ANALYSIS AND DESIGN OF AN AC/DC CONVERTER FOR OFFSHORE WIND TURBINES

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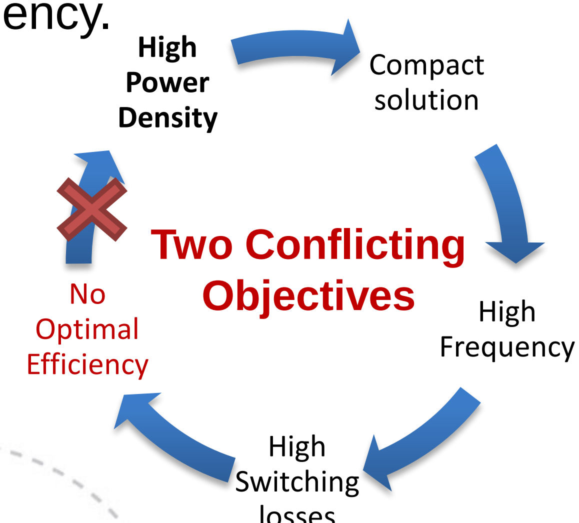
Outline:

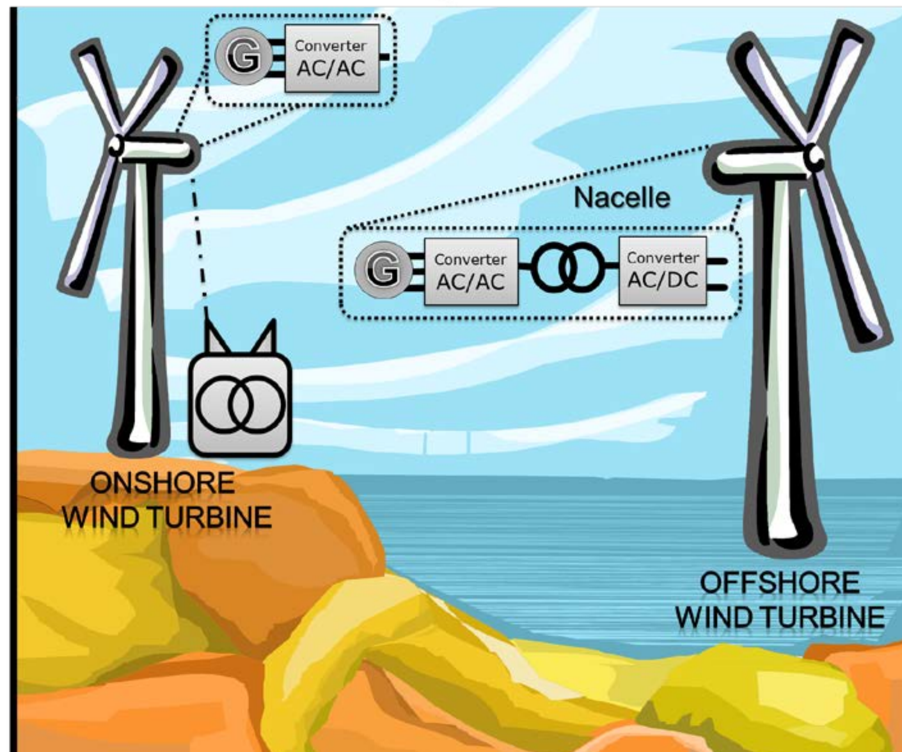
1. Introduction
2. Parameters of design
3. Methodology for evaluation of Performance indicators
4. Main results
5. Conclusions

Offshore Wind turbine challenges

Optimal design targeting two objectives

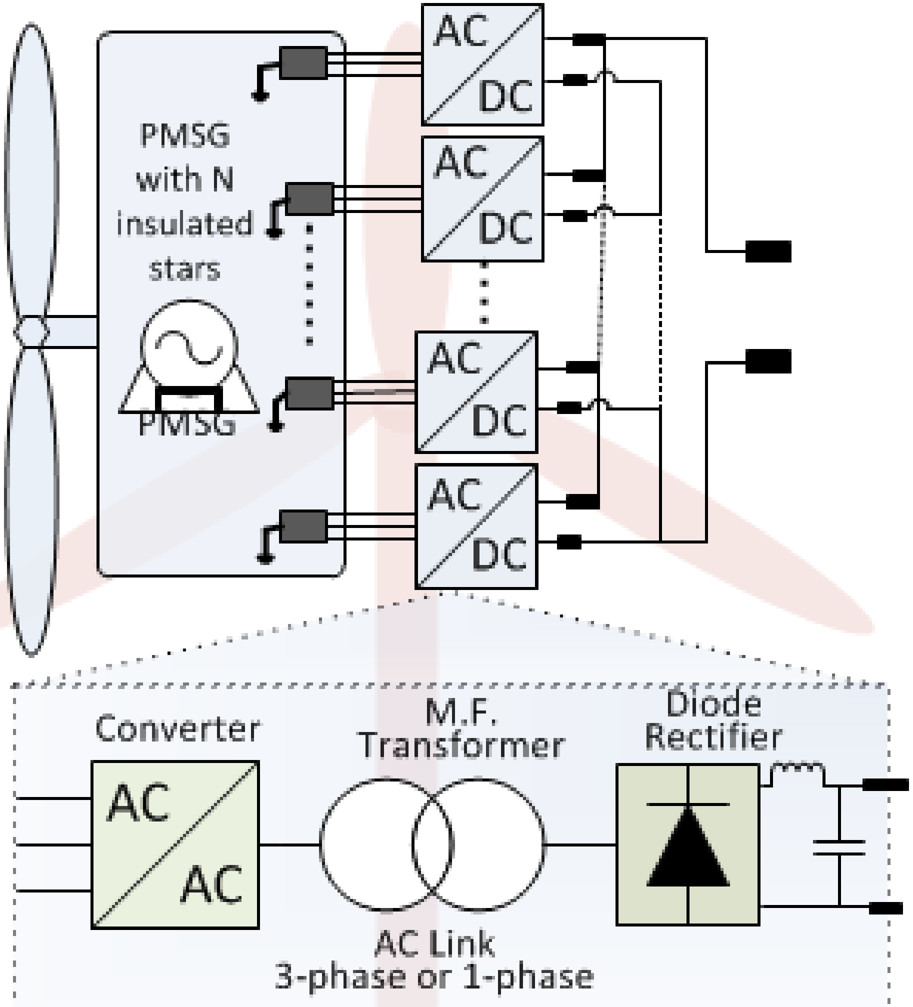
1. Maximize efficiency (η): Reduce power losses. Less conversion stages.
2. Maximize power density (ρ) of conversion system: Minimize weight/Size for a given power. Increase the Frequency.





Assumption: DC Grid is more convenient for offshore wind farms [MEYER]
New WECS architectures for offshore applications. Design taken into account all stages of the system.

Wind Energy conversion System



AC/DC Converter Module

Modular Power converter with N sub-modules.

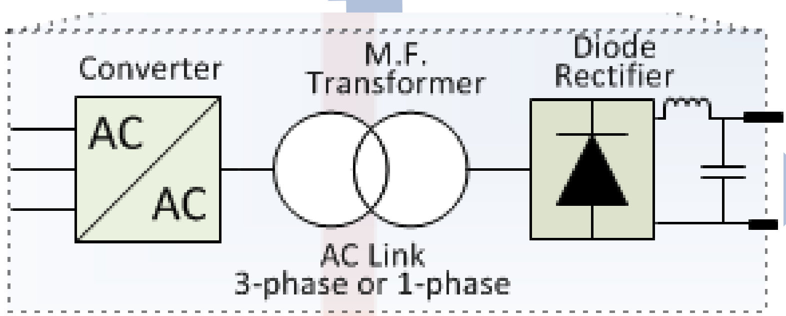
Current source operation
➔ series connection

