Design Methods and Tools for Power Electronics

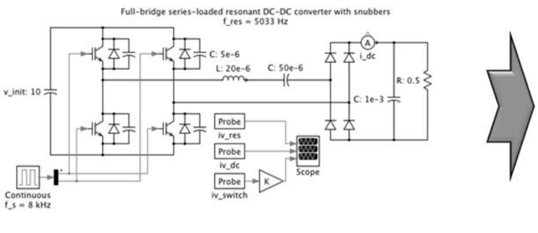
T. Meynard – G. Fontes
Laplace – N7 – CNRS
Toulouse

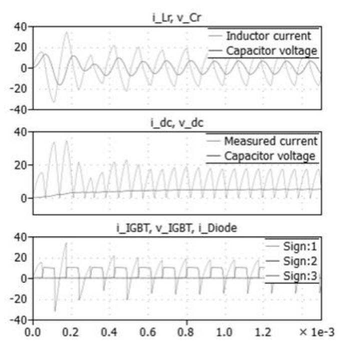
Outline of the presentation

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

SIMULATION VS DESIGN

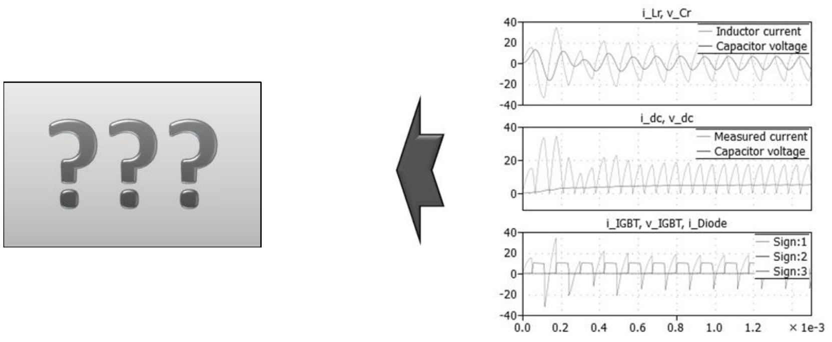
Standard simulation tools





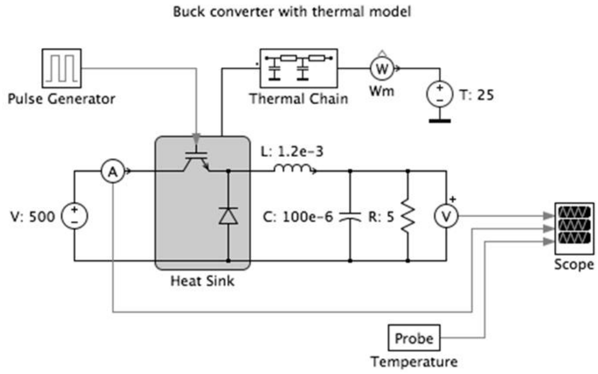
Simulation is an injection :
one circuit gives a single set of waveforms.

Design tools



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

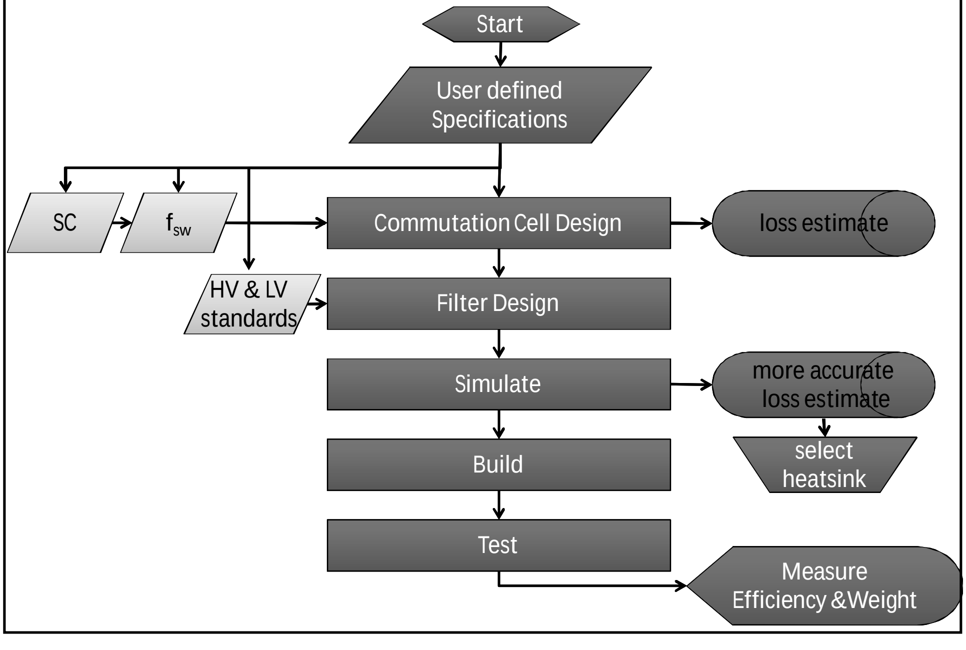
Hidden quantities in standard simulation tools



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



Start

User defined Specifications

SC

f_{sw}

HV & LV standards

Commutation Cell Design

loss estimate

Filter Design

Simulate

more accurate loss estimate

select heatsink

Build

Test

Measure Efficiency &Weight

COMMUTATION CELL DESIGN

Find the MacroSwitch with the best efficiency

Rules of the game

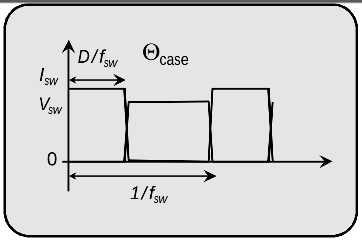
a) Define a global switch requirement (Voltage current, Frequency, Duty Cycle, Case Temperature,..)

b) Evaluate the limit of operation of a switch to determine haw 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

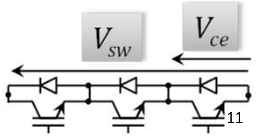


2-Find number of series connected switches

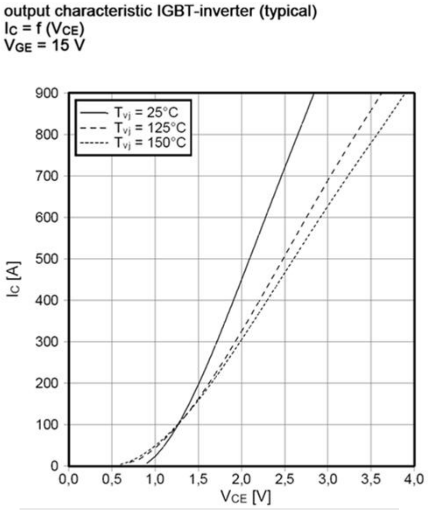
Voltage to be switched
+
Maximum collector-emitter voltage in switching mode

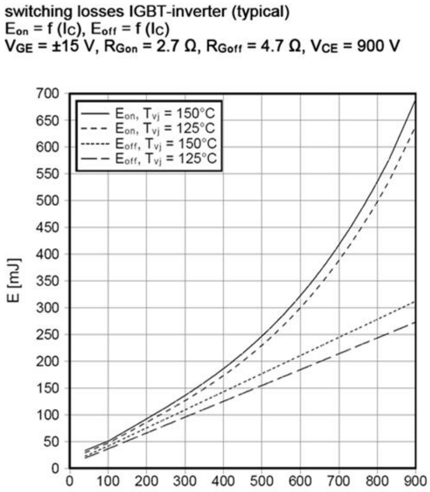
Number of series connected switches

$$n_{Series} = \mathrm{int}\left(\frac{V_{sw}}{V_{\mathrm{margin}} \cdot V_{CE\max}}\right) + 1$$



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

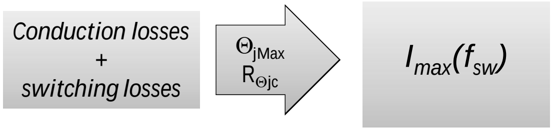

output characteristic IGBT-inverter (typical)
$I_C = f(V_{CE})$
$V_{GE} = 15$ V


switching losses IGBT-inverter (typical)
$E_{on} = f(I_C)$, $E_{off} = f(I_C)$
$V_{GE} = \pm 15$ V, $R_{Gon} = 2.7\ \Omega$, $R_{Goff} = 4.7\ \Omega$, $V_{CE} = 900$ V

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

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

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



Conduction losses
+
switching losses

Θ_{jMax}
$R_{\Theta jc}$

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

Conduction losses + Switching losses = Maximum Power extracted

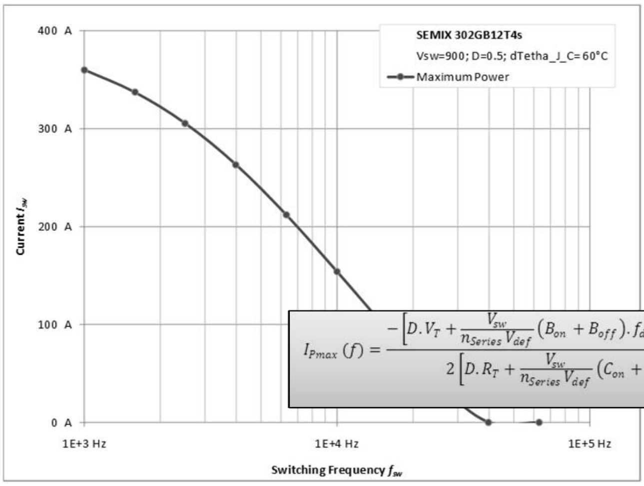
$$D.(R_T.I^2 + V_T.I) + f_{déc}\frac{V_{sw}}{n_{Series}V_{def}}\left[(A_{on} + A_{off}) + (B_{on} + B_{off}).I + (C_{on} + C_{off}).I^2\right] = \frac{\Delta\theta}{R_{th}}$$

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

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

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

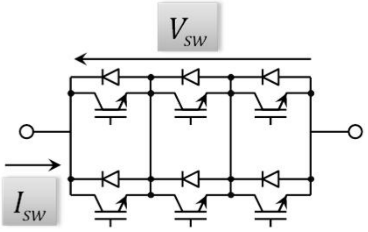
Current /frequency operating area of a switch Maximum Power



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

4-Find number of parallel connected switches

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



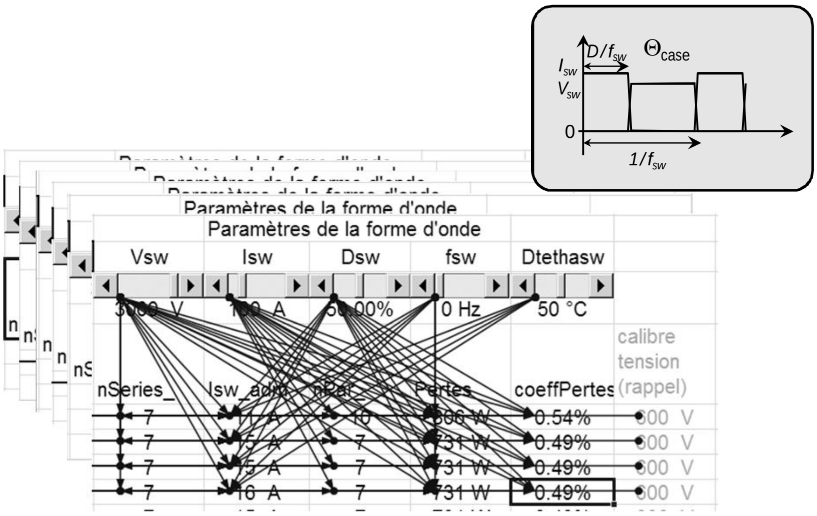
5-Find losses and efficency

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

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

6-Build a MacroSwitch with each component of the database

Explore IGBT database

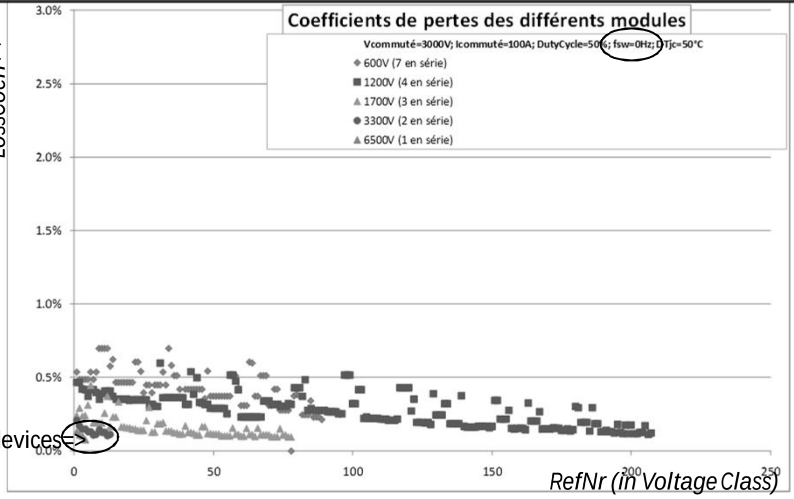


Paramètres de la forme d'onde

Vsw	Isw	Dsw	fsw	Dtethasw	
3000 V	100 A	50.00%	0 Hz	50 °C	
nSeries_	Isw_adm	nPar_	Pertes	coeffPertes	calibre tension (rappel)
7	11 A	10	806 W	0.54%	600 V
7	15 A	7	731 W	0.49%	600 V
7	15 A	7	731 W	0.49%	600 V
7	16 A	7	731 W	0.49%	600 V

Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT database

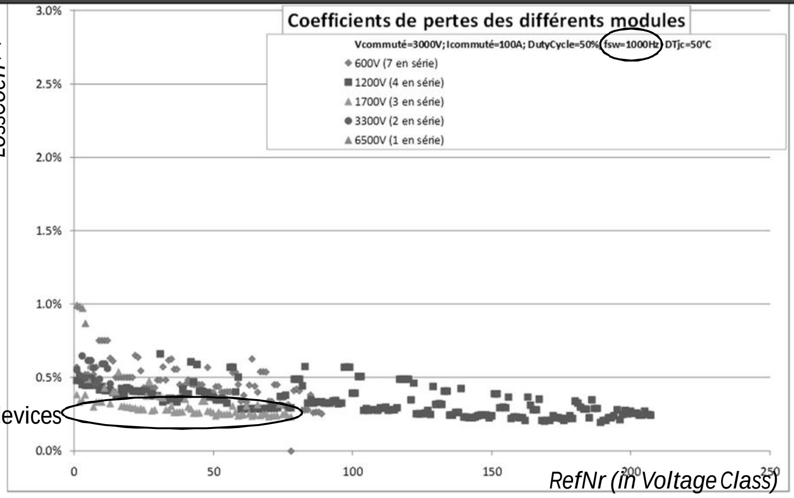


6500Vdevices=>

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

Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT database

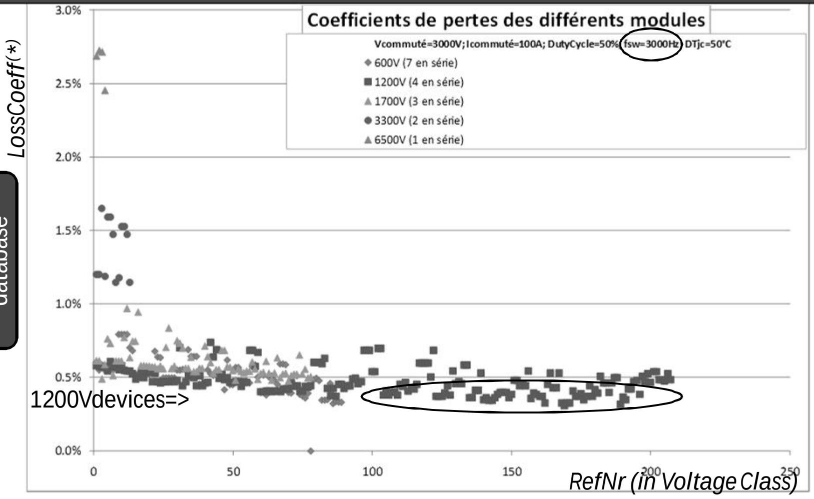


1700Vdevices
=>

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

Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT database



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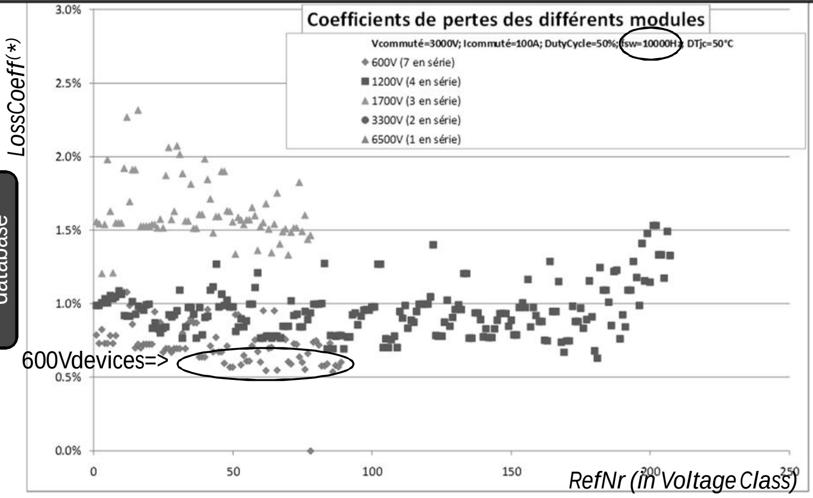
Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT database



(*) LossCoeff = Loss in one switch / Ouput 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.

