Design Methods and Tools for Power Electronics

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Outline of the presentation

• Simulation vs Design
• Semi Analytic Design
• Designing with objects and optimization
SIMULATION VS DESIGN
Simulation is an injection:
one circuit gives a single set of waveforms.
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

Commutation Cell Design

Filter Design

Simulate

Build

Test

loss estimate

more accurate loss estimate

select heatsink

Measure Efficiency & Weight

SC → \( f_{sw} \) → HV & LV standards
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

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

2-Find number of series connected switches

\[
V_{SW} = \text{int}\left( \frac{V_{SW}}{V_{\text{margin}} \cdot V_{CE\text{ max}}} \right) + 1
\]
3-Find Maximum Current per switch for this profile: evaluate variation of losses as a function of the current

output characteristic IGBT-inverter (typical)

\[ I_C = f(V_{CE}) \]
\[ V_{GE} = 15 \text{ V} \]

\[ V_{CE} \text{ [V]} \]

switching losses IGBT-inverter (typical)

\[ E_{on} = f(I_C), E_{off} = f(I_C) \]
\[ V_{GE} = \pm15 \text{ V}, R_{Gon} = 2.7 \text{ Ω}, R_{Goff} = 4.7 \text{ Ω}, V_{CE} = 900 \text{ V} \]

\[ V_{CE} \text{ [mJ]} \]

\[ => P_{cond} = V_{CE} I = (V_T + R_T I) I = V_T I + R_T I^2 \]

\[ => P_{sw} = f_{sw} E_{on,off} = f_{sw} \left( A_{on,off} + B_{on,off} I + C_{on,off} I^2 \right) \]
3- Find Maximum Current per switch for this profile: solve thermal equation

Conduction losses + Switching losses = Maximum Power extracted

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

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

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

\[ I_{P_{max}}(f) = \frac{- \left[ D \cdot V_T + \frac{V_{sw}}{n_{Series} V_{def}} (B_{on} + B_{off}) \cdot f_{déc} \right] \pm \sqrt{\Delta_{Discriminant}}}{2 \left[ D \cdot R_T + \frac{V_{sw}}{n_{Series} V_{def}} (C_{on} + C_{off}) \cdot f_{déc} \right]} \]
Current /frequency operating area of a switch

Maximum Power

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

SEMIX 302GB12T4s
Vsw=900; D=0.5; d\Theta_J_C= 60°C

Maximum Power
4- Find number of parallel connected switches

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

5- Find losses and efficiency

\[
P_{\text{losses composant}} = D \cdot \left( R_T \cdot \left( \frac{I}{n_{Par}} \right)^2 + V_T \cdot \frac{I}{n_{Par}} \right) + f_{\text{déc}} \cdot \frac{V_{sw}}{V_{\text{def}}} \cdot \left( A_{on} + A_{off} \right) + \left( B_{on} + B_{off} \right) \cdot \frac{I}{n_{Par}} + \left( C_{on} + C_{off} \right) \cdot \left( \frac{I}{n_{Par}} \right)^2
\]

\[
\text{Efficiency} = 1 - \frac{n_{\text{Series}} \cdot n_{Par} \cdot P_{\text{losses composant}}}{P_{\text{out}}}
\]
6-Build a MacroSwitch with each component of the database
Find the IGBT-based MacroSwitch with the best efficiency

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Series Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>600V</td>
<td>7</td>
</tr>
<tr>
<td>1200V</td>
<td>4</td>
</tr>
<tr>
<td>1700V</td>
<td>3</td>
</tr>
<tr>
<td>3300V</td>
<td>2</td>
</tr>
<tr>
<td>6500V</td>
<td>1</td>
</tr>
</tbody>
</table>

Coefficients de pertes des différents modules

- \( V_{\text{commuté}} = 3000 \text{V} \)
- \( I_{\text{commuté}} = 100 \text{A} \)
- DutyCycle = 50%
- \( f_{\text{sw}} = 0 \text{Hz} \)
- \( DT_{\text{jc}} = 50^\circ \text{C} \)

\[ \text{LossCoeff} = \frac{\text{Loss in one switch}}{\text{Output Power}} \] (Buck converter configuration)