Voltage source operation
➔ parallel connection

Parameters of design

Number of modules

Converter Topology

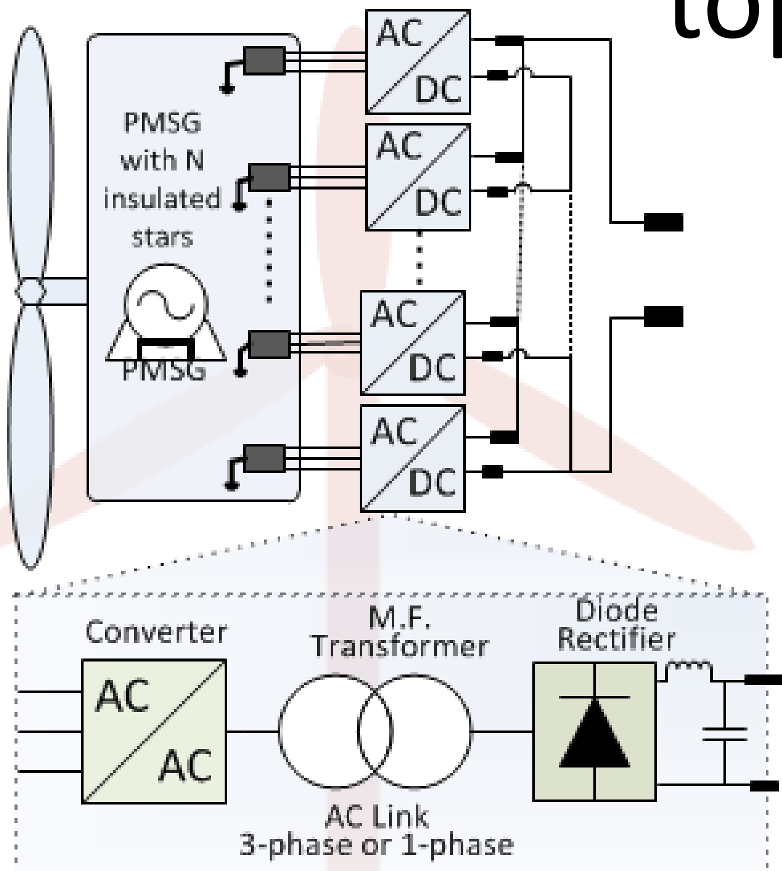


AC/DC Converter Module

Ac-Link Frequency

Single or three phase AC-Link

Parameters of design – Converter topology

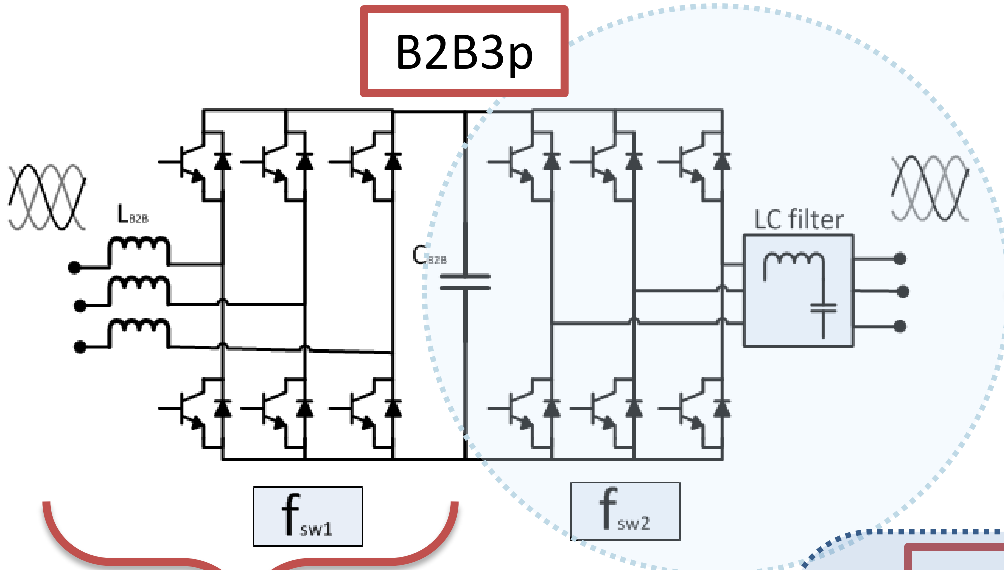


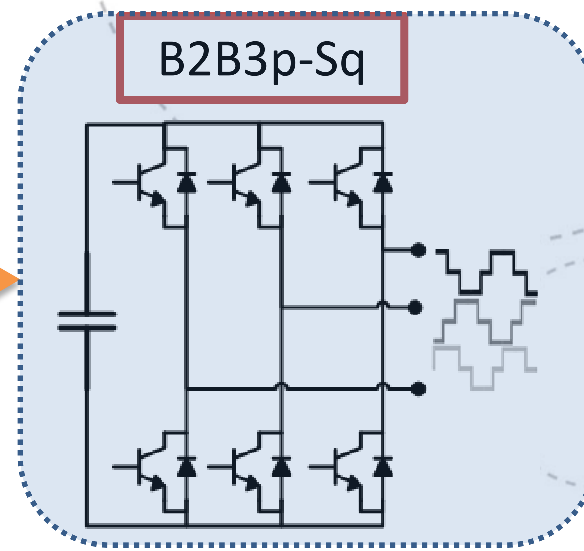
AC/DC Converter Module

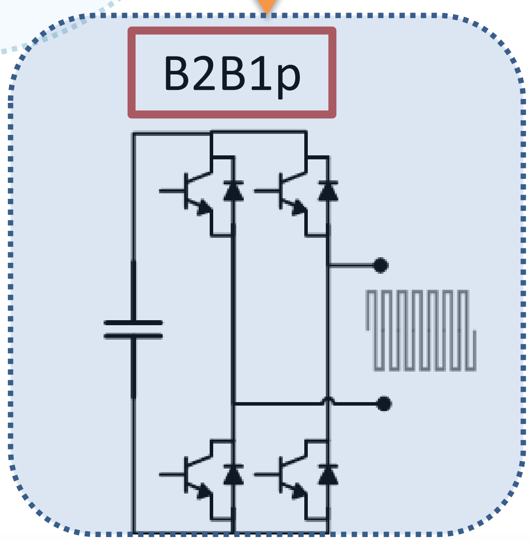
AC-LINK	Converter Topology (AC/AC)		
3 phase Sinusoidal waveform	B2B Back-to-Back	IMC Indirect Matrix Converter **[Holtsmark]**	DMC Direct Matrix Converter **[Holtsmark]**
Squared waveform	B2B-3p Back-to-Back with 3-phase output	B2B-1p Back-to-Back with 1-phase output	RMC Reduced Matrix Converter **[Garces]**

**Holtsmark and Molinas, "Matrix converter efficiency in a high frequency link offshore WECS," in IECON 2011.*
***A. Garces. "Design, Operation and control of series connected power converters for offshore wind parks". Thesis for the Degree of Doctor of Philosophy. NTNU 2012.*

Back to Back topologies







$\mathbf{f_{sw1}}$ can be lower than **fsw2**.
It is optimized for each power rating.
$\mathbf{f_{sw2}}$ should be higher than transformer freq. ($\mathbf{f_{tr}}$) for B2B3p.
It is equal to 6*$\mathbf{f_{tr}}$ in this study.

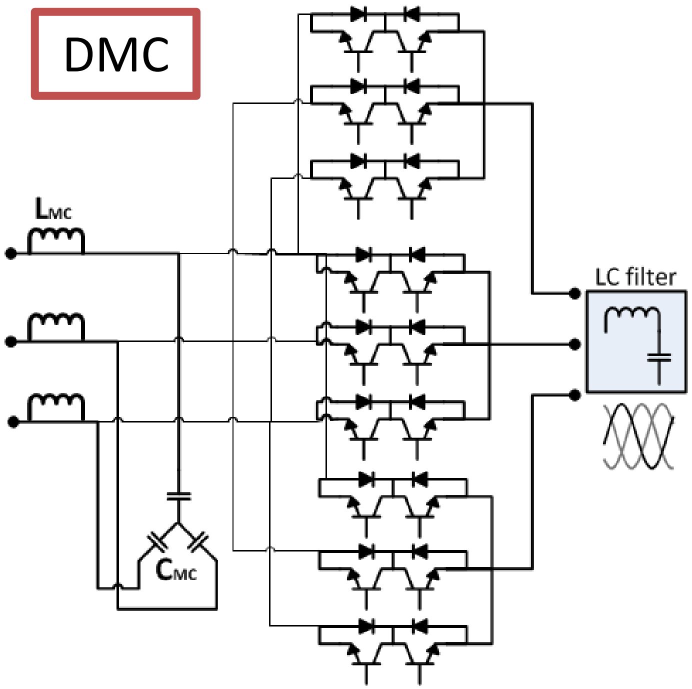
Squared waveform

$$\mathbf{f_{sw2} = f_{tr}}$$

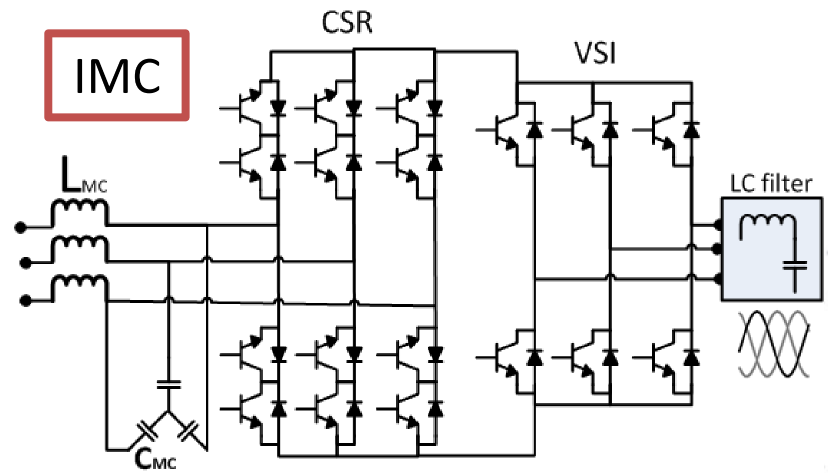
- More restrictions at transformer design (inductance)

Matrix Topologies

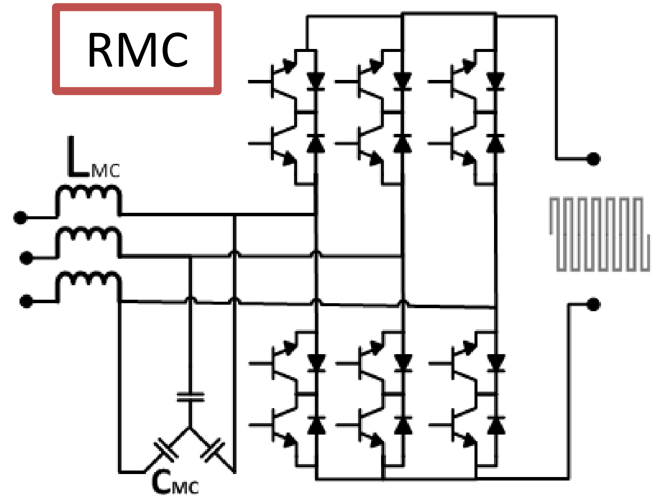
DMC



IMC

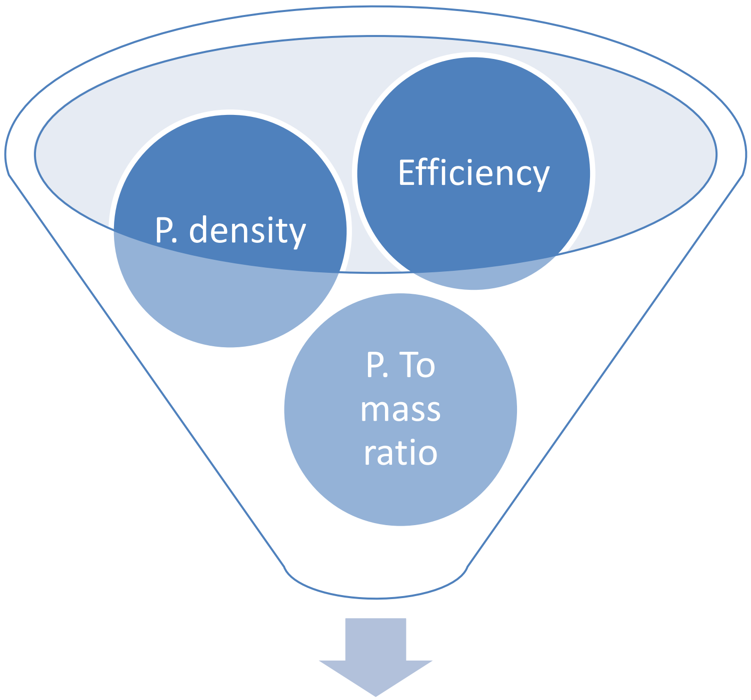


RMC



- Bidirectional switch is required
- Higher number of IGBTs
- LC input filter
- No DC-Link capacitor
- Clamp circuit required

Performance Indicators



Performance indicator

Pareto frontier

Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{losses}}{P_{in}}$$

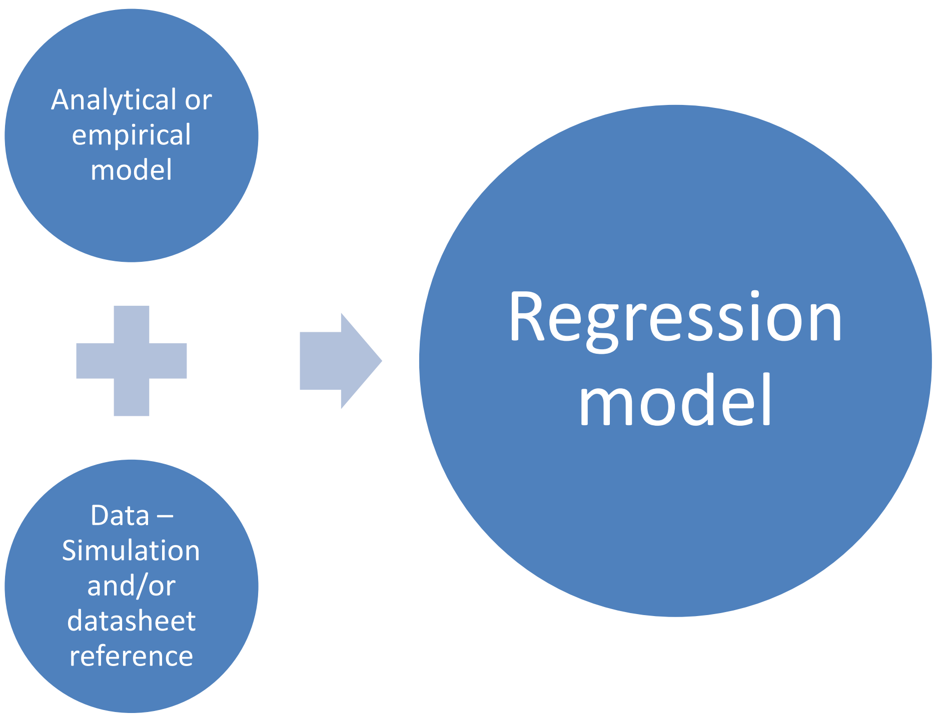
Power Density

$$\rho = \frac{P_{out}}{vol} = \frac{P_{in} - P_{losses}}{volume}$$

Power to mass ratio

$$\gamma = \frac{P_{out}}{mass} = \frac{P_{in} - P_{losses}}{mass}$$

Methodology for evaluation of Performance indicators



- Evaluation of power losses, volume and weight.
- Model of the main elements in the system.

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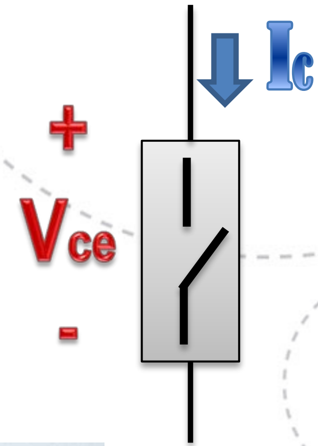
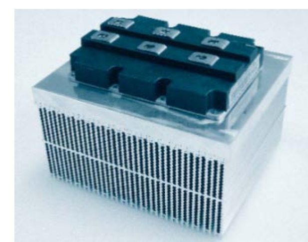
Methodology for evaluation of Performance indicators

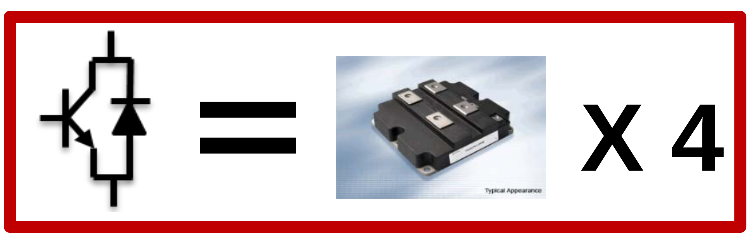
	AC/AC converter	Converter Filters	Medium Freq. Transformer	Diode Rectifier and DC filter
Power Losses	**Semiconductors, Heat sink fan,** driver losses.	**Inductor – Reactor,** AC Capacitor	Core, Winding and isolation	Diode module, DC inductor
Volume	**IGBT Module, Heat sink, DC capacitor,** driver system, protection system.	**Inductor and AC capacitors**	Core, winding and isolation	Diode module, heat sink, DC inductor and DC capacitor.

