

Design Methods and Tools for Power Electronics

T. Meynard – G. Fontes

Laplace – N7 – CNRS

Toulouse

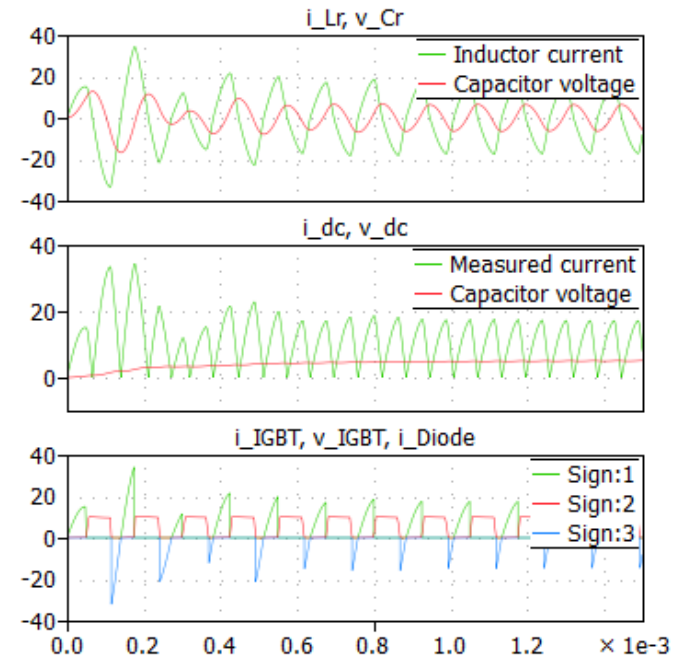
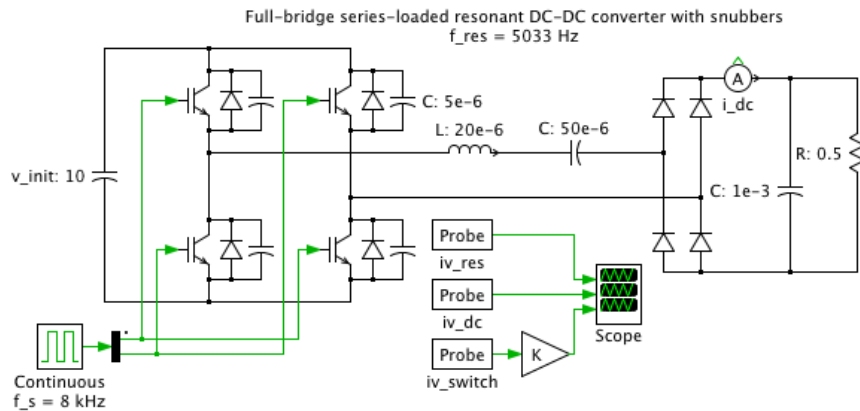


Outline of the presentation

- Simulation vs Design
- Semi Analytic Design
- Designing with objects and optimization

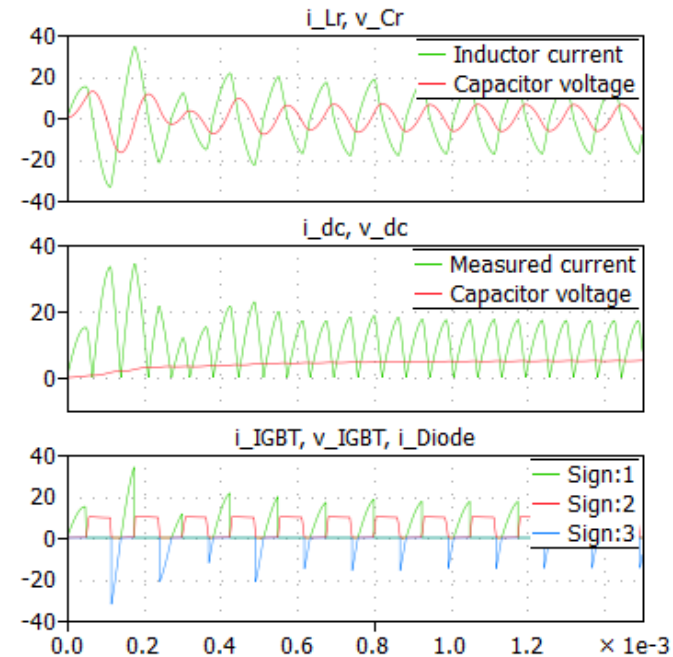
SIMULATION VS DESIGN

Standard simulation tools



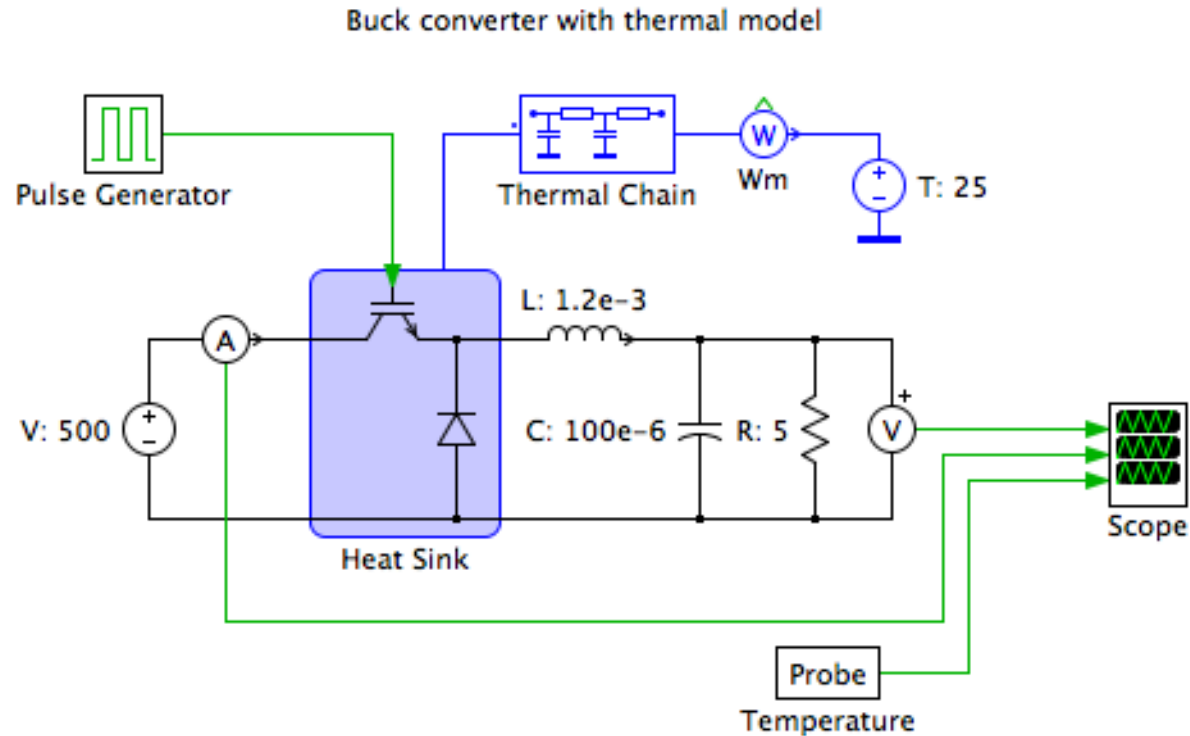
Simulation is an injection :
one circuit gives a single set of waveforms.

Design tools



Design is NOT an injection :
there can be an infinity of solution for a given set of specifications
(and sometimes NO solution!...)

Hidden quantities in standard simulation tools



Which of the components in this circuit is the biggest? => L? C? the heatsink?

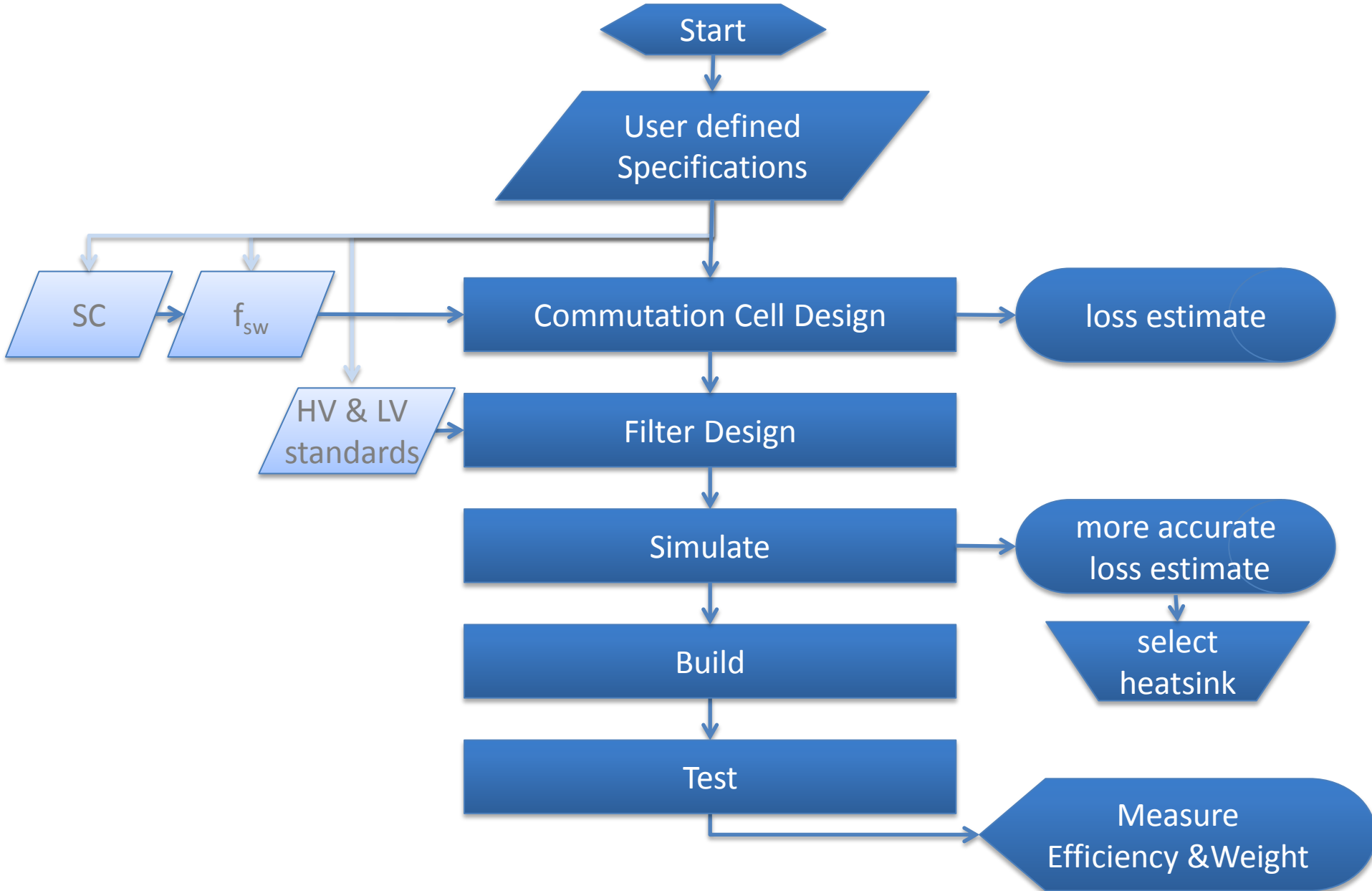
Which of the components in this circuit is the most expensive?

If L is halved and C doubled to get the same voltage ripple, will the filter be smaller?

Or less expensive?

SEMI ANALYTIC DESIGN

A standard design process



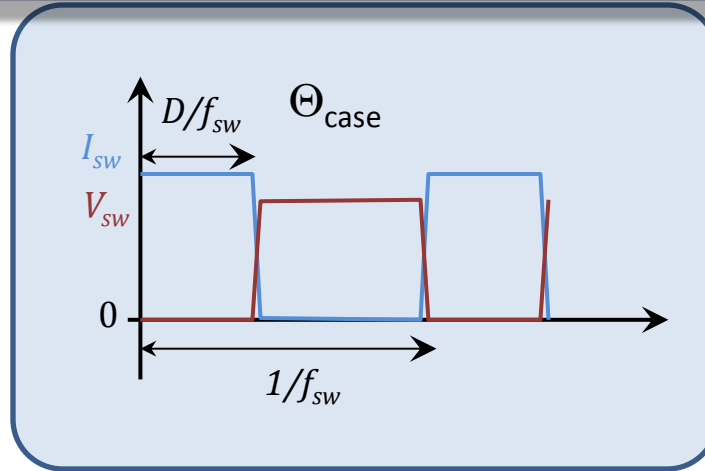
COMMUTATION CELL DESIGN

Find the MacroSwitch with the best efficiency

Rules of the game

- a) Define a global switch requirement (Voltage current, Frequency, Duty Cycle, Case Temperature,..)
- b) Evaluate the limit of operation of a switch to determine how many must be connected in series and parallel to fulfill requirements
- c) Evaluate losses and other characteristics of the design
- d) Repeat a) to c) for each component and compare results and make a choice

1-Define MacroSwitch requirements



2-Find number of series connected switches

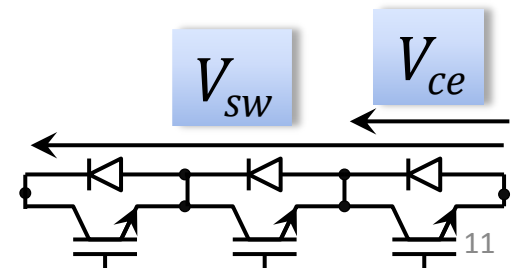
Voltage to be switched

+

Maximum collector-emitter voltage in switching mode

$$n_{Series} = \text{int}\left(\frac{V_{sw}}{V_{margin} \cdot V_{CEmax}}\right) + 1$$

Number of series connected switches

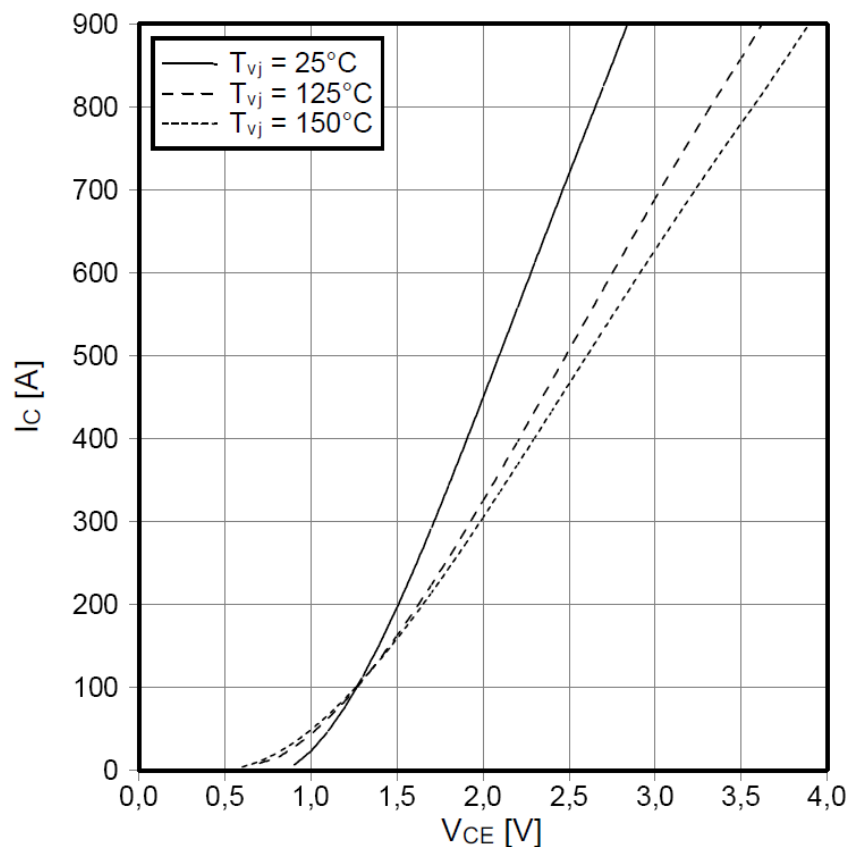


3-Find Maximum Current per switch for this profile : evaluate variation of losses as a function of the current

output characteristic IGBT-inverter (typical)

$I_C = f(V_{CE})$

$V_{GE} = 15 \text{ V}$

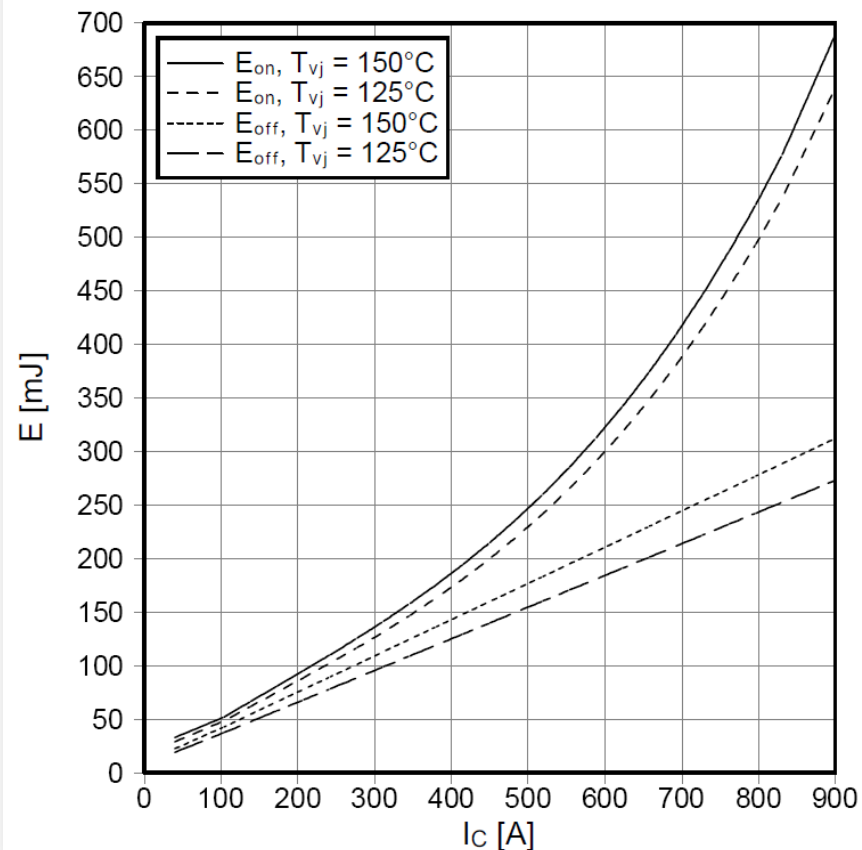


$$\Rightarrow P_{cond} = V_{CE} I = (V_T + R_T I) I = V_T I + R_T I^2$$

switching losses IGBT-inverter (typical)

$E_{on} = f(I_C), E_{off} = f(I_C)$

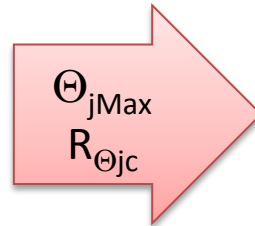
$V_{GE} = \pm 15 \text{ V}, R_{Gon} = 2.7 \ \Omega, R_{Goff} = 4.7 \ \Omega, V_{CE} = 900 \text{ V}$



$$\Rightarrow P_{sw} = f_{sw} E_{on,off} = f_{sw} (A_{on,off} + B_{on,off} I + C_{on,off}^{12} I^2)$$

3-Find Maximum Current per switch for this profile : solve thermal equation

Conduction losses
+
switching losses



$I_{max}(f_{sw})$

Conduction losses + Switching losses = Maximum Power extracted

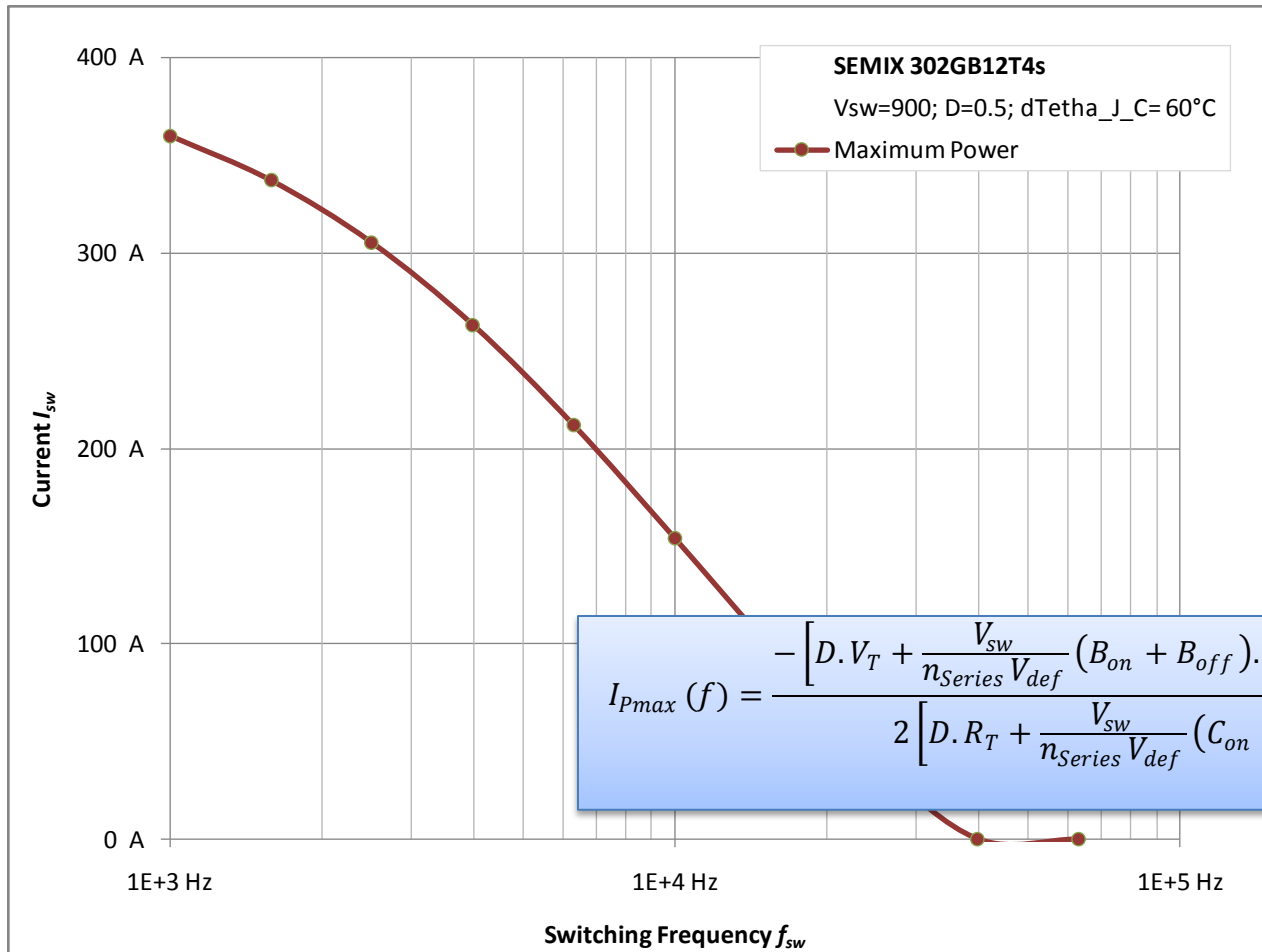
$$D \cdot (R_T \cdot I^2 + V_T \cdot I) + f_{dec} \frac{V_{sw}}{n_{Series} V_{def}} [(A_{on} + A_{off}) + (B_{on} + B_{off}) \cdot I + (C_{on} + C_{off}) \cdot I^2] = \frac{\Delta\theta}{R_{th}}$$

$$\Delta_{Discriminant} = \left[D \cdot V_T + \frac{V_{sw}}{n_{Series} V_{def}} (B_{on} + B_{off}) \cdot f_{dec} \right]^2 - 4 \left[D \cdot R_T + \frac{V_{sw}}{n_{Series} V_{def}} (C_{on} + C_{off}) \cdot f_{dec} \right] \cdot \left[\frac{V_{sw}}{n_{Series} V_{def}} (A_{on} + A_{off}) \cdot f_{dec} - \frac{\Delta\theta}{R_{th}} \right]$$

$$\left[D \cdot R_T + \frac{V_{sw}}{n_{Series} V_{def}} (C_{on} + C_{off}) \cdot f_{dec} \right] \cdot I^2 + \left[D \cdot V_T + \frac{V_{sw}}{n_{Series} V_{def}} (B_{on} + B_{off}) \cdot f_{dec} \right] I + \left[\frac{V_{sw}}{n_{Series} V_{def}} (A_{on} + A_{off}) \cdot f_{dec} - \frac{\Delta\theta}{R_{th}} \right] = 0$$

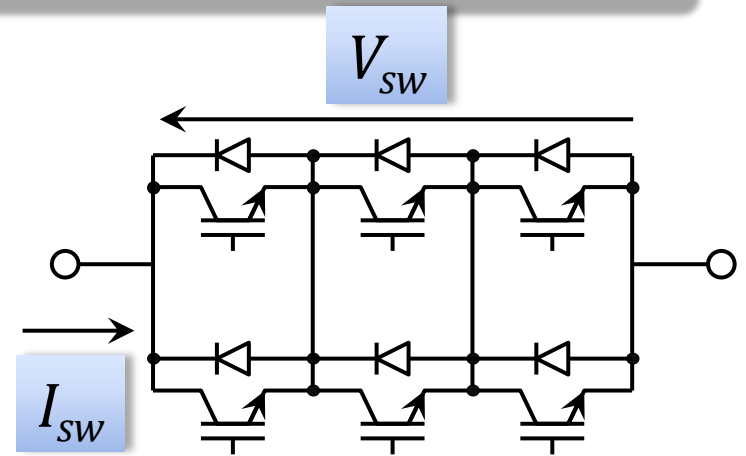
$$I_{Pmax}(f) = \frac{- \left[D \cdot V_T + \frac{V_{sw}}{n_{Series} V_{def}} (B_{on} + B_{off}) \cdot f_{dec} \right] \pm \sqrt{\Delta_{Discriminant}}}{2 \left[D \cdot R_T + \frac{V_{sw}}{n_{Series} V_{def}} (C_{on} + C_{off}) \cdot f_{dec} \right]}$$

Current /frequency operating area of a switch Maximum Power



4-Find number of parallel connected switches

$$n_{Par} = \text{int} \left(\frac{I_{required}}{I_{allowed}^{max}} \right) + 1$$



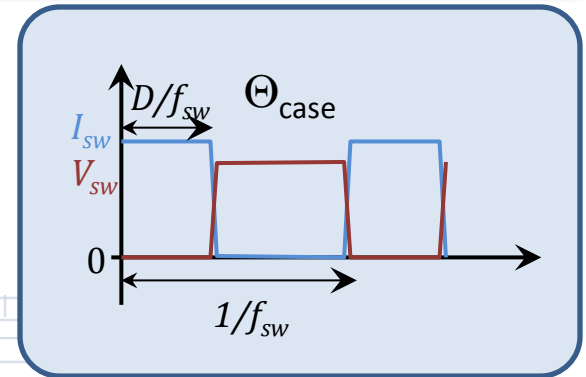
5-Find losses and efficiency

$$Pertes_{composant} = D \cdot \left(R_T \cdot \left(\frac{I}{n_{Par}} \right)^2 + V_T \cdot \frac{I}{n_{Par}} \right) + f_{dec} \frac{V_{sw}}{n_{Series} V_{def}} \left[(A_{on} + A_{off}) + (B_{on} + B_{off}) \cdot \frac{I}{n_{Par}} + (C_{on} + C_{off}) \cdot \left(\frac{I}{n_{Par}} \right)^2 \right]$$

$$Efficiency = 1 - \frac{n_{Series} \cdot n_{Par} \cdot Pertes_{composant}}{P_{out}}$$

6-Build a MacroSwitch with each component of the database

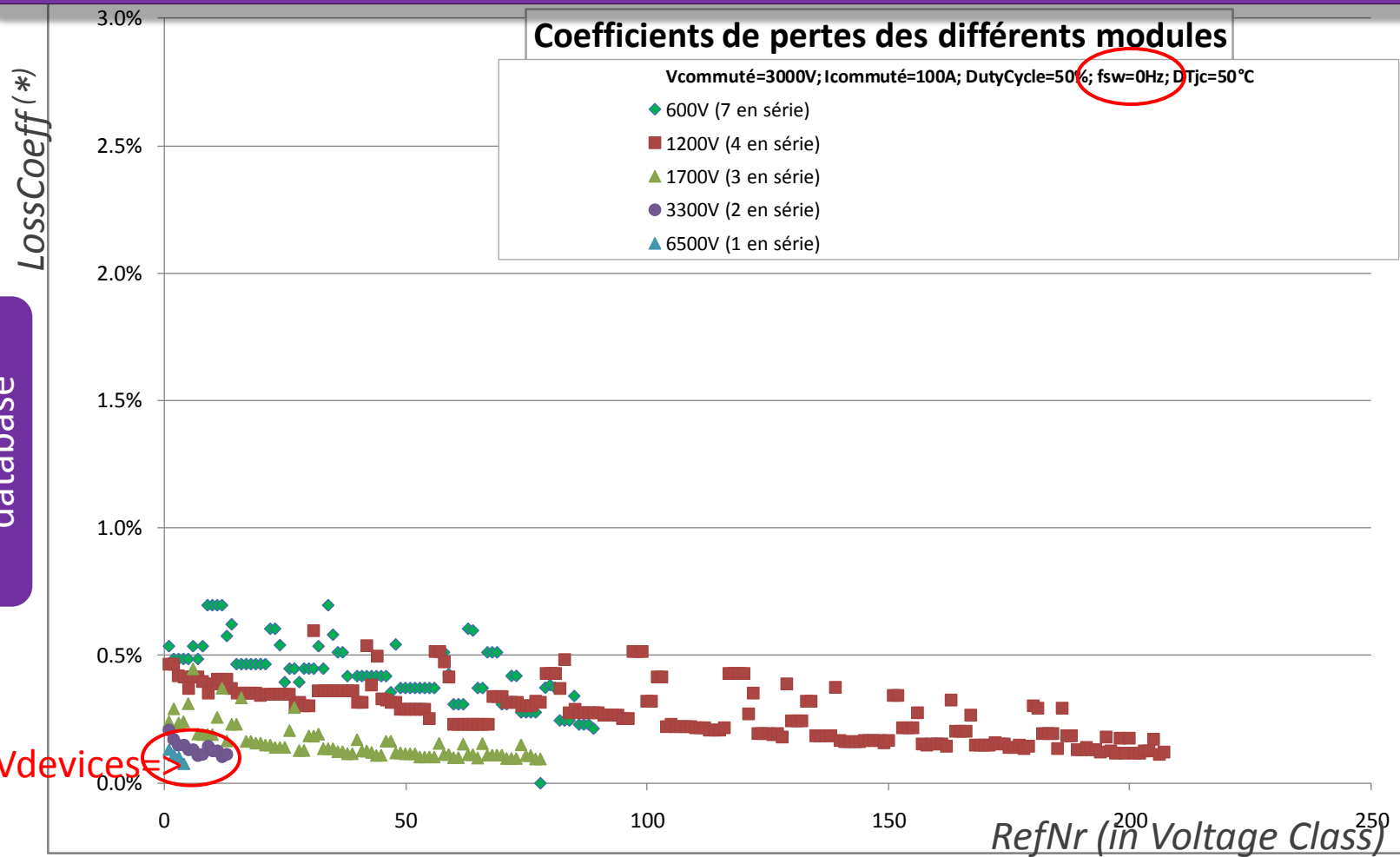
Explore IGBT
database



Paramètres de la forme d'onde		Paramètres de la forme d'onde		Paramètres de la forme d'onde		Paramètres de la forme d'onde		Paramètres de la forme d'onde	
Vsw	Isw	Dsw	fsw	Dtethasw					
3000 V	10 A	50.00%	0 Hz	50 °C					
nSeries_	Isw_adm	nPar_	Pertes	coeffPertes	calibre	tension	(rappel)		
7	11 A	10	806 W	0.54%	500 V				
7	15 A	7	731 W	0.49%	500 V				
7	15 A	7	731 W	0.49%	500 V				
7	16 A	7	731 W	0.49%	500 V				

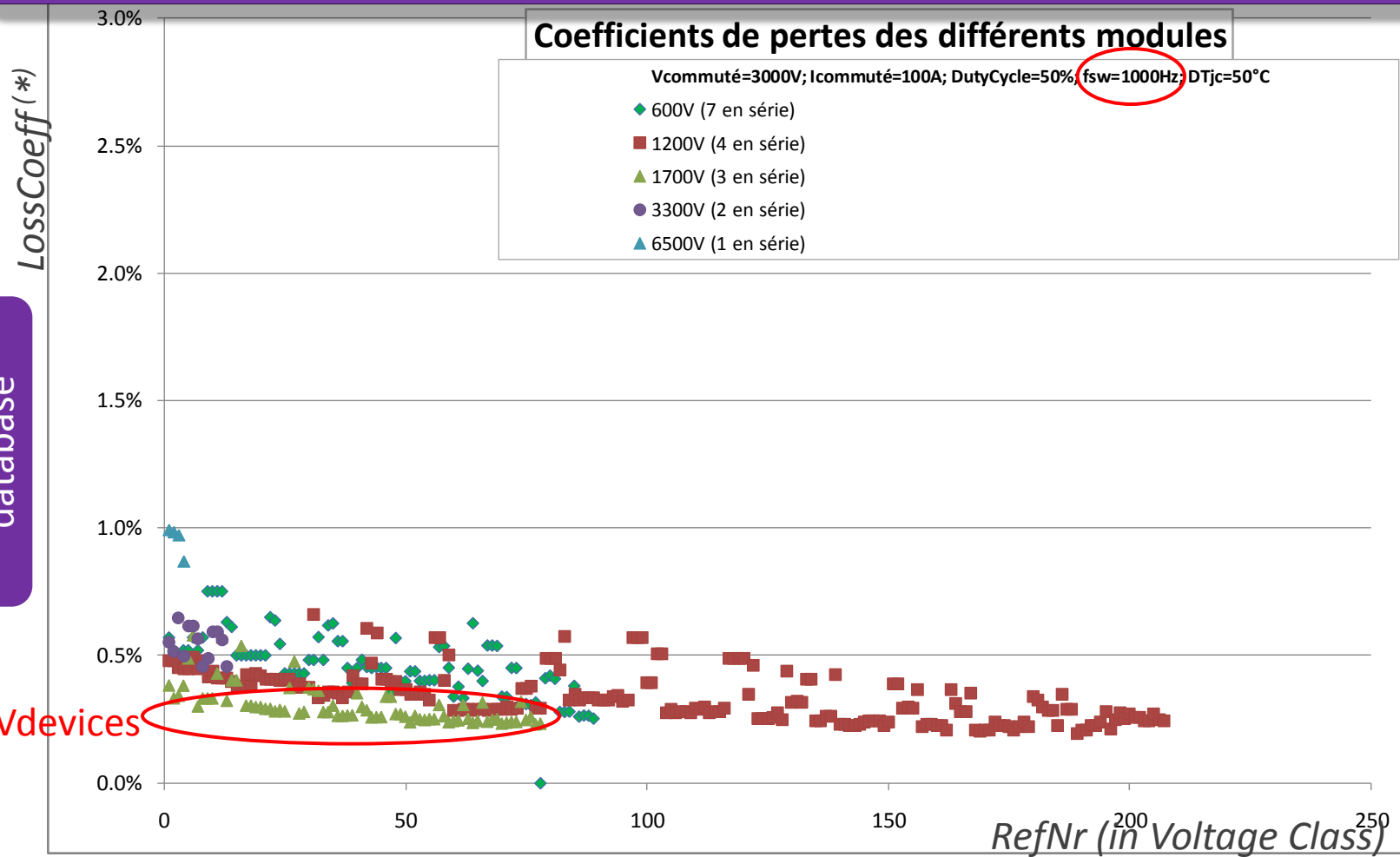
Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT
database



