WATKINS-JOHNSON TOPOLOGY INTEGRATED IN A FULL-BRIDGE CONVERTER

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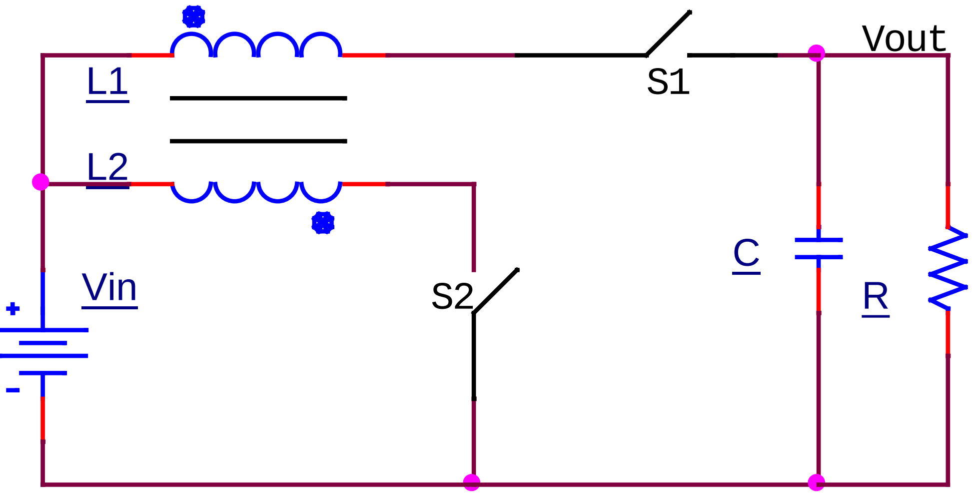
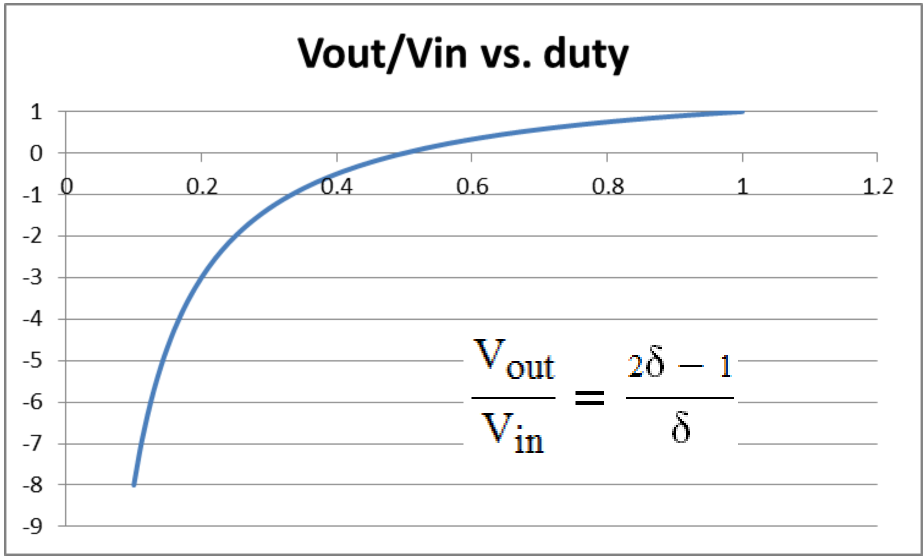
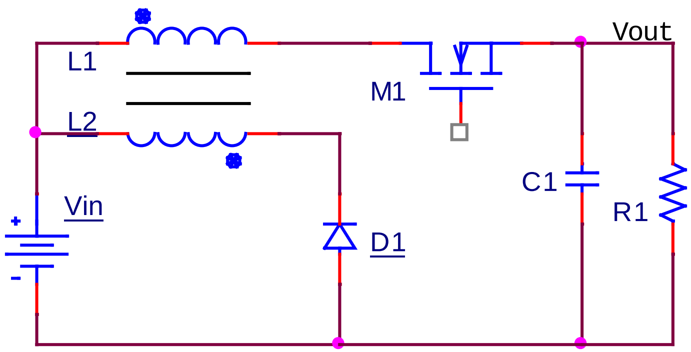
Contents

The Watkins-Johnson topology: basic



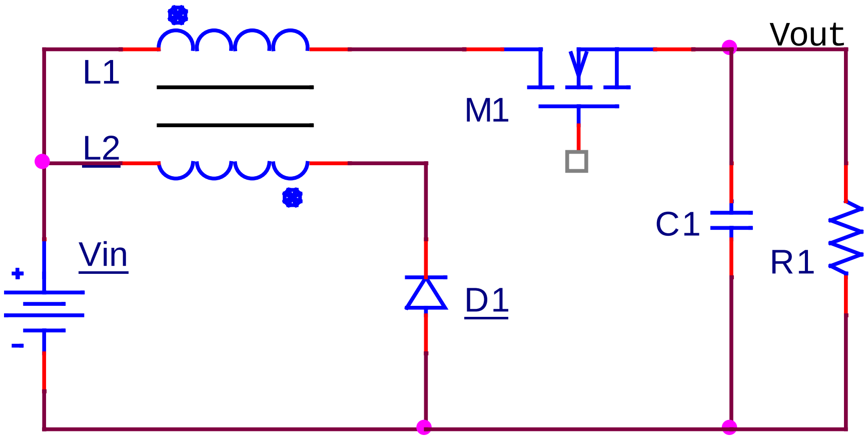


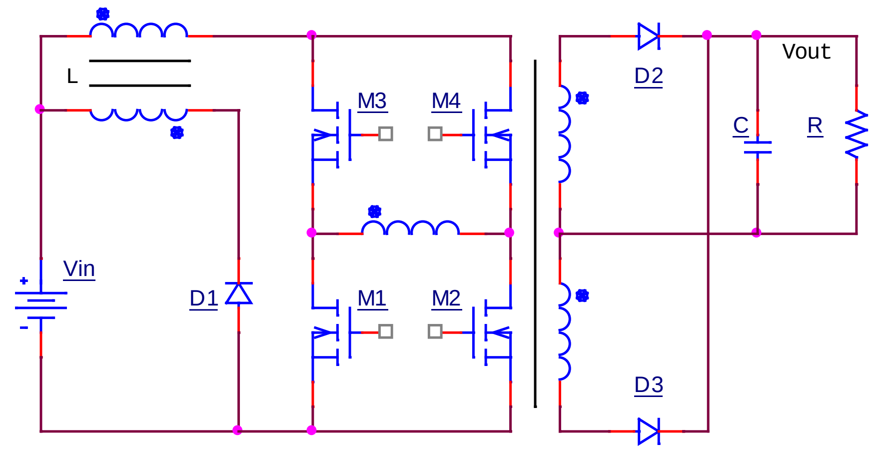
Basic topology with bidirectional switches and the related transfer ratio

