Multi-objective Optimization of a Modular Power Converter Based on Medium Frequency AC-Link for Offshore DC Wind Park

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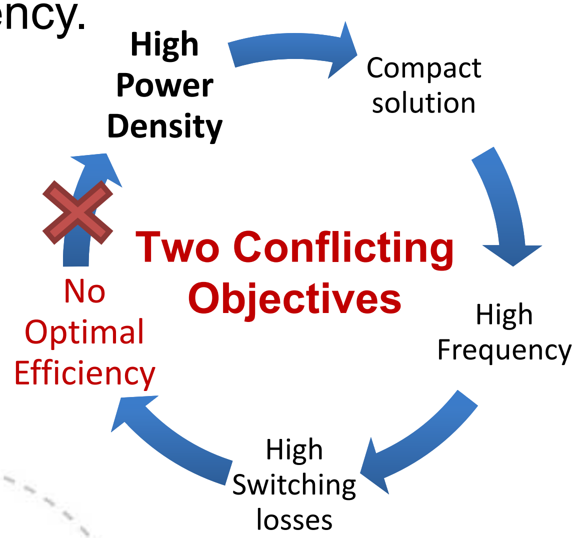
Outline:

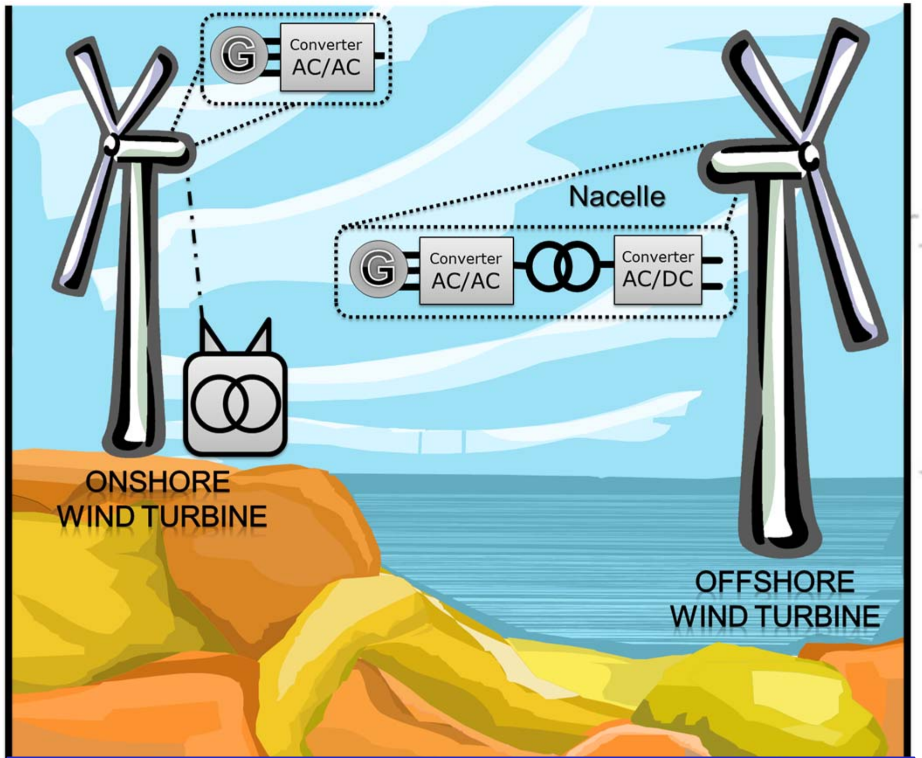
1. **<u>Introduction</u>**
2. Power converter topologies
3. Models and Constraints
4. Results
5. Conclusions

Offshore Wind turbine challenges

Optimal design targeting three objectives

Maximize efficiency (η): Reduce power losses. Less conversion stages.
Maximize power density (ρ) and
Maximize Ratio power to mass (σ) of conversion system: Minimize weight/Size for a given power. Increase the Frequency.



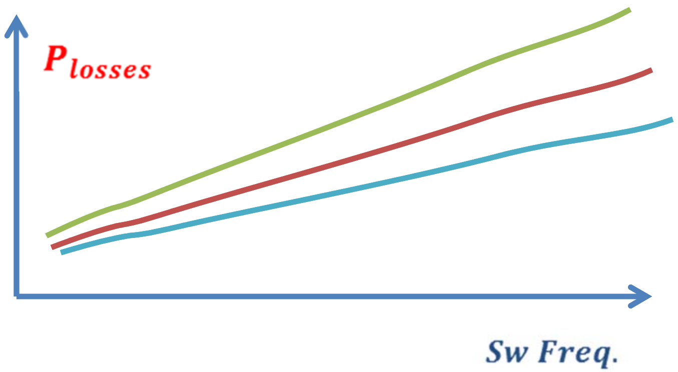


Assumption: DC Grid is more convenient for offshore wind farms [MEYER]
New WECS architectures for offshore applications. Design taken into account all stages of the system.

Study of operative frequency in Power converter

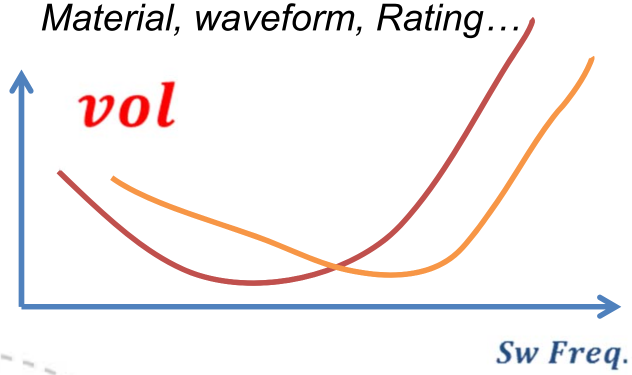
Power electronics:

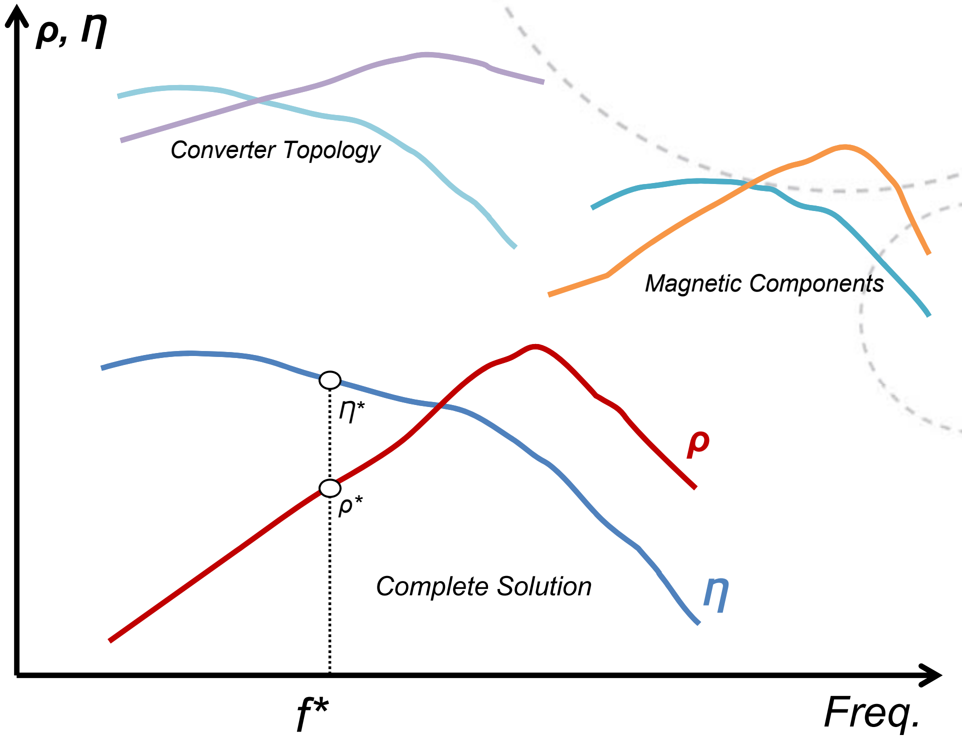
- *IGBT Module, Topology, Modulation…*



Magnetic components

- *Material, waveform, Rating…*

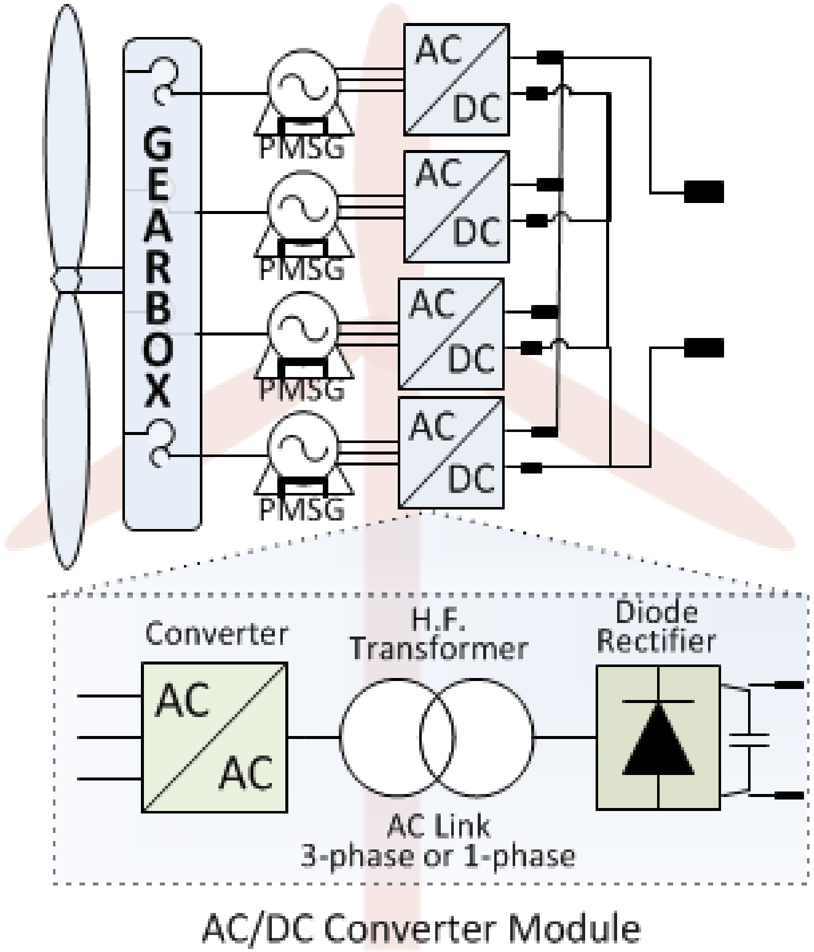


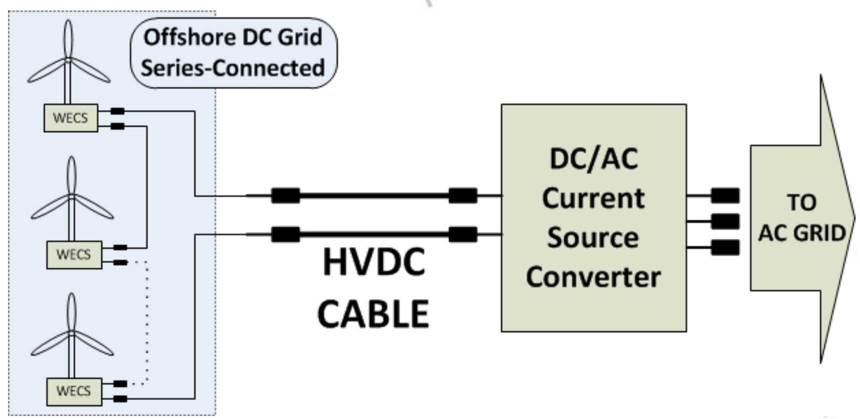


f : Optimal Operating Frequency*

Different stages ➔ Optimum
Take into account all stages in the Power converter

WECS Studied*

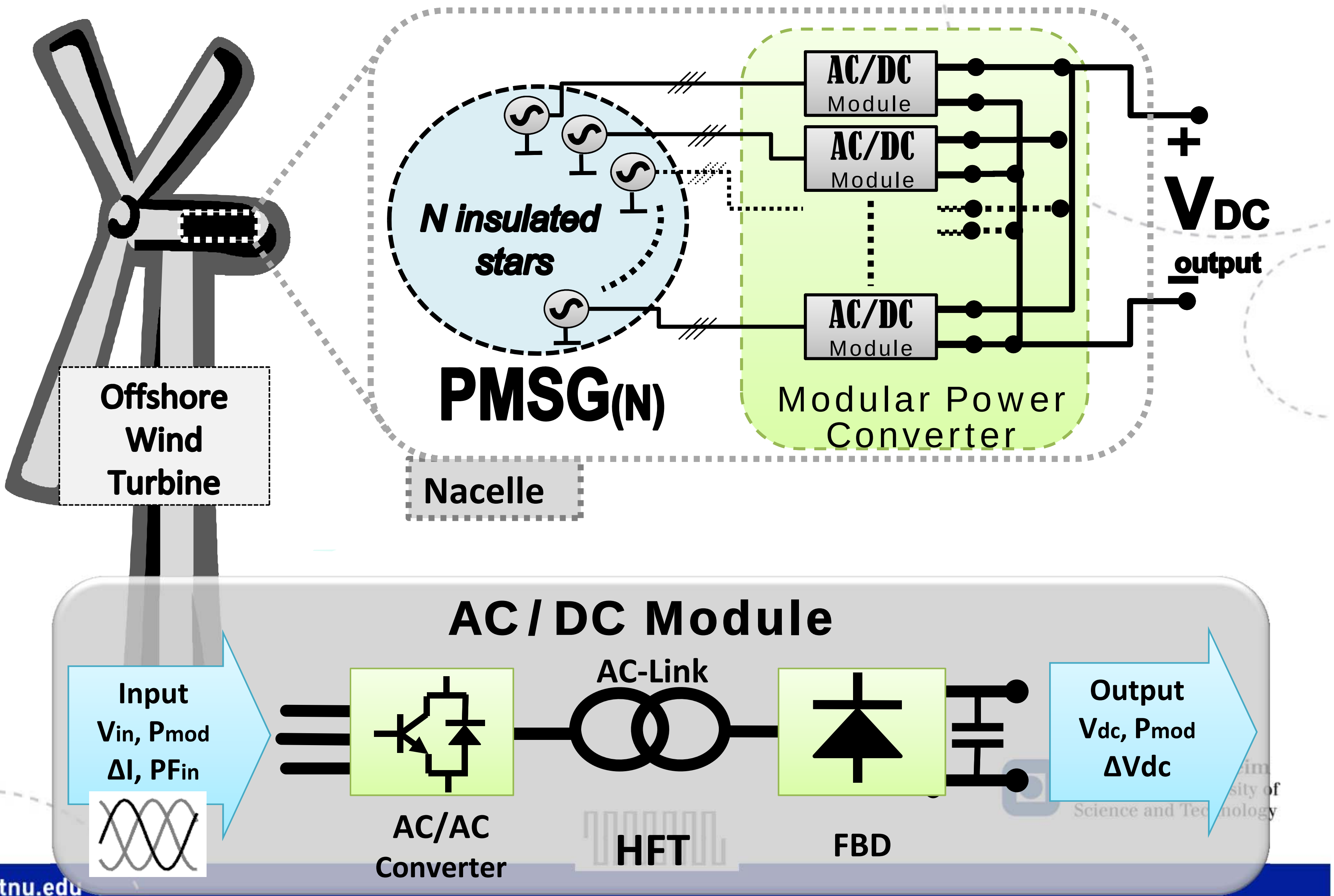




- Modularity ➔ Reliability.
- Transformer: Insulation, Ratio.
  - Flexibility for series or parallel connection.
- Constrains parameters:
  - Circuit breaker Technology
  - Generator Voltage and Power rating

*A. Mogstad, M. Molinas, "Power collection and integration on the electric grid from offshore wind parks," In proc. NORPIE 2008,

WECS Studied: Modular Power Converter



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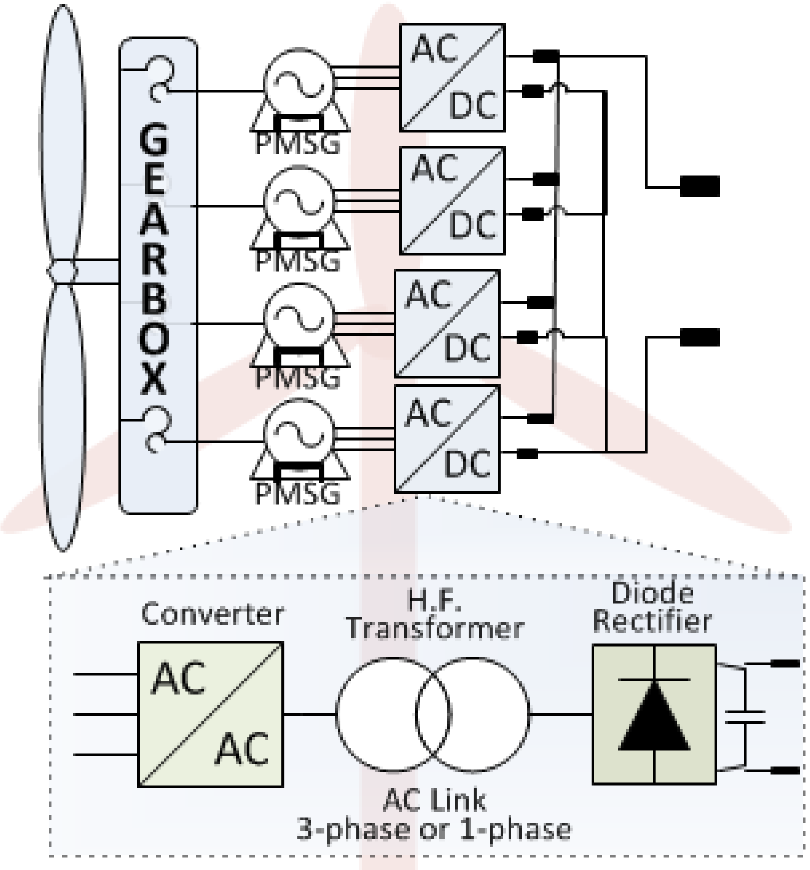
Case of Study



