DESIGN OF AN EMC FILTER FOR AN AUTOMOTIVE ON BOARD CHARGER

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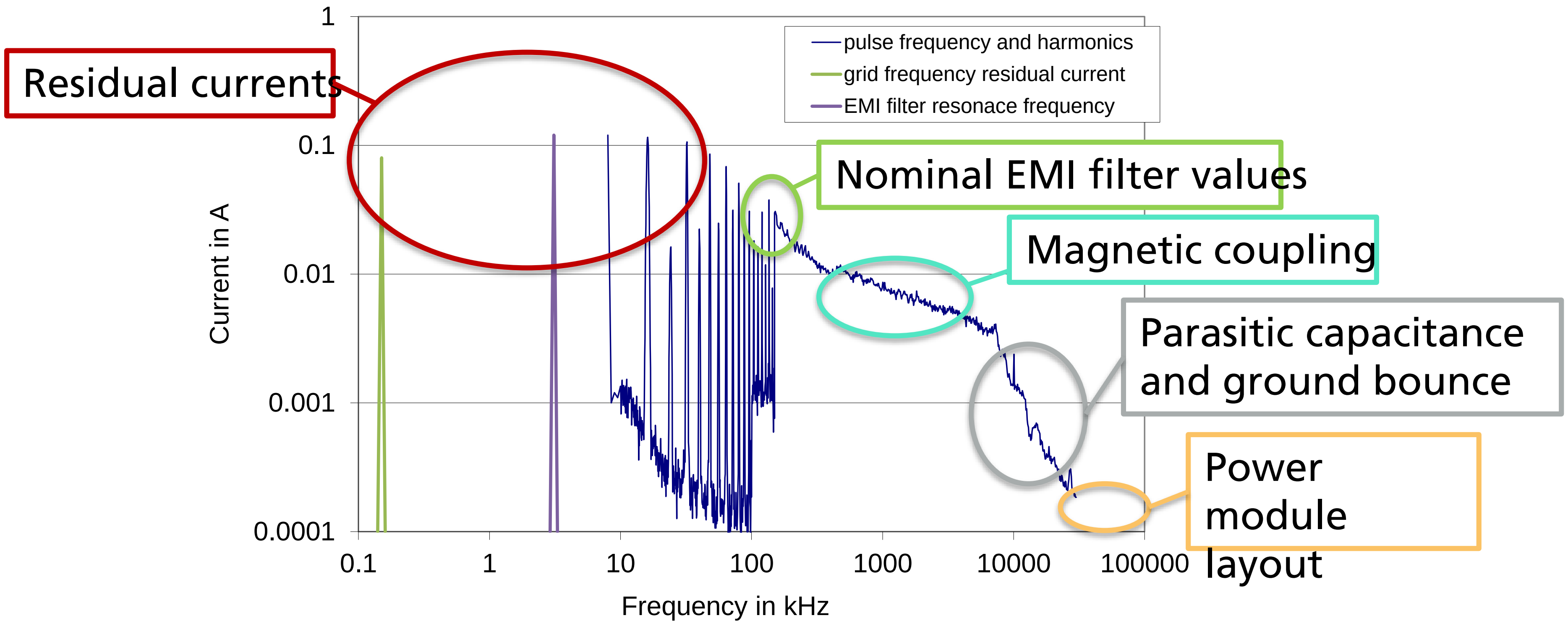
Which EMI effects can be simulated to accelerate the design process?

Power electronics always generate interference, because they transform energy by switching. These effects are mostly evaluated in frequency domain and ways of prediction shall be demonstrated.

Different effects dominate depending on the frequency and simulation methods have to be adapted accordingly



Which EMI effects can be simulated to accelerate the design process?

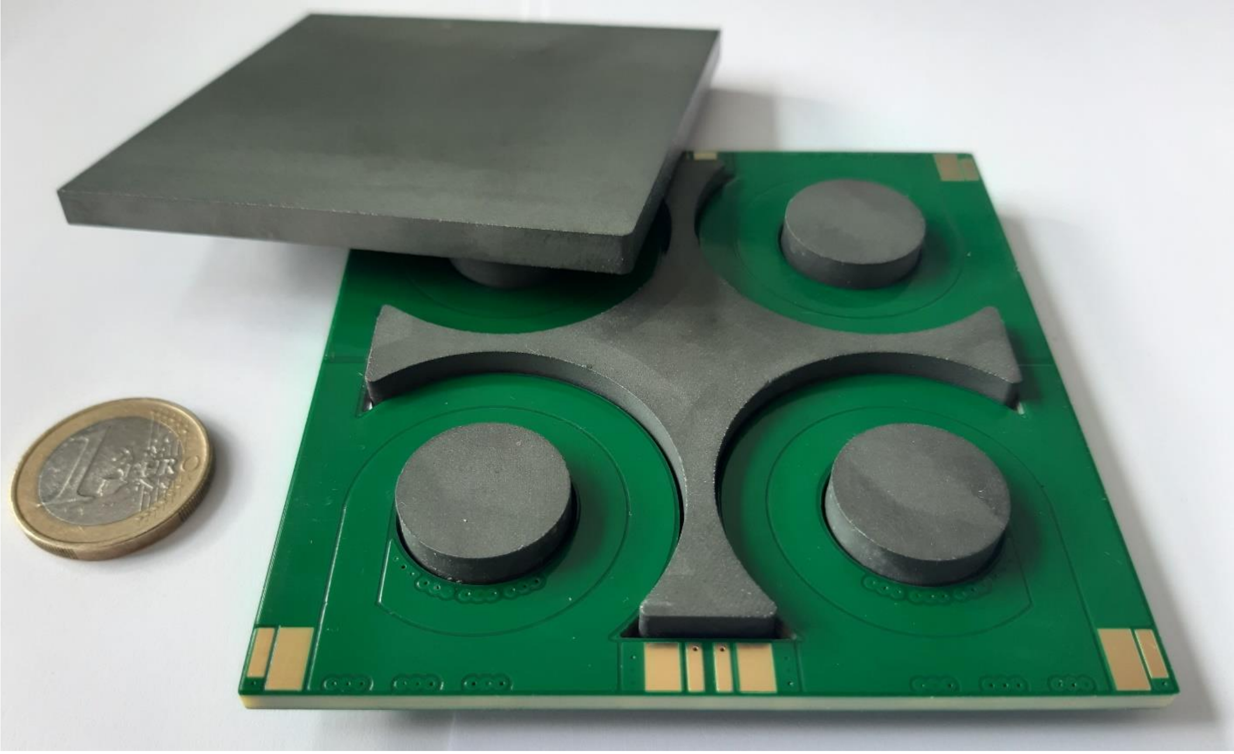
	Simulation complexity*	Modeling effort*	Unknown parameters	Expert knowledge*
Residual currents	3	3	Grid properties	4
Nominal filter values	3	4	many	5
Magnetic coupling	8	8	many	8
Parasitic capacitance	3	3	medium	4
Ground bounce	8	8	very many	10
Radiated emissions/ power module layout	8	10	very many	10