Power semiconductor model

- Switch model
  - Semiconductor Losses
    - Semiconductor Module parameter
    - Circuit parameters
  - Volume, weight
    - Semiconductor module
    - Heat sink
      - Structure
      - Fan







Power rating limitation.
Parallel connection
➔ current derating

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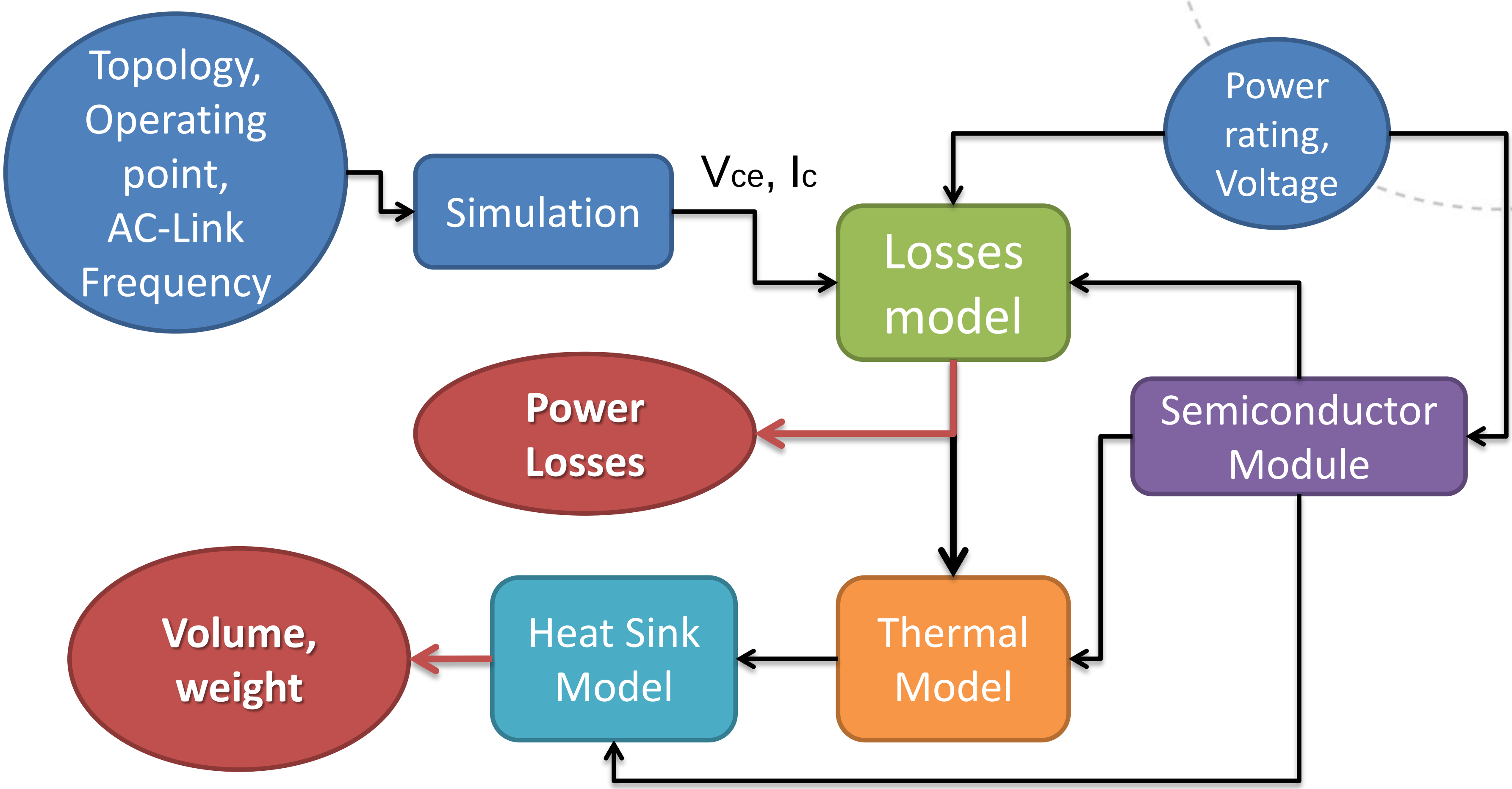
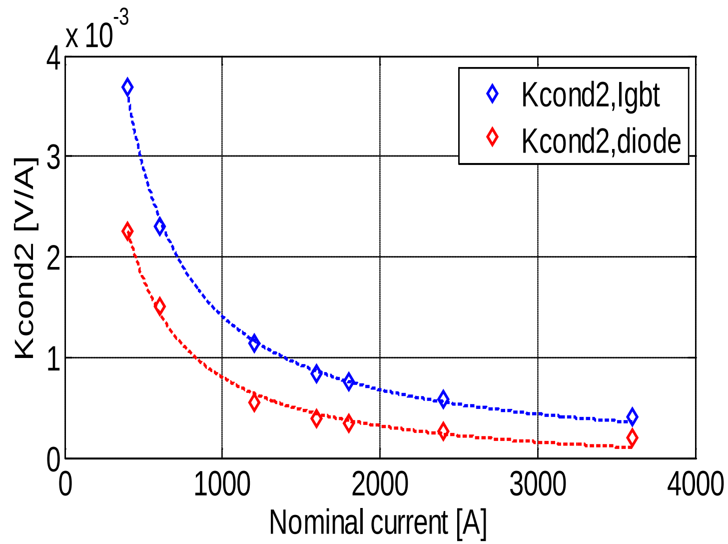
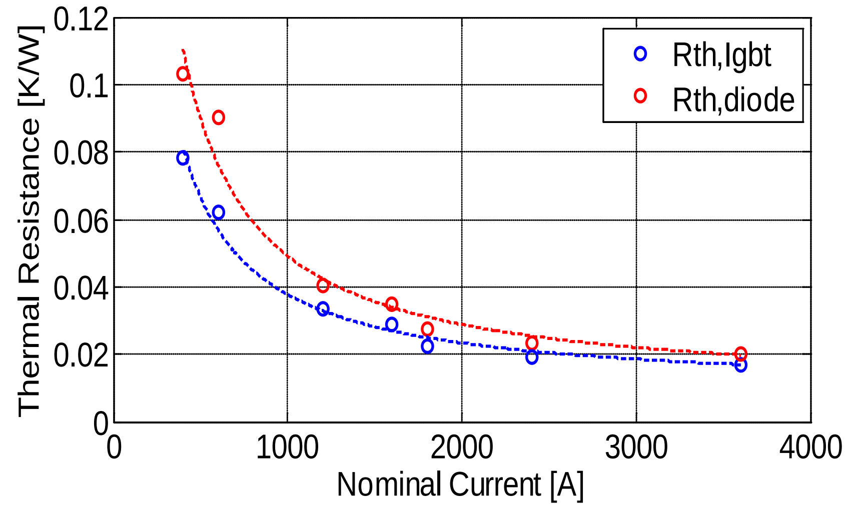
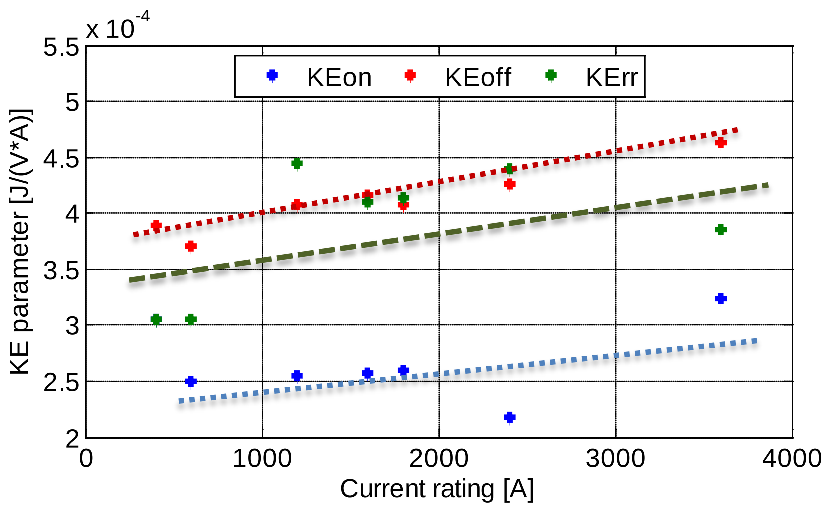
Power semiconductor model

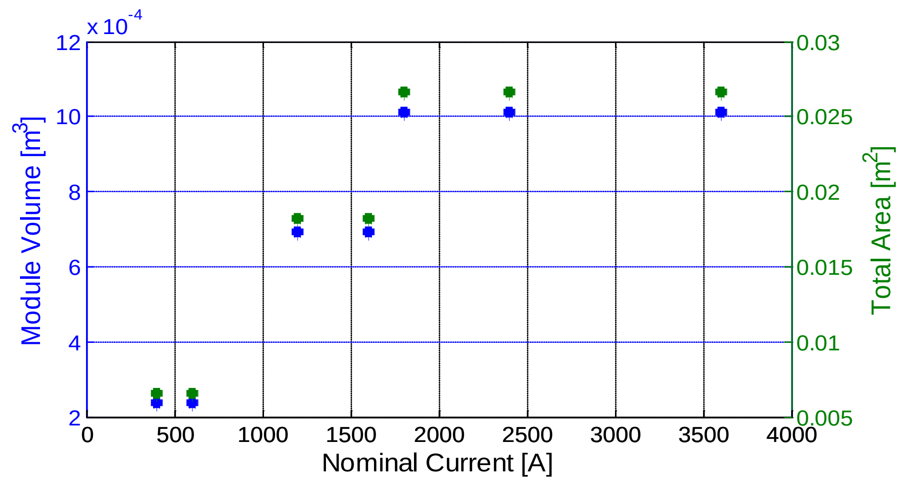


Parameter variation of semiconductor module



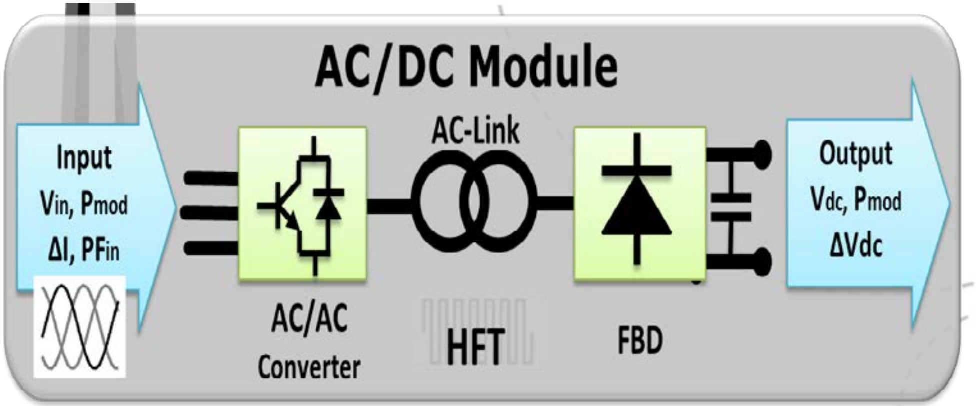






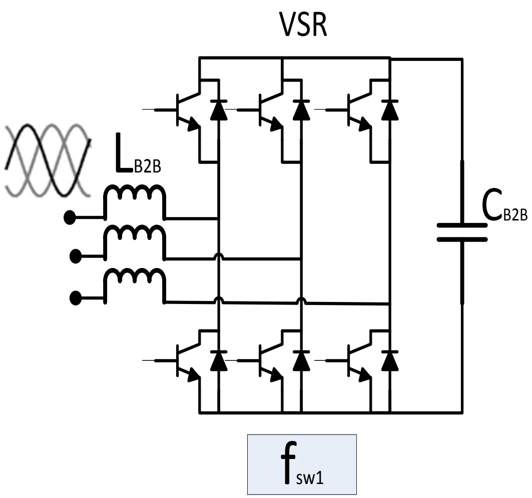
Parameters and Design Constraints

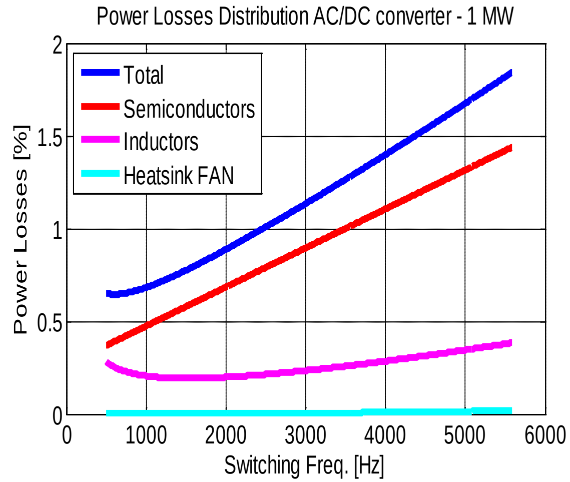
Parameter	Value
Total Power	10 [MW]
Input Voltage	690[V]
Output DC Voltage	33 [kV]
Generator Frequency	50[Hz]
DC-Link Voltage ripple	1%
Current Input ripple	20%
Current Output ripple	20%
Generator Power factor	0.9
Magnetic material	Metglas alloy 2605SA1
Max. DT Transformer	70 K
AC-Link Freq. [kHz]	[0.2, 10]
Power x module [MW]	[0.2, 10]