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

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

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

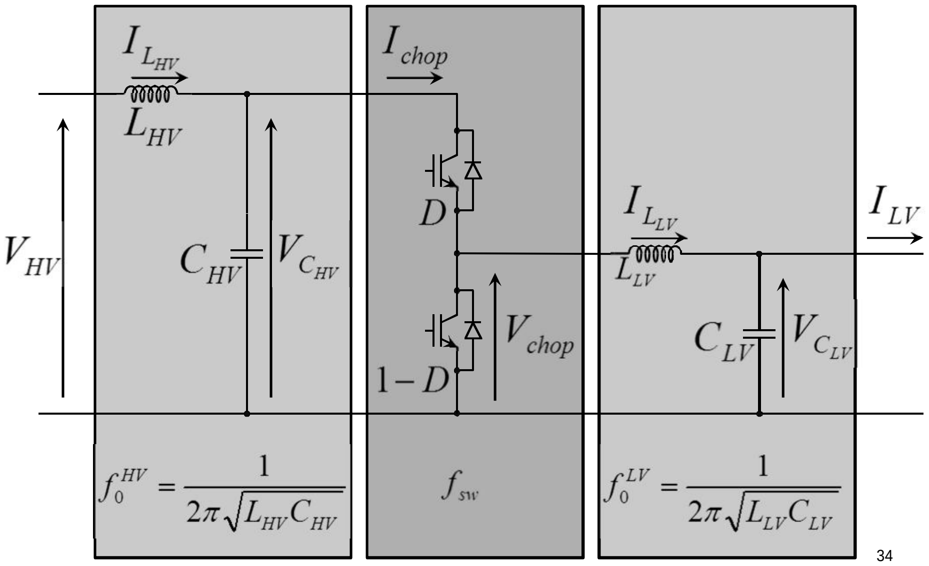
PASSIVE COMPONENTS FOR MULTILEVEL CONVERTERS

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



$$f_0^{HV} = \frac{1}{2\pi\sqrt{L_{HV}C_{HV}}}$$

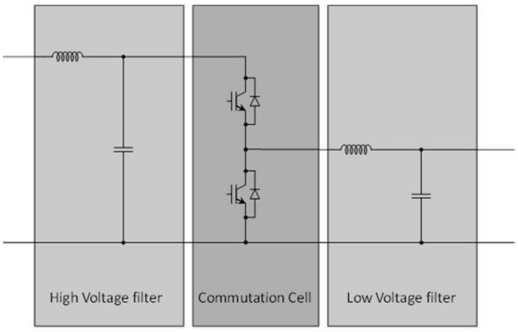
$$f_{sw}$$

$$f_0^{LV} = \frac{1}{2\pi\sqrt{L_{LV}C_{LV}}}$$

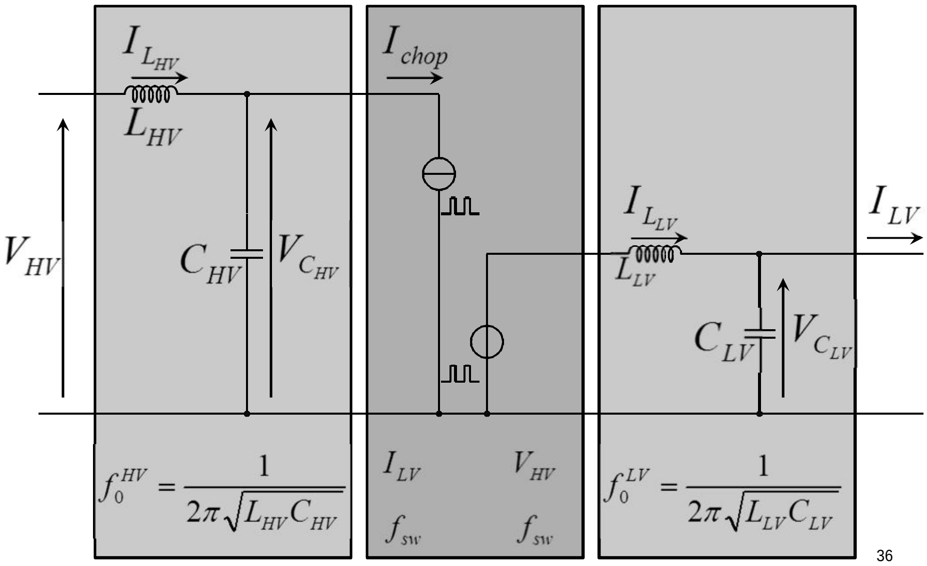
One (of the many) approach of filter design

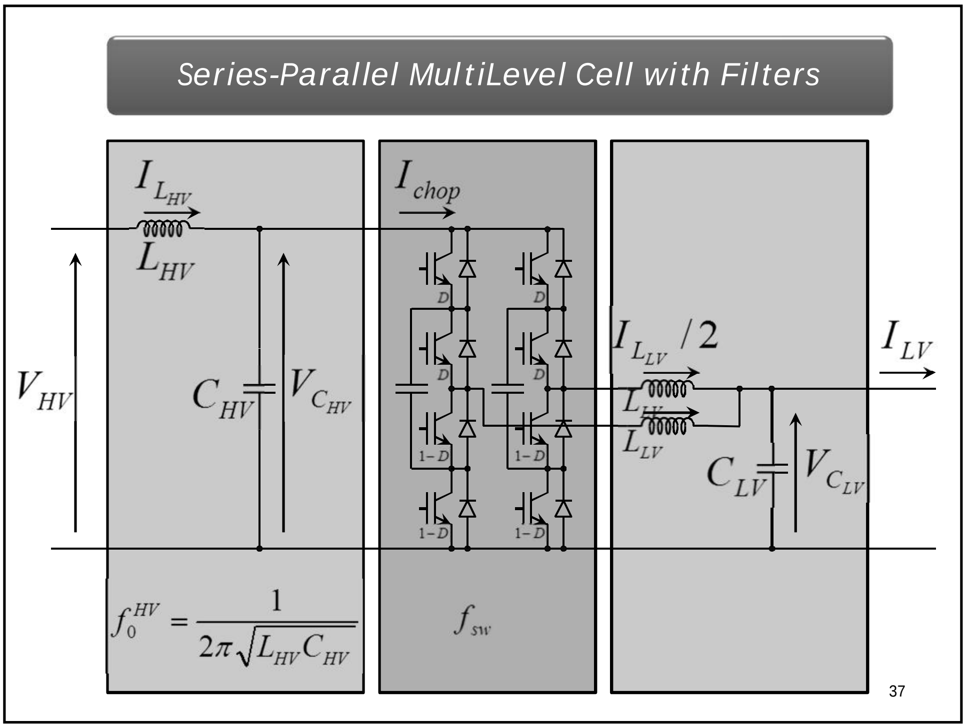
Different functions of passive components

- 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 curent ripple and and HV voltage ripple (Steady-state)



AC Equivalent circuit of a Two-Level Cell





Series-Parallel MultiLevel Cell with Filters

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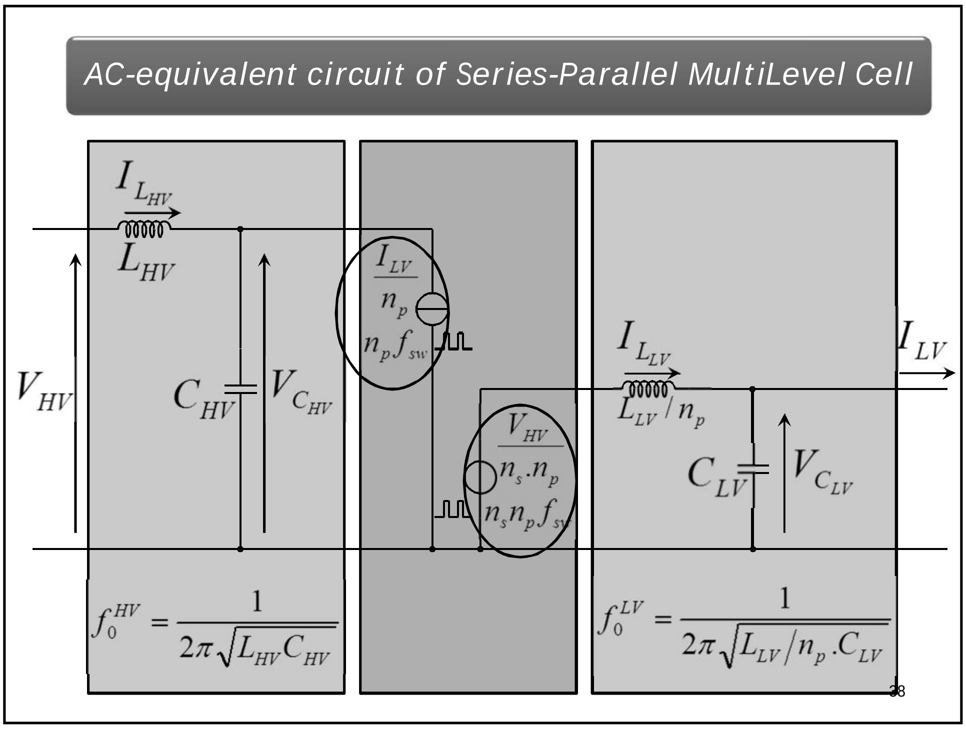

AC-equivalent circuit of Series-Parallel MultiLevel Cell

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Req #1

Steady state, time domain : worst case ripples

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

$$\left.\begin{aligned} V^{LV}_{ripple\%} &= \frac{V^{LV}_{pk-ripple}}{V_{HV}} = \frac{2}{\pi}\frac{1}{n_p n_s}\left(\frac{f^{LV}_0}{n_p n_s f_{sw}}\right)^2 \\ f^{LV}_0 &= \frac{1}{2\pi\sqrt{L_{LV}/n_p . C_{LV}}} \end{aligned}\right\} \Rightarrow \boxed{\sqrt{L_{LV}/n_p\, C_{LV}} = \frac{1}{2\pi(n_p n_s)^{1.5} f_{sw}\sqrt{\frac{\pi}{2}V^{LV}_{ripple\%}}}}$$

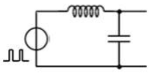
Pulsation on the High Voltage side (2nd order filter)

$$\left.\begin{aligned} I^{HV}_{ripple\%} &= \frac{I^{HV}_{pk-ripple}}{I_{LV_{\max}}} = \frac{2}{\pi}\frac{1}{n_p}\left(\frac{f^{HV}_0}{n_p f_{sw}}\right)^2 \\ f^{HV}_0 &= \frac{1}{2\pi\sqrt{L_{HV}.C_{HV}}} \end{aligned}\right\} \Rightarrow \boxed{\sqrt{L_{HV} C_{HV}} = \frac{1}{2\pi . n_p^{1.5} f_{sw}\sqrt{\frac{\pi}{2}I^{HV}_{ripple\%}}}}$$

Req #1

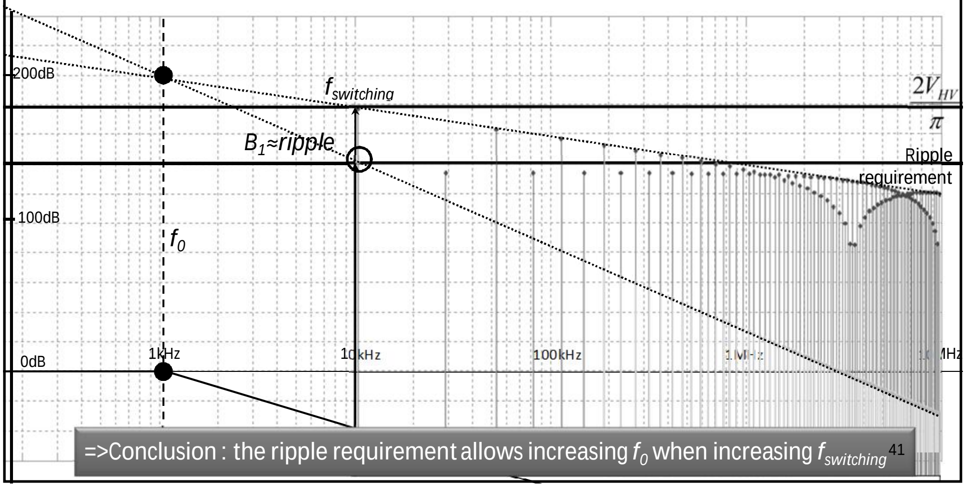
Ripples : from time domain to frequency domain

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

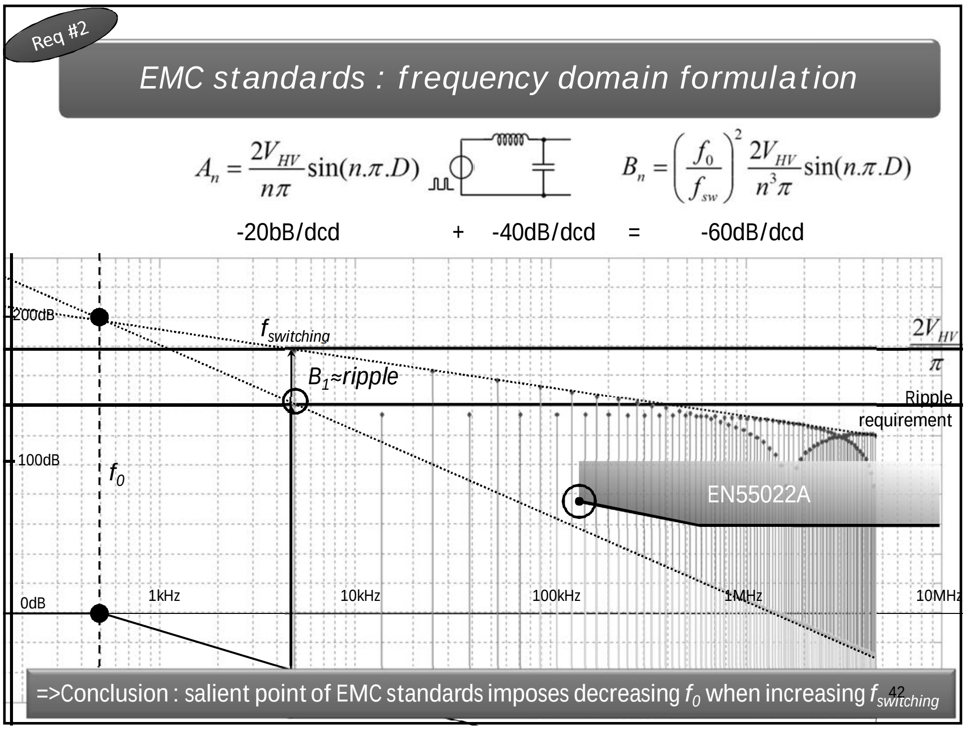


$$B_n = \left(\frac{f_0}{f_{sw}}\right)^2 \frac{2V_{HV}}{n^3\pi}\sin(n.\pi.D)$$

-20bB/dcd + -40dB/dcd = -60dB/dcd



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



Req #2

EMC standards : frequency domain formulation

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

-20bB/dcd + -40dB/dcd = -60dB/dcd

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

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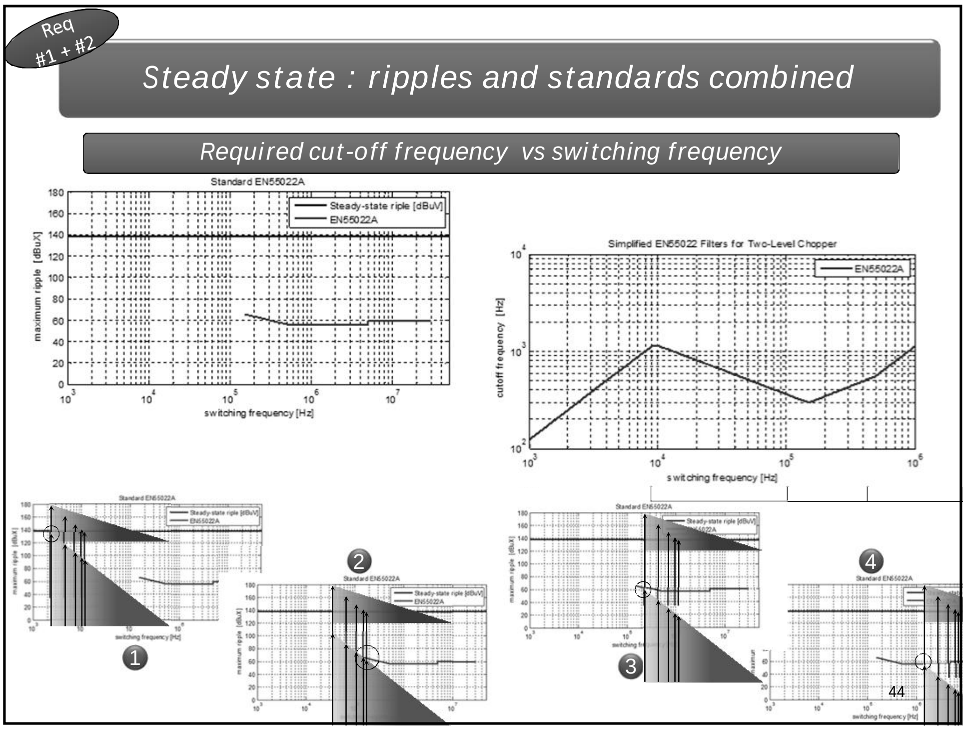