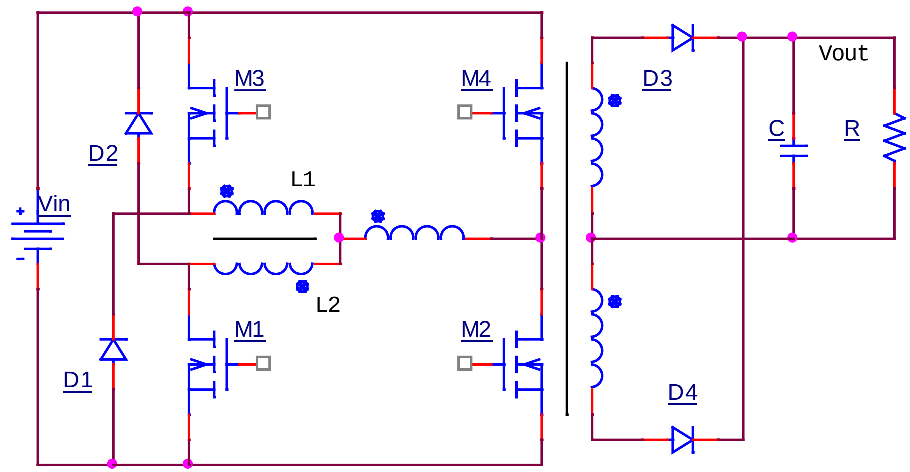


Practical realization with MOSFET and diode

Topology integration in a Full-Bridge

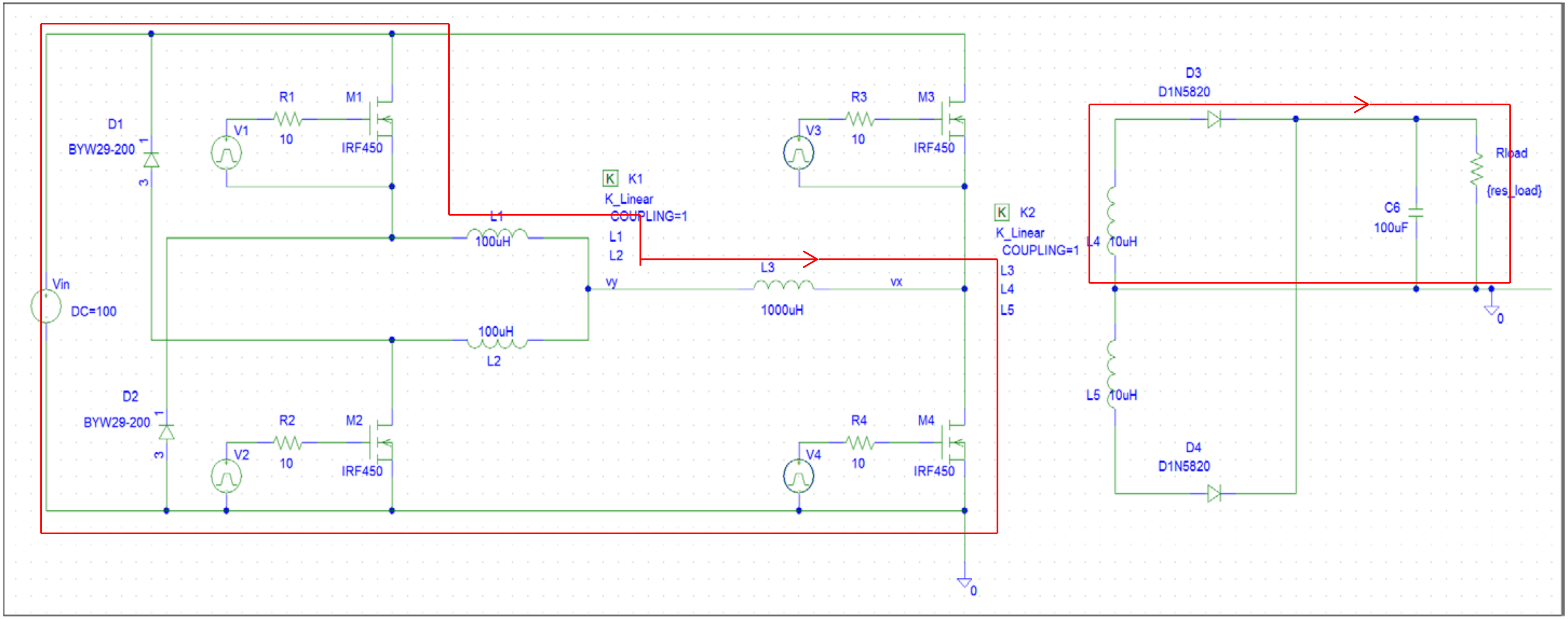




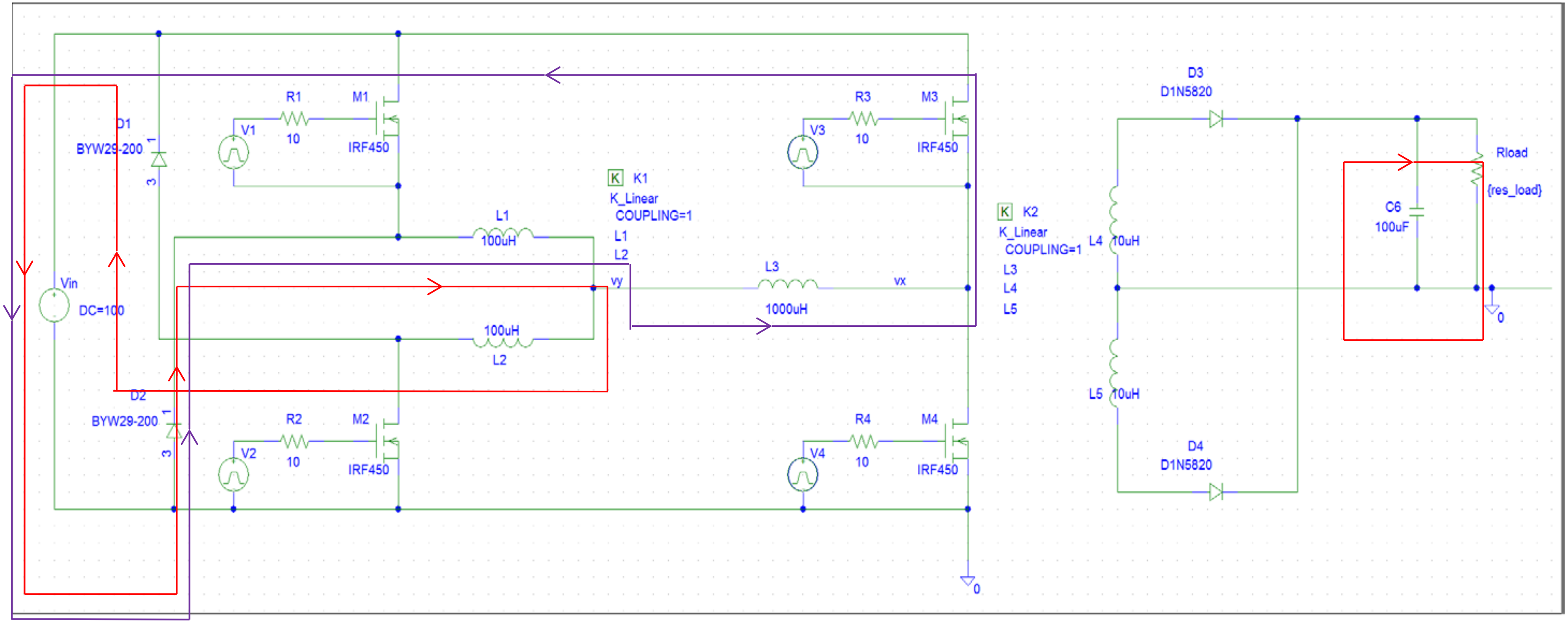


- For a normal WJ converter the inductor can flow only in one direction - CCM or DCM
- In the new topology there is no difference between CCM and DCM