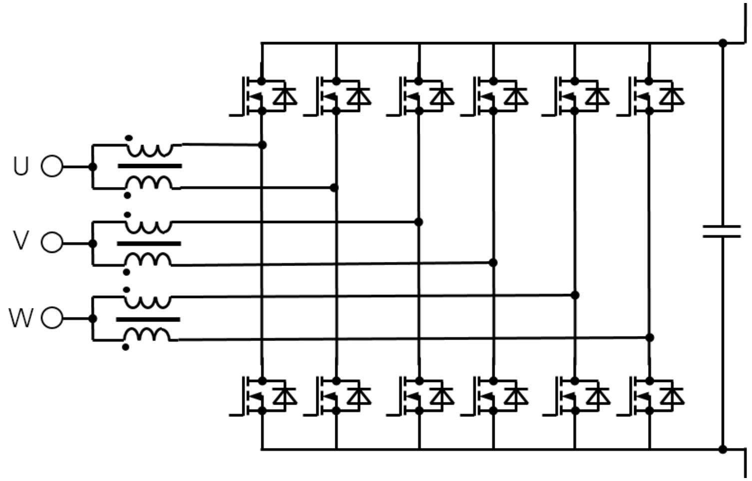
⇦ Today´s talk

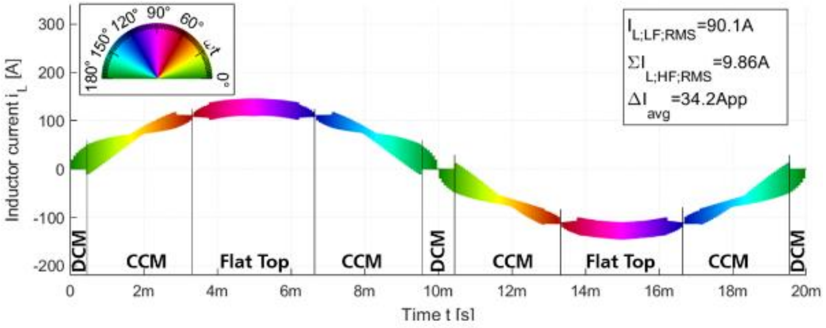
* On a scale of 0 (low) to 10 (high)

Practical example: 3-phase PFC for a 22kW OBC

- Two interleaved half bridges for each phase, 1200V SiC semiconductors, PCB based coupled inductor, 140kHz switching frequency
- Optimization goal: a EMI filter to comply with the EMI standards and to fulfill the 2.5mA residual current limit (this limits the y-capacitors to a total value of about 47nF)







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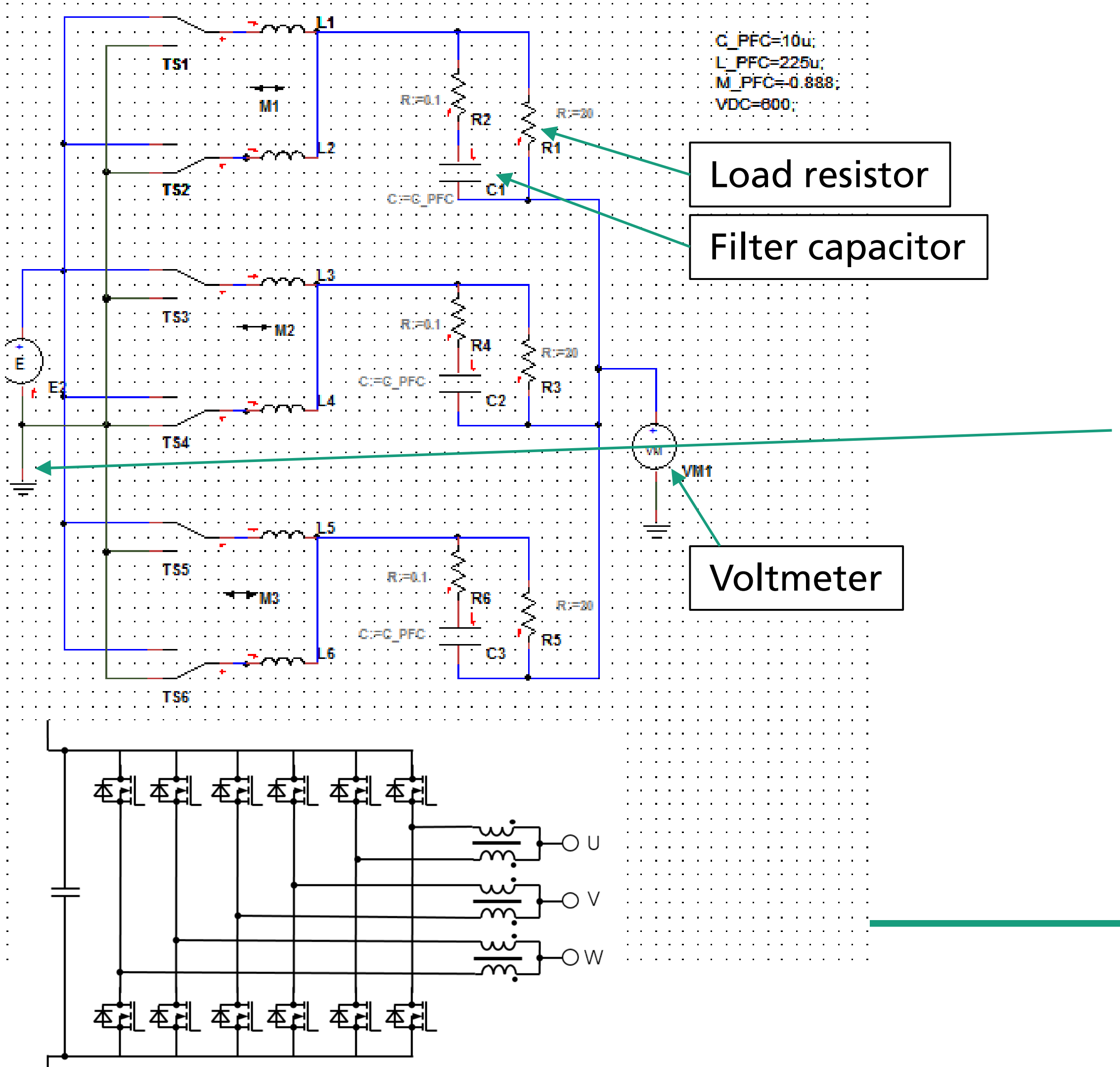
1st step: Setting up a functional simulation in time domain