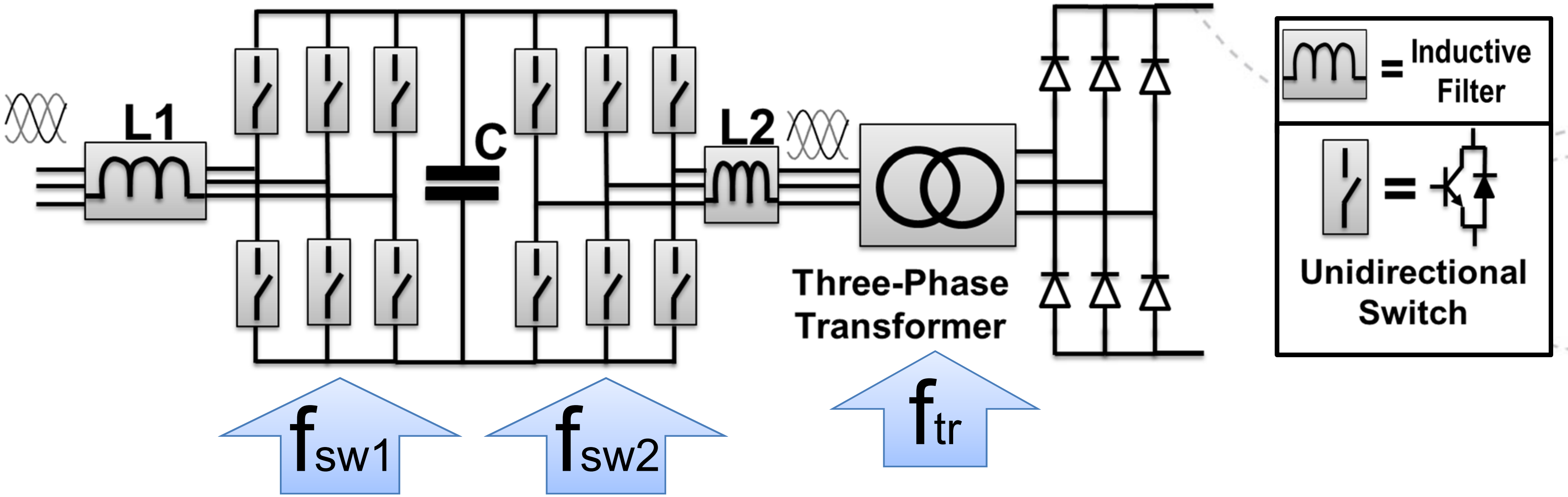
AC/DC Converter Module

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-3pSq** B2B with 3-phase output	B2B-1p B2B with 1-phase output	RMC Reduced Matrix Converter **[Garces]**

Selection of the AC-Link frequency and the Power per module in order to obtain the best relation of the three objectives

**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.*

Module based on Back-to-Back Converter topology (B2B)

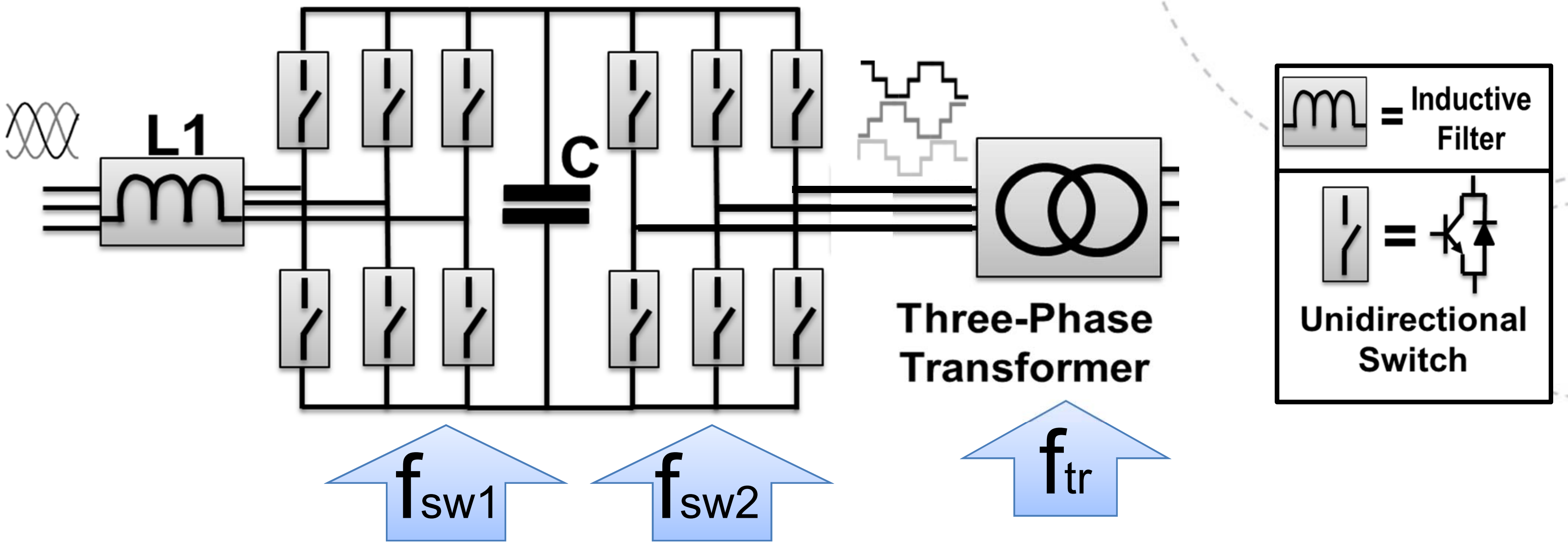


f_{tr} : AC-Link frequency. Operating transformer frequency.

f_{sw1} : Switching Freq. generator side. It can be lower than sw. freq. of transformer side. It is optimized in this study. Minimum value of 500[Hz] (10*50Hz).

f_{sw2} : Switching Freq. transformer side. It should be higher than transformer freq. It is equal to 6***f_{tr}** in this study.

Module based on Back-to-Back Converter with three phase squared wave output.(B2B3p-Sq)

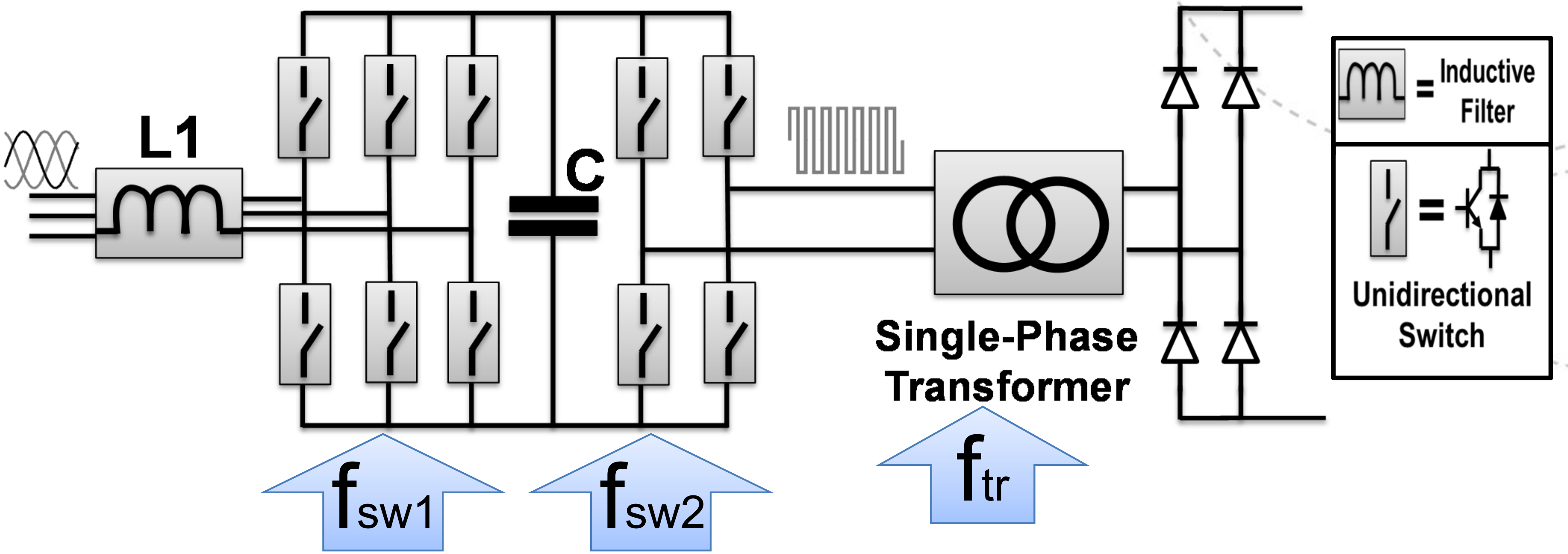


f_{tr} : AC-Link frequency. Operating transformer frequency.

f_{sw1} : Switching Freq. generator side. It can be lower than sw. freq. of transformer side. Optimal selection in the switching frequency. Minimum value of 500[Hz] (10*50Hz).

f_{sw2} : Switching Freq. transformer side. It is equal to the transformer freq.