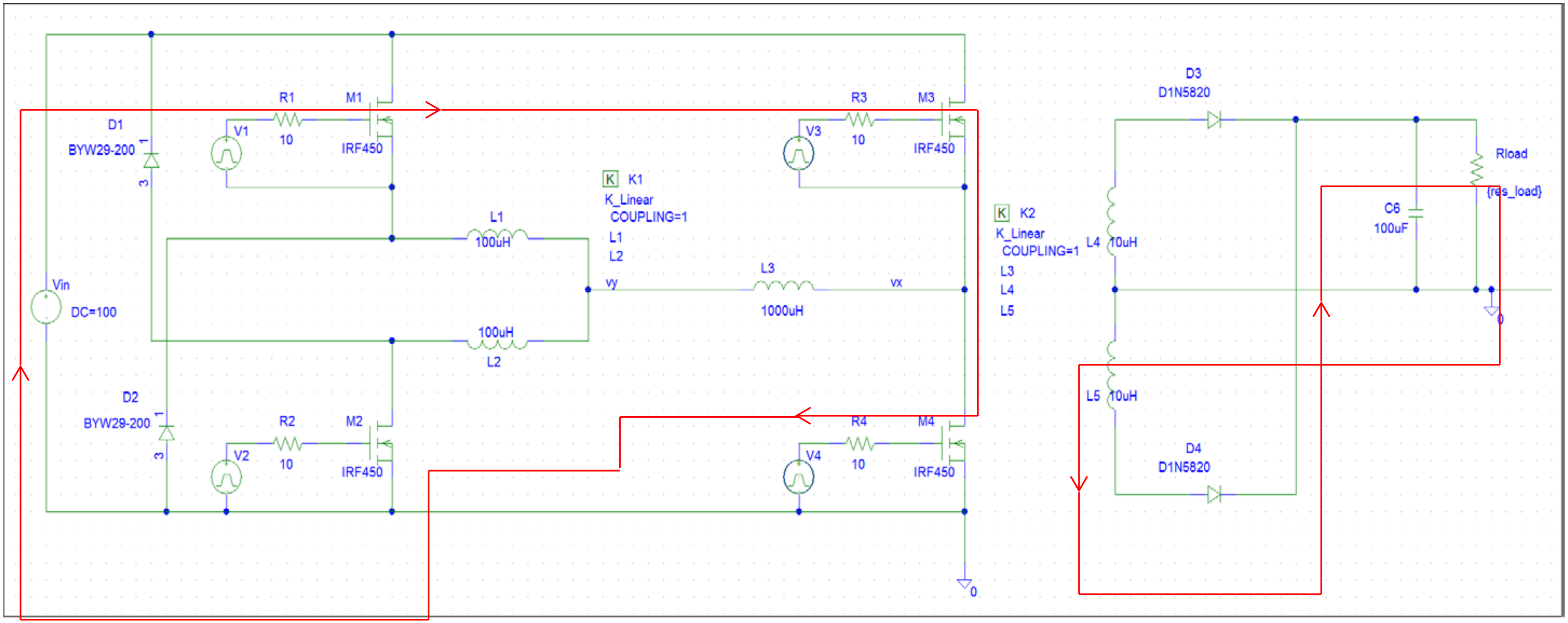
Operation: from T0 to T1 (On Time)



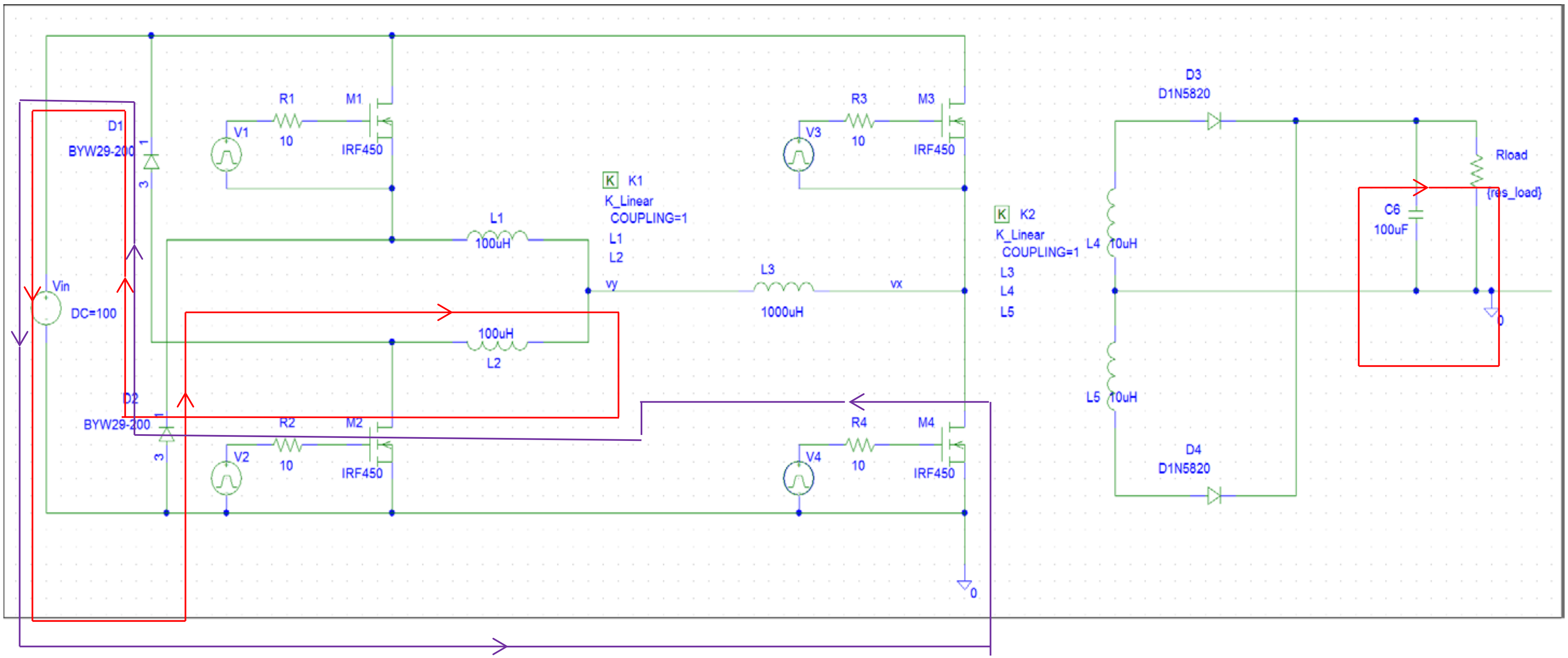
Operation: from T1 to T2 (Off Time)



