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Effect of the Operating Mode on the Magnetics of Boost and Flyback Converters: TM v. CCM

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Quantitative Criteria Needed!

- Which is a better system solution: TM or CCM?
  - Smaller/cheaper
  - More efficient

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Part One: Boost Converters

CCM

- **Lower RMS currents, lower switch conduction/copper(?) losses**
- **Lower peak to peak AC ripple, lower input DM EMI**
- **Switch turn ON and Boost diode reverse recovery loss**

TM

- **Higher RMS currents, higher switch conduction/copper (?) losses**
- **Valley turn ON (ZVS for Vin<1/2Vout), Boost diode ZCS turn off, lower switching loss.**

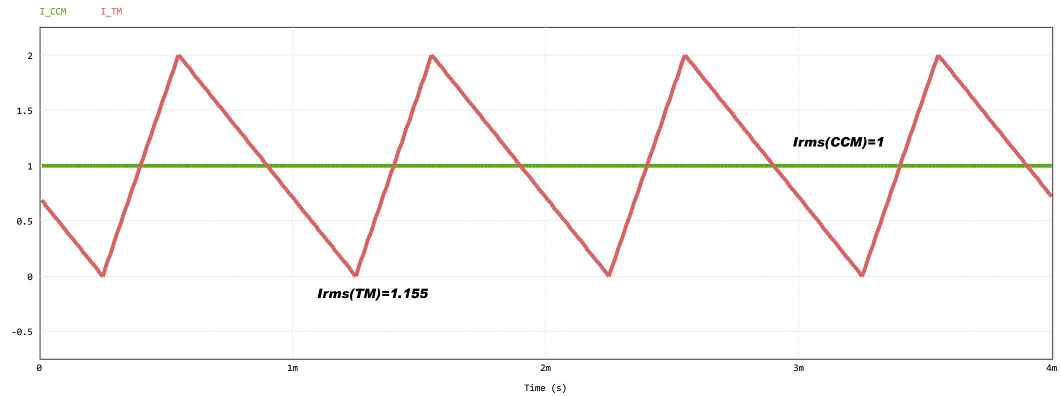
Calibrating expectations: The RMS current reduction

<u>For perfect CCM (zero ripple current):</u>

1 $$Irms_{.tm} = \frac{2Iave}{\sqrt{3}}$$

2 $$Irms_{.ccm} = Iave$$

3 $$\frac{Irms_{.tm}}{Irms_{.ccm}} = \frac{2}{\sqrt{3}} = 1.155$$



The maximum possible (15.5%) Irms reduction requires infinite inductance!!!

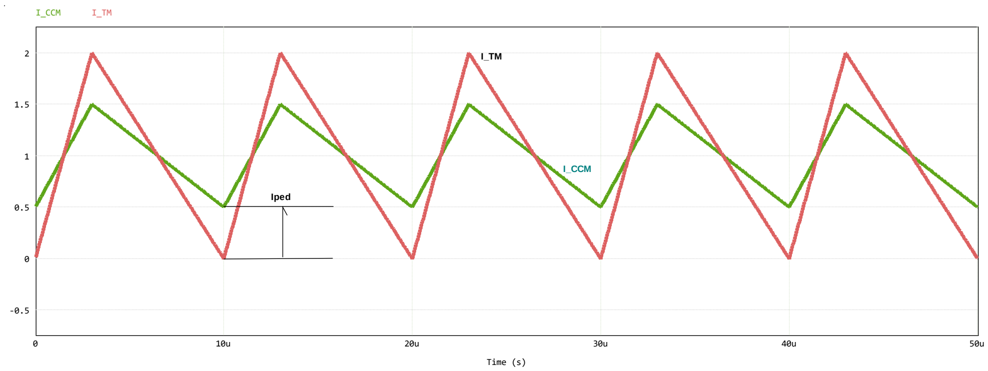
Discussion: Increasing inductance

- Switching frequency is typically maintained below 150kHz (the fundamental outside the EMI band)
  - A good ferrite can operate at ~100kHz with ΔB of 300mT (0-300mT peak, close to saturation)