- Select a circuit simulator with good simulation stability, e.g. Portunus or Simplorer (not SPICE)
- Model semiconductors as ideal switches, add inductors, filter capacitors and a load



One very important influence is the ground connection

- In this example a hard ground connection for the DC link is assumed. Then the filter has to take the full common mode voltage and gets significantly bigger. In many OBCs the DC/DC converter decouples the DC link from ground. Then this connection has to be replaced by the parasitic coupling capacitance of the transformer
- Parasitic capacitance between transistors and heat sink will be added later

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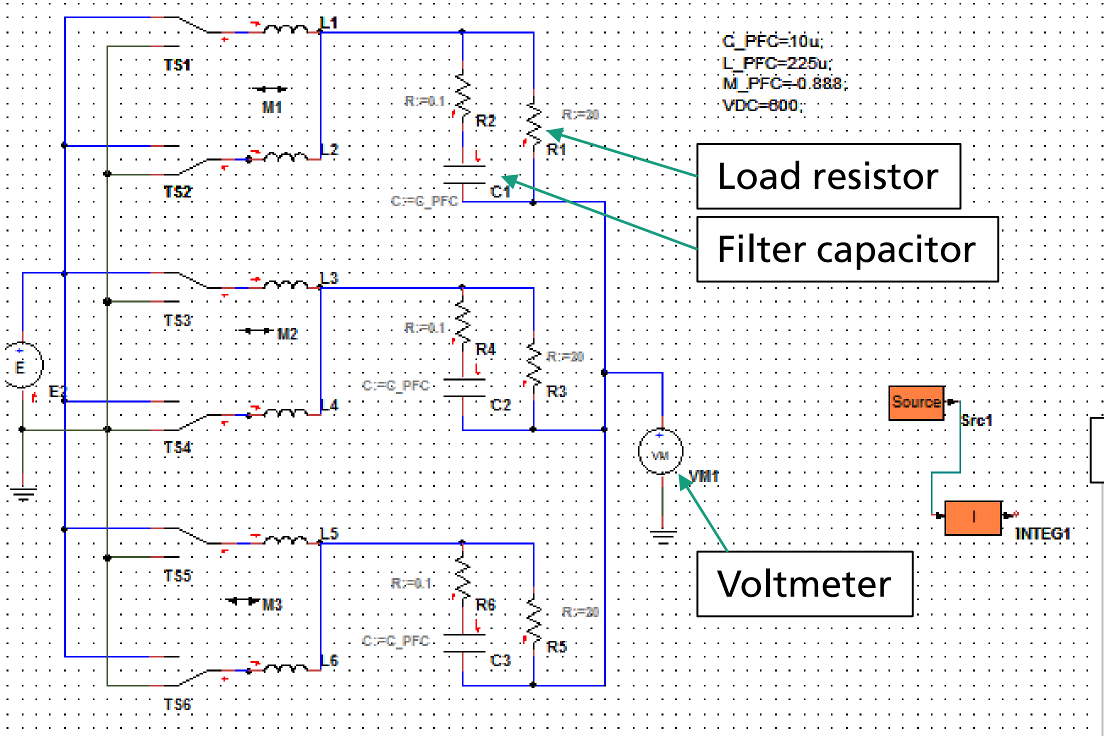
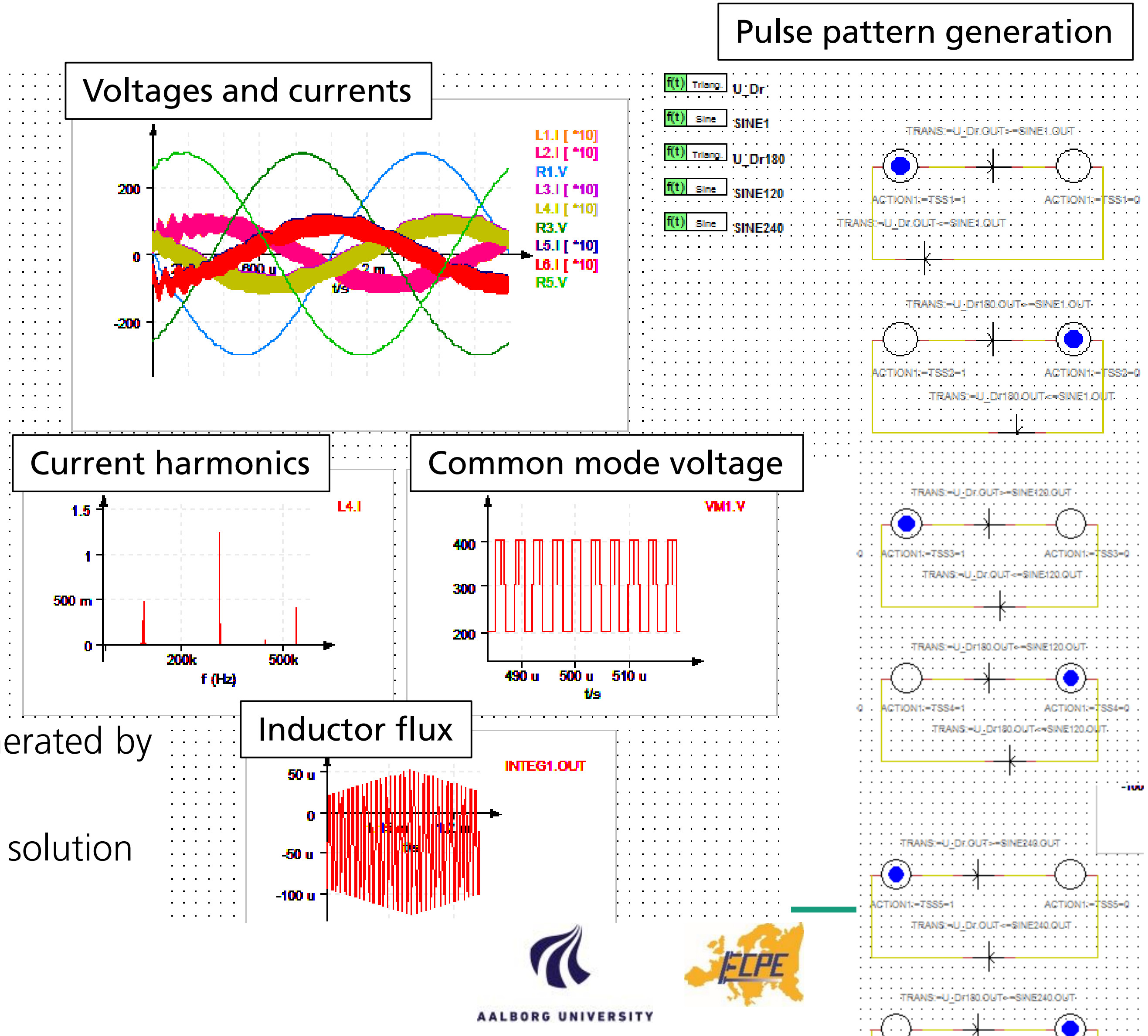
1st step: Setting up a functional simulation in time domain

