High-Performance Analog

Benefits of CCM v TM in PFC Applications: A Comparison

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Why consider CCM instead of TM?

Potential Benefits:

- Lower RMS and AC ripple current in the inductor and the switch
  - Lower winding loss
  - Lower Differential Mode EMI

Drawback:

- ZVS lost, added switching loss may wipe out the benefits
  - GaN helps at high frequency.

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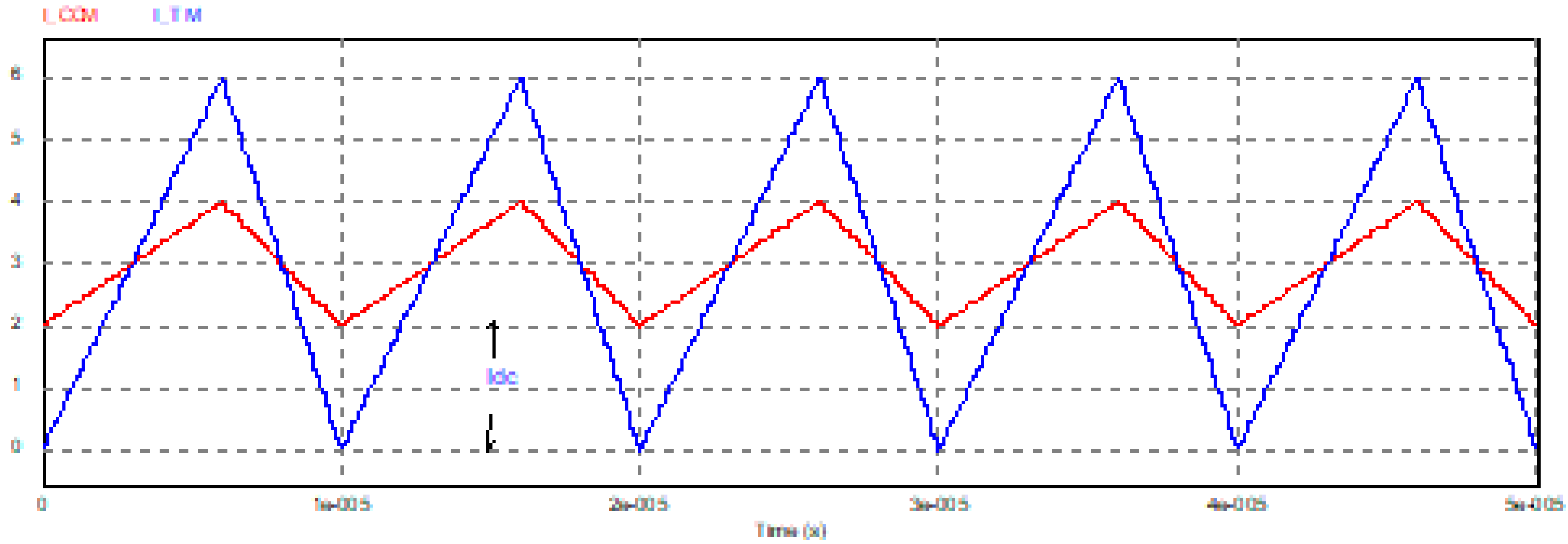
Inductor currents in TM and TM (with decreased air gap)



Methodology

- **This analysis will quantify the change in inductor loss resulting from moving from TM to CCM operation.**
- **Analysis constraints**:
  - Frequency, duty cycle and average inductor current remain same for both modes.
  - In TM the AC flux density swing in the inductor is limited by core loss and not by saturation
  - Peak flux density in TM lower than the saturation flux by a factor **K_B:**

$$K_B = B_{peak} / B_{sat}$$

Under these conditions, the airgap can be reduced, allowing buildup of a DC current "pedestal" I_{dc}, so the converter operates in CCM.

Note: since the inductor's no. of turns remains unchanged, the AC flux swing is not affected by the change in airgap!!!

Loss analysis

- Since the winding is unchanged and the spectral composition of the currents is the same for both TM and CCM, **the conduction losses in the inductor will be proportional to the square of ratio of the RMS currents.**
- Defining:

$$\alpha(K_B)=Irms_{CCM}(KB)^2/Irms_{TM}^2$$

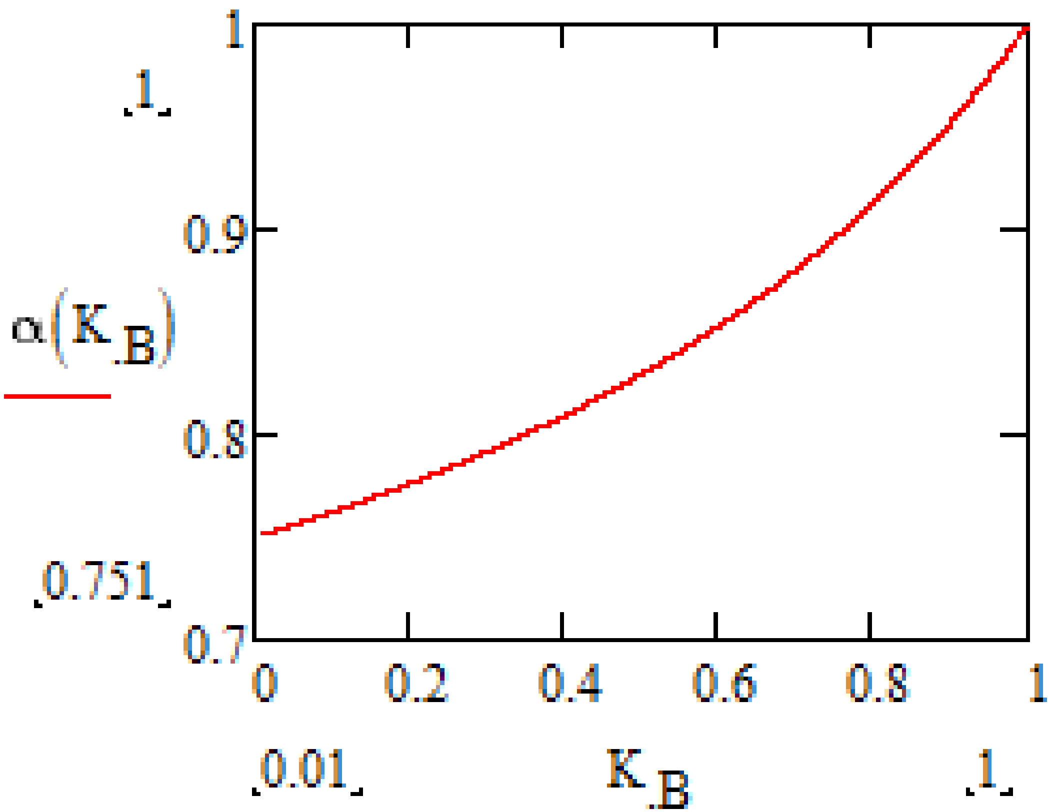
- **$\alpha(K_B)$ is a function of only the flux density derating factor K_B it is useful for all operating frequencies.**

Loss analysis

- Some algebra (Mathcad file available) yields the following expression for **$\alpha(K_B)$**:

$$\alpha(K_B) := \frac{4 \cdot K_B^{\,2} - 6 \cdot K_B + 3}{(K_B - 2)^2}$$

Effect on inductor conduction loss



- As expected, lower $\mathbf{K_B}$ (more flux derating) yields lower conduction loss
  - With no flux derating ($\mathbf{K_B}$=1, i.e. peak flux swing limited by saturation, not by loss) operation regresses to TM and there is no loss reduction

Interim Summary and Conclusions

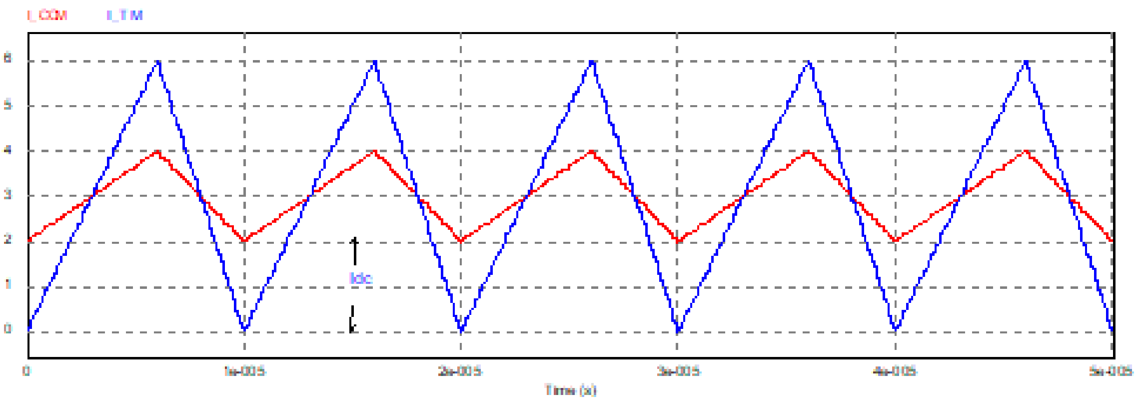
- If the core losses forces a derating of the peak flux density to a fraction of the saturation flux, CCM operation can be obtained by reducing the air gap of the inductor.
- The inductor and switch conduction losses will decrease.
- This approach is productive if the decreasing conduction losses is noticeably higher than the increase in switching losses of CCM operation.
- As we will show below, if the switching frequency is low enough to allow flux density swing be close to the saturation flux, CCM operation will require an inductor that may be considerably larger than the one required for TM operation.