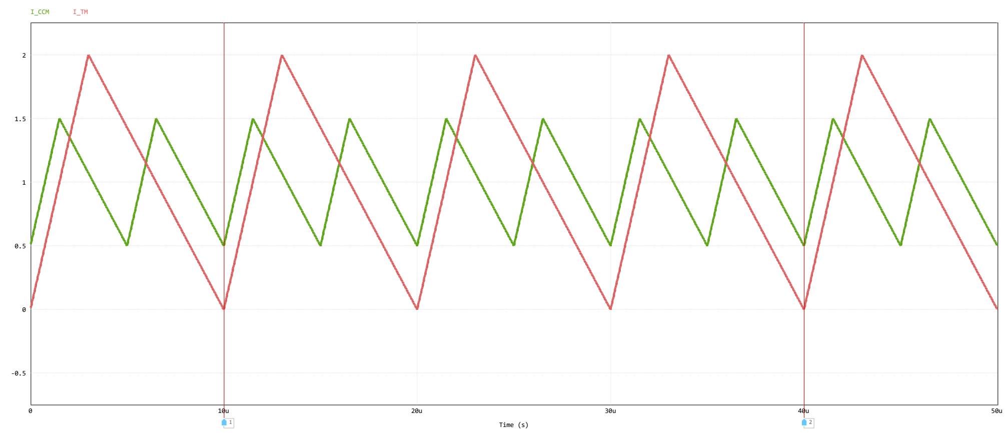
- <u>If the inductor is designed to operate in TM close to saturation, the inductance cannot be increased by decreasing the air gap.</u>

- <u>The inductance can be increased by increasing the number of turns and the air gap</u>

From TM to CCM



Same frequency, 2x inductance:
ΔB unaffected.



Same inductance, 2x frequency:
ΔB decreases

Glossary

k: Inductor ripple reduction factor ($=L_{ccm}/L_{tm}$)

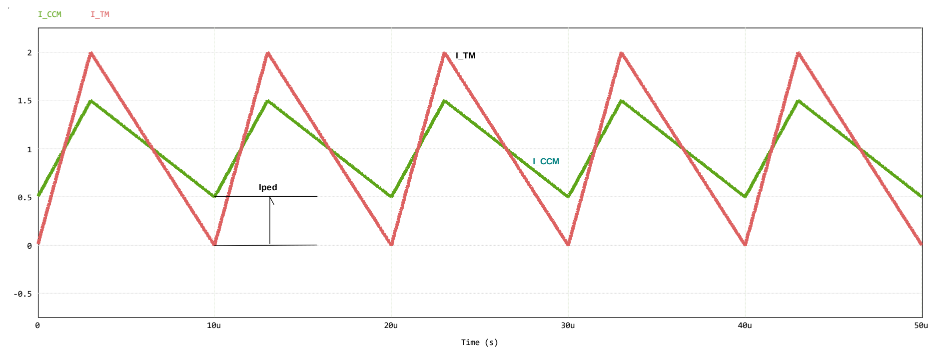
Iped: DC Pedestal of the inductor current

Iave: Average output current

Δ I: PTP inductor ripple current

N_{ccm}: Turns of the CCM inductor

N_{tm}: Turns of the TM inductor



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Quantitative analysis: CCM Values normalized to TM values (Mathcad file available)