Module based on Back-to-Back single-phase Converter topology (B2B-1p)

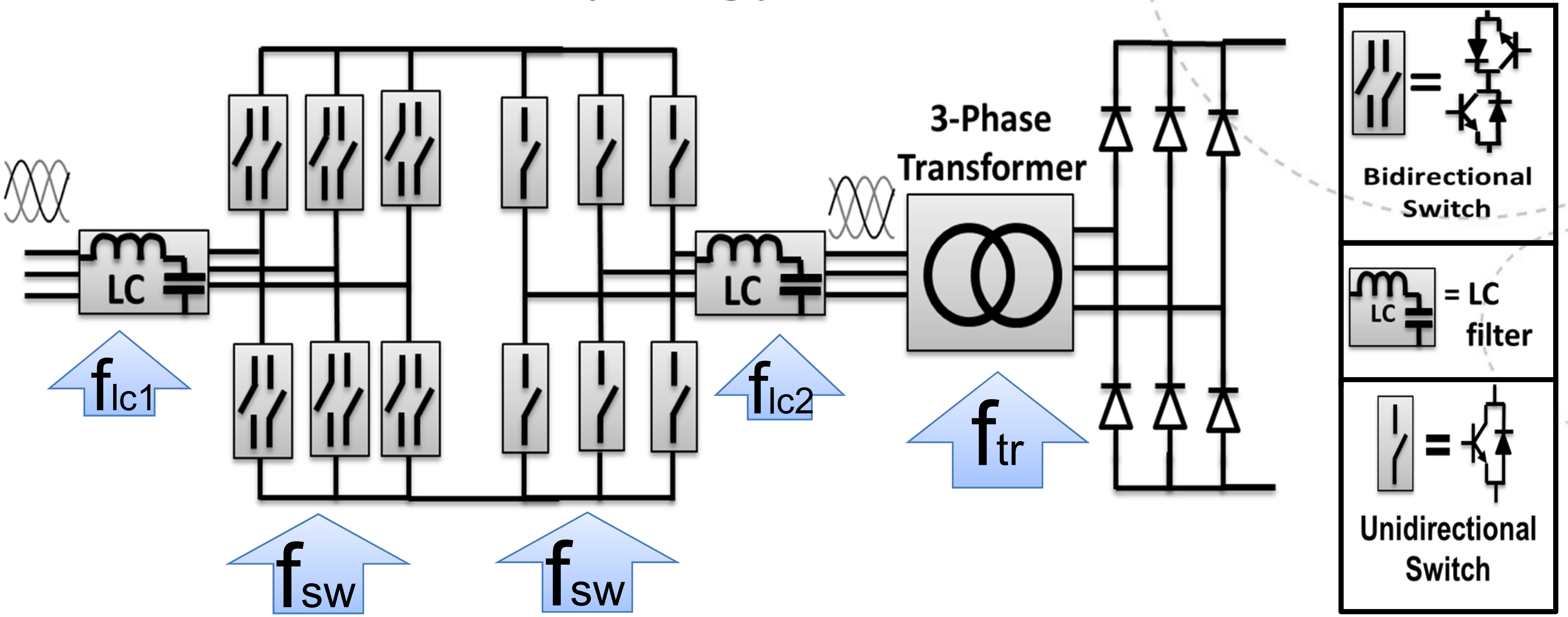


f_{tr} : AC-Link frequency. Operating transformer frequency.

f_{sw1} : Switching Freq. generator side. It can be lower than sw. freq. of transformer side. It is optimized in this study. Minimum value of 500[Hz] (10*50Hz).

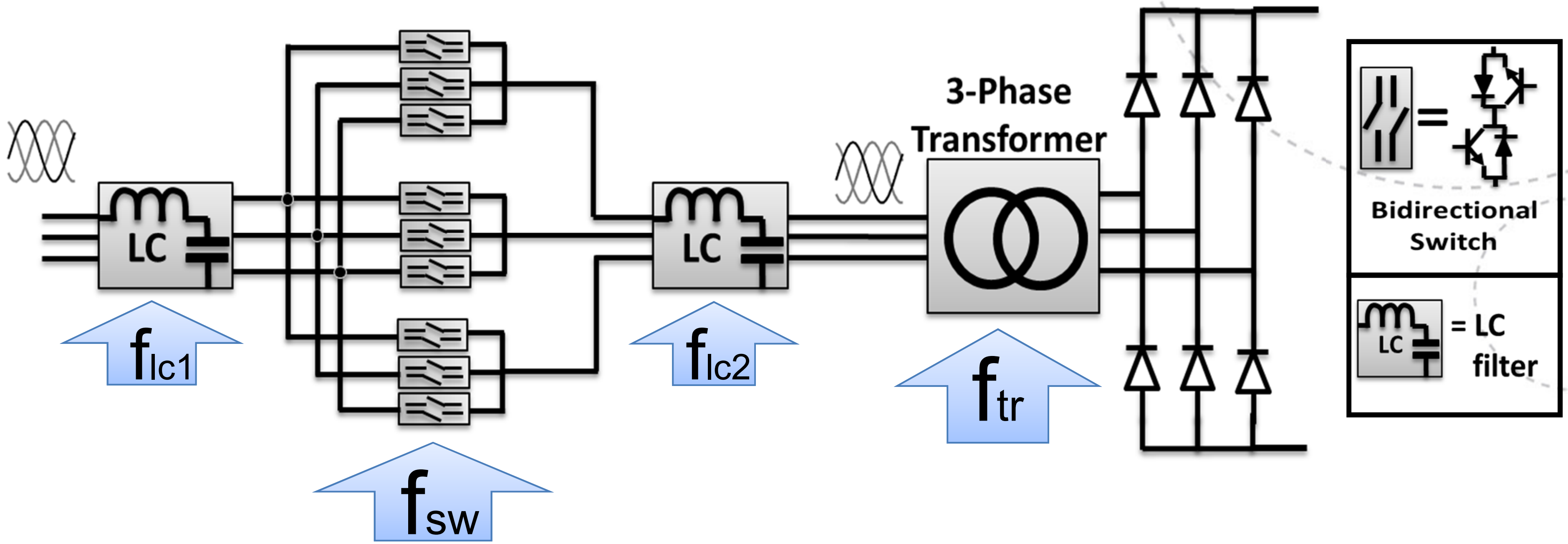
f_{sw2} : Switching Freq. transformer side. It is equal to transformer freq.

Module based on Indirect Matrix Converter topology (IMC)



f_{tr} : AC-Link frequency. Operating transformer frequency.
f_{sw} : Switching Freq. It should be higher than transformer freq. It is equal to $6*f_{tr}$ in this study.
f_{lc} : Cut-off frequency of LC filter. Setting it to be 3 times lower than the switching frequency and limiting it to 20 times the supply frequency (20*50=1[KHz]).
*In this study the Clamp Circuit is not taken into account.