Req #1 + #2

Steady state : ripples and standards combined

Required cut-off frequency vs switching frequency

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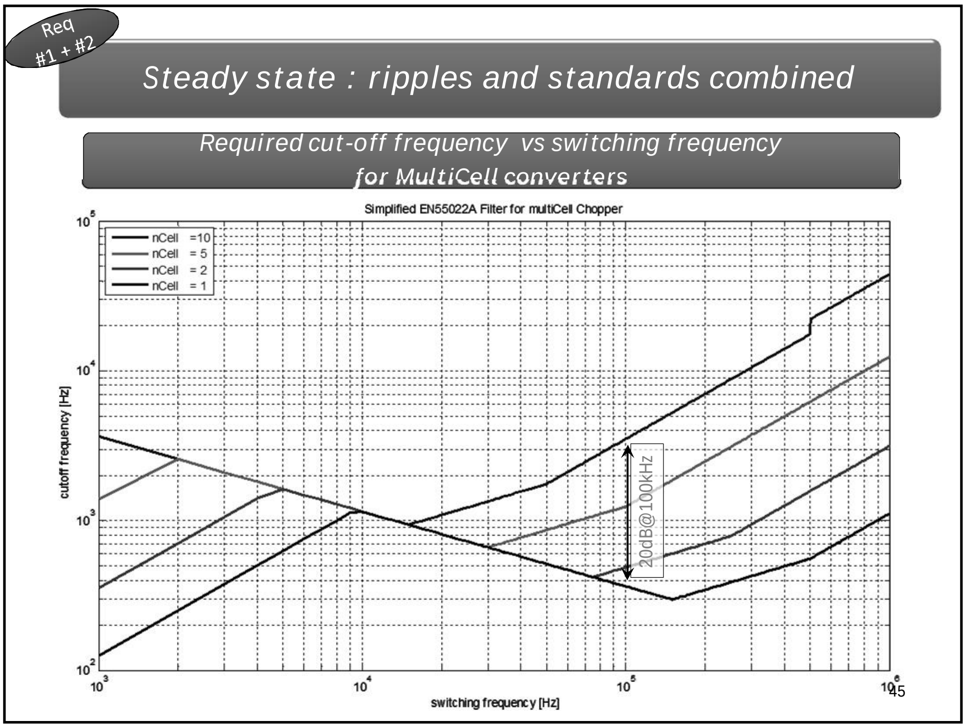
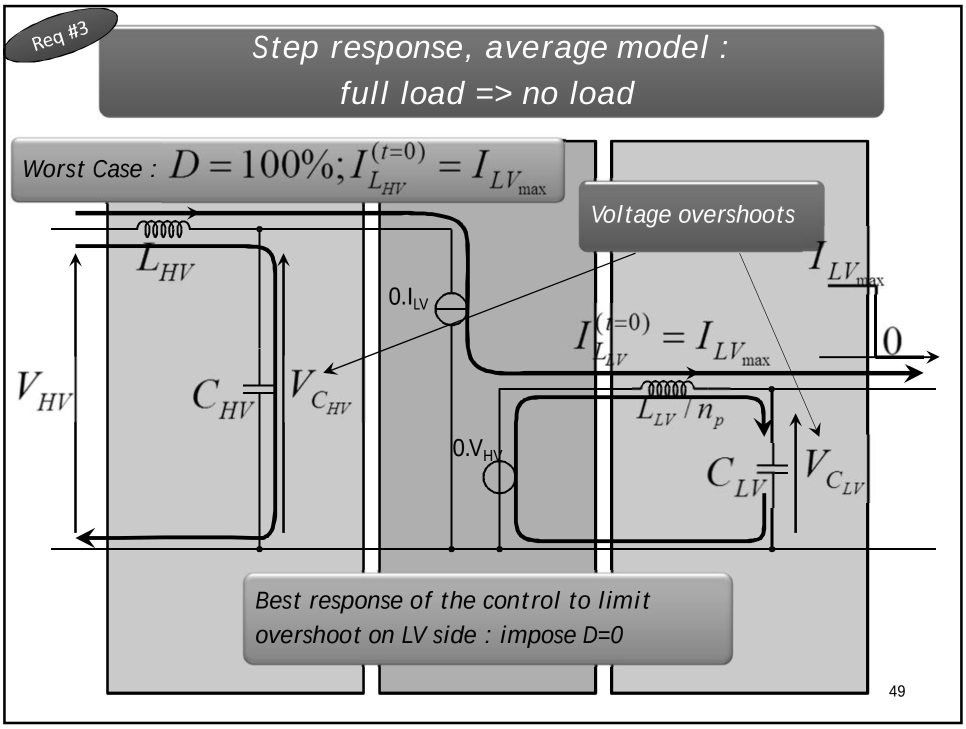

Req #1 + #2

Steady state : ripples and standards combined

Required cut-off frequency vs switching frequency for MultiCell converters


Req #3

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

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

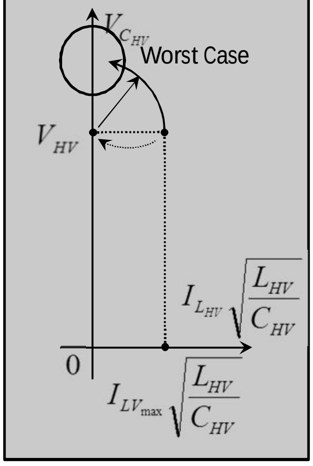
Voltage overshoots

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

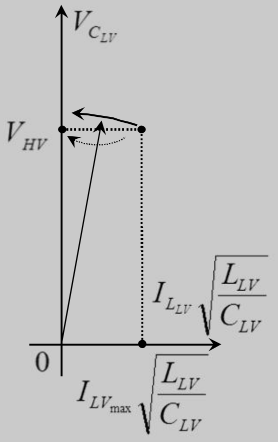
Req #3

Step response, state plane analysis full load => no load

High Voltage Side



Low Voltage Side

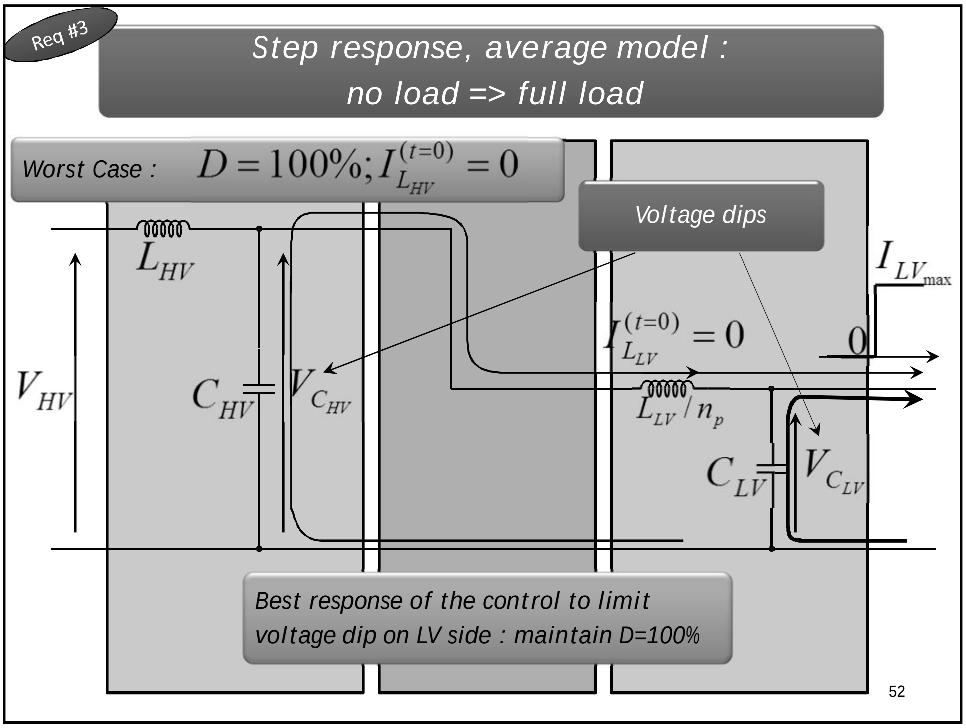


Req #3

Full load => no load : dynamic requirement HV side

Limit the voltage overshoot on the High Voltage Side

$$V^{HV}_{ovrsht\,\%} = \frac{I_{LV}\cdot\sqrt{\frac{L_{HV}}{C_{HV}}}}{V_{HV}} \text{..........} \Rightarrow \text{..............} \sqrt{\frac{L_{HV}}{C_{HV}}} = \frac{V_{HV}\cdot V^{HV}_{ovrsht\,\%}}{I_{LV\max}}$$



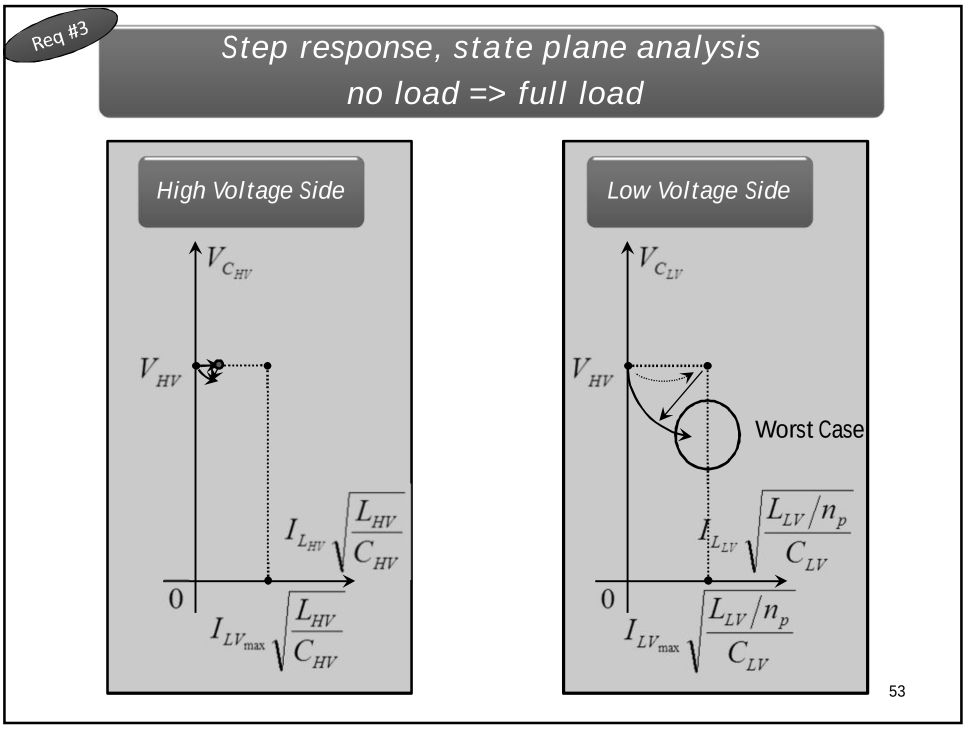
Req #3

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

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

Voltage dips

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



Req #3

Step response, state plane analysis no load => full load

High Voltage Side

Low Voltage Side

Req #3

No load => Full load : dynamic requirement LV side

Limit the voltage dip on the Low Voltage Side

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

Req
#1 + #2 + #3

Calculation of the components

High Voltage side

$$\begin{cases} n_{Cell} = n_p \\ Rip_{\%} = I_{ripple\%}^{HV} = \dfrac{I_{pk-ripple}^{HV}}{I_{LV_{\max}}} \\ f_0 = \dfrac{1}{2\pi\sqrt{L_{HV}.C_{HV}}} \end{cases}$$

Low Voltage side

$$\begin{cases} n_{Cell} = n_p.n_s \\ Rip_{\%} = V_{ripple\%}^{LV} = \dfrac{V_{pk-ripple}^{LV}}{V_{HV}} \\ f_0 = \dfrac{1}{2\pi\sqrt{L_{LV}/n_p.C_{LV}}} \end{cases}$$

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

Valid for uncoupled AND coupled magnetic components

Req
#1 + #2 + #3

Calculation of the components

High Voltage side

$$\begin{cases}\sqrt{\dfrac{L_{HV}}{C_{HV}}} = \dfrac{V_{HV}.V_{ovrsht\%}^{HV}}{I_{LV_{\max}}}\\ \sqrt{L_{HV}.C_{HV}} = \dfrac{1}{2\pi.f_0^{HV}}\end{cases}$$

$$\Rightarrow\begin{cases}L_{HV} = \dfrac{V_{HV}.V_{ovrsht\%}^{HV}}{2\pi.f_0^{HV}I_{LV_{\max}}}\\ C_{HV} = \dfrac{I_{LV_{\max}}}{2\pi.f_0^{HV}V_{HV}.V_{ovrsht\%}^{HV}}\end{cases}$$

Low Voltage side

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

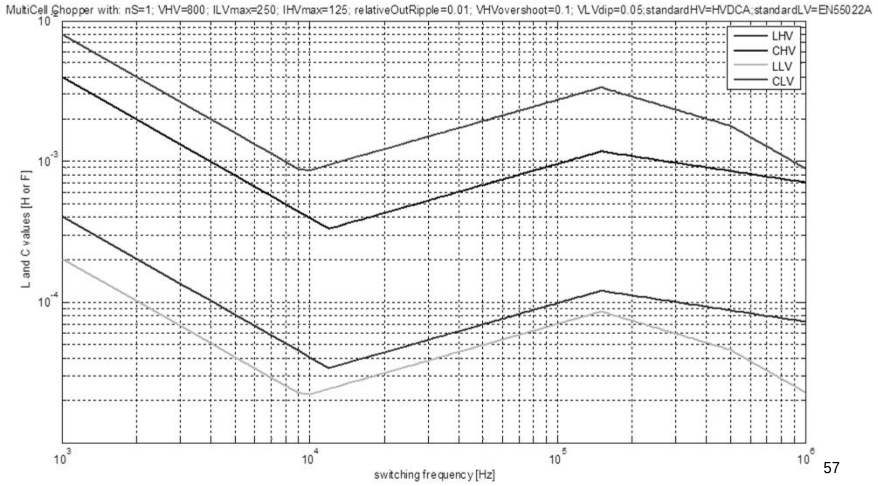
$$\Rightarrow\begin{cases}L_{LV}/n_p = \dfrac{V_{HV}.V_{dip\%}^{LV}}{2\pi.f_0^{LV}I_{LV_{\max}}}\\ C_{LV} = \dfrac{I_{LV_{\max}}}{2\pi.f_0^{LV}V_{HV}.V_{dip\%}^{LV}}\end{cases}$$

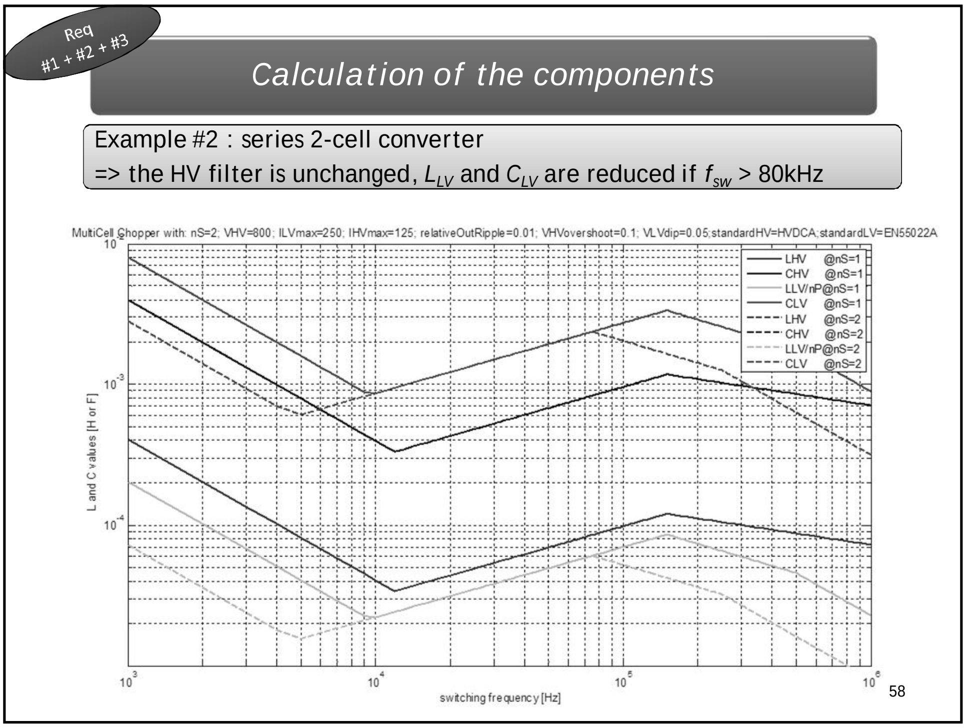
Valid for uncoupled AND coupled magnetic components

Req
#1 + #2 + #3

Calculation of the components

Example #1 : 2-level converter
=> from 10 to 150kHz, the tendancy is an *increase* of passive components

