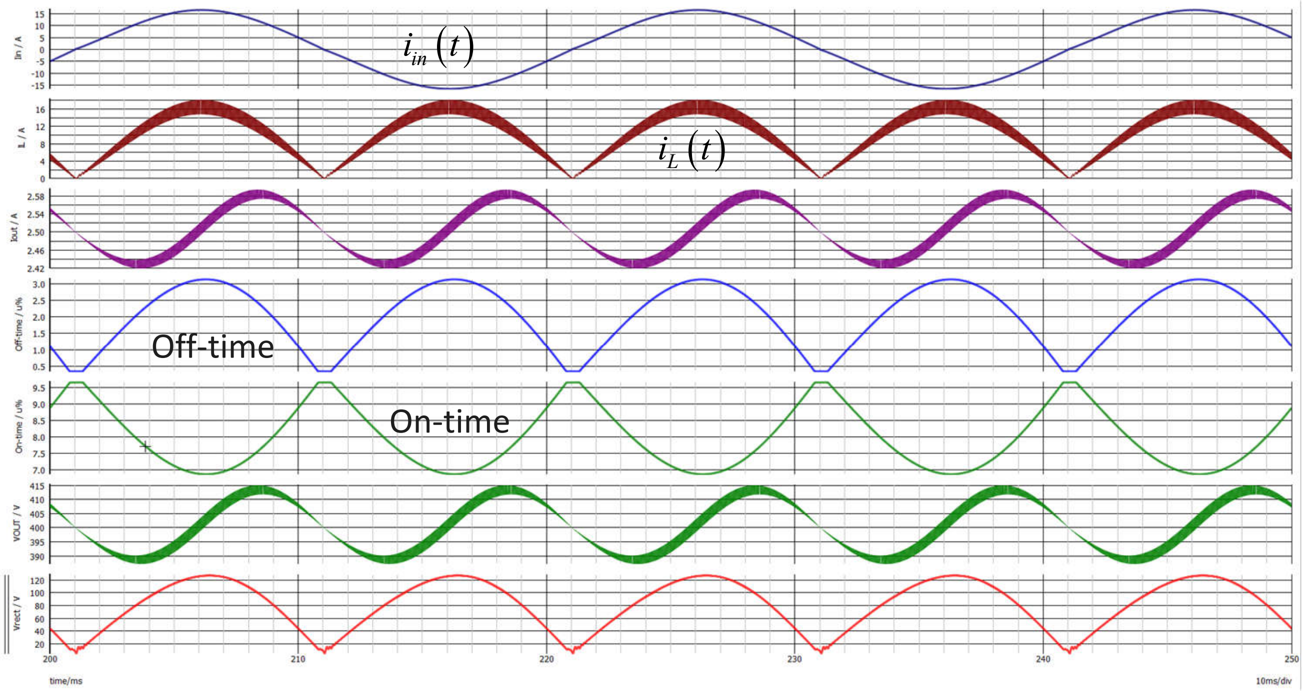
✓ The average off-time is modulated along the input sinewave

Part of my 80+ ready-made templates available here

Simulation Results

- The input current waveform is perfectly sinusoidal and undistorted

V_{in} = 100 V rms, P_{out} = 1 kW



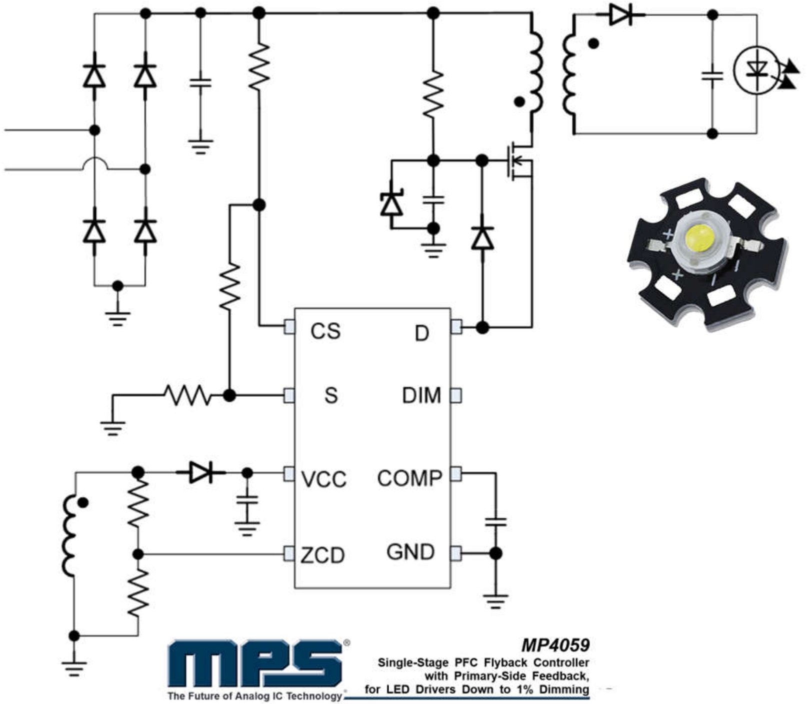
Distortion data:

P_{out} = 1 kW
V_{in} = 100 V rms THD = 3%
V_{in} = 230 V rms THD = 6%

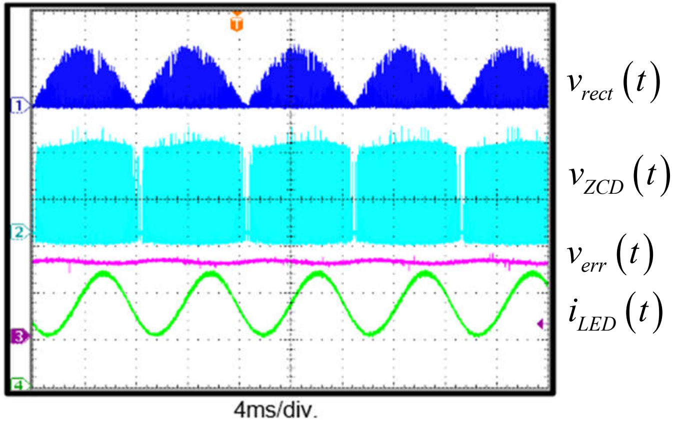
Regulated output voltage

Single-Stage Converter

- It is possible to combine a PFC function with a flyback converter
- Very popular in lighting applications where bandwidth is naturally low



✓ Operates in quasi-resonant mode
✓ Power factor is usually greater than 0.9
✓ Constant on-time voltage-mode operation



Typical operating waveforms – 120 V rms

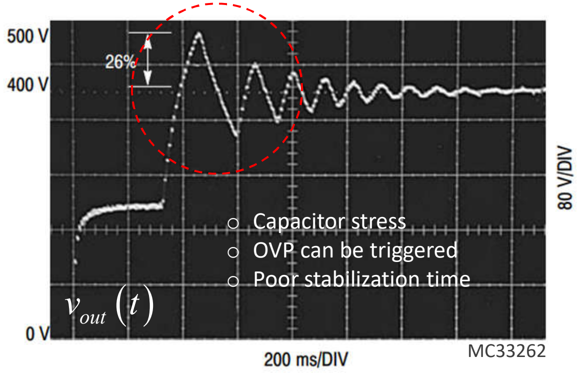
Agenda

- Notions of Power Factor
- Power Factor Correction Structures
- Processing the Power
- Loop Compensation of a PFC
- Solutions from Future Suppliers

The Need for Stability

- A PFC is usually a boost converter operated in different conduction modes:
  - Continuous Conduction Mode or CCM: high-power system, usually > 300 W
  - Boundary/Borderline Conduction Mode or BCM: small to moderate power < 300 W
  - Many derived structures like interleaved or totem-pole for higher power levels
- The PFC controller implements a control law: how to force a sinusoidal input current?
  - In BCM converters, it is usually a constant on-time control, voltage- or current-mode
  - In CCM, there are usually proprietary control laws optimizing distortion and efficiency

Regardless of the implementation, loop analysis is important to guarantee a stable and reliable operation