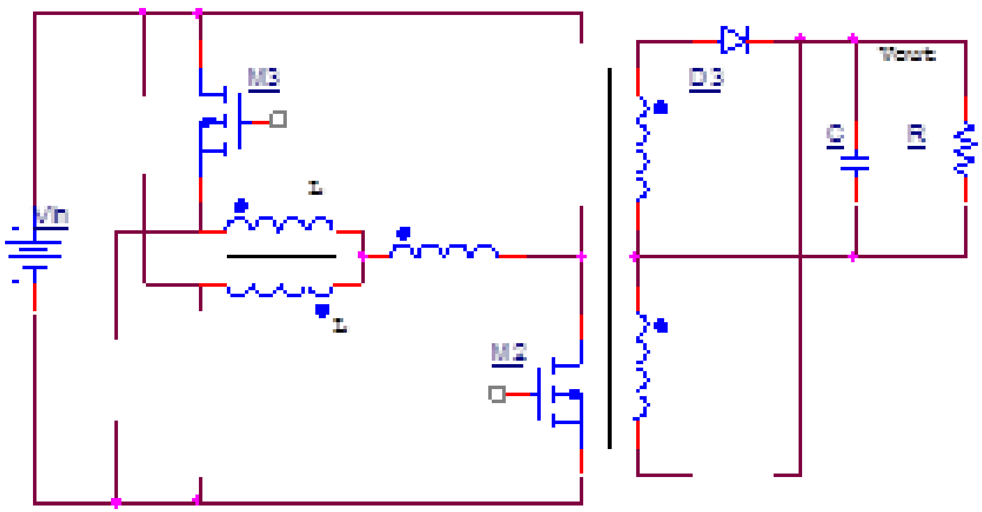
Operation: from T2 to T3 (On Time)



Operation: from T3 to T4 (Off Time)



Continuous Current Mode: governing equations during On Time



i_{on}: is the current in the inductance during on time

n: is the transformer ratio N_p/N_s

R_L: is parasitic resistance of L

R_C: is the ESR of C

R: is the Resistive Load

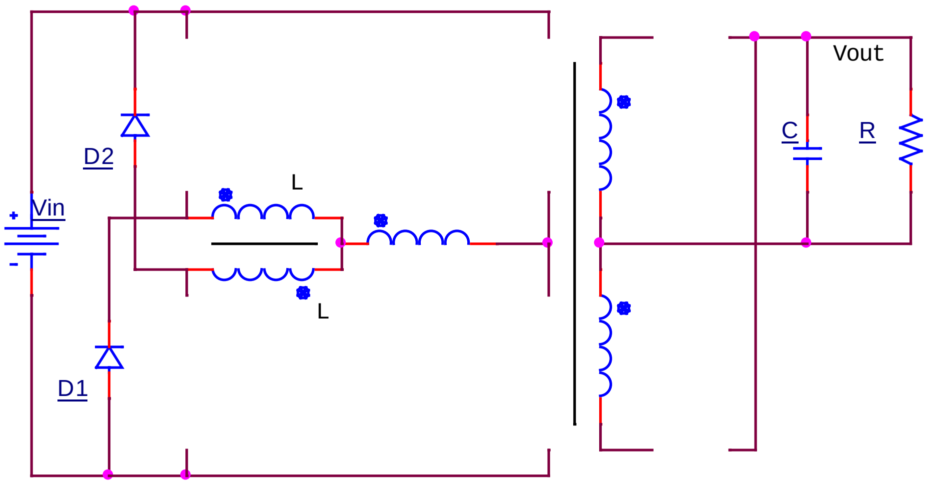
$$L \cdot \frac{d}{dt} i_{on} = v_{in} - R_L \cdot i_{on} - n \cdot \left(v_{out} + V_{ds}\right)$$

$$C \cdot \frac{d}{dt} v_c = n \cdot i_{on} - \frac{v_{out}}{R}$$

$$v_{out} = v_c + R_c \cdot i_c$$

$$i_{in} = i_{on}$$

Continuous Current Mode: governing equations during Off Time



$$L_{12} \cdot \frac{d}{dt} i_{off} = -2 \cdot R_L \cdot i_{off} - 2 V_{dp} - v_{in}$$

$$C \cdot \frac{d}{dt} v_c = \frac{-v_{out}}{R}$$

$$i_{in} = -\frac{i_{on}}{2}$$

$$v_{out} = v_c + R_c \cdot i_c$$

L_{12} is the inductance of the 2 mutual inductance in series
I_{off} is the current in the inductance during off time
R_L is parasitic resistance of L
R_C is the ESR of C
R is the Resistive Load

Continuous Current Mode: averaging of the governing equations

Considering that $\mathbf{L_{12}=4*L}$ and that $\mathbf{i_{off} = i_{on}/2}$W the Off phase inductor equation become:

$$4 \cdot L \cdot \frac{d}{dt}\frac{i_{on}}{2} = -2 \cdot R_L \cdot \frac{i_{on}}{2} - 2V_{dp} - v_{in}$$

Rearranging for the Off phase we have

$$L \cdot \frac{d}{dt} i_{on} = -R_L \cdot \frac{i_{on}}{2} - V_{dp} - \frac{v_{in}}{2}$$

Continuous Current Mode: averaging of the governing equations

$$L \cdot \frac{d}{dt} i_{on} = v_{in} - R_L \cdot i_{on} - n \cdot (v_{out} + V_{ds})$$

$$C \cdot \frac{d}{dt} v_c = n \cdot i_{on} - \frac{v_{out}}{R}$$

$$v_{out} = v_c + R_c \cdot i_c$$

$$i_{in} = i_{on}$$

ON

$$L \cdot \frac{d}{dt} i_{on} = -R_L \cdot \frac{i_{on}}{2} - V_{dp} - \frac{v_{in}}{2}$$

$$C \cdot \frac{d}{dt} v_c = \frac{-v_{out}}{R}$$

$$v_{out} = v_c + R_c \cdot i_c$$

$$i_{in} = -\frac{i_{on}}{2}$$

OFF

$$L \cdot \left(\frac{d}{dt} i_{avg}\right) = \left(\frac{3 \cdot \delta}{2} - \frac{1}{2}\right) \cdot v_{in\_avg} - \frac{(\delta + 1) \cdot R_L}{2} \cdot i_{on\_avg} - (1 - \delta) \cdot V_{dp} - \delta \cdot n \cdot V_{ds} - \delta \cdot n \cdot v_{out\_avg}$$

$$C \cdot \left(\frac{d}{dt} v_{c\_avg}\right) = \delta \cdot n \cdot i_{avg} - \frac{v_{out\_avg}}{R}$$