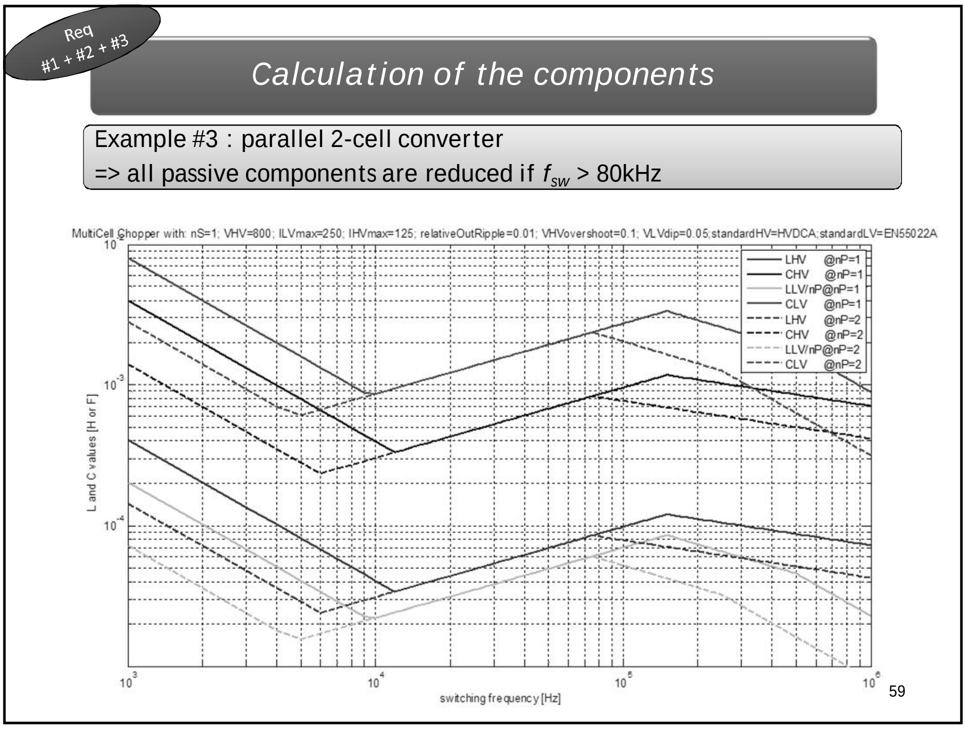




Req
#1 + #2 + #3

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} > 80kHz



Req
#1 + #2 + #3

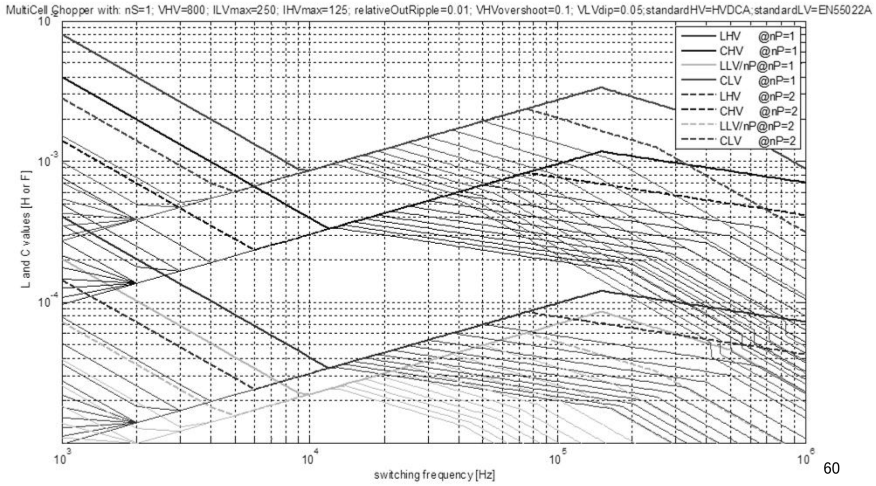
Calculation of the components

Example #3 : parallel 2-cell converter
=> all passive components are reduced if f_{sw} > 80kHz

Req
#1 + #2 + #3

Calculation of the components

Example #4 : parallel multiCell converter
=> with 10 // cells, all passive components start decreasing at f_{sw} > 15kHz

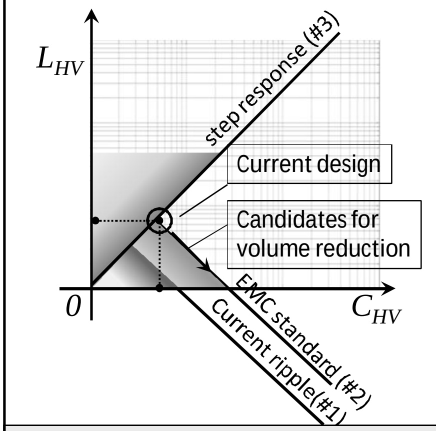


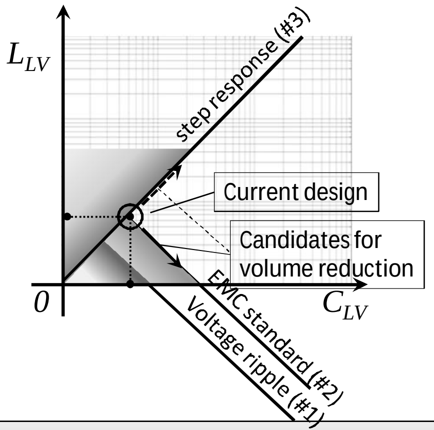
Req
#1 + #2 + #3

Combined requirements

High Voltage side

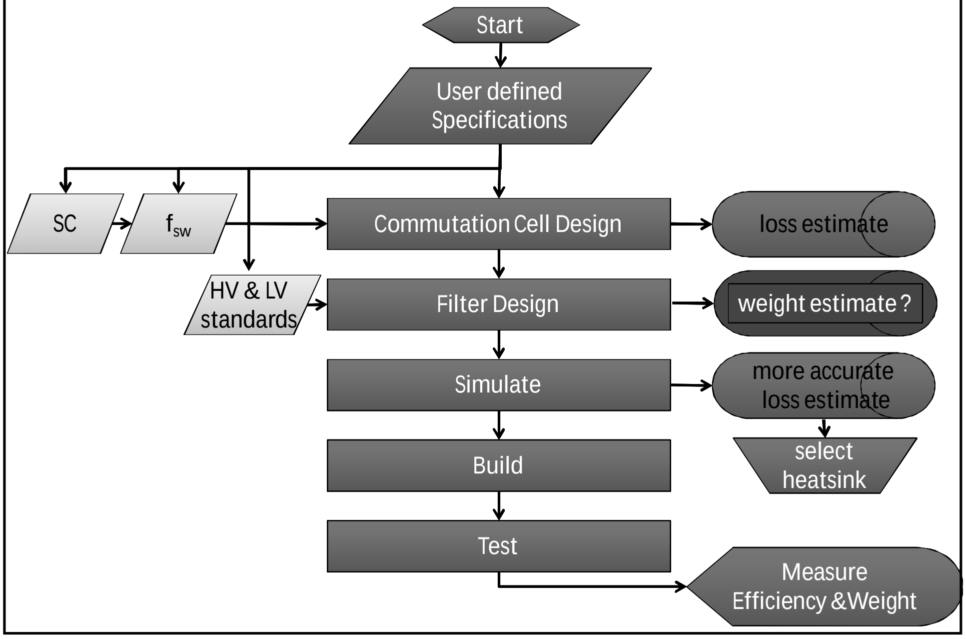
Low Voltage side





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



Start

User defined Specifications

SC

f_{sw}

HV & LV standards

Commutation Cell Design

Filter Design

Simulate

Build

Test

loss estimate

weight estimate ?

more accurate loss estimate

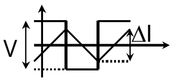
select heatsink

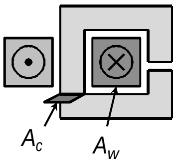
Measure Efficiency & Weight

VOLUME OF PASSIVE COMPONENTS AND FILTERS FOR MULTILEVEL CONVERTERS

Area Product of Magnetic Components : Inductors

Basic formulation





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

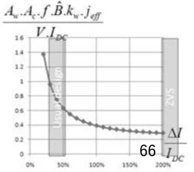
$$\boxed{A_w.A_c = L.\hat{I}.\frac{I_{eff}}{\hat{B}.k_w.j_{eff}}}$$

Advantage : allows selecting the core

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

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

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



Area Product of Magnetic Components : Inductors

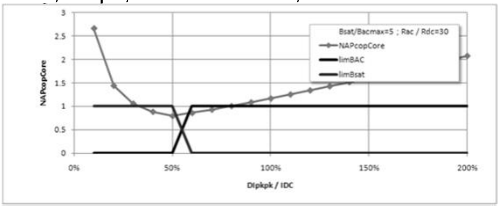
Improved

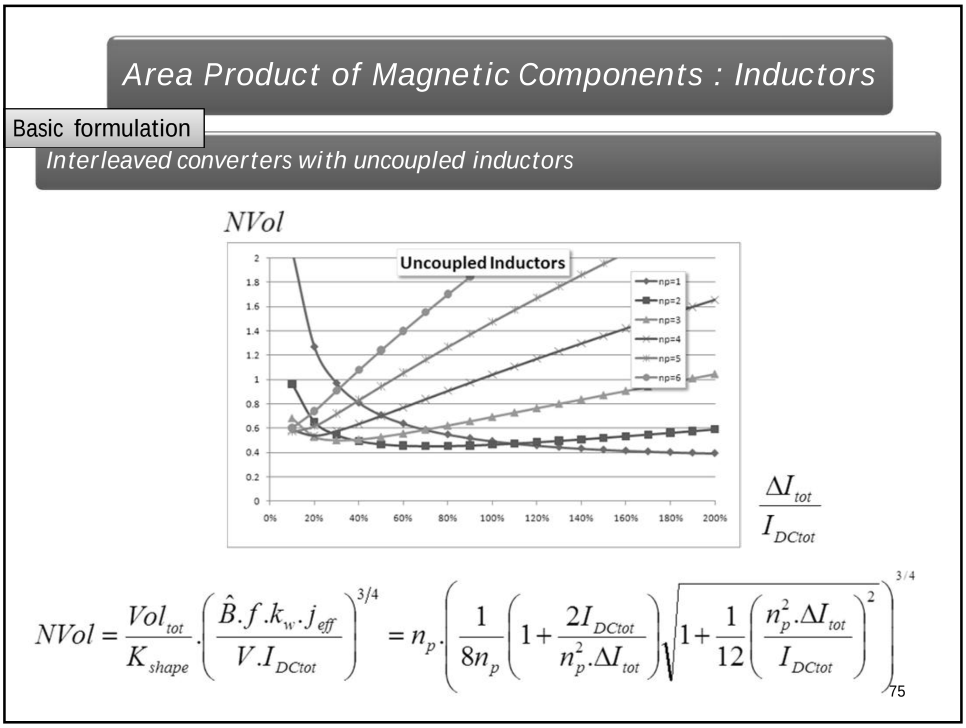
Improved formulation #3 : combining copper losses and core losses

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

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

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…





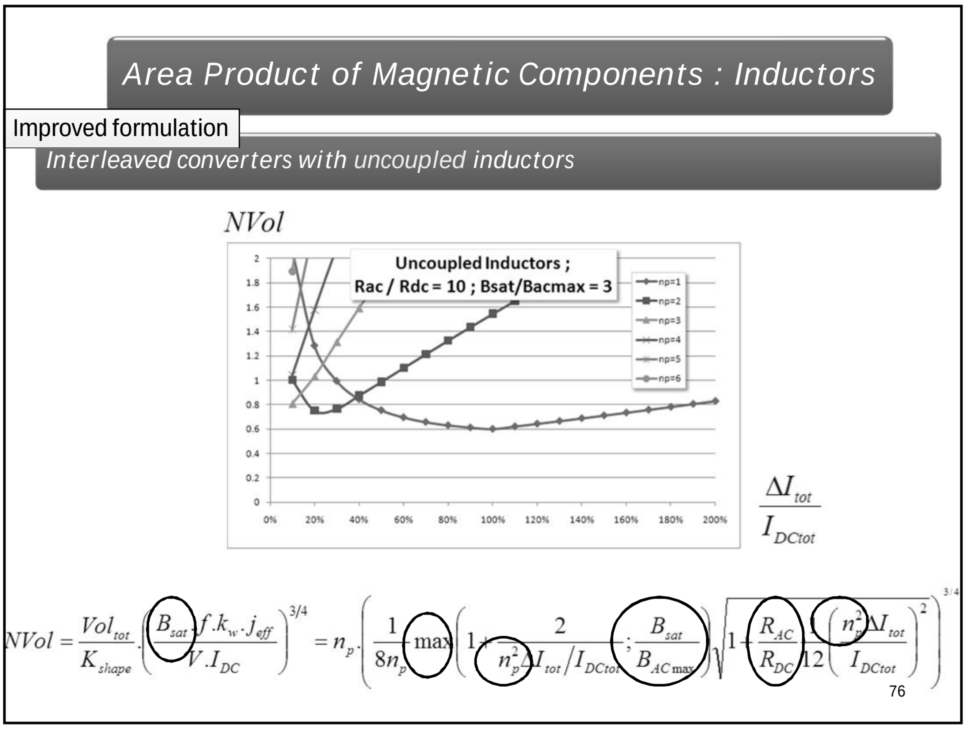
Area Product of Magnetic Components : Inductors

Basic formulation

Interleaved converters with uncoupled inductors

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

75



Area Product of Magnetic Components : Inductors

Improved formulation

Interleaved converters with uncoupled inductors

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

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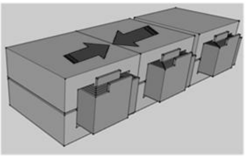
Area Product of Magnetic Components : ICTs

Basic formulation

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

Compared with uncoupled inductors:
- Fluxes unchanged ,
- Current ripples reduced



$$\left.\begin{array}{l}\Delta I_{tot}=\dfrac{\Delta I_{ind}}{\cancel{n_p}}\boxed{.n_p}\\ I_{DCtot}=n_p.I_{DCind}\end{array}\right\}\Rightarrow\frac{\Delta I_{ind}}{I_{DCind}}=\frac{\cancel{n_p}\Delta I_{tot}\boxed{/n_p}}{I_{DCtot}/n_p}=\frac{\cancel{n_p^2}\Delta I_{tot}}{I_{DCtot}}$$

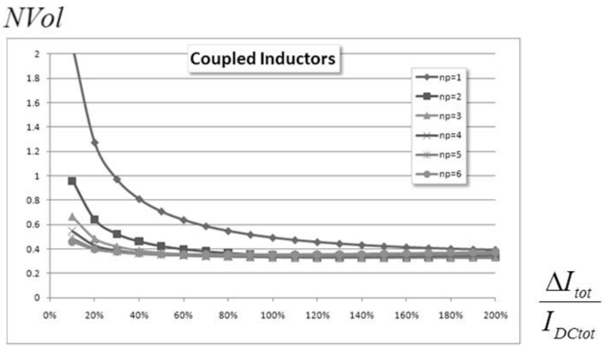
=> Total volume of the n_p coupled inductors :

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

Area Product of Magnetic Components : ICTs

Basic formulation

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

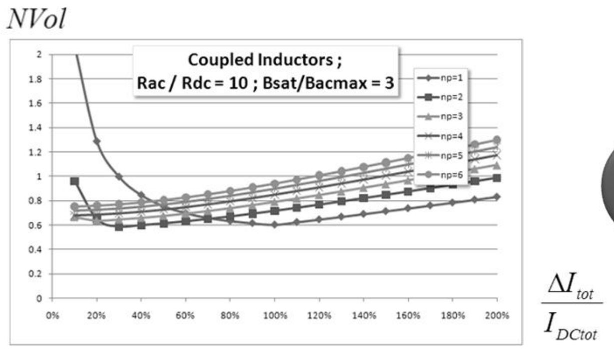


$$NVol=\frac{Vol_{tot}}{K_{shape}}.\left(\frac{\hat{B}.f.k_w.j_{eff}}{V.I_{DC}}\right)^{3/4}=n_p.\left(\frac{1}{8n_p}\left(1+\frac{2I_{DCtot}}{n_p^2.\Delta I_{tot}}\right)\sqrt{1+\frac{1}{12}\left(\frac{\Delta I_{tot}}{I_{DCtot}}\right)^2}\right)^{3/4}$$

Area Product of Magnetic Components : ICTs

Improved formulation

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



Excel Link

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

Minimum volume of LV-side uncoupled inductors and InterCell Transformers

Crossing(f_1=f_2)