(*) LossCoeff = Loss in one switch / Output Power (Buck converter configuration)

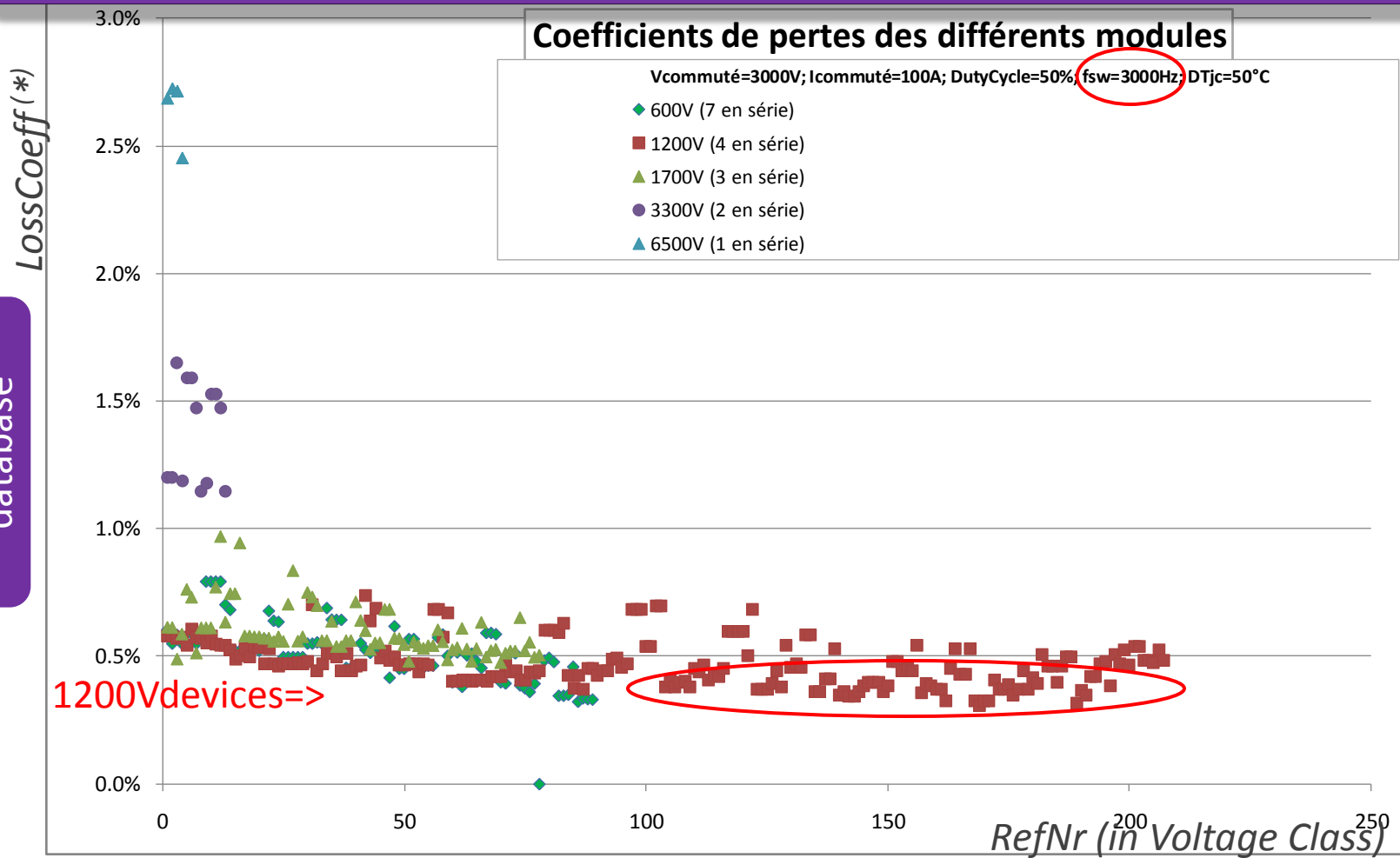
Find the IGBT-based MacroSwitch with the best efficiency



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Find the IGBT-based MacroSwitch with the best efficiency

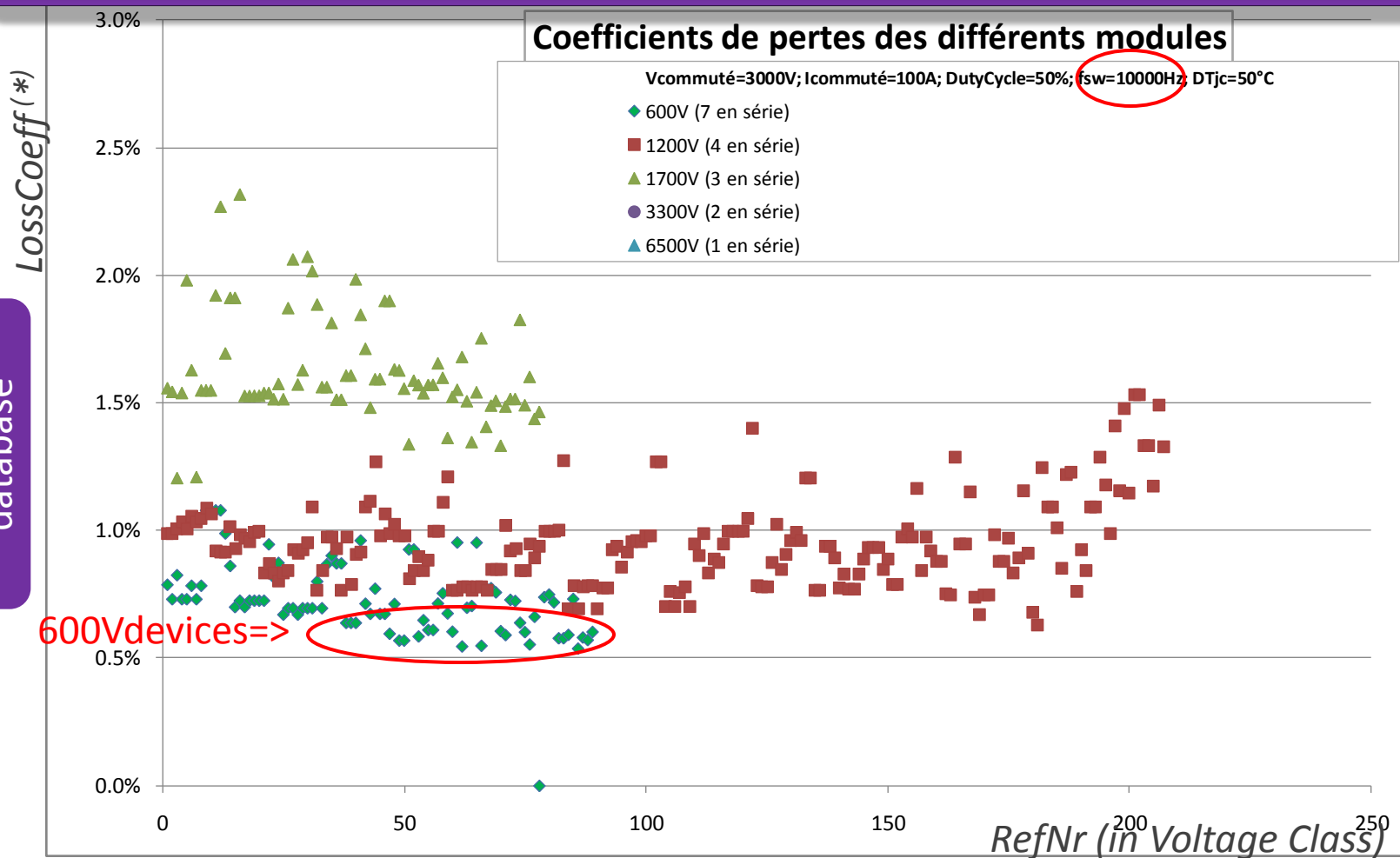
Explore IGBT
database



(*) LossCoeff = Loss in one switch / Output Power (Buck converter configuration)

Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT
database



(*) LossCoeff = Loss in one switch / Output Power (Buck converter configuration)

EXTENSION OF THE METHOD FOR VOLTAGE SOURCE INVERTERS WITH COMPLEX CONTROL PATTERNS

Rules of the game

Split the system in :

- a modulation/topology dependant subsystem,
- and a device specific subsystem.

$$P_{cond} = \frac{1}{T} \int_0^T v \cdot i \cdot dt = \frac{1}{T} \int_0^T (V_T + R_T i) \cdot i \cdot dt = V_T \left(\frac{1}{T} \int_0^T i \cdot dt \right) + R_T \cdot \left(\frac{1}{T} \int_0^T i^2 \cdot dt \right) = V_T \cdot i_{avg} + R_T \cdot i_{RMS}^2$$

$$P_{switching} = f_{mod} \cdot \left(\sum_{OFF \Rightarrow ON} \frac{V_{cell}}{V_{def}} (A_{on} + B_{on} \cdot I_{cell} + C_{on} \cdot I_{cell}^2) + \sum_{ON \Rightarrow OFF} \frac{V_{cell}}{V_{def}} (A_{off} + B_{off} \cdot I_{cell} + C_{off} \cdot I_{cell}^2) \right)$$

$$P_{switching} = \frac{f_{mod}}{V_{def}} \cdot \left(A_{on} \sum_{OFF \Rightarrow ON} V_{cell_{on}} + B_{on} \sum_{OFF \Rightarrow ON} V_{cell_{on}} \cdot I_{cell_{on}} + C_{on} \sum_{OFF \Rightarrow ON} V_{cell_{on}} \cdot I_{cell_{on}}^2 + A_{off} \sum_{ON \Rightarrow OFF} V_{cell_{off}} + B_{off} \sum_{ON \Rightarrow OFF} V_{cell_{off}} \cdot I_{cell_{off}} + C_{off} \sum_{ON \Rightarrow OFF} V_{cell_{off}} \cdot I_{cell_{off}}^2 \right)$$

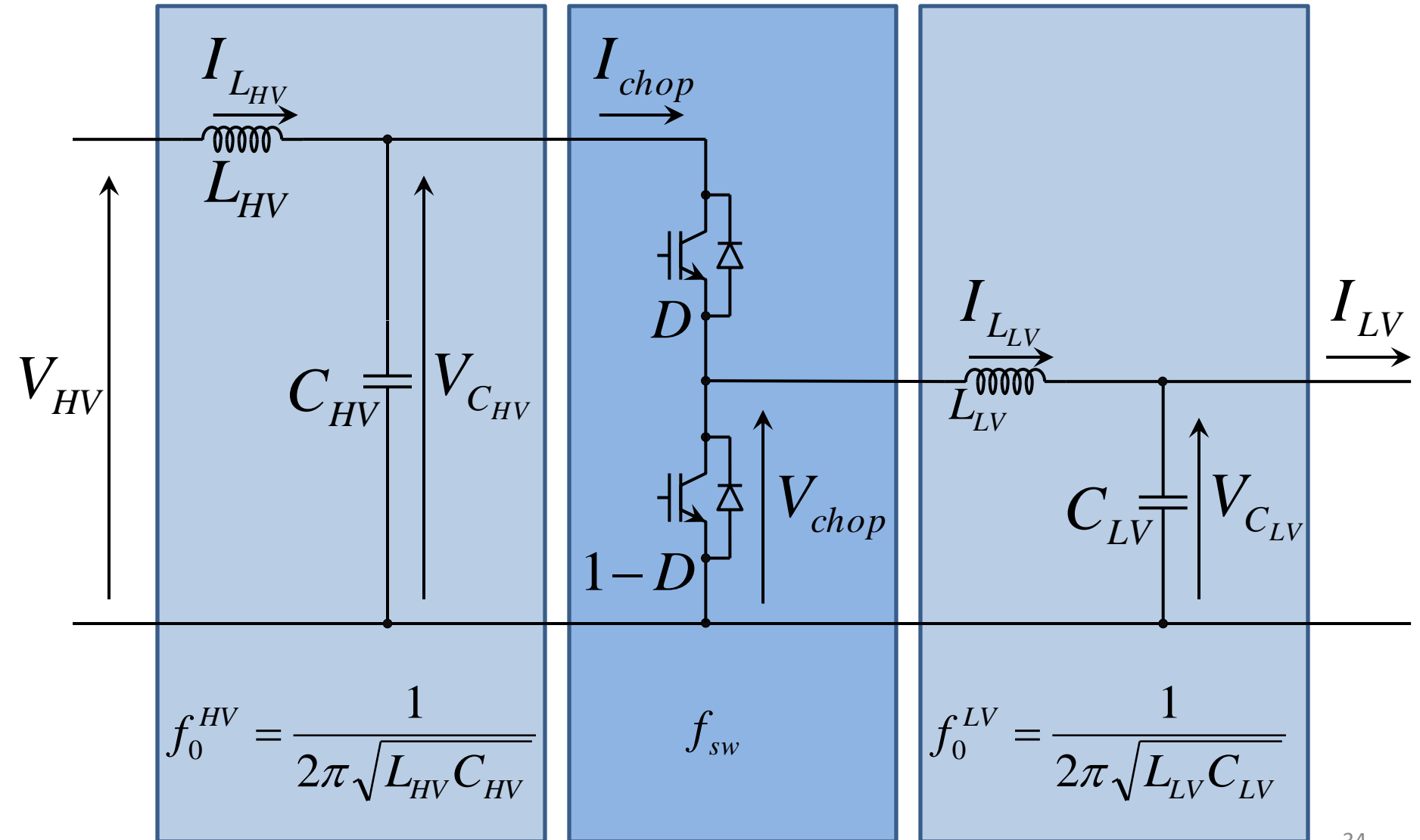
PASSIVE COMPONENTS FOR MULTILEVEL CONVERTERS

Rules of the game

- Establish design criteria for filters and specific/internal components
- Apply them to all configuration
- Compare stored energy
- Evaluate converter size or cost based on a combined lost/stored energy criterion

FILTER DESIGN FOR MULTILEVEL CONVERTERS

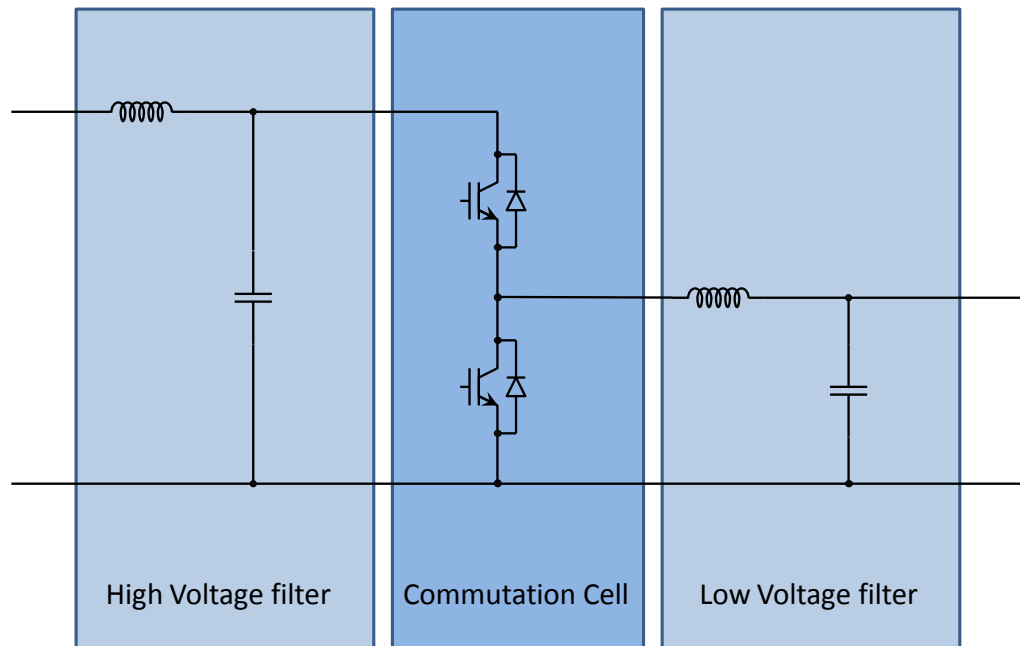
Commutation Cell with Filters



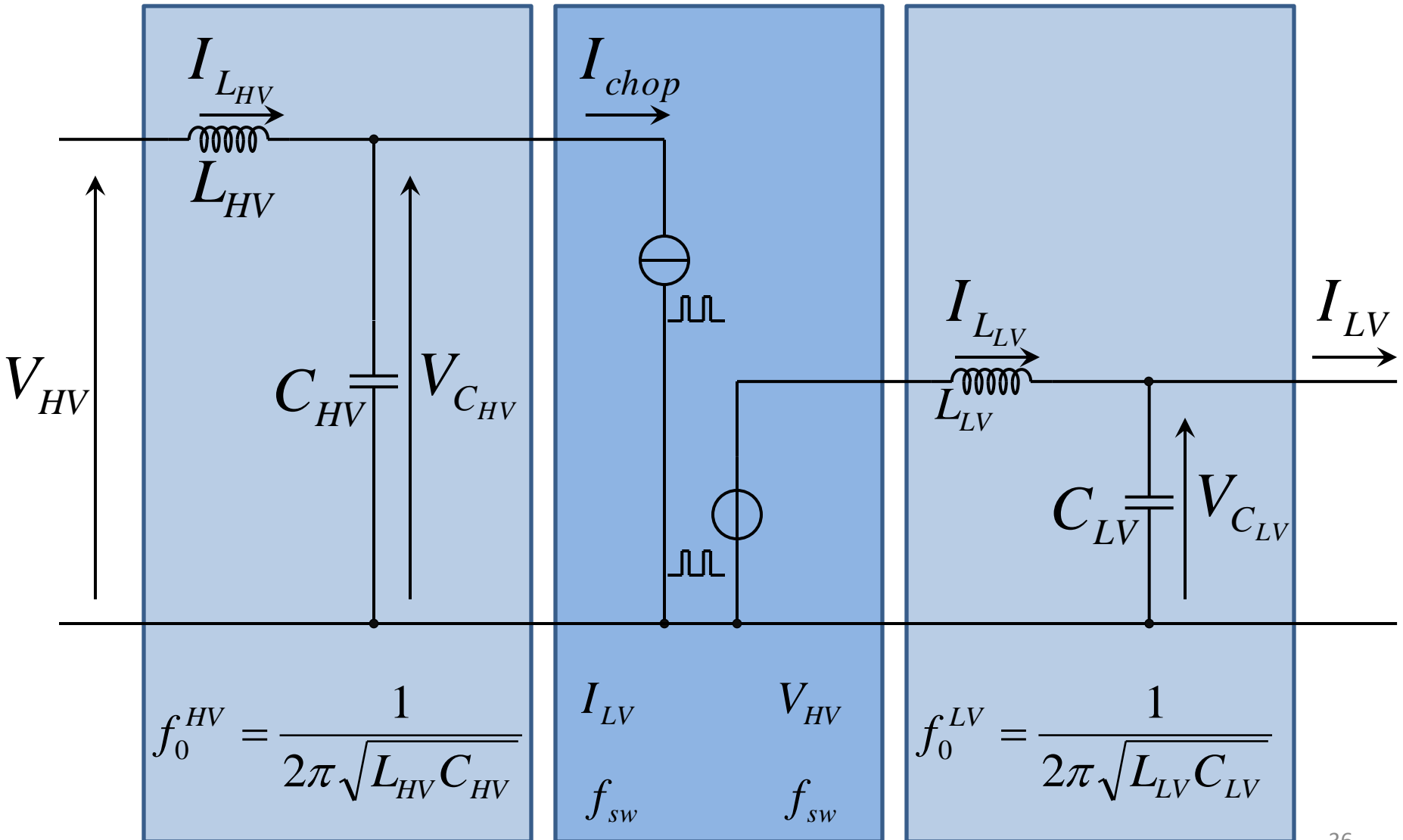
One (of the many) approach of filter design

Different functions of passive components

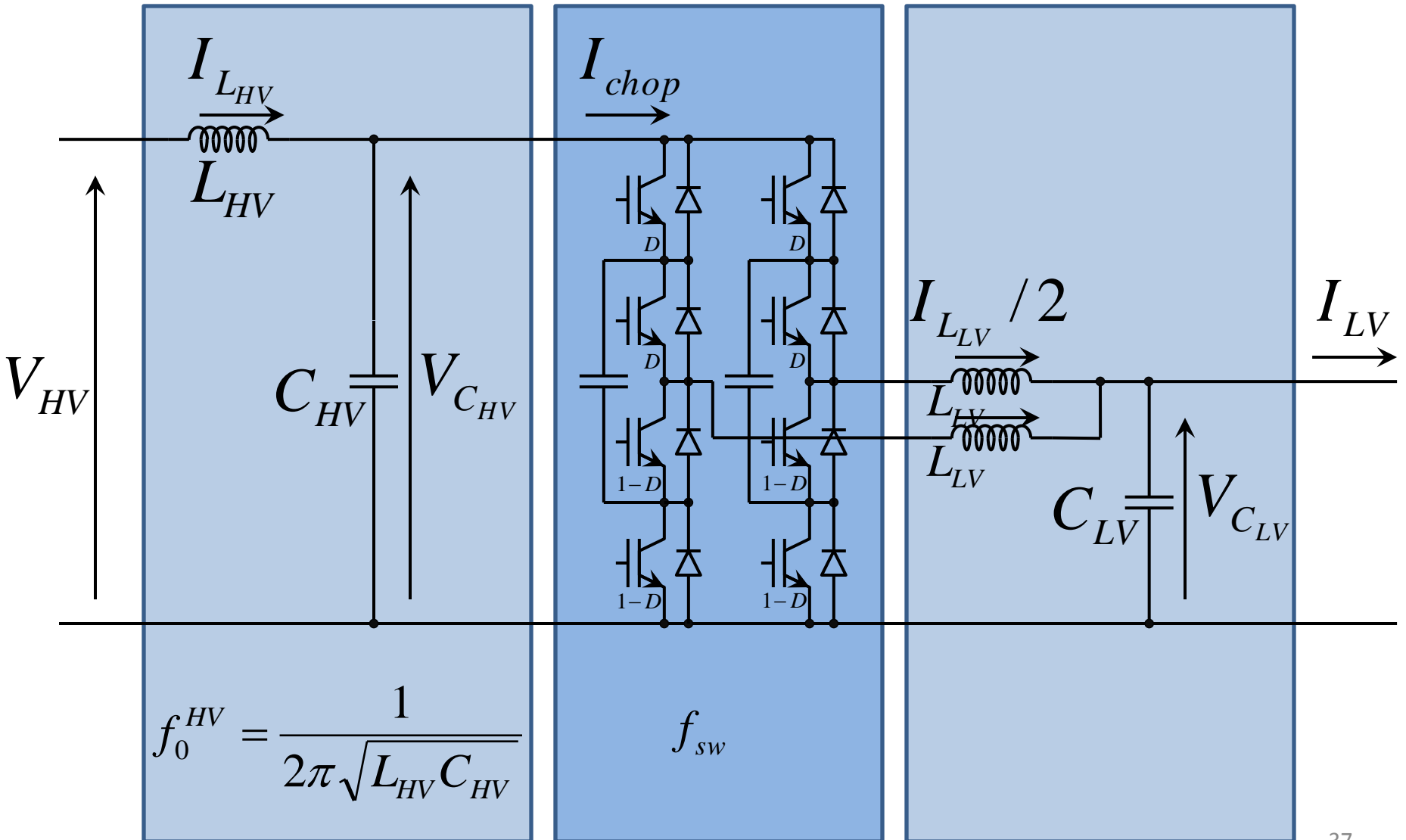
- Limit the impact of the converter on the external world :
=> limit the ripples of current on HV side and voltage on the LV side (Steady-state)
- Limit the impact of the external world on the converter :
=> limit HV and LV variations induced by load steps (Transient response)
- Limit the impact of the converter on itself :
=> limit the ripples of current ripple and and HV voltage ripple (Steady-state)



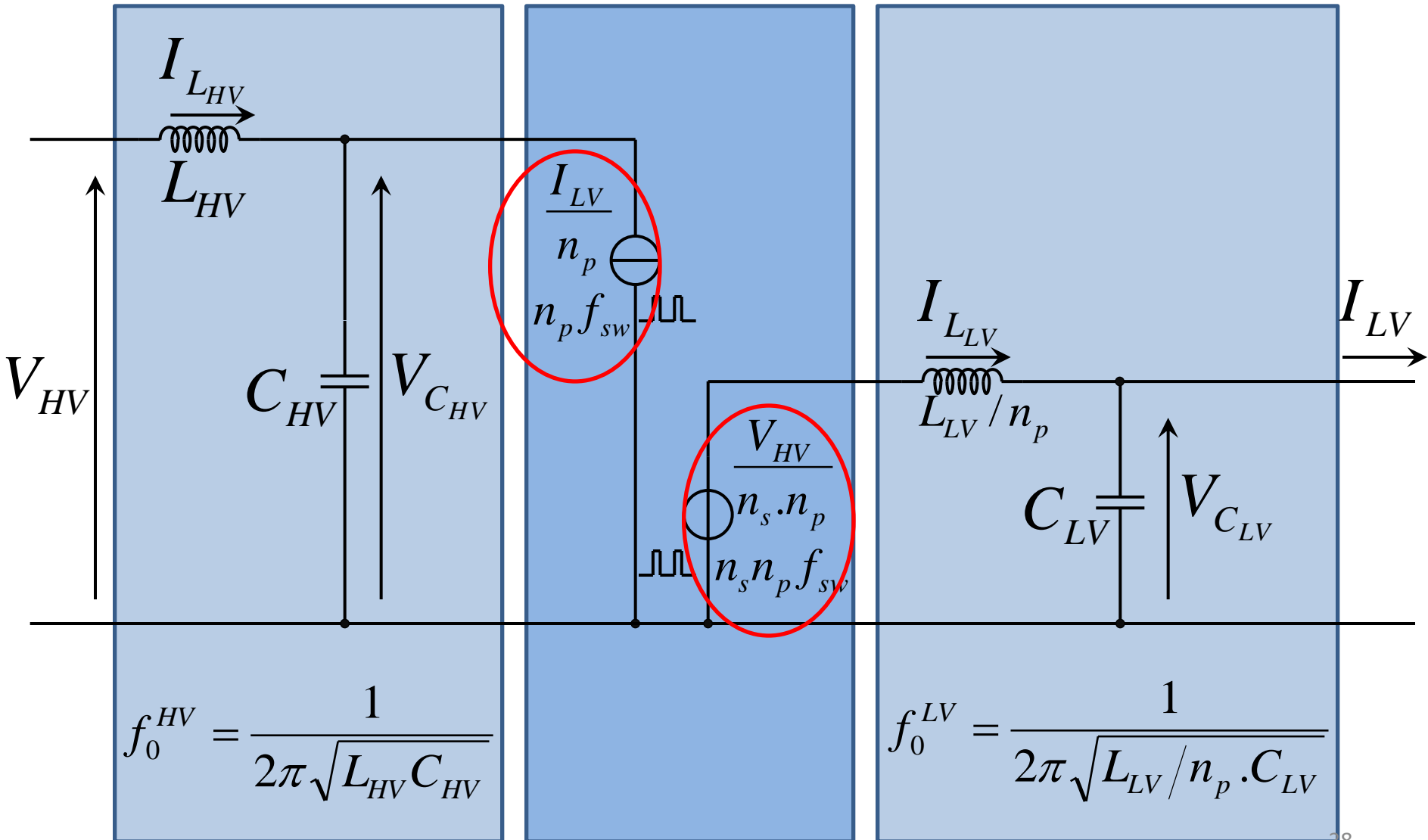
AC Equivalent circuit of a Two-Level Cell



Series-Parallel MultiLevel Cell with Filters



AC-equivalent circuit of Series-Parallel MultiLevel Cell



Steady state, time domain : worst case ripples

Pulsation on the Low Voltage side (2nd order filter)

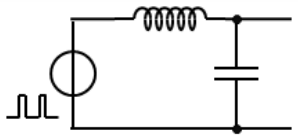
$$\left. \begin{aligned}
 V_{\text{ripple}\%}^{LV} &= \frac{V_{\text{pk-ripple}}^{LV}}{V_{HV}} = \frac{2}{\pi} \frac{1}{n_p n_s} \left(\frac{f_0^{LV}}{n_p n_s f_{sw}} \right)^2 \\
 f_0^{LV} &= \frac{1}{2\pi \sqrt{L_{LV}/n_p \cdot C_{LV}}}
 \end{aligned} \right\} \Rightarrow \sqrt{L_{LV}/n_p \cdot C_{LV}} = \frac{1}{2\pi (n_p n_s)^{1.5} f_{sw} \sqrt{\frac{\pi}{2} V_{\text{ripple}\%}^{LV}}}$$

Pulsation on the High Voltage side (2nd order filter)

$$\left. \begin{aligned}
 I_{\text{ripple}\%}^{HV} &= \frac{I_{\text{pk-ripple}}^{HV}}{I_{LV_{\max}}} = \frac{2}{\pi} \frac{1}{n_p} \left(\frac{f_0^{HV}}{n_p f_{sw}} \right)^2 \\
 f_0^{HV} &= \frac{1}{2\pi \sqrt{L_{HV} \cdot C_{HV}}}
 \end{aligned} \right\} \Rightarrow \sqrt{L_{HV} \cdot C_{HV}} = \frac{1}{2\pi \cdot n_p^{1.5} f_{sw} \sqrt{\frac{\pi}{2} I_{\text{ripple}\%}^{HV}}}$$

Ripples : from time domain to frequency domain

$$A_n = \frac{2V_{HV}}{n\pi} \sin(n.\pi.D)$$

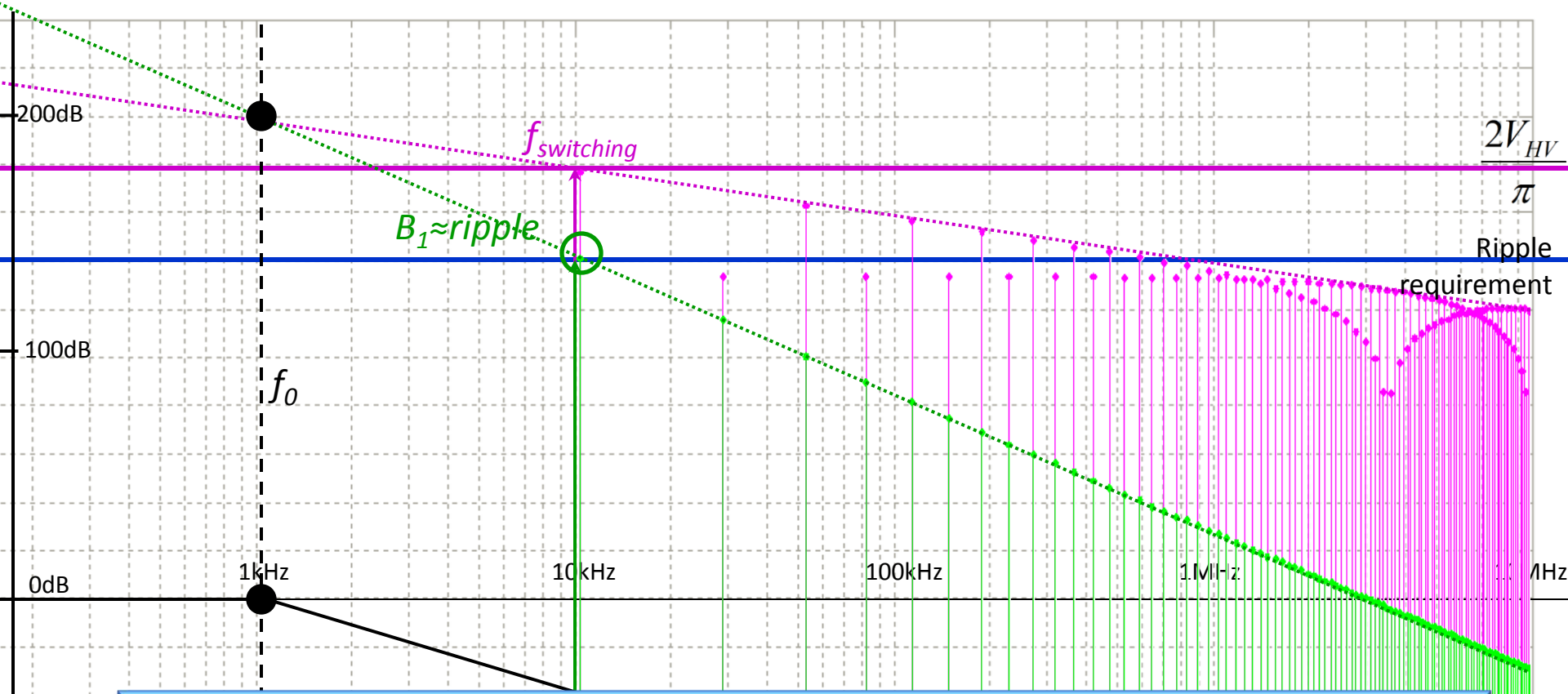


$$B_n = \left(\frac{f_0}{f_{sw}}\right)^2 \frac{2V_{HV}}{n^3\pi} \sin(n.\pi.D)$$

-20dB/dcd

+ -40dB/dcd

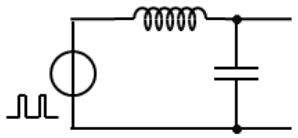
= -60dB/dcd



=>Conclusion : the ripple requirement allows increasing f_0 when increasing $f_{switching}$