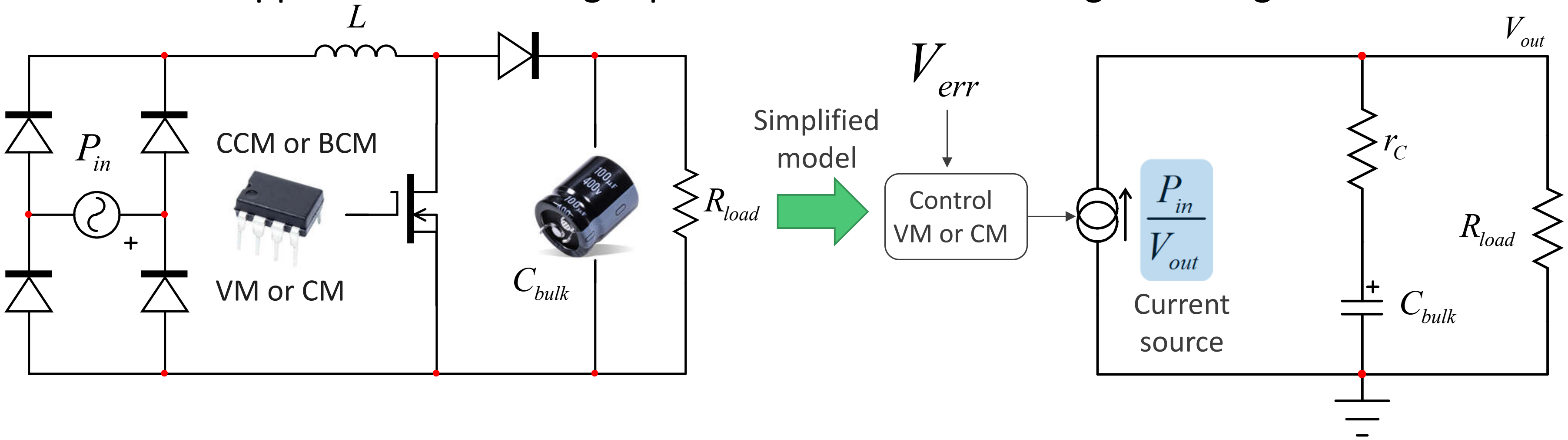
Modeling a Power Factor Correction Stage

- Several ways exist to model switching converters

✓ State-space averaging (SSA), PWM switch model, 1st-order approximation etc.

- A PFC is a slow system in essence with crossover frequency below 10 Hz

✓ 1st-order approximation averages power without considering switching mechanism



➢ If the load is a regulated switching converter, the incremental resistance is negative

A General Formula to Express the Output Power

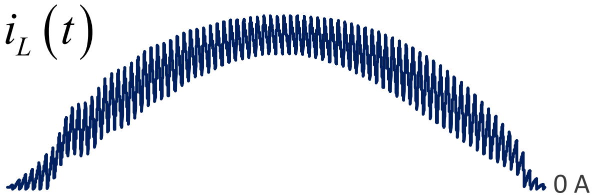
- A generic PFC control law obeys the following formula:

$$P_{in,avg} = \frac{K \cdot V_{in,rms}{}^{m} \cdot V_{control}}{V_{out}{}^{n}}$$

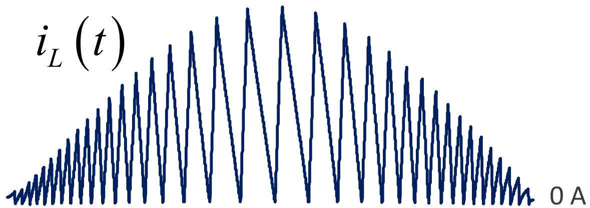
✓ m characterizes the input-voltage feed-forward
✓ n is 1 in general for predictive-sensing stages
✓ K is a constant which depends on the modulator, L, R_{sense} etc.

✓ This is a large-signal expression which needs to be linearized
✓ The corresponding model does not predict high-frequency phenomenon like RHPZ
✓ Perfect for low-frequency approach of a naturally-slow PFC stage

- Works for any type of operation, CCM, CrM/BCM, fixed or variable frequency etc.



CCM, fixed frequency



CrM, variable frequency

J. Turchi, D. Dalal, *Power Factor Correction: from Basics to Optimization*, Technical Seminar, APEC 2014

Example with CrM Power Factor Correction

- The power transmitted by a power stage operated in CrM obeys the formula:

$$P_{in,avg} = \frac{V_{ac}^{2}}{2L} G_{PWM} V_{err}$$

✓ constant on-time voltage-mode control
✓ G_{PWM} represents the modulator small-signal gain
✓ L is the boost inductor value

NCP1608
NCP1622
L6562
L6564
MP44019
MP44018

100% efficiency

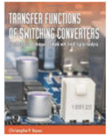
$$P_{in} = P_{out}$$

$$I_{out} = \frac{V_{ac}^{2}}{2LV_{out}} G_{PWM} V_{err}$$

Nonlinear expression!

- Run partial differentiation to obtain small-signal coefficients:

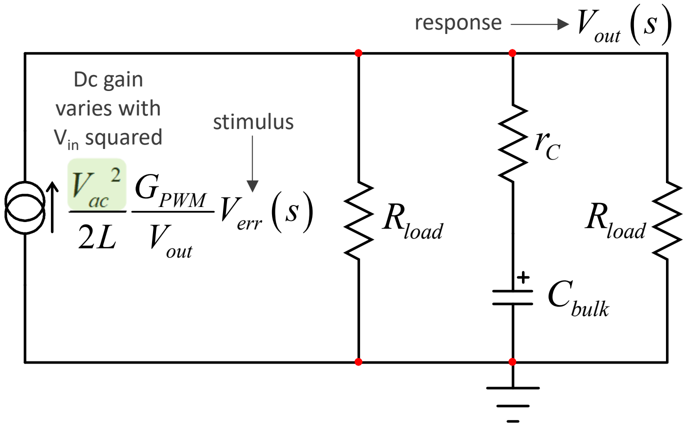
$$\hat{i}_{out} = \frac{\partial}{\partial V_{out}} \left(\frac{V_{ac}^{2}}{2L} \frac{G_{PWM} V_{err}}{V_{out}} \right) \Bigg|_{\hat{v}_{err}=0} \hat{v}_{out} + \frac{\partial}{\partial V_{err}} \left(\frac{V_{ac}^{2}}{2L} \frac{G_{PWM} V_{err}}{V_{out}} \right) \Bigg|_{\hat{v}_{out}=0} \hat{v}_{err}$$



C. Basso, *Transfer Functions of Switching Converters*, Faraday Press 2021

Modeling a Power Factor Correction Stage

- From the small-signal equation, build the complete simplified model



ESR contribution high frequency only

$$H(s) = H_0 \frac{1+\frac{s}{\omega_z}}{1+\frac{s}{\omega_p}} \approx H_0 \frac{1}{1+\frac{s}{\omega_p}}$$

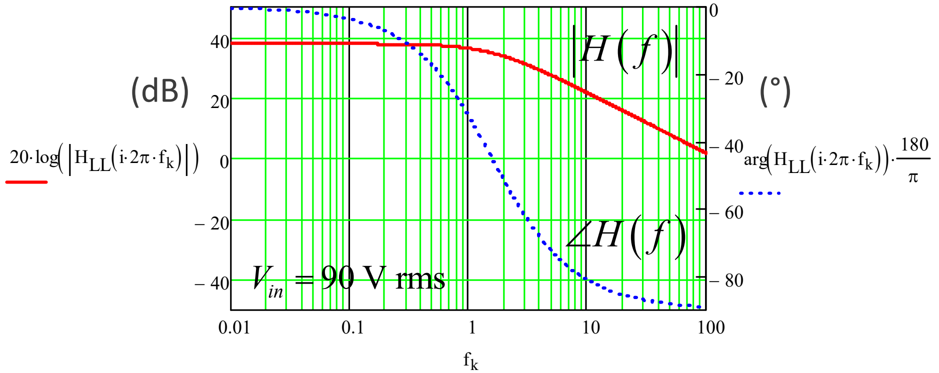
$$H_0 = \frac{V_{ac}^2}{4L}\frac{R_{load}G_{PWM}}{V_{out}} \qquad \omega_p \approx \frac{2}{R_{load}C_{bulk}}$$

- Assume the following specifications:

$$P_{in} = 144\ \text{W}$$
$$V_{out} = 380\ \text{V}$$
$$L = 250\ \mu\text{H}$$
$$C_{bulk} = 200\ \mu F$$
$$R_{load} = 1\ \text{k}\Omega$$

$$H_0 = 78 \approx 38\ \text{dB}$$
$$f_p \approx 1.6\ \text{Hz}$$

Plot power stage (LL)