$$v_{out\_avg} = v_{c\_avg} + R_c \cdot i_{c\_avg}$$

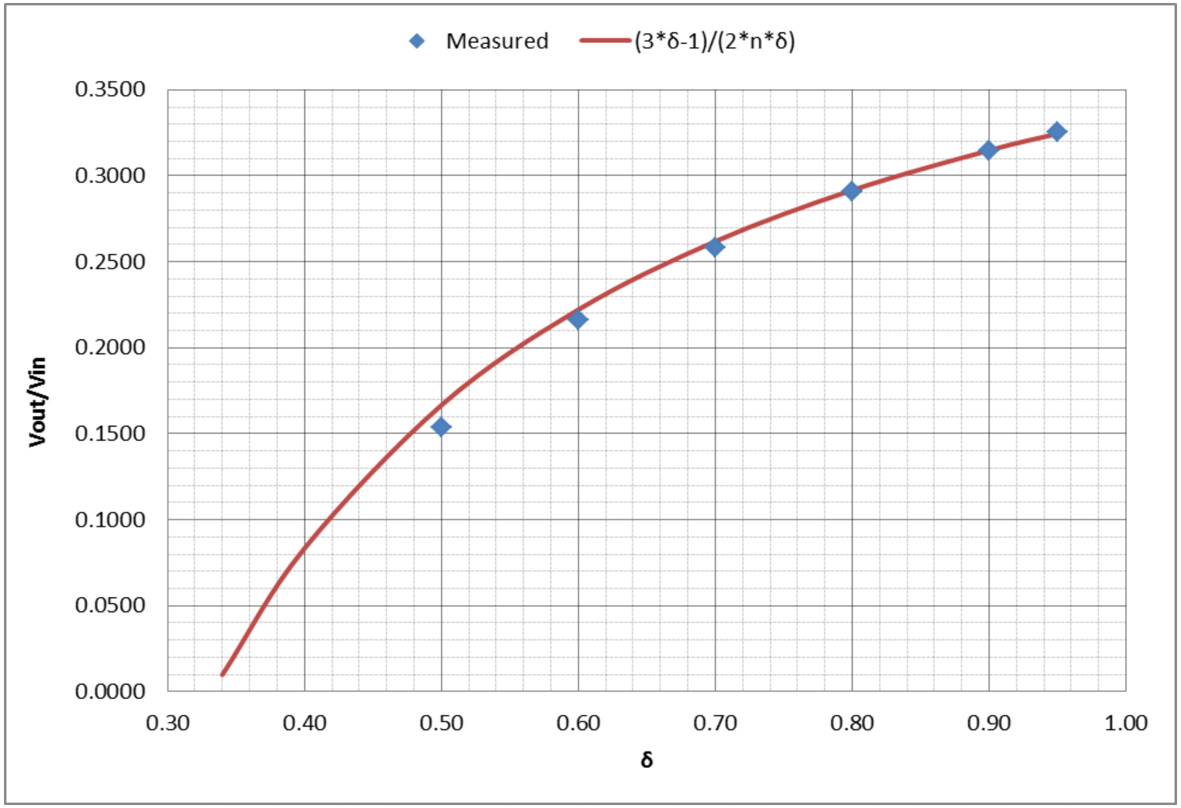
$$i_{in\_avg} = \left(\frac{3 \cdot \delta}{2} - \frac{1}{2}\right) \cdot i_{avg}$$

AVERAGE

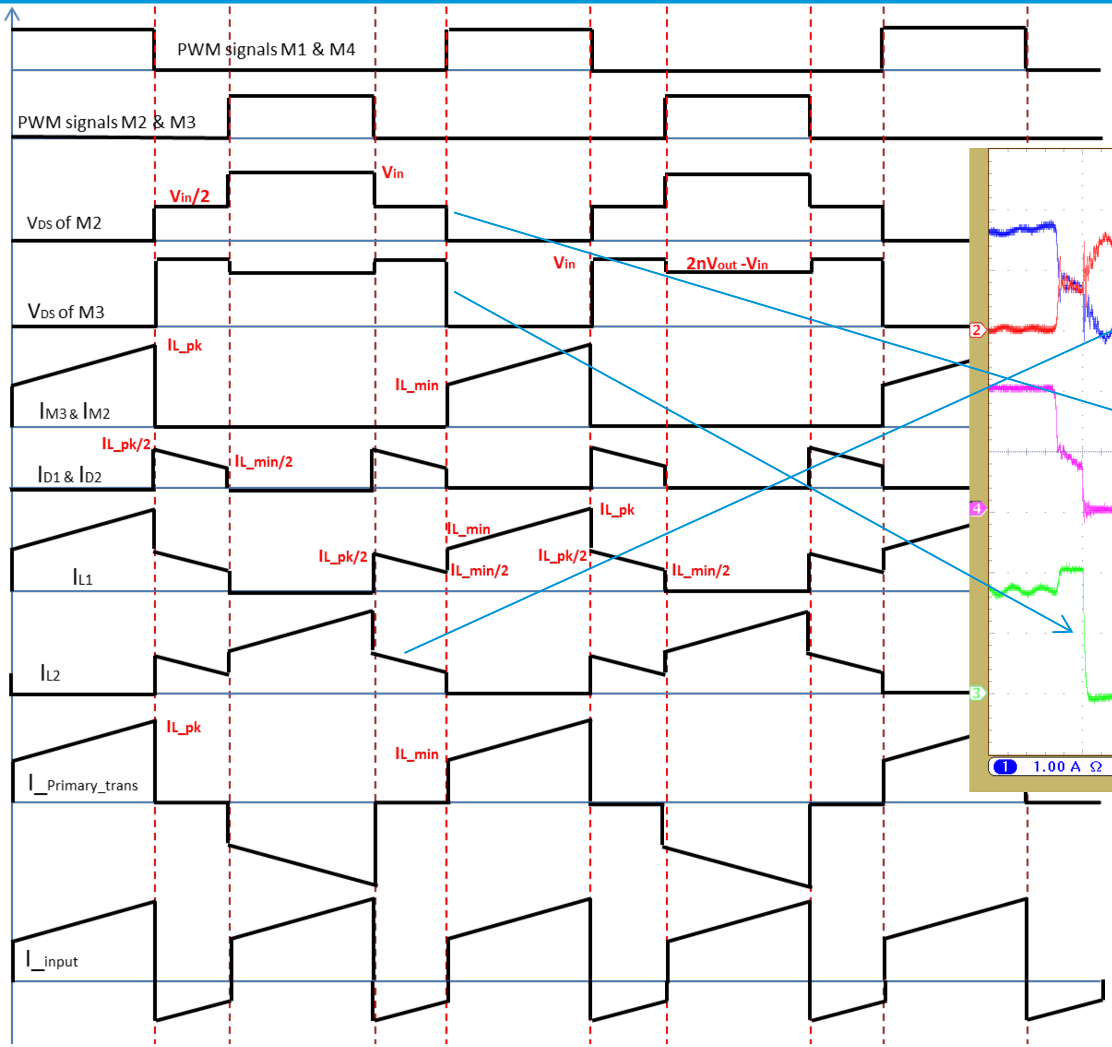
Continuous Current Mode: Test results in DC