EMC standards : frequency domain formulation

$$A_n = \frac{2V_{HV}}{n\pi} \sin(n.\pi.D)$$

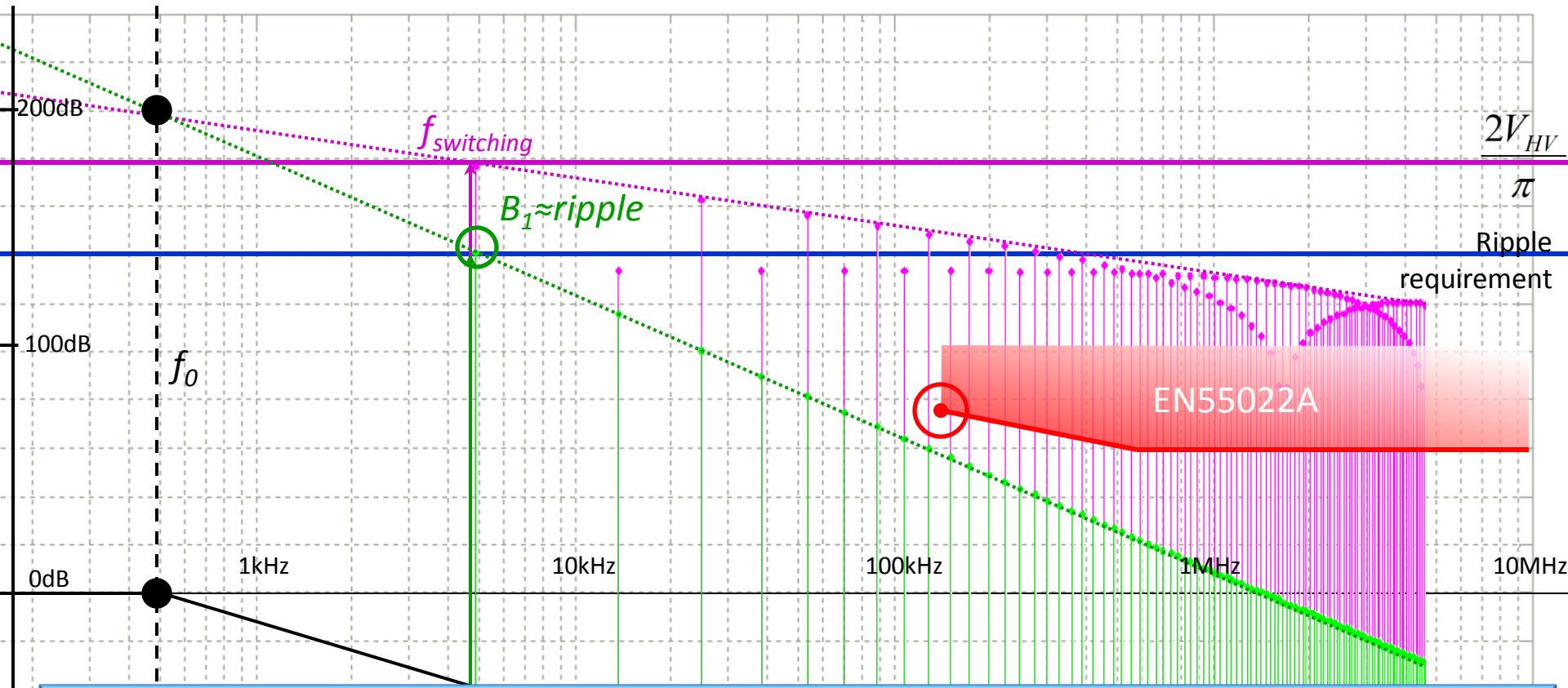


$$B_n = \left(\frac{f_0}{f_{sw}}\right)^2 \frac{2V_{HV}}{n^3\pi} \sin(n.\pi.D)$$

-20dB/dcd

+ -40dB/dcd

= -60dB/dcd

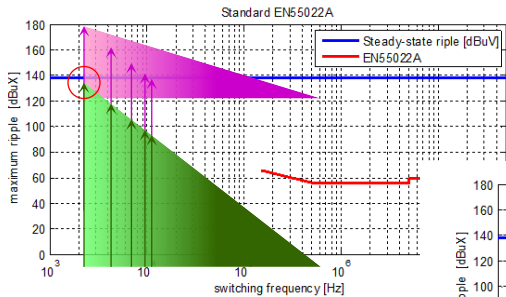
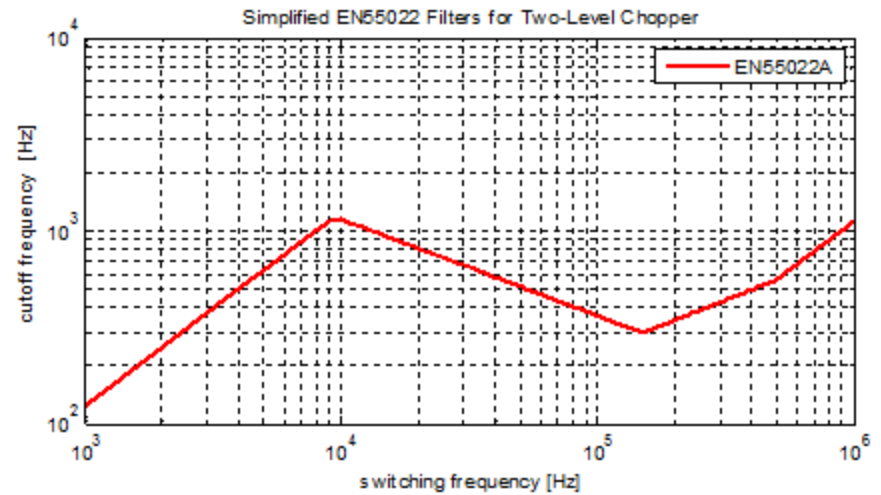
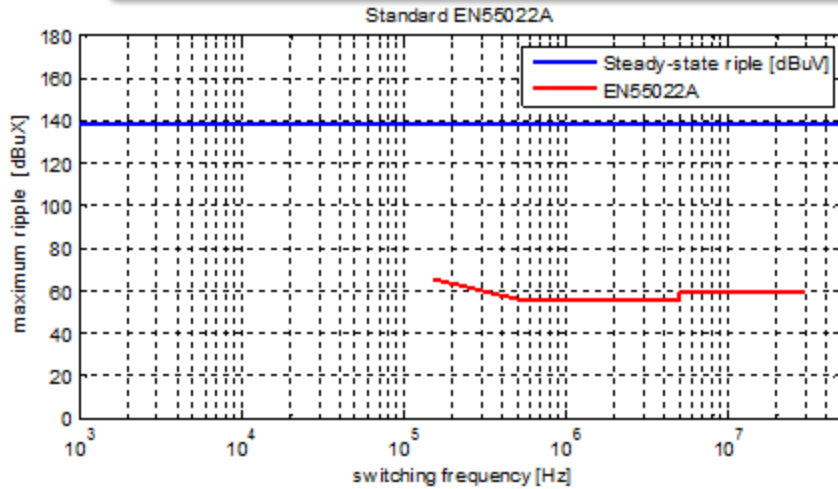


=>Conclusion : salient point of EMC standards imposes decreasing f_0 when increasing $f_{switching}$

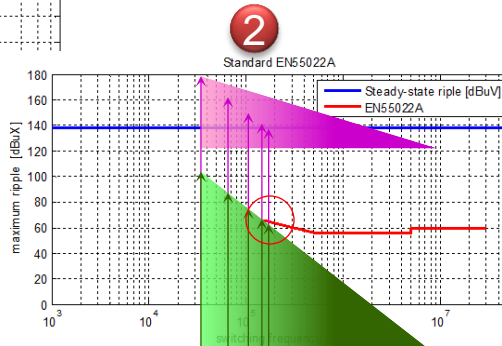
Req #1 + #2

Steady state : ripples and standards combined

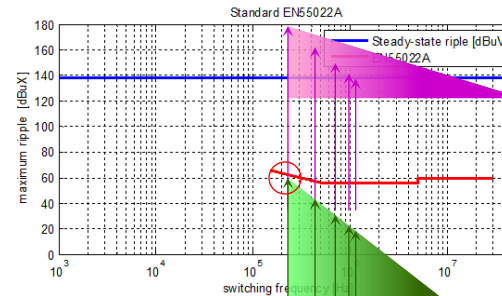
Required cut-off frequency vs switching frequency



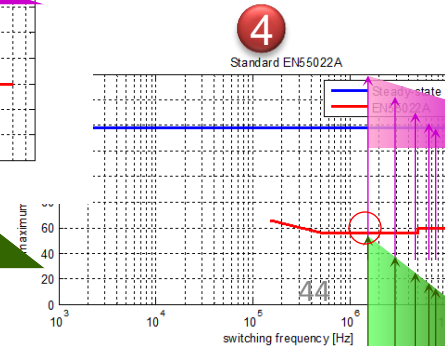
1



2



3

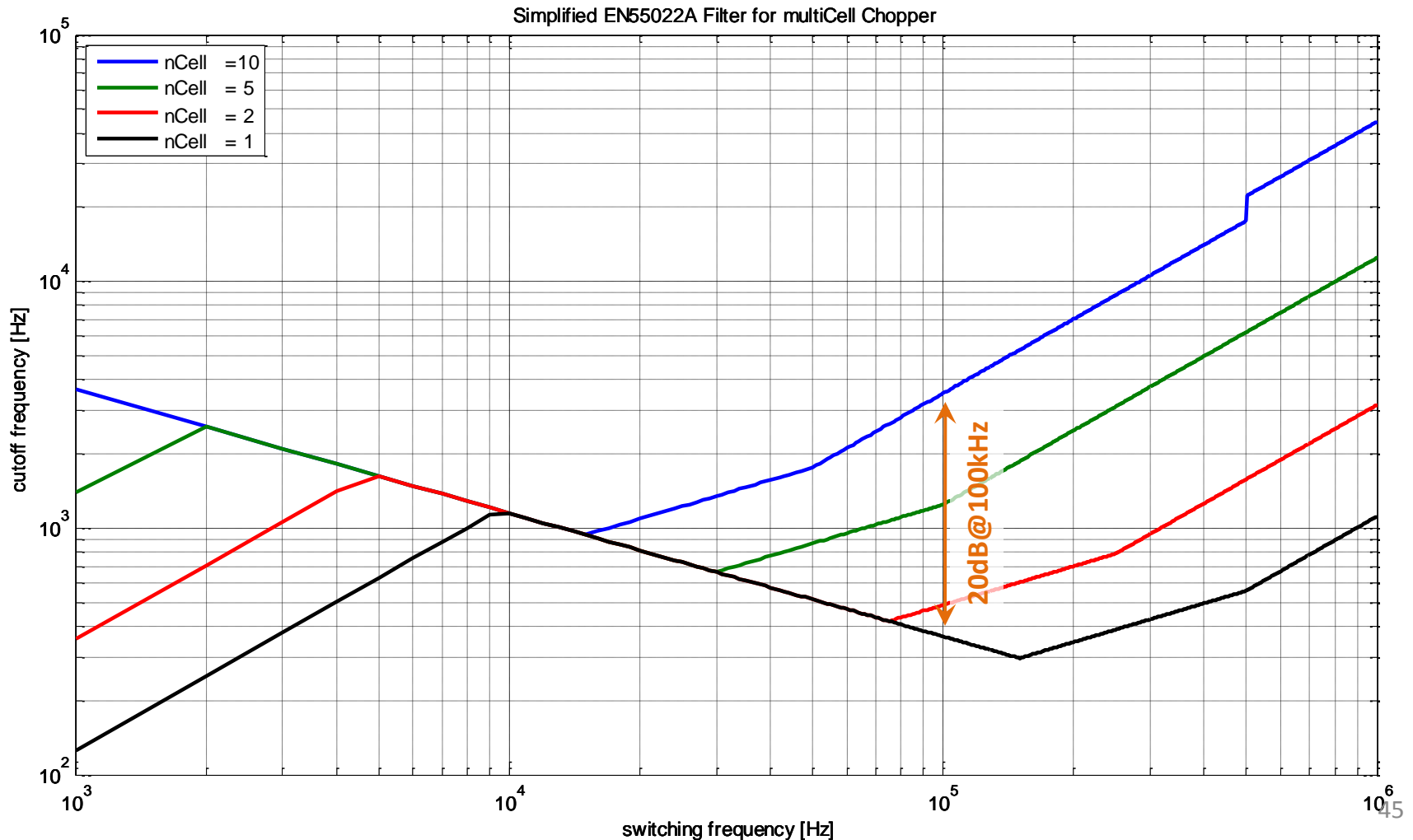


4

Req
#1 + #2

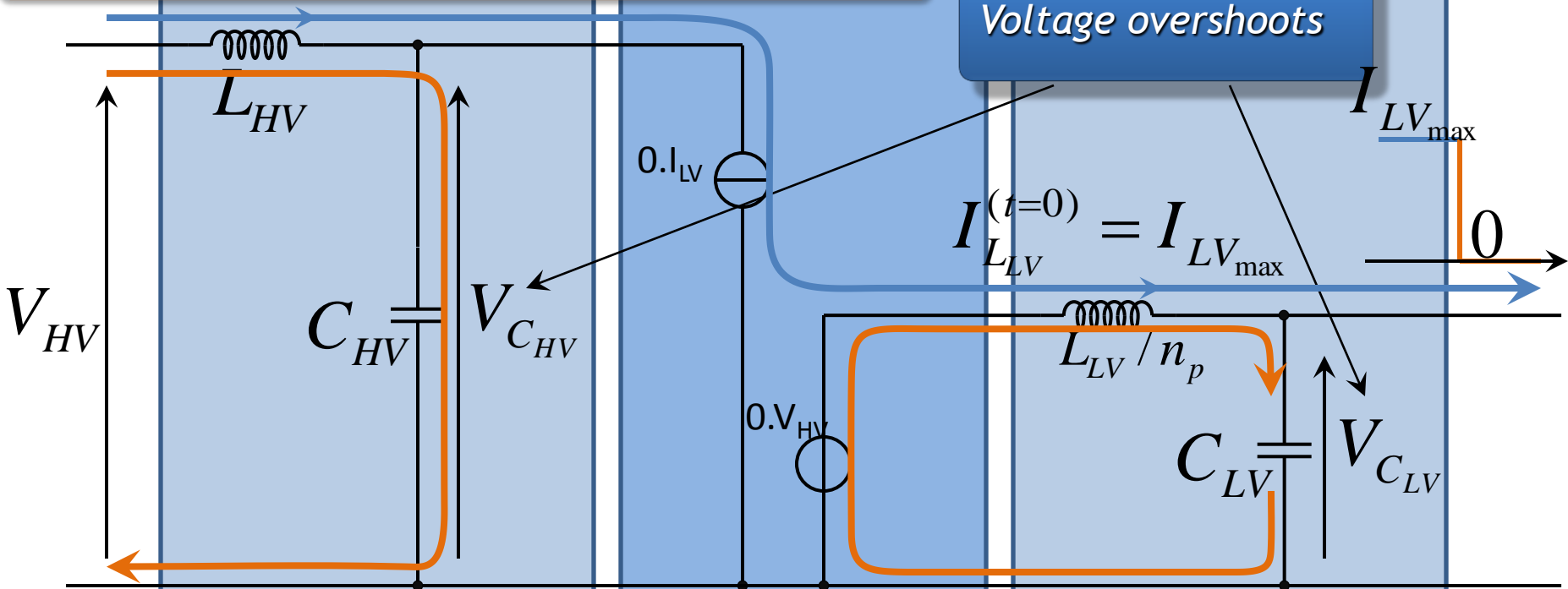
Steady state : ripples and standards combined

Required cut-off frequency vs switching frequency for MultiCell converters



Step response, average model : full load => no load

Worst Case : $D = 100\%$; $I_{L_{HV}}^{(t=0)} = I_{LV_{max}}$

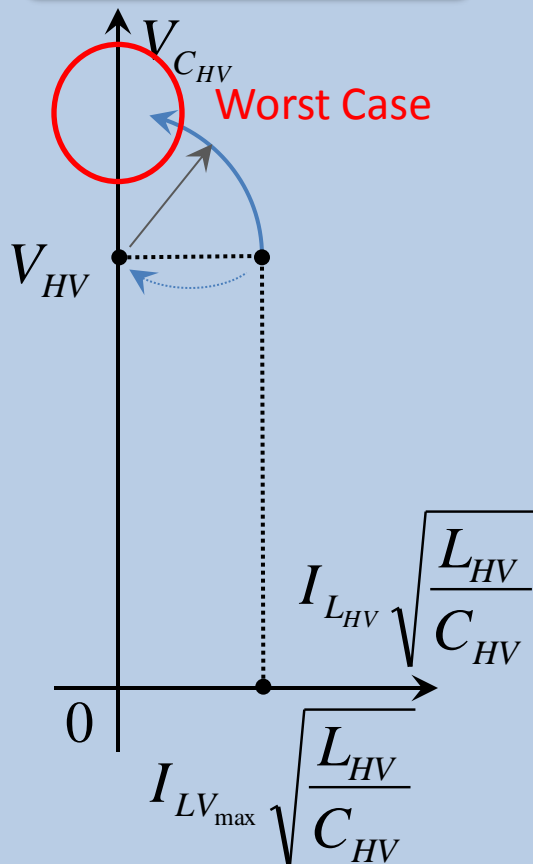


Best response of the control to limit overshoot on LV side : impose $D=0$

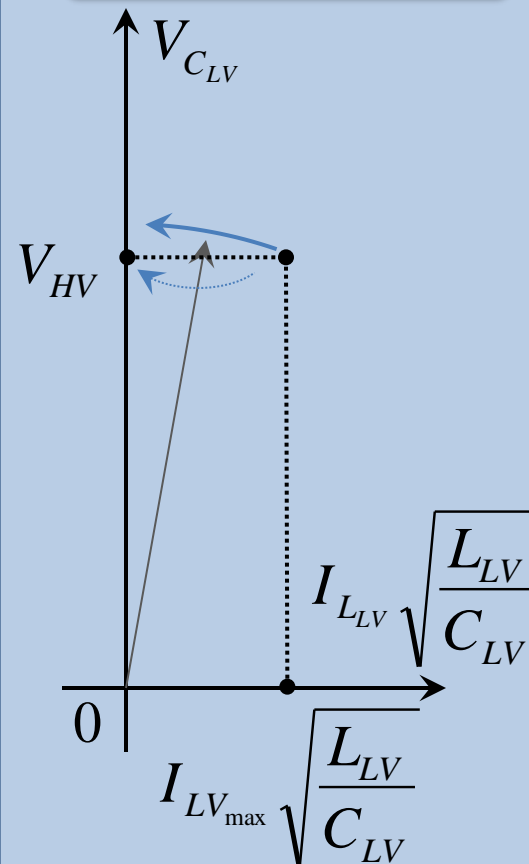
Step response, state plane analysis

full load => no load

High Voltage Side



Low Voltage Side



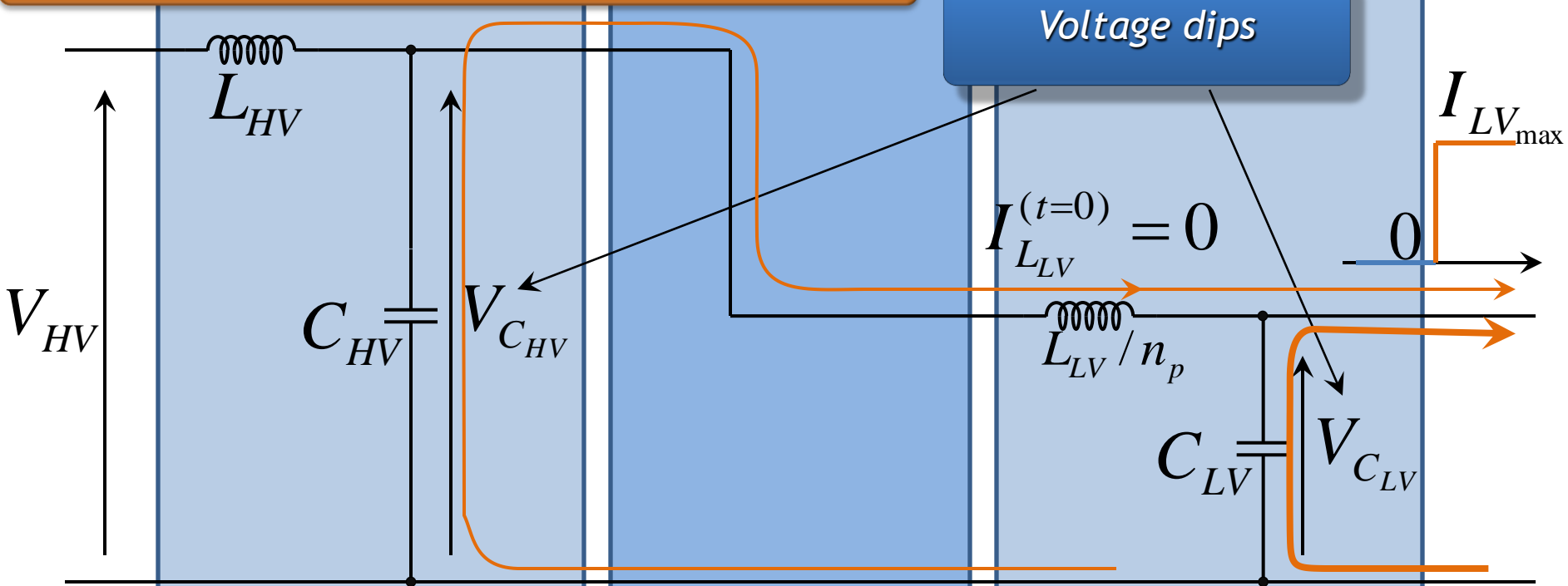
Full load => no load : dynamic requirement HV side

Limit the voltage overshoot on the High Voltage Side

$$V_{ovrsh\%}^{HV} = \frac{I_{LV} \cdot \sqrt{\frac{L_{HV}}{C_{HV}}}}{V_{HV}} \dots \Rightarrow \dots \sqrt{\frac{L_{HV}}{C_{HV}}} = \frac{V_{HV} \cdot V_{ovrsh\%}^{HV}}{I_{LV\max}}$$

Step response, average model : no load => full load

Worst Case : $D = 100\%$; $I_{L_{HV}}^{(t=0)} = 0$

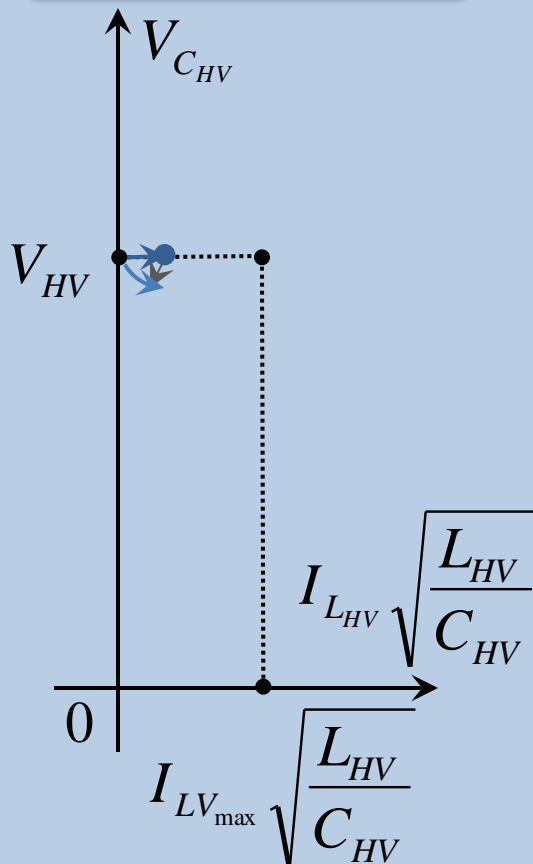


**Best response of the control to limit
voltage dip on LV side : maintain $D=100\%$**

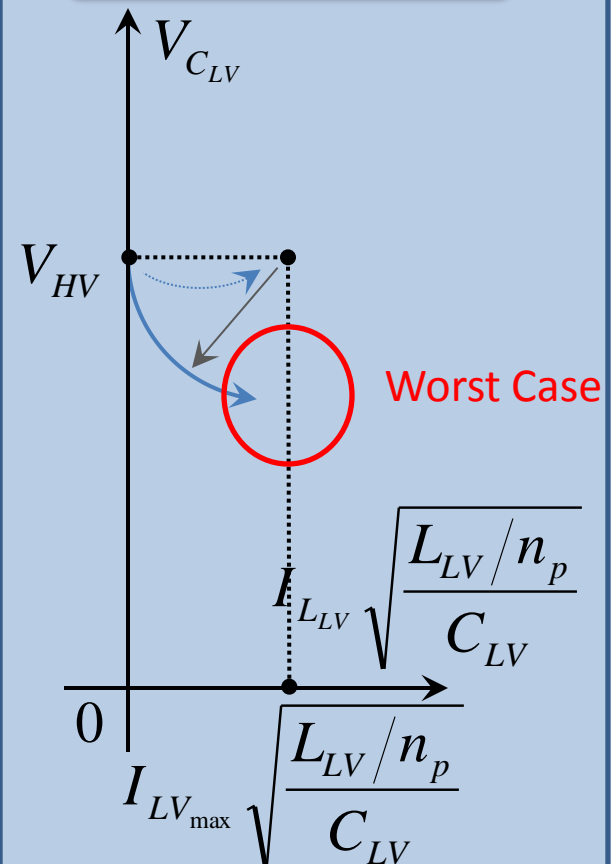
Step response, state plane analysis

no load => full load

High Voltage Side



Low Voltage Side



No load => Full load : dynamic requirement LV side

Limit the voltage dip on the Low Voltage Side

$$V_{dip}^{LV} = \frac{I_{LV} \cdot \sqrt{\frac{L_{LV}}{n_p C_{LV}}}}{V_{HV}} \dots \Rightarrow \dots \sqrt{\frac{L_{LV}/n_p}{C_{LV}}} = \frac{V_{HV} \cdot V_{dip}^{LV}}{I_{LV_{max}}}$$

Calculation of the components

High Voltage side

$$\left\{ \begin{array}{l} n_{Cell} = n_p \\ Rip_{\%} = I_{ripple}^{HV} \% = \frac{I_{pk-ripple}^{HV}}{I_{LV_{max}}} \\ f_0 = \frac{1}{2\pi\sqrt{L_{HV} \cdot C_{HV}}} \end{array} \right.$$



Low Voltage side

$$\left\{ \begin{array}{l} n_{Cell} = n_p \cdot n_s \\ Rip_{\%} = V_{ripple}^{LV} \% = \frac{V_{pk-ripple}^{LV}}{V_{HV}} \\ f_0 = \frac{1}{2\pi\sqrt{L_{LV}/n_p \cdot C_{LV}}} \end{array} \right.$$



$$f_0 = \min \left(n_{Cell}^{1.5} f_{sw} \sqrt{\frac{\pi}{2} Rip_{\%}} ; \sqrt{gab(\max(f_{salient}, n_{Cell} \cdot f_{sw})) \frac{\pi \cdot \max(f_{salient}, n_{Cell} \cdot f_{sw})^3}{2V_{HV} \cdot f_{sw}}} \right)$$

Calculation of the components

High Voltage side

$$\begin{cases} \sqrt{\frac{L_{HV}}{C_{HV}}} = \frac{V_{HV} \cdot V_{ovrsh\%}^{HV}}{I_{LV_{max}}} \\ \sqrt{L_{HV} \cdot C_{HV}} = \frac{1}{2\pi \cdot f_0^{HV}} \end{cases}$$

$$\Rightarrow \begin{cases} L_{HV} = \frac{V_{HV} \cdot V_{ovrsh\%}^{HV}}{2\pi \cdot f_0^{HV} I_{LV_{max}}} \\ C_{HV} = \frac{I_{LV_{max}}}{2\pi \cdot f_0^{HV} V_{HV} \cdot V_{ovrsh\%}^{HV}} \end{cases}$$

Low Voltage side

$$\begin{cases} \sqrt{\frac{L_{LV}/n_p}{C_{LV}}} = \frac{V_{HV} \cdot V_{dip\%}^{LV}}{I_{LV_{max}}} \\ \sqrt{L_{LV}/n_p \cdot C_{LV}} = \frac{1}{2\pi \cdot f_0^{LV}} \end{cases}$$

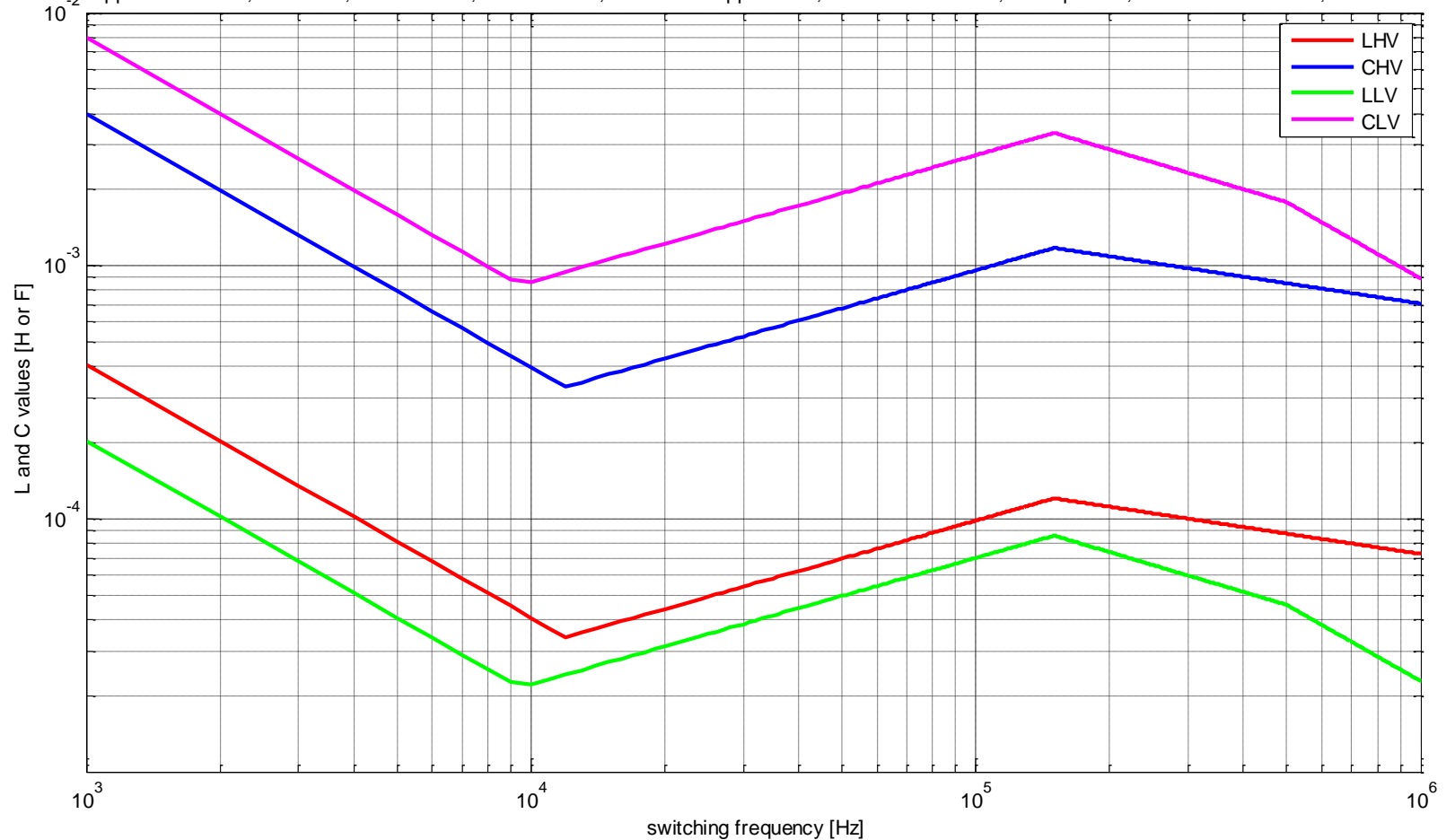
$$\Rightarrow \begin{cases} L_{LV}/n_p = \frac{V_{HV} \cdot V_{dip\%}^{LV}}{2\pi \cdot f_0^{LV} I_{LV_{max}}} \\ C_{LV} = \frac{I_{LV_{max}}}{2\pi \cdot f_0^{LV} V_{HV} \cdot V_{dip\%}^{LV}} \end{cases}$$

Calculation of the components

Example #1 : 2-level converter

=> from 10 to 150kHz, the tendency is an *increase* of passive components

MultiCell Chopper with: nS=1; VHV=800; ILVmax=250; IHVmax=125; relativeOutRipple=0.01; VHVovershoot=0.1; VLVDip=0.05; standardHV=HVDC; standardLV=EN55022A



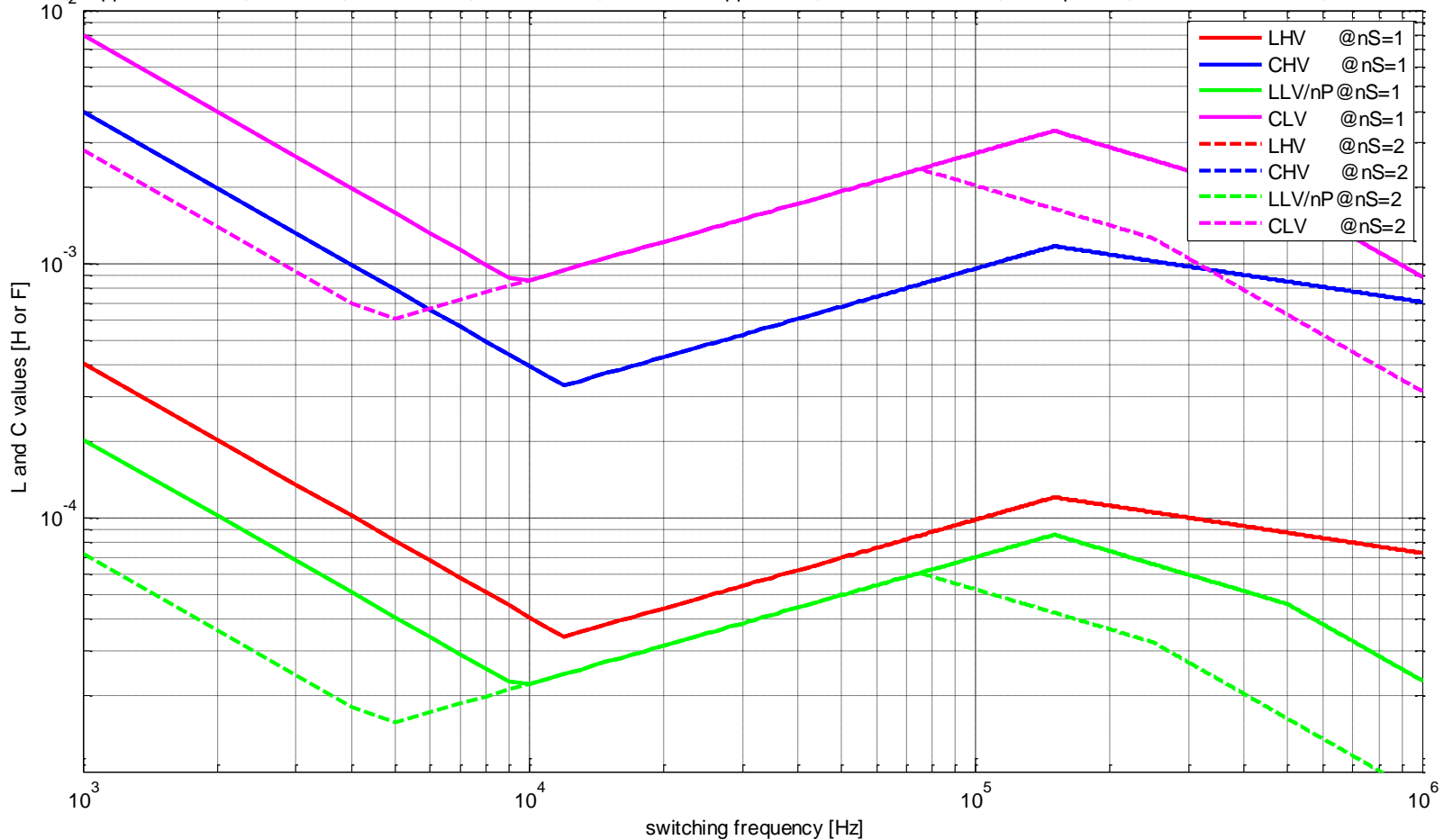
Req
#1 + #2 + #3

Calculation of the components

Example #2 : series 2-cell converter

=> the HV filter is unchanged, L_{LV} and C_{LV} are reduced if $f_{sw} > 80\text{kHz}$