Compensation Strategy for the PFC

- Without specific treatment, dc gain changes with line input squared
- For ratio of 2.3 between 265 V and 90 V rms input, gain changes by $2.94^2 \approx 9$
- Select a crossover f_c = 50 Hz at a 265-V input to keep at least 8-10 Hz at lowest line

$$\left|H(f_c)\right| = \frac{H_0}{\sqrt{1+\left(\frac{f_c}{f_p}\right)^2}} = 26.6$$

gain excess

↑ 50 Hz

$$\angle H(f_c) = -\tan^{-1}\left(\frac{f_c}{f_p}\right) = -88°$$

↑ 50 Hz

Go for a type 2

- Bring a 1/26.6 or 28.5-dB attenuation at 50 Hz
- For a 70° phase margin, boost the phase by:

$$boost = 70° - (-88) - 90 = 68°$$

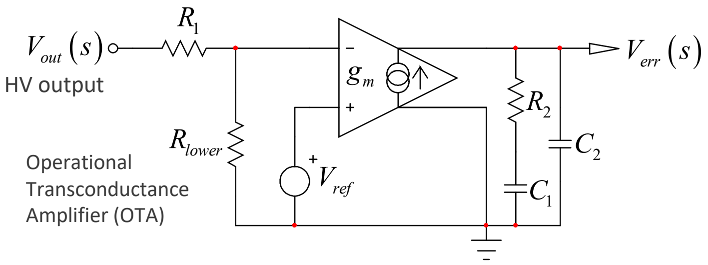
- One pole and one zero to boost the phase by 68°
- f_p = 260 Hz
- f_z = 9.6 Hz

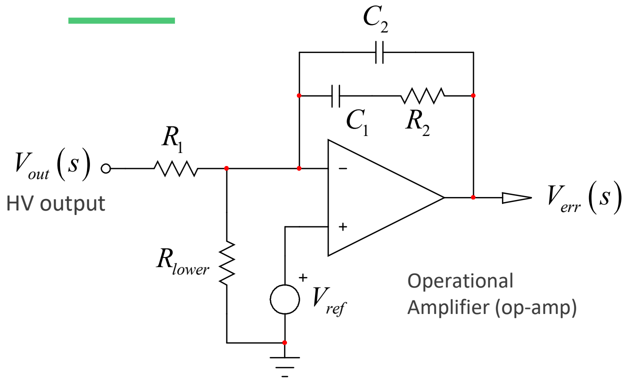
$$G(s) = G_0 \frac{1+\frac{\omega_z}{s}}{1+\frac{s}{\omega_p}}$$

Type 2 compensator

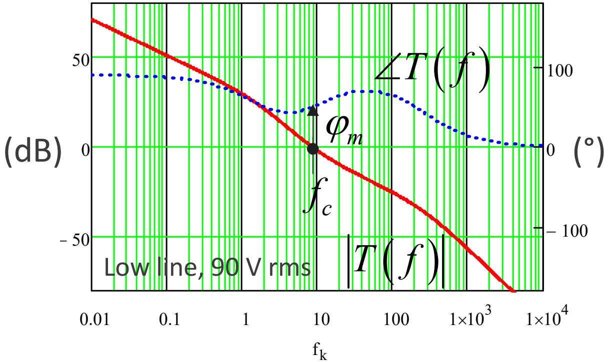
Check Compensated Response

- A type 2 compensator is needed

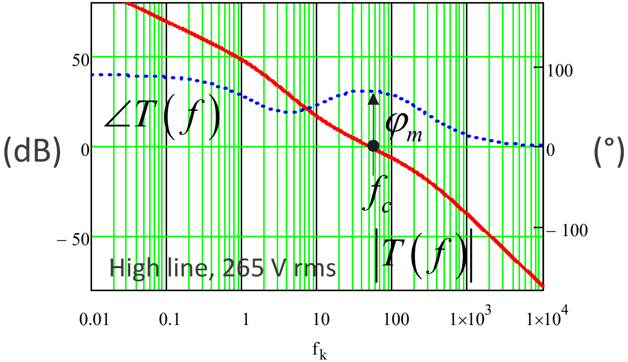




- Check crossover and phase margin at the input line extremes $T(s) = H(s)G(s)$



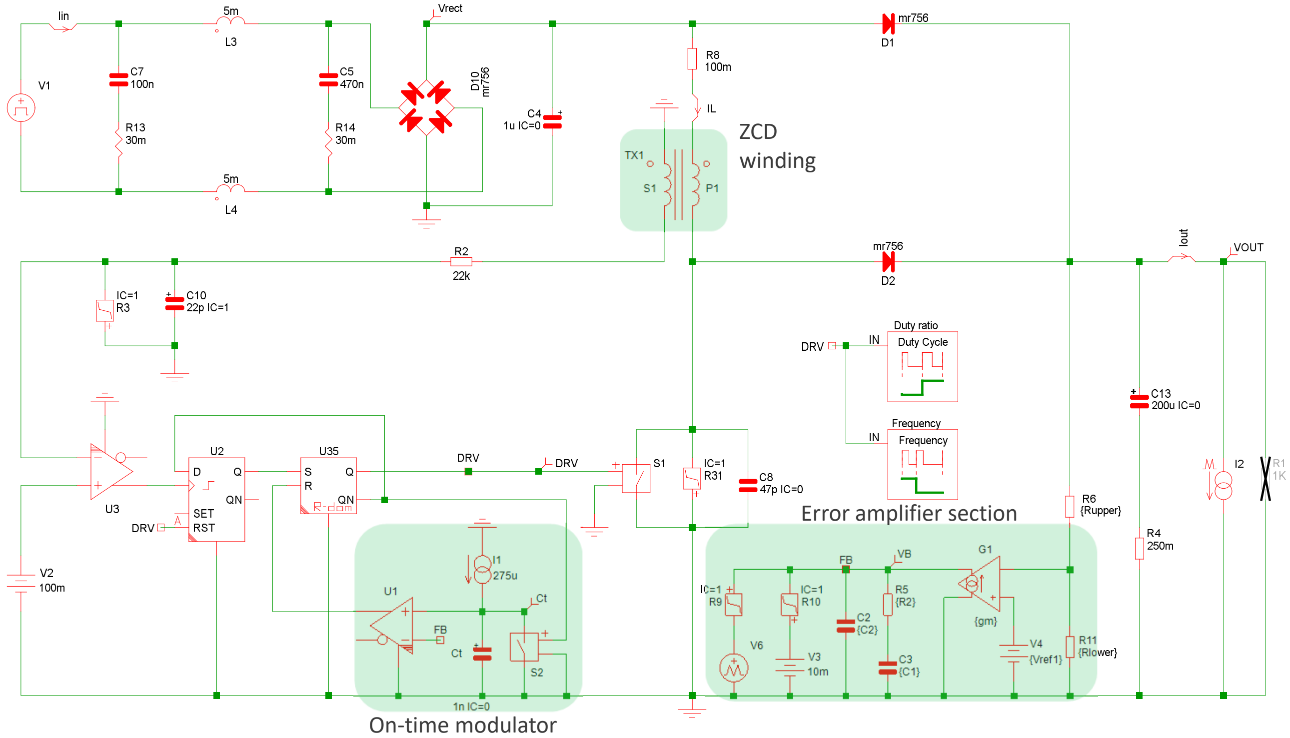
$f_c = 8.5\ \text{Hz} \quad \varphi_m = 50°$