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

⇒ Ripple giving the minimum volume of Magnetic Component :

uncoupled

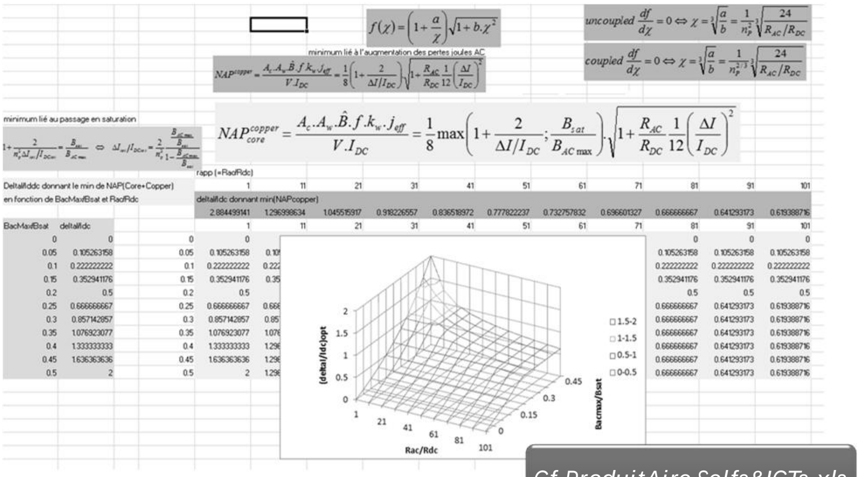
$$\chi=\min\left(\frac{1}{n_P^2}\sqrt[3]{\frac{24}{R_{AC}/R_{DC}}}\quad;\quad\frac{2}{n_P^2}\frac{\frac{B_{AC\max}}{B_{sat}}}{1-\frac{B_{AC\max}}{B_{sat}}}\right)$$

coupled

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

Minimum volume of LV-side uncoupled inductors and InterCell Transformers

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



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

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

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

minimum lié à l'augmentation des pertes joules AC

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

minimum lié au passage en saturation

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

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

DeltaI/Idc donnant le min de NAP(Core+Copper)
en fonction de BacMax/Bsat et Rac/Rdc

rapp (=Rac/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

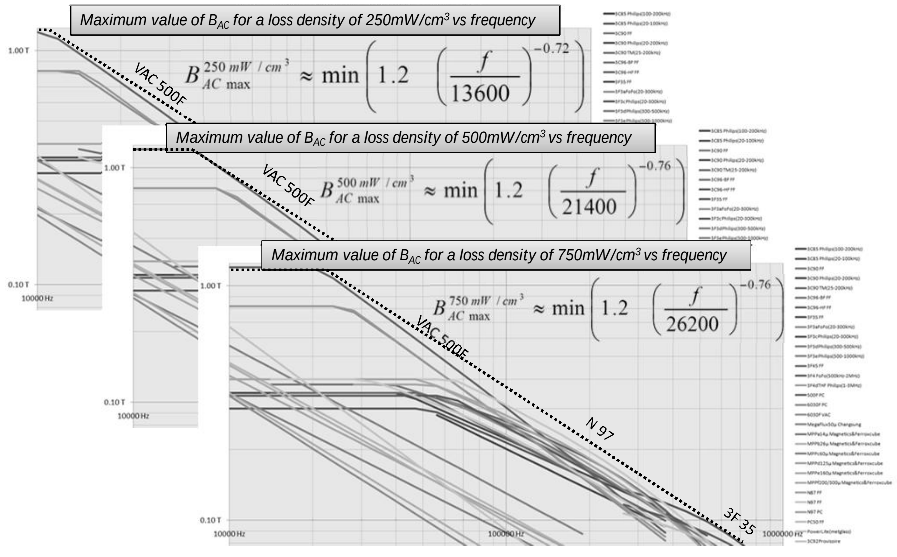
BacMax/Bsat	deltaI/Idc
0	0
0.05	0.105263158
0.1	0.222222222
0.15	0.352941176
0.2	0.5
0.25	0.666666667
0.3	0.857142857
0.35	1.076923077
0.4	1.333333333
0.45	1.636363636
0.5	2

	1	81	91	101
0	0	0	0	0
0.05	0.105263158	0.105263158	0.105263158	0.105263158
0.1	0.222222222	0.222222222	0.222222222	0.222222222
0.15	0.352941176	0.352941176	0.352941176	0.352941176
0.2	0.5	0.5	0.5	0.5
0.25	0.666666667	0.666666667	0.641293173	0.619388716
0.3	0.857142857	0.666666667	0.641293173	0.619388716
0.35	1.076923077	0.666666667	0.641293173	0.619388716
0.4	1.333333333	0.666666667	0.641293173	0.619388716
0.45	1.636363636	0.666666667	0.641293173	0.619388716
0.5	2	0.666666667	0.641293173	0.619388716

Cf ProduitAire Selfs&ICTs.xls

Minimum volume of LV-side uncoupled inductors and InterCell Transformers

Technology-related data : Core loss limitation



Maximum value of B_{AC} for a loss density of 250mW/cm³ vs frequency

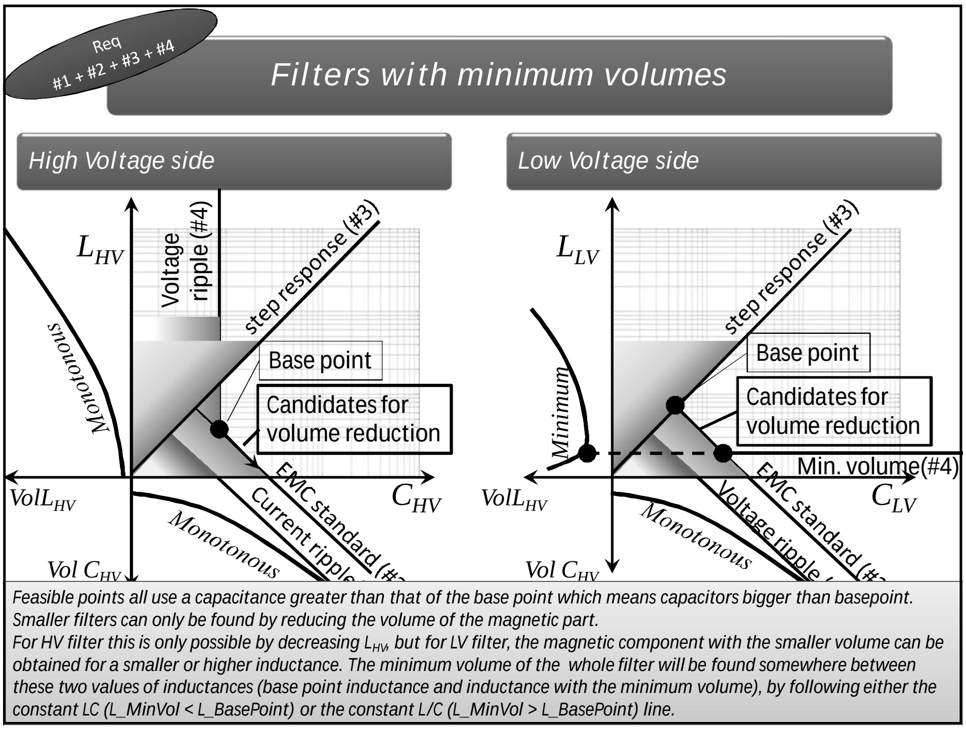
$$B_{AC\ \max}^{250\ mW\ /\ cm^3}\approx\min\left(1.2\quad\left(\frac{f}{13600}\right)^{-0.72}\right)$$

Maximum value of B_{AC} for a loss density of 500mW/cm³ vs frequency

$$B_{AC\ \max}^{500\ mW\ /\ cm^3}\approx\min\left(1.2\quad\left(\frac{f}{21400}\right)^{-0.76}\right)$$

Maximum value of B_{AC} for a loss density of 750mW/cm³ vs frequency

$$B_{AC\ \max}^{750\ mW\ /\ cm^3}\approx\min\left(1.2\quad\left(\frac{f}{26200}\right)^{-0.76}\right)$$

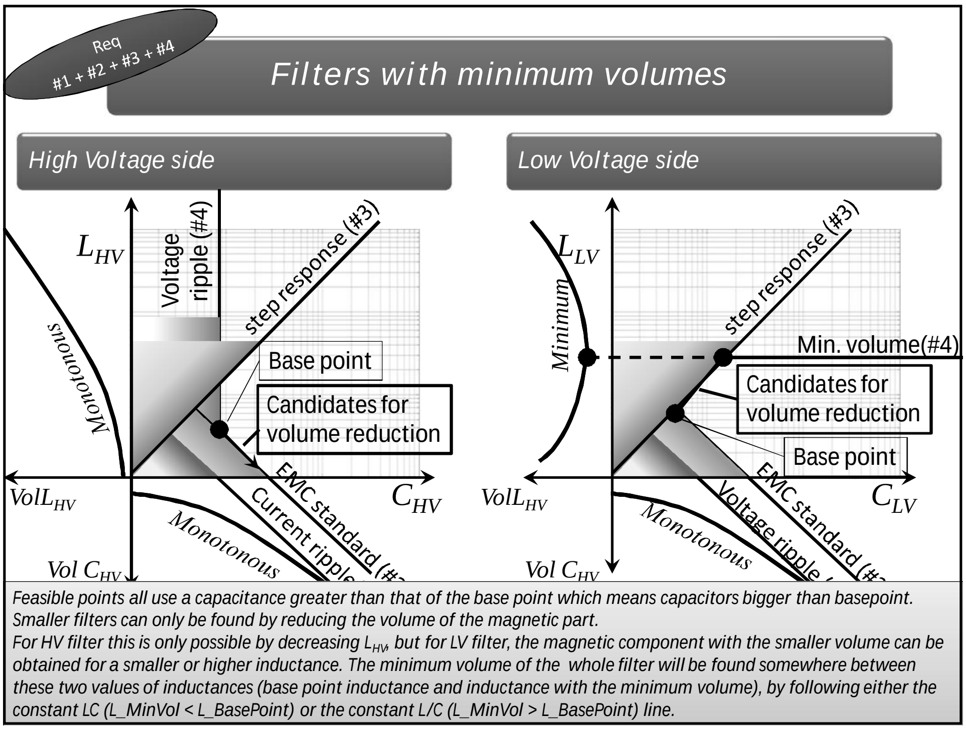


Filters with minimum volumes

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.



Filters with minimum volumes

High Voltage side

Low Voltage side

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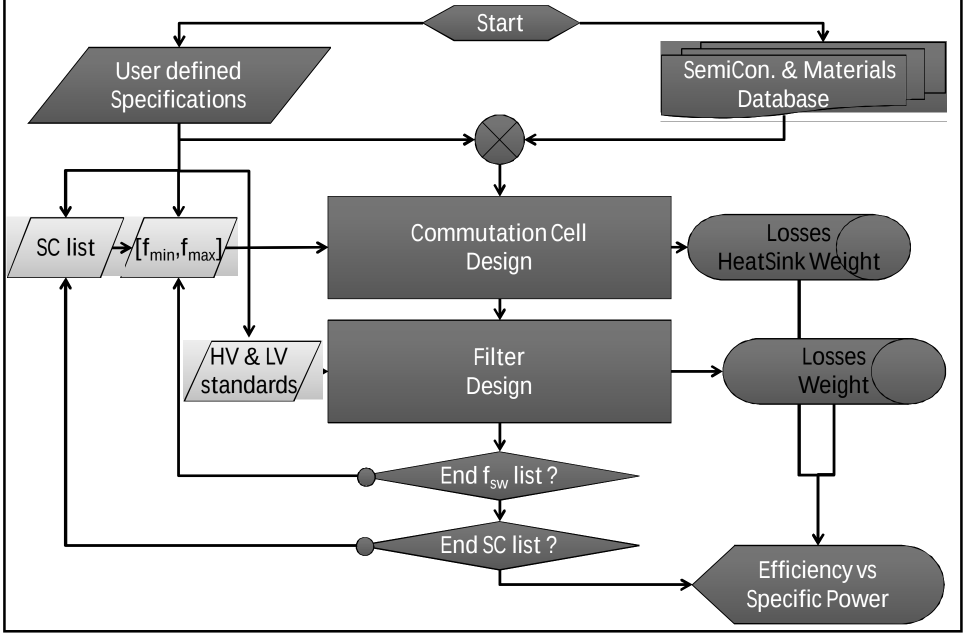
Design process



Start

User defined Specifications

SemiCon. & Materials Database

SC list

$[f_{min}, f_{max}]$

Commutation Cell Design

Losses HeatSink Weight

HV & LV standards

Filter Design

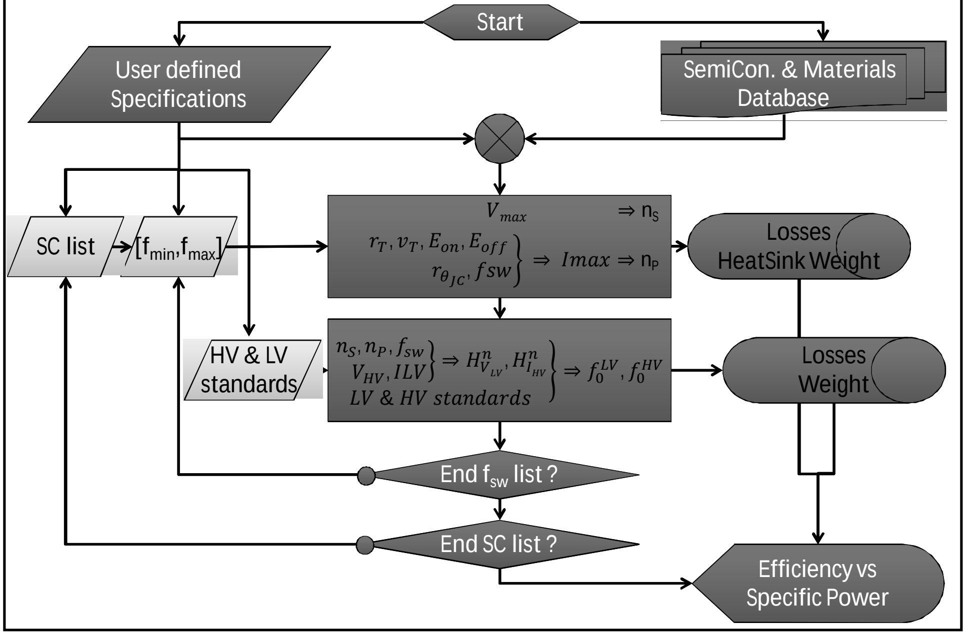
Losses Weight

End f_{sw} list ?

End SC list ?

Efficiency vs Specific Power

Design process



Start

User defined Specifications

SemiCon. & Materials Database

SC list

$[f_{min}, f_{max}]$

$V_{max} \Rightarrow n_S$

$\left.\begin{matrix} r_T, v_T, E_{on}, E_{off} \\ r_{\theta_{JC}}, fsw \end{matrix}\right\} \Rightarrow Imax \Rightarrow n_P$

Losses HeatSink Weight

HV & LV standards

$\left.\begin{matrix} \left.\begin{matrix} n_S, n_P, f_{sw} \\ V_{HV}, ILV \end{matrix}\right\} \Rightarrow H^n_{V_{LV}}, H^n_{I_{HV}} \\ LV\ \&\ HV\ standards \end{matrix}\right\} \Rightarrow f_0^{LV}, f_0^{HV}$

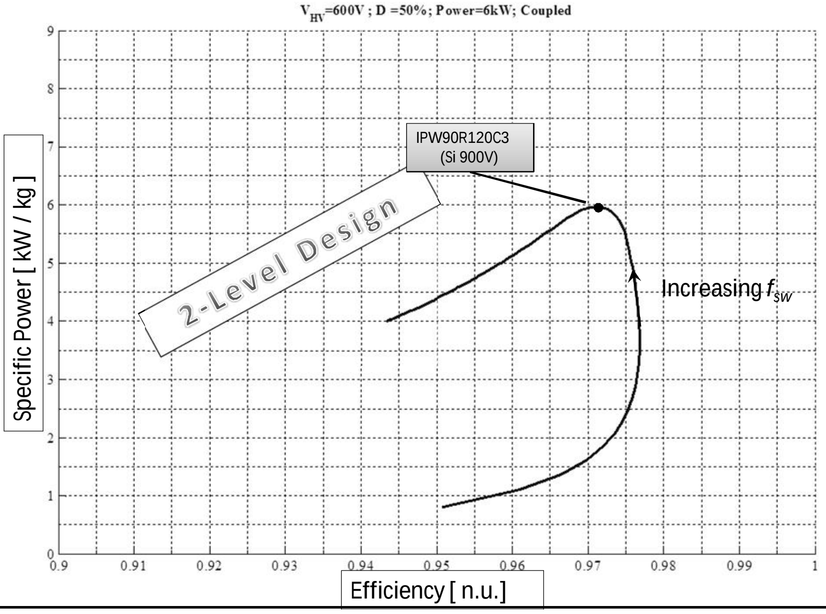
Losses Weight

End f_{sw} list ?

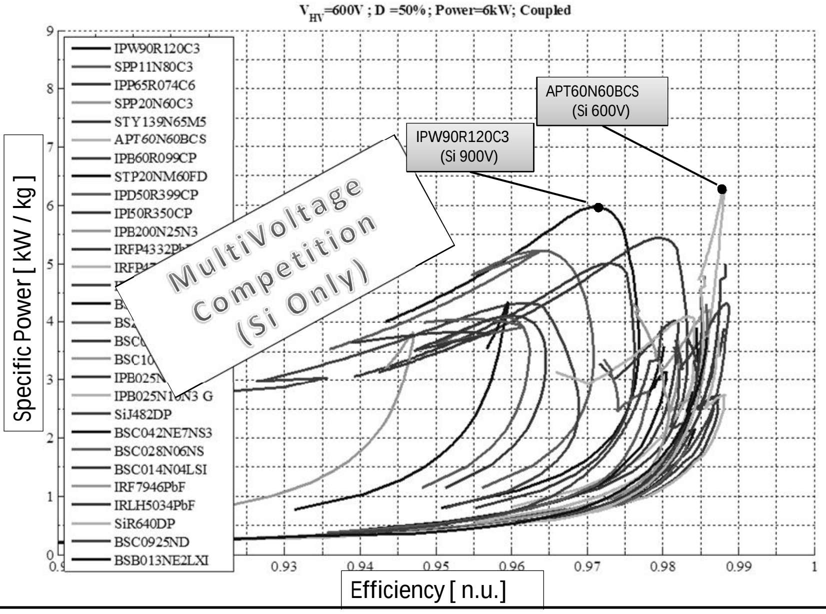
End SC list ?