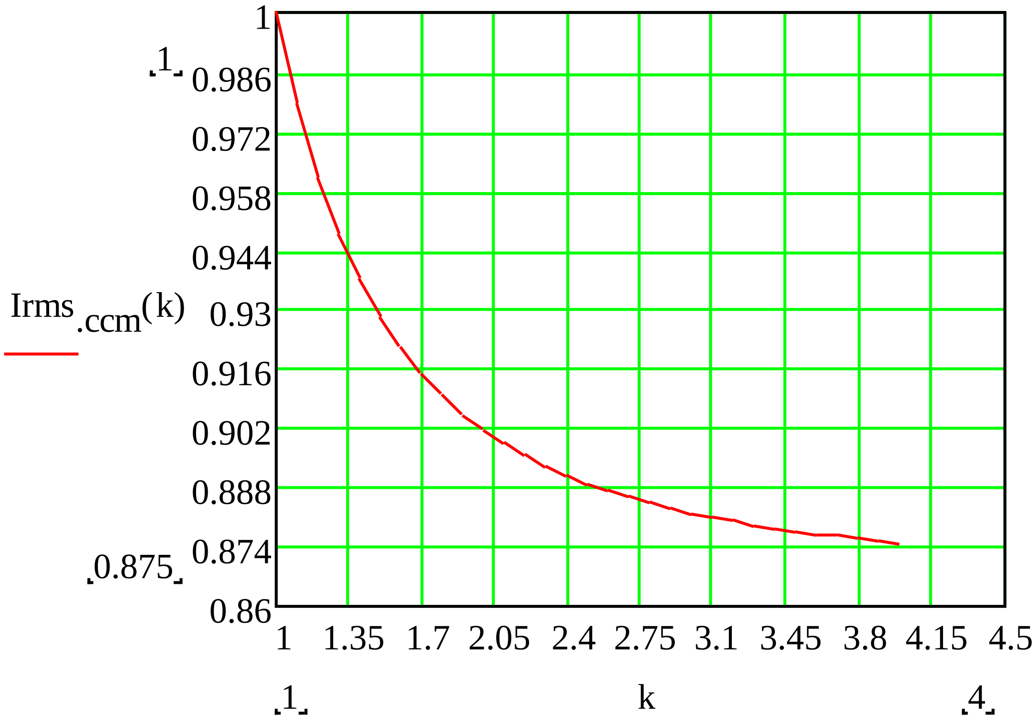
1 $$N_{.ccm}(k) := \frac{k+1}{2}$$

2 $$Rdc_{.ccm}(k) := \left[\frac{(k+1)}{2}\right]^2$$

3 $$Irms_{.ccm}(k) := \frac{\sqrt{\frac{1}{k^2}+3}}{2}$$

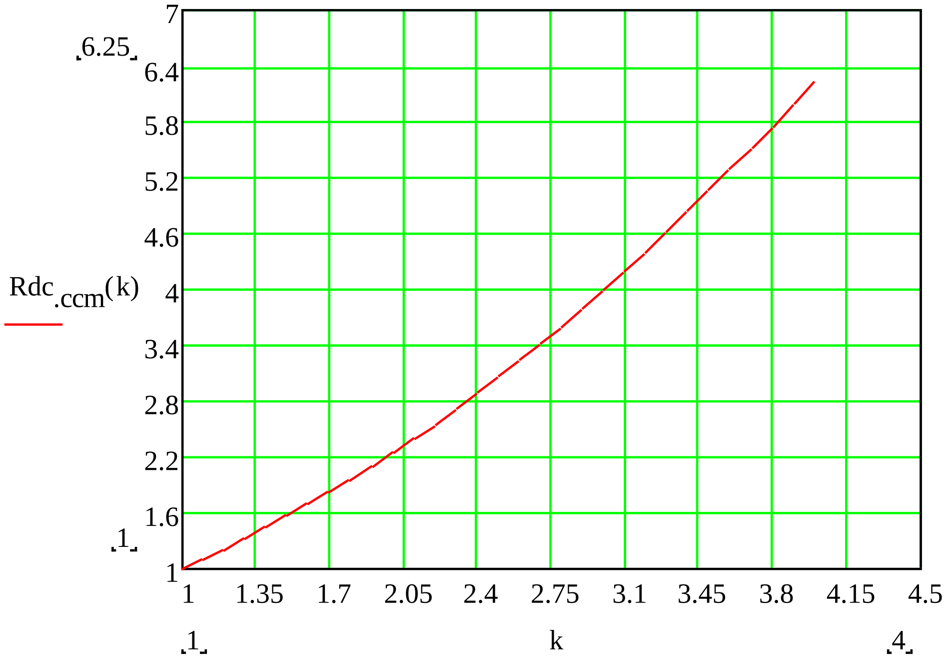
RMS Current v CCM Depth (normalized to TM value)

$$Irms_{.ccm}(k) := \frac{\sqrt{\frac{1}{k^2} + 3}}{2}$$



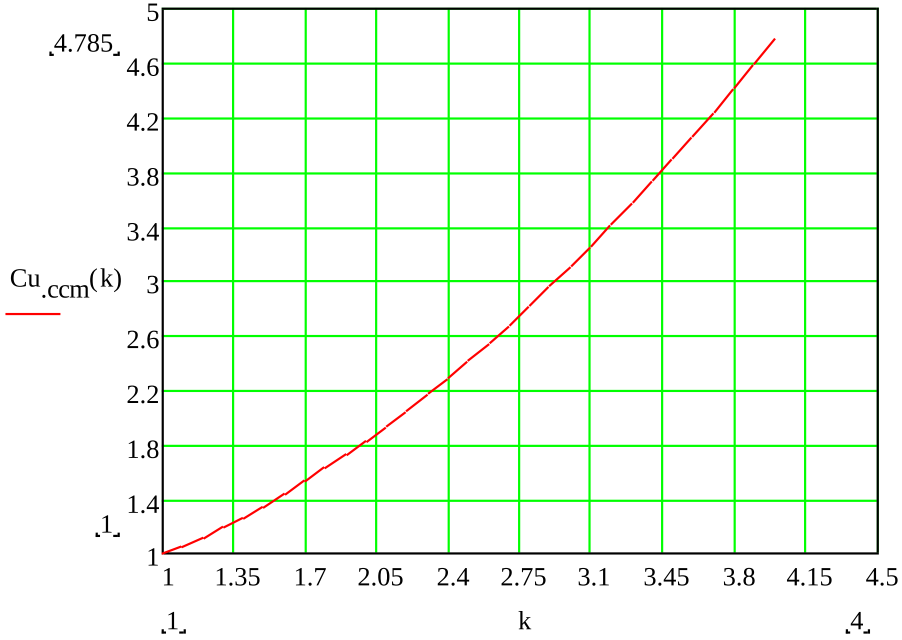
DC Resistance v ripple attenuation factor (CCM Depth)

$$Rdc_{ccm}(k) := \left[\frac{(k+1)}{2}\right]^2$$



Copper Loss v CCM Depth (gross estimate!)