Additional formulas for design

2 $$L_{.ccm} = \frac{2 \cdot L_{.tm} - K_{.B} \cdot L_{.tm}}{K_{.B}}$$

3 $$\Delta I_{.ccm} = -\frac{K_{.B} \cdot \Delta I_{.tm}}{K_{.B} - 2}$$

4 $$Idc = \frac{\Delta I_{.tm} \cdot (K_{.B} - 1)}{K_{.B} - 2}$$



These formulas are used to calculate the inductor parameters as a function of K_B when converting a TM design to CCM

K_B=1: Qualitative analysis of TM vs. CCM inductor

- If for the TM inductor the peak flux density already close to saturation - inductance cannot be increased by reducing the gap.
- To go into CCM the number of terms must be increased to allow room for the DC flux "pedestal" and the airgap increased.

K_B=1: Qualitative analysis of TM vs. CCM inductor

- CCM by Reducing ripple current from Ipk(TM) to Ipk(TM)/5
  - Requires 5X higher inductance.
  - Can be obtained increasing the number turns by a factor of 5 and increasing the airgap by the same factor (to avoid saturation by the added turns).
  - The inductor winding wire is now 5x longer and is cross-section area is reduced by the same factor.
  - The DC resistance of the winding increases by a factor of 25!
  - IrmsCCM2/IrmsTM2 decreases by a match lower factor, so the conduction losses in the inductor will increase drastically.
  - To reduce the losses we need to use a larger core!

CCM v. TM: Impact on the inductor's Area Product

- The Area Product (WaAc) of a magnetic component is defined as the product of the area of the core's window and magnetic path cross-section.
  - The WaAc Product is proportional to the product of inductance, peak and RMS currents in the magnetic component:

$$WaAc = Kx \cdot L \cdot Ipk \cdot Irms \quad (5)$$

where Kx is a Proportionality constant

- The magnetic component volume is related to area product:

$$V = (WaAc)^{\frac{3}{4}} \quad (6)$$

CCM v. TM: Impact on the inductor's Area Product

- From equations 2-4 we can derive:

(7)

$$WaAc_{.ccm} = Kx \frac{\Delta I_{.tm}^{2} \cdot \left(\frac{\sqrt{3} \cdot K_{.B}}{3} - K_{.B} + 1 \right)}{K_{.B}^{2} - 4 \cdot K_{.B} + 4} \cdot \frac{2 \cdot L_{.tm} - K_{.B} \cdot L_{.tm}}{K_{.B}}$$

By definition:

(8)

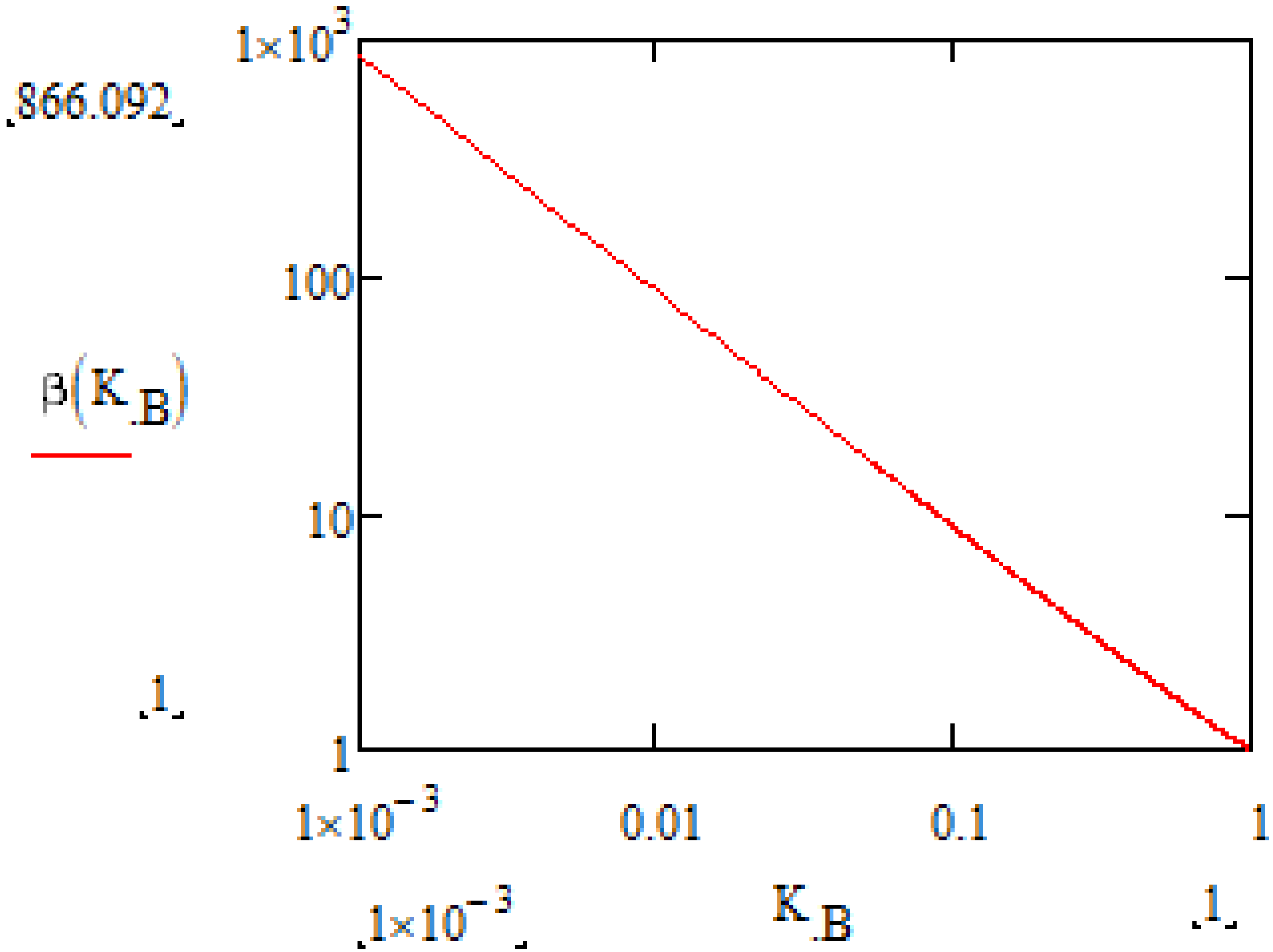
$$WaAc_{.tm} = Kx \frac{\Delta I_{.tm}^{2}}{\sqrt{3}} \cdot L_{.tm}$$