$f_c = 50\ \text{Hz} \quad \varphi_m = 70°$

Simulate the Converter after Compensation

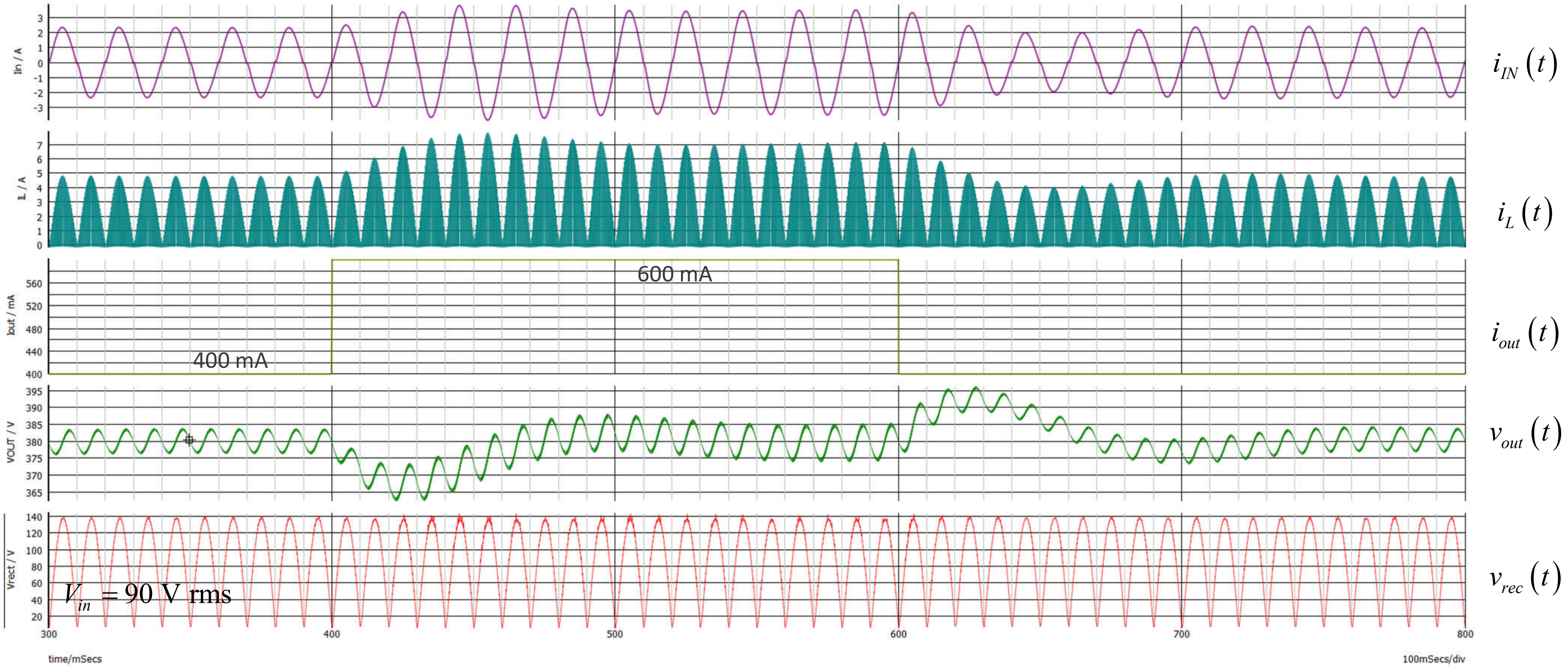
- SIMPLIS® is well suited for simulating power factor correction stages
- The program can plot the ac response from a switching circuit and simulates fast



Templates can be freely downloaded from https://cbasso.pagesperso-orange.fr/Spice.htm

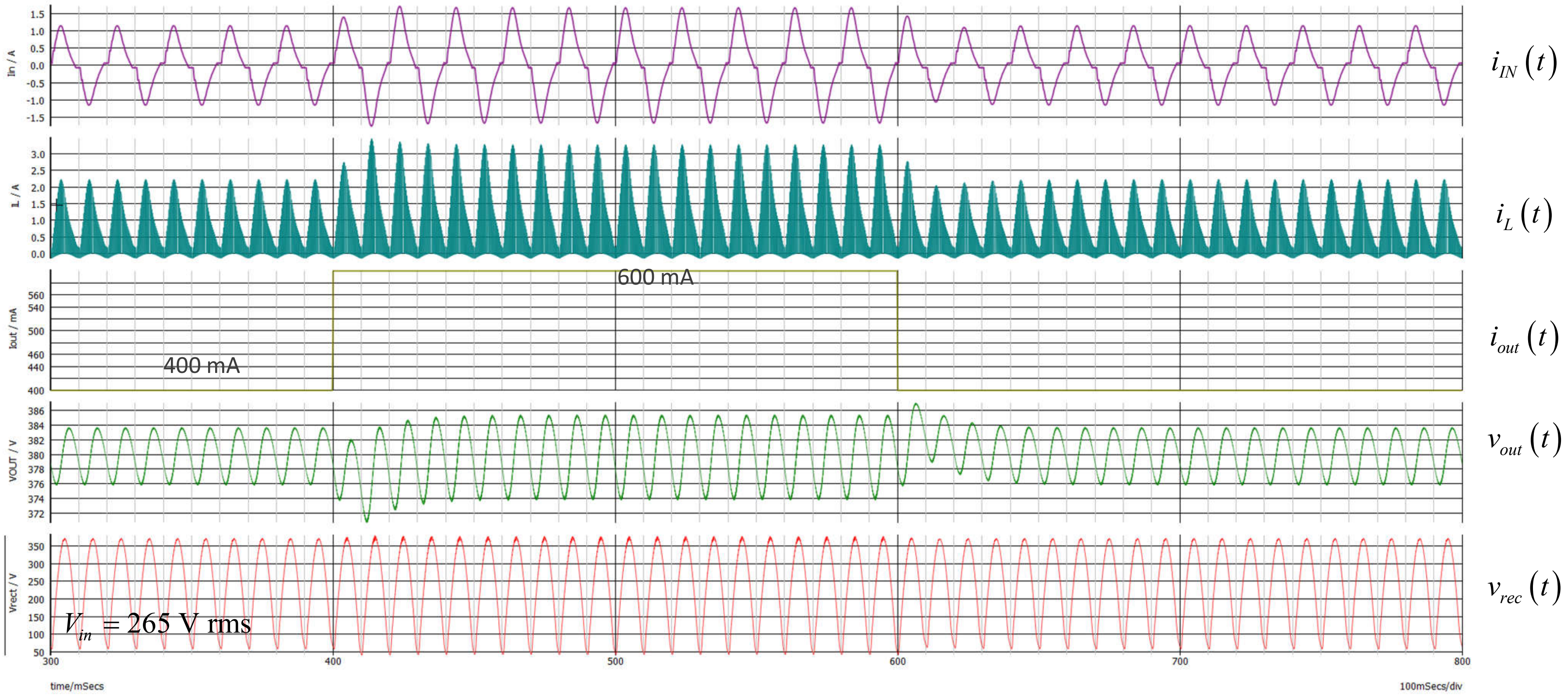
Check Transient Response is Acceptable

- The output current is stepped from 400 to 600 mA at the lowest 90-V rms input voltage



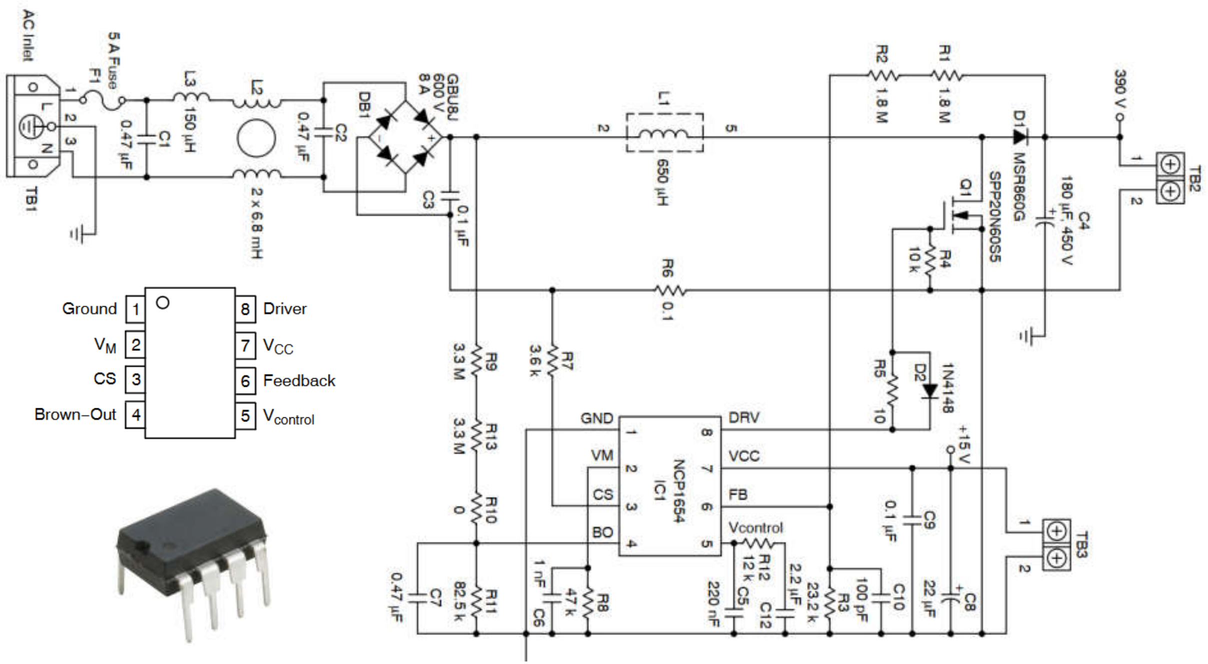
Transient Response at High Line

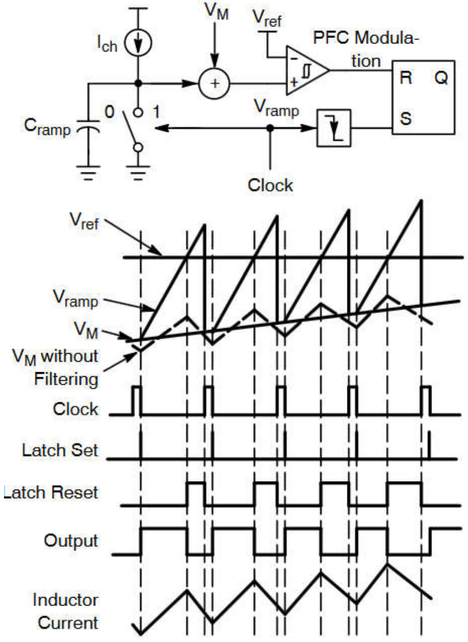
- In high-line conditions, the PFC is stable but given the higher crossover, distortion suffers