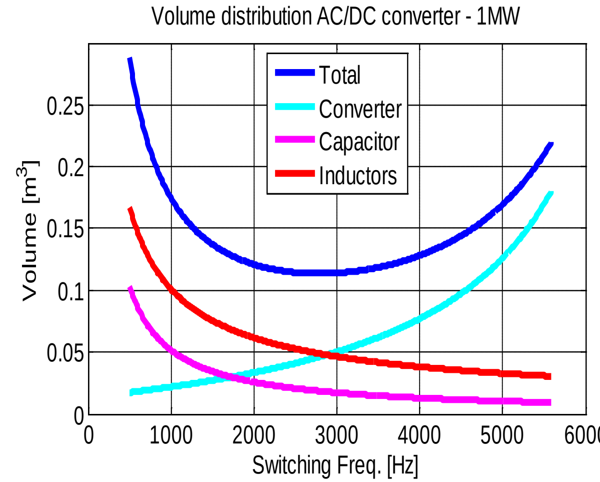


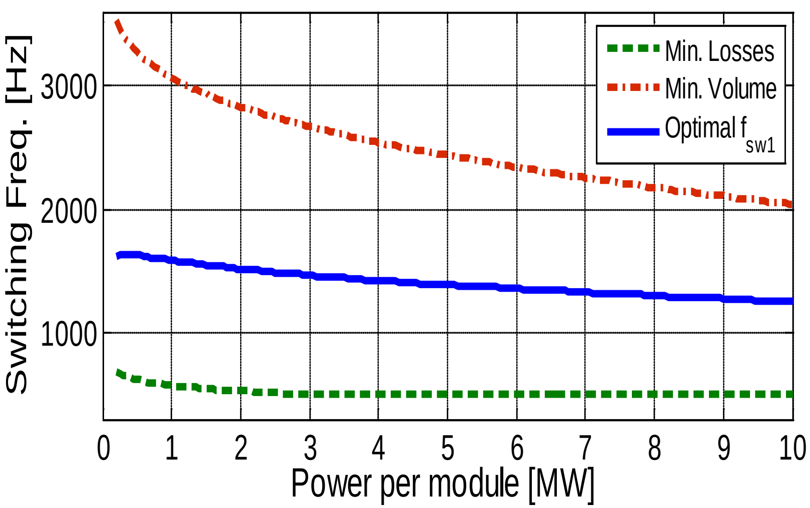
Device	Reference
Ref. Inductor (filters)	Siemens 4EU and 4ET
Ref. DC-link Capacitor	EPCOS MKP DC B256XX
Ref. AC-Capacitor	EPCOS MKP AC B2536XX
IGBT Module	Infineon IGBT4 FZXXR17HP4
DIODE Module	Infineon IGBT3 DDXXS33HE3
Heat Sink	Bonded Fin - DAU series BF
Axial FAN – Heat sink	Semikron SKF 3-230 series

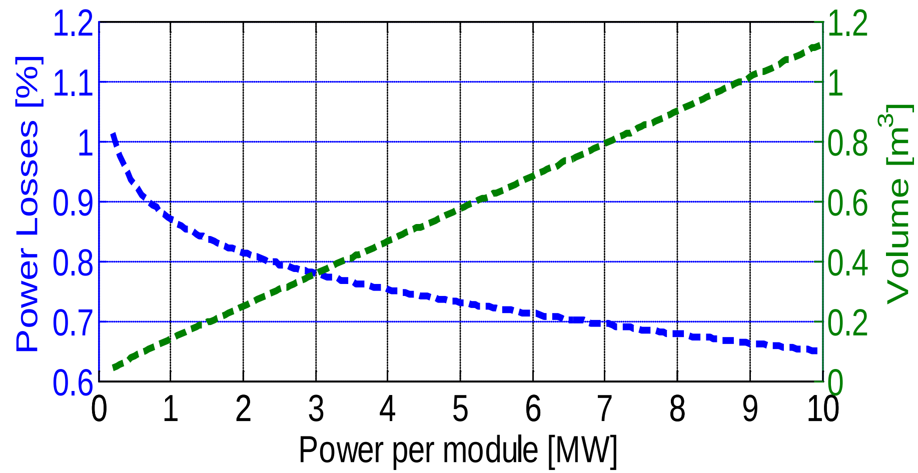
B2B – Selection of f_{sw1}



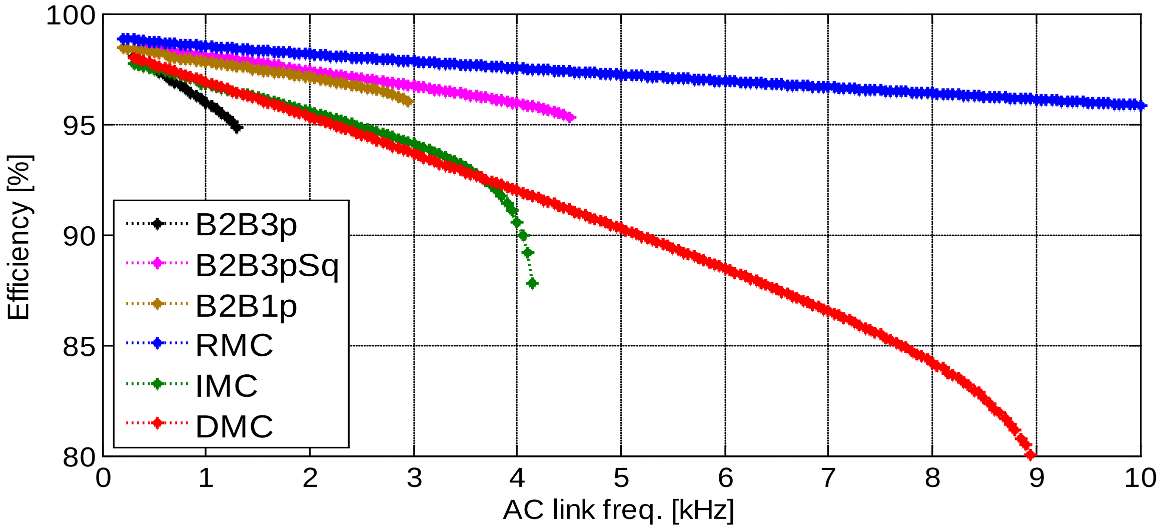


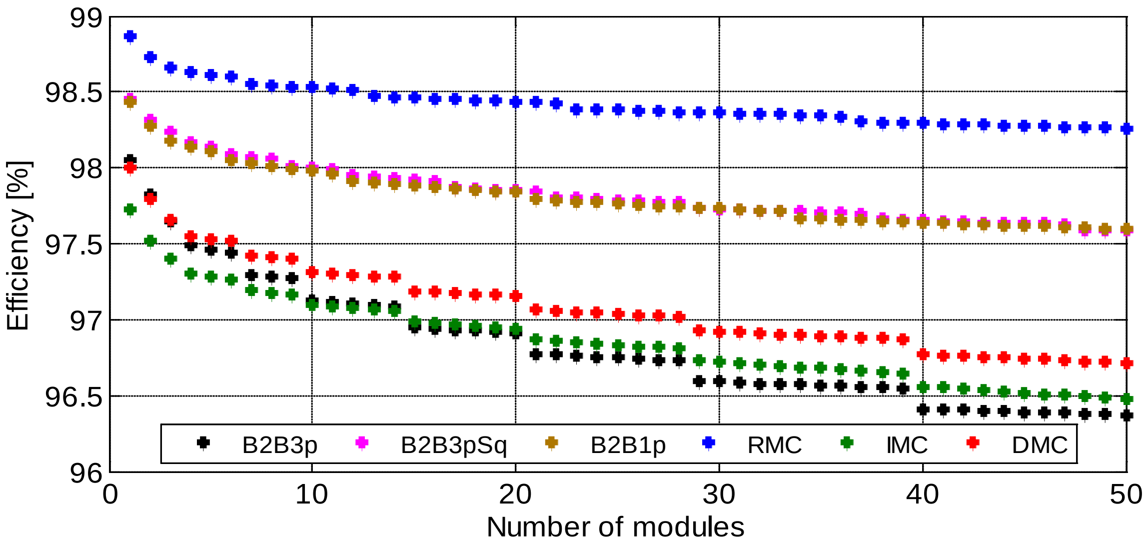






Efficiency





The slope is less steep in solutions based on squared waveform in the AC-Link.

The RMC solutions are the most efficient for any number of modules or AC-link frequency.

Solutions based on matrix topologies present less variation in efficiency when increase in the number of modules

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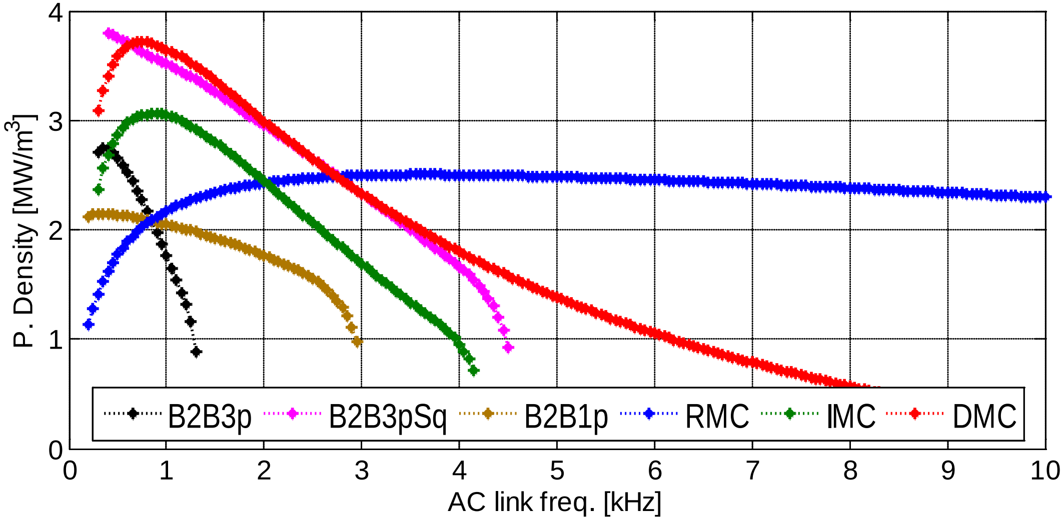
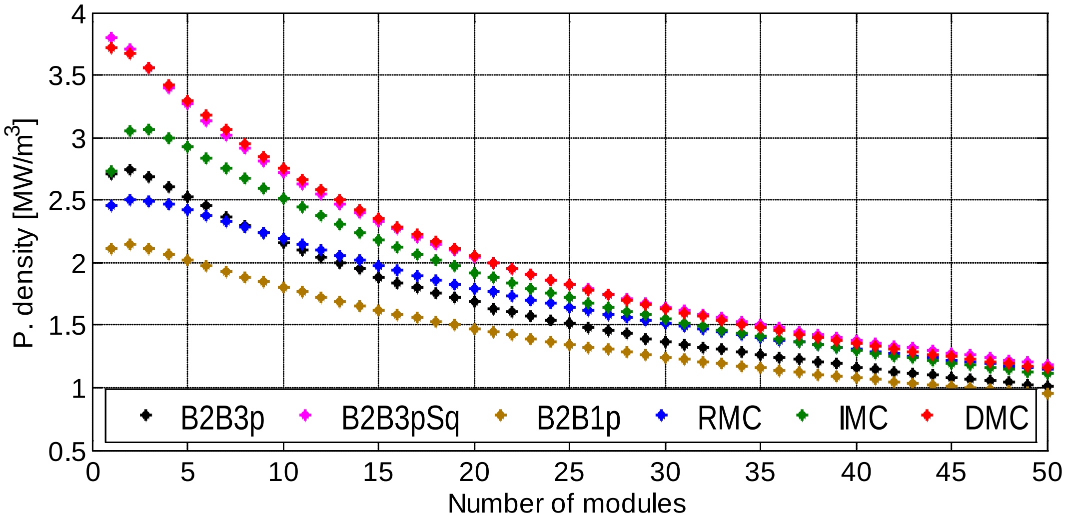
Power Density



- Similar maximum values are obtained with DMC and B2B3pSq topologies.
- B2B3pSq ➔ 400 to 600 Hz
- DMC ➔ 700 to 1000 Hz



- Low number of modules present the highest power density in all solution, however there is an optimum number of modules for each topology.