Module based on Direct Matrix Converter topology (DMC)



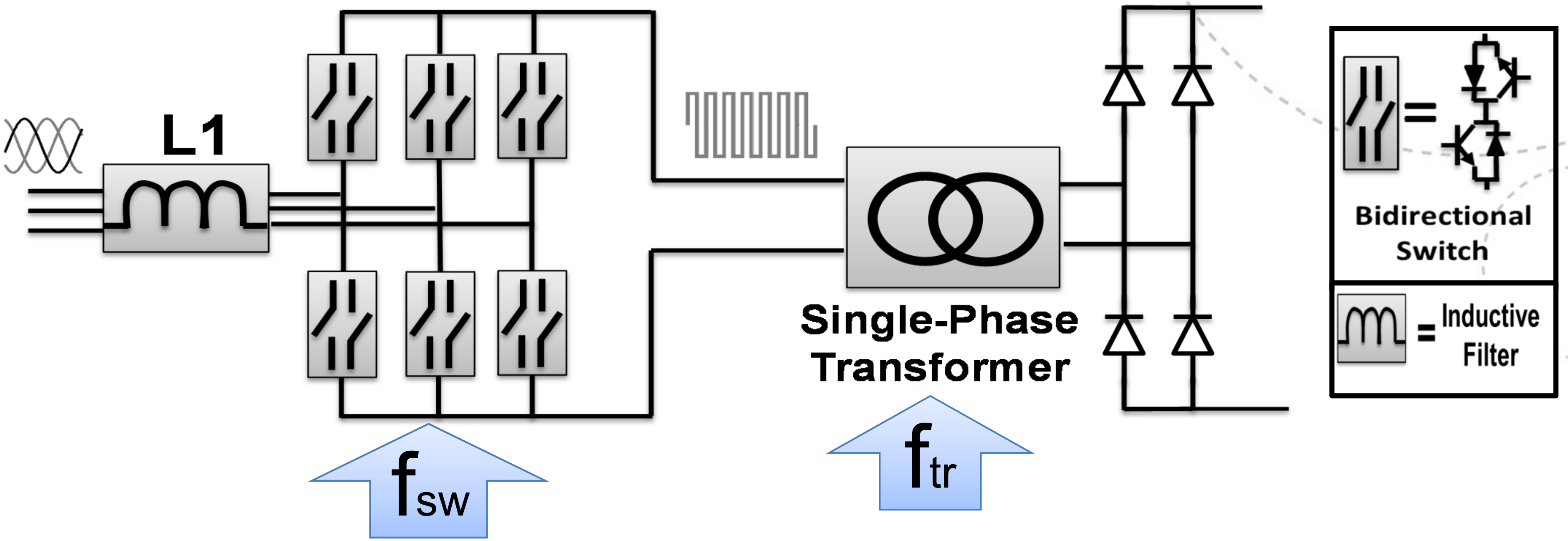
f_{tr} : AC-Link frequency. Operating transformer frequency.

f_{sw} : Switching Freq. It should be higher than transformer freq. It is equal to 6*f_{tr} in this study.

f_{lc} : Cut-off frequency of LC filter. Setting it to be 3 times lower than the switching frequency and limiting it to 20 times the supply frequency (20*50=1[KHz]).

*In this study the Clamp Circuit is not taken into account.

Module based on Reduced Matrix Converter topology (RMC)



f_{tr} : AC-Link frequency. Operating transformer frequency.

f_{sw} : Switching Freq. It is equal to transformer freq. The minimum value is 800[Hz], this limit is considered controllability and harmonics distortion in generator side.
*In this study the Clamp Circuit is not taken into account.

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Objectives Evaluation

Efficiency

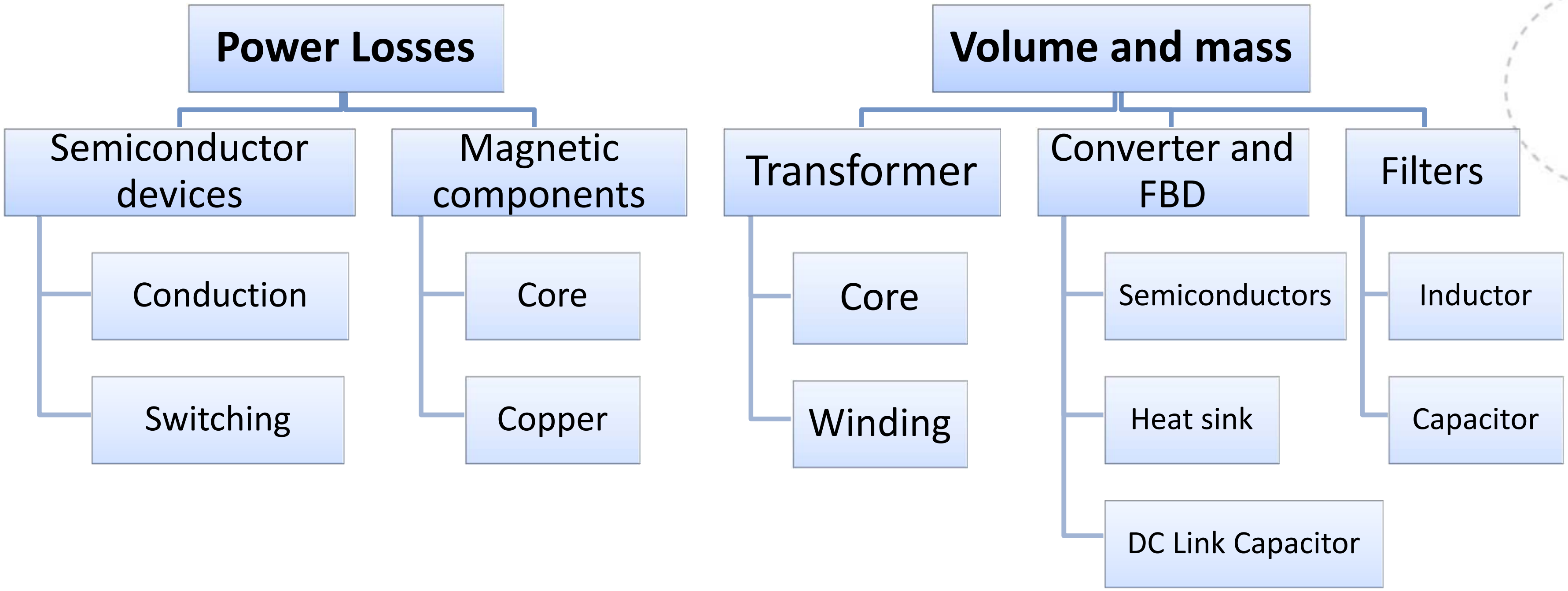
$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{losses}}{P_{in}}$$

Power Density

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

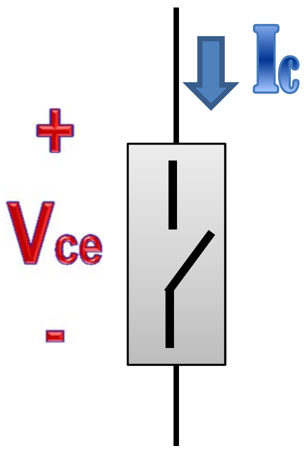
Ratio Power to mass

$$\sigma = \frac{P_{in} - P_{losses}}{mass}$$



Barrera and Molinas. "A Simple procedure to evaluate the efficiency and power density of power conversion topologies for offshore wind turbines." In proc. DeepWind 2012. Elsevier Energy Procedia.

Semiconductor Losses



Conduction

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

$$V_{ce}(t) = K_{ce1} + K_{ce2} \cdot I_c(t)$$

Switching

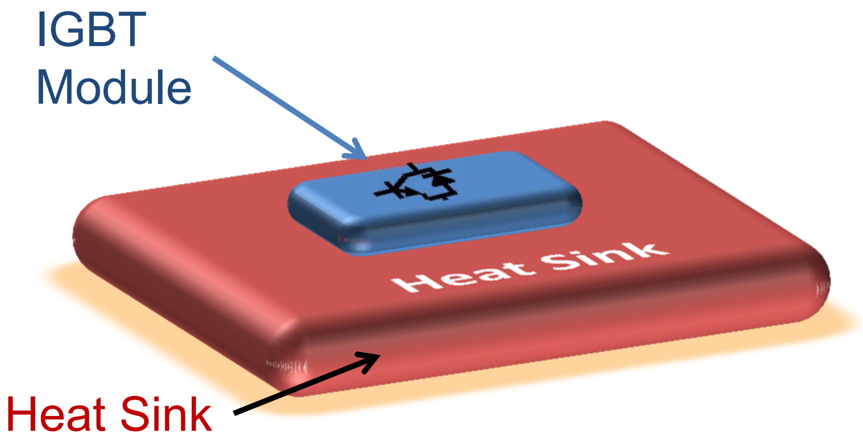
$$P_{sw} = \frac{1}{T}\sum_{T} E_{on} + E_{off} + E_{rr}$$

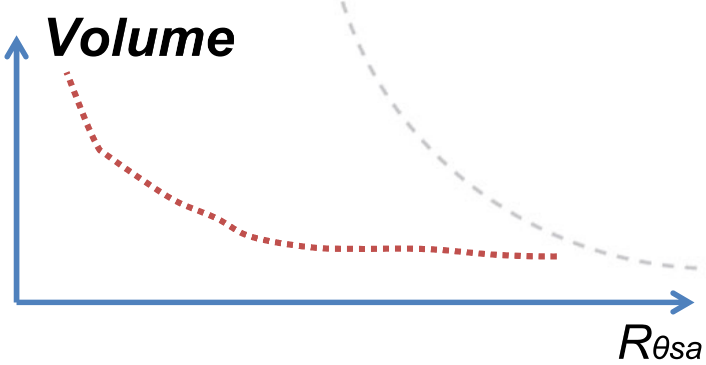
$$E_{sw} = E_{test}\frac{V_{ce}(t) \cdot I_c(t)}{V_{test} \cdot I_{test}}$$