Compensating a CCM PFC

- We take the example of a 1-kW PFC operated in continuous conduction mode
- An averaged model is used to extract the control-to-output transfer function
- The predictive controller is the NCP1654 from onsemi



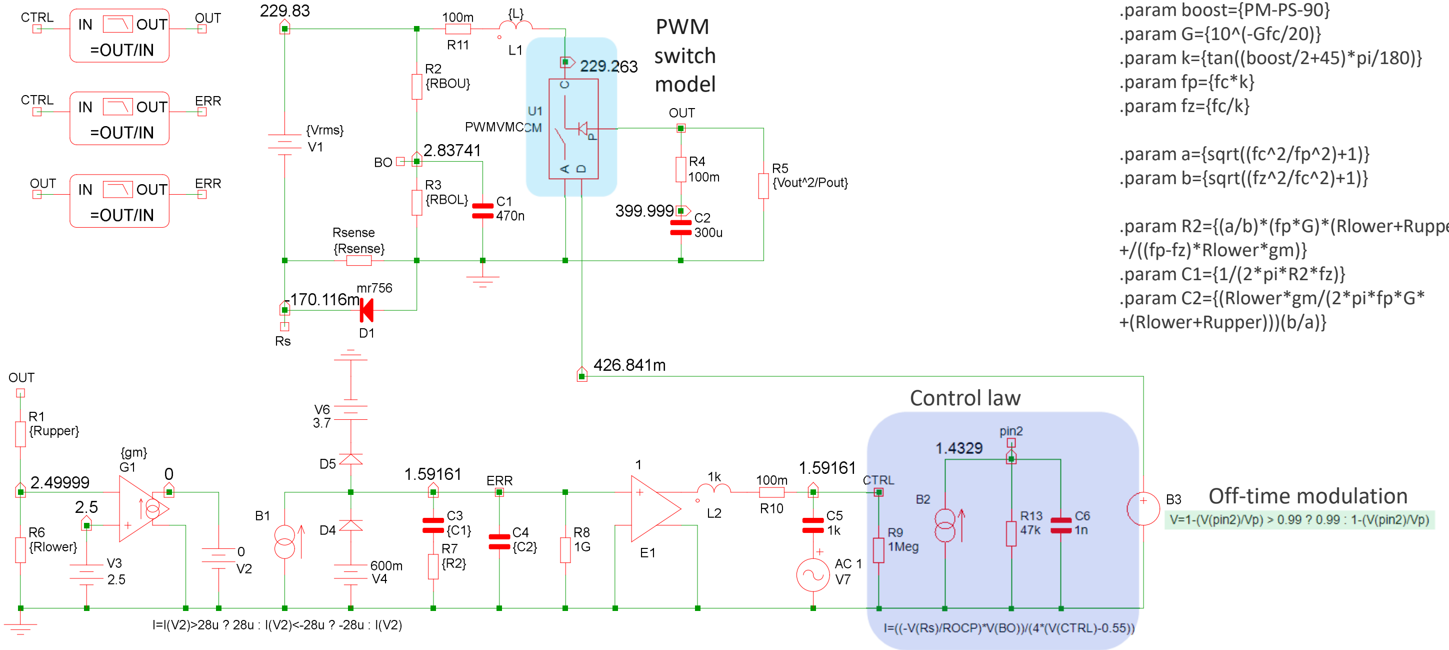


Predictive scheme of NCP1654

Closing the Loop

- The control-to-output transfer function is obtained with an averaged SPICE model
- Some in-line behavioral equations describe the controller's internals
- ✓ Works in ac and transient analyzes

Automatic computation



.param gm=200u
.param boost={PM-PS-90}
.param G={10^(-Gfc/20)}
.param k={tan((boost/2+45)*pi/180)}
.param fp={fc*k}
.param fz={fc/k}

.param a={sqrt((fc^2/fp^2)+1)}
.param b={sqrt((fz^2/fc^2)+1)}

.param R2={(a/b)*(fp*G)*(Rlower+Rupper)
+/((fp-fz)*Rlower*gm)}
.param C1={1/(2*pi*R2*fz)}
.param C2={(Rlower*gm/(2*pi*fp*G*
+(Rlower+Rupper)))(b/a)}

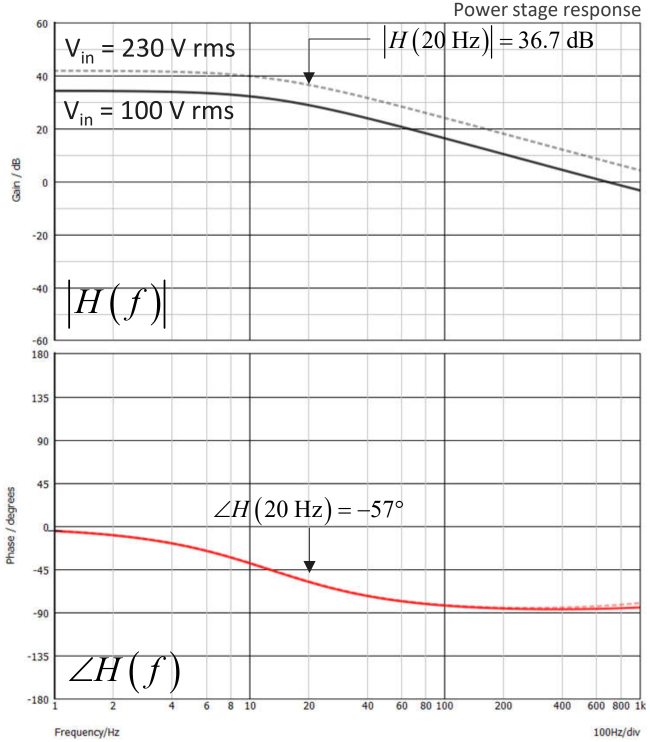
.param Vrms=230
.param Vout=400
.param Pout=1.3k
.param L=54u

.param RBOL=82.5k
.param RBOU=6.6Meg
.param ROCP=3.8k
.param Vp=2.5
.param Rsense=30m
.param Ib=100u
.param Rupper={(Vout-2.5)/Ib}
.param Rlower={2.5/Ib}

.param fc=20
.param Gfc=36.7
.param ps=-60
.param pm=60

The Power Stage Response

- The control-to-output transfer function is the starting point for compensation
- Infer a compensation strategy by reading information from magnitude and phase



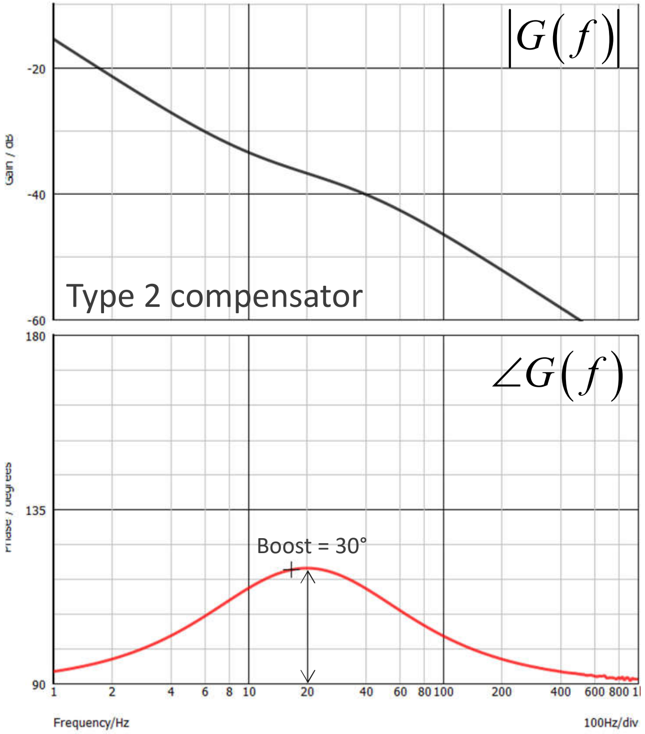
- ✓ Crossover cannot be too high otherwise ripple may pollute the control voltage
  - ➢ If too high then ripple will bring distortion and produce third harmonic
  - ➢ Too low brings an unacceptable slow transient response
- ✓ Without feedforward the crossover may theoretically move with a factor of 9 in high- and low-line conditions
- ✓ NCP1654 feedforward limits the change in crossover frequency