(*) LossCoeff = Loss in one switch / Output Power (Buck converter configuration)
Find the IGBT-based MacroSwitch with the best efficiency

Coefficients de pertes des différents modules

Vcommuté=3000V; Icommuté=100A; DutyCycle=50%; fsw=1000Hz; DTjc=50°C

- 600V (7 en série)
- 1200V (4 en série)
- 1700V (3 en série)
- 3300V (2 en série)
- 6500V (1 en série)

Explore IGBT database

1700V devices

=>

(*LossCoeff = Loss in one switch / Output Power (Buck converter configuration)
Find the IGBT-based MacroSwitch with the best efficiency

Explore IGBT database

Coefficients de pertes des différents modules

Vcommuté=3000V; Icommuté=100A; DutyCycle=50%; fsw=3000Hz; DTjc=50°C

- 600V (7 en série)
- 1200V (4 en série)
- 1700V (3 en série)
- 3300V (2 en série)
- 6500V (1 en série)

LossCoeff*(*) = Loss in one switch / Output Power (Buck converter configuration)
Find the IGBT-based MacroSwitch with the best efficiency

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Coefficients de pertes des différents modules

\[ \text{LossCoeff} = \frac{\text{Loss in one switch}}{\text{Output Power}} \] (Buck converter configuration)

(*) 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.

\[ P_{\text{cond}} = \frac{1}{T} \int_T^T v_i \cdot dt = \frac{1}{T} \int_T^T (V_T + R_T i) \cdot dt = V_T \left( \frac{1}{T} \int_T^T i \cdot dt \right) + R_T \left( \frac{1}{T} \int_T^T i^2 \cdot dt \right) = V_T i_{\text{avg}} + R_T i_{\text{RMS}} \]

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

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

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

\[ f_0^{LV} = \frac{1}{2\pi \sqrt{L_{LV} C_{LV}}} \]
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 current ripple and HV voltage ripple (Steady-state)
AC Equivalent circuit of a Two-Level Cell

\[ I_{L_{HV}} \quad L_{HV} \]

\[ V_{HV} \quad C_{HV} \quad V_{C_{HV}} \]

\[ f_{0}^{HV} = \frac{1}{2\pi \sqrt{L_{HV} C_{HV}}} \]

\[ I_{LV} \quad V_{HV} \]

\[ f_{sw} \quad f_{sw} \]

\[ f_{0}^{LV} = \frac{1}{2\pi \sqrt{L_{LV} C_{LV}}} \]

\[ I_{L_{LV}} \quad L_{LV} \]

\[ V_{C_{LV}} \quad C_{LV} \]
Series-Parallel MultiLevel Cell with Filters

\[
\begin{align*}
V_{HV} & \quad I_{LHV} \\
HVC & \quad V_{C_{HV}} \\
f_{0}^{HV} &= \frac{1}{2\pi \sqrt{L_{HV} C_{HV}}} \\
I_{chop} & \quad f_{sw} \\
\frac{I_{LV}}{2} & \quad I_{L_{LV}} \\
C_{LV} & \quad V_{C_{LV}}
\end{align*}
\]
AC-equivalent circuit of Series-Parallel MultiLevel Cell

\[ I_{LV} = \frac{n_p I_{HV}}{n_s n_p f_{sw}} \]

\[ V_{HV} = V_{C_{HV}} \]

\[ C_{HV} \]

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

\[ f_0^{LV} = \frac{1}{2\pi \sqrt{L_{LV} / n_p C_{LV}}} \]
Steady state, time domain: worst case ripples