- Add a pulse pattern generation and let it run



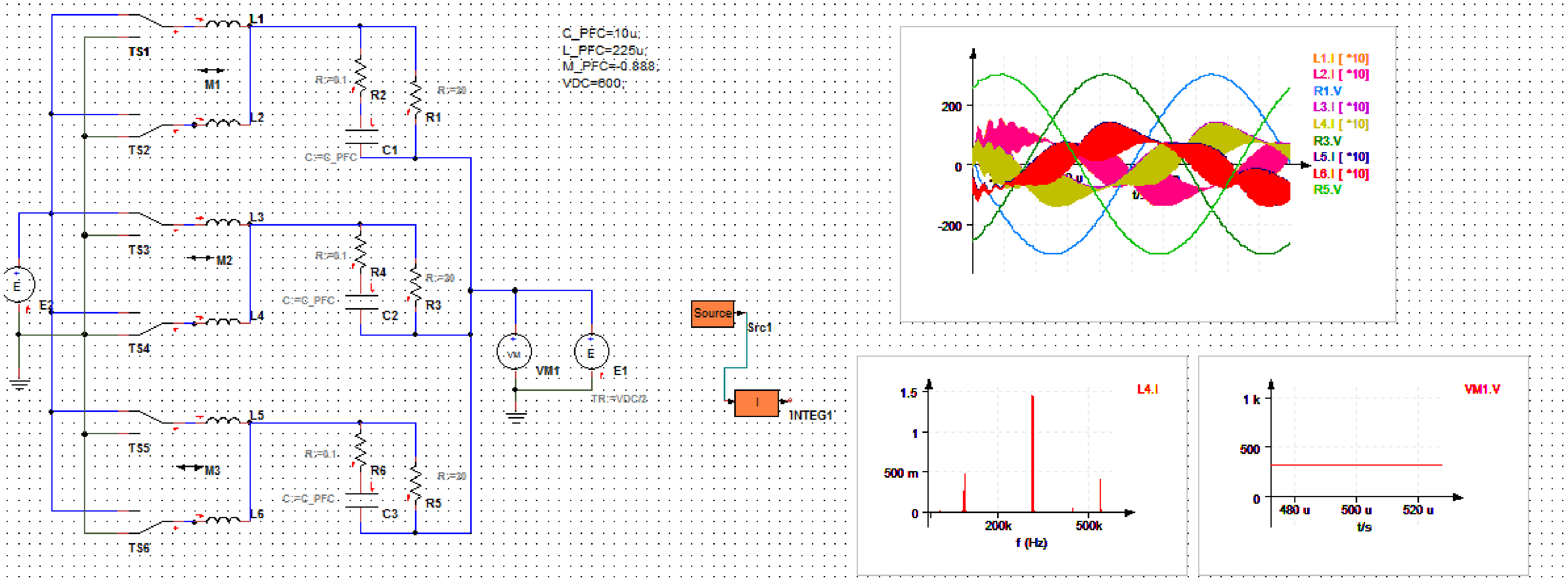


The common mode diagram depicts the CM voltage generated by this circuit, which has to be filtered

- Clamping the star point of the 3 phases would be one solution to handle these voltages (next slides)

1st step: Setting up a functional simulation in time domain

- Clamped star point: the current stress in the main inductors gets higher, the higher the DC voltage the more significant