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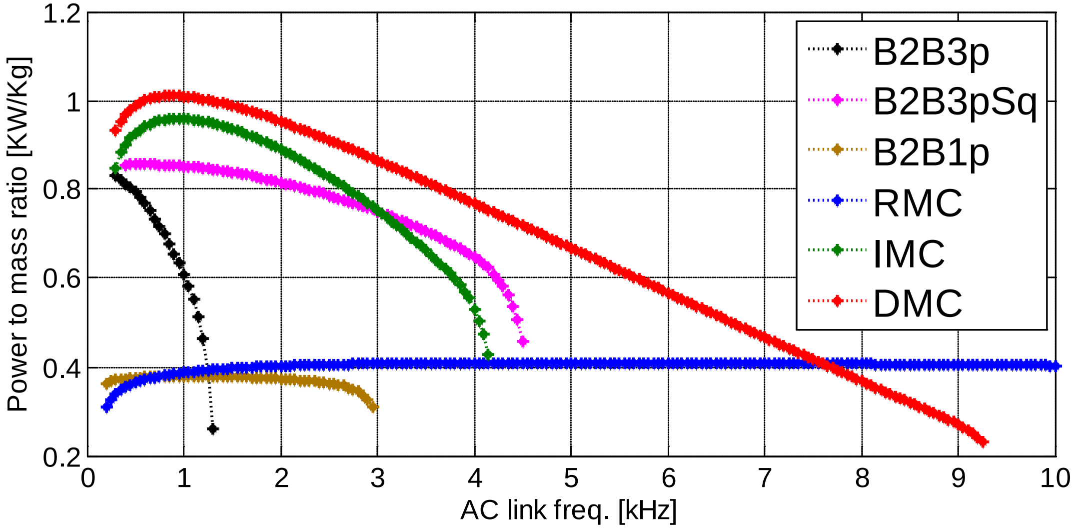
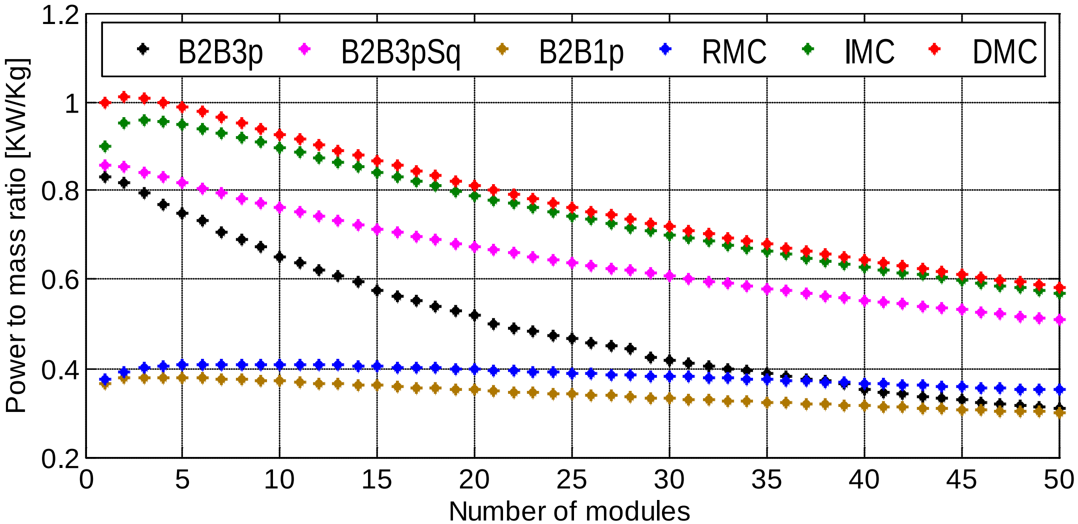
Power to mass ratio





- DMC and IMC solutions present the maximum values of Power to mass ratio.
- For RMC solution the maximum values are obtained at high freq.
- The optimal number of modules for max. P. to mass ratio is higher than the case of max. power density.
- An increase in the number of modules is less drastic in RMC and B2B1p solutions.

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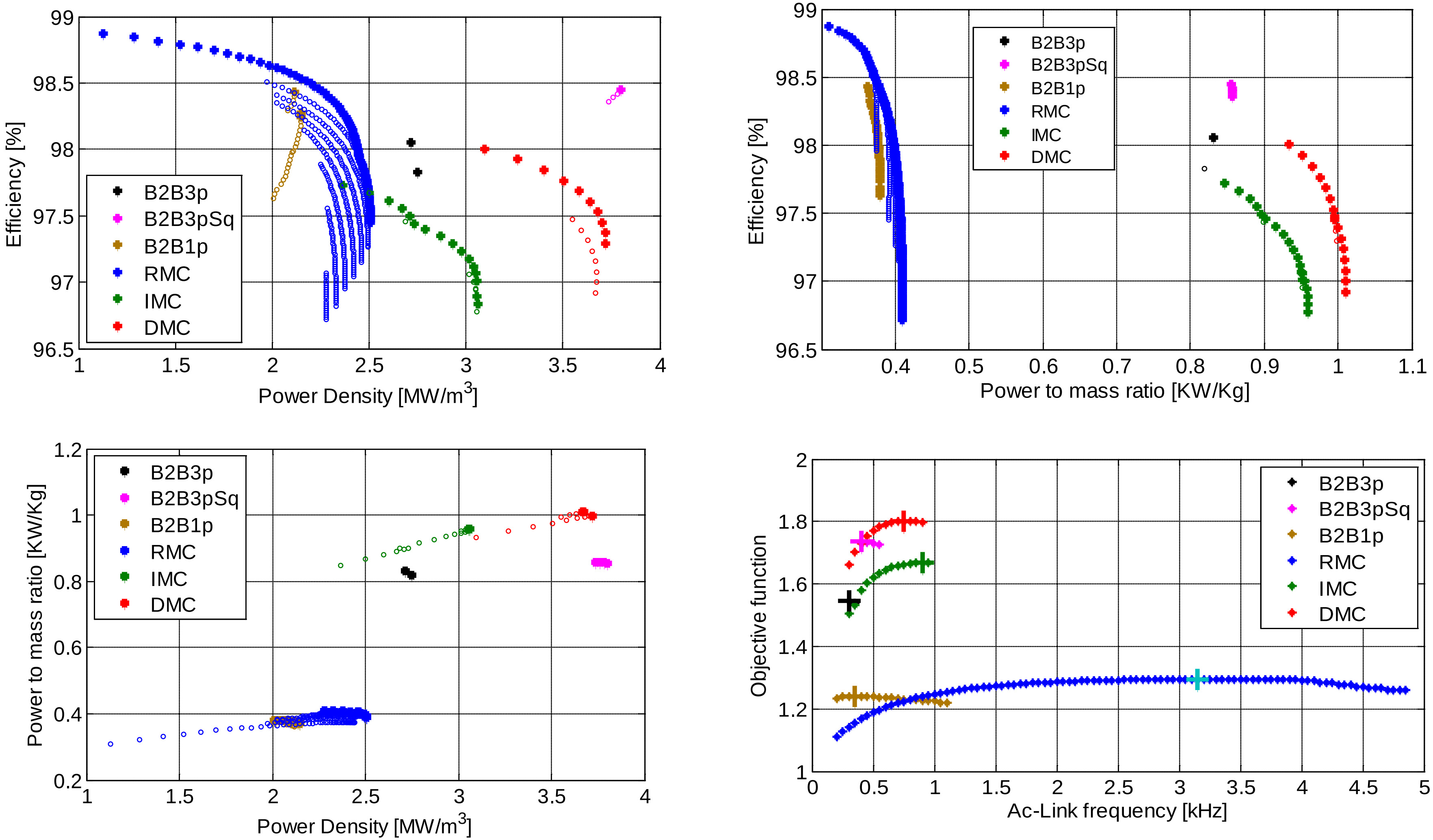
Pareto surface



Conclusions

- WECS based on DMC and B2B3pSq topologies will lead the best trade-off between efficiency and power density in range of AC-Link frequencies from 200[Hz] to 3[KHz].

- RMC topology has better performance when AC-link frequency is required to be above 3[kHz].

Thanks for your attention

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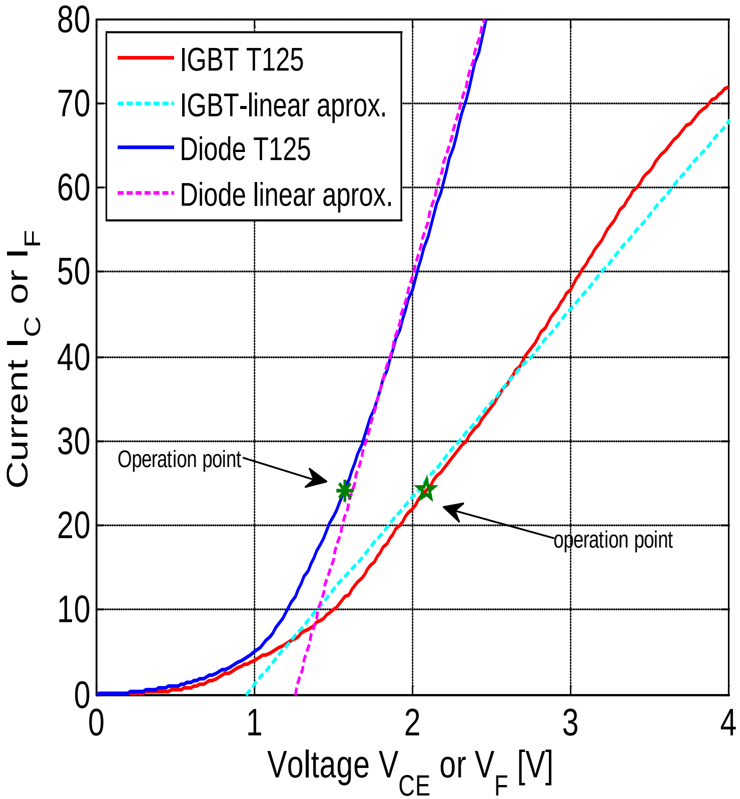
Power semiconductor - Conduction losses