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

\[
V_{LV_{ripple\%}} = \frac{V_{LV_{pk-ripple}}}{V_{HV}} = \frac{2}{\pi n_p n_s} \left( \frac{f^L V_0}{n_p n_s f_{sw}} \right)^2
\]

\[
f^L V_0 = \frac{1}{2\pi \sqrt{L_{LV}/n_p . C_{LV}}}
\]

\[
\Rightarrow \sqrt{L_{LV}/n_p . C_{LV}} = \frac{1}{2\pi (n_p n_s)^{1.5} f_{sw} \sqrt{\frac{\pi}{2} V_{LV_{ripple\%}}}}
\]

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

\[
I_{HV_{ripple\%}} = \frac{I_{HV_{pk-ripple}}}{I_{LV_{max}}} = \frac{2}{\pi n_p} \left( \frac{f^H V_0}{n_p f_{sw}} \right)^2
\]

\[
f^H V_0 = \frac{1}{2\pi \sqrt{L_{HV}. C_{HV}}}
\]

\[
\Rightarrow \sqrt{L_{HV}. C_{HV}} = \frac{1}{2\pi n_p^{1.5} f_{sw} \sqrt{\frac{\pi}{2} I_{HV_{ripple\%}}}}
\]
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

Case 1: \( f_{sw} < f_{salient} \Rightarrow \)

\[ \sin(2Dn\pi) \]

Ripples: from time domain to frequency domain

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

Conclusion: the ripple requirement allows increasing \( f_0 \) when increasing \( f_{switching} \).
EMC standards: frequency domain formulation

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

\[-20\text{dB/dcd} + -40\text{dB/dcd} = -60\text{dB/dcd}\]

Conclusion: salient point of EMC standards imposes decreasing \( f_0 \) when increasing \( f_{\text{switching}} \).
Steady state: ripples and standards combined

Required cut-off frequency vs switching frequency
Steady state: ripples and standards combined

Required cut-off frequency vs switching frequency for MultiCell converters

Simplified EN55022A Filter for multiCell Chopper

- $n_{Cell} = 10$
- $n_{Cell} = 5$
- $n_{Cell} = 2$
- $n_{Cell} = 1$

$20\text{dB@100kHz}$
Step response, average model:
full load => no load

Worst Case:
\[ D = 100\%; I_{LHV}^{(t=0)} = I_{LV_{max}} \]

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

Voltage overshoots

\[ I_{LV_{max}}^{(t=0)} = I_{LV_{max}} \]

\[ L_{LV}/n_p \]

\[ 0.I_{LV} \]

\[ 0.V_{HV} \]
Step response, state plane analysis
full load => no load

High Voltage Side

Low Voltage Side

Worst Case

$V_{HV}$

$I_{L_HV} \sqrt{\frac{L_{HV}}{C_{HV}}}$

$I_{L_LV} \sqrt{\frac{L_{LV}}{C_{LV}}}$

$I_{L_{max}} \sqrt{\frac{L_{HV}}{C_{HV}}}$

$I_{L_{max}} \sqrt{\frac{L_{LV}}{C_{LV}}}$
**Full load => no load : dynamic requirement HV side**

Limit the voltage overshoot on the High Voltage Side

\[
V_{ovrsht\%}^{HV} = \frac{I_{LV} \cdot \sqrt{\frac{L_{HV}}{C_{HV}}}}{V_{HV}} \quad \Rightarrow \quad \sqrt{\frac{L_{HV}}{C_{HV}}} = \frac{V_{HV} \cdot V_{ovrsht\%}^{HV}}{I_{LV_{\text{max}}}}
\]
Step response, average model: no load => full load

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

Voltage dips

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

Worst Case
No load => Full load: dynamic requirement LV side

Limit the voltage dip on the Low Voltage Side

\[ V_{dip}^{LV} = I_{LV} \cdot \sqrt{\frac{L_{LV}}{n_p C_{LV}}} \]

\[ \sqrt{\frac{L_{LV}}{n_p}} = \frac{V_{HV} \cdot V_{dip}^{LV}}{I_{LV_{max}}} \]
Calculation of the components