Defining the ratio of $WaAc_{CCM}$ to $WaAc_{TM}$ as $\beta(K_B)$ we get:

(9)

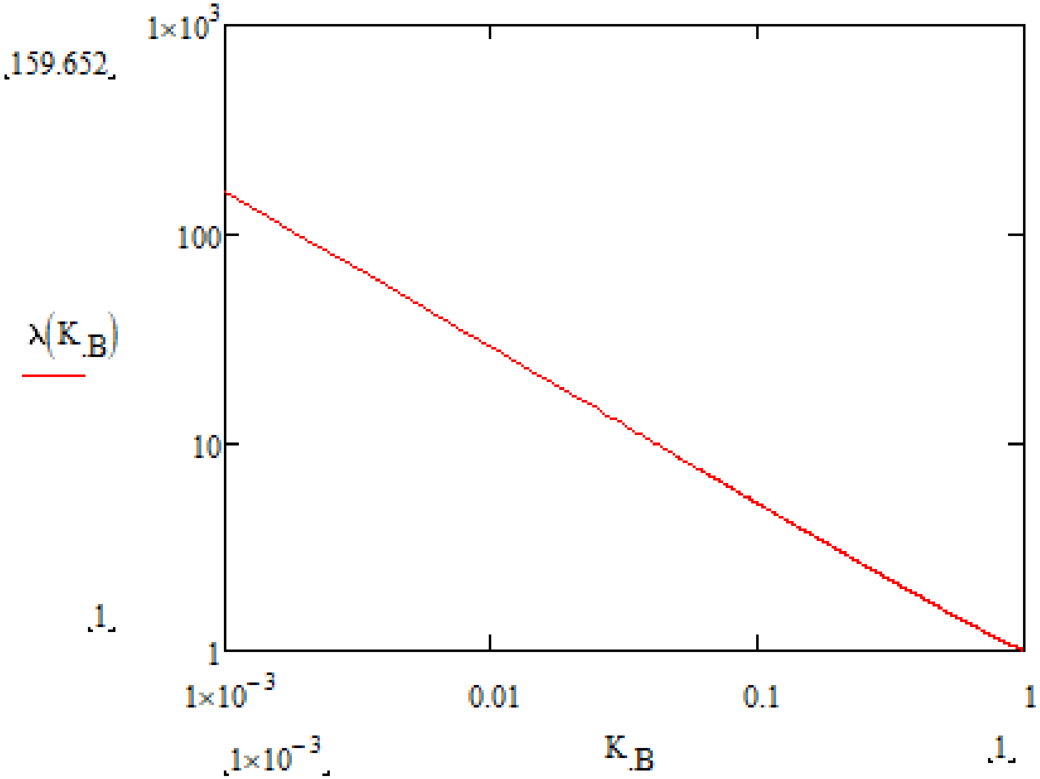
$$\beta\left(K_{.B}\right) := \frac{\sqrt{3}}{2 \cdot K_{.B}} + \frac{\frac{\sqrt{3}}{2} - 1}{K_{.B} - 2}$$