$$P_{cond} = \frac{1}{T}\int_{t_0}^{t_0+T} V_{ce}(t)\cdot I_c(t)\cdot dt\,;$$

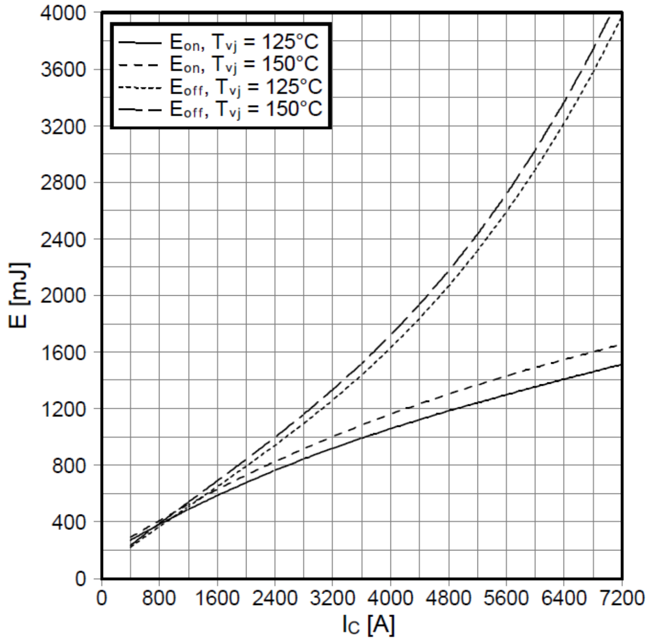
$$V_{ce}(t) = K_{cond1} + K_{cond2}\cdot\ I_c(t)$$

$$P_{cond} = \frac{1}{T}\int_{t_0}^{t_0+T} (K_{cond1} + K_{cond2}\cdot\ I_c(t)\ )\cdot I_c(t)\cdot dt$$

$$P_{cond} = \frac{1}{T}\int_{t_0}^{t_0+T} K_{cond1}\cdot I_c(t) + K_{cond2}\cdot\ I_c(t)^2\cdot dt$$

$$P_{cond} = K_{cond1}\cdot I_{c(avg)} + K_{cond2}\cdot\ {I_{c(rms)}}^2$$

Power semiconductor - Switching losses



$$P_{sw} = \frac{1}{T}\sum_{T} E_{on} + E_{off} + E_{rr}$$

$$E_{sw} = E(I_c)\frac{V_{ce}}{V_{test}}$$

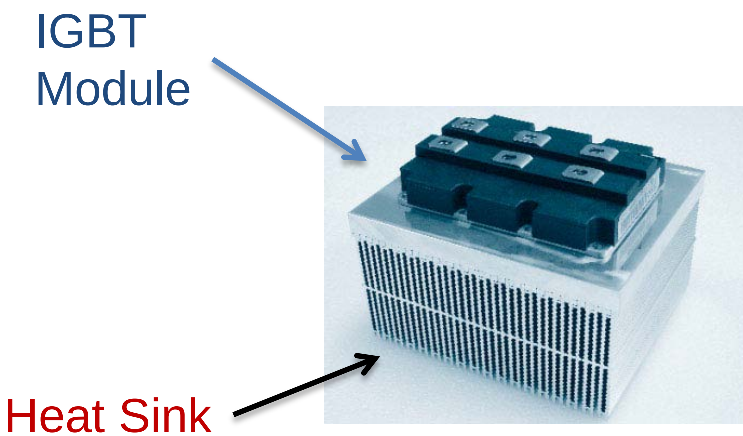
$$E_{sw} = \frac{E_{test}}{V_{test} \cdot I_{test}} V_{ce(t^*)} \cdot I_{c(t^*)}$$

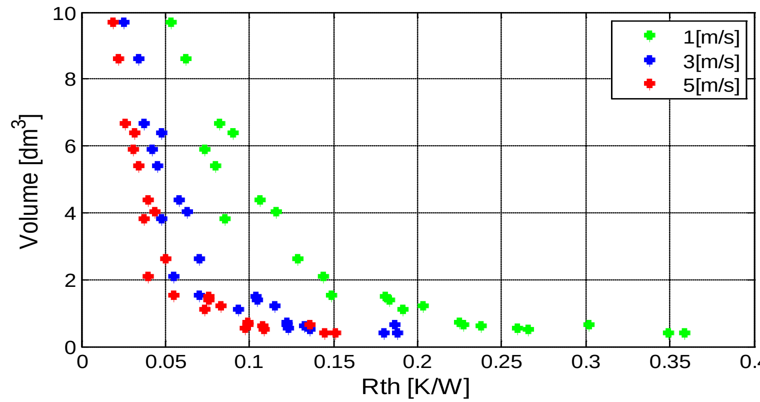
$$P_{sw} = K_E \cdot V_{ce_{(avg)}} \cdot I_{c_{(avg)}} \cdot fun_{sw}(f_{sw}, f_0, mod)$$

$$fun_{sw} = \sum_{i=0:3} K_{sw,i} \cdot \left(\frac{f_{sw}}{f_0}\right)$$

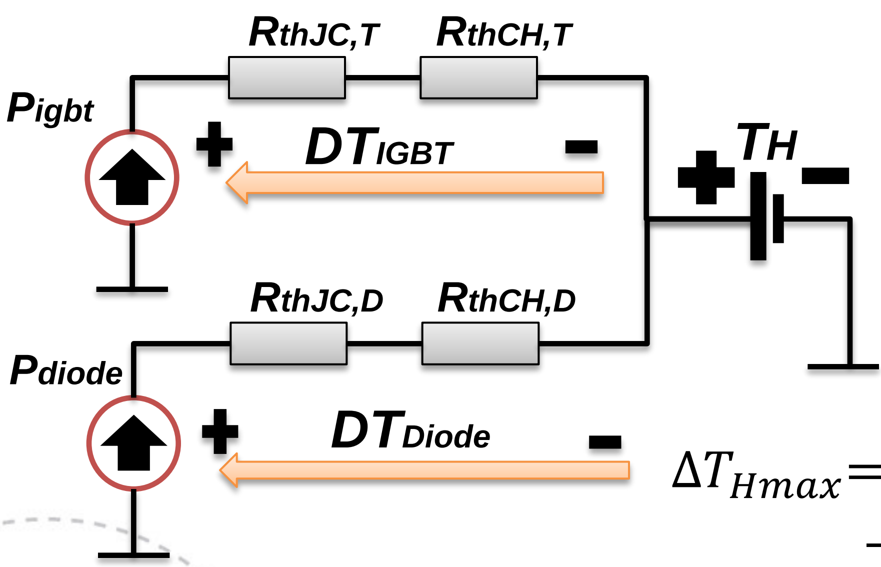
$K_{sw,i}$ depends on the converter topology and the modulation strategy

Heat sink volume





Heat sink volume dependents of thermal resistance. Based on Datasheet information.



$$Vol_{HS} = \frac{K_{HS}}{R_{\theta sa}} = \frac{K_{HS}}{\Delta T_{Hmax}} P_{loss}$$

ΔT_{Hmax} based on worst case assumption in thermal design.

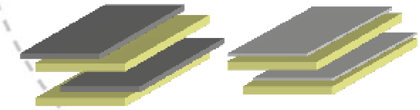
$$\Delta T_{Hmax} = K_{SFT} \cdot T_{jmax} - T_{amb} - max\{R_{th,igbt} \cdot P_{igbt} \,;\, R_{th,diode} \cdot P_{diode},\}$$

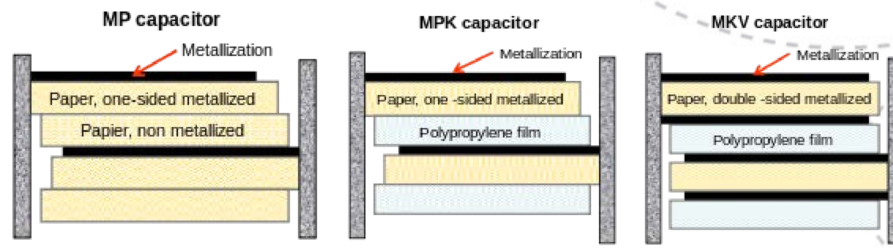
Example: Capacitor Volume (1)

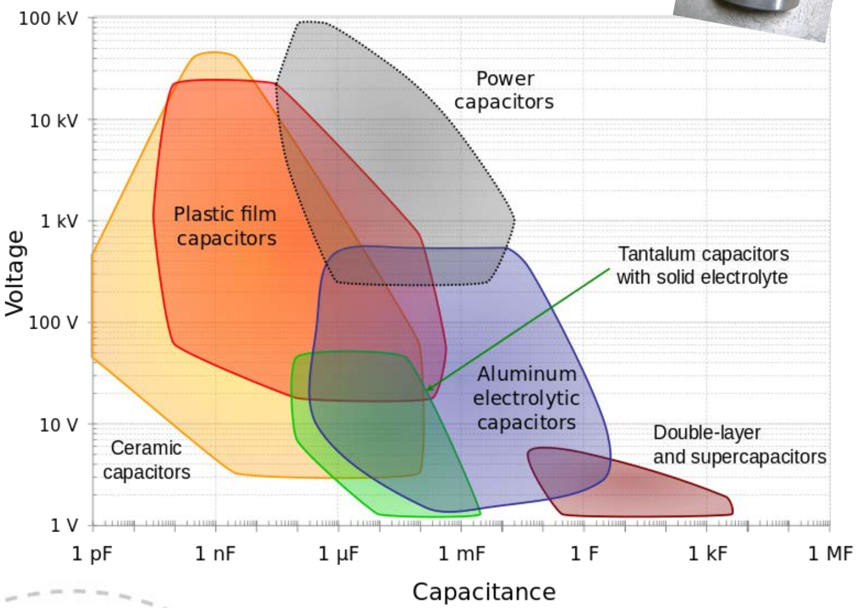
1. Selecting type and technology

Type: Film power capacitors

Technology?







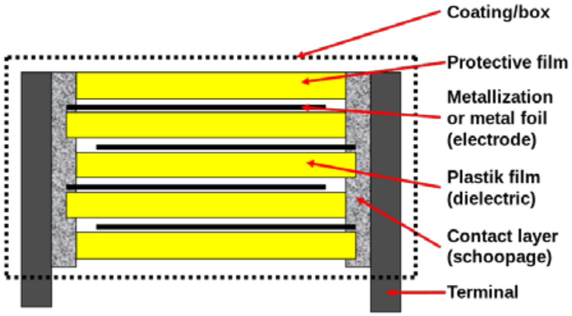
Source: http://en.wikipedia.org/wiki/Types_of_capacitor

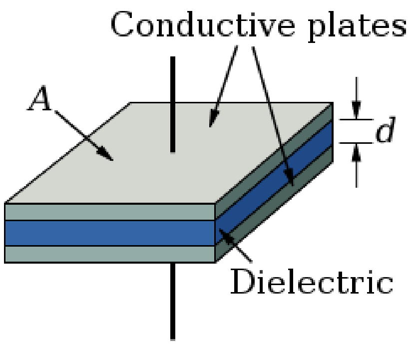
Suggestion of the manufacturer for the type of application

- TDK
  - Power Capacitors for Wind Power Generation
    - EPCOS
      - Technology: **MKP**
        - DC series
        - AC Series

Example: Capacitor Volume (2)

2. Obtaining the model





$$C \approx \frac{\epsilon \cdot A}{d}$$

$$E_{stored} = \frac{1}{2} C \cdot V^2$$

The breakdown voltage (*Vb*) is defined by the separation of the electrodes and dielectric strength.

$$V \propto V_b \propto d$$

$$volume \propto A \cdot d$$

$$E_{stored} \propto \frac{\epsilon \cdot A}{d} \cdot d^2 \propto A \cdot d$$

$$volume \propto E_{stored} \propto C \cdot V^2$$

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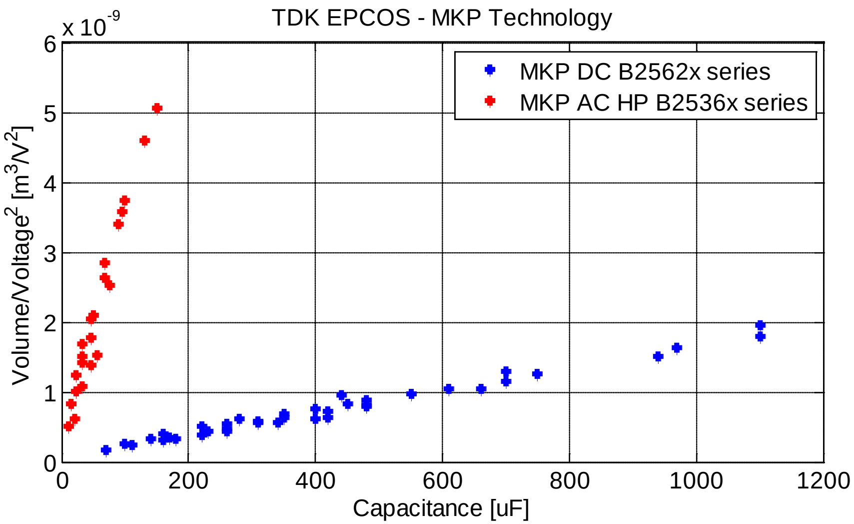
Example: Capacitor Volume (3)