$$Cu_{.ccm}(k) := Rdc_{.ccm}(k) \cdot Irms_{.ccm}(k)^2$$



In reality, the effective resistance of the winding does not increase as fast as the DC resistance, but <u>the rapid Rdc increase with k is a big red flag!</u>

The accurate loss value will be calculated numerically

TM v CCM inductor loss factors

- Fundamentals: TM inductor is the benchmark, core is the same or smaller for the CCM inductor.
- CCM:
  - More turns of thinner wire, more layers, larger air gap
  - Lower AC flux swing, lower core loss
  - Lower AC ripple, same DC current
- No simple analytical way to design the inductors and calculate losses

Switching losses and DM EMI considerations

Switching Loss:

In TM with input voltage lower than 1/2 the output voltage, the Boost switch can be turned ON with zero voltage across it.

Switching loss will be essentially zero.

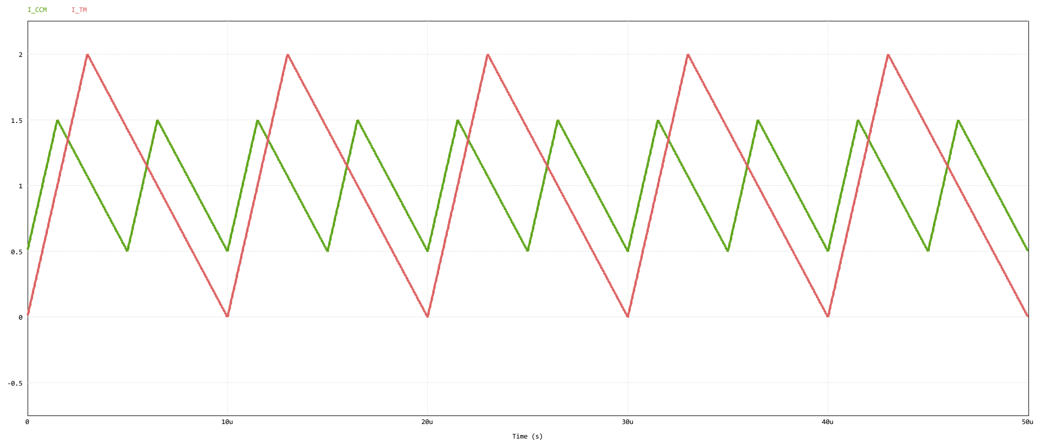
In CCM operation, the Vds of the switch at turn ON is always equal to output voltage.

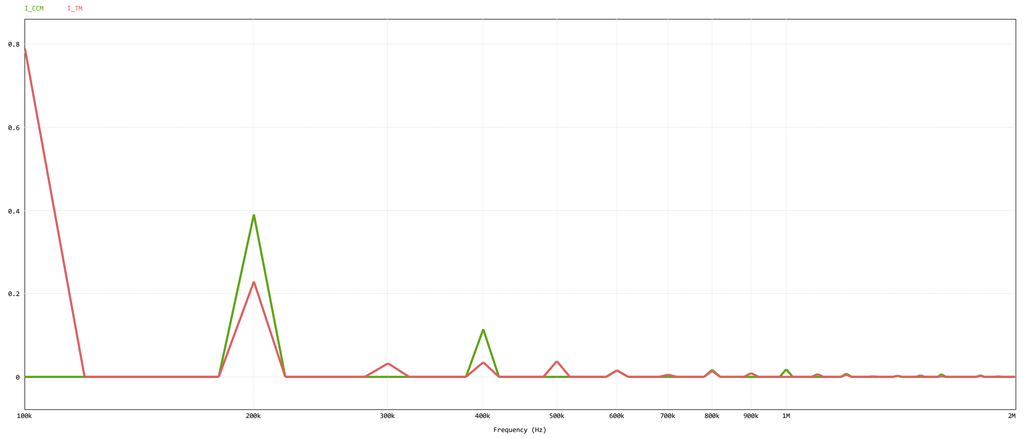
- Switching loss may be substantial.
- The full switching loss occurs immediately upon entering CCM – long before any noticeable RMS current reduction is realized.