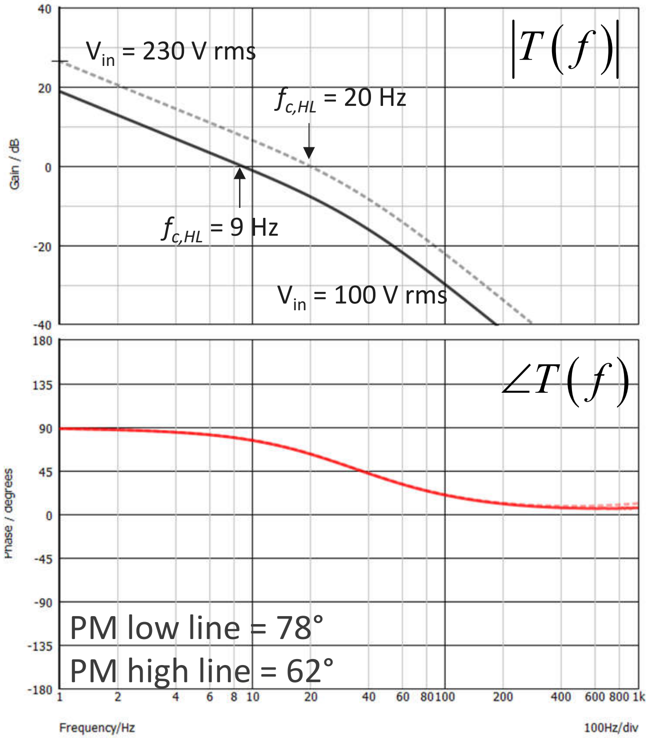
Select f_c in high-line conditions
to obtain 5-10 Hz at low line
$f_{c,HL}$ = 20 Hz

J. Turchi, D. Dalal, *Power Factor Correction: from Basics to Optimization*, Technical Seminar, APEC 2014

Check Loop Gain

- The dc input voltage in an ac analysis is the rms voltage of the source
  - Enter 100 V dc and 230 V dc for respective low- and high-line simulations





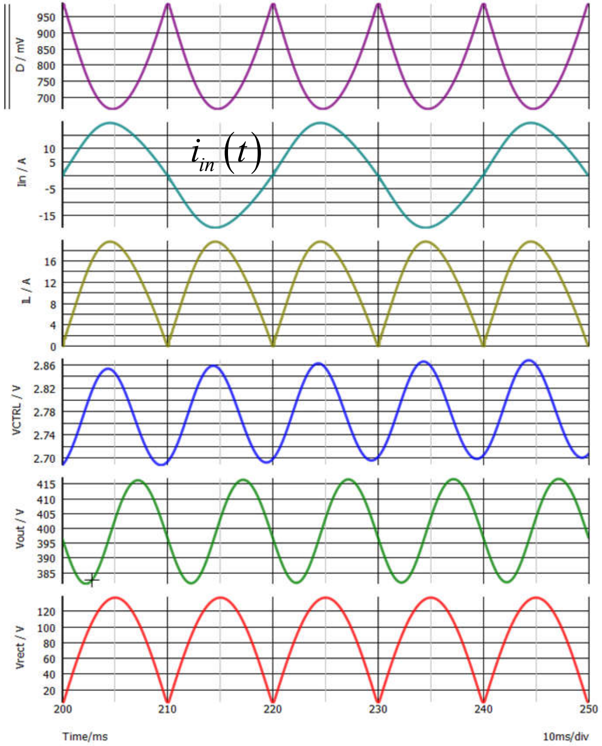
Computed values:

Vrms = 230
Vout = 400
Pout = 1.3k
L = 54u
RBOL = 82.5k
RBOU = 6.6Meg
ROCP = 3.8k
Vp = 2.5
Rsense = 30m
Ib = 100u
Rupper = 3.975Meg
Rlower = 25k
fc = 20
Gfc = 36.7
ps = -60
pm = 60
gm = 200u
boost = 30
G = 14.621771745m
k = 1.73205080757
fp = 34.6410161514
fz = 11.5470053838
a = 1.15470053838
b = 1.15470053838
R2 = 17.546126093k
C1 = 785.54219388n
C2 = 392.77109694n

Compensator

Transient Response Performance

- The large-signal average model lends itself well to a transient simulation
- The input current at low line shows a good harmonic distortion figure of 4.2%

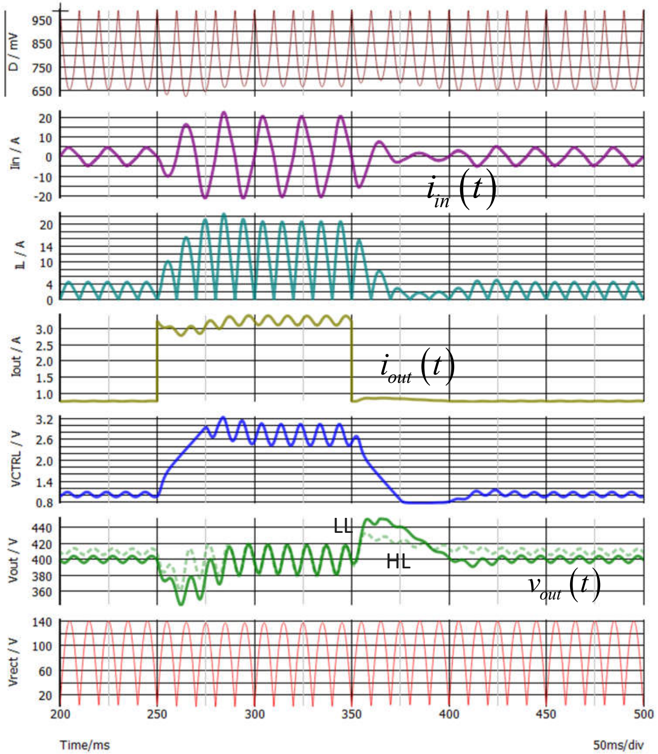


THD_{LL} =4.23%

THD_{HL} =6.33%

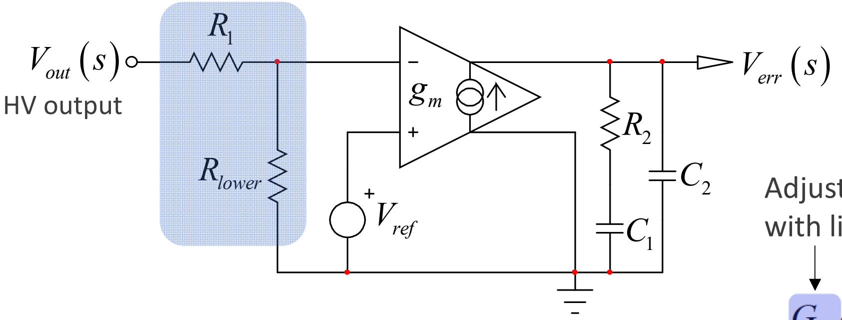
The output current is stepped from 300 W to 1.3 kW with a 1-A/µs slope

The transient response is stable at low and high line



Internal Digital Compensation

- The NCP1680 embeds an internal type 2 compensator
- A low-pass filter then follows to reduce the ripple contribution
- ✓ Mid-band gain is adjusted based on the input line value



$$G(s) = \frac{V_{err}(s)}{V_{out}(s)} = -G_0 \frac{1 + \frac{\omega_z}{s}}{1 + \frac{s}{\omega_p}}$$