MultiCell Chopper with: nS=2; VHV=800; ILVmax=250; IHVmax=125; relativeOutRipple=0.01; VHVovershoot=0.1; VLVdip=0.05; standardHV=HVDC; standardLV=EN55022A

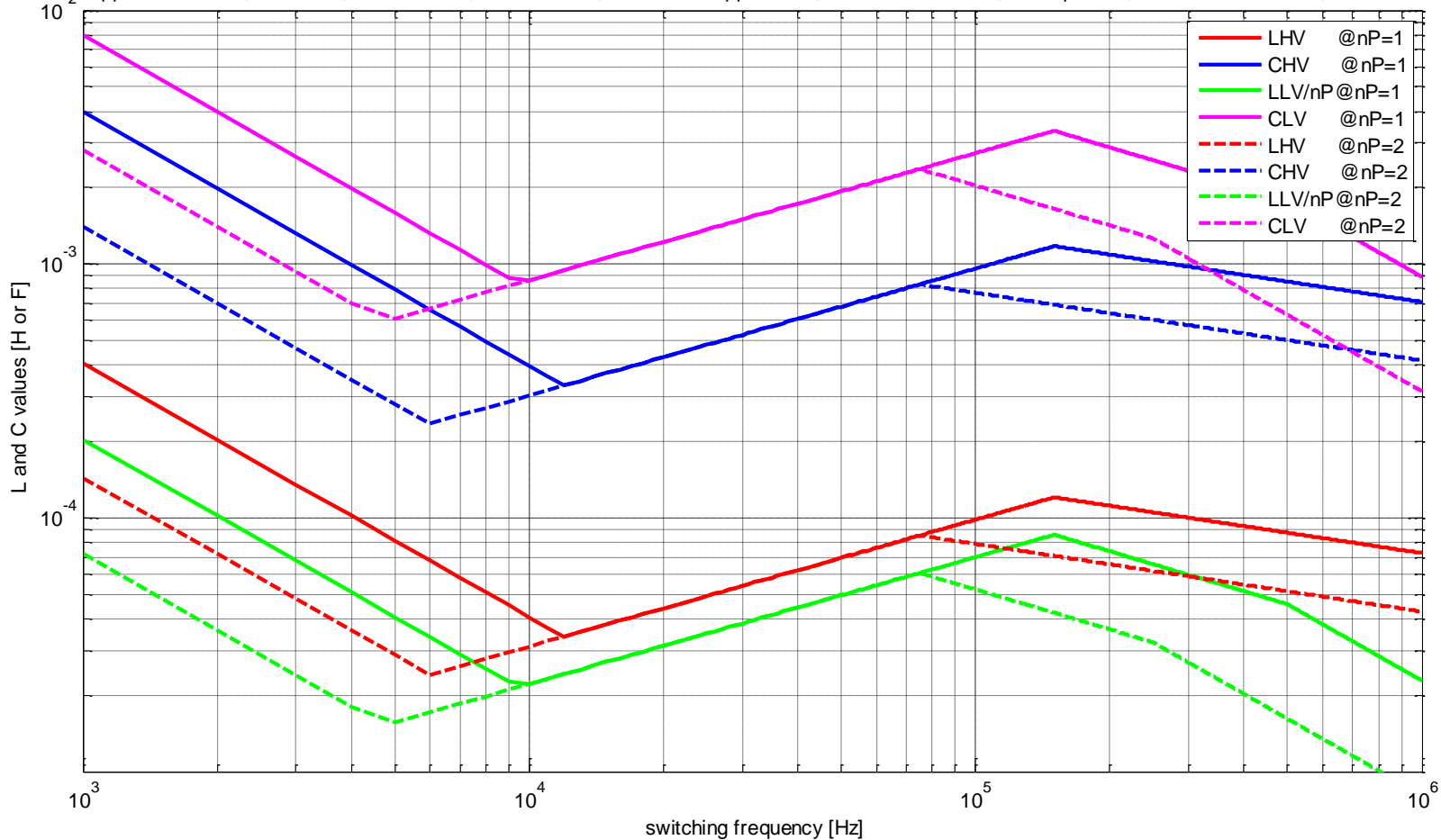


Calculation of the components

Example #3 : parallel 2-cell converter

=> all passive components are reduced if $f_{sw} > 80\text{kHz}$

MultiCell Chopper with: nS=1; VHV=800; ILVmax=250; IHVmax=125; relativeOutRipple=0.01; VHVovershoot=0.1; VLVdip=0.05; standardHV=HVDC; standardLV=EN55022A



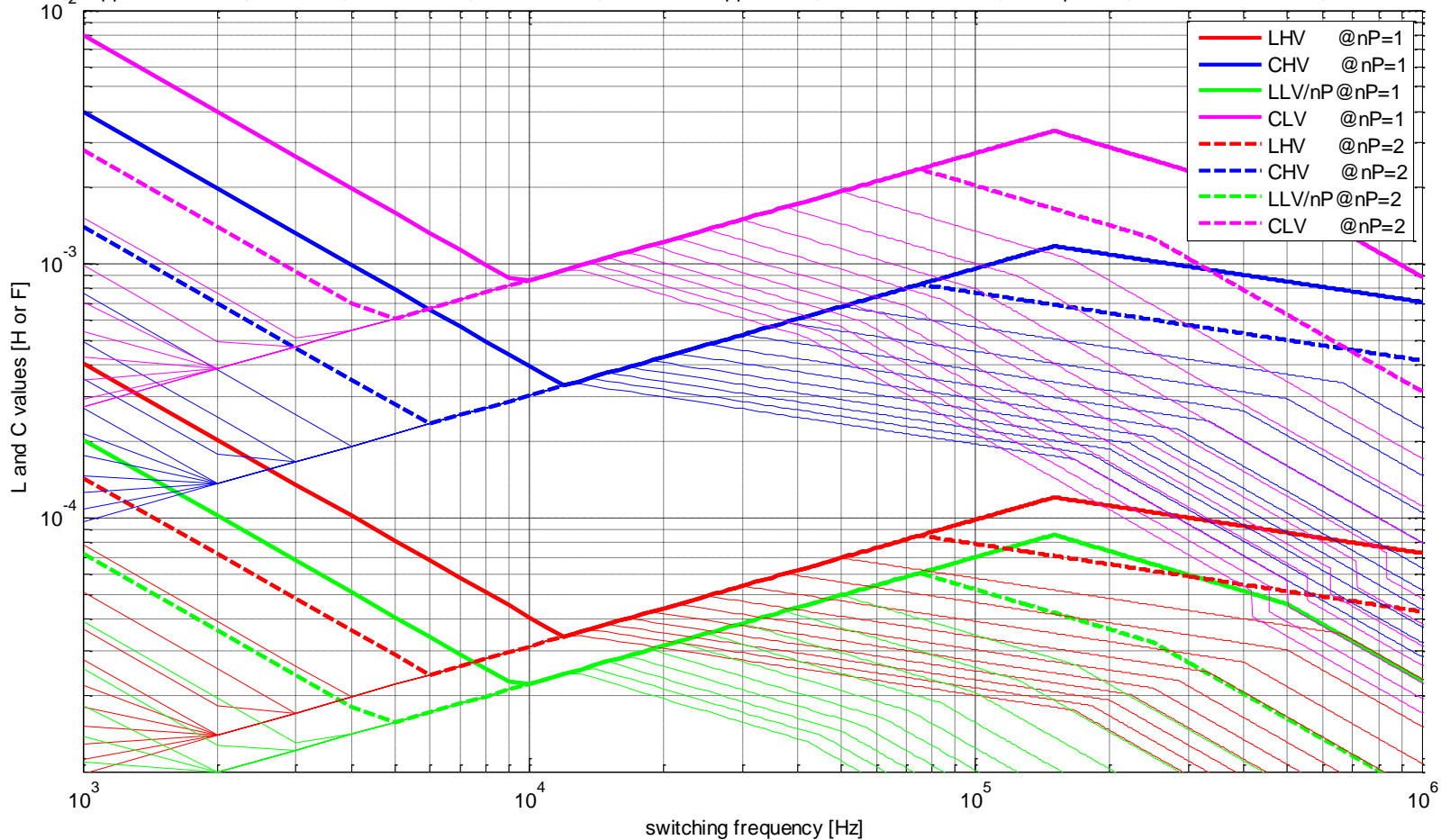
Req
#1 + #2 + #3

Calculation of the components

Example #4 : parallel multiCell converter

=> with 10 // cells, all passive components start decreasing at $f_{sw} > 15\text{kHz}$

MultiCell Chopper with: nS=1; VHV=800; ILVmax=250; IHVmax=125; relativeOutRipple=0.01; VHVovershoot=0.1; VLVdip=0.05; standardHV=HVDC; standardLV=EN55022A

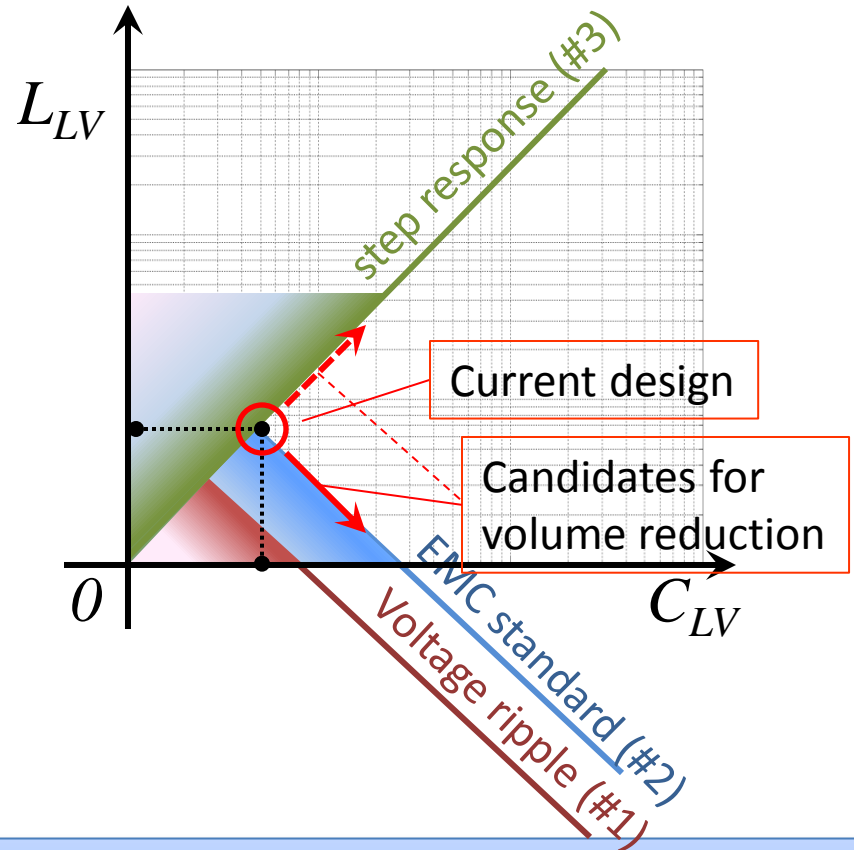
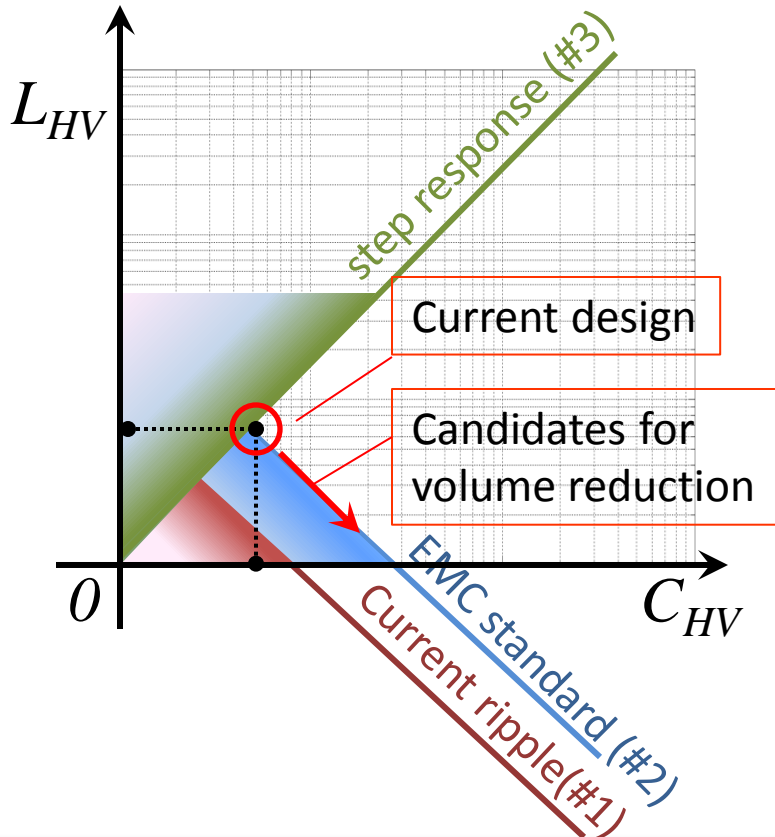


Req
#1 + #2 + #3

Combined requirements

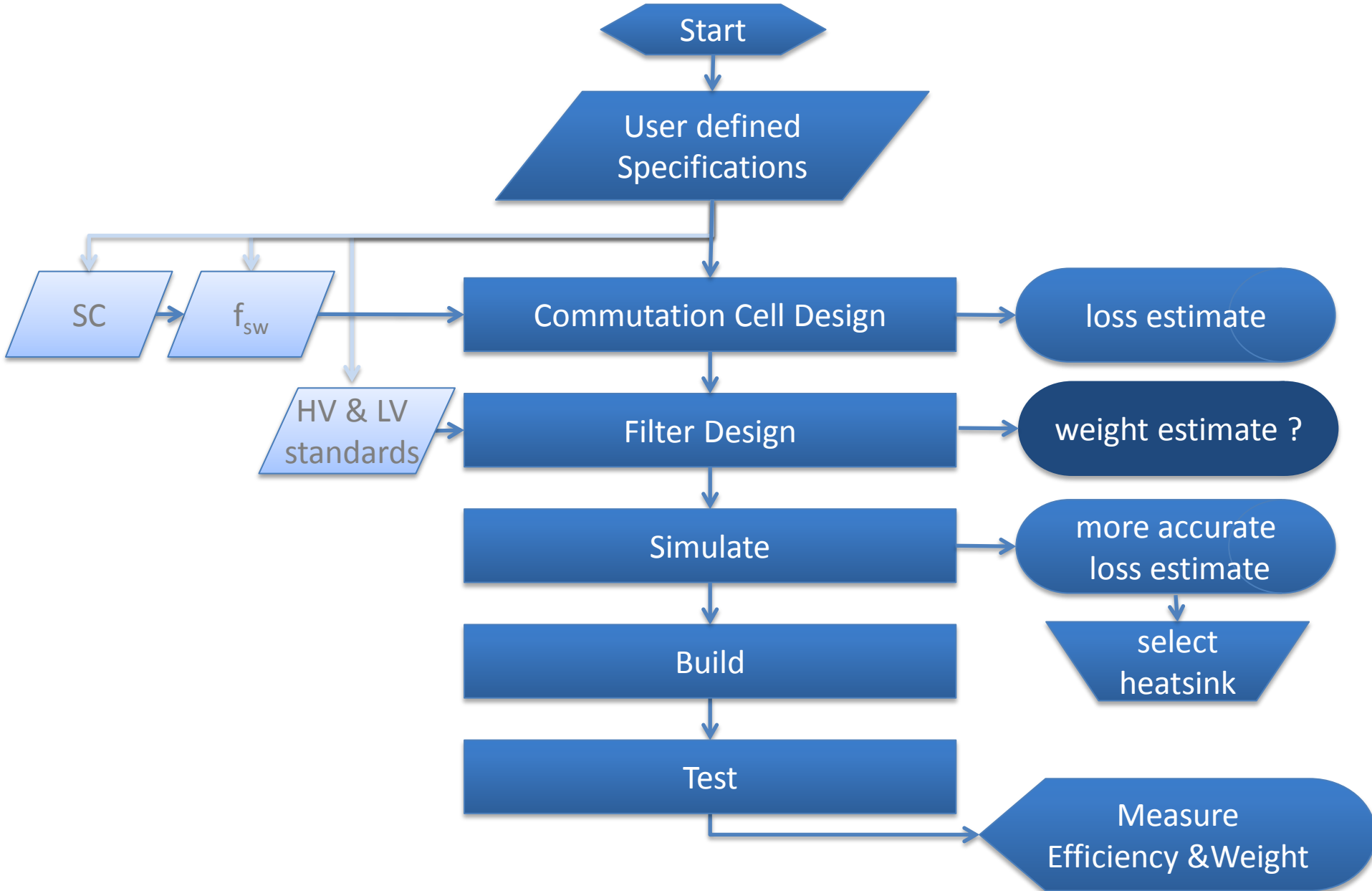
High Voltage side

Low Voltage side



For the same amount of energy, magnetic components are (2 to 10 times??) bigger, heavier and more expensive than capacitor => Reducing the inductances and increasing the capacitance leaves room for optimization...
(and increasing the inductance must not be rejected a priori!)

A standard design process



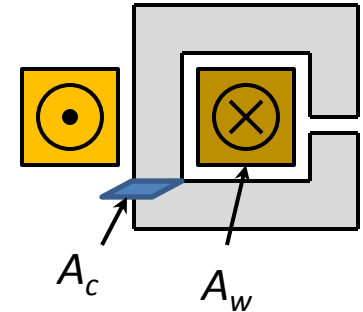
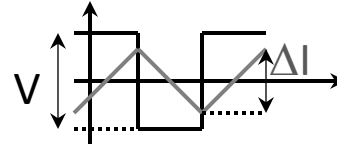
VOLUME OF PASSIVE COMPONENTS AND FILTERS FOR MULTILEVEL CONVERTERS

Area Product of Magnetic Components : Inductors

Basic formulation

$$\hat{B} = \frac{L \cdot \hat{I}}{n_t \cdot A_c}$$

$$j_{eff} = \frac{n_t \cdot I_{eff}}{k_w \cdot A_w}$$



$$A_w \cdot A_c = L \cdot \hat{I} \cdot \frac{I_{eff}}{\hat{B} \cdot k_w \cdot j_{eff}}$$

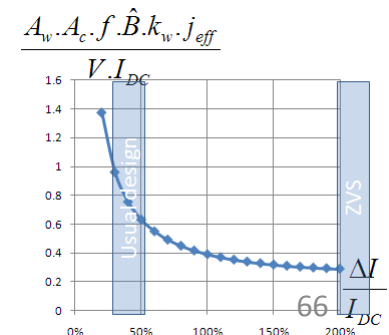
Advantage : allows selecting the core

Drawback : L , \hat{I} and I_{eff} are not independent variables so the influence of L for example is not obvious

Taking into account : $L = \frac{V}{4\Delta I \cdot f}$; $\hat{I} = I_{DC} \cdot \left(1 + \frac{\Delta I}{2I_{DC}}\right)$ and $I_{eff} = I_{DC} \sqrt{1 + \frac{1}{12} \left(\frac{\Delta I}{I_{DC}}\right)^2}$

we get :

$$A_w \cdot A_c = \frac{V \cdot I_{DC} \cdot \left(1 + \frac{\Delta I}{2I_{DC}}\right) \cdot \sqrt{1 + \frac{1}{12} \left(\frac{\Delta I}{I_{DC}}\right)^2}}{4 \left(\frac{\Delta I}{I_{DC}}\right) \cdot f \cdot \hat{B} \cdot k_w \cdot j_{eff}}$$



Area Product of Magnetic Components : Inductors

Improved

Improved formulation #3 : combining copper losses and core losses

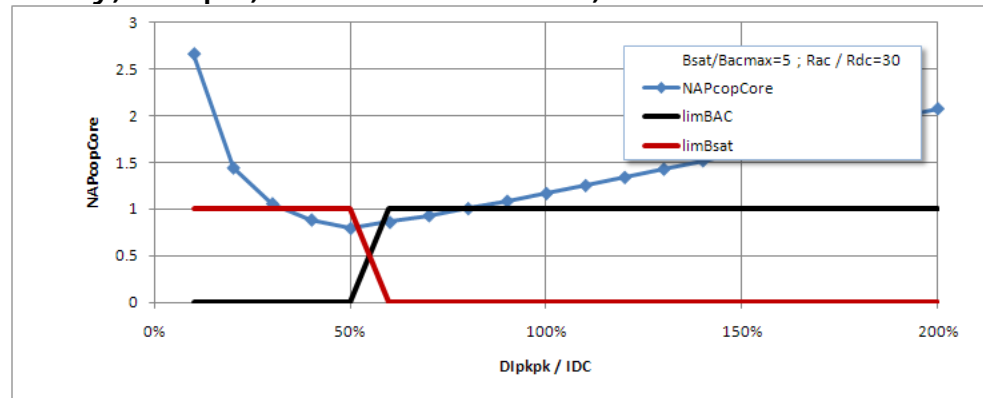
Limits on Core Loss Density and Copper Loss Density can be combined to form an Improved Normalized Area Product :

$$NAP_{core}^{copper} = \frac{A_c \cdot A_w \cdot B_{sat} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} = \frac{1}{8} \max \left(1 + \frac{2}{\Delta I / I_{DC}} ; \frac{B_{sat}}{B_{ACmax}} \right) \cdot \sqrt{1 + \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left(\frac{\Delta I}{I_{DC}} \right)^2}$$

Though elegant, this formulation could be misleading :

B_{ACmax} and R_{AC}/R_{DC} are very difficult to determine a priori :

- B_{ACmax} should be chosen to limit core temperature rise which in practice depends on f and core material (loss), size (volume/surface ratio), shape, cooling conditions...
- R_{AC}/R_{DC} depends on f , shape, number of turns, conductor material...

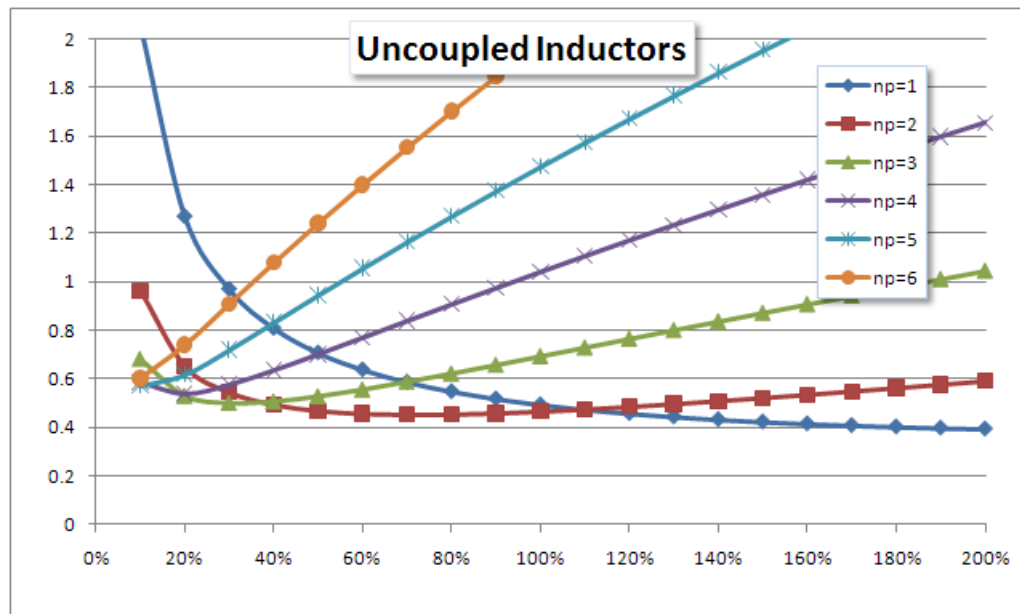


Area Product of Magnetic Components : Inductors

Basic formulation

Interleaved converters with uncoupled inductors

$NVol$



$\frac{\Delta I_{tot}}{I_{DCtot}}$

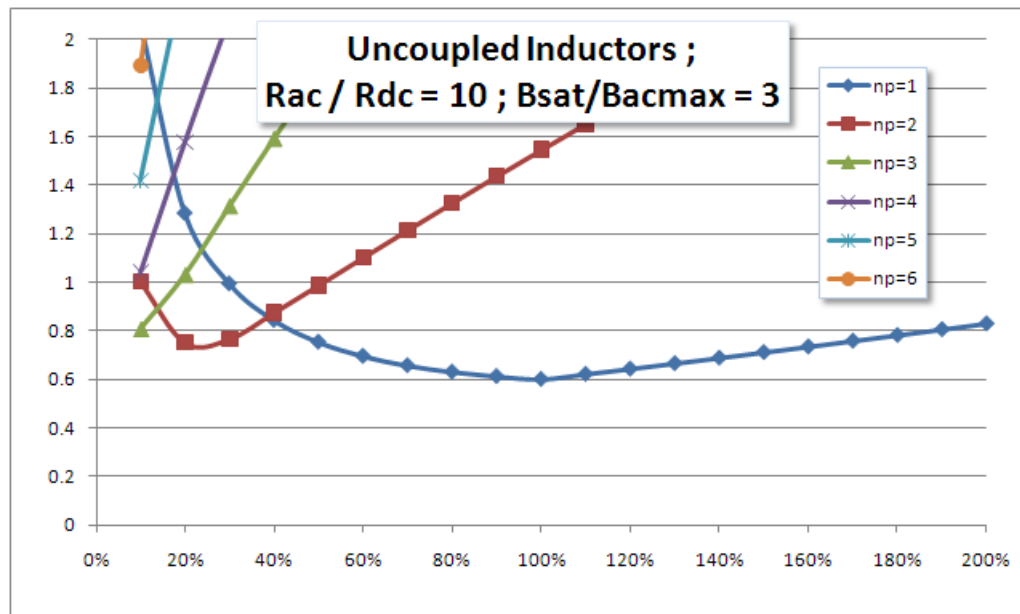
$$NVol = \frac{Vol_{tot}}{K_{shape}} \cdot \left(\frac{\hat{B} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DCtot}} \right)^{3/4} = n_p \cdot \left(\frac{1}{8n_p} \left(1 + \frac{2I_{DCtot}}{n_p^2 \cdot \Delta I_{tot}} \right) \sqrt{1 + \frac{1}{12} \left(\frac{n_p^2 \cdot \Delta I_{tot}}{I_{DCtot}} \right)^2} \right)^{3/4}$$

Area Product of Magnetic Components : Inductors

Improved formulation

Interleaved converters with *uncoupled* inductors

NVol



$$\frac{\Delta I_{tot}}{I_{DCtot}}$$

$$NVol = \frac{Vol_{tot}}{K_{shape}} \cdot \left(\frac{B_{sat} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} \right)^{3/4} = n_p \cdot \left(\frac{1}{8n_p} \max \left(1 + \frac{2}{n_p^2} \frac{\Delta I_{tot}}{I_{DCtot}} ; \frac{B_{sat}}{B_{ACmax}} \right) \sqrt{1 - \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left(\frac{n_p^2 \Delta I_{tot}}{I_{DCtot}} \right)^2} \right)^{3/4}$$

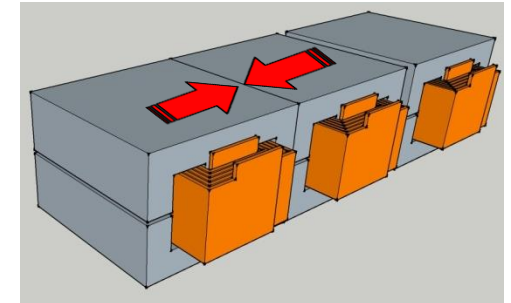
Area Product of Magnetic Components : ICTs

Basic formulation

Interleaved converters with **coupled** inductors (or InterCell Transformers = ICTs)

Compared with uncoupled inductors:

- Fluxes unchanged ,
- Current ripples reduced



$$\left. \begin{aligned} \Delta I_{tot} &= \frac{\Delta I_{ind} \cdot n_p}{n_p} \\ I_{DCtot} &= n_p \cdot I_{DCind} \end{aligned} \right\} \Rightarrow \frac{\Delta I_{ind}}{I_{DCind}} = \frac{\cancel{n_p} \Delta I_{tot} / \underline{\underline{n_p}}}{I_{DCtot} / n_p} = \frac{\cancel{n_p}^2 \Delta I_{tot}}{I_{DCtot}}$$

=> Total volume of the n_p **coupled** inductors :

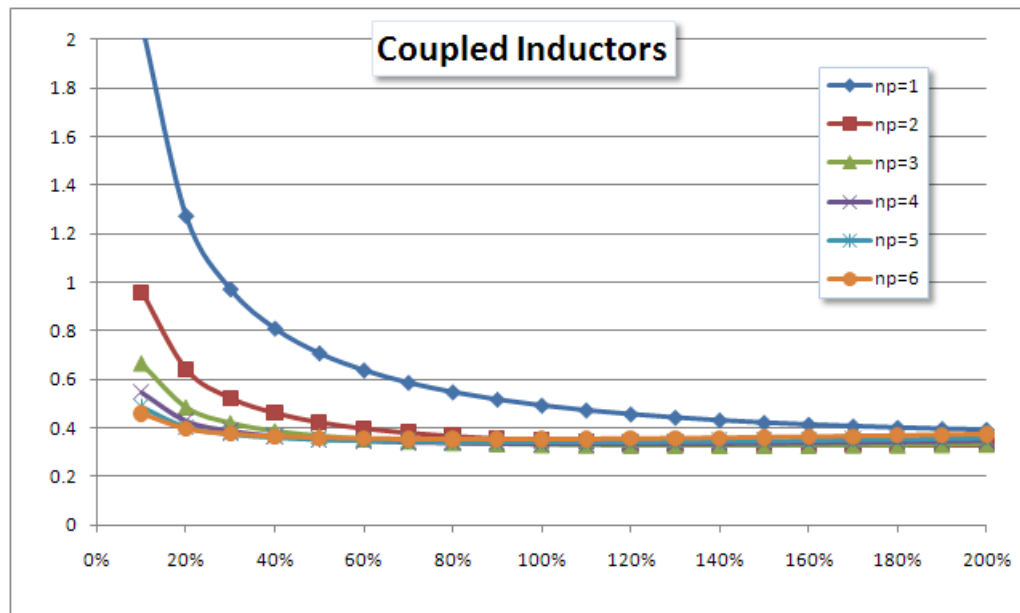
$$Vol_{tot} = n_p \cdot K_{shape} \left(\frac{V \cdot \frac{I_{DCtot}}{n_p} \cdot \left(1 + \frac{2I_{DCtot}}{n_p^2 \cdot \Delta I_{tot}} \right) \sqrt{1 + \frac{1}{12} \left(\frac{\cancel{n_p}^2 \cdot \Delta I_{tot}}{I_{DCtot}} \right)^2}}{8 \hat{B} \cdot f \cdot k_w \cdot j_{eff}} \right)^{3/4}$$

Area Product of Magnetic Components : ICTs

Basic formulation

Interleaved converters with **coupled** inductors (or InterCell Transformers = ICTs)

$NVol$



$$\frac{\Delta I_{tot}}{I_{DCtot}}$$

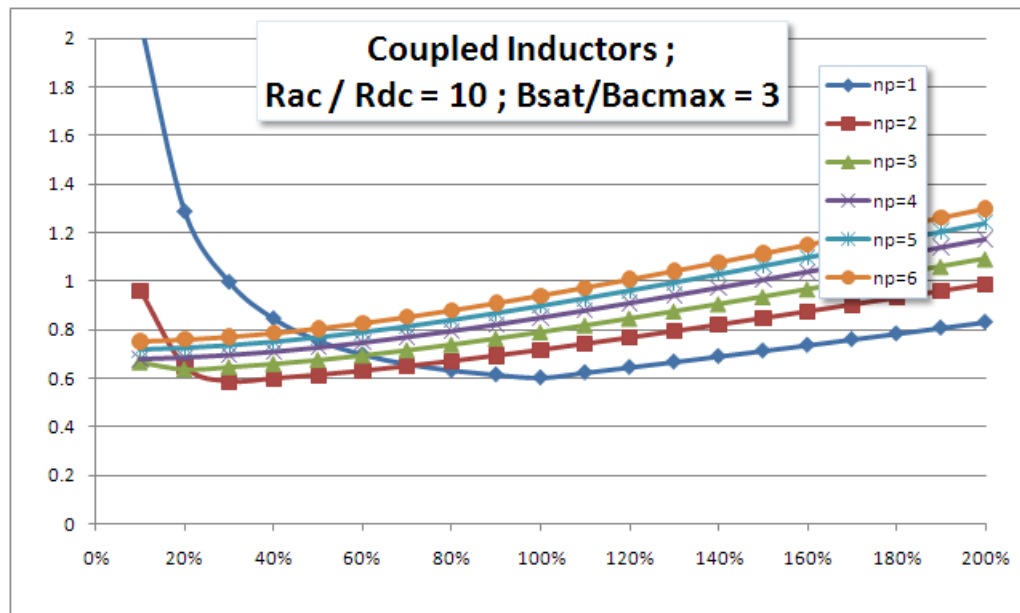
$$NVol = \frac{Vol_{tot}}{K_{shape}} \cdot \left(\frac{\hat{B} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} \right)^{3/4} = n_p \cdot \left(\frac{1}{8n_p} \left(1 + \frac{2I_{DCtot}}{n_p^2 \cdot \Delta I_{tot}} \right) \sqrt{1 + \frac{1}{12} \left(\frac{\Delta I_{tot}}{I_{DCtot}} \right)^2} \right)^{3/4}$$

Area Product of Magnetic Components : ICTs

Improved formulation

Interleaved converters with **coupled** inductors (or InterCell Transformers = ICTs)

NVol



$$\frac{\Delta I_{tot}}{I_{DCtot}}$$

$$NVol = \frac{Vol_{tot}}{K_{shape}} \cdot \left(\frac{B_{sat} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} \right)^{3/4} = n_p \cdot \left(\frac{1}{8n_p} \max \left(1 + \frac{2}{n_p^2} \frac{\Delta I_{tot}}{I_{DCtot}} ; \frac{B_{sat}}{B_{ACmax}} \right) \sqrt{1 + \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left(\frac{\Delta I_{tot}}{I_{DCtot}} \right)^2} \right)^{3/4}$$

Minimum volume of LV-side uncoupled inductors and InterCell Transformers

Crossing($f_1=f_2$)

$$1 + \frac{2}{n_p^2 \Delta I_{tot} / I_{DCtot}} = \frac{B_{sat}}{B_{AC\ max}} \Leftrightarrow \Delta I_{tot} / I_{DCtot} = \frac{2}{n_p^2} \frac{\frac{B_{AC\ max}}{B_{sat}}}{1 - \frac{B_{AC\ max}}{B_{sat}}}$$