High Voltage side

\[ n_{Cell} = n_p \]

\[ Rip\% = I_{ripple}^{HV} = \frac{I_{HV}^{pk-ripple}}{I_{LV}^{max}} \]

\[ f_0 = \frac{1}{2\pi \sqrt{L_{HV} \cdot C_{HV}}} \]

Low Voltage side

\[ n_{Cell} = n_p \cdot n_s \]

\[ Rip\% = V_{ripple}^{LV} = \frac{V_{LV}^{pk-ripple}}{V_{HV}} \]

\[ f_0 = \frac{1}{2\pi \sqrt{L_{LV} / n_p \cdot C_{LV}}} \]

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

Valid for uncoupled AND coupled magnetic components
Calculation of the components

**High Voltage side**

\[
\begin{align*}
\sqrt{L_{HV}/C_{HV}} &= \frac{V_{HV} \cdot V_{HV}^{\text{ovrshf}\%}}{I_{LV_{\text{max}}}} \\
\sqrt{L_{HV} \cdot C_{HV}} &= \frac{1}{2\pi \cdot f_0^{HV}}
\end{align*}
\]

⇒

\[
\begin{align*}
L_{HV} &= \frac{V_{HV} \cdot V_{HV}^{\text{ovrshf}\%}}{2\pi \cdot f_0^{HV} \cdot I_{LV_{\text{max}}}} \\
C_{HV} &= \frac{I_{LV_{\text{max}}}}{2\pi \cdot f_0^{HV} \cdot V_{HV} \cdot V_{HV}^{\text{ovrshf}\%}}
\end{align*}
\]

**Low Voltage side**

\[
\begin{align*}
\sqrt{L_{LV}/n_p \cdot C_{LV}} &= \frac{V_{HV} \cdot V_{LV}^{\text{dip}\%}}{I_{LV_{\text{max}}}} \\
\sqrt{L_{LV}/n_p} &= \frac{1}{2\pi \cdot f_0^{LV}}
\end{align*}
\]

⇒

\[
\begin{align*}
L_{LV}/n_p &= \frac{V_{HV} \cdot V_{LV}^{\text{dip}\%}}{2\pi \cdot f_0^{LV} \cdot I_{LV_{\text{max}}}} \\
C_{LV} &= \frac{I_{LV_{\text{max}}}}{2\pi \cdot f_0^{LV} \cdot V_{HV} \cdot V_{LV}^{\text{dip}\%}}
\end{align*}
\]

Valid for uncoupled AND coupled magnetic components
Example #1: 2-level converter

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

Example #2: series 2-cell converter

=> the HV filter is unchanged, \( L_{LV} \) and \( C_{LV} \) are reduced if \( f_{SW} > 80\text{kHz} \)
Calculation of the components

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

MultiCell Chopper with: $n_S=1$; $V_{HV}=800$; $ILV_{max}=250$; $IHV_{max}=125$; $\text{relativeOutRipple}=0.01$; $V_{HVovershoot}=0.1$; $V_{LVdip}=0.05$; $\text{standardHV}=\text{HVDCa}$; $\text{standardLV}=\text{EN55022A}$

- $LHV_{nP=1}$
- $\text{CHV}_{nP=1}$
- $LLV/nP_{nP=1}$
- $CLV_{nP=1}$
- $LHV_{nP=2}$
- $\text{CHV}_{nP=2}$
- $LLV/nP_{nP=2}$
- $CLV_{nP=2}$
Example #4: parallel multiCell converter
=> with 10 cells, all passive components start decreasing at $f_{sw} > 15\text{kHz}$
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 capacitors. => 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

1. Start
2. User defined Specifications
3. Commutation Cell Design
4. Filter Design
5. Simulate
6. Build
7. Test
8. Measure Efficiency & Weight

- SC
- \( f_{sw} \)
- HV & LV standards

- loss estimate
- weight estimate?
- more accurate loss estimate
- select heatsink
VOLUME OF PASSIVE COMPONENTS AND FILTERS FOR MULTILEVEL CONVERTERS
Area Product of Magnetic Components: Inductors