EMI:

Although the amplitude of the current ripple decreases as the frequency increases, the fundamental moves move into the EMI band, resulting in a worse DM EMI than at the lower frequency (example 100kHz v 200kHz)

CCM By Frequency Increase





- Frequency doubled from 100kHz to 200kHz
- Ripple attenuated 2x

- Inductor loss may actually be lower, but:
  - Substantial switching loss added
  - DM EMI will actually be worse (the fundamental now inside the EMI band)

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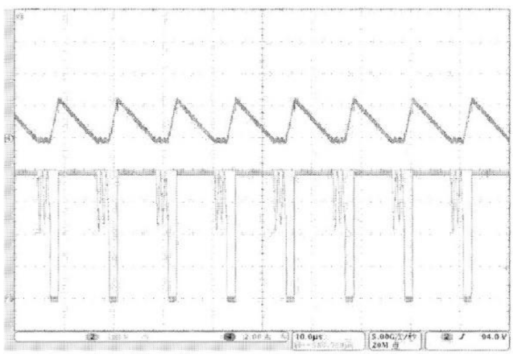
CCM Turn ON switching loss estimate (from an EVM)

Hardware, Software, Testing Requirements, and Test Results

Figure 10. PFC Inductor Current and Switching Node Waveform at 230-VAC, Half Loa



NOTE: CH2: PFC switch node voltage (100 V/div, bandwidth: 20 MHz);
CH4: PFC inductor current (2 A/div, bandwidth: 20 MHz);
Test condition: VIN = 230-V AC/60 Hz; IOUT = 100% load

Switching node ringing period to:
1.77usec
Boost inductor L value:
269uH
Calculated switching node capacitance C_{sw}:
$C_{sw}=(To/2\pi)^2{}_*1/L=295pF$
Switching Node Energy:
$E_{sw}=V^2*C_{sw}/2=23.6uJ$
Switching Loss @ Fsw=100kHz:
2.36W!!!
This analysis neglects additional switching losses that may be caused by the reverse recovery of the boost diode

TM Benefits

TM operation enables recovery of the switching node energy, while CCM dissipates the switching node energy as a result of the inherent hard switching operation

The switching node capacitance and energy may be dominated by factors other than the capacitances of the switch and of the boost diode.

- **Replacing Si SJ with WBG may not provide substantial improvement.**

The loss associated with dissipating the switching node energy may be <u>substantial, rendering CCM operation w/o ZVS unattractive at frequency > 100kHz</u>

Part Two: Flyback Converters

"Perfect" CCM:

- Also requires Infinite inductance!
- Winding currents still pulsed, (not DC as for Boost), high frequency current present – proximity and skin loss not eliminated
  - DM EMI benefit from CCM less than for Boost (rectangular v. sawtooth currents)
- V_{ds} of primary switch is lower at low input voltage, so the turn ON loss in CCM lower than for Boost converter.

Use Frenetic tool to compare CCM to TM transformer on same core.

Numerical Analysis (done by L. Nicieza, Frenetic)

- **Methodology:**
  - **Optimize inductor design in TM**
  - **Search for minimum inductor loss in CCM (on same or smaller core) for increasing values of the ripple attenuation factor k and compare to losses in TM.**

Remember the added switching losses when entering CCM (particularly onerous for Boost applications with low Vin, high Vout) !!!

TM &CCM Operation with Fixed ON Time

- Well known that a Boost converter operating in TM with fixed ON time presents a resistive load to the rectified line voltage..
- TI has developed a control method that allows **extension of the simple fixed ON time method to CCM operation**.
  - The converter will be aresistive load in both TM and CCM.

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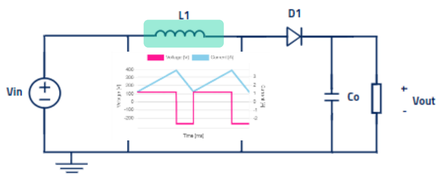
TM Inductor Optimization

1 - Design Requirements

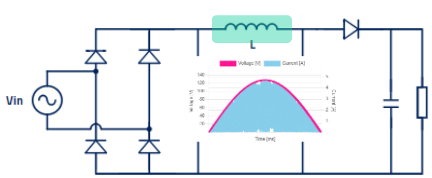
Boost Case

- Input Voltage = 90V
- Output Voltage = 390V
- Output Power = 300W
- T ambient = 25°C
- Cooling = Free Convection
- Fsw = 120 kHz



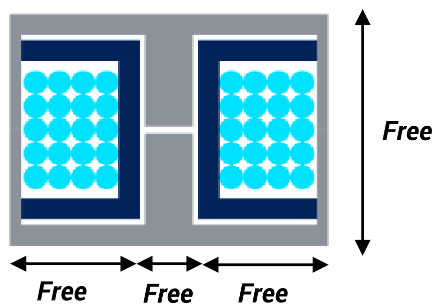
PFC Case

- Input Voltage = 90V
- Output Voltage = 390V
- Output Power = 150W
- T ambient = 25°C
- Cooling = Free Convection
- Fsw_max_TM = 120kHz
- Fsw_CCM = 120kHz



2 - Design Constraints

- Custom cores could be used to get the smallest possible size
- Best in class wires
- Distributed gaps are allowed
- Any combination of material and shape could be used



All dimensions can be customized to minimize the size and maximize the performance