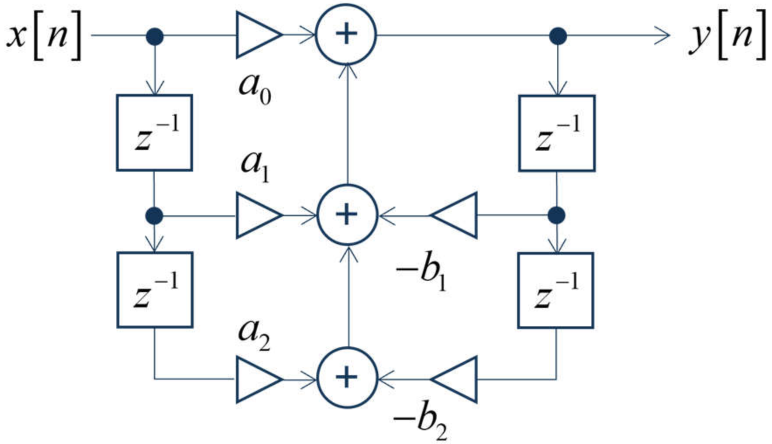
Adjusted with line

$G_0 \approx 13.6\ \text{dB}$

$\omega_z \approx 1.44\ \text{Hz}$

$\omega_p \approx 68\ \text{Hz}$

Type 2 compensator – analogue version

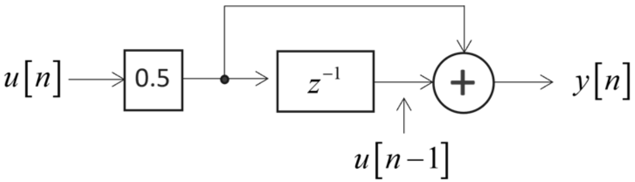


Digital implementation

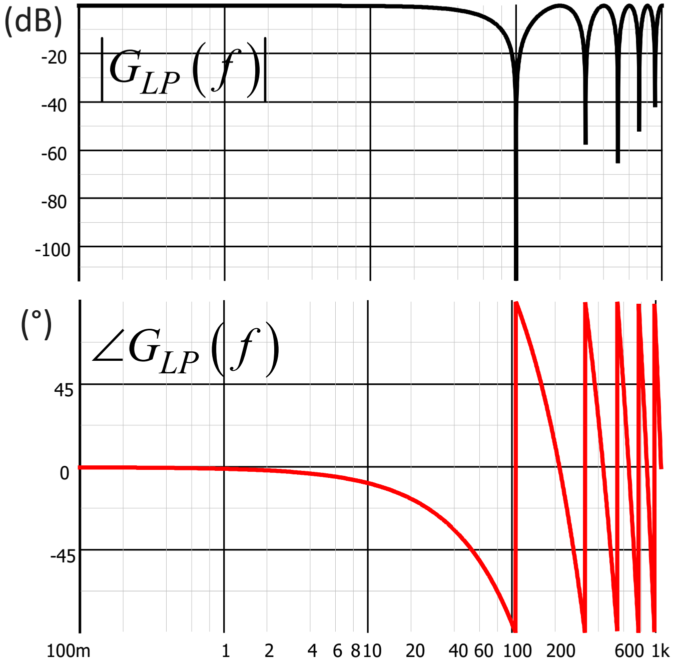
A Low-Pass Filter Reduces Feedback Ripple

- A low-pass filter is inserted in series with the compensator
- The digital implementation of this filter brings efficient output ripple rejection
- The sampling frequency is adjusted depending on the line frequency

$$y[n] = 0.5\left(u[n] + u[n-1]\right)$$



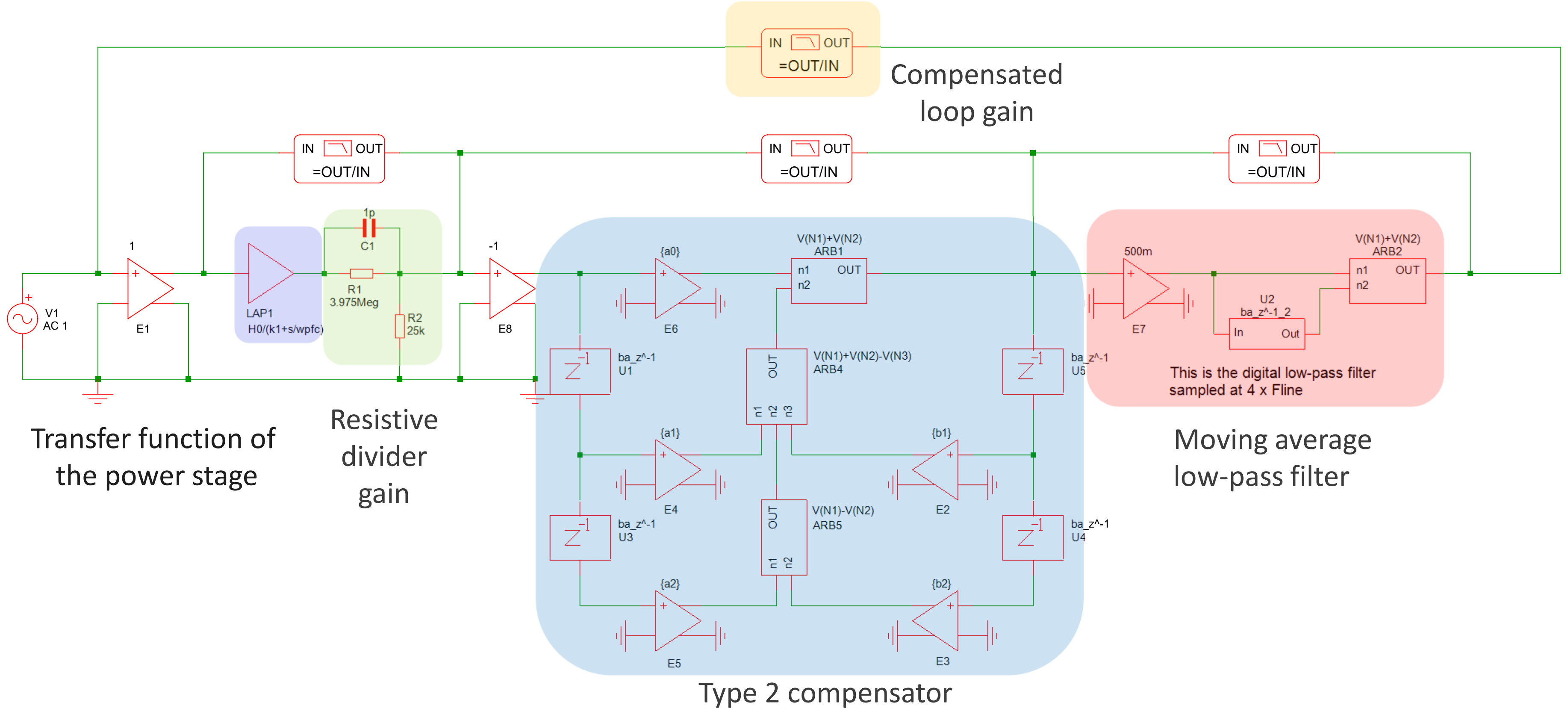
$$G(s) \approx \frac{1 + \frac{s}{\omega Q_N} + \left(\frac{s}{\omega}\right)^2}{1 + \frac{s}{\omega Q_D} + \left(\frac{s}{\omega}\right)^2}$$



- ✓ Sampling frequency is $4F_{line}$
- ✓ It sets a notch at twice the line frequency