CCM v. TM: Impact on the inductor's Area Product β(KB) is the ratio of CCM/TM AP's



CCM v. TM: Impact on the inductor's volume
$\lambda(KB)$ is the ratio of the CCM to TM inductor volume)

- By using eq.(6) we can graph the ratio of the CCM to TM $\gamma(KB)$ vs. the flux derating factor K_B:



Discussion

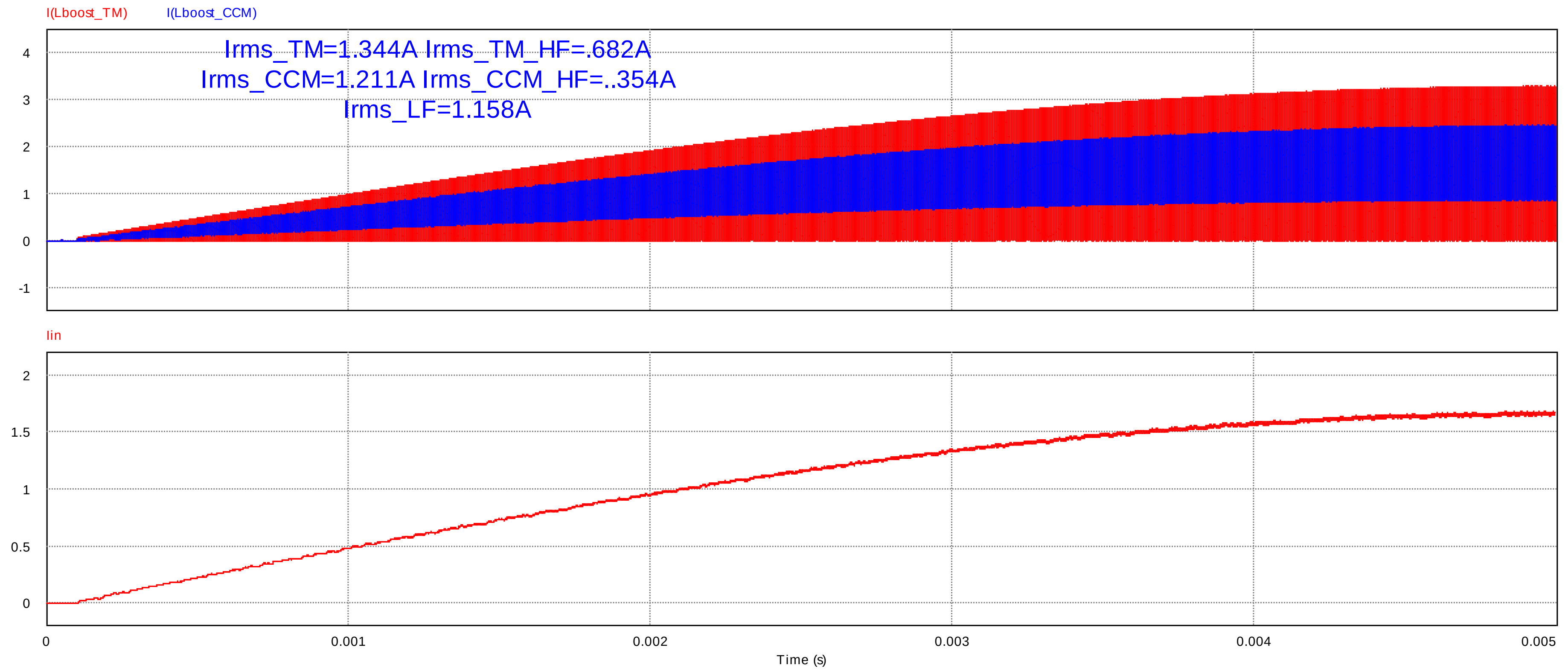
- If no flux density derating is forced by the operating frequency, CCM operation will inevitably require a larger inductor than TM operation.
- The reduction in the switch/inductor RMS currents offered by "deep CCM" operation is modest – **a maximum of 15.47% for <u>infinite</u> inductance (that's a BIG inductor!).**
- The benefits of "shallow" CCM are also questionable.
  - Reduction of RMS currents may be insignificant
  - Switching losses may be considerably higher than for ZVS/QR switching offered by TM operation.