Evaluate at moment of each switching action.
Switch On, Switch Off and Reverse Recovery

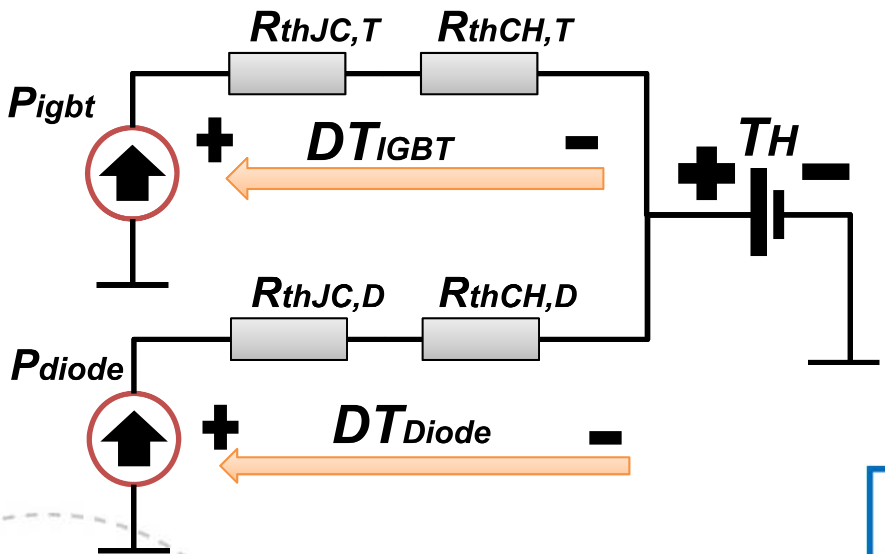
Number of switching actions are dependent of modulation scheme.

Converter 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.

$$\boxed{Vol_{conv.} = n_{sw} \cdot (vol_{device} + vol_{HS})}$$

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*,**.

$$L_{B2B} \propto \frac{V_{DC}}{I_{rms} f_{sw}}$$

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.

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

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

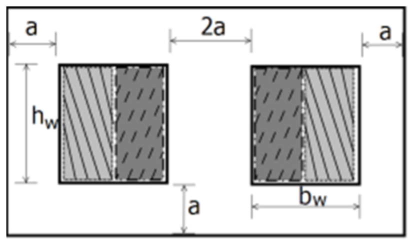
K_δ as a function of frequency, winding design (layers, conductor)

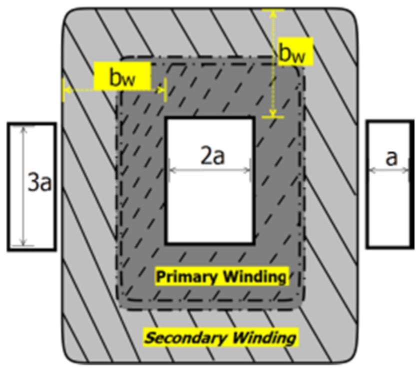
Transformer volume and losses

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

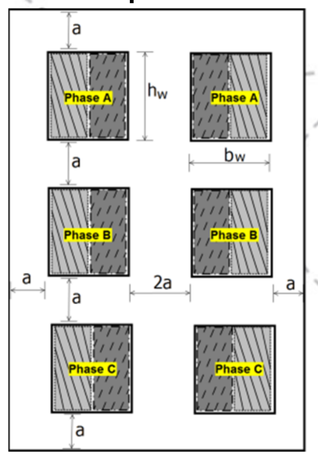
1-phase*





Transformer Superior view

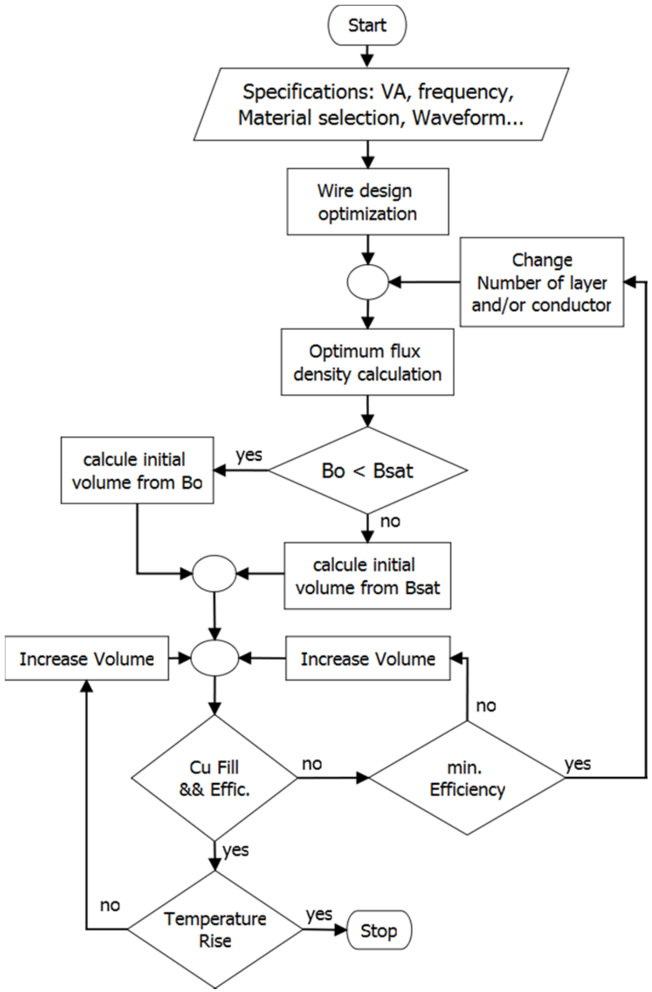
3-phase**

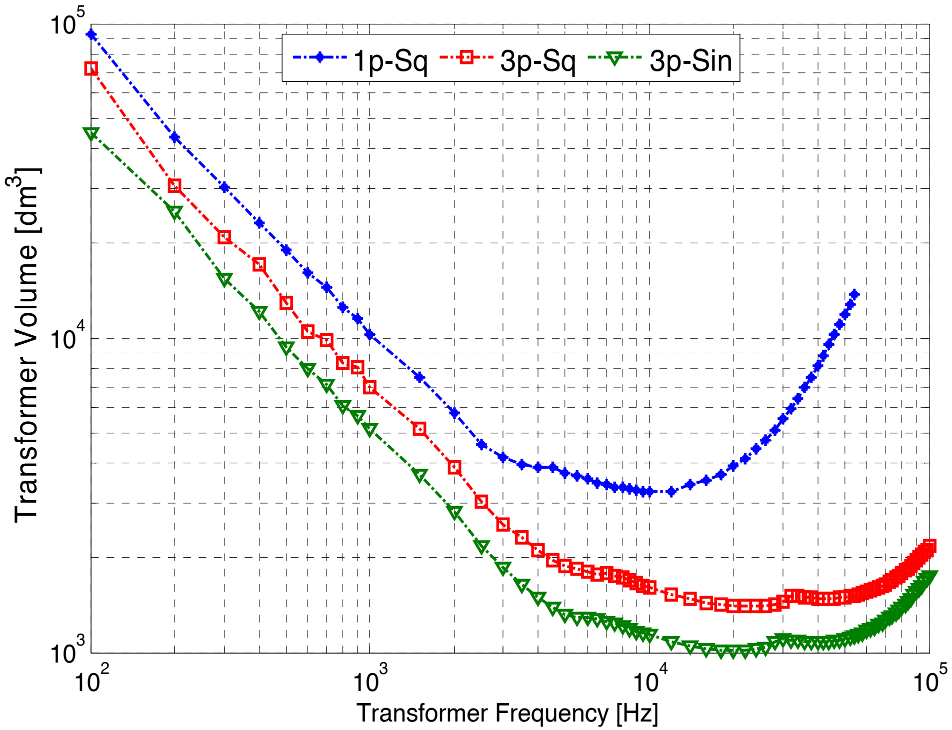


Front view

*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: Transformer volume evaluation
P= 625 [kW] Voutput = 33 [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