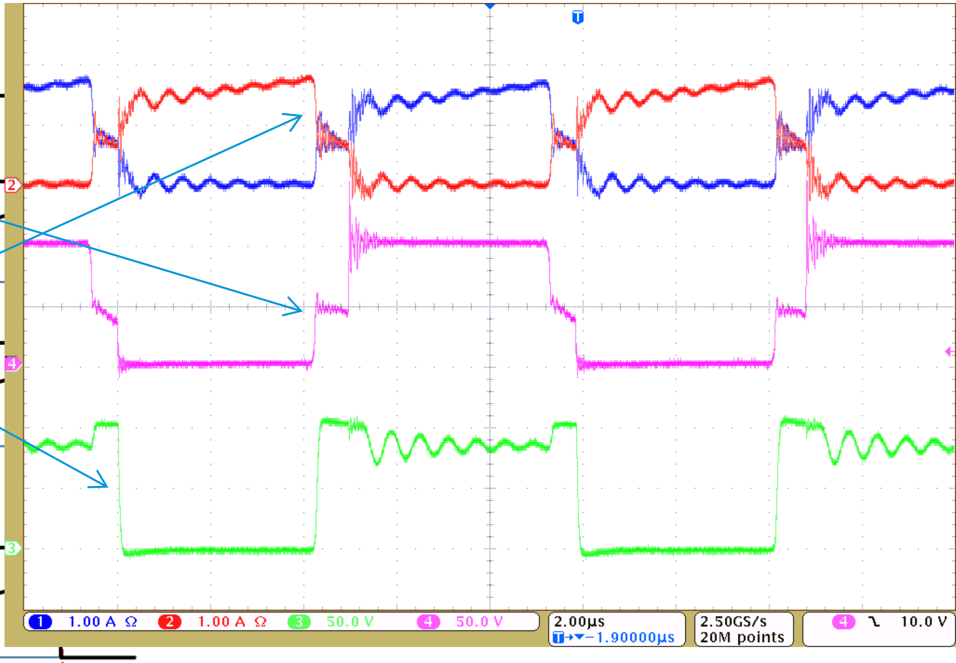
The DC case is described by the previous equations imposing the derivative equal to zero. From the inductor equation and considering an ideal converter we find the transfer ratio of the converter is:

$$\frac{V_{out}}{V_{in}} = \frac{3 \cdot \delta - 1}{n \cdot 2 \cdot \delta}$$

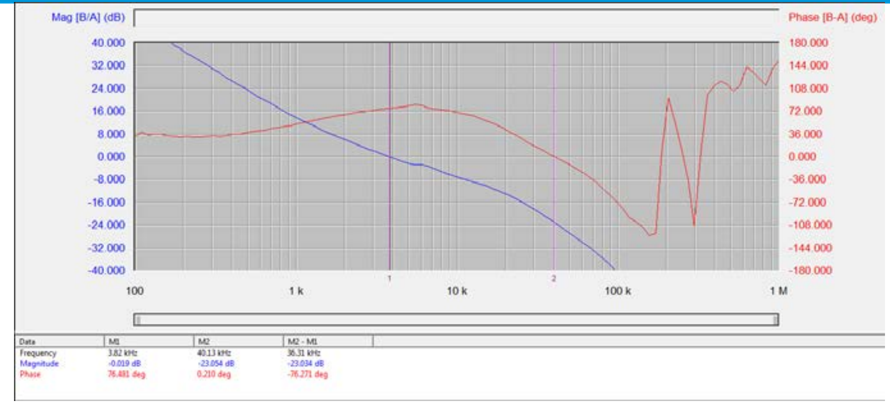


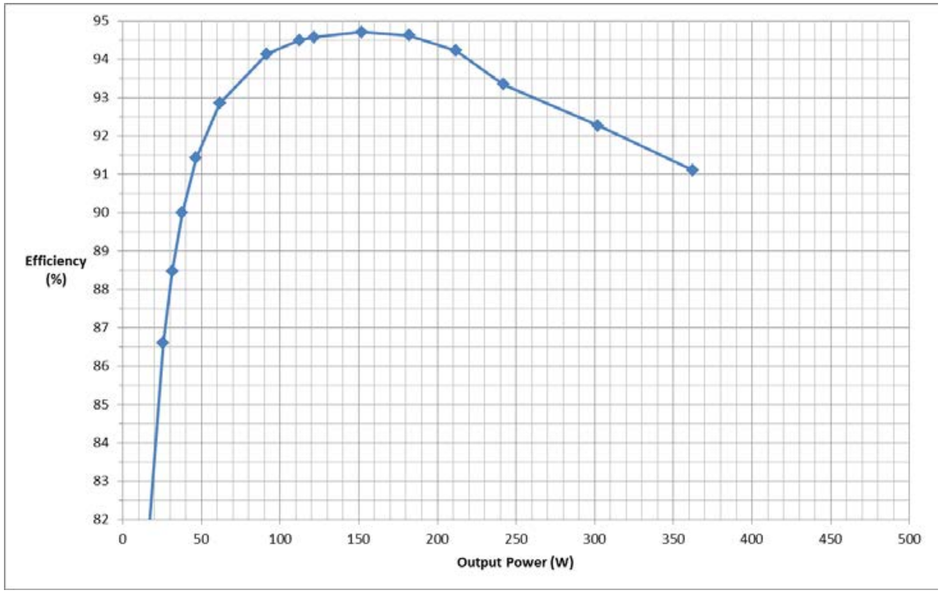
Continuous Current Mode: measured main waveforms



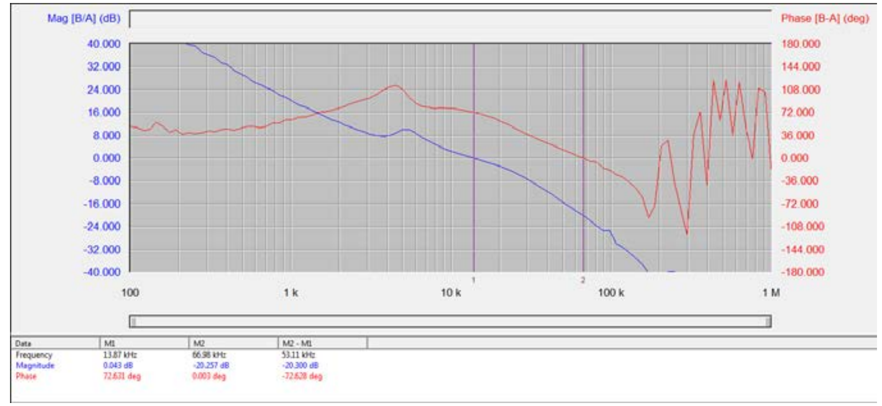


Continuous Current Mode: efficiency and stability measurements





10W & 200W load:
G_margin>10dB,
F_margin>60deg



Without much optimization effort the efficiency of the BB is >92% up to 300W.