TM v CCM in an actual 150W, 200kHz PFC application

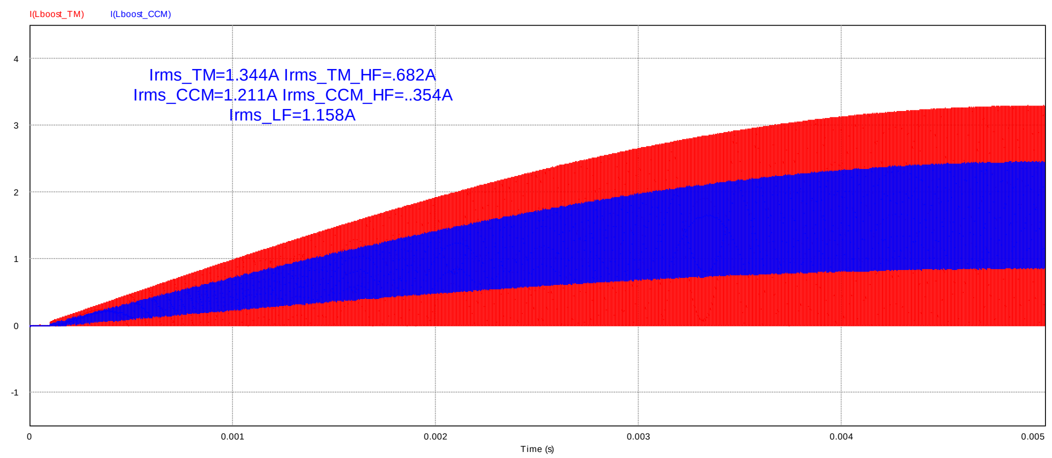
Inputs for analysis

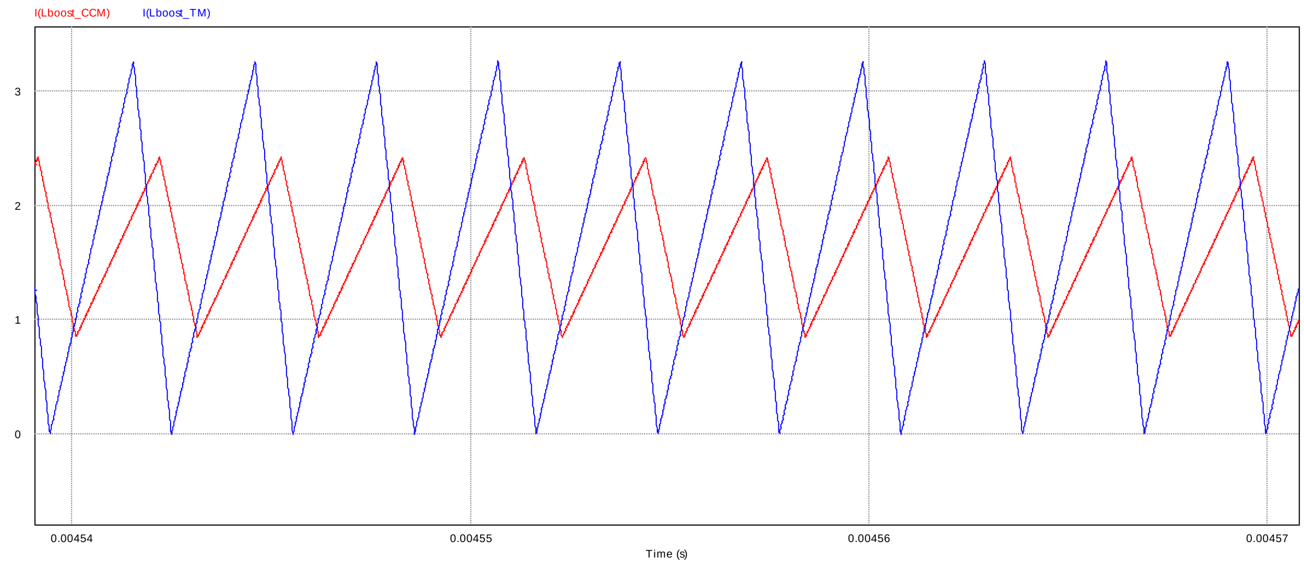
- 150W high density PFC Converter
  - Input voltage: 85-265Vac.
  - Output power: 150W
  - Inductance: 80uH
  - Frequency: ~200kHz at the peak of 85Vac Input voltage
  - K_B=.7 (constrained by core loss)
  - **To illustrate effect of the winding AC resistance, assumed Rac=2Rdc**
- Operation simulated for TM and CCM
  - CCM/TM Loss ratio calculated from the simulated waveforms