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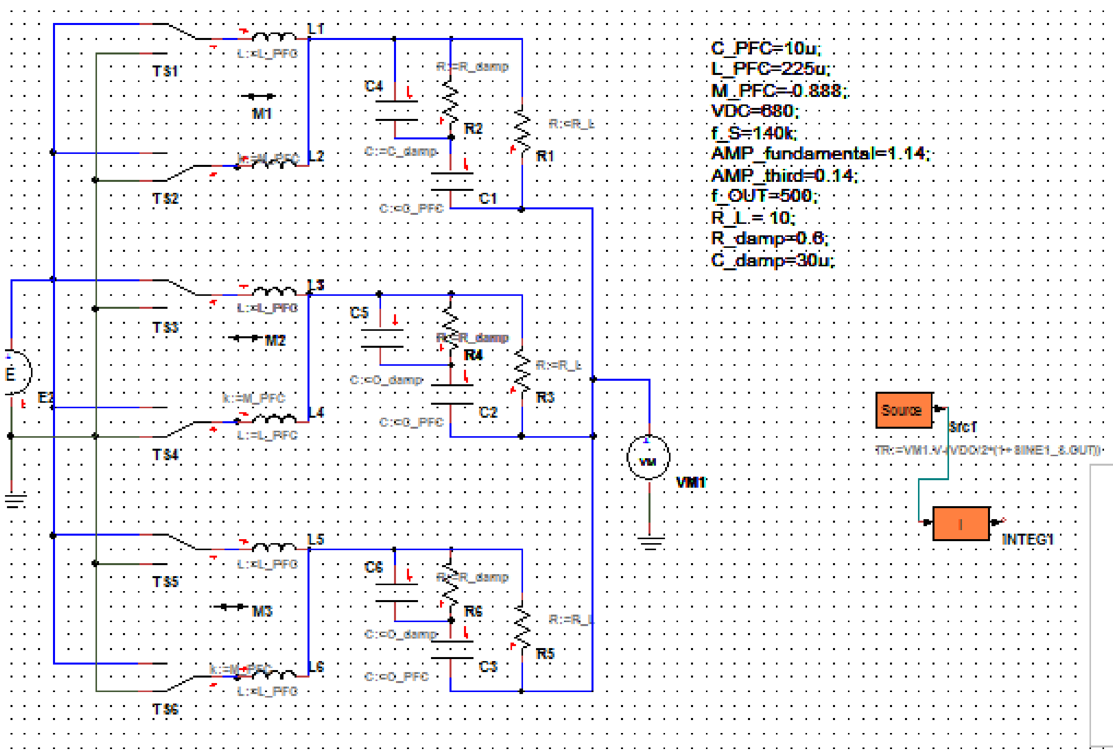
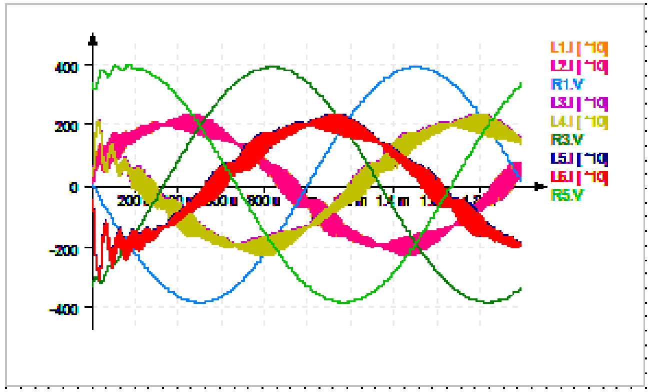
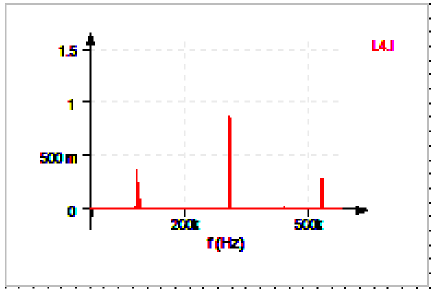
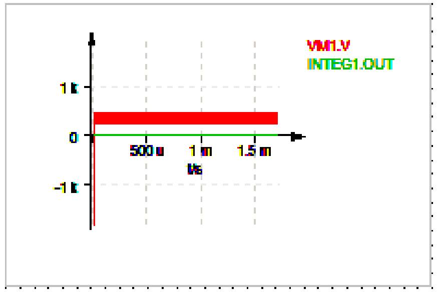
1st step: Setting up a functional simulation in time domain

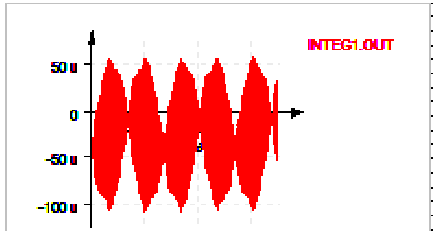
- Parameter adjustment: 3rd harmonic implementation and higher DC link voltage-> significant inductor current reduction











Next step: design of a common mode choke to take the CM voltage

- Max. flux taken from simulation: 160µVs, thermally effective about 120µVs

Next step: design the first common mode inductor

- Max. flux taken from simulation: 160µVs, thermally effective about 120µVs (at 280 kHz)
- This is a high excitation, therefor a loss optimized ferrite has to be used, e.g. N87 from TDK

R 58.3 × 32.0 × 18.0 **B64290A0043, B64290L0043**

■ Uncoated / epoxy coating

R 58.3 × 32.0 × 18.0 (mm)
R 2.295 × 1.260 × 0.709 (inch)

Dimensions

d_a (mm)	d_i (mm)	Height (mm)	d_a (inch)	d_i (inch)	Height (inch)	
58.3 ±1.0	32.0 ±0.7	18.0 ±0.5	2.295 ±0.039	1.260 ±0.028	0.709 ±0.020	uncoated [1]
60.1 max.	30.5 min.	19.3 max.	2.366 max.	1.201 min.	0.760 max.	coated

Characteristics and ordering codes

Mate-rial	A_L value	μ_i (approx.)	Ordering code	Magnetic characteristics				Approx. weight
	nH			$\Sigma l/A$ mm^{-1}	l_e mm	A_e mm^2	V_e mm^3	g
K10	1500 ±25%	700	B64290A0043X010	0.58	134.0	230.0	30710	160
N87	4800 ±25%	2200	B64290L0043X087					

First try:

- ring core R58
- With 5 turns and a linked flux of 120µVs a flux density of 100mT is reached ☺
- Core losses calculation: Ve * Pv = 30170mm³ * 390kW/m³ = 12W ☹
- With 7 turns losses reduce, core losses depend by the power of 2.2 from the amplitude: 5^2.2/7^2.2=0.48
- 5.7W core losses, with 2.5mm dia wire 2.6W copper losses add: better solution

SIFERRIT materials
N87

Material properties

	Symbol	Unit	
Preferred application			Power transformers
Material			N87
Base material			MnZn
Initial permeability (T = 25 °C)	μ_i		2200 ±25%
Flux density (H = 1200 A/m, f = 10 kHz)	B_S (25 °C) B_S (100 °C)	mT mT	490 390
Coercive field strength (f = 10 kHz)	H_c (25 °C) H_c (100 °C)	A/m A/m	21 13
Optimum frequency range	f_{min} f_{max}	kHz kHz	25 500
Hysteresis material constant	η_B	10^{-6}/mT	<1.0
Curie temperature	T_C	°C	>210
Mean value of α_F at 25 … 55 °C		10^{-6}/K	4
Density (typical values)		kg/m³	4850
Relative core losses (typical values)	P_V		
25 kHz, 200 mT, 100 °C		kW/m³	57
100 kHz, 200 mT, 100 °C		kW/m³	375
300 kHz, 100 mT, 100 °C		kW/m³	390
500 kHz, 50 mT, 100 °C		kW/m³	215