Simulation Model of the Converter in CCM

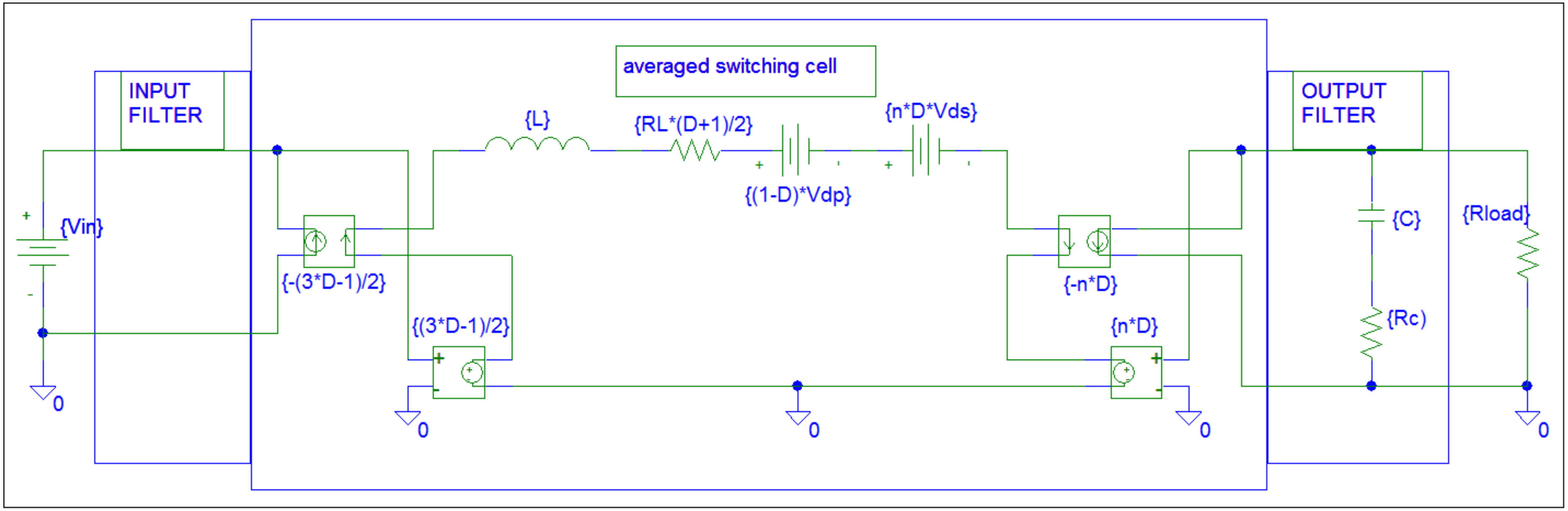
$$L \cdot \left(\frac{d}{dt} i_{avg}\right) = \left(\frac{3 \cdot \delta}{2} - \frac{1}{2}\right) \cdot v_{in\_avg} - \frac{(\delta + 1) \cdot R_L}{2} \cdot i_{on\_avg} - (1 - \delta) \cdot V_{dp} - \delta \cdot n \cdot V_{ds} - \delta \cdot n \cdot v_{out\_avg}$$

$$C \cdot \left(\frac{d}{dt} v_{c\_avg}\right) = \delta \cdot n \cdot i_{avg} - \frac{v_{out\_avg}}{R}$$

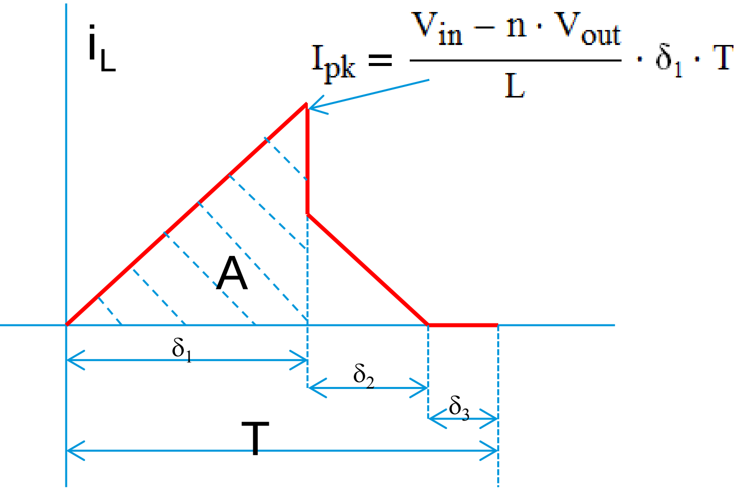
$$v_{out\_avg} = v_{c\_avg} + R_c \cdot i_{c\_avg}$$

$$i_{in\_avg} = \left(\frac{3 \cdot \delta}{2} - \frac{1}{2}\right) \cdot i_{avg}$$

AVERAGE



Discontinuous Current Mode: Transfer Ratio



$$I_{L\_avg\_on} = \frac{1}{n} \cdot \frac{V_{out}}{R}$$

But also:

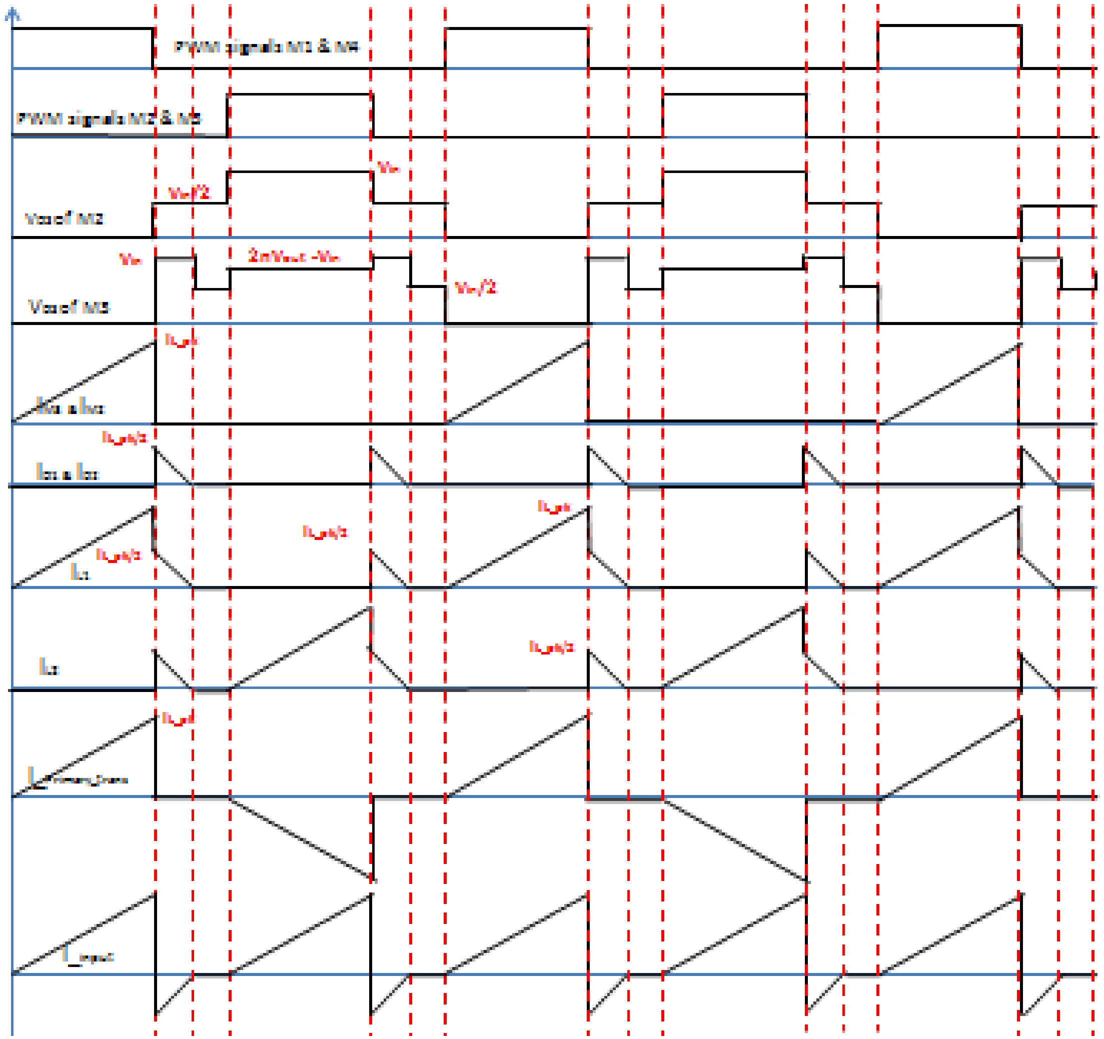
$$I_{L\_avg\_on} = \frac{A}{T} = \frac{V_{in} - n \cdot V_{out}}{L} \cdot \delta_1 \cdot \delta_1 \cdot T$$