Input (after EMI filter) and Boost Inductors currents L_{TM}=80uH, L_{CCM}=166uH



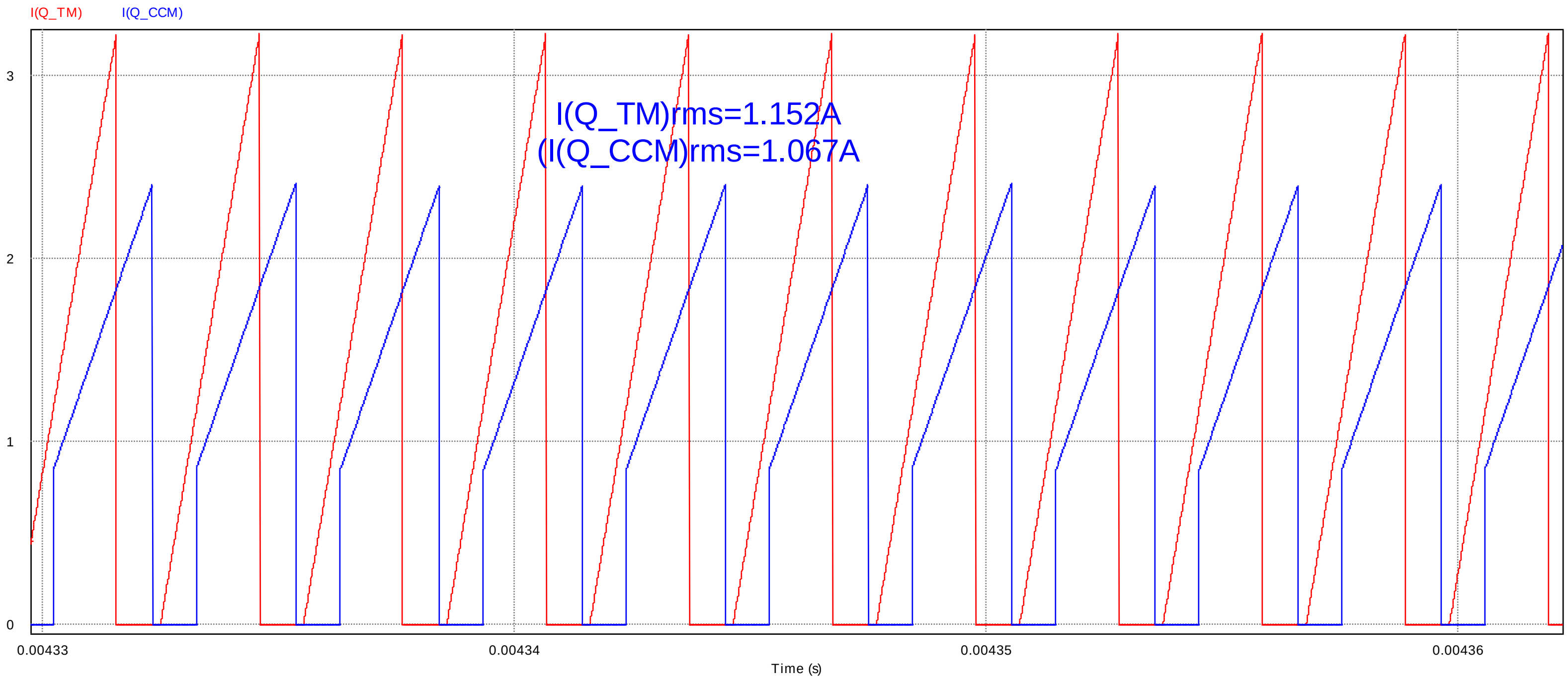
Inductor Waveforms: TM and CCM (detail)





Switch Current TM v CCM

- Psw(CCM)/Psw(TM)=.81
- CCM reduces the switch conduction loss by 19%



Winding loss reduction for Rac=2Rdc

Ratio of TM to CCM winding losses (α) :

(10) $$\alpha = \frac{Pcu_{.CCM}}{Pcu_{.TM}} = \frac{Rdc_{.CCM} \cdot Irms_{.LF}^{2} + Irms_{.HFccm}^{2} \cdot Rac_{.CCM}}{Rdc_{.TM} \cdot Irms_{.LF}^{2} + Irms_{.HFtm}^{2} \cdot Rac_{.TM}}$$

- Since there is no change to the winding, the AC and DC resistances are identical for both TM and CCM. Assuming Rac=2 Rdc yields:
- (11) $$\frac{1.158^2 + .354^2 \cdot 2}{1.158^2 + .682^2 \cdot 2} = 0.701$$
- This represents a 30% reduction in winding loss (accuracy of this result depends on the validity of the assumptions):
  - Rac=2Rdc
  - Gap reduction does not affect winding loss (plausible, as H_{ac} decreases also)

Comparison to the analytical result

From the analysis:

(12) $$\alpha(K_B) := \frac{4 \cdot K_B^2 - 6 \cdot K_B + 3}{(K_B - 2)^2}$$

$$\alpha(.65) = 0.866$$

From the simulation:

(13) $$\frac{1.158^2 + .354^2}{1.158^2 + .682^2} = 0.812$$

Pretty close!