Basic formulation

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

\[ j_{\text{eff}} = \frac{n_t \cdot I_{\text{eff}}}{k_w \cdot A_w} \]

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

Advantage: allows selecting the core

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

Taking into account:

\[ L = \frac{V}{4 \Delta I \cdot f} \]

\[ \hat{I} = I_{\text{DC}} \left( 1 + \frac{\Delta I}{2I_{\text{DC}}} \right) \]

\[ I_{\text{eff}} = I_{\text{DC}} \sqrt{1 + \frac{1}{12} \left( \frac{\Delta I}{I_{\text{DC}}} \right)^2} \]

we get:

\[ A_w \cdot A_c = \frac{V \cdot I_{\text{DC}} \left( 1 + \frac{\Delta I}{2I_{\text{DC}}} \right) \sqrt{1 + \frac{1}{12} \left( \frac{\Delta I}{I_{\text{DC}}} \right)^2}}{4(\Delta I/I_{\text{DC}}) \cdot f \cdot \hat{B} \cdot k_w \cdot j_{\text{eff}}} \]
Area Product of Magnetic Components: Inductors

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:

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

Though elegant, this formulation could be misleading:

- \(B_{AC \text{ max}}\) and \(R_{AC}/R_{DC}\) are very difficult to determine a priori:
  - \(B_{AC \text{ max}}\) 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...

![Graph](image-url)
Area Product of Magnetic Components: Inductors

Interleaved converters with uncoupled inductors

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

Interleaved converters with **uncoupled** inductors

---

**Area Product of Magnetic Components: Inductors**

\[ NVol = \frac{Vol_{tot}}{K_{shape}} \left( \frac{B_{sat} f_k w_j}{V I_{DC}} \right)^{3/4} = n_p \left( \frac{1}{8 n_p \max} \left( 1 + \frac{n_p^2 \Delta I_{tot}}{I_{DCtot}} ; \frac{B_{sat}}{B_{AC max}} \right) \right)^{3/4} \]

\[ \frac{\Delta I_{tot}}{I_{DCtot}} \]
**Area Product of Magnetic Components : ICTs**

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

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

\[
\Delta I_{tot} = \frac{\Delta I_{ind}}{n_p} \cdot n_p
\]

\[
I_{DCtot} = n_p \cdot I_{DCind}
\]

\[
\Rightarrow \frac{\Delta I_{ind}}{I_{DCind}} = \frac{n_p \Delta I_{tot}}{I_{DCtot}/n_p} = \frac{n_p^2 \Delta I_{tot}}{I_{DCtot}}
\]

\[
Vol_{tot} = n_p \cdot K_{shape}
\]

\[
V \cdot \frac{I_{DCtot}}{n_p} \cdot \left(1 + \frac{2I_{DCtot}}{n_p^2 \cdot \Delta I_{tot}}\right) \sqrt[3/4]{1 + \frac{1}{12} \left(\frac{n_p^2 \cdot \Delta I_{tot}}{I_{DCtot}}\right)^2}
\]

\[
= 8\hat{B}.f.k_w.j_{eff}
\]

=> Total volume of the \( n_p \) coupled inductors:
Area Product of Magnetic Components: ICTs

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

Basic formulation

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

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

**Area Product of Magnetic Components : ICTs**

\[ NVol = \frac{Vol_{tot}}{K_{shape}} \left( \frac{B_{sat} \cdot f \cdot k \cdot j_{eff}}{V \cdot I_{DC}} \right)^{3/4} = n_p \cdot \left( \frac{1}{8n_p} \right) \max \left( \frac{1}{1 + n_p^2 \Delta I_{tot} / I_{DCtot}} ; \frac{B_{sat}}{B_{AC \max}} \right) \left[ 1 + \frac{R_{AC}}{R_{DC}} \frac{1}{12} \left( \frac{\Delta I_{tot}}{I_{DCtot}} \right)^2 \right]^{3/4} \]
Minimum volume of LV-side uncoupled inductors and InterCell Transformers