Eliminating IL_avg_on from the two equations:

$$\frac{V_{out}}{V_{in}} = \frac{\delta^2}{n \cdot \left(K + \delta^2\right)}$$

Where: $$K = \frac{2 \cdot L}{n^2 \cdot R \cdot T}$$

Discontinuous Current Mode: main waveforms



CCM and DCM boundary conditions

The boundary condition is a function of the duty cycle/

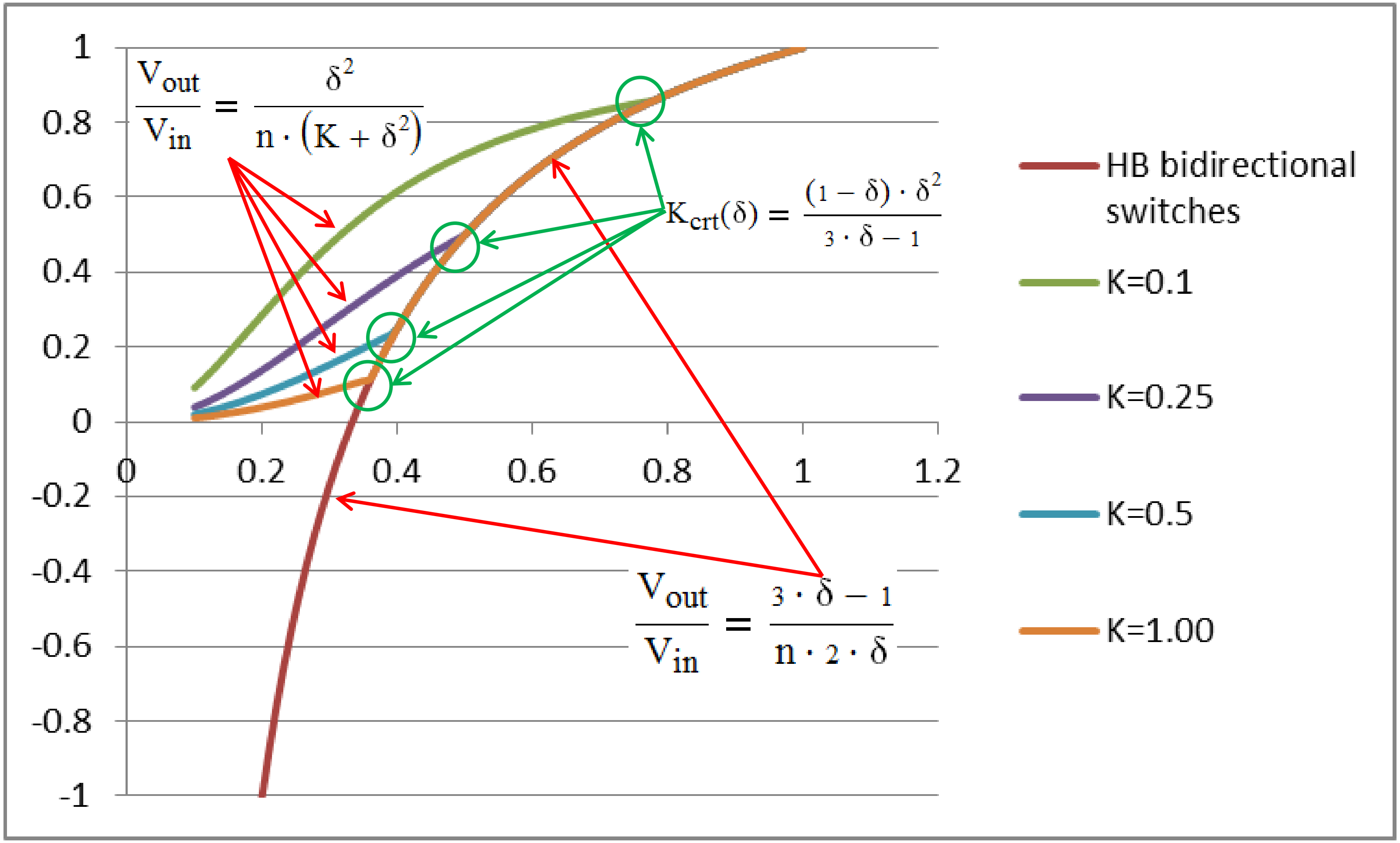
$$K_{crt}(\delta) = \frac{(1-\delta)\cdot\delta^2}{3\cdot\delta - 1}$$

If: $K = \dfrac{2\cdot L}{n^2\cdot R\cdot T} > K_{crt}(\delta)$ the converter is in CCM

If: $K = \dfrac{2\cdot L}{n^2\cdot R\cdot T} < K_{crt}(\delta)$ the converter is in DCM

So for high values of K (high loads) the converter will be in CCM for most of the duty-cycle domain range. For K=infinite (output in short circuit) the converter will be always in CCM and when duty < 1/3 the output is 0V.

Converter Transfer Ratio in CCM and DCM



Advantages and Disadvantages of the topology

Advantages:

- **Low voltage stress on switches**: maximum static voltage on the active components is Vin, while in the classical Watkins-Johnson converter the Voltage stress is 2*Vin.
- **Simple output stage**: No inductance on the secondary side, hence topology suitable for HV applications.
- **Galvanic isolation**
- **High power handling capability**: topology suitable for high power applications due to the Full Bridge stage.

Advantages and Disadvantages of the topology

Advantages:

- **Operation possible in a wide input voltage range**
- **Stable**: easy to implement a stable control loop
- **Simple controller**: a simple PWM controller do the job
- **No uncontrolled overvoltage failure**: at maximum duty-cycle Vout=Vin/n

Disadvantages:

- **Alternating input current**

Further work

- Study control loop stability in detail
- Study the effect of the “parasitics” of the inductor and of the transformer
- Efficiency optimization, also finding conditions for partial ZVS operations
- Study how to achieve full ZVS operations
- Implement HV output stage
- Develop a modular approach to increase output power

Questions or comments?