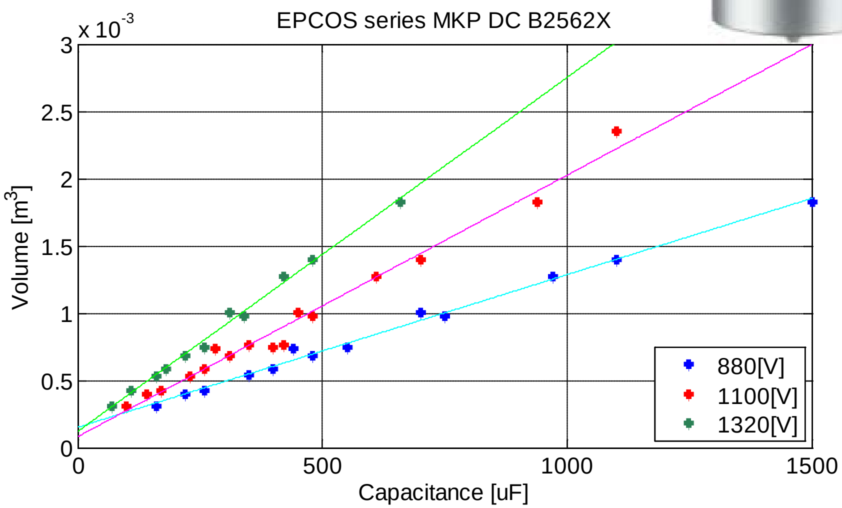
3. Regression model

$$vol = (K_{11} \cdot C + K_{10})(K_{22}V^2 + K_{21}V + K_{20})$$

$$vol = K_1(V) \cdot C + K_0(V)$$

K_0 and K_1 depends of application voltage





Magnetic components losses

- Core Losses → based on Steinmetz equation

$$P_{core} = K_{core} \cdot Vol_{core} \cdot f^{\alpha_c} \cdot B^{\beta_c}$$

highly dependent of magnetic material, volume and waveform voltage

- Copper Losses → losses of all windings

$$P_{cu} = \sum_{i=1}^{nw} K_{cu(i)} \frac{\rho_{cu} N_{(i)} MLT_{(i)}}{A_{w(i)}} I_i^{\,2} (1 + THD^2)$$

K_δ as a function of frequency, winding design (layers, conductor)

Transformer volume and losses

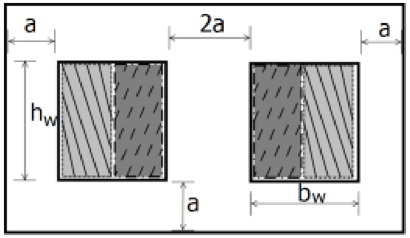
Design process aims to minimize the volume of the transformer taking into account some assumptions.

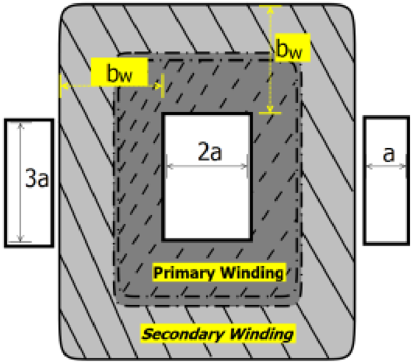
- Type transformer structure
  - ➢ dry shell-type transformers
  - ➢ optimal set of relative dimensions***

- Temperature rise
  - ➢ α Power losses
  - ➢ α 1 / (surface area)

- Power rating
  - each winding carry the same current density

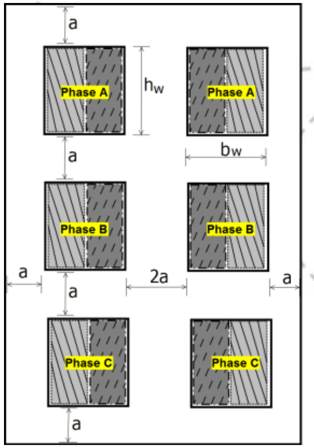
1-phase*





Transformer
Superior view

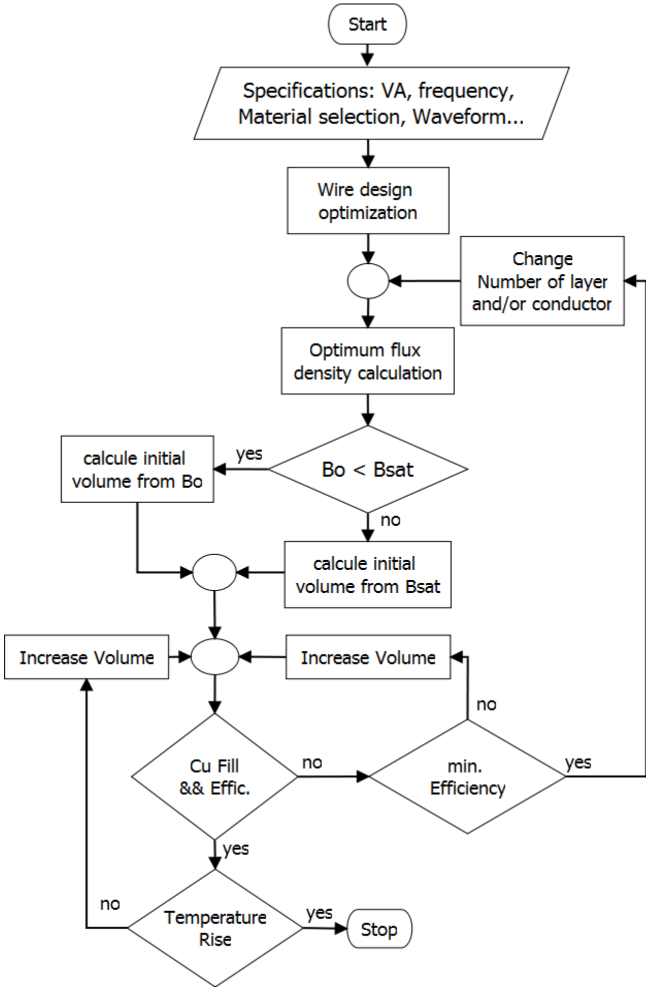
3-phase**

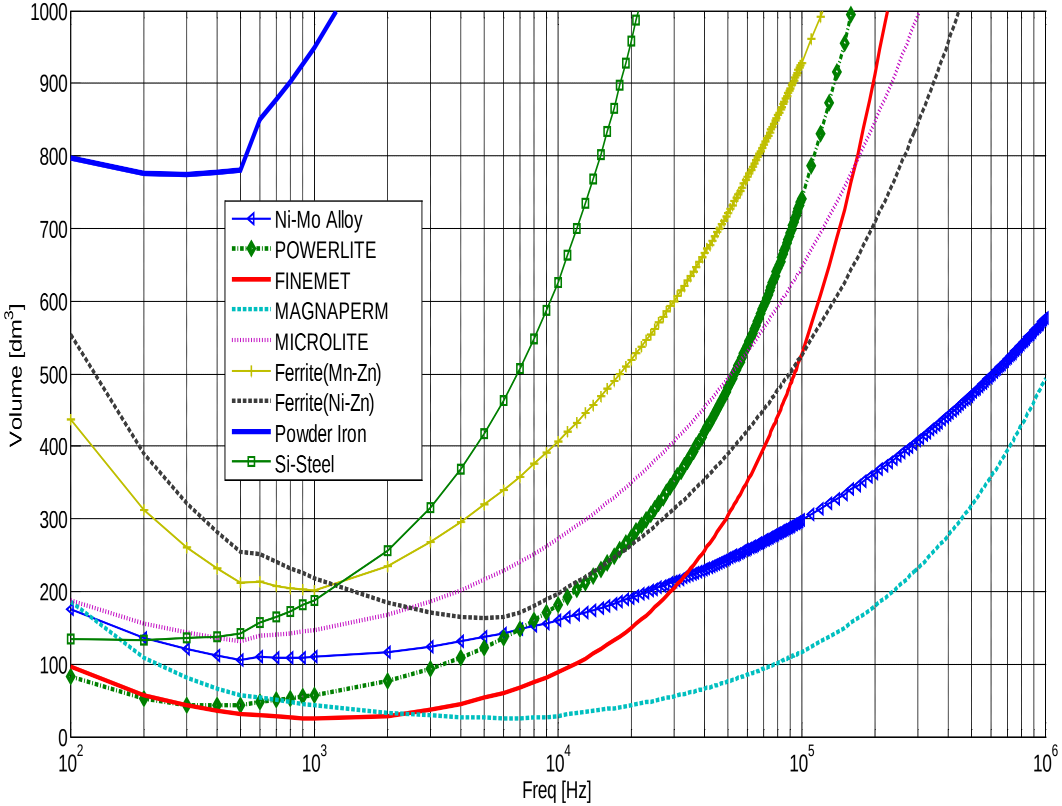


Front view

*S. Meier, et al. “Design Considerations for Medium-Frequency Power Transformers in Offshore Wind Farms.” IEEE 2010.
** T. Mclyman. “Transformer and Inductor Design Handbook.” CRC Press 2004.
***N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications, and Design, 3rd ed. Wiley, Oct. 2002

Transformer volume and losses

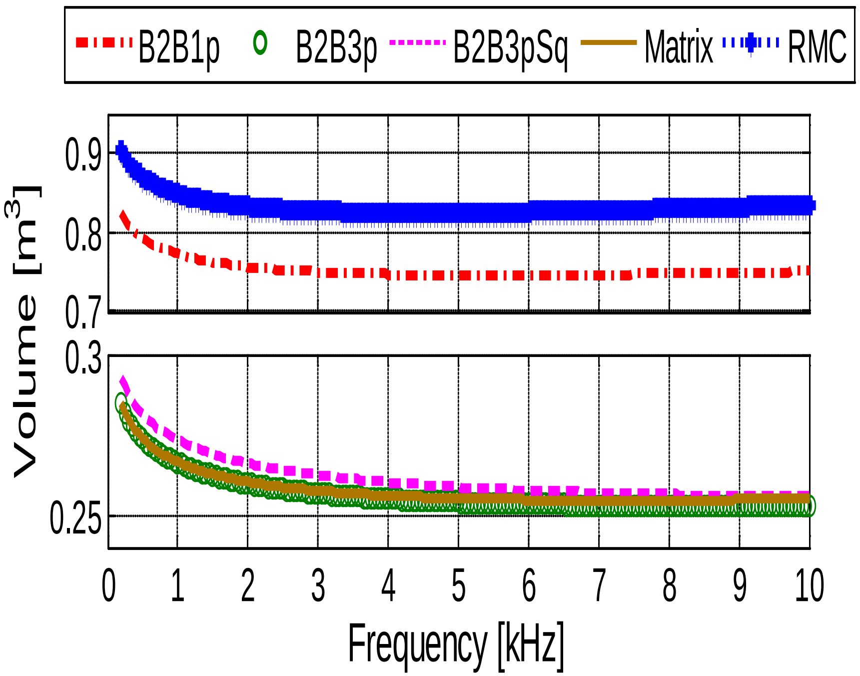


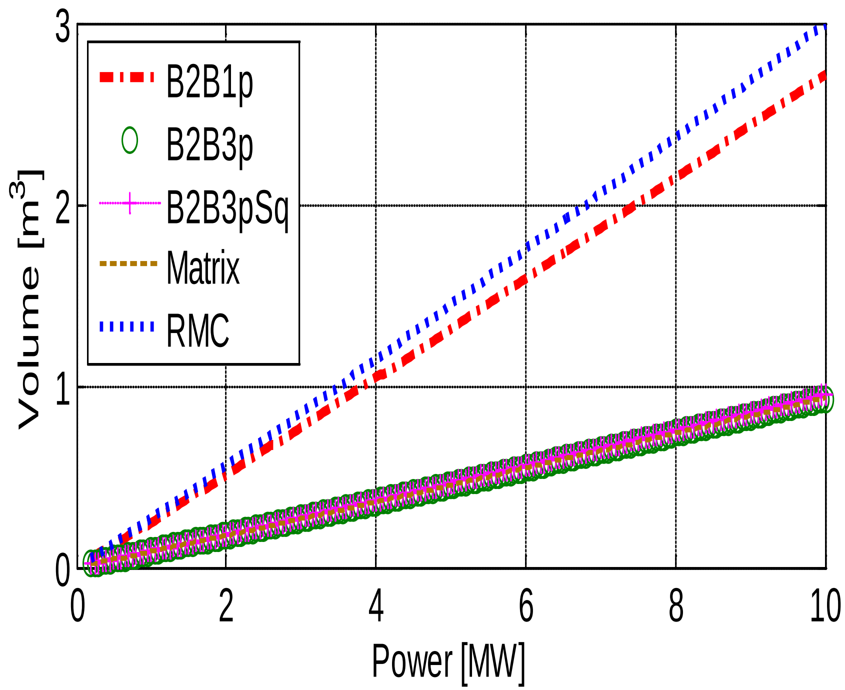


Example: Single-phase transformer volume
S= 100 [KVA] V = 1 [KV]