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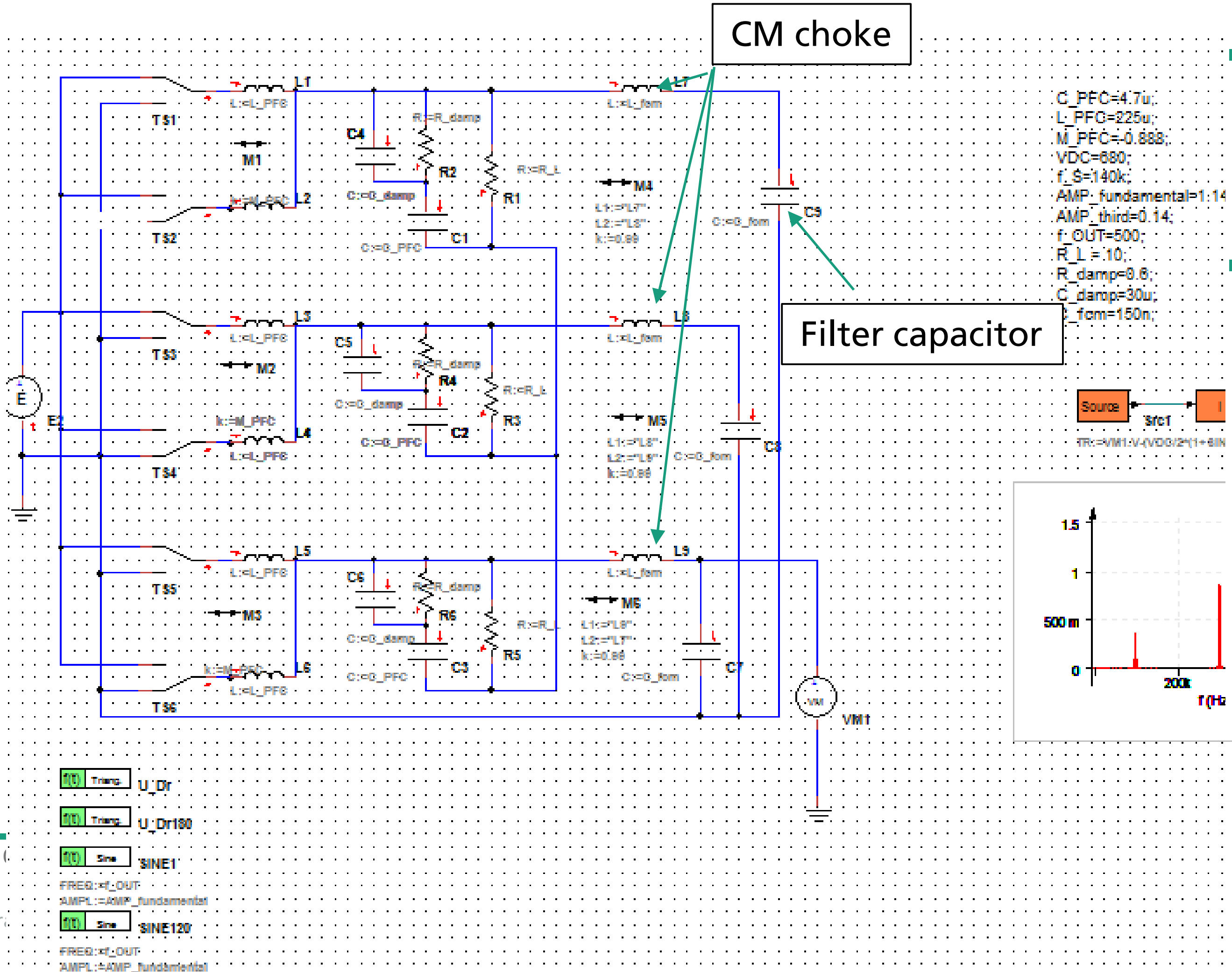
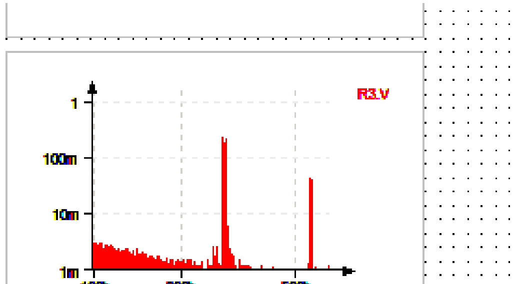
Select a capacitor to form a filter

- The nominal inductance of the common mode choke is Al*N² = 4800nH * 49 = 235µH
- A decent filter stage should achieve 40dB: choke impedance at 280 kHz is 413Ω, so the capacitor should have 100 times less impedance (40dB), this is 4.1Ω or 140nF



- Here the common mode is coupled back to the DC link, the restriction of y-capacitor value does not have to obeyed, as it does not connect to Protective Earth (PE)
- Next step: differential mode. Interference level across R3 is 200mV$_{rms}$ (see diagram), which corresponds to 106dBµV. Required according to the standards is 45dBµV



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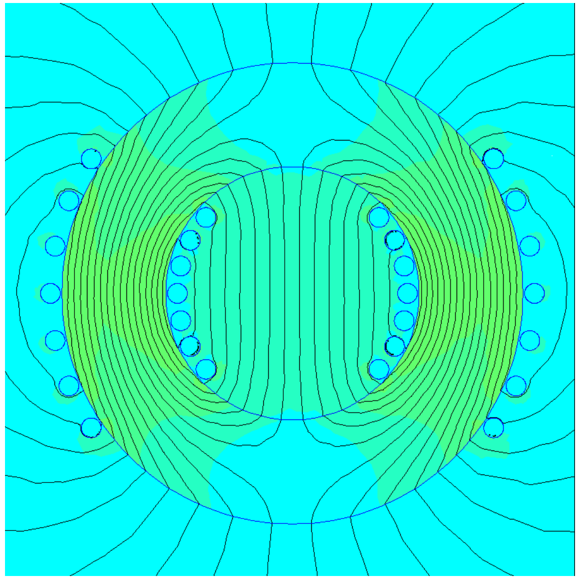
Differential mode filter