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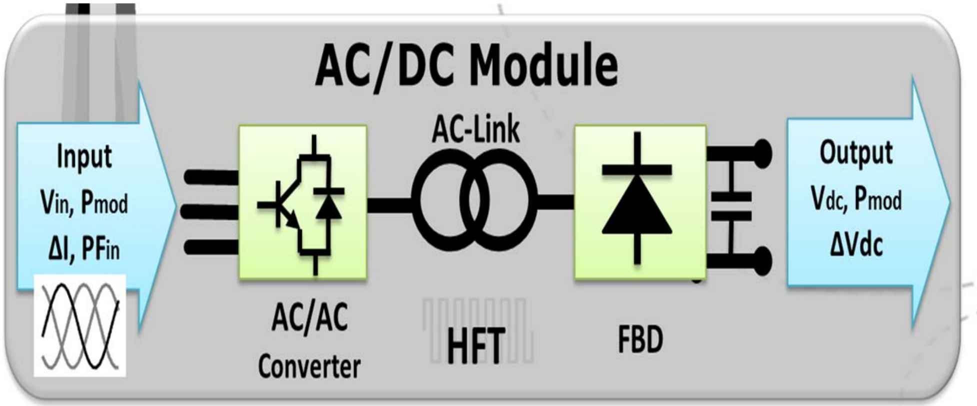
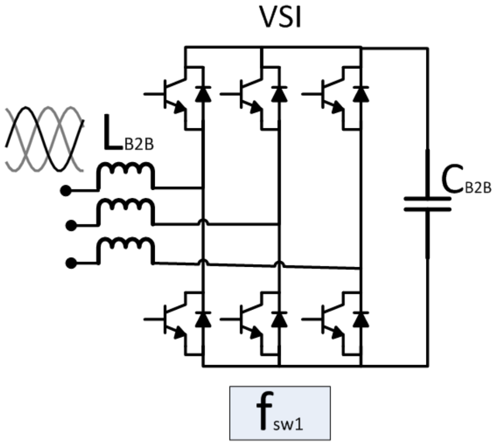
Parameters and Design Constraints

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]	[0.5, 10]
Power x module [MW]	[0.2, 10]

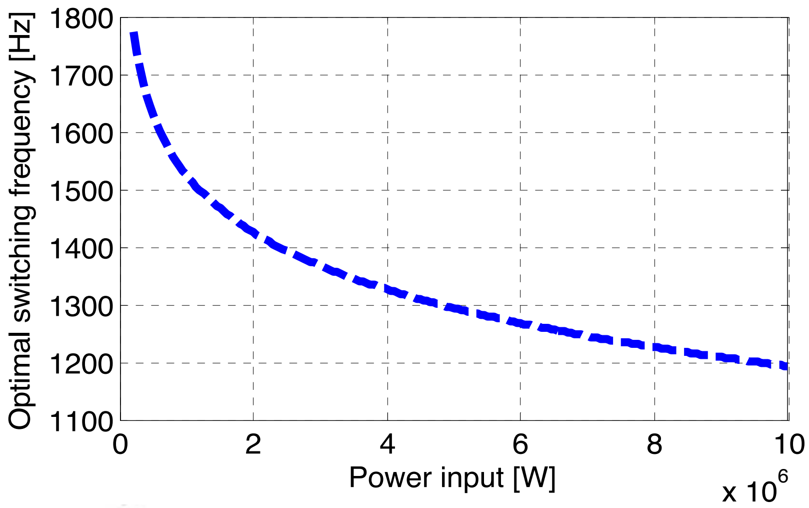


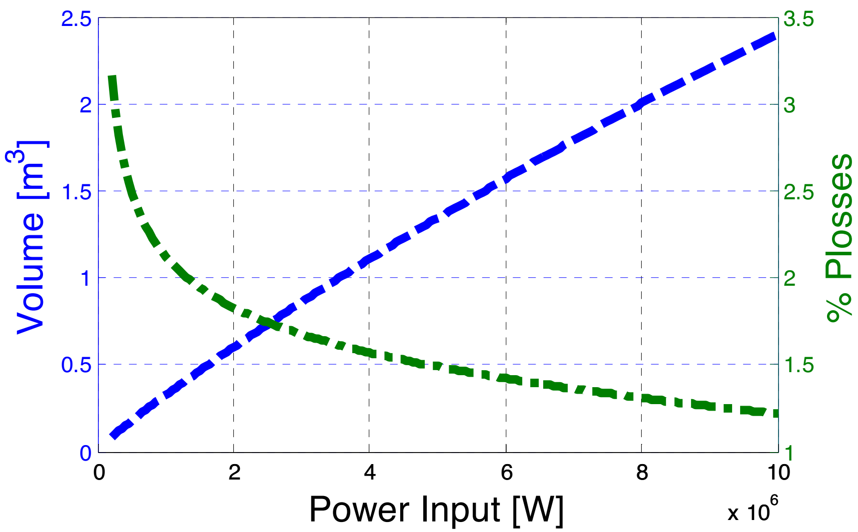
Device	Reference
Ref. Inductor (filters)	Siemens 4EU and 4ET
Ref. DC-link Capacitor	EPCOS MKP DC B256
Ref. AC-Capacitor	EPCOS MKP AC B2536
IGBT Module	Infineon IGBT4 FZXXR17HP4
DIODE Module	Infineon IGBT3 DDXXS33HE3
Heat Sink	Bonded Fin - DAU series BF
Axial FAN – Heat sink	Semikron SKF 3-230 series

Back-to-Back Topologies: Generator Side VSI and input filter

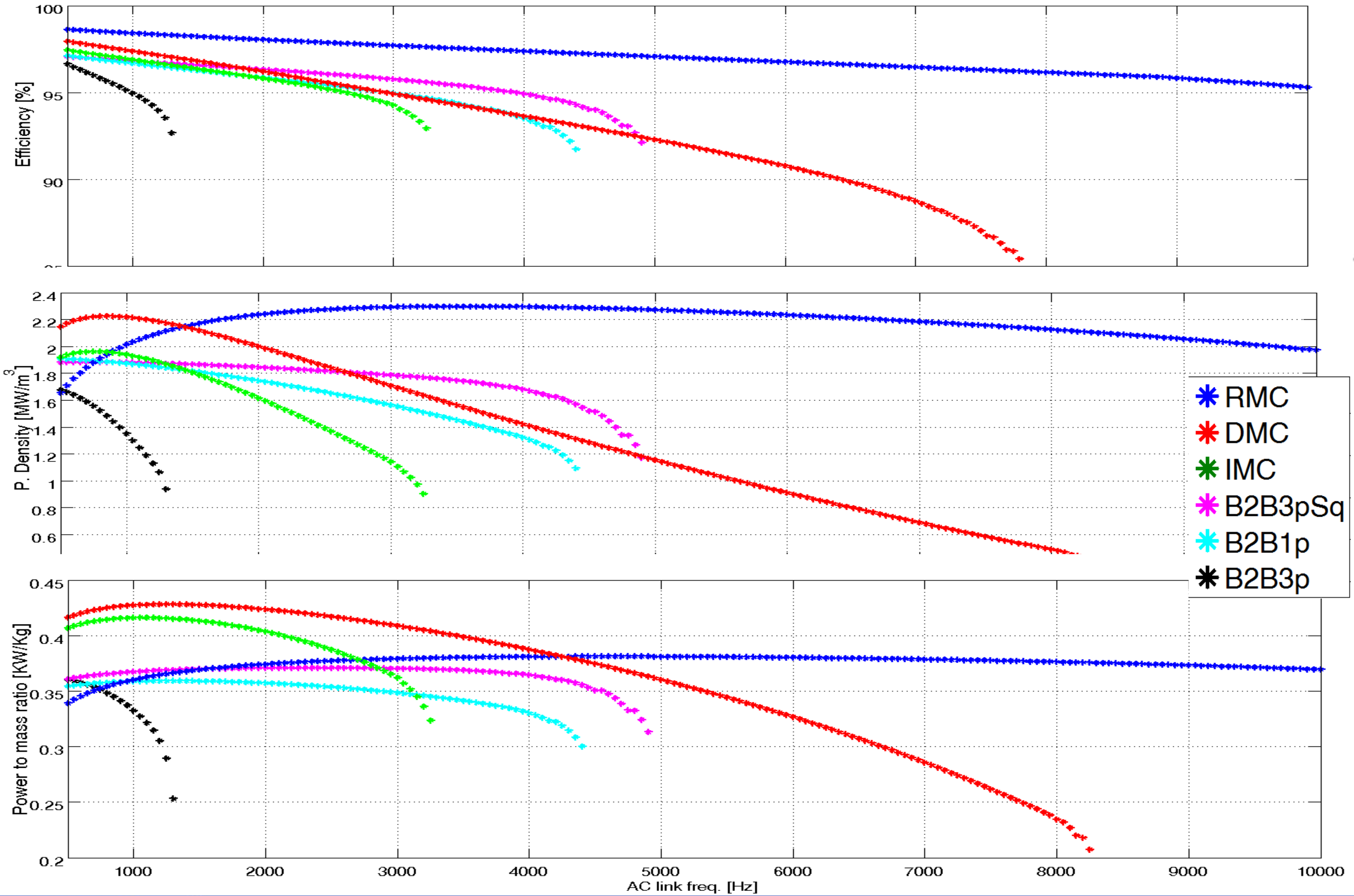


Optimal selection of switching frequency.