⇒ Ripple giving the minimum volume of Magnetic Component :

uncoupled

$$\chi = \min \left(\frac{1}{n_p^2} \sqrt[3]{\frac{24}{R_{AC} / R_{DC}}} ; \frac{2}{n_p^2} \frac{\frac{B_{AC\ max}}{B_{sat}}}{1 - \frac{B_{AC\ max}}{B_{sat}}} \right)$$

coupled

$$\chi = \min \left(\frac{1}{n_p^{2/3}} \sqrt[3]{\frac{24}{R_{AC} / R_{DC}}} ; \frac{2}{n_p^2} \frac{\frac{B_{AC\ max}}{B_{sat}}}{1 - \frac{B_{AC\ max}}{B_{sat}}} \right)$$

Minimum volume of LV-side uncoupled inductors and InterCell Transformers

Ripple giving the minimum volume (as a function of B_{ACmax}/B_{sat} and $\Delta I/I_{DC}$)



$$f(\chi) = \left(1 + \frac{a}{\chi}\right) \sqrt{1 + b \cdot \chi^2}$$

$$\text{uncoupled } \frac{df}{d\chi} = 0 \Leftrightarrow \chi = \sqrt[3]{\frac{a}{b}} = \frac{1}{n_p^{2/3}} \sqrt[3]{\frac{24}{R_{AC}/R_{DC}}}$$

minimum lié à l'augmentation des pertes joules AC

$$NAP^{copper} = \frac{A_c \cdot A_w \cdot \hat{B} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} = \frac{1}{8} \left(1 + \frac{2}{\Delta I/I_{DC}}\right) \sqrt{1 + \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left(\frac{\Delta I}{I_{DC}}\right)^2}$$

$$\text{coupled } \frac{df}{d\chi} = 0 \Leftrightarrow \chi = \sqrt[3]{\frac{a}{b}} = \frac{1}{n_p^{2/3}} \sqrt[3]{\frac{24}{R_{AC}/R_{DC}}}$$

minimum lié au passage en saturation

$$1 + \frac{2}{n_p^2 \Delta I/I_{DC}} = \frac{B_{sat}}{B_{ACmax}} \Leftrightarrow \Delta I_{sat}/I_{DCsat} = \frac{2}{n_p^2} \frac{B_{ACmax}}{B_{sat}}$$

$$NAP^{core} = \frac{A_c \cdot A_w \cdot \hat{B} \cdot f \cdot k_w \cdot j_{eff}}{V \cdot I_{DC}} = \frac{1}{8} \max\left(1 + \frac{2}{\Delta I/I_{DC}}; \frac{B_{sat}}{B_{ACmax}}\right) \sqrt{1 + \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left(\frac{\Delta I}{I_{DC}}\right)^2}$$

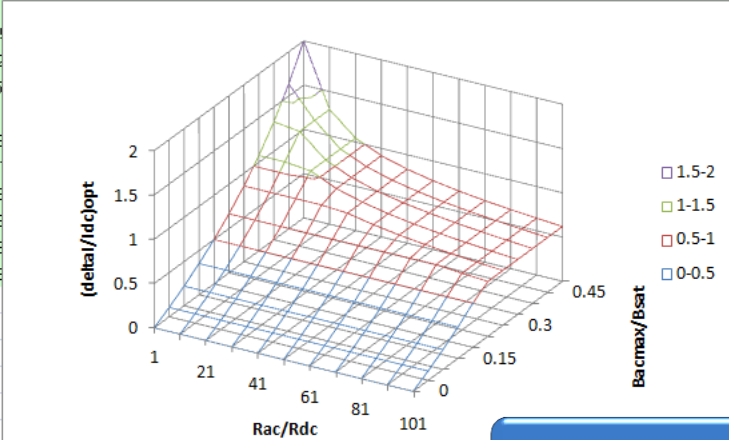
DeltaI/Idc donnant le min de NAP(Core+Copper) en fonction de BacMaxBsat et Rad/Rdc

deltai/Idc donnant min(NAPcopper)

BacMax/Bsat	deltai/Idc	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0	0	0	0.105263158	0.222222222	0.352941176	0.5	0.666666667	0.857142857	1.076923077	1.333333333	1.636363636	2

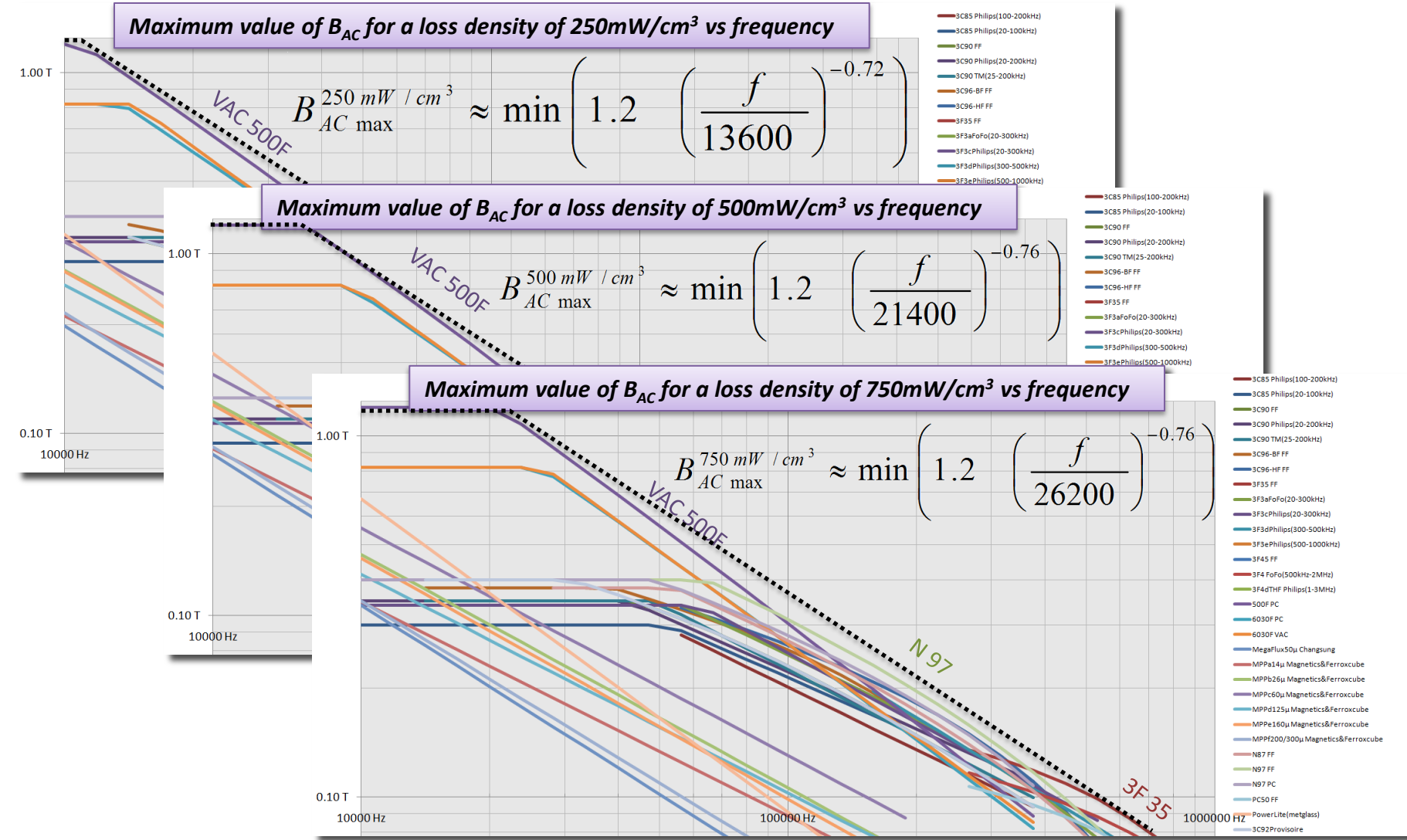
rapp (=Rad/Rdc)	1	11	21	31	41	51	61	71	81	91	101
deltai/Idc donnant min(NAPcopper)	2.884499141	1.296998634	1.045515917	0.918226557	0.836518972	0.777822237	0.732757832	0.696601327	0.666666667	0.641293173	0.619388716

rapp (=Rad/Rdc)	1	11	21	31	41	51	61	71	81	91	101
0	0	0	0	0	0	0	0	0	0	0	0
0.05	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158	0.105263158
0.1	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222	0.222222222
0.15	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176	0.352941176
0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.25	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667	0.666666667
0.3	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857	0.857142857
0.35	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077	1.076923077
0.4	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333	1.333333333
0.45	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636	1.636363636
0.5	2	2	2	2	2	2	2	2	2	2	2



Minimum volume of LV-side uncoupled inductors and InterCell Transformers

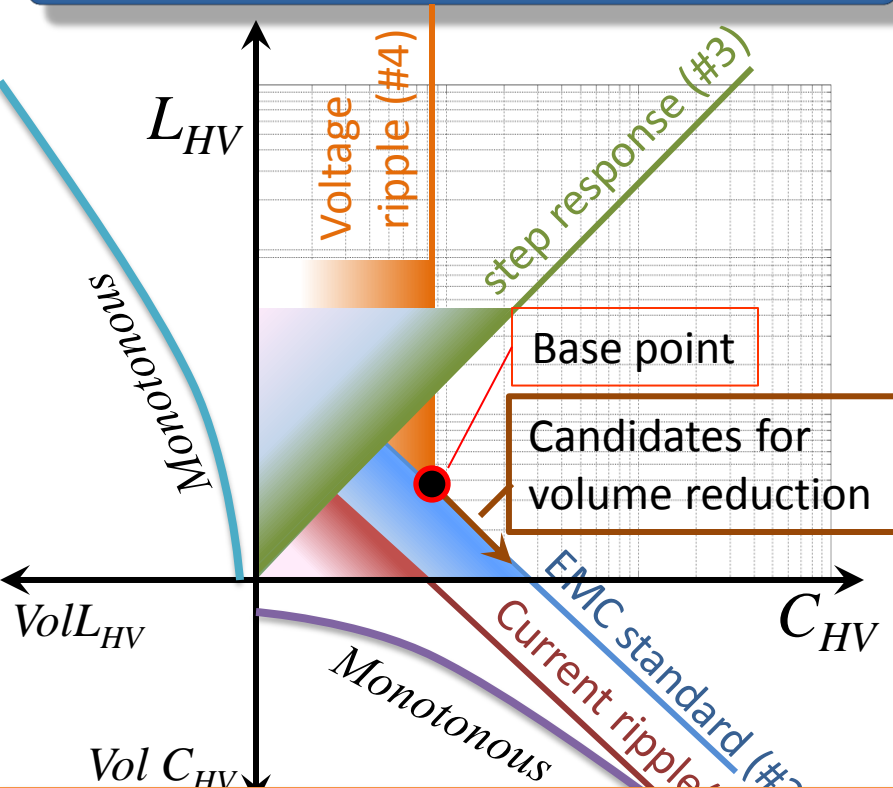
Technology-related data : Core loss limitation



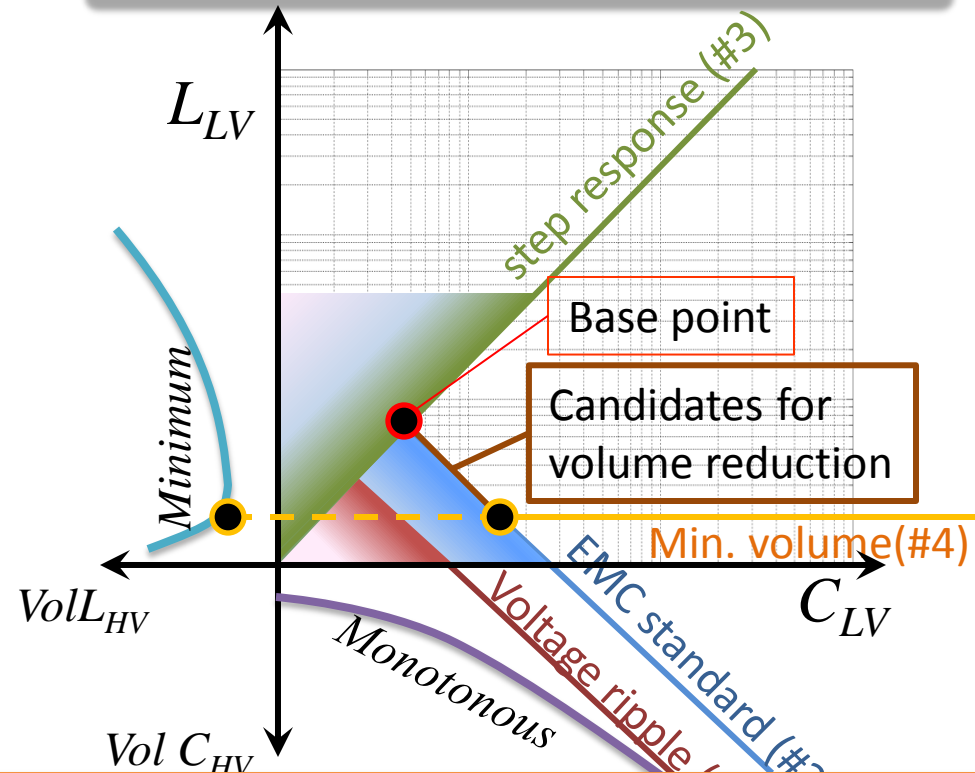
Req
#1 + #2 + #3 + #4

Filters with minimum volumes

High Voltage side



Low Voltage side

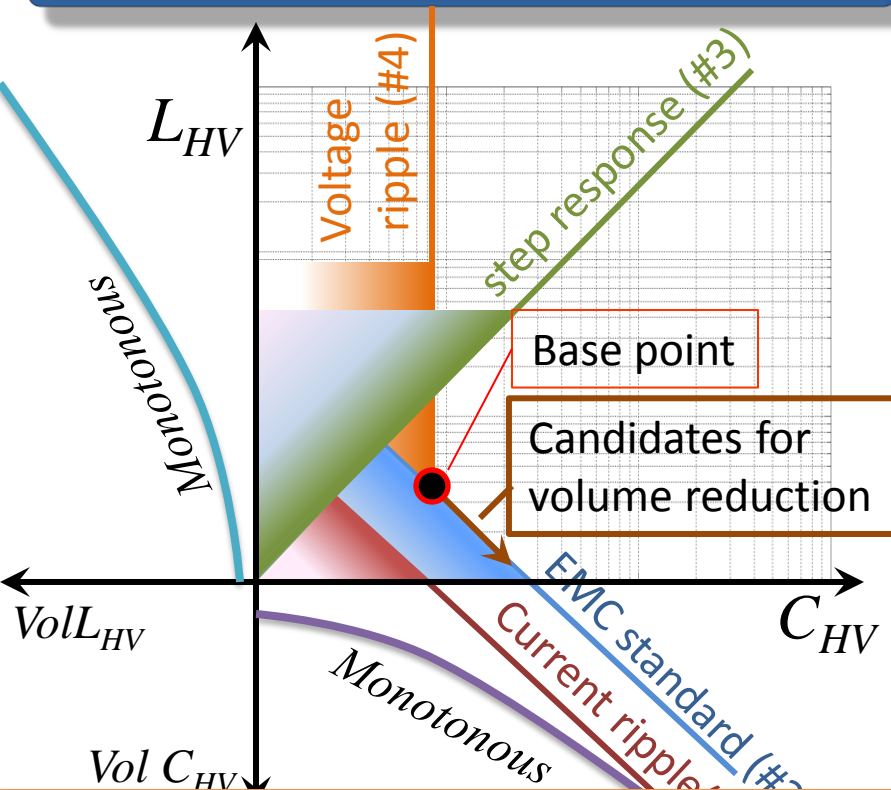


Feasible points all use a capacitance greater than that of the base point which means capacitors bigger than basepoint. Smaller filters can only be found by reducing the volume of the magnetic part. For HV filter this is only possible by decreasing L_{HV} , but for LV filter, the magnetic component with the smaller volume can be obtained for a smaller or higher inductance. The minimum volume of the whole filter will be found somewhere between these two values of inductances (base point inductance and inductance with the minimum volume), by following either the constant LC ($L_{MinVol} < L_{BasePoint}$) or the constant L/C ($L_{MinVol} > L_{BasePoint}$) line.

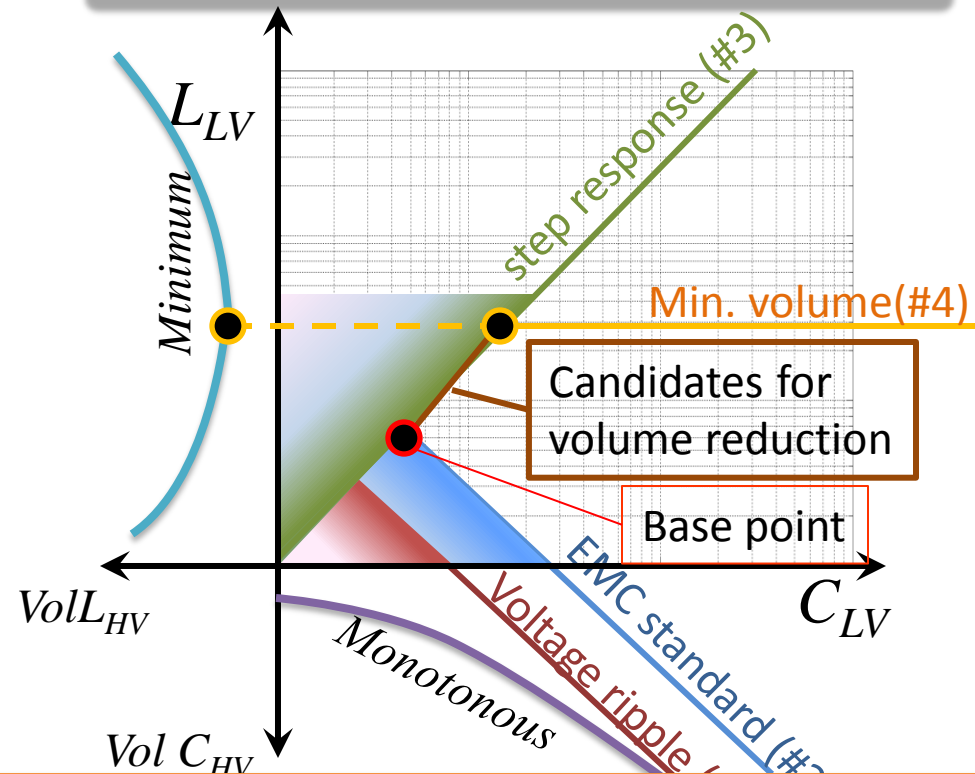
Req
#1 + #2 + #3 + #4

Filters with minimum volumes

High Voltage side

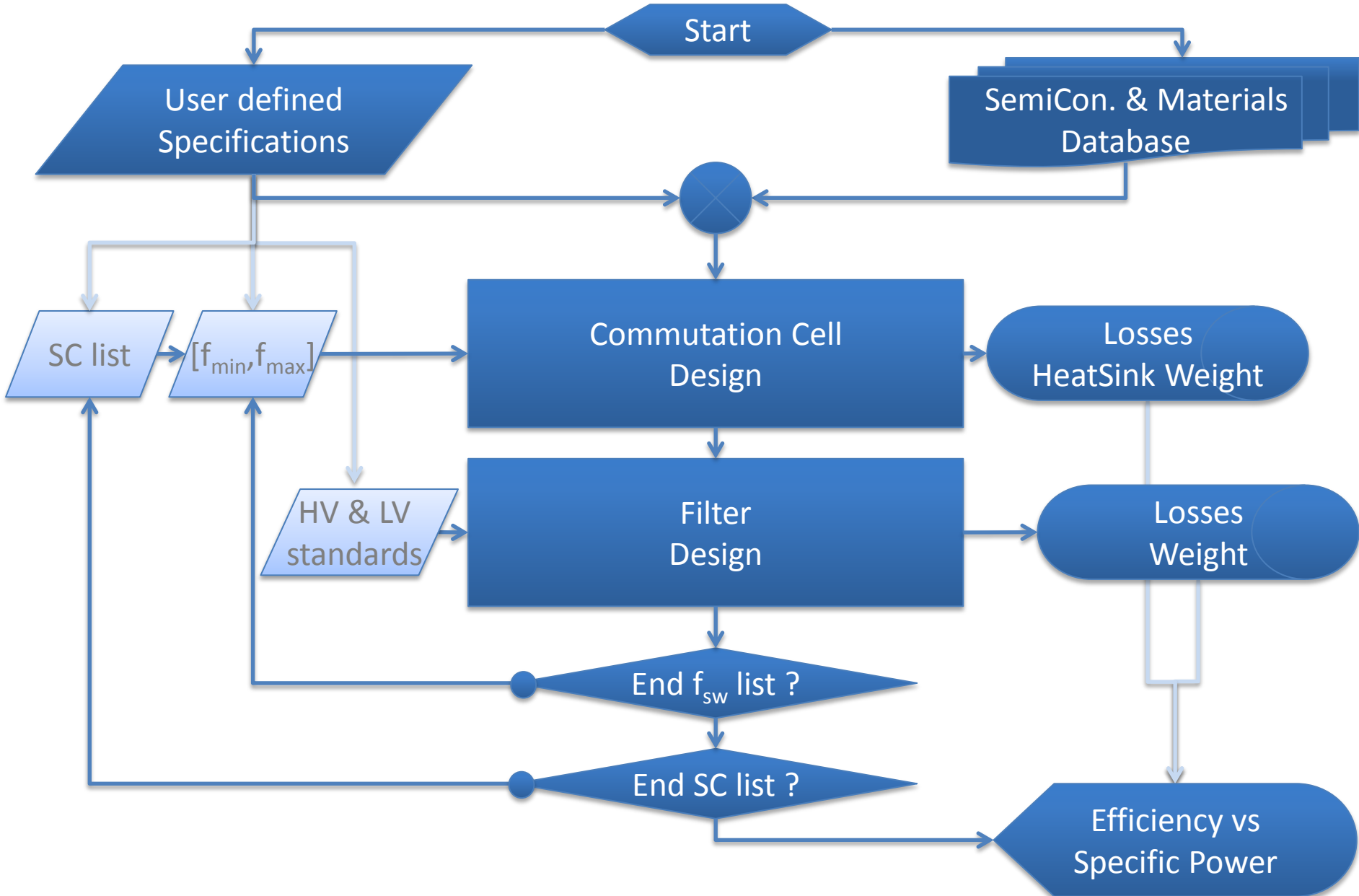


Low Voltage side

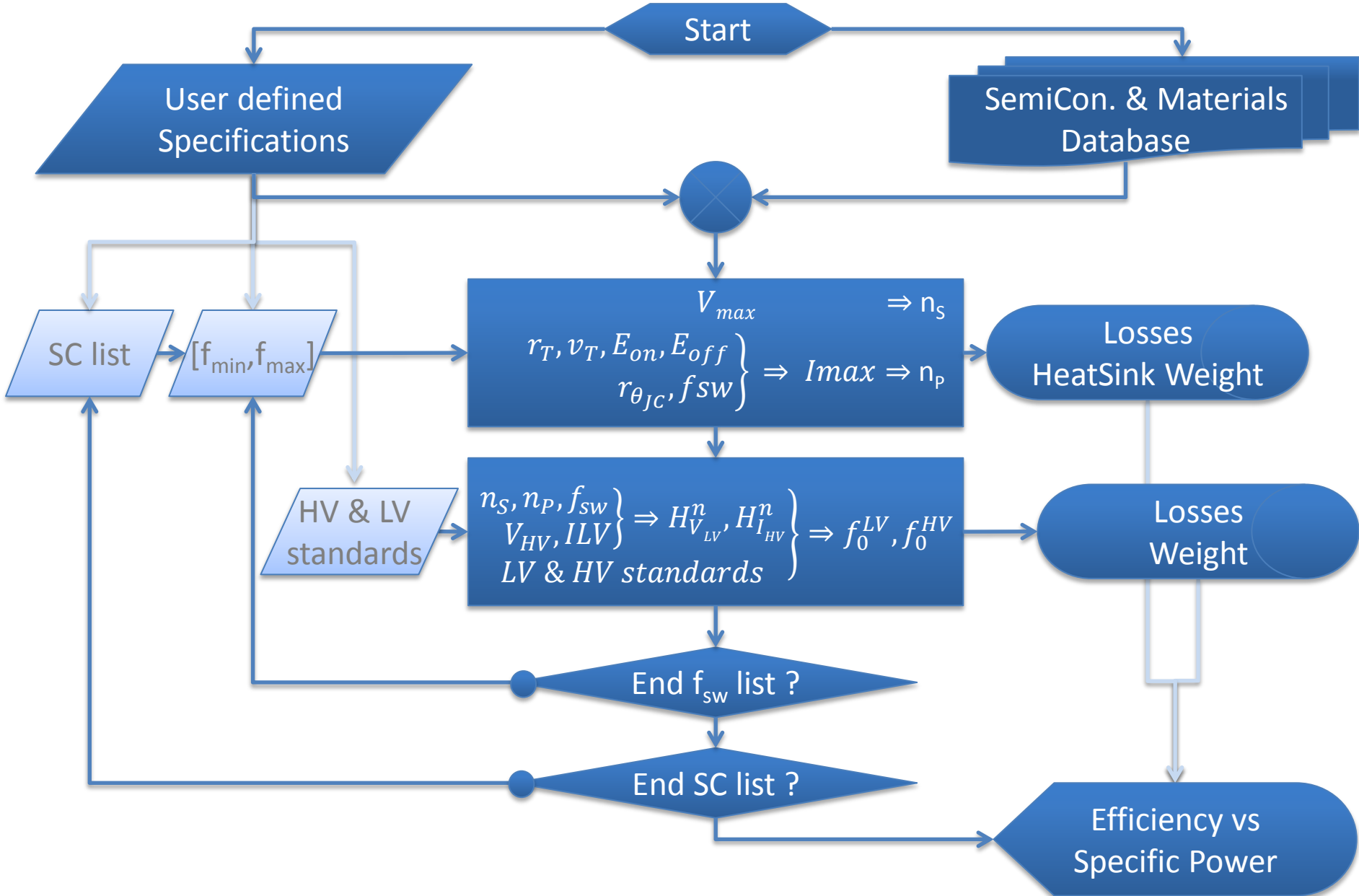


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Design process

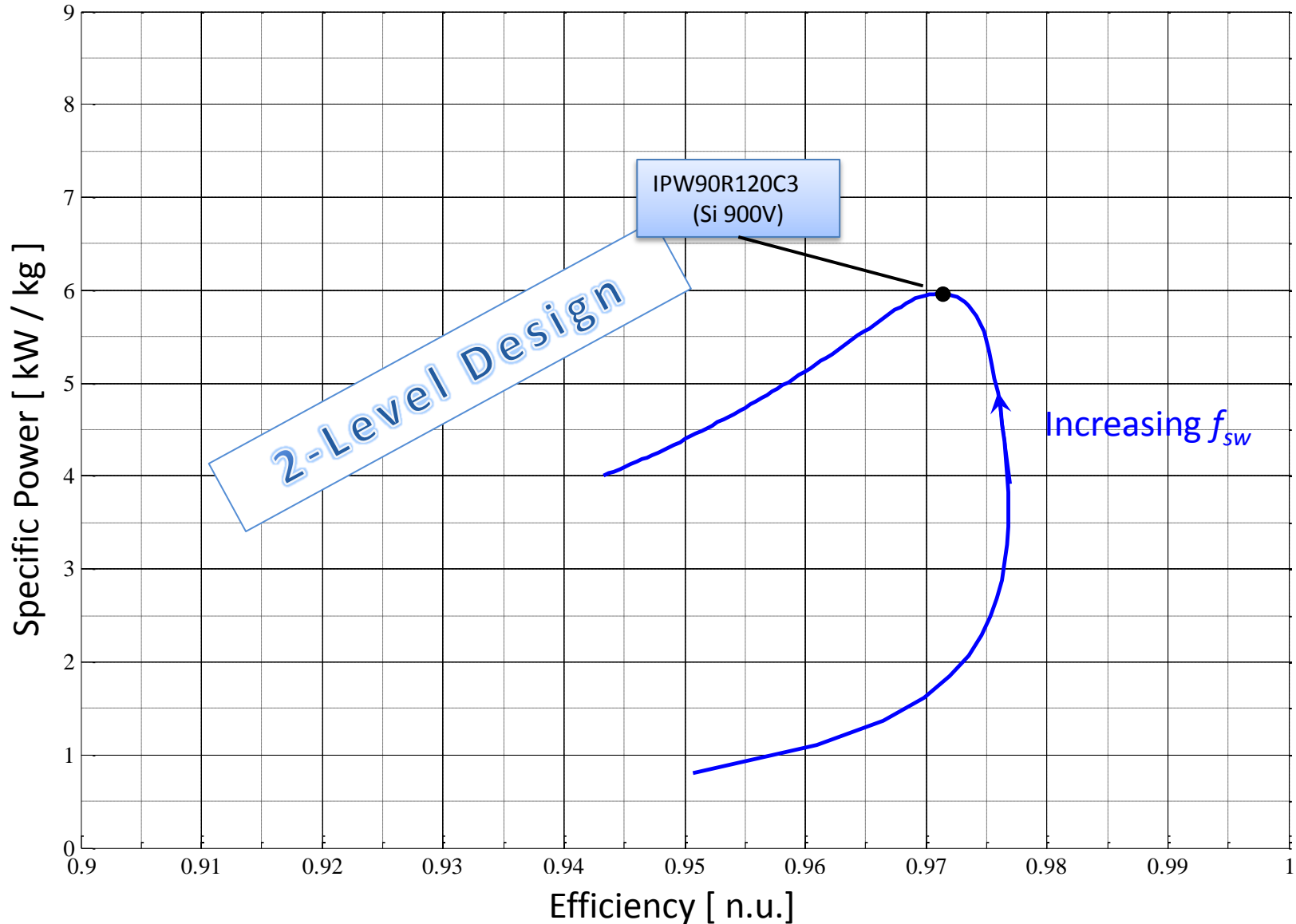


Design process



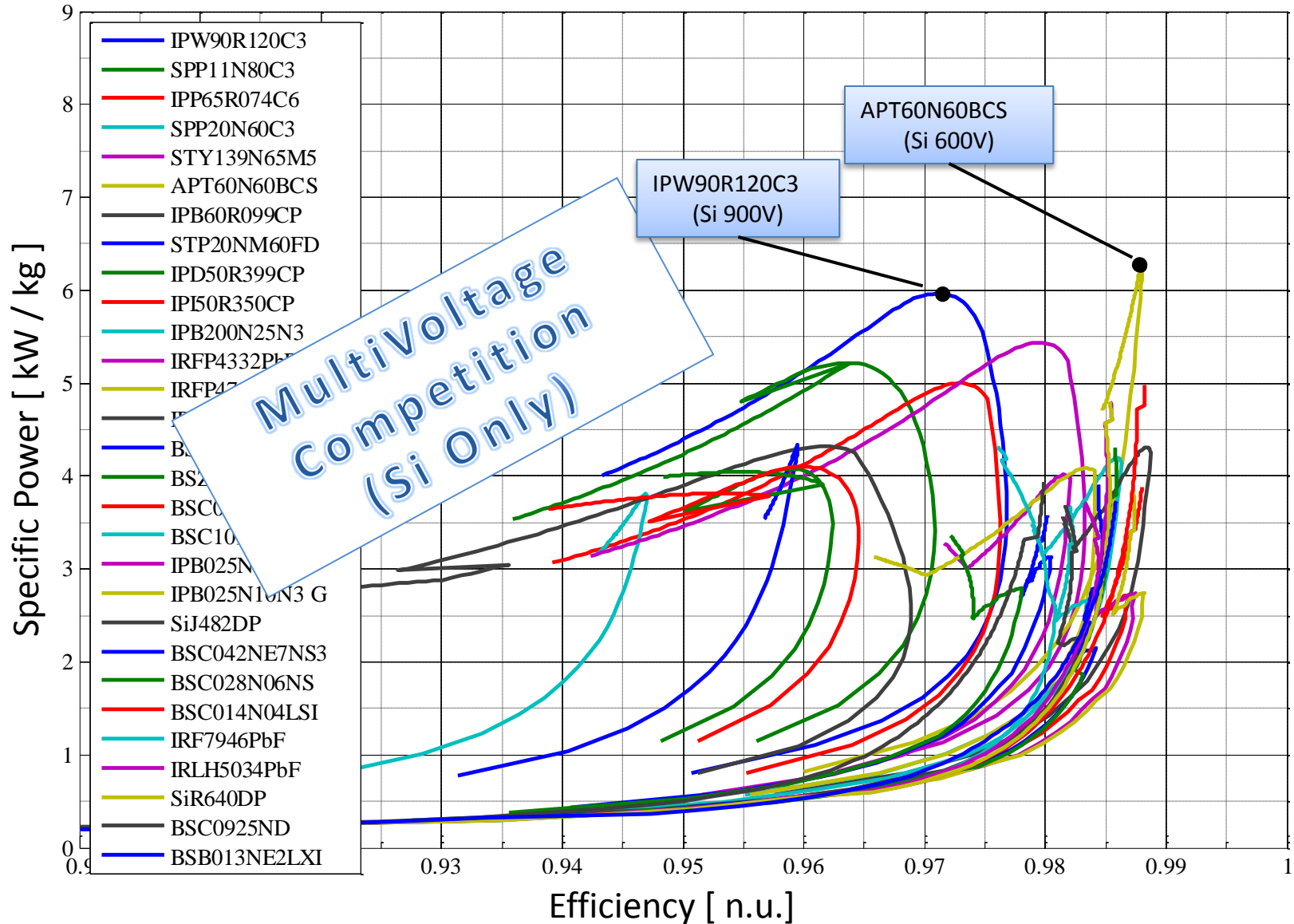
Combining SC data and passive component data :
feasible points in the (SpecificPower,Efficiency) plane