3 - Procedure of the analysis

- Minimize the inductor size in TM mode
- Change to CCM mode keeping the fsw constant
  (in the PFC case
  fsw_ccm = min_fsw_TM)
- Keep the TM Inductor Core fixed
- Optimize the winding for the CCM operation
- Increase inductance and optimize again

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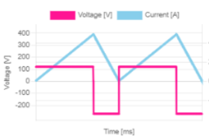
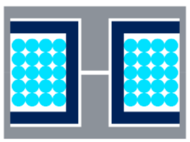
300 W Boost TM v. CCM results

TM – Boost





L = 142 uH
20 Turns
Custom PQ 25/17
Material Ferrite 3C97
Litz 40x0,1 mm
Rdc = 57 mOhms

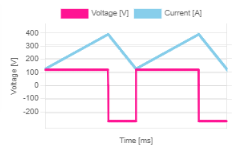
Total Losses = 1,32W

$\Delta I = 4,94A$

Simulation Results

BpkT (mT)=	334
Core Losses (W)=	0.712
Winding Losses (W)=	0.606
Total Losses (W)=	1.32
Max Temp (°C)=	67
Core Surface Temp (°C)=	61
Winding Surface Temp (°C)=	67
Central Leg Surface Temp (°C)=	64

CCM – Boost



L = 274 uH
30 Turns
Custom PQ 25/17
Material Ferrite 3C97
Litz 25x0,1 mm
Rdc = 138 mOhms

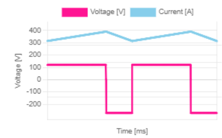
Total Losses = 1,38W

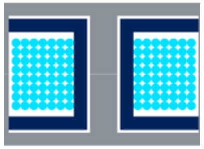
$\Delta I = 2,52\ A$

Simulation Results

BpkT (mT)=	328.652
Core Losses (W)=	0.234
Winding Losses (W)=	1.142
Total Losses (W)=	1.38
Max Temp (°C)=	76
Core Surface Temp (°C)=	60
Winding Surface Temp (°C)=	76
Central Leg Surface Temp (°C)=	65

CCM – Boost





L = 1281 uH
56 Turns
Custom PQ 25/17
Powder Edge 125
Round 0,56 mm
Rdc = 198 mOhms

Total Losses = 2,07W

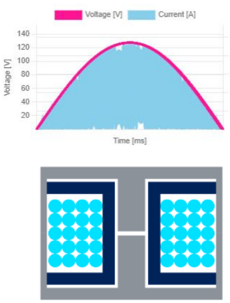
$\Delta I = 0,56\ A$

Simulation Results

BpkT (mT)=	616
Core Losses (W)=	0.436
Winding Losses (W)=	1.634
Total Losses (W)=	2.07
Max Temp (°C)=	95
Core Surface Temp (°C)=	75
Winding Surface Temp (°C)=	95
Central Leg Surface Temp (°C)=	78

150 W PFC TM V.CCM Results

TM - PFC



L = 142 uH
20 Turns
Custom PQ 25/17
Material Ferrite 3C97
Litz 40x0,1 mm
Rdc = 57 mOhms

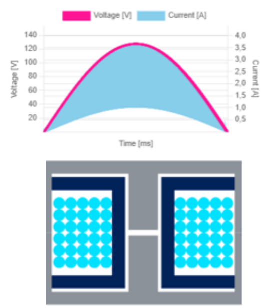
Total Losses = 0,6W

$\Delta I = 4,71\ A$

Simulation Results

BpkT (mT)=	326.57
Core Losses (W)=	0.333
Winding Losses (W)=	0.268
Total Losses (W)=	0.6
Max Temp (°C)=	45
Core Surface Temp (°C)=	43
Winding Surface Temp (°C)=	45
Central Leg Surface Temp (°C)=	44

CCM – PFC



L = 274 uH
30 Turns
Custom PQ 25/17
Material Ferrite 3C97
Litz 25x0,1 mm
Rdc = 138 mOhms

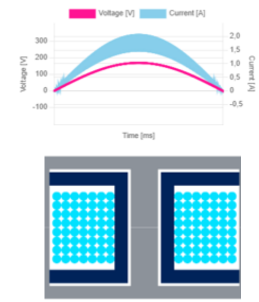
Total Losses = 0,84W

$\Delta I = 2,61\ A$

Simulation Results

BpkT (mT)=	324
Core Losses (W)=	0.314
Winding Losses (W)=	0.522
Total Losses (W)=	0.84
Max Temp (°C)=	55
Core Surface Temp (°C)=	49
Winding Surface Temp (°C)=	55
Central Leg Surface Temp (°C)=	51

CCM – PFC (not viable Bmax)



Simulation Results

BpkT (mT)=	492.324
Core Losses (W)=	0.315
Winding Losses (W)=	0.579
Total Losses (W)=	0.89
Max Temp (°C)=	56
Core Surface Temp (°C)=	50
Winding Surface Temp (°C)=	56
Central Leg Surface Temp (°C)=	51

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Low Power Boost conclusions

- CCM needs larger inductance and therefore larger number of turns. As the number of turns increases given the fix window space the DC resistance increases and the conduction losses increase

- Going from TM to CCM with ferrite does not add major benefit because the current ripple attenuation achieved with bigger power loss is very small.