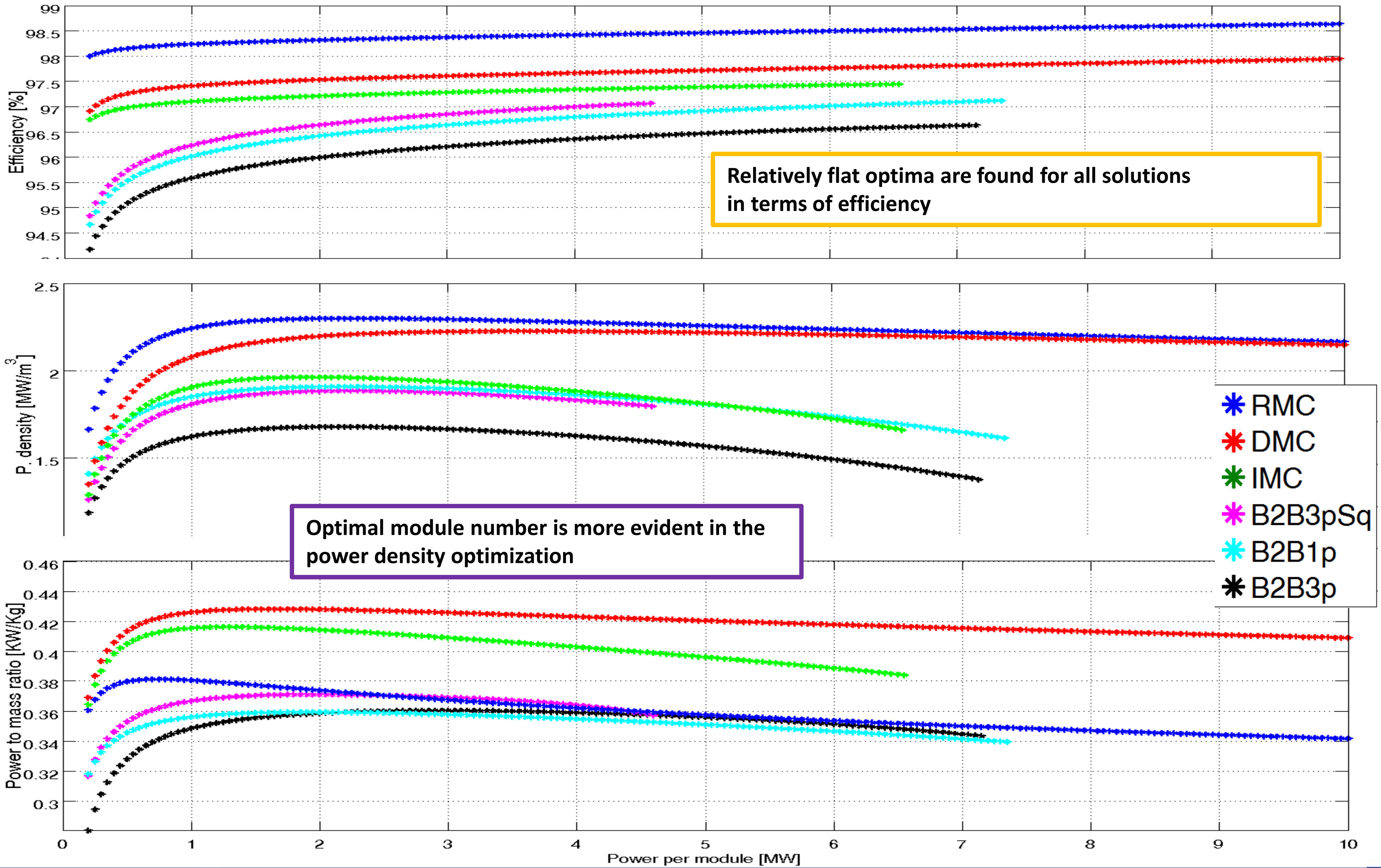




AC Link Frequency



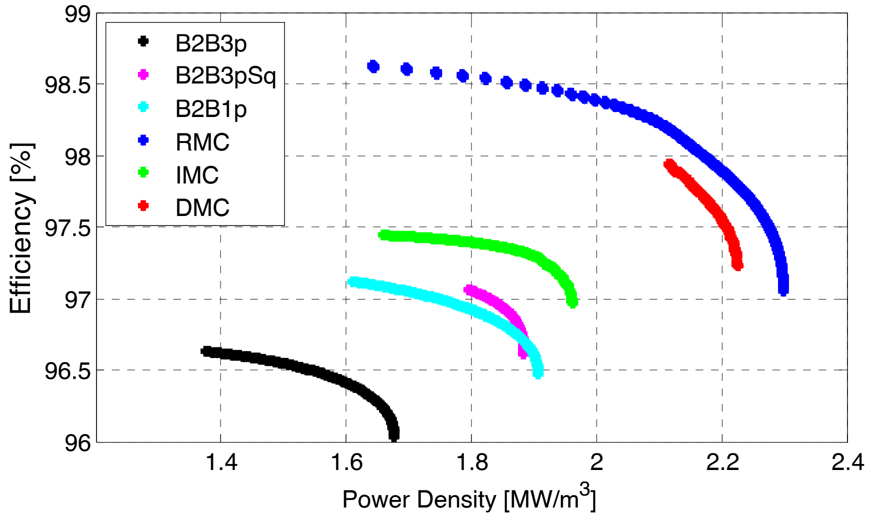
Power per module



Relatively flat optima are found for all solutions in terms of efficiency

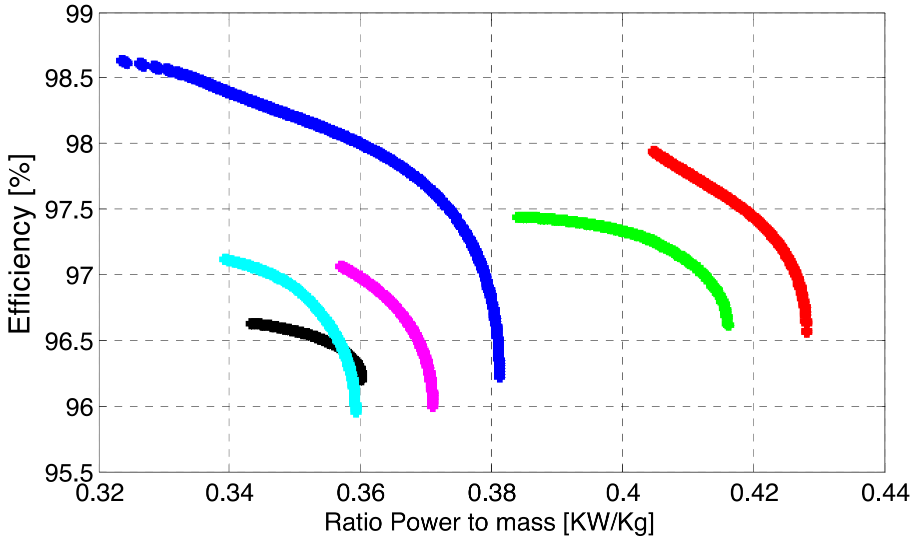
Optimal module number is more evident in the power density optimization

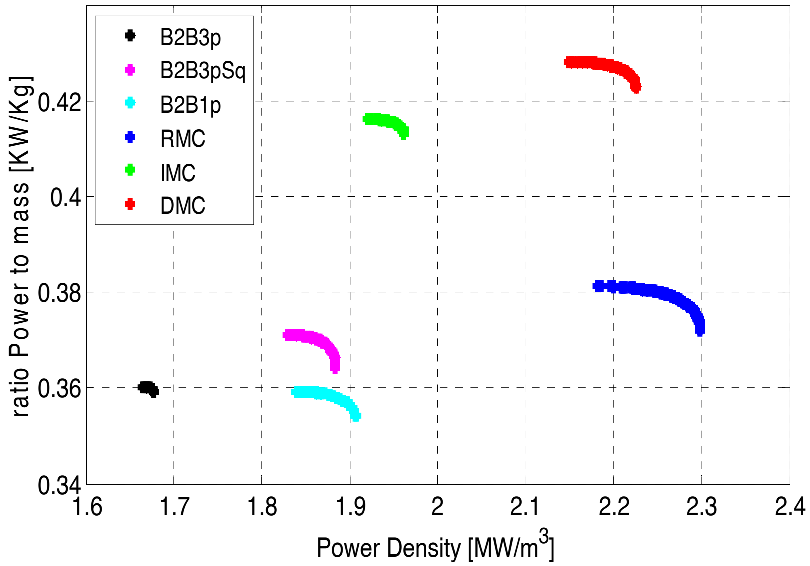
Pareto Front



RMC the best tradeoff between efficiency and power density

DMC the best tradeoff between Efficiency and ratio power to mass





Conclusions

- Six different modular power converters solution based on medium frequency link have been compared and their convenience for offshore WECS is evaluated.

- It has been found that WECS based on RMC and square wave AC-Link will lead the best tradeoff between efficiency and power density in range of AC-Link frequencies from 500[Hz] to 10[KHz].

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Thanks for your attention

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