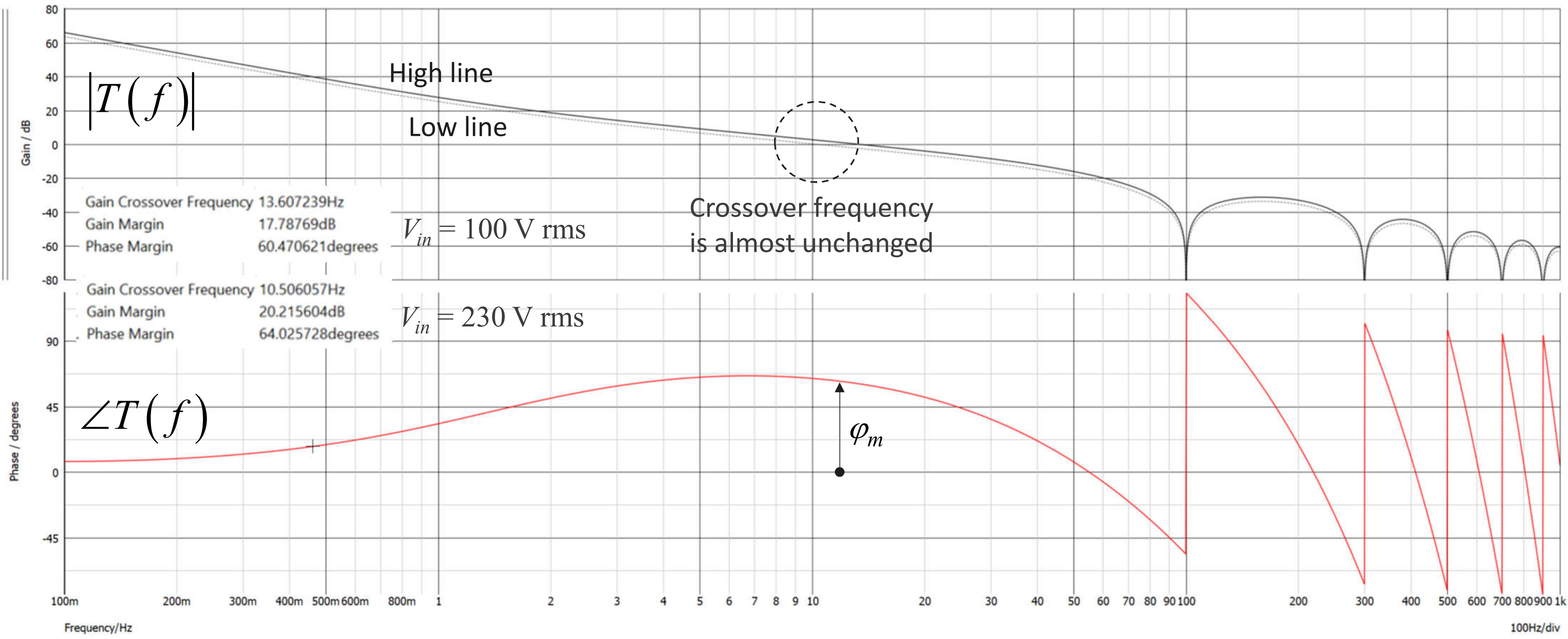
SIMetrix Compensated Simulation

- The digital filter is simulated with delay lines and fed by a Laplace expression



Typical Results for a 300-W Board

- The 300-W TPPFC features a constant crossover frequency regardless of input line

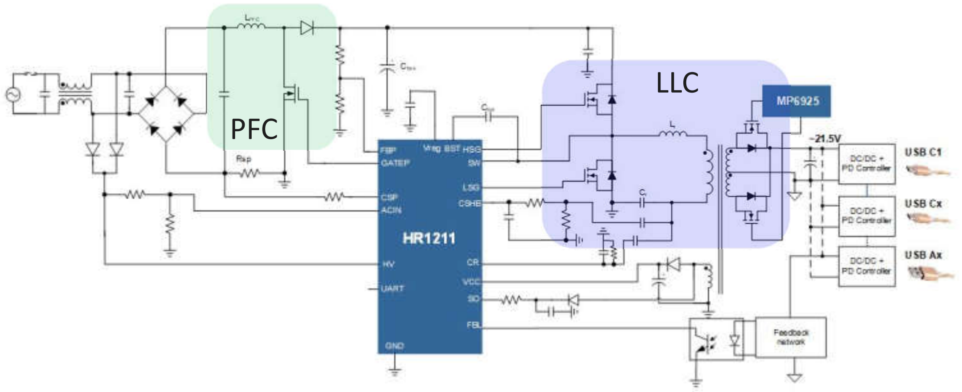


Agenda

- Notions of Power Factor
- Power Factor Correction Structures
- Processing the Power
- Loop Compensation of a PFC
- Solutions from Future Suppliers

Power Factor Controller Selection

- The selection of a PFC controller depends on various parameters:
  - ✓ Constant on-time in BCM for low power, up to 200-300 W
  - ✓ Want higher power in BCM: go for interleaved PFC
  - ✓ Average mode control and CCM for high power, up to several kW
  - ✓ Need for optimized efficiency? Go for multi-mode operation
  - ✓ Need for the best efficiency? Go for a totem-pole PFC
  - ✓ For compact design, go for a combo chip combining a PFC and a switching controller
    - TEA2017: PFC and LLC
    - FAN6921BMR: PFC and QR flyback
    - IDP2308: PFC and LLC
    - STCMB1: PFC and LLC
    - HR1213: PFC and LLC



PFC Controllers from MPS

Part-Number	Structure	Operating Frequency	Control Mode	Operating Mode	HV pin	Package
MP44018A	Boost	Variable	VM	BCM	—	SO-8
MP44019	Boost	Variable	VM	BCM	—	SO-8
MP44010	Boost	Variable	VM	BCM	—	SO-8
HR1213	Combo LLC	Variable Fixed	CM	CCM MM	√	SO-20
HR1210	Combo LLC	Variable Fixed	CM	CCM MM	√	SO-20
HR1211	Combo LLC	Variable Fixed	VM	CCM MM	√	SO-16

https://www.monolithicpower.com/en/products/ac-dc/pfc-llc-controllers/pfc-llc-combo-controller.html

PFC Controllers from onsemi

Part-Number	Structure	Operating Frequency	Control Mode	Operating Mode	HV pin	Package
NCP1623	Boost	Variable	VM	BCM	—	TSOP-6
NCL2801	Boost	Variable	VM	BCM	—	SO-8
NCP1654	Boost	Fixed	CM	CCM	—	SO-8
NCP1680	Totem-pole	Variable	VM	BCM	√	SO-16
NCP1681	Totem-pole	Variable Fixed	CM	CCM MM	√	SO-20N
FAN6921	Combo QR	Variable	VM	BCM	√	SO-16
NCP1937	Combo QR	Variable	VM	BCM	√	
NCP1618	Boost	Variable Fixed	CM	CCM MM	√	SOIC-9
NCP1632	Interleaved	Variable	VM	BCM	—	SO-20

https://www.onsemi.com/products/power-management/ac-dc-power-conversion/power-factor-controllers

PFC Controllers from NXP

Part-Number	Structure	Operating Frequency	Control Mode	Operating Mode	HV pin	Package
TEA19162HT	Boost	Variable	VM	BCM	—	SO-8
TEA19162T	Boost	Variable	VM	BCM	—	SO-8
TEA2017AAT	Combo LLC	Variable Fixed	CM	CCM MM	√	SO-16
TEA2016AAT	Combo LLC	Variable Fixed	CM	CCM MM	√	SO-16

✓ The two standalone PFCs can be teamed up with LLC controller TEA19161T

https://www.nxp.com/products/power-management/ac-dc-solutions/ac-dc-controllers-with-integrated-pfc:MC_49476

PFC Controllers from Infineon

Part-Number	Structure	Operating Frequency	Control Mode	Operating Mode	HV pin	Package
ICE2PCS01/G	Boost	Adjustable	CM	CCM	—	DIP/SO-8
ICE3PCS01G	Boost	Adjustable	CM	CCM	—	SO-14
ICE3PCS03G	Boost	Adjustable	CM	CCM	—	SO-8
ICE3PCS05/G	Boost	Adjustable	CM	CCM	—	DIP/SO-8
IRS2505LPBF	Boost	Variable	VM	BCM	—	SOT23-5

✓ ICE3PCS03G and ICE3PCS01G include an internal digital compensation

https://www.infineon.com/cms/en/product/power/ac-dc-power-conversion/ac-dc-pwm-pfc-controller/pfc-ccm-continuous-conduction-mode-ics/

PFC Controllers from ST

Part-Number	Structure	Operating Frequency	Control Mode	Operating Mode	HV pin	Package
L6562A	Boost	Variable	VM	BCM	—	DIP/SO-8
L6563S	Boost	Variable	CM	BCM	—	SO-14
L6564	Boost	Variable	CM	BCM	—	SSOP-10
L6564H	Boost	Variable	CM	BCM	√	SO-14
L4984D	Boost	Nearly Fixed	CM	FOT	—	SSOP10
STCMB1	Combo LLC	Variable Fixed	VM	BCM	√	SO-20W

https://www.st.com/en/power-management/pfc-controllers.html#

Conclusion

- ❑ Nonlinear loads force the unnecessary circulation of reactive power
- ❖ Reactive power flows in the grid and heats up distribution wires
- ❑ Mains rectification brings a poor power factor and distorts the current
- ✓ Power factor correction forces the absorption of a sinusoidal current
- ✓ It reduces the circulating reactive power and reduces the rms current
- ❑ The boost converter is a popular structure and can operate in:
- ✓ Borderline conduction mode up to 200-300 W
- ✓ Continuous conduction mode for high output levels beyond 1 kW
- ✓ Multi-mode combine best of both worlds for optimized efficiency
- ❑ The totem-pole PFC becomes popular owing to wide-bandgap components
- ❑ A PFC is a closed-loop system: pay attention to the stability