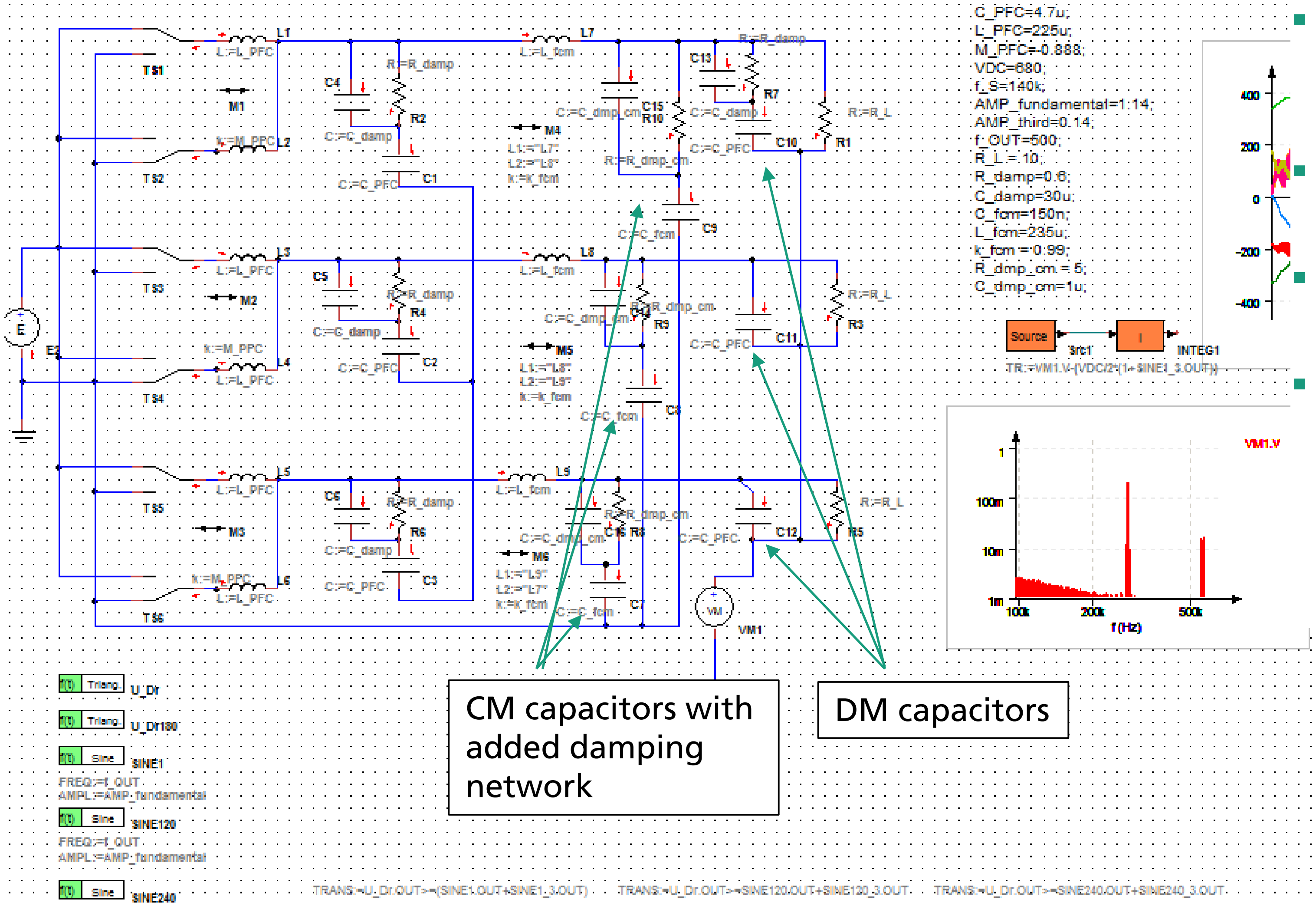
The stray inductance of the choke is used for differential mode filtering

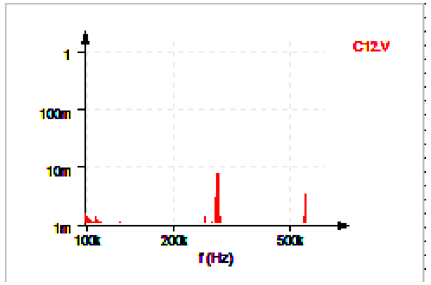


Stray field lines of a 2 phase common mode choke

- Typically the stray inductance of a common mode choke is 1% of its nominal inductance, in our case 2.4µH -> 4.1Ω at 280kHz
- The same capacitors like for the first stage are used: 4.7µF -> 121mΩ
- This filter stage gives 30dB, another one with the same attenuation is needed

Filter topology up to now





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- The same capacitors like for the first stage are used: 4.7µF -> 121mΩ
- This filter stage gives 30dB, another one with the same attenuation is needed
- Common mode level (VM1.V in diagram) is 200mV (106dBµV), this will require two more CM inductors

Second common mode inductor

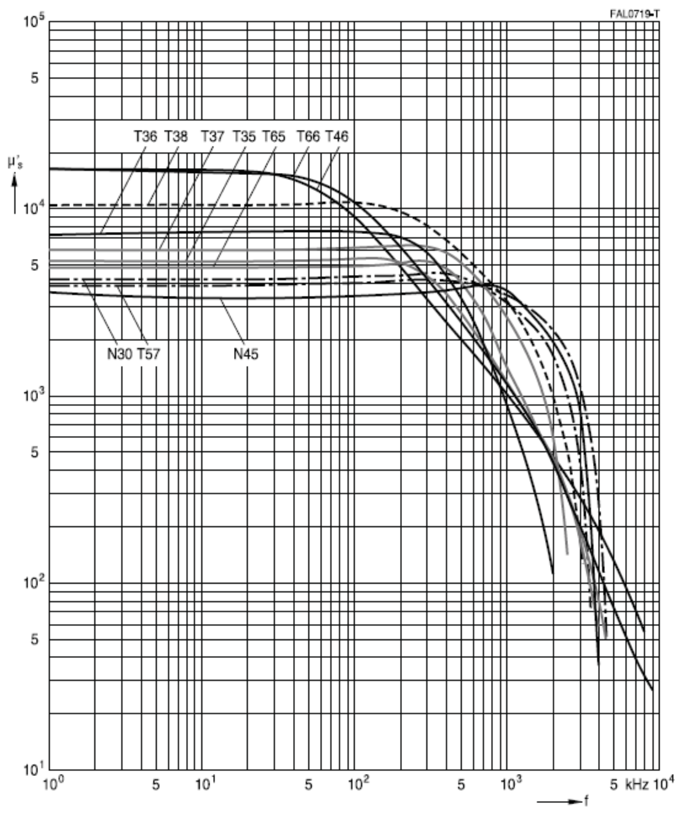
- This common mode choke is not loss limited any more, the focus is on high impedance