Efficiency vs Specific Power

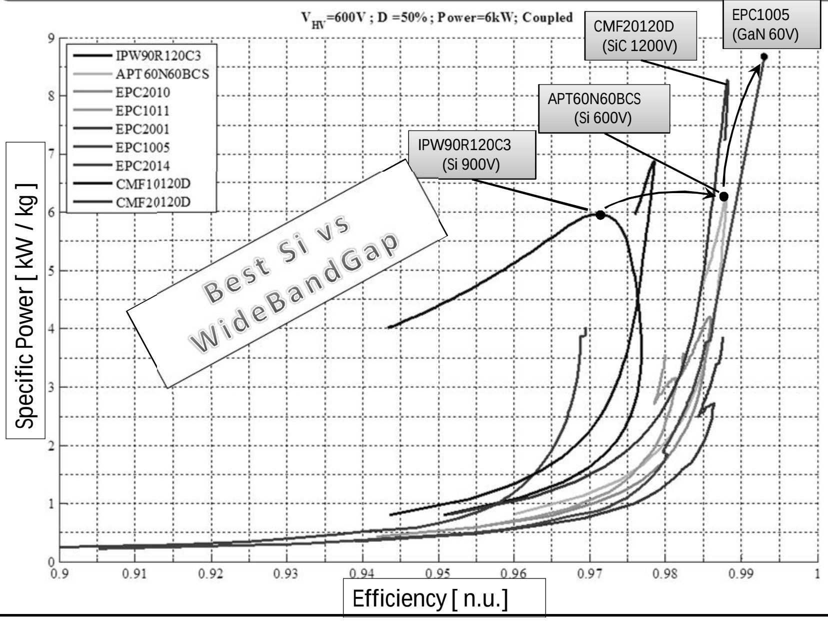
Combining SC data and passive component data :
feasible points in the (SpecificPower,Efficiency) plane



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



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



CMF20120D
(SiC 1200V)

EPC1005
(GaN 60V)

APT60N60BCS
(Si 600V)

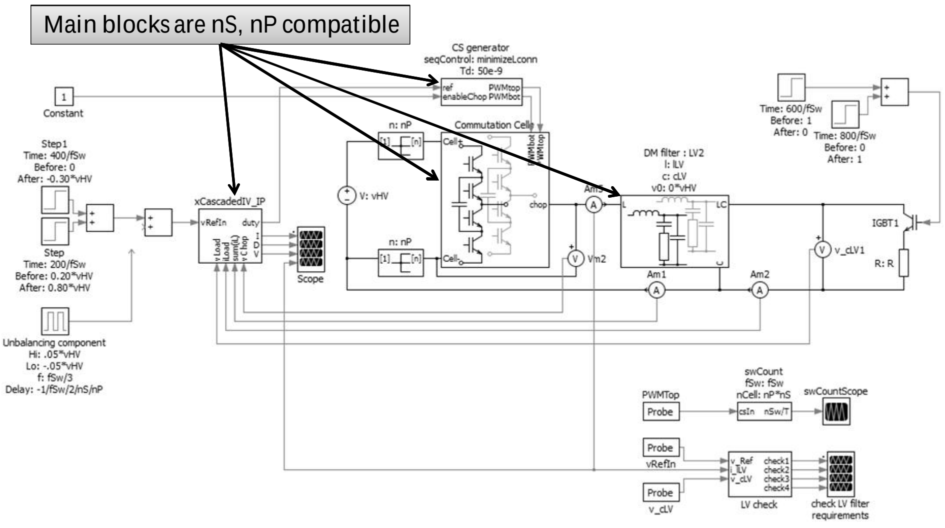
IPW90R120C3
(Si 900V)

Best Si vs
WideBandGap

Specific Power [kW / kg]

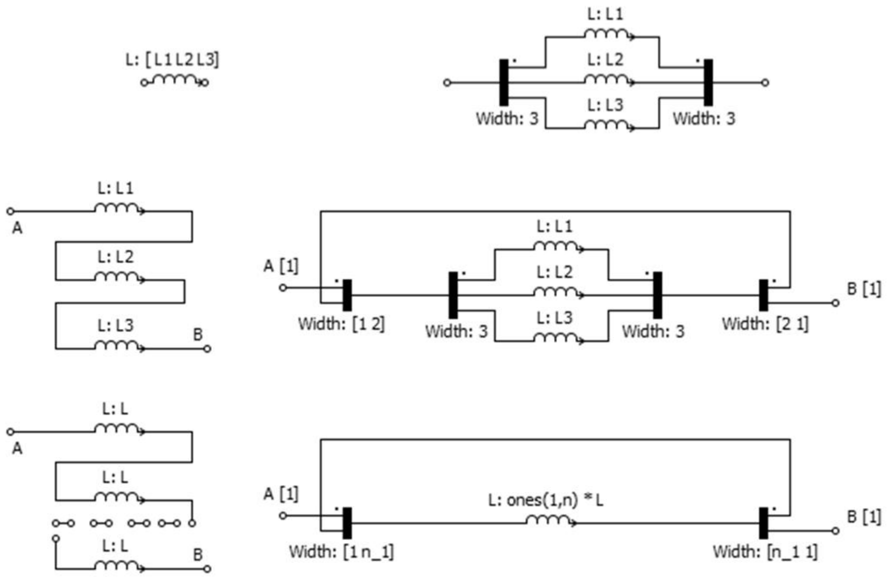
Efficiency [n.u.]

Design check

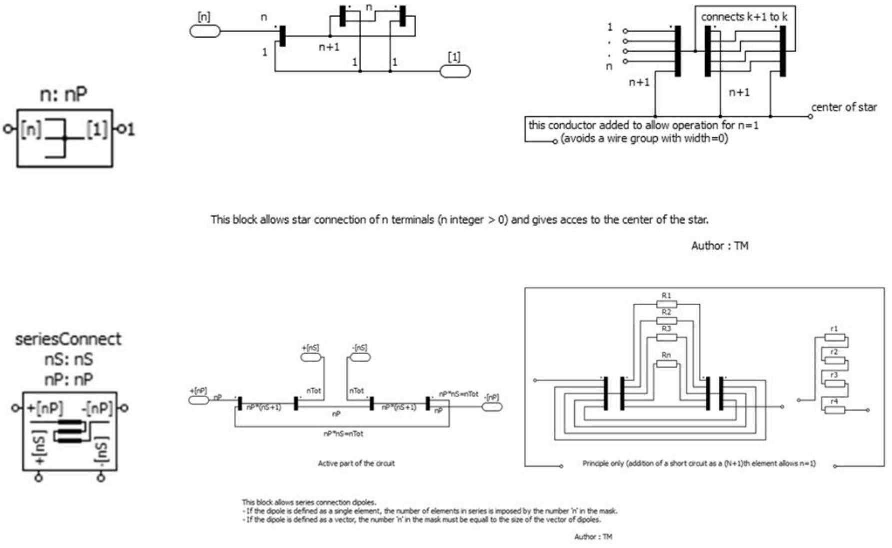


Main blocks are nS, nP compatible

Graphic Vectorization in PLECS



Dedicated blocks to help vectorization



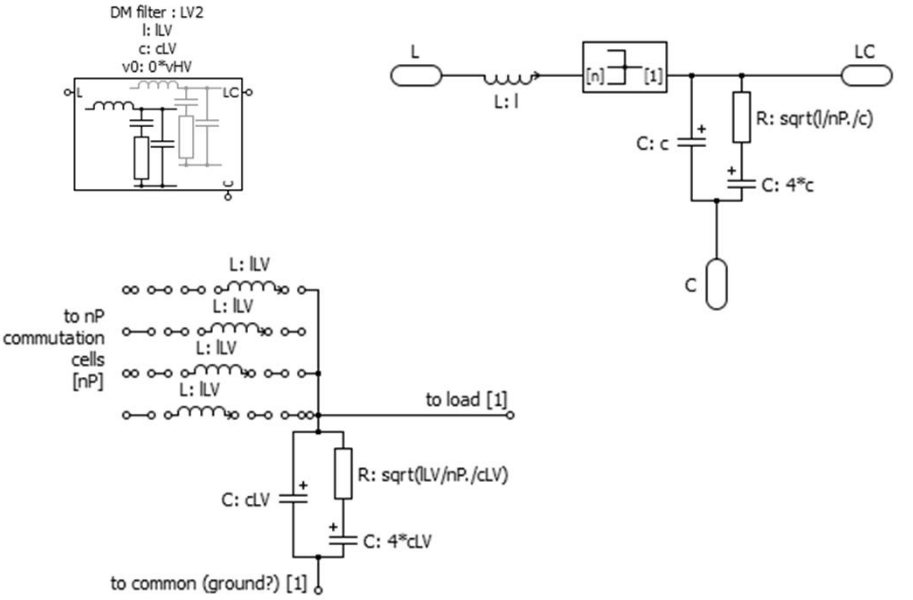
This block allows star connection of n terminals (n integer > 0) and gives acces to the center of the star.

Author : TM

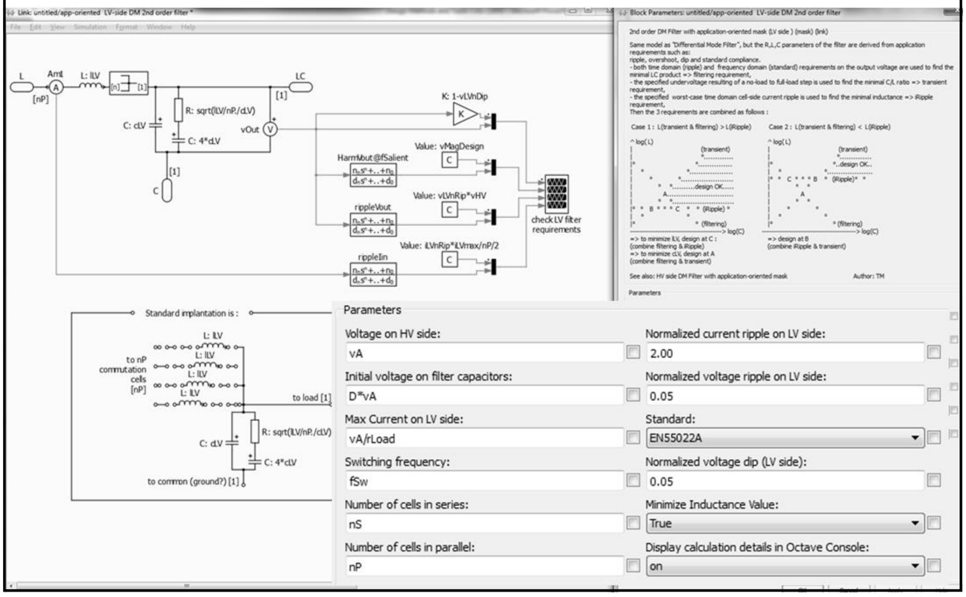
This block allows series connection dipoles.
- If the dipole is defined as a single element, the number of elements in series is imposed by the number 'n' in the mask.
- If the dipole is defined as a vector, the number 'n' in the mask must be equall to the size of the vector of dipoles.

Author : TM

Vectorized filters



Vectorized filters with pre-design



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(iRipple)

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

Case 2 : L(transient & filtering) < L(iRipple)

=> design at B
(combine iRipple & transient)

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

Author: TM

Parameters

Voltage on HV side: vA ☐

Initial voltage on filter capacitors: D*vA ☐

Max Current on LV side: vA/rLoad ☐

Switching frequency: fSw ☐

Number of cells in series: nS ☐

Number of cells in parallel: nP ☐

Normalized current ripple on LV side: 2.00 ☐

Normalized voltage ripple on LV side: 0.05 ☐

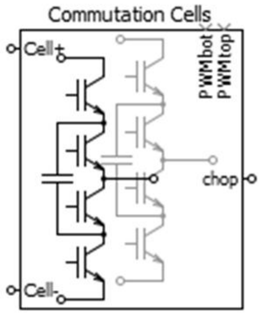
Standard: EN55022A ☐

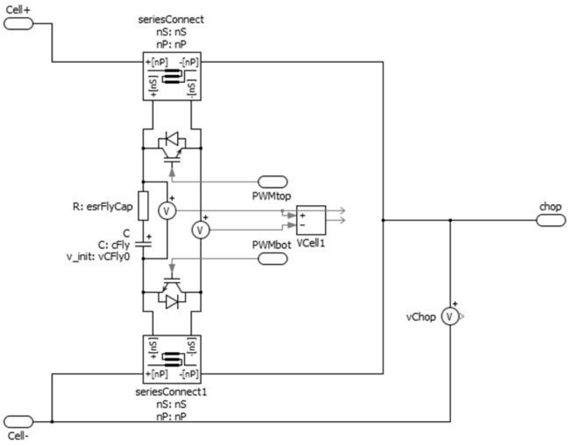
Normalized voltage dip (LV side): 0.05 ☐

Minimize Inductance Value: True ☐

Display calculation details in Octave Console: on ☐

Vectorized commutation cell

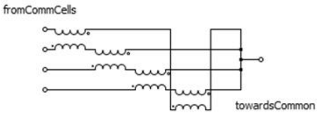


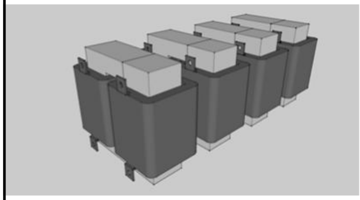


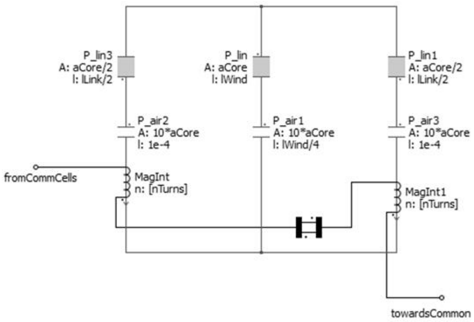
MacroCell is composed of Flying Cap Legs (nS commutation cells in series) that can typically be used in parallel connection (nP legs in parallel). Ideally, all commutation cells should all be controlled with the same duty cycle, but those in series with a phase-shift of 2pi/nS, and those in parallel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

Author : TM

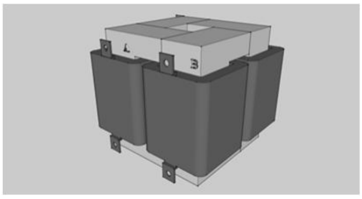
Vectorized Cyclic Cascade InterCell Transformer

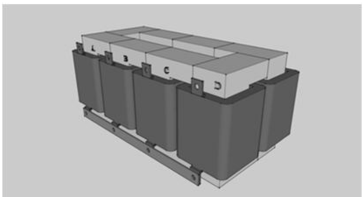


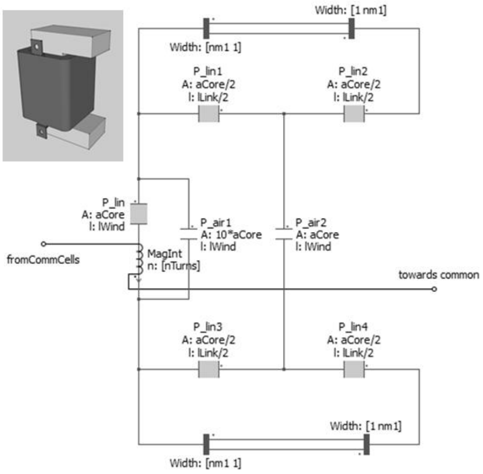




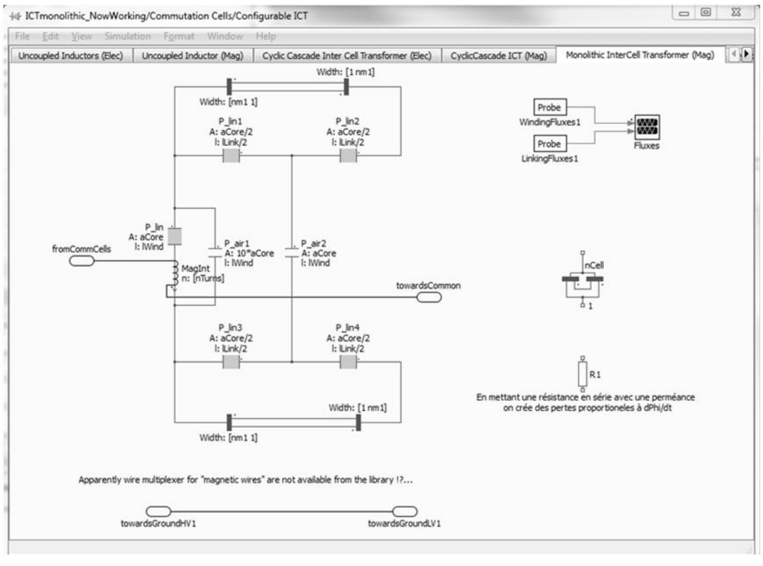
Vectorized Monolithic InterCell Transformer







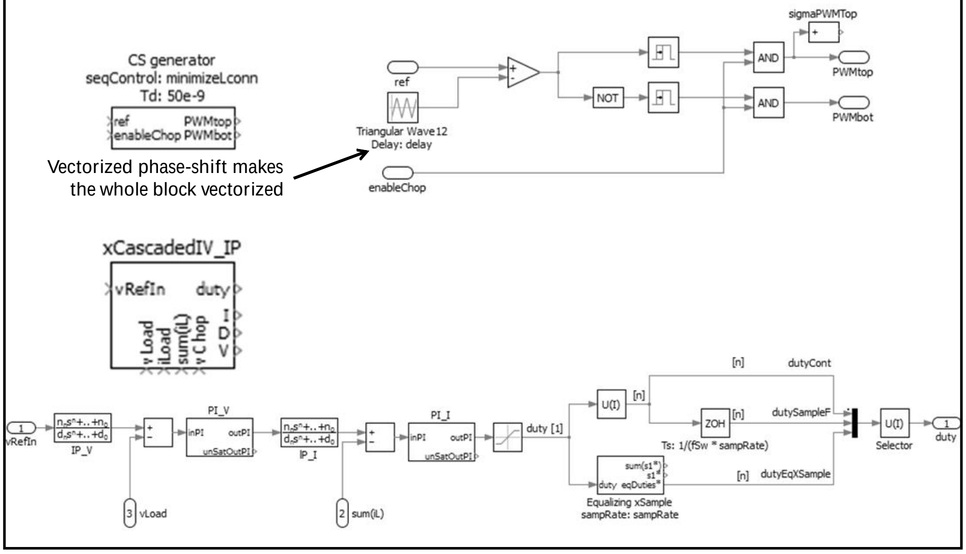
Vectorized and configurable magnetic components for interleaved converters



En mettant une résistance en série avec une perméance
on crée des pertes proportioneles à dPhi/dt

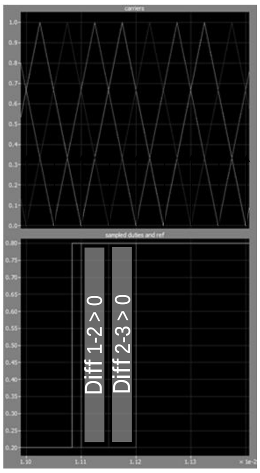
Apparently wire multiplexer for "magnetic wires" are not available from the library !?...