*Optimum flux density calculation based on W. G. Hurley, W. H. Wolfle, and J. G. Breslin, “Optimized transformer design: inclusive of high-frequency effects,” IEEE Transactions on Power Electronics, vol. 13, no. 4, pp. 651–659, Jul. 1998.
**Wire design based on Litz wire structure: http://www.elektrisola.com/litz-wire/technical-data/formulas.html

Transformer volume

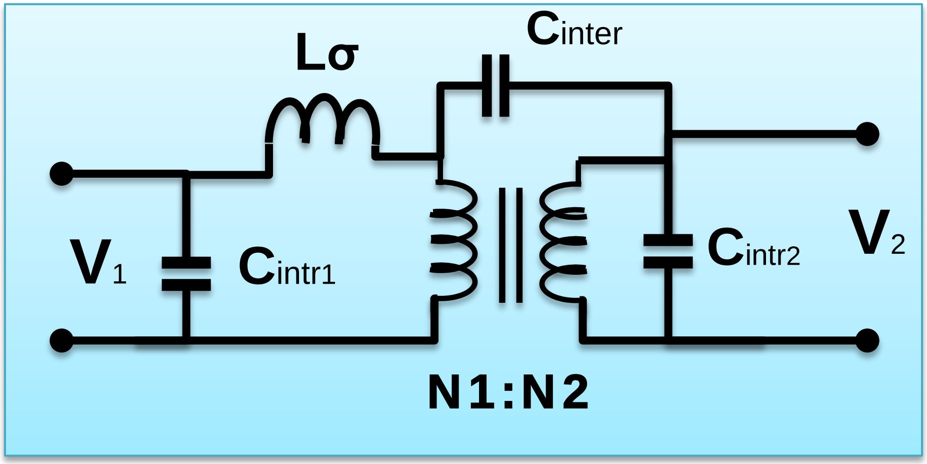




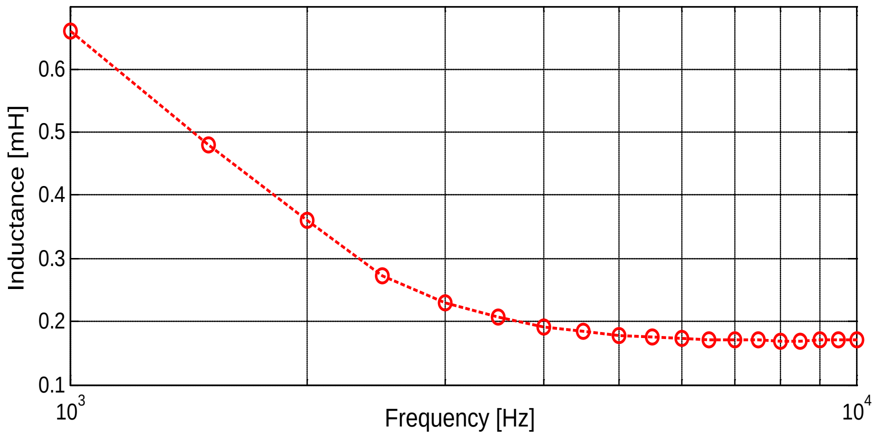
a) Volume dependence frequency and power = 3[MVA].
b) Volume dependence power and frequency = 1[kHz].

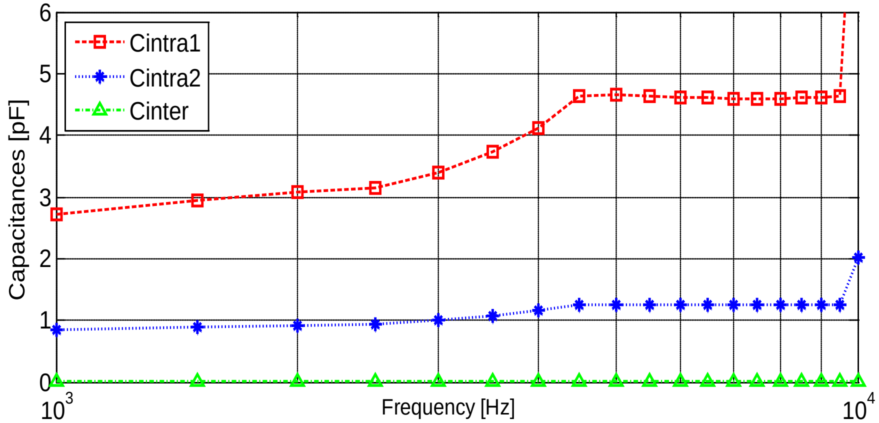
High Frequency Transformer

Electric model of High Frequency transformer. Parameters obtained from the design procedure*.



Example. Transformer 690V/3.3kV, 625kW





*S. Meier, et al. “Design Considerations for Medium-Frequency Power Transformers in Offshore Wind Farms.” IEEE 2010.

DC link Capacitor

Proportional model in order to estimate the capacitor volume from the reference capacitor.*

$$Vol_{Cap} = \frac{C}{C_{ref}} \left(\frac{V_{DC}}{V_{ref}} \right)^2 \cdot Vol_{ref}$$

- The capacitance is designed in order to limit the DC voltage ripple*.

$$C \propto \frac{I_{rms}}{V_{DC} f_{sw}}$$

*M. Preindl and S. Bolognani, "Optimized design of two and three level full-scale voltage source converters for multi-MW wind power plants at different voltage levels," in IECON 2011.

Filters

The Inductance is designed in order to limit the current ripple*,**.

$$L_{B2B} \propto \frac{V_{DC}}{I_{rms} f_{sw}} \qquad L_{MC} \propto \frac{{V_{LL}}^2}{f_{sw} \cdot P} \qquad C_{MC} \propto \frac{P}{f_{sw} \cdot {V_{LL}}^2}$$

Proportional model in order to estimate the Inductor volume* and losses from the reference Inductor.

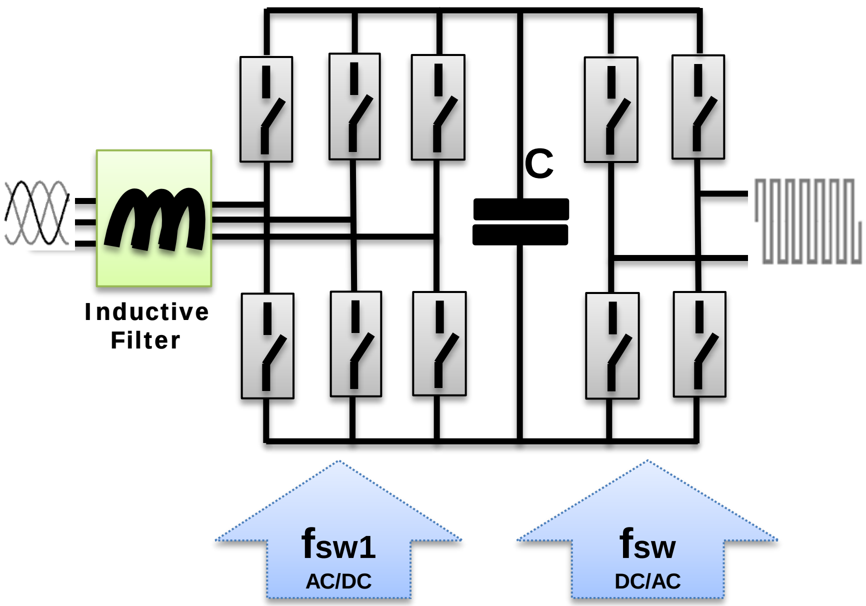
$$Vol_{induc.} = K_{ind} \cdot \left(L_{filter} \cdot I^2\right)^{3/4}$$

$$P_{loss\_L} = \left(P_{cuRef} + P_{coreRef} \cdot \left(\frac{f_{ref}}{f}\right)^{\frac{(7\alpha-2)}{(12\beta-\alpha)}}\right) \cdot \left(\frac{Vol_{ind.}}{Vol_{Ref}}\right)$$

*M. Preindl and S. Bolognani, "Optimized design of two and three level full-scale voltage source converters for multi-MW wind power plants at different voltage levels," in IECON 2011.
**M. hamouda, F. Fnaiech, and K. Al-Haddad, "Input filter design for SVM Dual-Bridge matrix converters," in 2006 IEEE International Symposium on Industrial Electronics, vol. 2. IEEE, Jul. 2006.

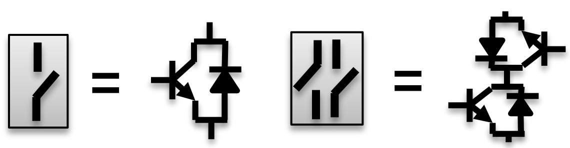
AC/AC Converter - Topologies

B2B-1P: Back-to-Back Converter with 1-phase square wave output

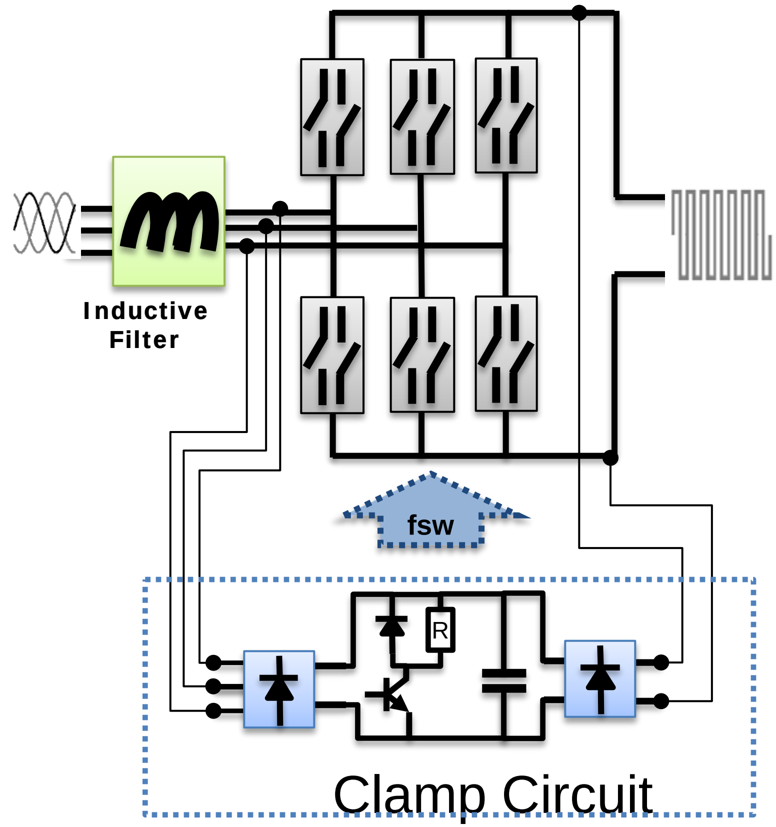


$$ratio_{sw} = \frac{f_{sw1}}{f_{sw}}$$

*Optimal selection in the ratio of switching frequency



RMC: Reduced Matrix Converter with Clamp circuit



Because of the absence of free wheeling path in the RMC, Protection scheme should be used to avoid over voltages.