**Crossing** (\(f_1=f_2\))

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

\[\Rightarrow \text{Ripple giving the minimum volume of Magnetic Component :}\]

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

\[
\chi = \min \left\{ \frac{1}{n_p^{2/3}} \sqrt[3]{\frac{24}{R_{AC}/R_{DC}}} ; \frac{2}{n_p^2} \right\} \frac{B_{AC\ max}}{B_{sat}}
\]
Minimum volume of LV-side uncoupled inductors and InterCell Transformers

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

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

Uncoupled $\frac{df}{d\chi} = 0 \iff \chi = \frac{\sqrt{a}}{\sqrt{b}}$  \quad \text{and} \quad \frac{R_{AC}}{R_{DC}} \leq \frac{24}{24}$

Coupled $\frac{df}{d\chi} = 0 \iff \chi = \frac{\sqrt{a}}{\sqrt{b}}$  \quad \text{and} \quad \frac{R_{AC}}{R_{DC}} \leq \frac{1}{24}$

Minimum view at the augmentation des parties pôles AC

$$N\text{AP}_{\text{core}} = \frac{A_c A_w B_{fc} k_w j_{eff}}{V_{I_{DC}}} - \frac{1}{8}\left(1 + \frac{2}{\Delta I/I_{DC}}\right)^2$$

$$\text{minimum view at saturation:}$$

$$1 = \frac{2}{n_1^2 \Delta I_{AC}/I_{DC}} = \frac{B_{AC}/B_{sat}}{\Delta I_{AC}/I_{DC}} = \frac{B_{AC}/B_{sat}}{\Delta I_{AC}/I_{DC}}$$

Minimum view at the augmentation des parties pôles DC

$$N\text{AP}_{\text{core}} = \frac{A_c A_w B_{fc} k_w j_{eff}}{V_{I_{DC}}} = \frac{1}{8}\max\left(1 + \frac{2}{\Delta I/I_{DC}}, \frac{B_{sat}}{B_{AC\text{max}}}\right)$$

$$\text{Minimum view at saturation:}$$

$$1 = \frac{2}{n_1^2 \Delta I_{AC}/I_{DC}} = \frac{B_{AC}/B_{sat}}{\Delta I_{AC}/I_{DC}} = \frac{B_{AC}/B_{sat}}{\Delta I_{AC}/I_{DC}}$$

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/cm$^3$ vs frequency

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

Maximum value of $B_{AC}$ for a loss density of 500mW/cm$^3$ vs frequency

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

Maximum value of $B_{AC}$ for a loss density of 750mW/cm$^3$ vs frequency

\[
B_{AC\, max}^{750\, mW/cm^3} \approx \min \left( 1.2 \left( \frac{f}{26200} \right)^{-0.76} \right)
\]
Filters with minimum volumes

High Voltage side

- **L<sub>HV</sub>**
  - Voltage ripple (#4)
  - EMC standard (#3)
  - Current ripple
  - Monotonous

- **Vol L<sub>HV</sub>**
  - Monotonous

- **C<sub>HV</sub>**
  - Candidates for volume reduction

Low Voltage side

- **L<sub>LV</sub>**
  - Step response (#3)

- **Vol L<sub>LV</sub>**
  - Voltage ripple (#4)
  - EMC standard (#3)
  - Monotonous

- **C<sub>LV</sub>**
  - Candidates for volume reduction

Base point

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<sub>HV</sub>, 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<sub>MinVol</sub> < L<sub>BasePoint</sub>) or the constant L/C (L<sub>MinVol</sub> > L<sub>BasePoint</sub>) line.
Filters with minimum volumes

High Voltage side

- $L_{HV}$
- $C_{HV}$
- Voltage ripple (#4)
- Step response (#3)
- Base point
- Candidates for volume reduction

Low Voltage side

- $L_{LV}$
- $C_{LV}$
- Voltage ripple (#3)
- Step response (#3)
- Min. volume (#4)
- Candidates for volume reduction
- Base point

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.
Design process

Start

User defined Specifications

SC list, [f_min, f_max], HV & LV standards

Commutation Cell Design

Filter Design

End f_{sw} list?