Vectorized regulator and control signal generator

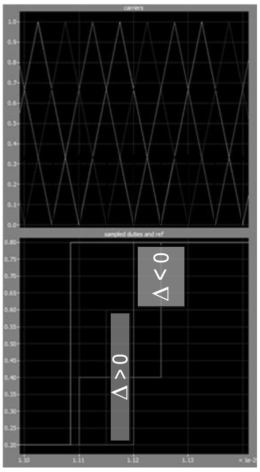


Vectorized phase-shift makes the whole block vectorized

Vectorized equalizing sampler



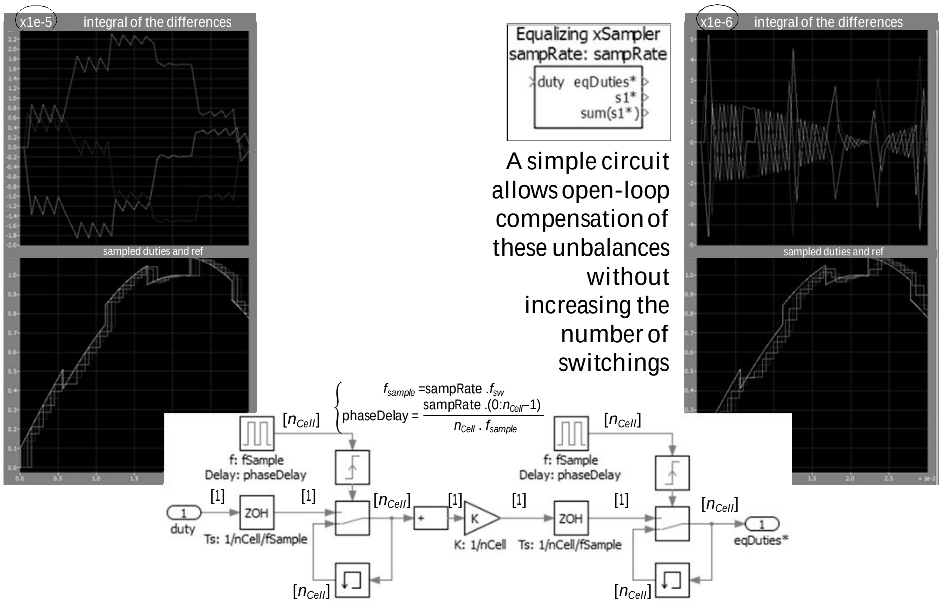
Sampling must be synchronized with carriers to avoid multiple switching in the same period



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

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

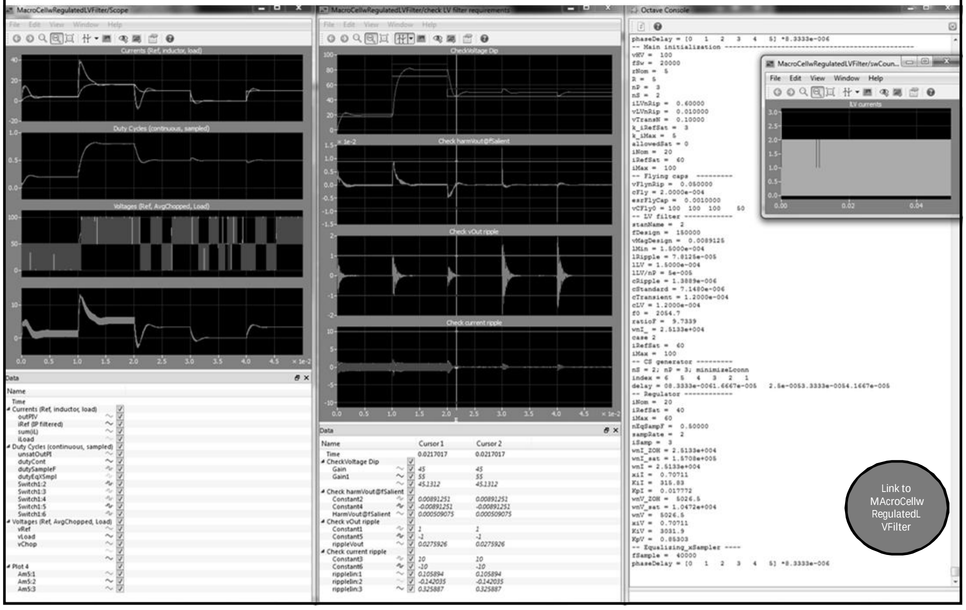
Vectorized equalizing sampler



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

$$\begin{cases} f_{sample} = \text{sampRate} \,.\, f_{sw} \\ \text{phaseDelay} = \dfrac{\text{sampRate} \,.(0{:}n_{Cell}-1)}{n_{Cell} \,.\, f_{sample}} \end{cases}$$

Design check



Data

Name	
Time	
Currents (Ref, inductor, load)	☑
outPIV	☑
iRef (lP filtered)	☑
sum(iL)	☑
iLoad	☑
Duty Cycles (continuous, sampled)	☑
unsatOutPI	☑
dutyCont	☑
dutySampleF	☑
dutyEqXSmpl	☑
Switch1:2	☑
Switch1:3	☑
Switch1:4	☑
Switch1:5	☑
Switch1:6	☑
Voltages (Ref, AvgChopped, Load)	☑
vRef	☑
vLoad	☑
vChop	☑
	☑
	☑
Plot 4	☑
Am5:1	☑
Am5:2	☑
Am5:3	☑

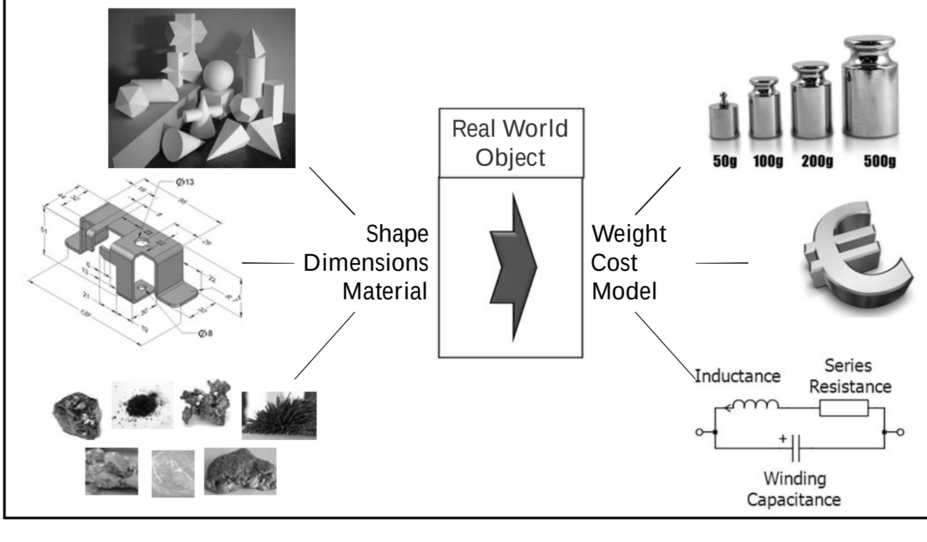
Data

Name		Cursor 1	Cursor 2
Time		0.0217017	0.0217017
CheckVoltage Dip	☑		
Gain	☑	45	45
Gain1	☑	55	55
	☑	45.1312	45.1312
Check harmVout@fSalient	☑		
Constant2	☑	0.00891251	0.00891251
Constant4	☑	-0.00891251	-0.00891251
HarmVout@fSalient	☑	0.000509075	0.000509075
Check vOut ripple	☑		
Constant1	☑	1	1
Constant5	☑	-1	-1
rippleVout	☑	0.0275926	0.0275926
Check current ripple	☑		
Constant3	☑	10	10
Constant6	☑	-10	-10
rippleIin:1	☑	0.105894	0.105894
rippleIin:2	☑	-0.142035	-0.142035
rippleIin:3	☑	0.325887	0.325887

```
phaseDelay = [0   1   2   3   4   5] *8.3333e-006
-- Main initialization -----------------------------------------------
vHV =  100
fSw =  20000
rNom =  5
R =  5
nP =  3
nS =  2
iLVnRip =  0.60000
vLVnRip =  0.010000
vTransN =  0.10000
k_iRefSat =  3
k_iMax =  5
allowedSat = 0
iNom =  20
iRefSat =  60
iMax =  100
-- Flying caps  ---------
vFlynRip =  0.050000
cFly = 2.0000e-004
esrFlyCap =  0.0010000
vCFly0 = 100  100  100    50
-- LV filter ------------
stanName =  2
fDesign =  150000
vMagDesign =  0.0089125
lMin = 1.5000e-004
lRipple = 7.8125e-005
lLV = 1.5000e-004
lLV/nP = 5e-005
cRipple = 1.3889e-006
cStandard = 7.1480e-006
cTransient = 1.2000e-004
cLV = 1.2000e-004
f0 =  2054.7
ratioF =  9.7339
wnI_ = 2.5133e+004
case 2
iRefSat =  60
iMax =  100
-- CS generator ---------
nS = 2; nP = 3; minimizeLconn
index = 6   5   4   3   2   1
delay = 08.3333e-0061.6667e-005   2.5e-0053.3333e-0054.1667e-005
-- Regulator ------------
iNom =  20
iRefSat =  40
iMax =  60
nEqSampF =  0.50000
sampRate =  2
iSamp =  3
wnI_ZOH = 2.5133e+004
wnI_sat = 1.5708e+005
wnI = 2.5133e+004
xiI =  0.70711
KiI =  315.83
KpI =  0.017772
wnV_ZOH =  5026.5
wnV_sat = 1.0472e+004
wnV =  5026.5
xiV =  0.70711
KiV =  3031.9
KpV =  0.85303
-- Equalizing_xSampler ----
fSample =  40000
phaseDelay = [0   1   2   3   4   5] *8.3333e-006
```

DESIGNING WITH OBJECTS AND OPTIMIZATION

A real-world object

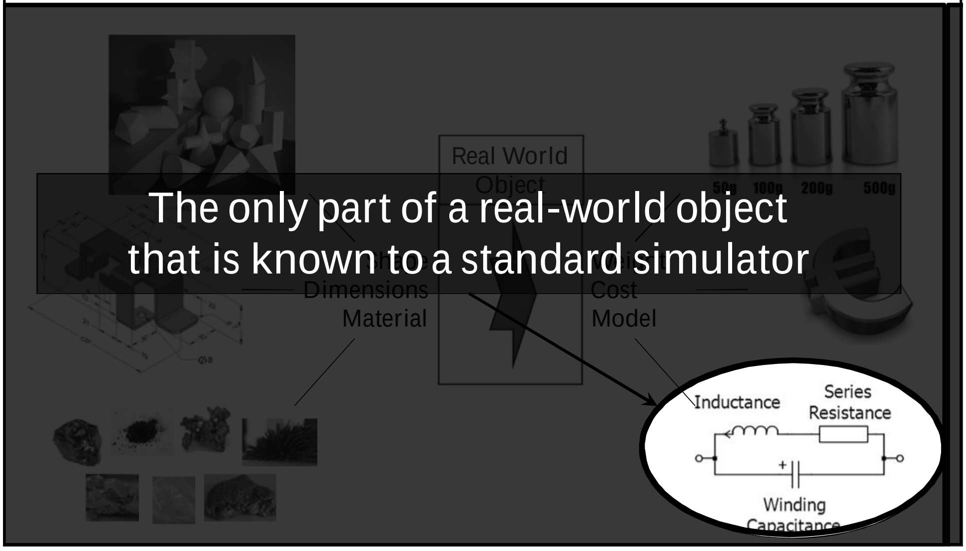


Real World Object

Shape
Dimensions
Material

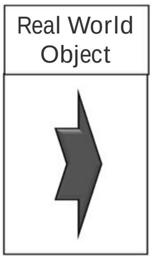
Weight
Cost
Model

A real-world object



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

Designing a real-world object

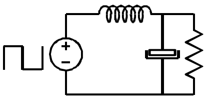


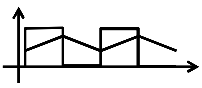
Apply stimuli according to specifications :

- Voltage,
- Current,
- Switching Pattern,
- Ambiant temperature
- …

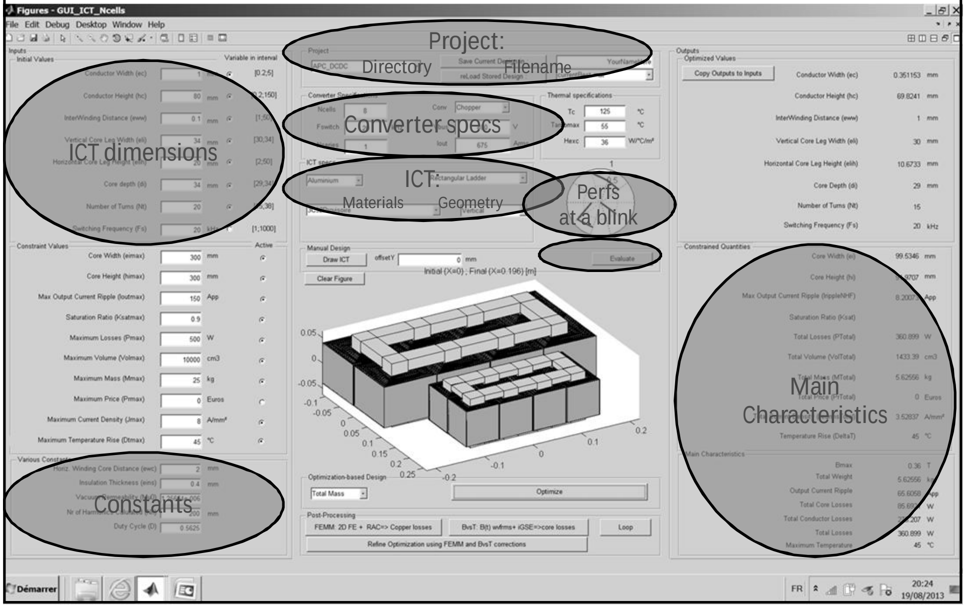
Check compatibility with maximum ratings :