EPCOS

SIFERRIT materials

Broadband transformers

Relative inductance component versus frequency
(measured with ring cores, measuring flux density $\hat{B} \leq 0{,}25$ mT)



Selection:

- ring core R58, material T38 for highest impedance at 280kHz
- 7 turns results in 833μH, 1500Ω at 280kHz
- 20nF y-caps are 28.4Ω, this results in a damping of 34dB (->72dBμV)
- In this topology a 3rd CM inductor is needed to fulfill the required 45dBμV. The same type is used, it damps together with the grid impedance represented by the LISN another 39dB
- For DM same procedure has to be carried out as shown before
- Now parasitic capacitances to ground have to added

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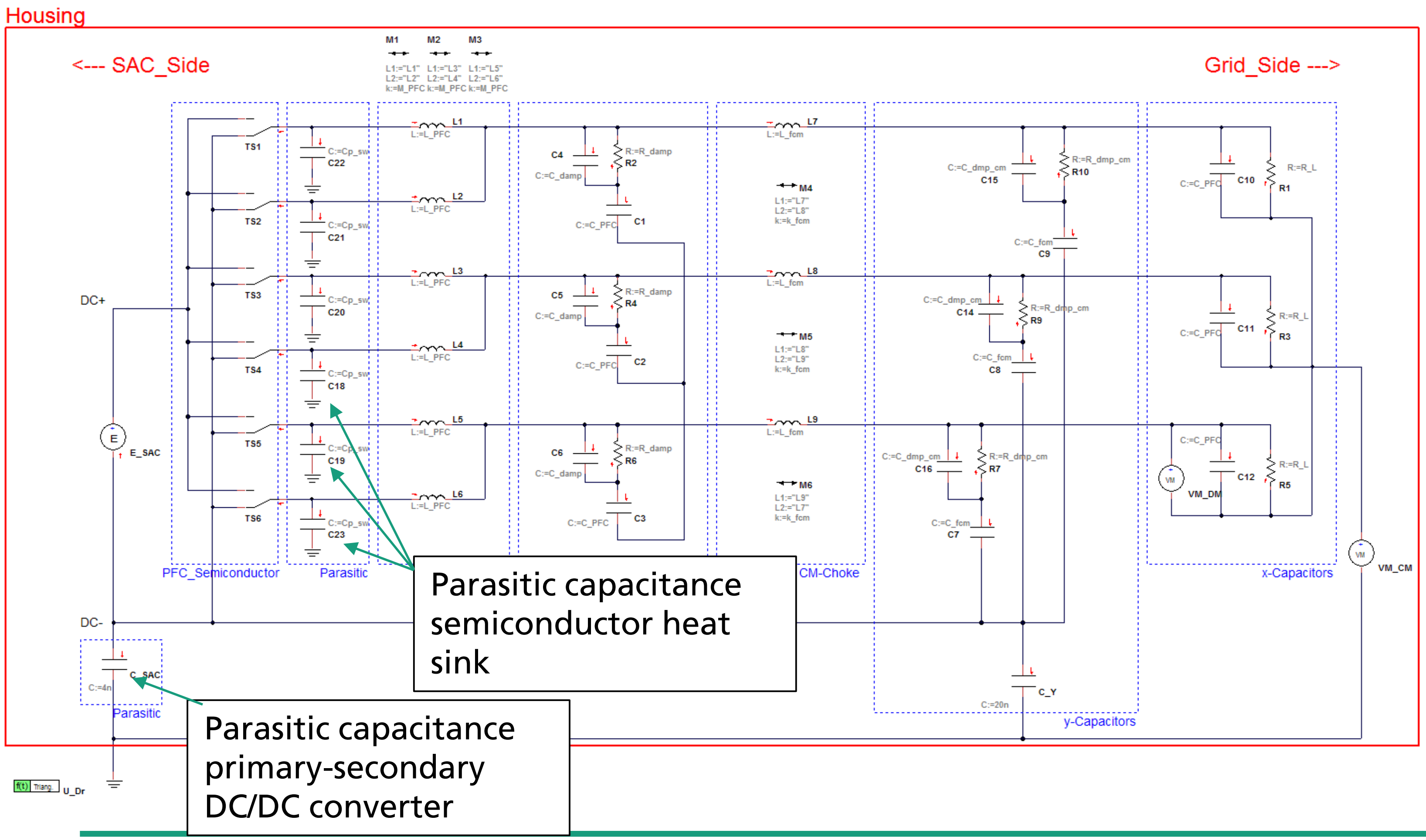
Parasitic ground capacitance

- A colleague redrew my schematic…



Result

- The designed filter is sufficient even with added parasitics
- In this filter topology the first CM choke takes the full CM voltage. Modifications with no connection of filters to the DC link will reduce the filtering effort

Simulation strategy used to define nominal filter values

- Use a simulator with good stability
- Model function with ideal switches:
  as switching speed gets relevant at much higher frequencies than the frequencies defining filter size it can be neglected in the first run
- Develop the filter starting from the switching semiconductors and directly connected components:
  building up and testing the simulation step by step helps to eliminate mistakes
- Add parasitic capacitances in very early stage of filter development:
  Semiconductor to heat sink, cable+motor capacitance, transformer capacitance
- Filter design by alternating high impedance components (chokes) and low impedance components (capacitors)
- Add some damping to reduce resonances