End SC list?

HeatSink Weight

Losses

Losses Weight

Efficiency vs Specific Power

SemiCon. & Materials Database
Combining SC data and passive component data: feasible points in the (SpecificPower, Efficiency) plane

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

Increasing $f_{sw}$

2-Level Design

IPW90R120C3 (Si 900V)
Combining SC data and passive component data: feasible points in the \((\text{SpecificPower},\text{Efficiency})\) plane

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

**MultiVoltage Competition (Si Only)**

- IPW90R120C3 (Si 600V)
- SPP11N80C3
- IPP65R074C6
- SPP20N60C3
- STY139N65M5
- APT60N60BCS
- IPB60R099CP
- STP20NM60FD
- IPD50R399CP
- IPI50R350CP
- IPB200N25N3
- IRFP4332PbF
- IRFP4768PbF
- IPB107N20N3
- BSB280N15NZ3
- BSC060N10NS3 G
- BSC109N10NS3 G
- IPB025N10N3 G
- SiJ482DP
- BSC042NE7NS3
- BSC028N06NS
- BSC14N04LSI
- IRF7946PbF
- IRLH5034PbF
- SiR640DP
- BSC0925ND
- BSB013NE2LXI

---

**Combining SC data and passive component data:**

Feasible points in the \((\text{SpecificPower},\text{Efficiency})\) plane

- \(V_{HV} = 600V\)
- \(D = 50\%\)
- \(\text{Power} = 6kW\)

**MultiVoltage Competition (Si Only):**

- IPW90R120C3 (Si 600V)
- SPP11N80C3
- IPP65R074C6
- SPP20N60C3
- STY139N65M5
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- IRFP4768PbF
- IPB107N20N3
- BSB280N15NZ3
- BSC060N10NS3 G
- BSC109N10NS3 G
- IPB025N10N3 G
- SiJ482DP
- BSC042NE7NS3
- BSC028N06NS
- BSC14N04LSI
- IRF7946PbF
- IRLH5034PbF
- SiR640DP
- BSC0925ND
- BSB013NE2LXI
Combining SC data and passive component data: feasible points in the (SpecificPower,Efficiency) plane

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

- **IPW90R120C3** (Si 900V)
- **APT60N60BCS** (Si 600V)
- **EPC1005** (GaN 60V)
- **EPC2010**
- **EPC1011**
- **EPC2001**
- **EPC1005**
- **EPC2014**
- **CMF10120D** (SiC 1200V)
- **CMF20120D**

Best Si vs WideBandGap
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 access to the center of the star.

Author: TM

This block allows series connection diodes.
- If the diode is defined as a single element, the number of elements in series is imposed by the number \( n' \) in the mask.
- If the diode is defined as a vector, the number \( n' \) in the mask must be equal to the size of the vector of diodes.

Author: TM
Vectorized filters
Vectorized filters with pre-design
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 $nP.nS.fSw$.

Author: TM
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

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.
A simple circuit allows open-loop compensation of these unbalances without increasing the number of switchings.
Design check
DESIGNING WITH OBJECTS AND OPTIMIZATION
A real-world object

Real World Object

Shape

Dimensions

Material

Weight

Cost

Model

Inductance

Series Resistance

Winding Capacitance
A real-world object

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

Real World Object
- Dimensions
- Material
- Cost
- Model

Inductance
Series Resistance
Winding Capacitance
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
- ...