$V_{HV}=600V$; $D=50\%$; Power=6kW ; Coupled

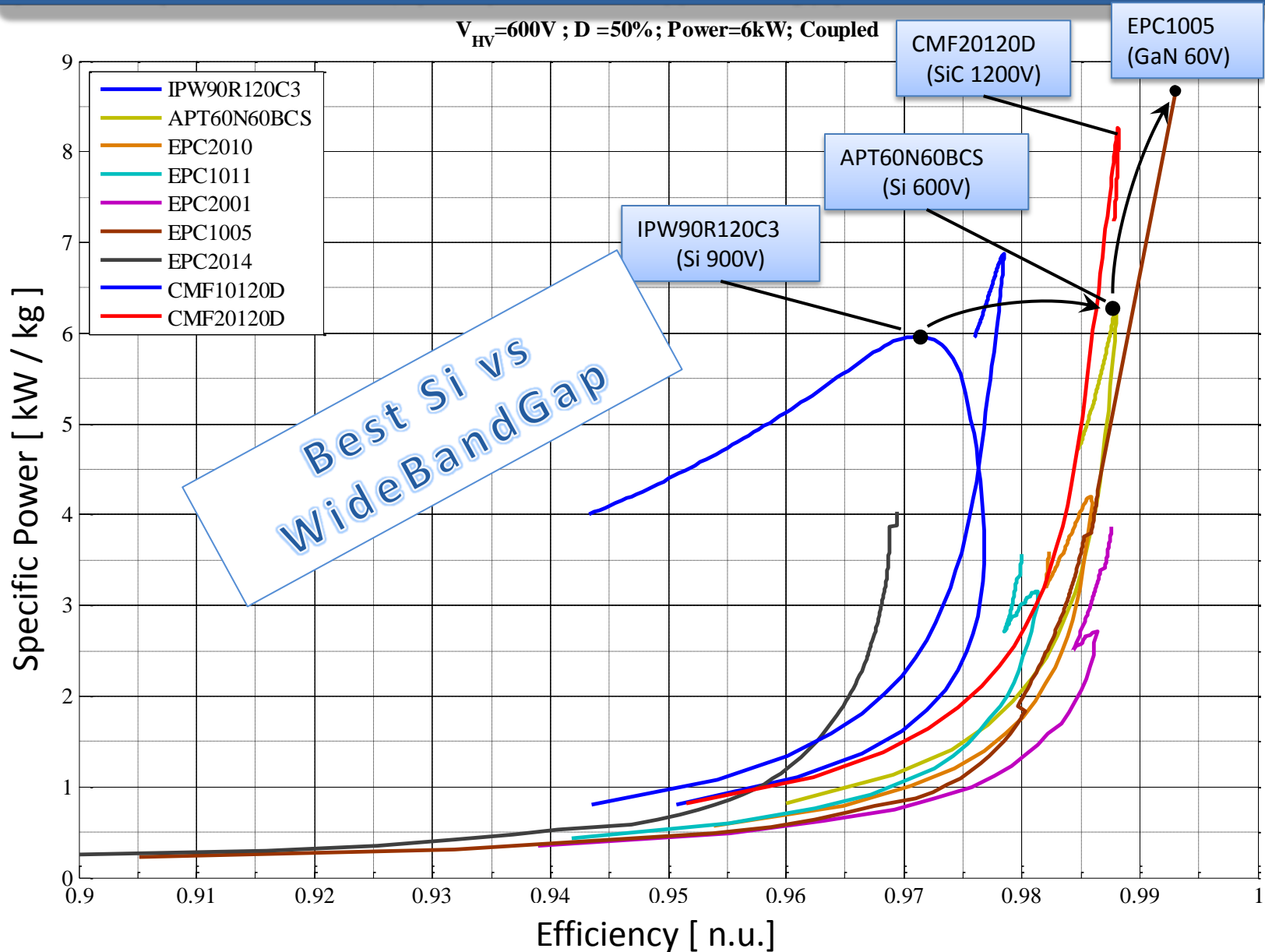


Combining SC data and passive component data :
feasible points in the (SpecificPower, Efficiency) plane

$V_{HV}=600V$; $D=50%$; Power=6kW ; Coupled

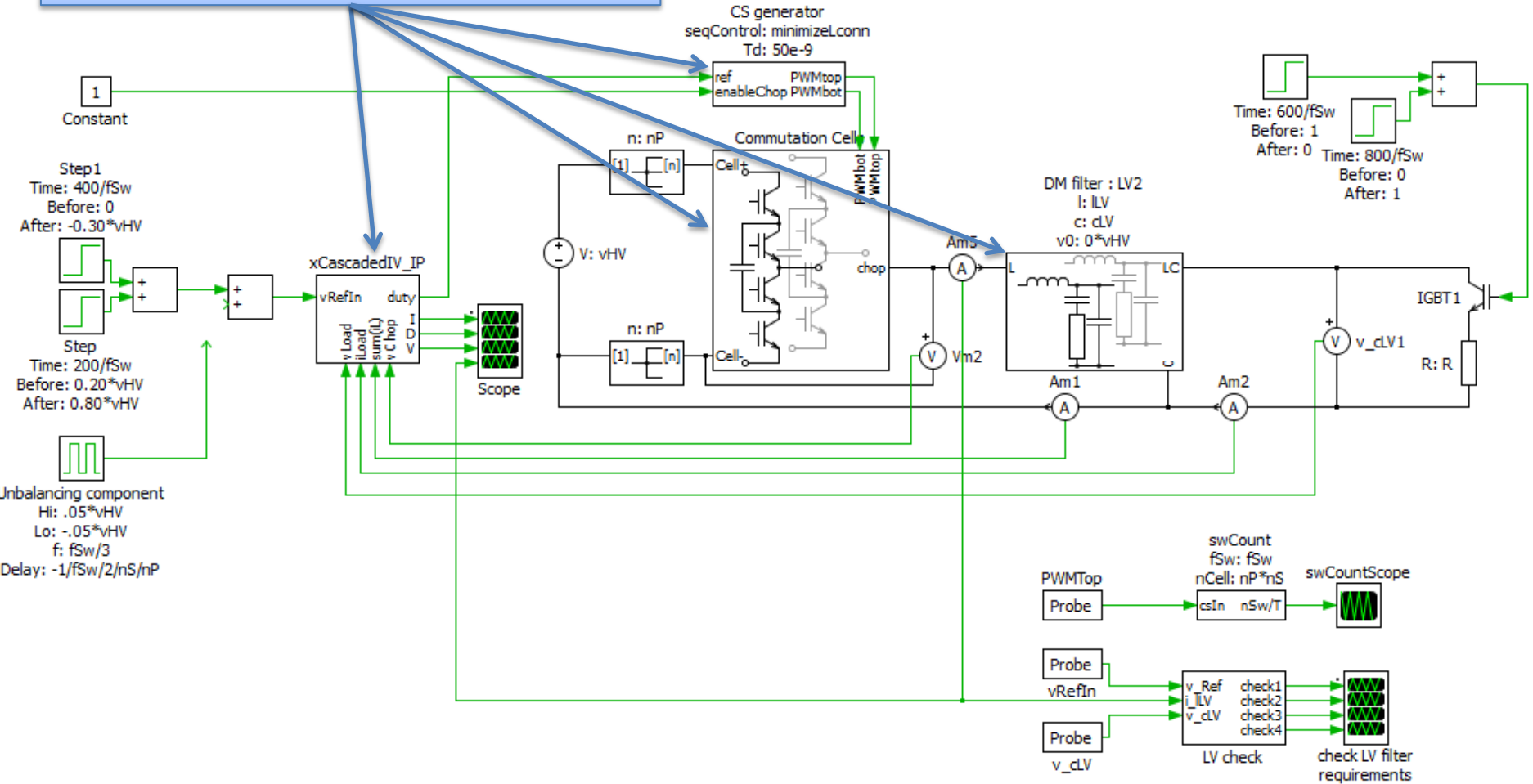


Combining SC data and passive component data :
feasible points in the (SpecificPower, Efficiency) plane



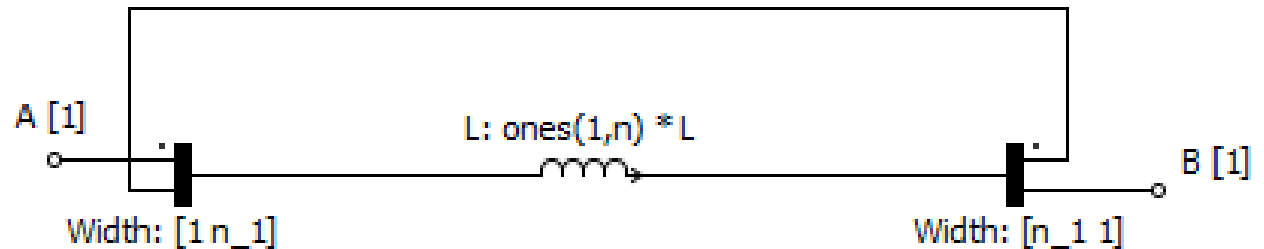
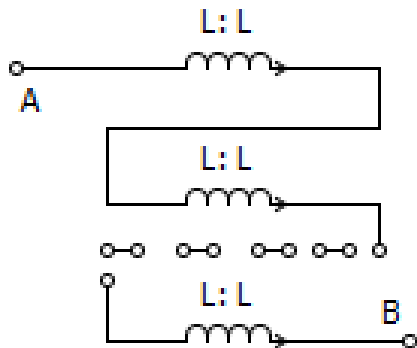
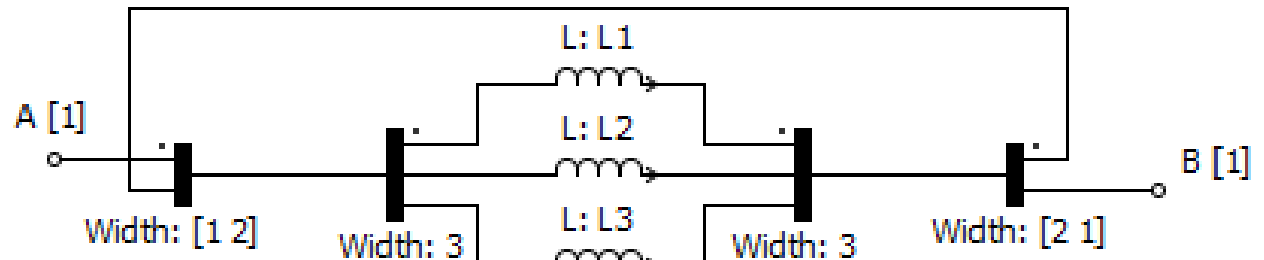
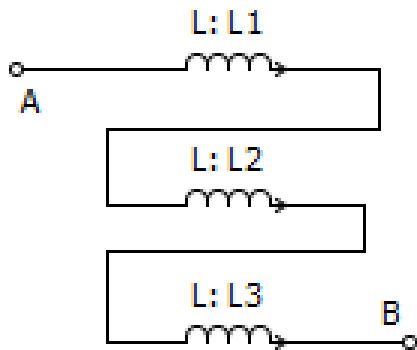
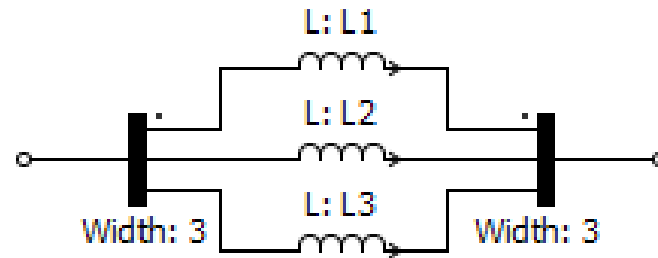
Design check

Main blocks are nS, nP compatible

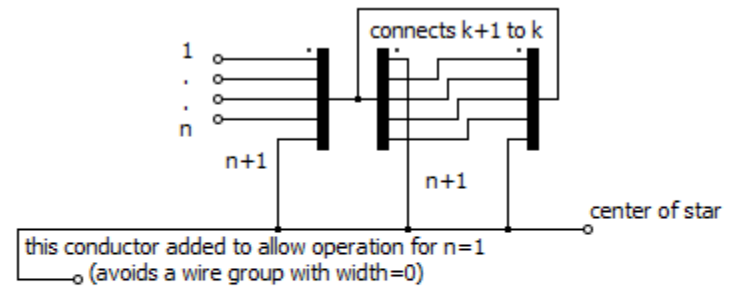
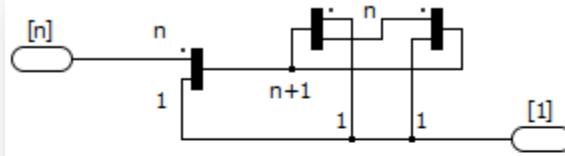
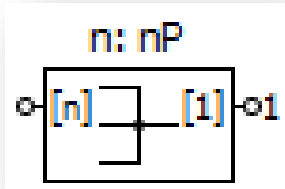


Graphic Vectorization in PLECS

L: [L1 L2 L3]

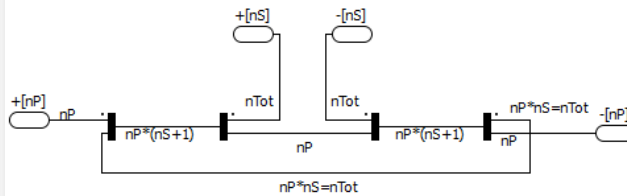
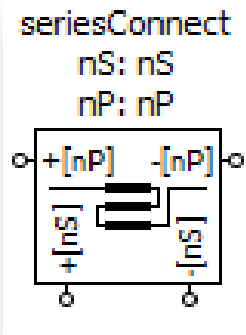


Dedicated blocks to help vectorization

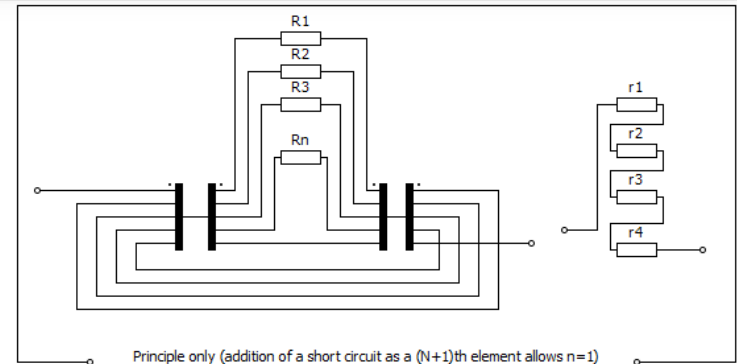


This block allows star connection of n terminals (n integer > 0) and gives access to the center of the star.

Author : TM



Active part of the circuit

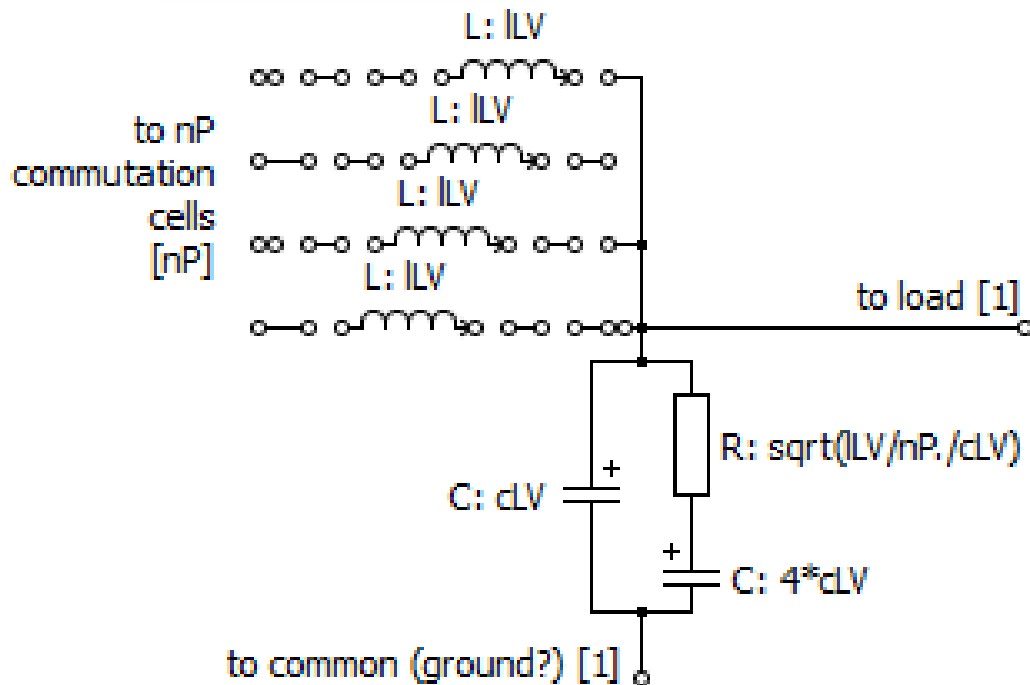
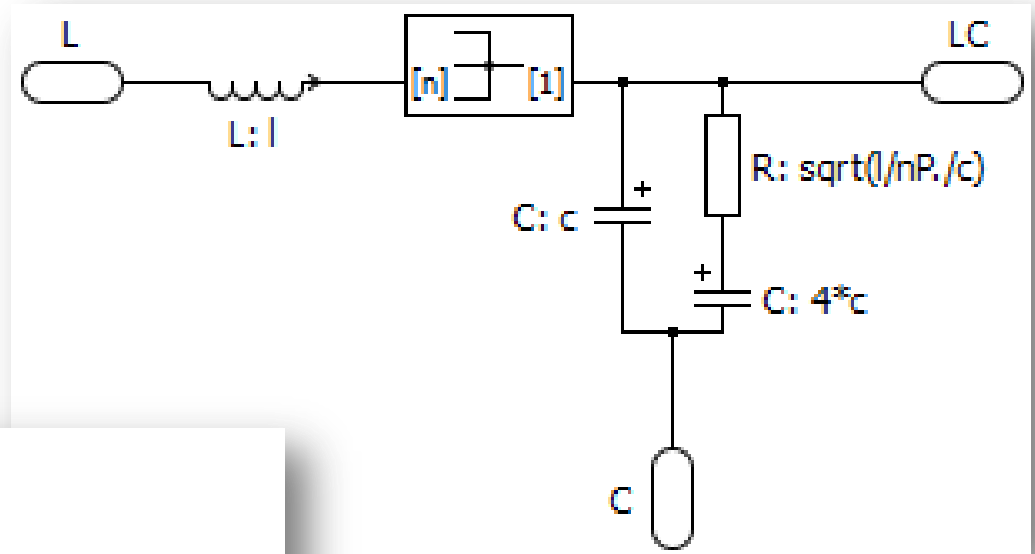
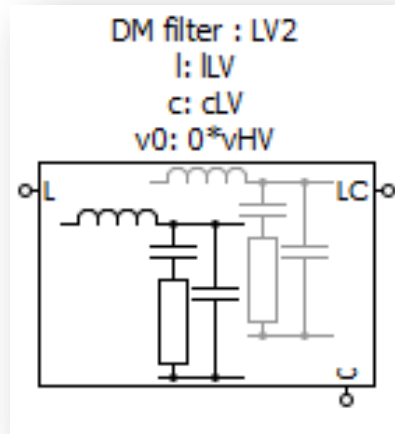


This block allows series connection dipoles.

- If the dipole is defined as a single element, the number of elements in series is imposed by the number 'n' in the mask.
- If the dipole is defined as a vector, the number 'n' in the mask must be equal to the size of the vector of dipoles.

Author : TM

Vectorized filters



Vectorized filters with pre-design

Block Parameters: untitled/app-oriented LV-side DM 2nd order filter

2nd order DM Filter with application-oriented mask (LV side) (mask) (link)

Same model as "Differential Mode Filter", but the R,L,C parameters of the filter are derived from application requirements such as:

- ripple, overshoot, dip and standard compliance.
- both time domain (ripple) and frequency domain (standard) requirements on the output voltage are used to find the minimal LC product => filtering requirement,
- the specified undervoltage resulting of a no-load to full-load step is used to find the minimal C/L ratio => transient requirement,
- the specified worst-case time domain cell-side current ripple is used to find the minimal inductance => iRipple requirement,

Then the 3 requirements are combined as follows :

Case 1 : L(transient & filtering) > L(Ripple) Case 2 : L(transient & filtering) < L(Ripple)

=> to minimize LV, design at C :
(combine filtering & iRipple)
=> to minimize dLV, design at A
(combine filtering & transient)

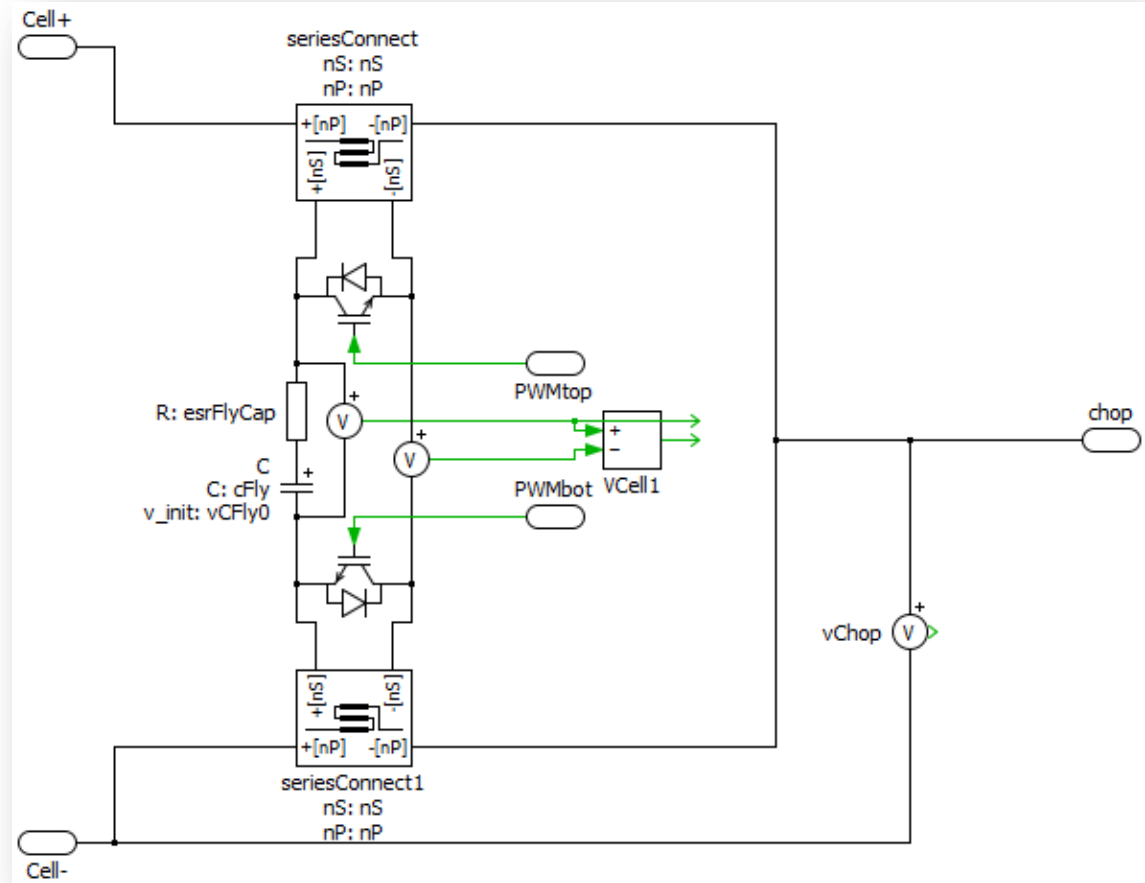
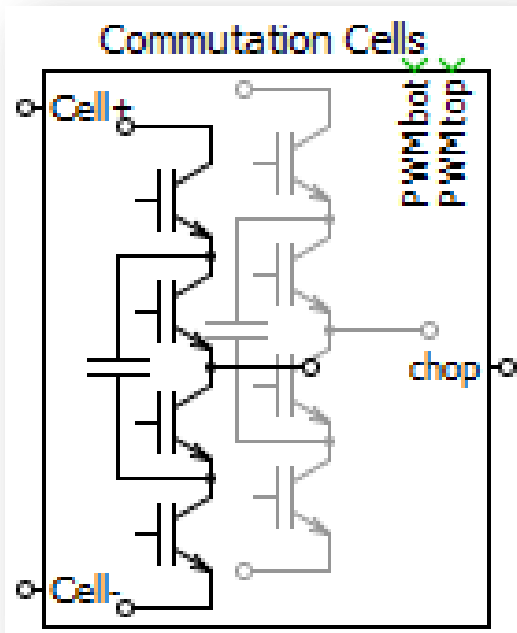
See also: HV side DM Filter with application-oriented mask Author: TM

Standard implantation is :

Parameters

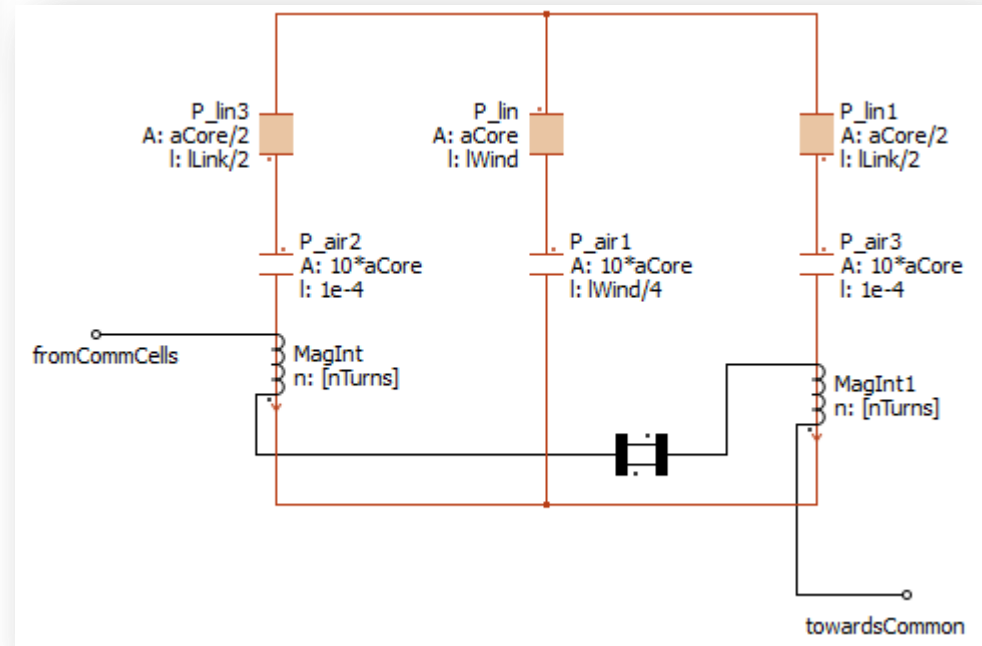
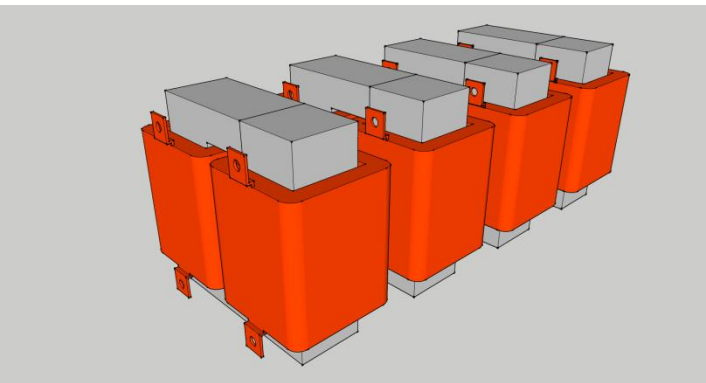
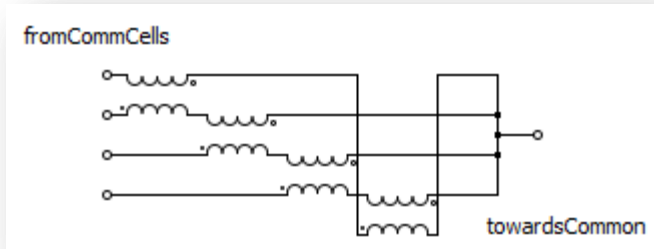
Voltage on HV side:	<input type="text" value="vA"/>	Normalized current ripple on LV side:	<input type="text" value="2.00"/>
Initial voltage on filter capacitors:	<input type="text" value="D*vA"/>	Normalized voltage ripple on LV side:	<input type="text" value="0.05"/>
Max Current on LV side:	<input type="text" value="vA/rLoad"/>	Standard:	<input type="text" value="EN55022A"/>
Switching frequency:	<input type="text" value="fSw"/>	Normalized voltage dip (LV side):	<input type="text" value="0.05"/>
Number of cells in series:	<input type="text" value="nS"/>	Minimize Inductance Value:	<input type="text" value="True"/>
Number of cells in parallel:	<input type="text" value="nP"/>	Display calculation details in Octave Console:	<input type="text" value="on"/>

Vectorized commutation cell

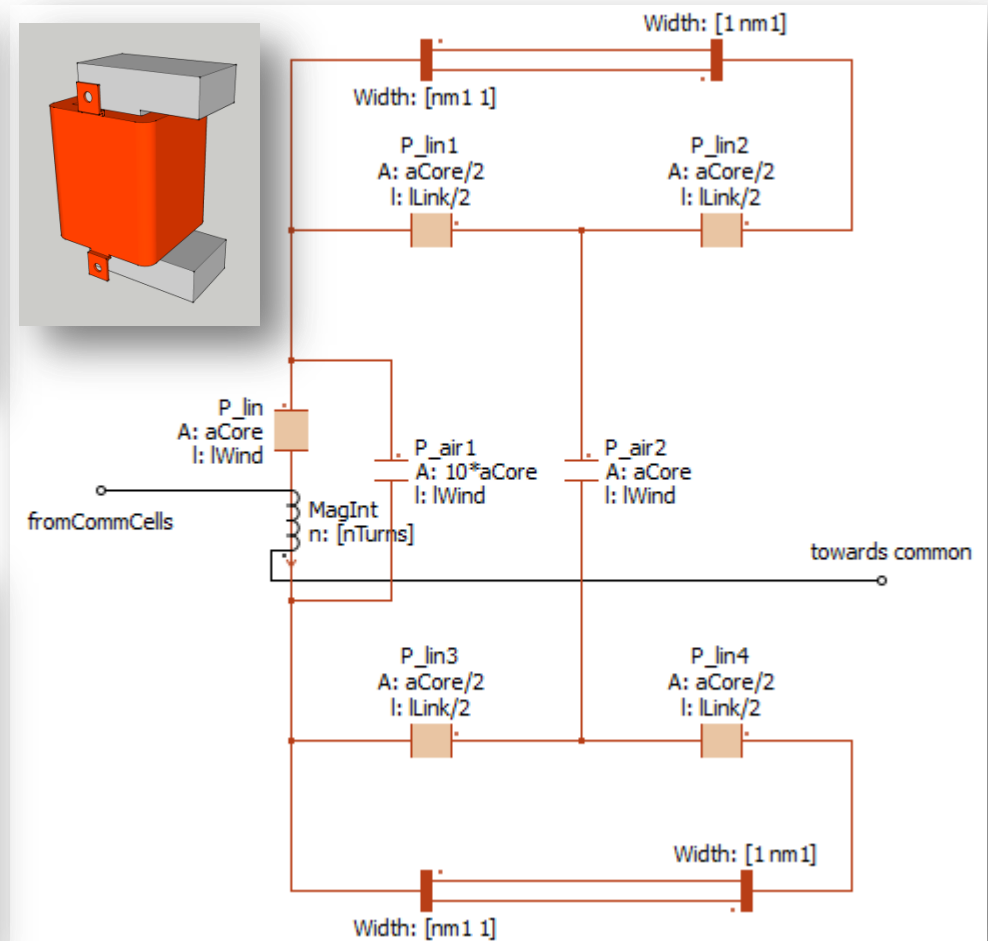
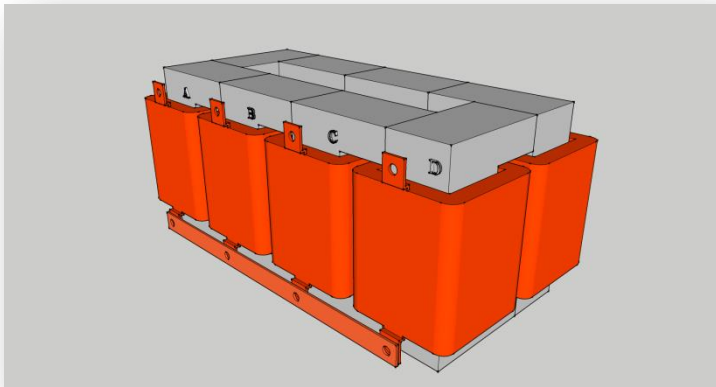
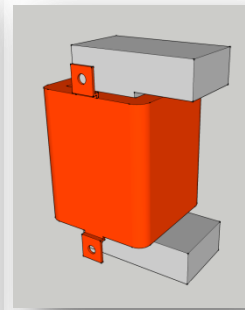
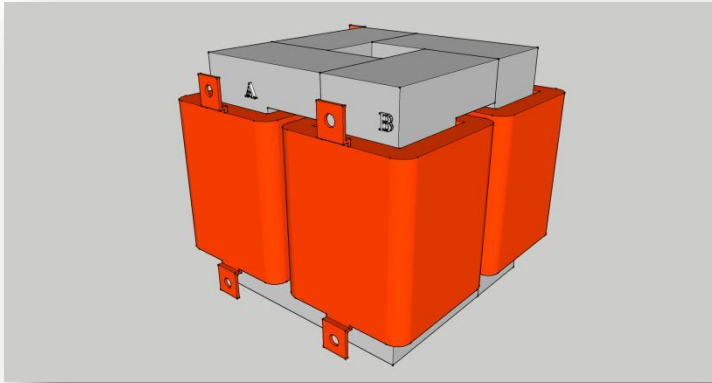


MacroCell is composed of Flying Cap Legs (nS commutation cells in series) that can typically be used in parallel connection (nP legs in parallel). Ideally, all commutation cells should all be controlled with the same duty cycle, but those in series with a phase-shift of $2\pi/nS$, and those in parallel with a phase-shift of $2\pi/nP$. When nP and nS are coprime, the input and output ripples are periodic at $nP \cdot nS \cdot f_{sw}$.