Effect of Total Loss

- Total switching node energy@400V is 5uJ
  - Includes switch, rectifier and stray capacitance
  - Total CCM switching loss Psw_{CCM} @200kHz: 1W
  - Total TM switching loss Psw_{TM} @200kHz: 0W
- TM inductor winding loss (measured):

$$Pcu_{tm}=.965W$$

- CCM Inductor winding loss :

$$Pcu_{ccm}=.965*(.812)=.784W$$

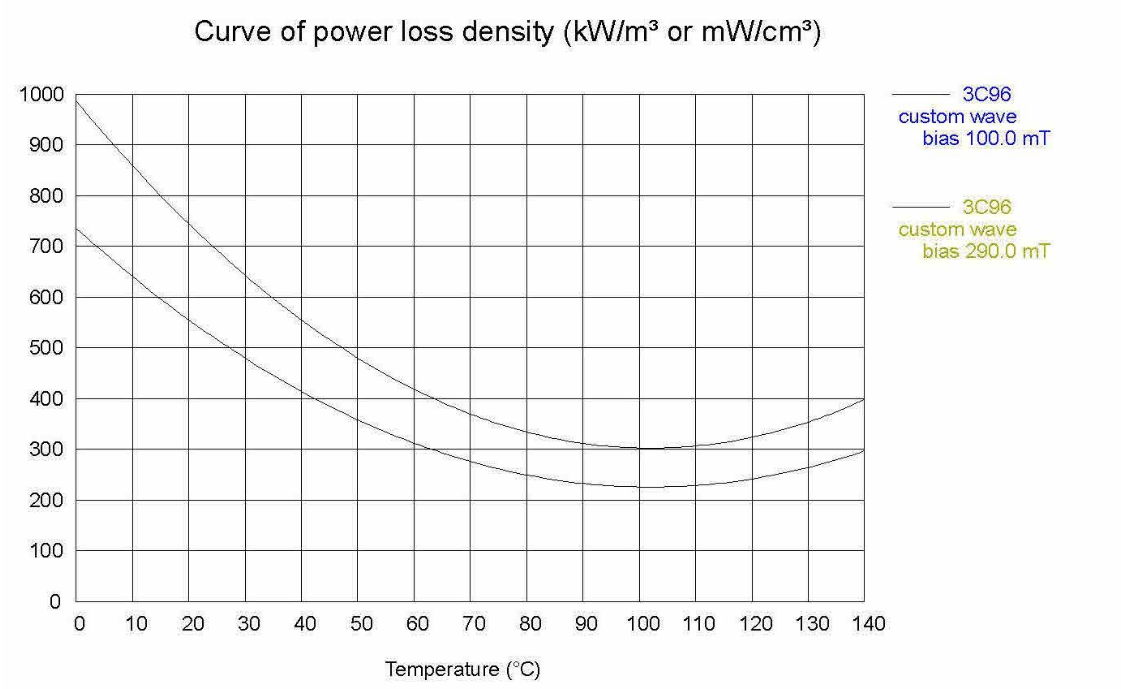
- Total loss impact:

$$P_{ccm}-P_{tm}=(Psw_{ccm}+Pcu_{ccm})-(0+Pcu_{tm})=.783W$$

Total loss increase is substantial – CCM is a bad idea for this case!

Worse yet: The added DC flux bias increases core loss!

- CCM increases the DC bias - core loss increases by a ~36% (see below).
- In a typical HF inductor design the copper losses are dominant, so the increased core loss is not a major problem.



Effect on EMI

- The factor of 2.075 increase in inductance reduces the peak to peak current ripple by the same factor, resulting in a 6.3db reduction in the DM EMI.
- The impact on cost, size and loss of the DM filter inductor needs to be quantified, but it is not decisive.

Inductors on powder cores

- Much higher saturation flux density (1.4T v. .4T for Ferrites)
- Let assume that in TM core loss limits the AC flux to 1/5 of Bsat (K_B=.28)
- If we go CCM by building up a DC "pedestal" that will push B_{pk} to B_{sat} , the output power can be increased significantly

Inductors on powder cores

- From Eq (1): $$L_{ccm} = \frac{2 \cdot L_{tm} - K_B \cdot L_{tm}}{K_B}$$

For K_B=.28, L_{ccm}=6.13*L_{tm}

In a powder core there is no gap to reduce - inductance can only be increased by selecting a higher permeability core.

  - Assuming that the permeability of the TM design was 20, we will need permeability of 20x6.13= 122.6 for the CCM inductor.
  - 125 Permeability is standard, the CCM inductor seems feasible.

- **Conclusion:**
  - **CCM may be a preferable solution at a frequency low enough to render switching losses insignificant and allow use of powder cores instead of ferrites.**

Summary and conclusions

- For **Ferrite cores** the benefit of CCM over TM operation is non-existent or at best marginal.
  - Although at high frequency lower K_B (more flux derating) may further reduce the winding loss in CCM, the loss of ZVS likely to offset this loss reduction.
  - As the switching frequency decreases, ferrites can be operated closer to Bsat so K_B increases, reducing the "free" DC flux buildup for CCM
- At power high and frequency low enough to **justify use of powder iron instead of ferrite** CCM may be beneficial
  - Needs to be verified quantitatively for the specific design
- Conclusions are also applicable to other PWM topologies.