Real World Object
Example: InterCell Transformer
Example: InterCell Transformer

- **Project**: Directory, Filename
- **Converter specs**: ICT dimensions after optimization
- **ICT dimensions**: at a blink
- **Materials**: Perfs
- **Geometry**: 1st Optimization
- **Constriants**: Check and refine opt.
- **Main Characteristics**
Designing a full system

\[ V_{HV} \]

\[ L_{HV} \]

\[ C_{HV} \]

\[ V_{CHV} \]

\[ I_{LV} / 2 \]

\[ I_{LV} \]

\[ C_{LV} \]

\[ V_{CLV} \]
<table>
<thead>
<tr>
<th>Source</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Inductance" /></td>
<td><img src="image2.png" alt="Inductance" /></td>
</tr>
<tr>
<td><img src="image3.png" alt="Capacitance" /></td>
<td><img src="image4.png" alt="Capacitance" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Resistor" /></td>
<td><img src="image6.png" alt="Resistor" /></td>
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<tr>
<td><img src="image7.png" alt="Inductance" /></td>
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</tr>
<tr>
<td><img src="image9.png" alt="Capacitance" /></td>
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</tr>
<tr>
<td><img src="image11.png" alt="Resistor" /></td>
<td><img src="image12.png" alt="Resistor" /></td>
</tr>
</tbody>
</table>

**Collect objects**

<table>
<thead>
<tr>
<th>Shape</th>
<th>Dimensions</th>
<th>Materials</th>
<th>Weight</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image13.png" alt="Shape1" /></td>
<td><img src="image14.png" alt="Dimensions1" /></td>
<td><img src="image15.png" alt="Materials1" /></td>
<td><img src="image16.png" alt="Weight1" /></td>
<td><img src="image17.png" alt="Losses1" /></td>
</tr>
<tr>
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<td><img src="image19.png" alt="Dimensions2" /></td>
<td><img src="image20.png" alt="Materials2" /></td>
<td><img src="image21.png" alt="Weight2" /></td>
<td><img src="image22.png" alt="Losses2" /></td>
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<td><img src="image25.png" alt="Materials3" /></td>
<td><img src="image26.png" alt="Weight3" /></td>
<td><img src="image27.png" alt="Losses3" /></td>
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<td><img src="image29.png" alt="Dimensions4" /></td>
<td><img src="image30.png" alt="Materials4" /></td>
<td><img src="image31.png" alt="Weight4" /></td>
<td><img src="image32.png" alt="Losses4" /></td>
</tr>
</tbody>
</table>

- Air speed
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) 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

Specified

Specified

duty cycle
??
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  \( \Rightarrow P_{HV}=P_{LV} \)
Constant \( v_{HV} \)  \( \Rightarrow \) 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 \( \nu_{AC}=D(t).\nu_{HV} \)
Equations used for approximate determination of the operating point

Assumptions:
$\Rightarrow$ linear systems, lossless commutation cell, $v_{HV}$ is constant

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

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

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

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

$$\Rightarrow \text{duty}(t) = \frac{v_{AC}^{opPoint}}{v_{HV}^{opPoint}}$$
Approximate time domain determination of the operating point
Approximate time domain determination of the operating point

opPoint known here
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 \((DC\; and\; f_{Ref})\):

\[
\begin{align*}
  r_{int} &= v_{in} - v_{HV}^N \\
  v_{opPoint}^{HV} &= \frac{v_{in}}{2} + \sqrt{v_{in}^2 - 4 \times r_{int} \times P_{AC}^{opPoint}} \\
  v_{AC}^{opPoint} &= \frac{|v_{load}|}{|v_{load}^N|} \angle (\varphi_{ref}^{opPoint} - \varphi_{load}^N) \\
  P_{AC}^{opPoint} &= P_{AC}^N \left(\frac{|v_{load}^{opPoint}|}{|v_{load}^N|}\right)^2
\end{align*}
\]

\[\Rightarrow \text{duty}(t) = \frac{v_{AC}^{opPoint}}{v_{HV}^{opPoint}}\]
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...

shape, materials, dimensions

FULL SYSTEM

Voltages, currents, temperatures, weight, losses

Objective

Constraints

Optimization routine