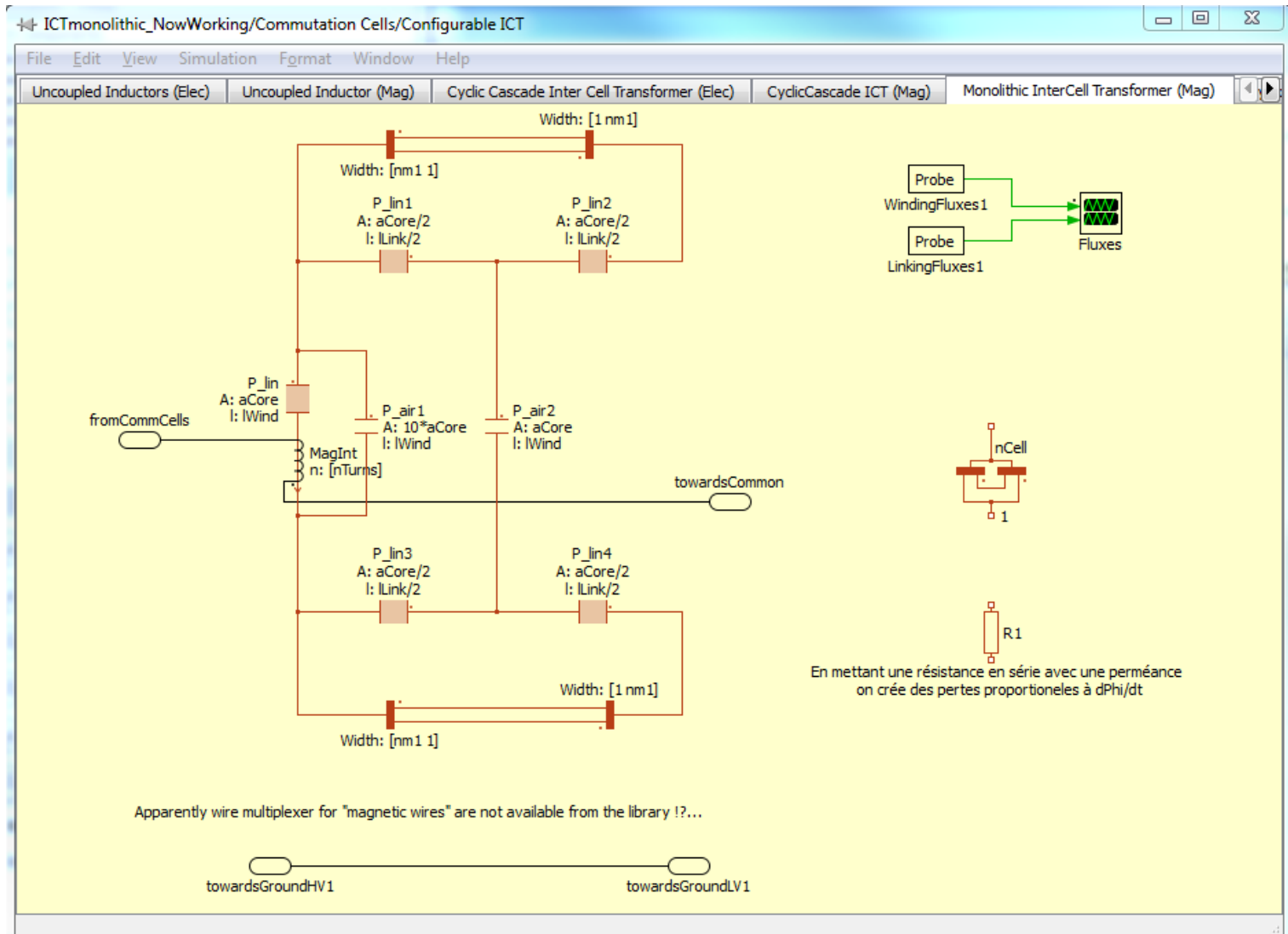
Vectorized Cyclic Cascade InterCell Transformer



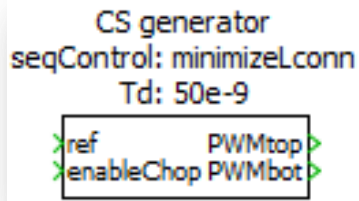
Vectorized Monolithic InterCell Transformer



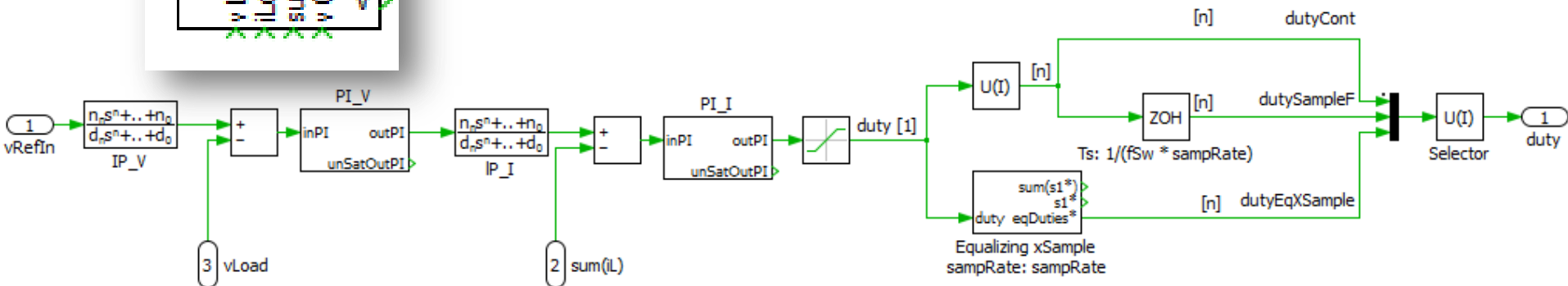
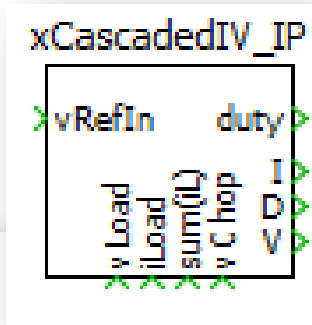
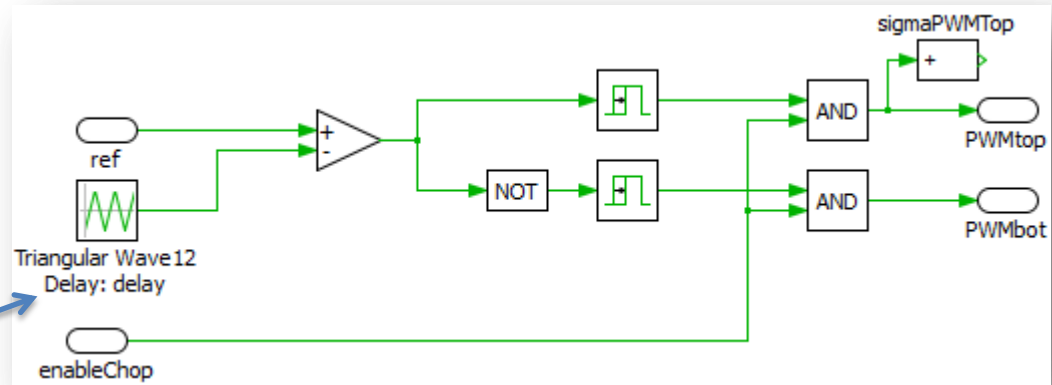
Vectorized and configurable magnetic components for interleaved converters



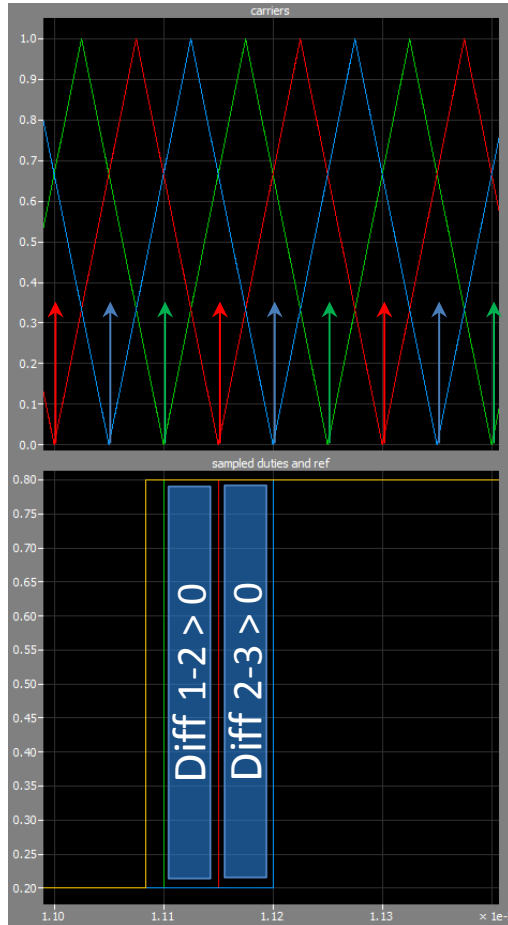
Vectorized regulator and control signal generator



Vectorized phase-shift makes the whole block vectorized



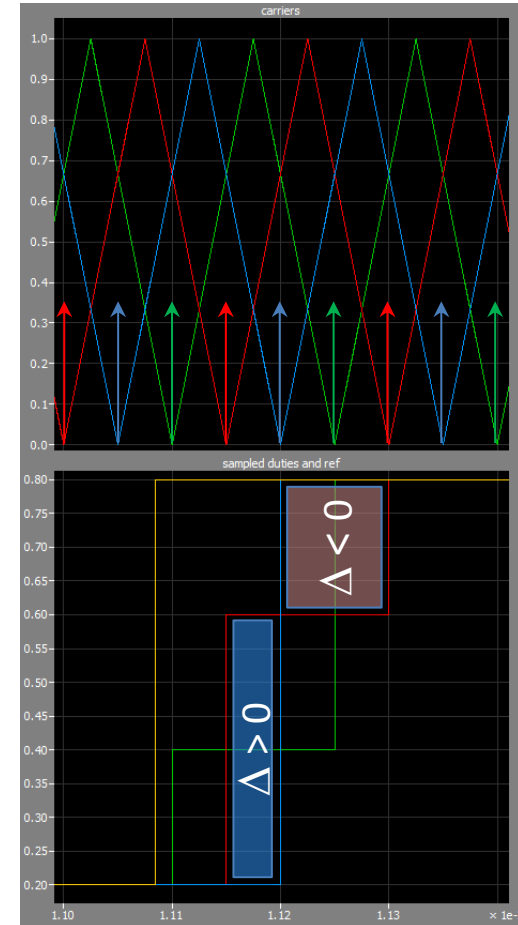
Vectorized equalizing sampler



Delayed sampling causes errors on the integral of the difference that are never compensated for

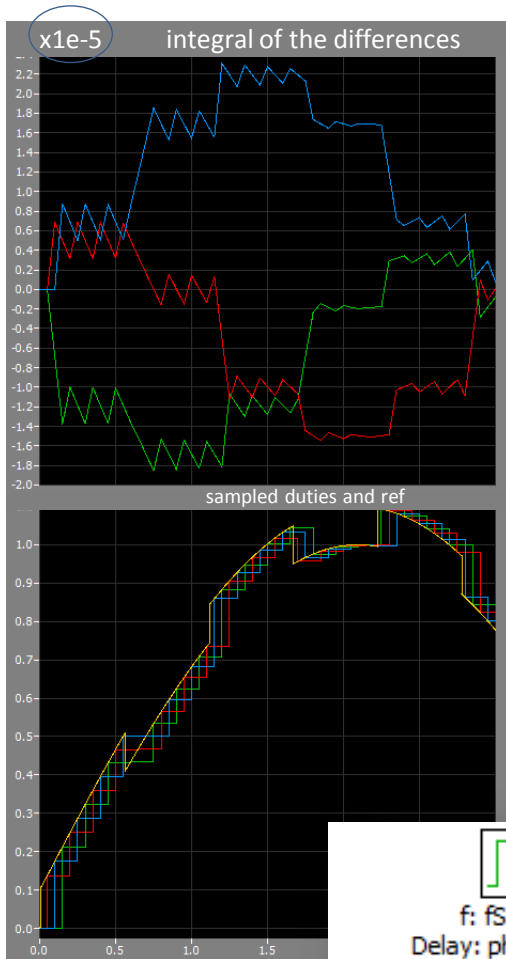


Sampling must be synchronized with carriers to avoid multiple switching in the same period



Each ref step must be handled to cancel the integral of the difference of any pair of control signals

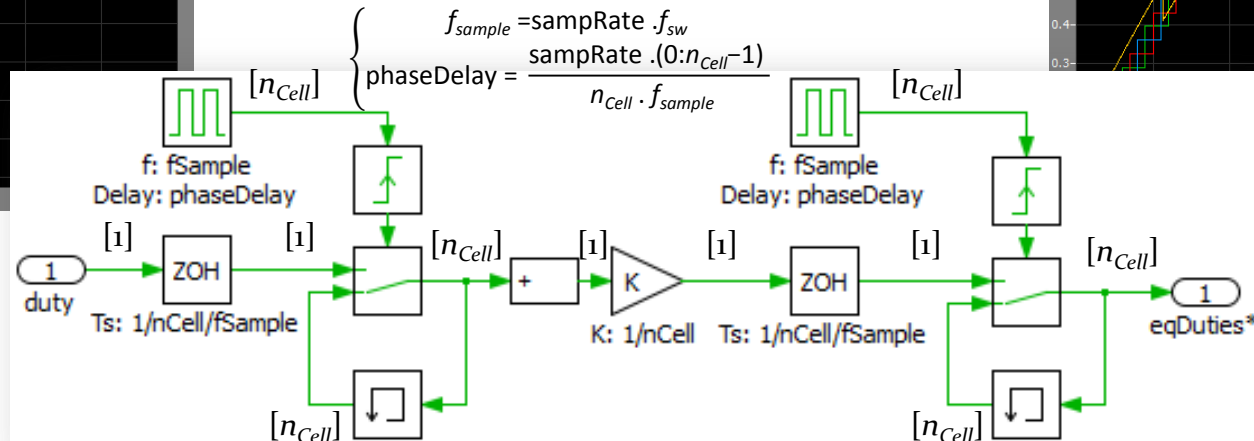
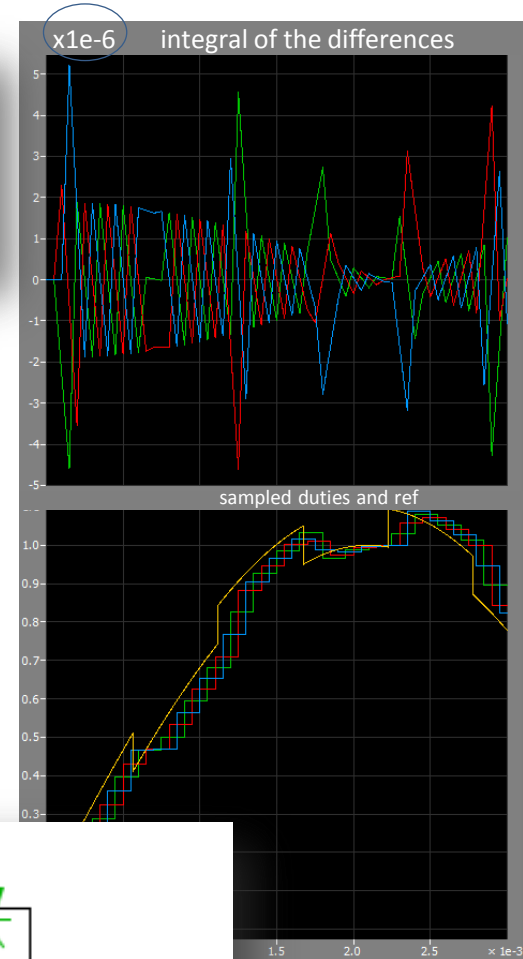
Vectorized equalizing sampler



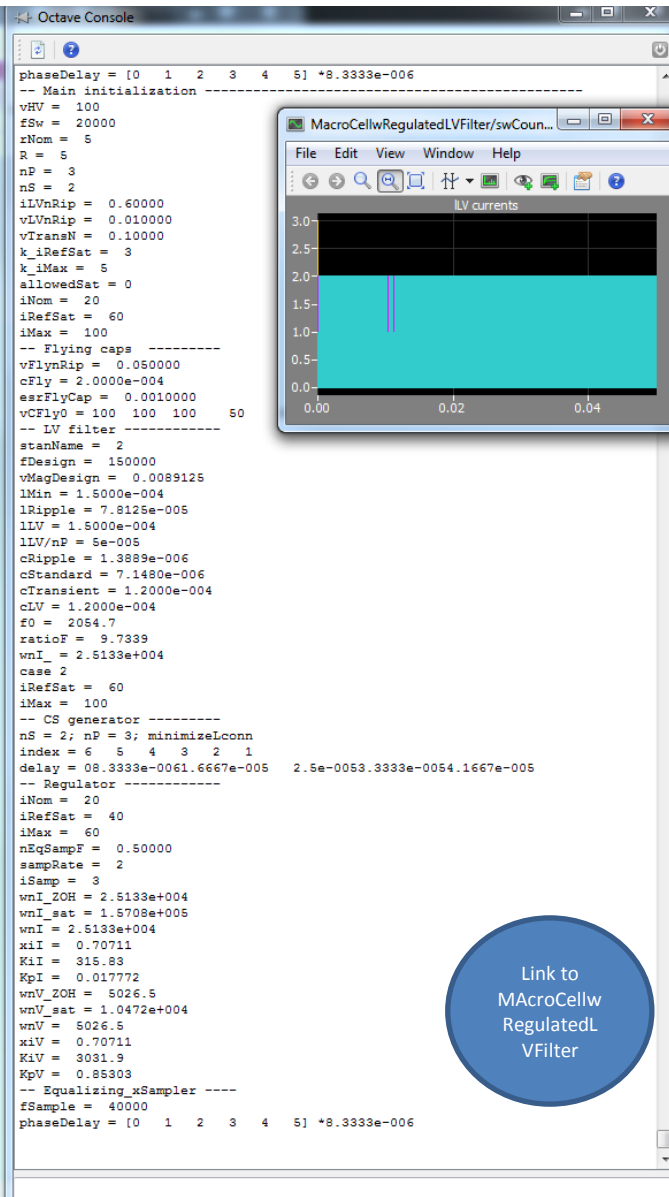
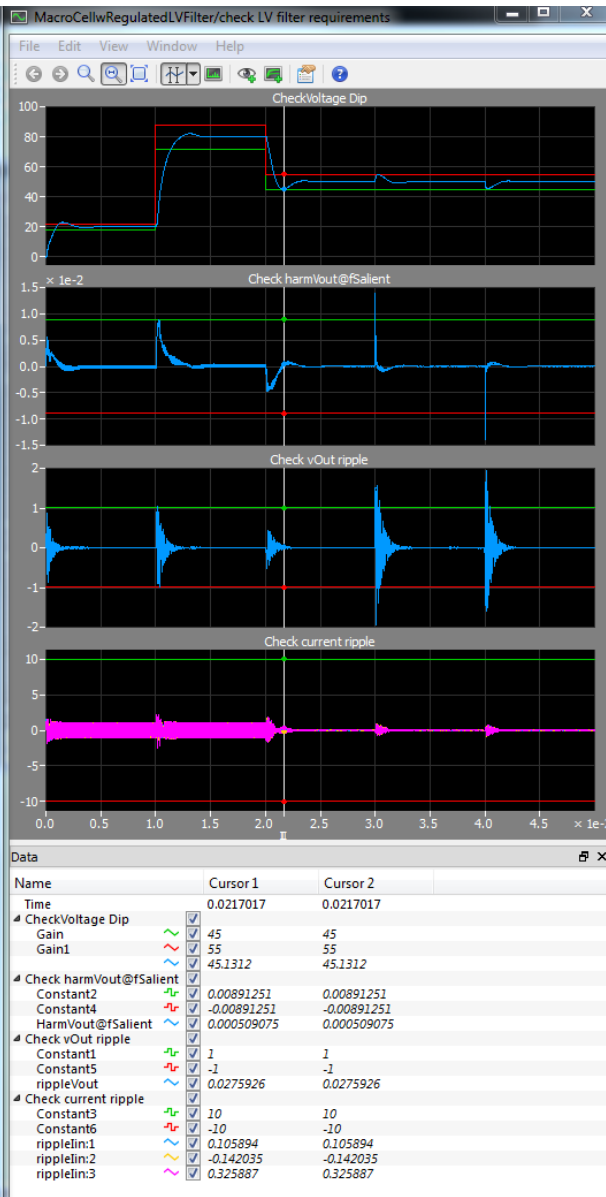
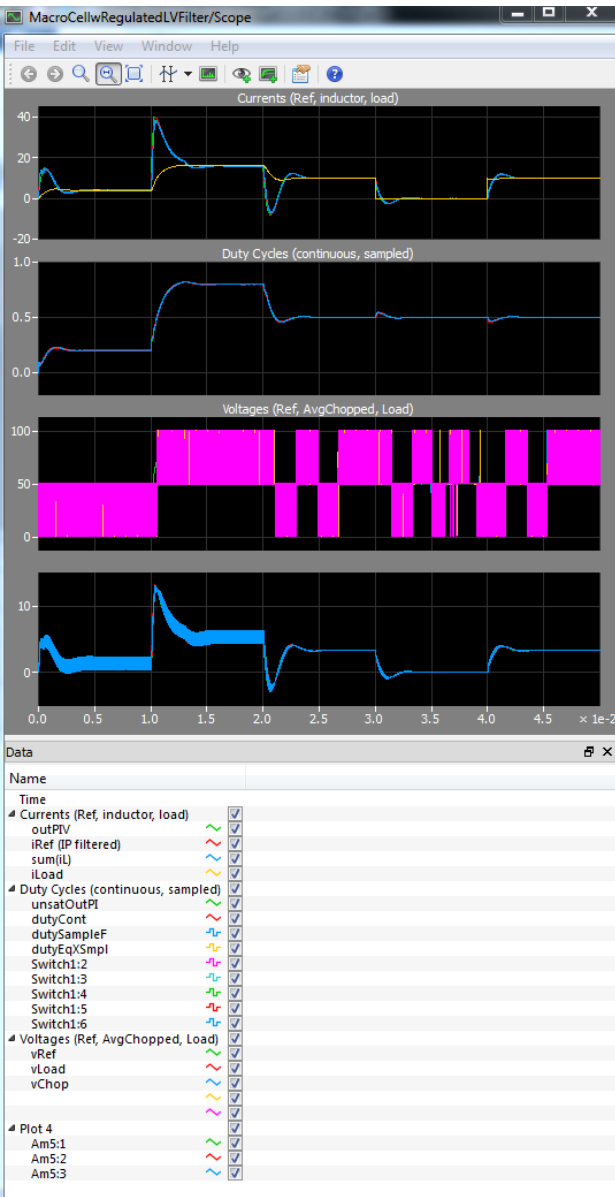
```

Equalizing xSampler
sampRate: sampRate
> duty eqDuties*
> s1*
> sum(s1*)
    
```

A simple circuit allows open-loop compensation of these unbalances without increasing the number of switchings



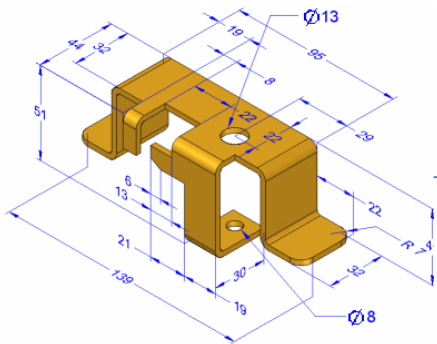
Design check



Link to
MacroCellw
RegulatedL
VFilter

DESIGNING WITH OBJECTS AND OPTIMIZATION

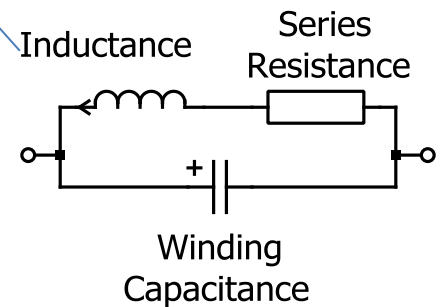
A real-world object



Shape
Dimensions
Material

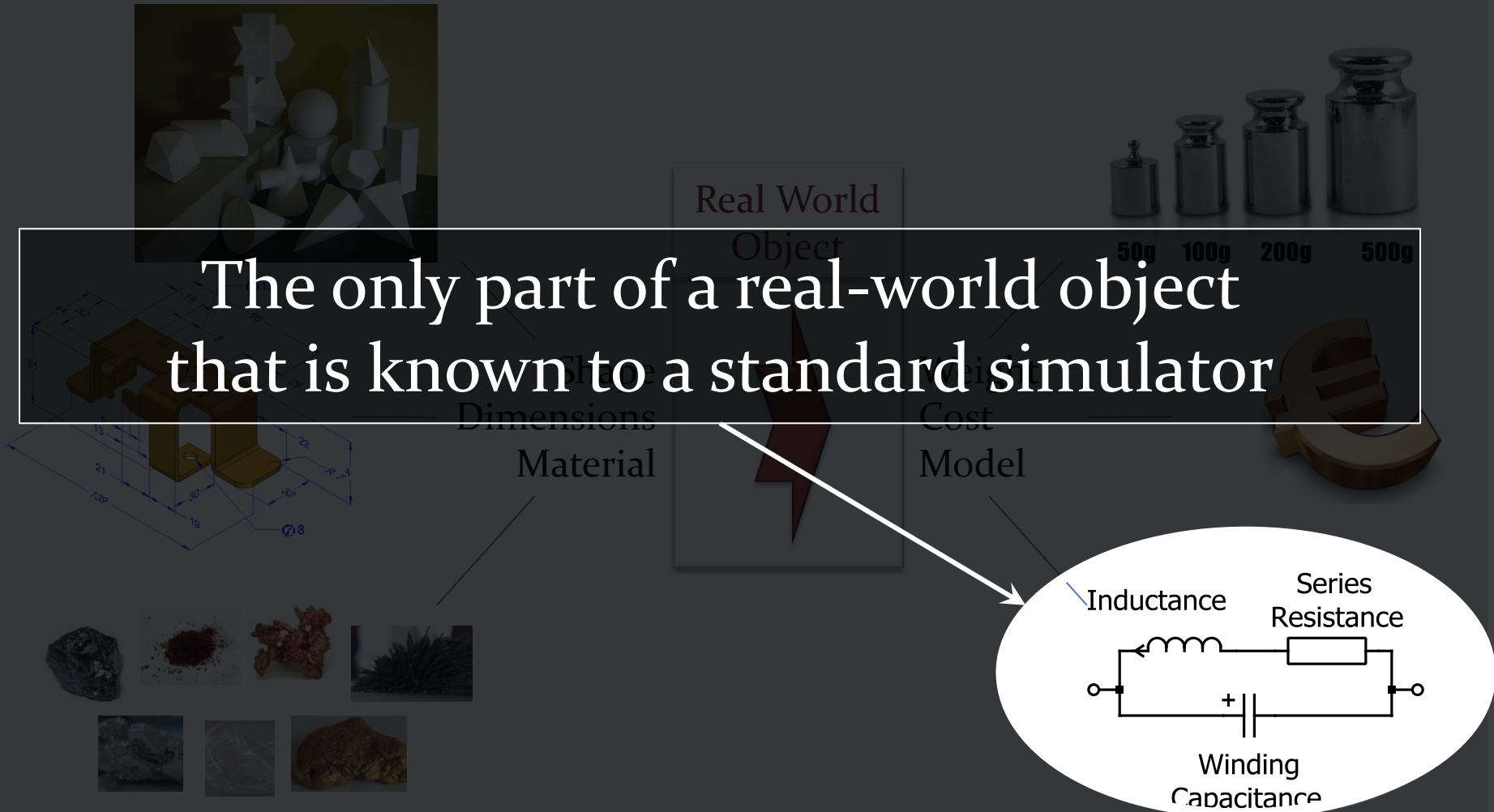


Weight
Cost
Model



A real-world object

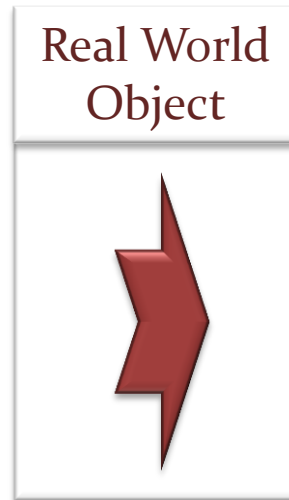
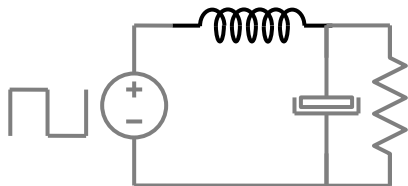
The only part of a real-world object that is known to a standard simulator



Designing a real-world object

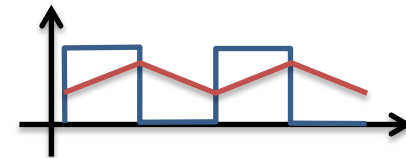
Apply stimuli according to specifications :

- Voltage,
- Current,
- Switching Pattern,
- Ambient temperature
- ...



Check compatibility with maximum ratings :

- Peak voltage
- Peak & RMS current
- Peak induction
- Losses => Temperature
- ...



Example : InterCell Transformer

Figures - GUI ICT_Ncells

File Edit Debug Desktop Window Help

Inputs

Initial Values

Variable in interval

Conductor Width (ec) 1 mm [0,2;5]

Conductor Height (hc) 80 mm [0,2;150]

InterWinding Distance (eww) 0.1 mm [1,50]

Vertical Core Leg Width (eli) 34 mm [30,34]

Horizontal Core Leg Height (elih) 20 mm [2,50]

Core depth (di) 34 mm [29,34]

Number of Turns (Nt) 20 [15,38]

Switching Frequency (Fs) 20 kHz [1,1000]

ICT dimensions

Project:

Project: APC_DCDC Directory: YourNameHere

Save Current Design in: CurrentBest.mat

reLoad Stored Design: CurrentBest.mat

Converter Specifications

Ncells: 8 Conv: Chopper

Fswitch: 20 kHz bus: 400 V

Series: 1 Iout: 675 Arms

Converter specs

Thermal specifications

Tc: 125 °C

Tambmax: 55 °C

Hexc: 36 W/°C/m²

ICT specs

Aluminium Materials: Rectangular Ladder Geometry

Vertical

Perfs at a blink

Manual Design

Draw ICT offsetY: 0 mm

Initial (X=0); Final (X=0.196) [m]

Clear Figure Evaluate

Outputs

Optimized Values

Copy Outputs to Inputs

Conductor Width (ec) 0.351153 mm

Conductor Height (hc) 69.8241 mm

InterWinding Distance (eww) 1 mm

Vertical Core Leg Width (eli) 30 mm

Horizontal Core Leg Height (elih) 10.6733 mm

Core Depth (di) 29 mm

Number of Turns (Nt) 15

Switching Frequency (Fs) 20 kHz

Constrained Quantities

Core Width (ei) 99.5346 mm

Core Height (hi) 99.9707 mm

Max Output Current Ripple (rippleNHF) 8.20073 App

Saturation Ratio (Ksat) 0.9

Total Losses (PTotal) 360.899 W

Total Volume (VoTotal) 1433.39 cm3

Total Mass (MTotal) 5.62556 kg

Total Price (PRTotal) 0 Euros

Total Current Density (JmaxTot) 3.52837 A/mm²

Temperature Rise (DeltaT) 45 °C

Main Characteristics

Bmax 0.36 T

Total Weight 5.62556 kg

Output Current Ripple 65.6058 App

Total Core Losses 85.6921 W

Total Conductor Losses 274.207 W

Total Losses 360.899 W

Maximum Temperature 45 °C

Constraint Values

Active

Core Width (eimax) 300 mm

Core Height (himax) 300 mm

Max Output Current Ripple (Ioutmax) 150 App

Saturation Ratio (Ksatmax) 0.9

Maximum Losses (Pmax) 500 W

Maximum Volume (Volmax) 10000 cm3

Maximum Mass (Mmax) 25 kg

Maximum Price (Prmax) 0 Euros

Maximum Current Density (Jmax) 8 A/mm²

Maximum Temperature Rise (Dtmx) 45 °C

Various Constant

Horiz. Winding Core Distance (ewc) 2 mm

Insulation Thickness (eins) 0.4 mm

Vacuum Permeability (Mu0) 1.25664e-006

Nr of Harmonics Calculated (Nhf) 200 mm

Duty Cycle (D) 0.5625

Constants

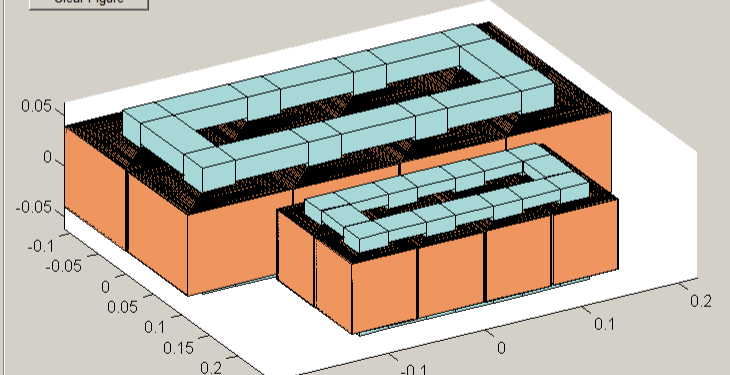
Optimization-based Design

Total Mass Optimize

Post-Processing

FEMM: 2D FE + RAC=> Copper losses BvsT: B(t) wfirms+ IGSE=>core losses Loop

Refine Optimization using FEMM and BvsT corrections



Example : InterCell Transformer

Figures - GUI ICT_Ncells

File Edit Debug Desktop Window Help

Inputs

Initial Values

Variable in interval

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Conductor Height (hc) 80 mm [0,2;150]

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Core depth (di) 34 mm [29;34]

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Maximum Losses (Pmax) 500 W

Maximum Volume (Volmax) 10000 cm3

Maximum Mass (Mmax) 25 kg

Maximum Price (Pmax) 0 Euros

Maximum Current Density (Jmax) 8 A/mm²

Maximum Temperature Rise (DTmax) 45 °C

Various Constant

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Insulation Thickness (eins) 0.4 mm

Vacuum Permeability (Mu0) 1.25664e-006

Nr of Harmonics Calculated (Nhr) 200 mm

Duty Cycle (D) 0.5625

Project:

Project: APC_DCDC Directory: YourNameHere

Save Current Design in: reLoad Stored Design: CurrentBest.max

Converter Specifications

Ncells: 8 Conv: Chopper

Fswitch: 20 kHz bus: 400 V

Series: 1 Iout: 675 Arms

Thermal specifications

Tc: 125 °C

Tambmax: 55 °C

Hexc: 36 W/°C/m²

ICT specs: Rectangular Ladder

Materials: Aluminium Geometry: Vertical

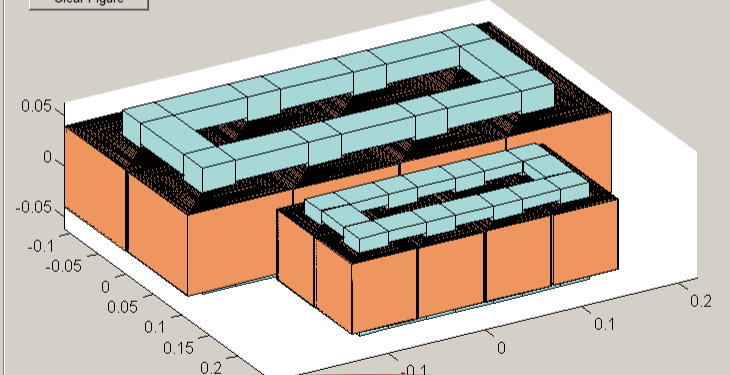
Perfs at a blink

Manual Design

Draw ICT offsetY: 0 mm Evaluate

Initial (X=0); Final (X=0.196) [m]

Clear Figure



Optimization-based Design 0.25 -0.2

Total Mass Optimize

Post-Processing

FEMM: 2D FE + RAC=> Core losses Dist: 2D Wires + GSE=> windings Loop

Re-fee Optimization using FEMM and BvsT corrections

Outputs

Optimized Values

Copy Outputs to Inputs

Conductor Width (ec) 0.351153 mm

Conductor Height (hc) 69.6241 mm

InterWinding Distance (eww) 1 mm

Vertical Core Leg Width (eli) 30 mm

Horizontal Core Leg Height (eliH) 10.6733 mm

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Total Mass (MTotal) 5.62556 kg

Total Price (PTotal) 0 Euros

Total Current Density (JeqrmsTotal) 3.52507 A/mm²

Temperature Rise (DeltaT) 45 °C

Main Characteristics

Bmax 0.36 T

Total Weight 5.62556 kg

Output Current Ripple 65.6058 App

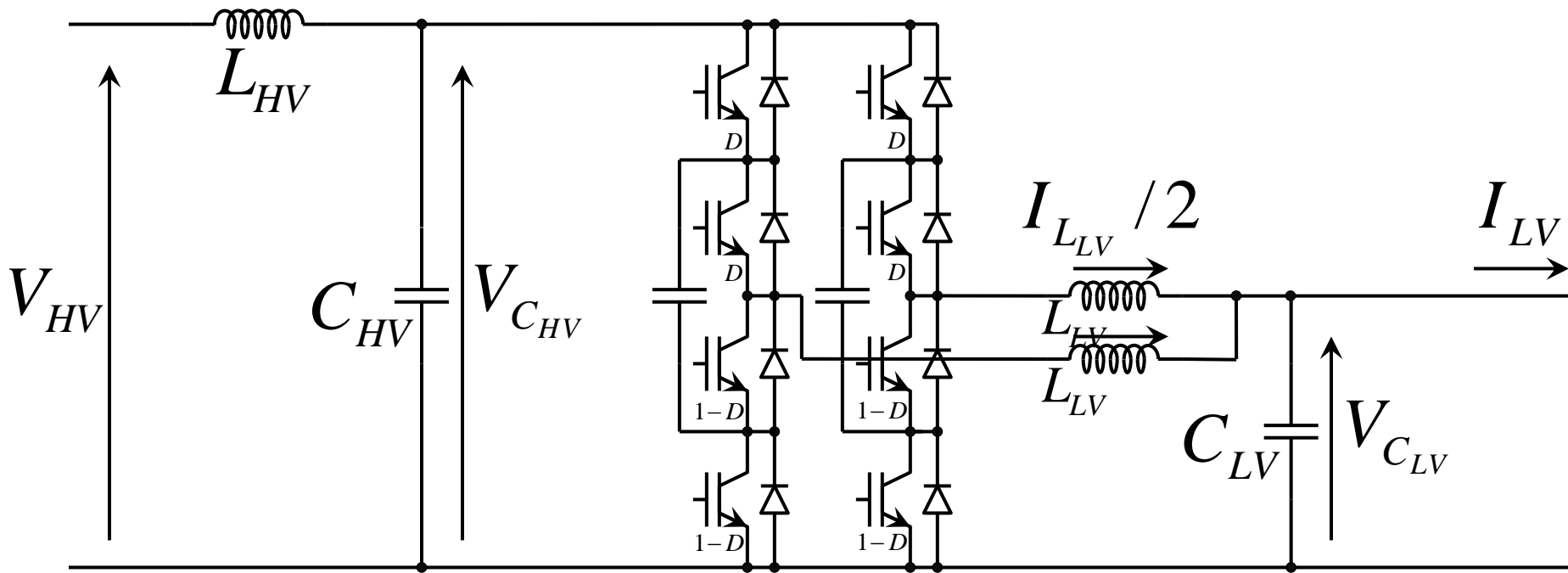
Total Core Losses 85.6921 W

Total Conductor Losses 275.207 W

Total Losses 360.899 W

Maximum Temperature 45 °C

Designing a full system



Collect objects

Source

shape dimensions materials



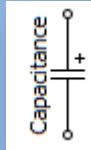
Weight



shape dimensions materials



Weight

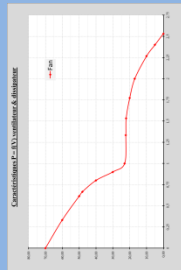


shape dimensions materials



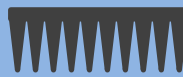
Weight

Air speed

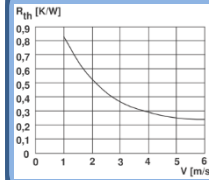


Losses??

shape dimensions materials

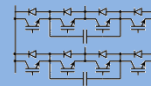


Weight

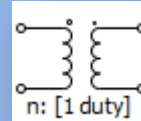


Losses??

shape dimensions materials



Weight

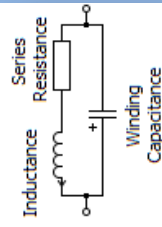


Losses??

shape dimensions materials



Weight

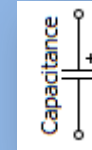


Losses??

shape dimensions materials

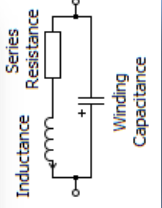
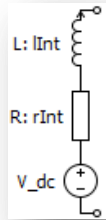
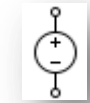
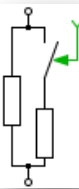


Weight



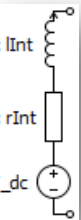
Losses??