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

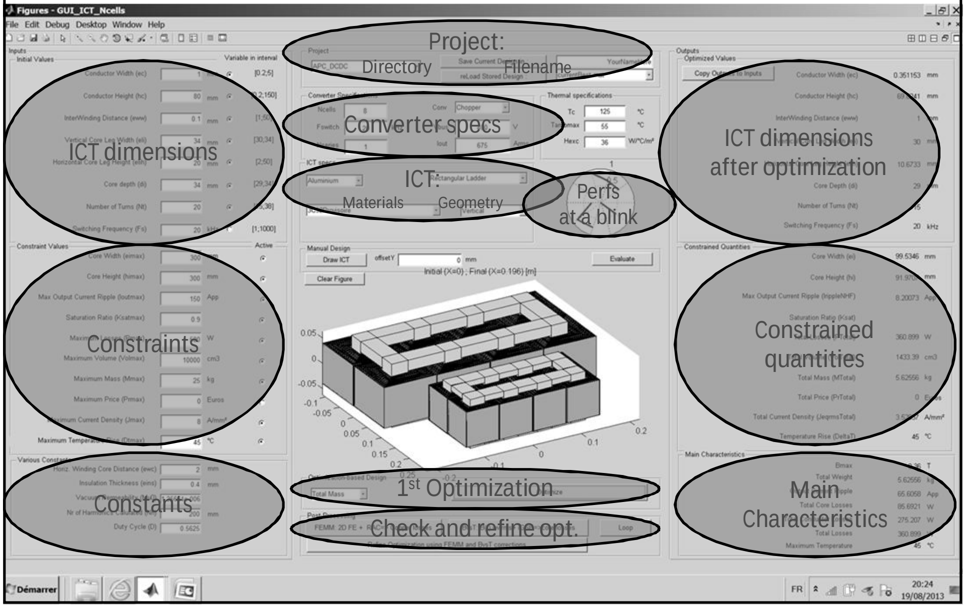




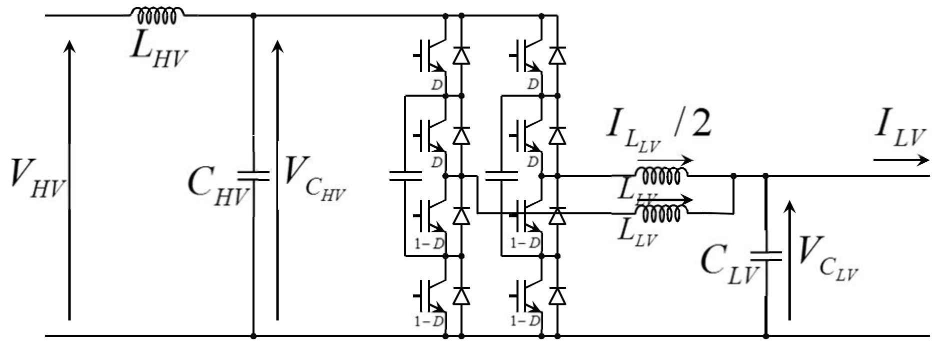
Example : InterCell Transformer



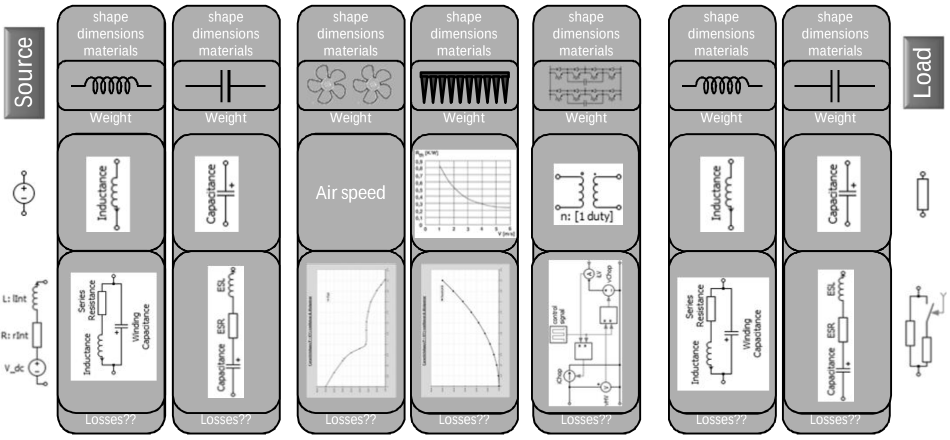
Example : InterCell Transformer



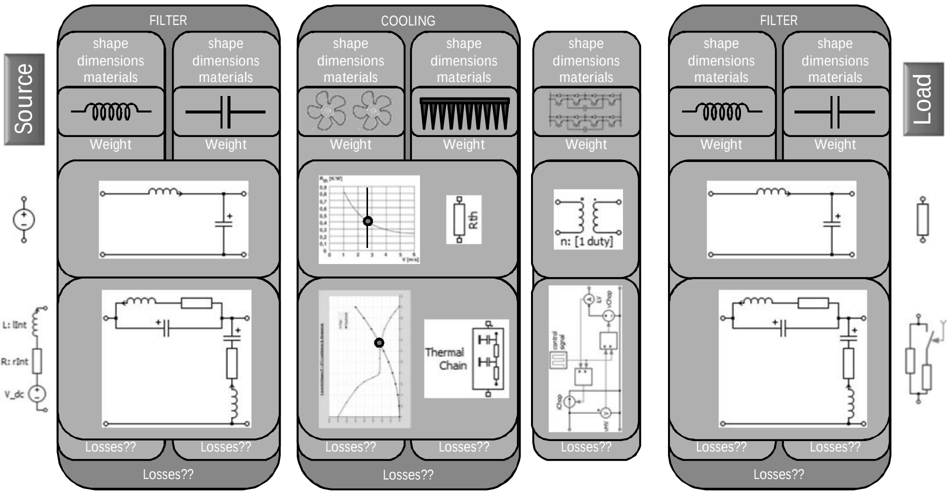
Designing a full system



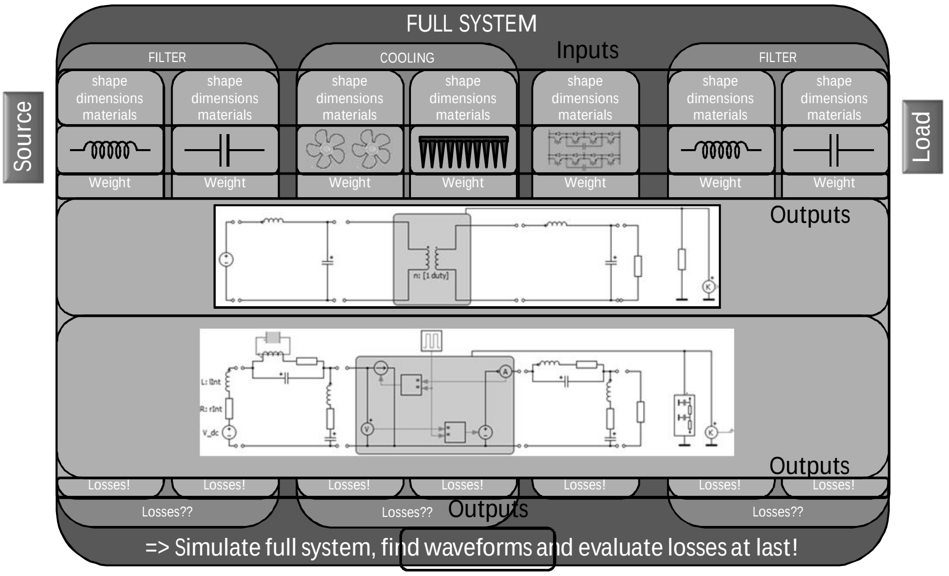
Collect objects



Compose objects



Build full system model and solve



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

Need for a fast solver

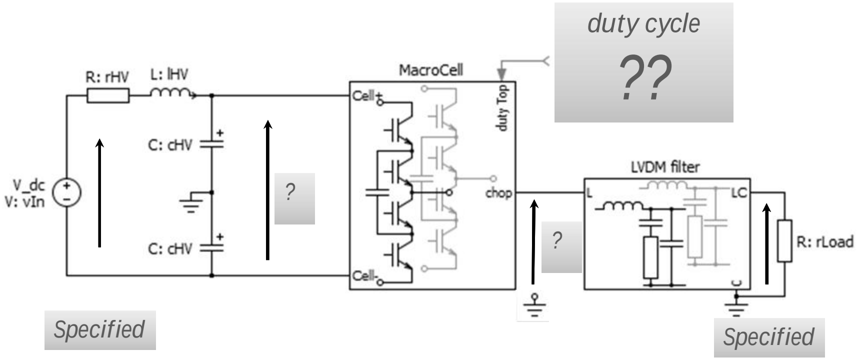
Steady-state waveforms are needed

- 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) characteritics 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



duty cycle

??

?

?

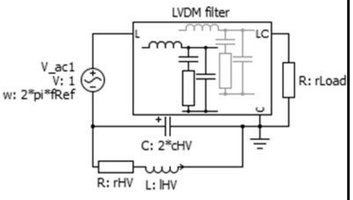
Specified

Specified

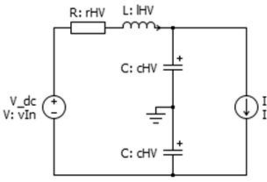
Principle used for approximate determination of the operating point

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

Apply 1V@fRef 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).v_{HV}

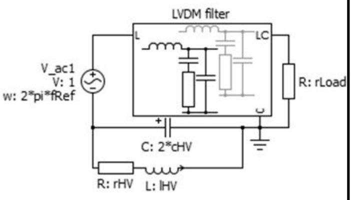


Equations used for approximate determination of the operating point

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

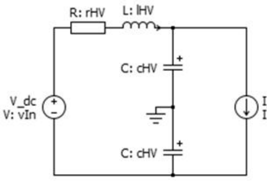
$$v_{AC}^{opPoint} = \frac{\left|v_{load}^{opPoint}\right|}{\left|v_{load}^{N}\right|} \angle\left(\varphi_{ref}^{opPoint} - \varphi_{load}^{N}\right)$$

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



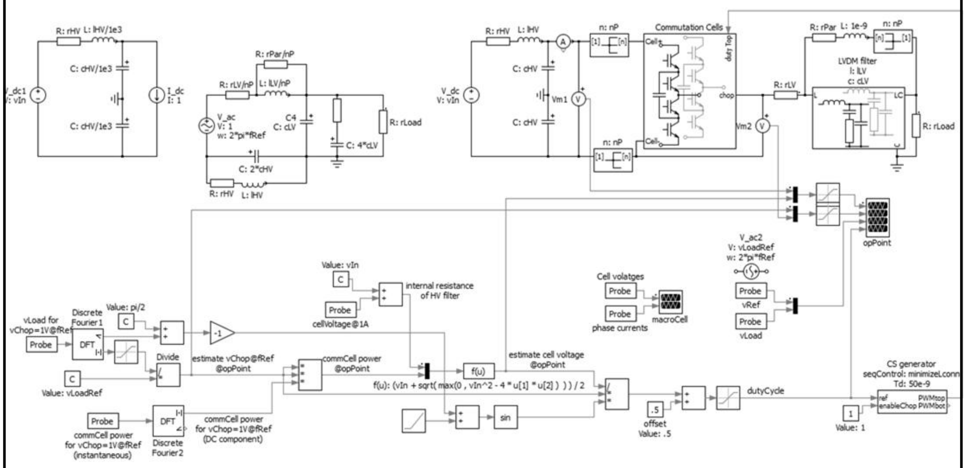
$$r_{int} = v_{in} - v_{HV}^{N}$$

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

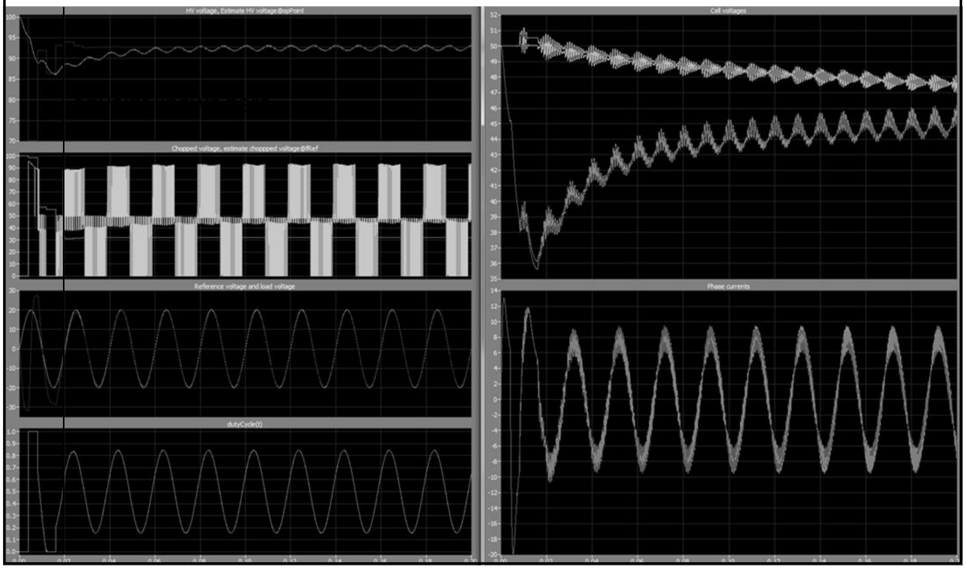


$$\Rightarrow duty(t) = \frac{v_{AC}^{opPoint}}{v_{HV}^{opPoint}}$$

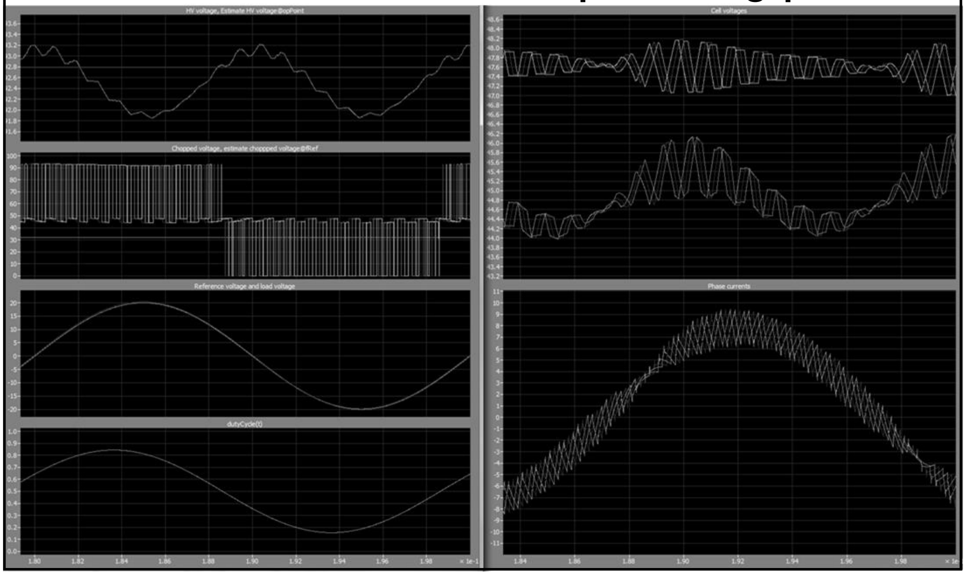
Approximate time domain determination of the operating point



Approximate time domain determination of the operating point

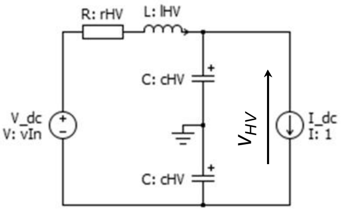


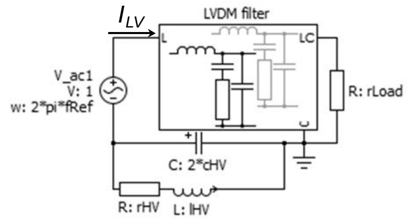
Approximate time domain determination of the operating point



Approximate frequency domain determination of the operating point

Solve separate 'normalized' circuit (I_{DC}=1A ; V_{AC}=1V ∠0°) using a single frequency! (*DC* and





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

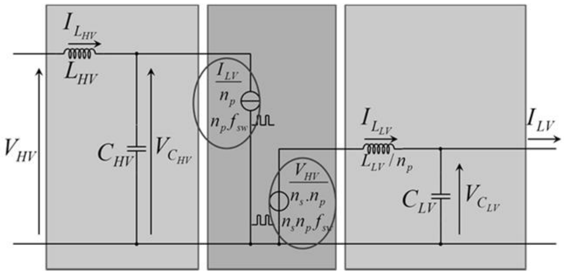
$$\begin{cases} v_{AC}^{opPoint} = \dfrac{\left|v_{load}^{opPoint}\right|}{\left|v_{load}^{N}\right|} \angle\left(\varphi_{ref}^{opPoint} - \varphi_{load}^{N}\right) \\ P_{AC}^{opPoint} = P_{AC}^{N}\left(\dfrac{\left|v_{load}^{opPoint}\right|}{\left|v_{load}^{N}\right|}\right)^{2} \end{cases}$$

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

Full frequency domain analysis using the operating point

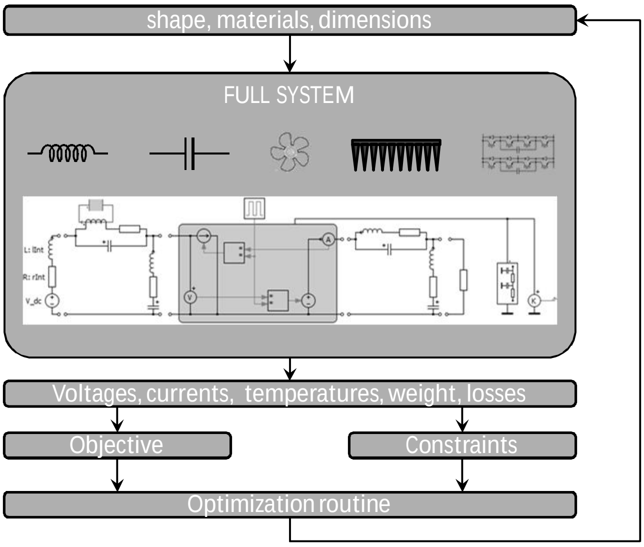
The control pattern *duty(t)* determined previously allows direct calculation of the steady state waveforms at a point that is very close to the specified point:

- The circuit is split in independant linear subcircuits
- The spectra of the souvrces 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…



shape, materials, dimensions

FULL SYSTEM

Voltages, currents, temperatures, weight, losses

Objective

Constraints

Optimization routine