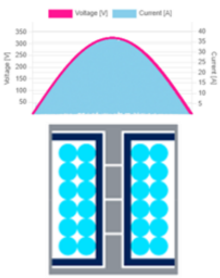
- Going from TM to CCM with powder cores could add some benefit from the current ripple attenuation perspective but it does not add any benefit from the losses perspective. Although the high frequency losses go down with smaller current ripple the larger RDC implies larger winding conduction losses

- At low power CCM does not provide any benefit in the inductor size or performance.

Is there any chance for the CCM at higher power?

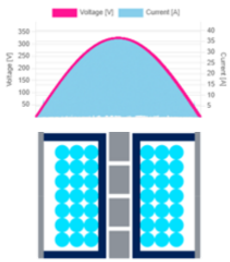
3kW & 12kW PFC Results

TM – PFC – 3kW 50 kHz



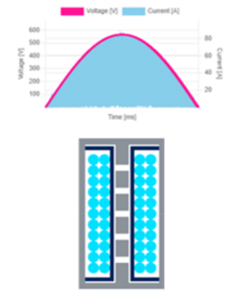
L = 34 uH
12 Turns
Custom EQ47
Material Ferrite 3C92
Litz 675x0,1 mm
Rdc = 4 mOhms
Total Losses = 3,43W
$\Delta I = 36,86\ A$

TM – PFC – 3kW 20 kHz



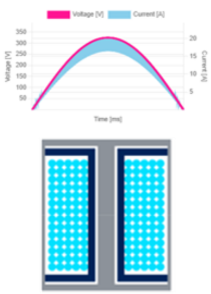
L = 84 uH
21 Turns
Custom EQ56
Material Ferrite 3C92
Litz 338x0,1 mm
Rdc = 14 mOhms
Total Losses = 5,34W
$\Delta I = 36,58\ A$

TM – PFC – 12kW 20 kHz



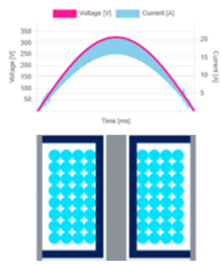
L = 84 uH
22 Turns
Custom E63
Material Ferrite 3C97
Litz 1121x0,071mm
Rdc = 16 mOhms
Total Losses = 25,6W
$\Delta I = 84,5A$

CCM – PFC – 3kW 50 kHz



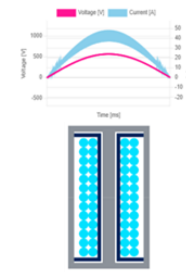
L = 340 uH
32 Turns
Custom EQ47
Powder Edge 125
Round 2 x 1,6 mm
Rdc = 15 mOhms
Total Losses = 6,6 W
$\Delta I = 7,34\ A$

CCM – PFC – 3kW 20 kHz



L = 672 uH
32 Turns
Custom EQ56
Powder Edge 125
Round 2,24mm
Rdc = 18,75 mOhms
Total Losses = 6,6 W
$\Delta I = 8,96\ A$

CCM – PFC – 12kW 20 kHz



L = 672 uH
26 Turns
Custom E63
Powder Edge 125
Round 3,15 mm
Rdc = 10,38 mOhms
Total Losses = 23,1 W
$\Delta I = 31,33\ A$

High power conclusions

- CCM can provide better performance and larger attenuation ratio when the power is high and the frequency is relatively low.
- For medium frequencies the TM inductors can still provide better performance than CCM ones. However the large current ripple should then be paid at the DM inductor and input capacitor size.
- For high frequency and large power the CCM does not help because with medium attenuation ratios the high frequency winding losses are too excessive and with large attenuation ratios the DC losses are too large.
- For the same magnetic size, the larger the size of the core and the better performance the powder core would offer because with the same number of turns it will offer a much larger inductance and therefore attenuation ratio.