Load

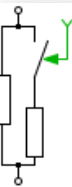


Compose objects

Source



Load



FILTER

shape dimensions materials	shape dimensions materials
Weight	Weight

Losses?? Losses??

Losses??

COOLING

shape dimensions materials	shape dimensions materials
Weight	Weight

Losses?? Losses??

Losses??

shape
dimensions
materials

Weight

Losses??

FILTER

shape dimensions materials	shape dimensions materials
Weight	Weight

Losses?? Losses??

Losses??

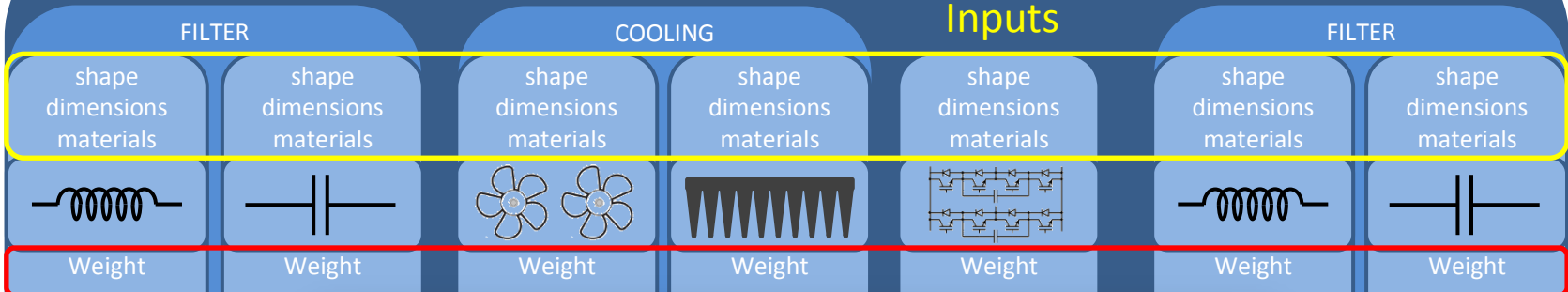
Build full system model and solve

Source

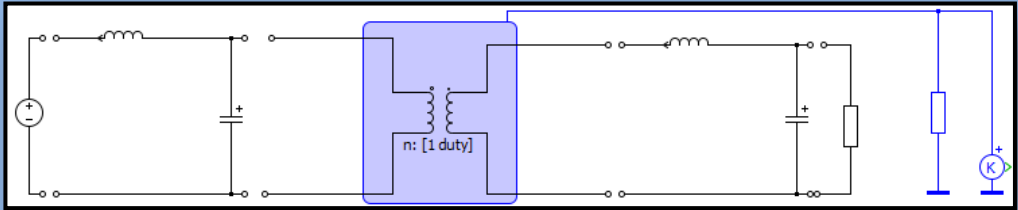
Load

FULL SYSTEM

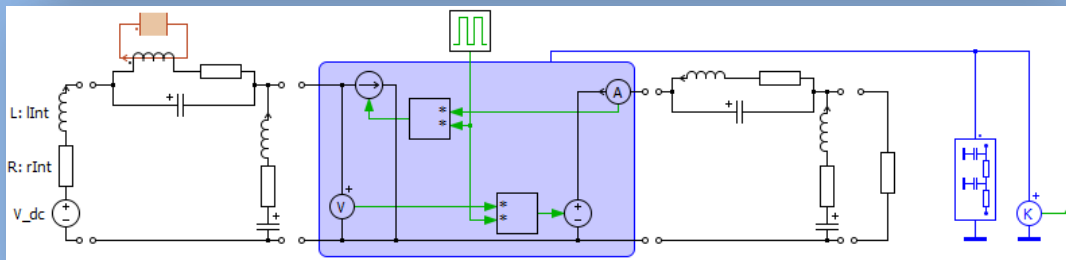
Inputs



Outputs



Outputs



Losses! Losses! Losses! Losses! Losses! Losses! Losses!

Losses??

Losses?? **Outputs**

Losses??

=> Simulate full system, find waveforms and evaluate losses at last!

Need for a fast solver

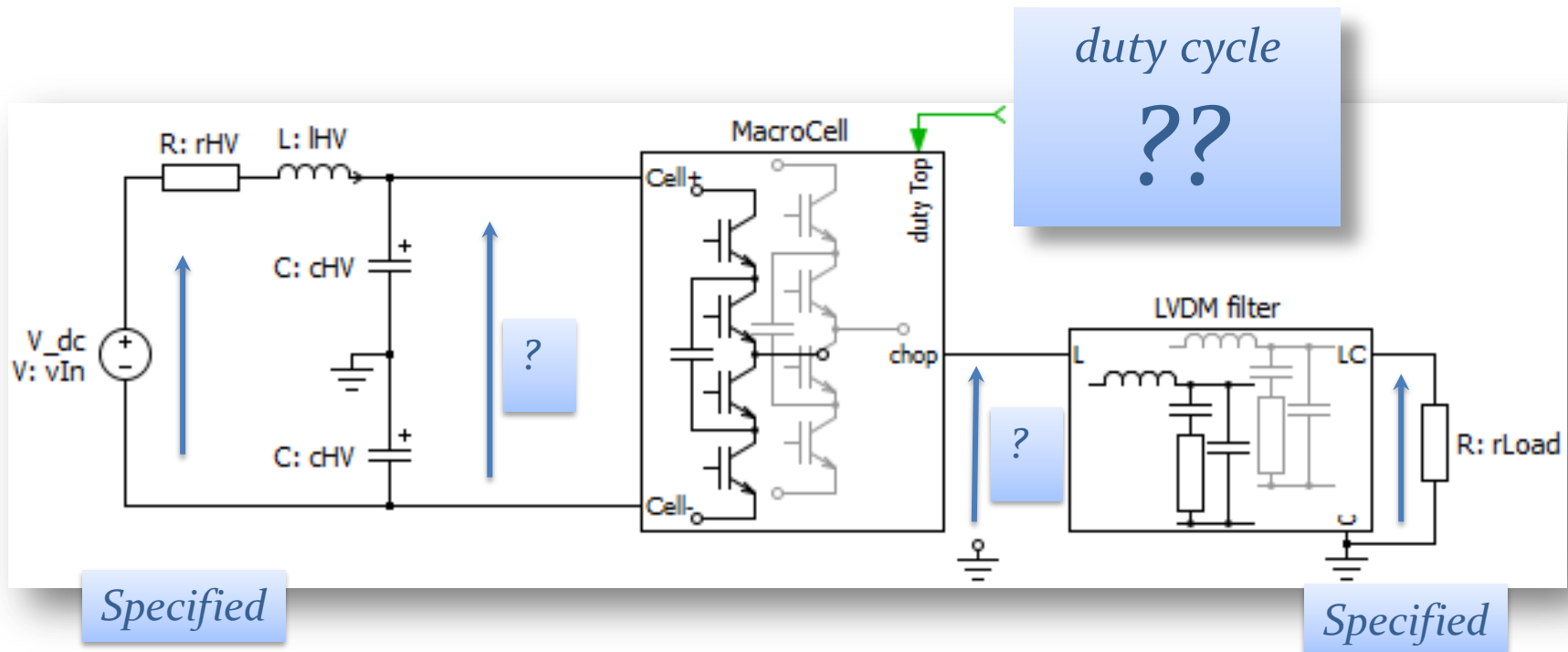
Steady-state waveforms are needed

- Accelerated determination of steady-state waveforms with a standard (time-domain) simulator is not the best choice.
- In most cases simplifications can be made to allow frequency domain analysis which inherently is a direct determination of steady state waveforms.

Main assumptions to allow standard frequency analysis (linear system) :

- Intrinsic non-linearities of components (saturation of permeability of magnetic materials, exponential $V(I)$ characteristics of diodes, etc) can be neglected :
- Voltage/current ripple applied to commutation cells can be neglected to decouple the HV and LV sides,
- Influence of spontaneous commutations can be neglected,

Direct determination of the operating point



Principle used for approximate determination of the operating point

Assumptions :

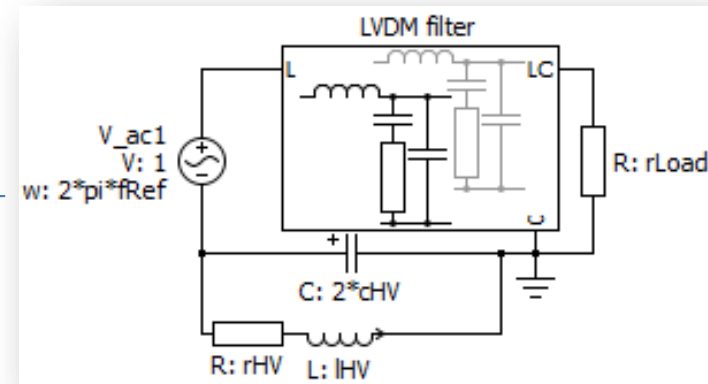
=> linear systems, lossless commutation cell, v_{HV} is constant

Apply $1V@f_{Ref}$ to the LV side and solve LV circuit

Find amplitude v_{load} per Volt and delay

Scale v_{AC} and select phase to match v_{load} specifications

Find power delivered by v_{AC} and scale for specs ($P_{LV} \# v_{AC}^2$)



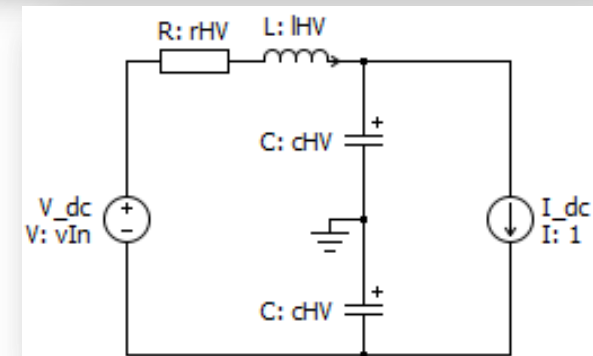
Lossless commutation cell => $P_{HV} = P_{LV}$

Constant v_{HV} => only i_{HV}^{DC} gives P_{HV}

Solve HV circuit with $I_{dc} = 1A$ and find internal resistance

Find i_{HV}^{DC} and v_{HV} such that $P_{HV} = P_{LV}$

Find duty cycle so that $v_{AC} = D(t) \cdot v_{HV}$



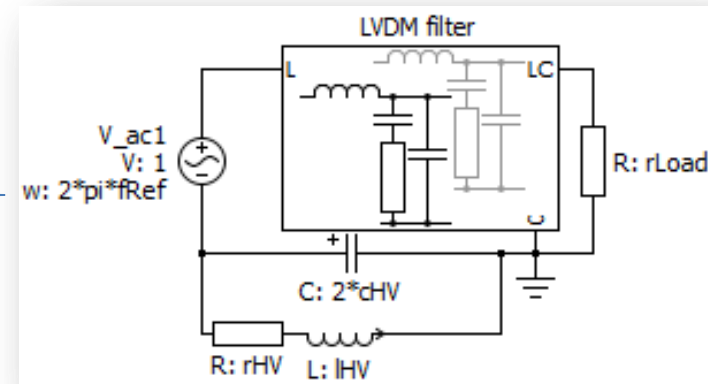
Equations used for approximate determination of the operating point

Assumptions :

=> linear systems, lossless commutation cell, v_{HV} is constant

$$v_{AC}^{opPoint} = \frac{|v_{load}^{opPoint}|}{|v_{load}^N|} \angle(\varphi_{ref}^{opPoint} - \varphi_{load}^N)$$

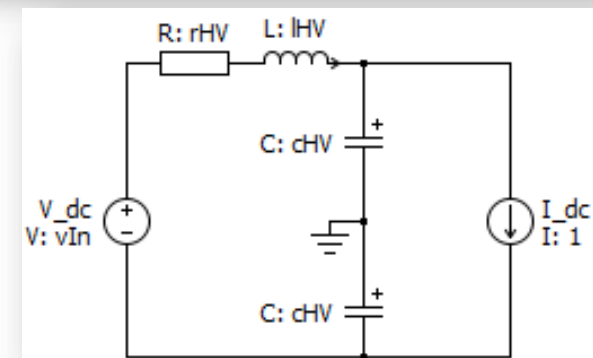
$$P_{AC}^{opPoint} = P_{AC}^N \left(\frac{|v_{load}^{opPoint}|}{|v_{load}^N|} \right)^2$$



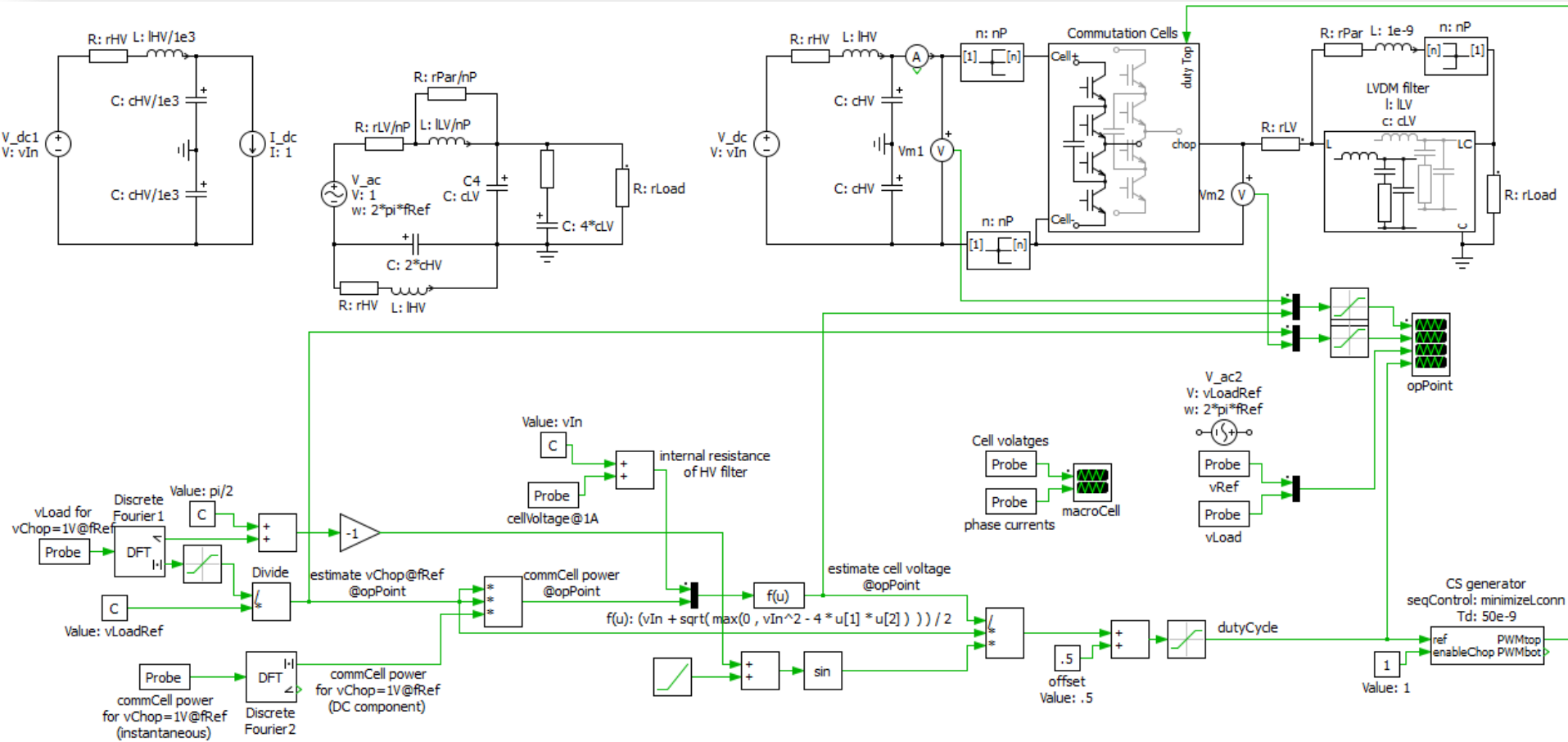
$$r_{int} = v_{in} - v_{HV}^N$$

$$v_{HV}^{opPoint} = \frac{v_{in}}{2} + \frac{\sqrt{v_{in}^2 - 4 \cdot r_{int} \cdot P_{AC}^{opPoint}}}{2}$$

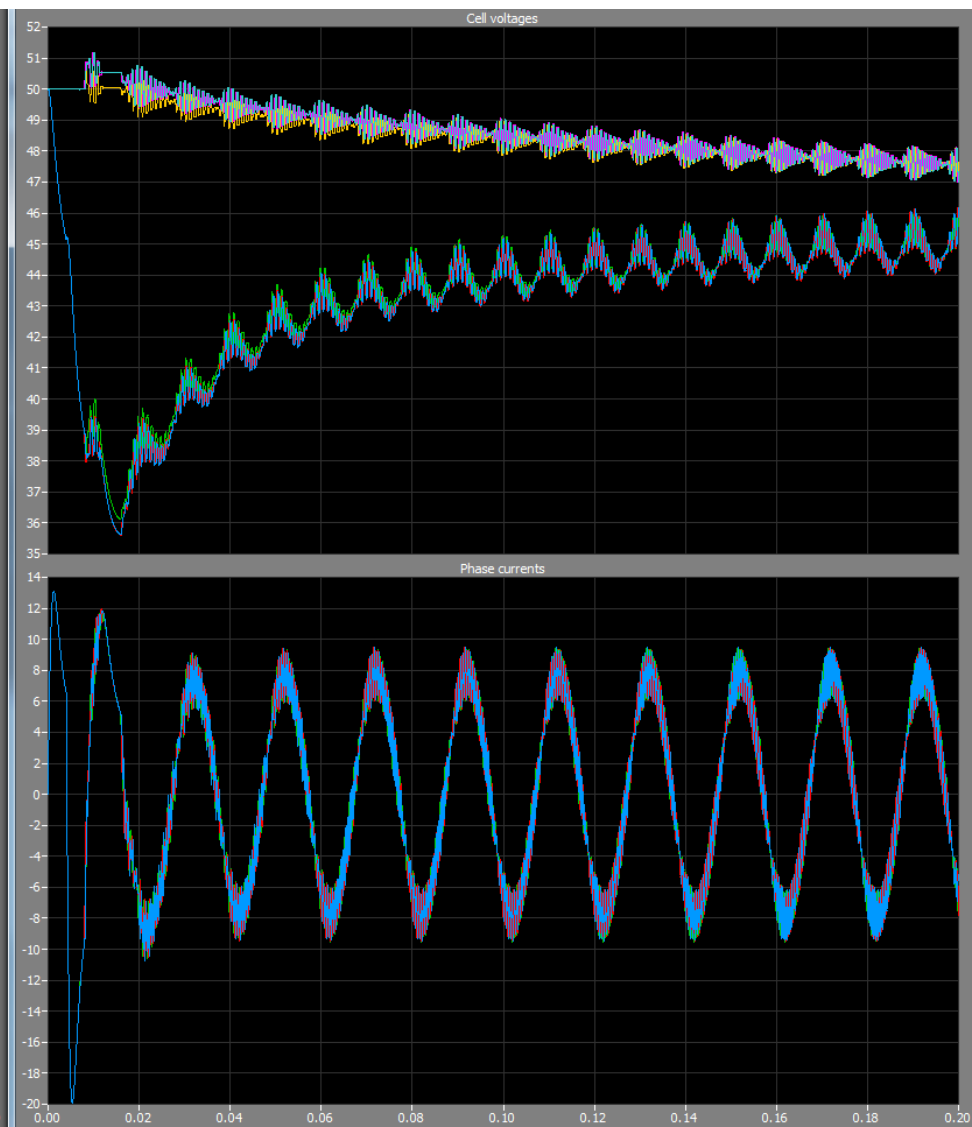
$$\Rightarrow duty(t) = \frac{v_{AC}^{opPoint}}{v_{HV}^{opPoint}}$$



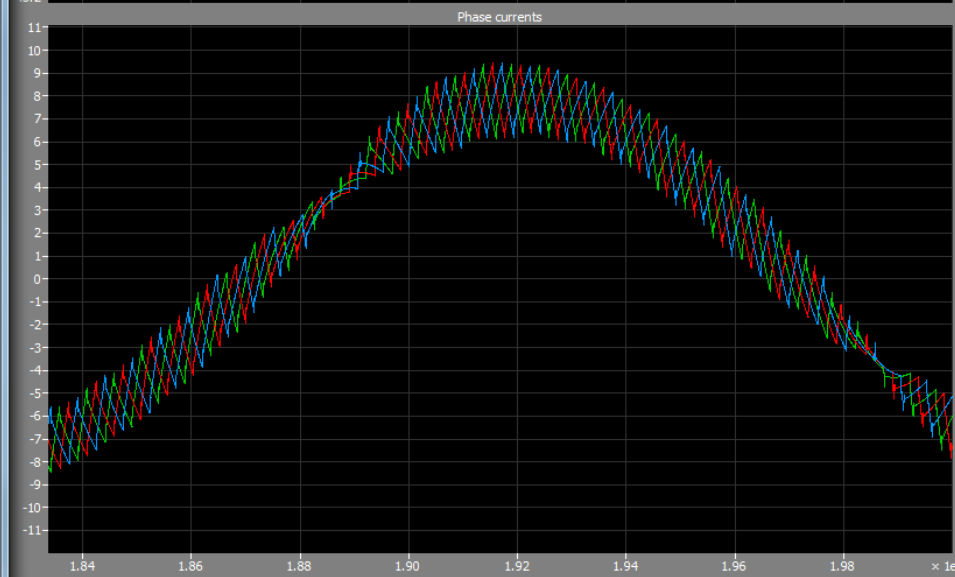
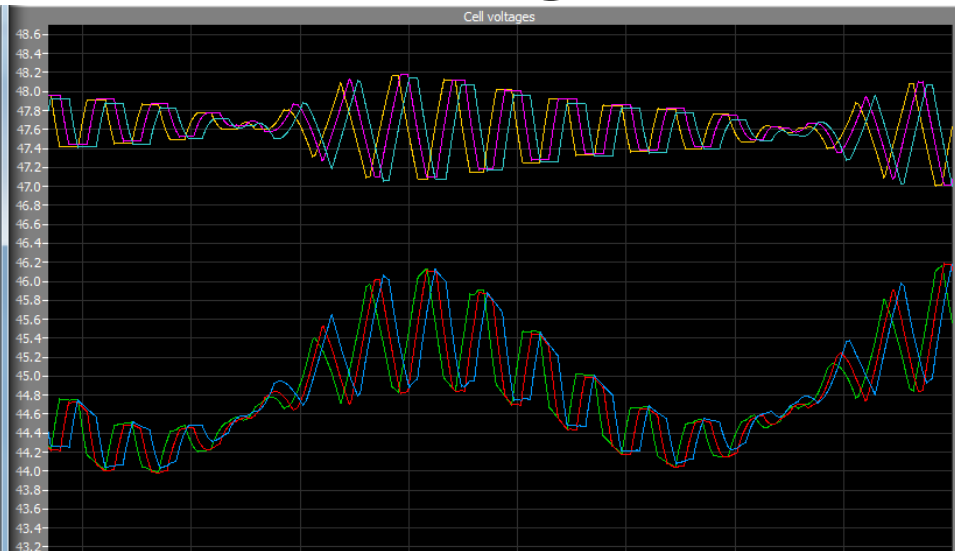
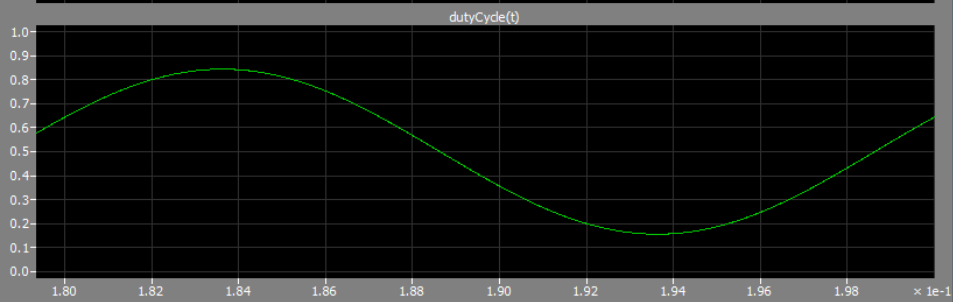
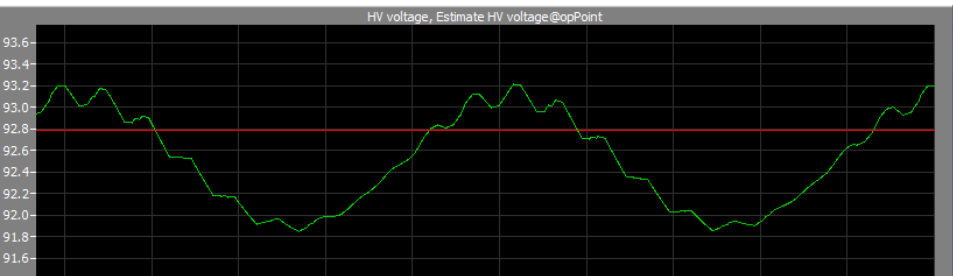
Approximate time domain determination of the operating point



Approximate time domain determination of the operating point

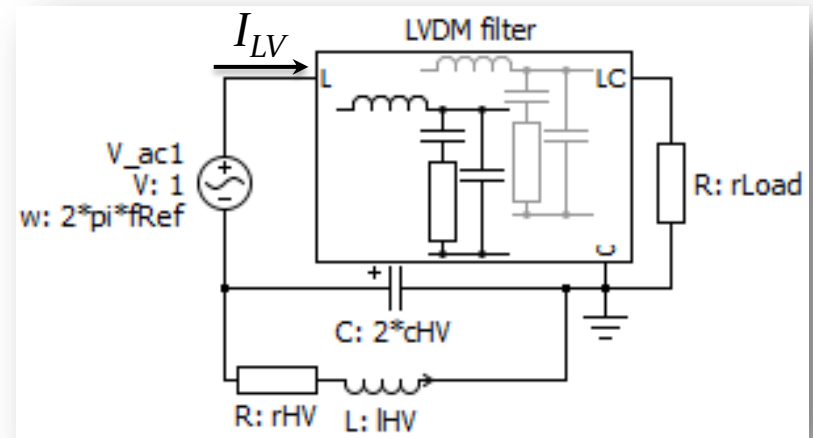
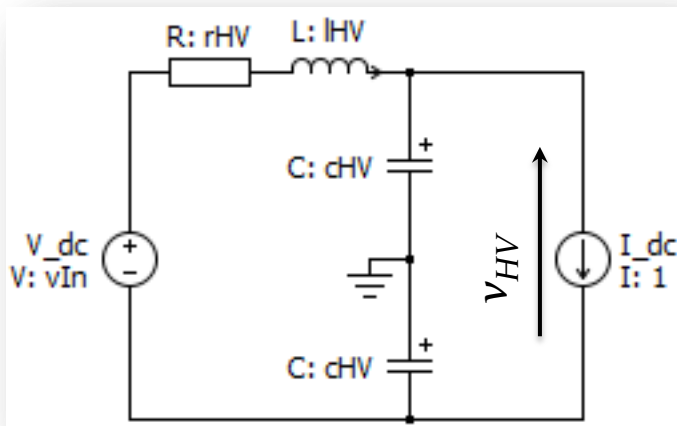


Approximate time domain determination of the operating point



Approximate frequency domain determination of the operating point

Solve separate 'normalized' circuit ($I_{DC}=1A$; $V_{AC}=1V \angle 0^\circ$) using a single frequency! (DC and f)



$$\begin{cases} r_{int} = v_{in} - v_{HV}^N \\ v_{HV}^{opPoint} = \frac{v_{in}}{2} + \frac{\sqrt{v_{in}^2 - 4 \cdot r_{int} \cdot P_{AC}^{opPoint}}}{2} \end{cases}$$

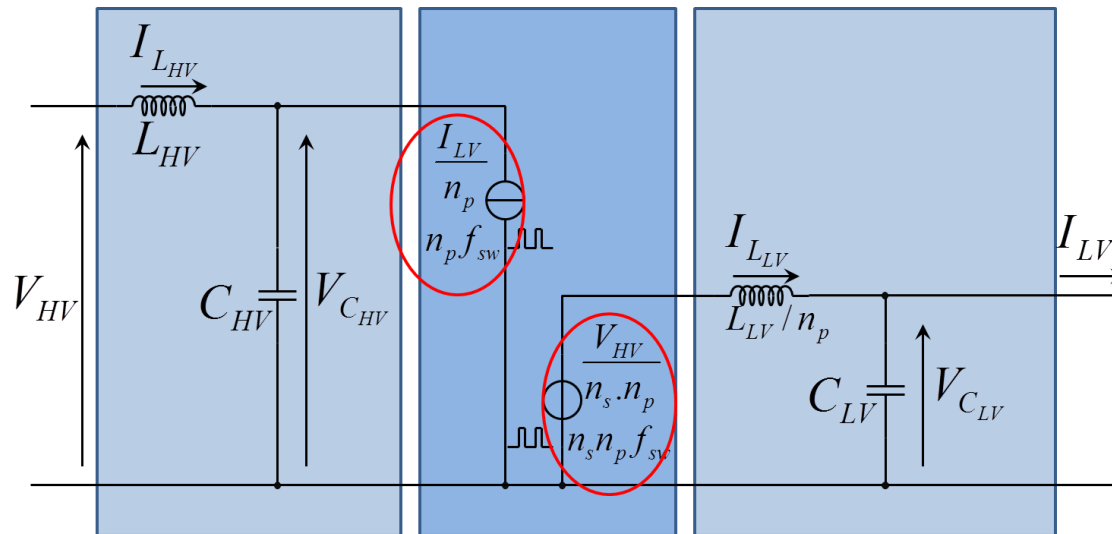
$$\begin{cases} v_{AC}^{opPoint} = \frac{|v_{load}^{opPoint}|}{|v_{load}^N|} \angle (\varphi_{ref}^{opPoint} - \varphi_{load}^N) \\ P_{AC}^{opPoint} = P_{AC}^N \left(\frac{|v_{load}^{opPoint}|}{|v_{load}^N|} \right)^2 \end{cases}$$

$$\Rightarrow duty(t) = \frac{v_{AC}^{opPoint}}{v_{HV}^{opPoint}}$$

Full frequency domain analysis using the operating point

The control pattern $duty(t)$ determined previously allows direct calculation of the steady state waveforms at a point that is very close to the specified point:

- The circuit is split in independant linear subcircuits
- The spectra of the sources are derived from $duty(t)$, $v_{HVDC}^{opPoint}$ and $i_{LVf_{Mod}}^{opPoint}$ (time domain multiplication by $duty(t)$ followed by FFT, or direct convolution of spectra)



- The circuit is solved in the frequency domain
- If necessary time waveforms regenerated using iFFT.

Optimize at last...