300W

20 Turns

Ferrite = 142 uH

Powder = 176 uH

x1,23 Inductance Increase

3kW

12 Turns

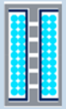
Ferrite = 34 uH

Powder = 67,9 uH

x2 Inductance Increase

12kW

22 Turns



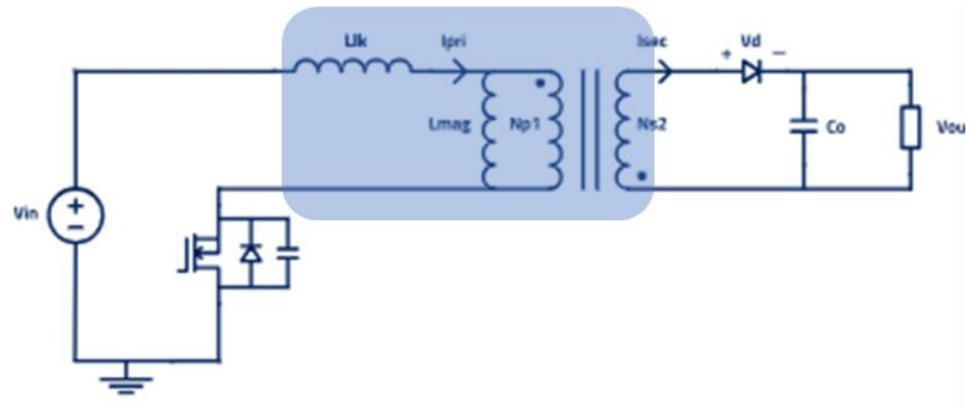
Ferrite = 84 uH

Powder = 509 uH

x6 Inductance Increase

Flyback Results

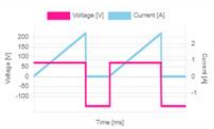
- The same procedure followed with the boost and PFC inductor has been done with a Flyback transformer. The transformer has been optimized for the TM operation and then the inductance has been doubled and tripled for CCM operation.
- As it happened with the inductors the CCM does not add any benefit for the transformer since larger number of turns and conduction losses are required.

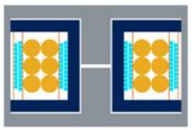


Input voltage = 70V
Output voltage = 20V
Output power = 65W
Fsw = 76kHz
Turns ratio = 7,5

Flyback Results

TM - Flyback



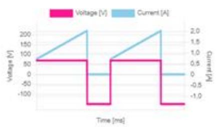


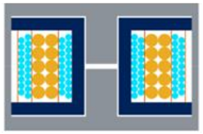
L = 237 uH
23 Turns
Custom PQ 24/15
Material Ferrite 3C95
Pri – 2xRound 0,25 mm
Sec – TIW Litz 45x0,1 mm
Rdc pri = 195 mOhms
RDC sec = 4 mOhms
Total Losses = 1,17W

Simulation Results

BpkT (mT)=	288
Core Losses (W)=	0.279
Winding Losses (W)=	0.894
Total Losses (W)=	1.17
Max Temp (°C)=	113
Core Surface Temp (°C)=	101
Winding Surface Temp (°C)=	113
Central Leg Surface Temp (°C)=	104

CCM – Flyback



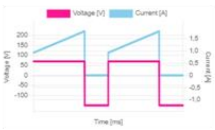


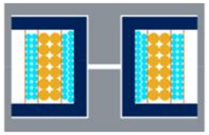
L = 483 uH
38 Turns
Custom PQ 24/15
Material Ferrite 3C95
Pri – Round 1x0,375 mm
Sec – 2xTIW Round 0,63 mm
Rdc pri = 295 mOhms
RDC sec = 7 mOhms
Total Losses = 1,73W

Simulation Results

BpkT (mT)=	268
Core Losses (W)=	0.083
Winding Losses (W)=	1.644
Total Losses (W)=	1.73
Max Temp (°C)=	137
Core Surface Temp (°C)=	112
Winding Surface Temp (°C)=	137
Central Leg Surface Temp (°C)=	119

CCM – Flyback





L = 718 uH
45 Turns
Custom PQ 24/15
Material Ferrite 3C95
Pri – Round 0,335 mm
Sec - 2xTIW Round 0,5 mm
Rdc pri = 424 mOhms
RDC sec = 12 mOhms
Total Losses = 2,18W

Simulation Results

BpkT (mT)=	302
Core Losses (W)=	0.056
Winding Losses (W)=	2.12
Total Losses (W)=	2.18
Max Temp (°C)=	150
Core Surface Temp (°C)=	120
Winding Surface Temp (°C)=	150
Central Leg Surface Temp (°C)=	127

And yet, CCM may be indispensable insome applications

- Entering CCM by increasing frequency increases power throughput without transformer saturation
  - Doubling the frequency increases power by a factor of 1.5

- The efficiency will deteriorate significantly, but this may not be a problem for high power delivery at a low duty cycle.
- A variety of applications will benefit for intermittent CCM (printers, audio amps, etc.)

High-Performance Analog

Summary and Conclusions

- At sub-kW, CCM operation of both Boost and Flyback converters is unlikely to offer power density or efficiency improvements
- CCM becomes attractive at >kW power levels
- CCM operation is beneficial for converters delivering pulsed power at low duty cycle.
  - Improved power density over TM.