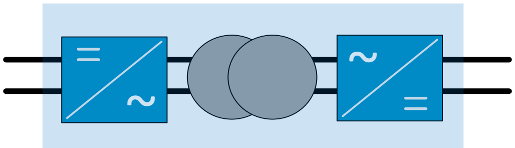
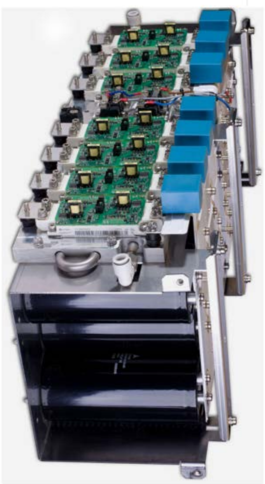
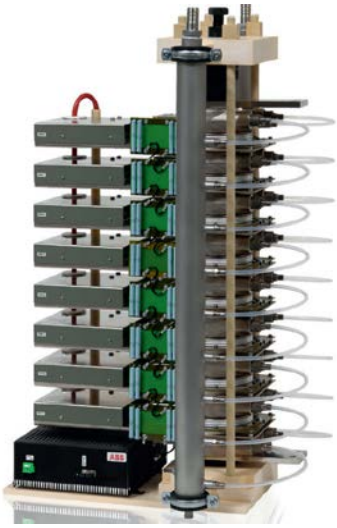
Selection Report

High power DC/DC Converters Technologies







CGD 05-april-2016

Version 1

This report is part of **Power Collection and Distribution in Medium Voltage DC Networks project**

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Contents

Version	Init	Date	Description
-1	CGD	02-10-2015	Document created
0	CGD	21-03-2016	Results added
1	CGD	05-04-2016	PCK comments added

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1. Introduction

This selection report has been developed to show the process and criteria for choosing the suitable medium voltage dc/dc converter topology.

Intended audience:

- Supervisors
- Post-doc researchers
- Partner Universities
- Partner Companies
- Other Phd Students

Main hypothesys:

Offshore HVDC –connected wind power plant collection networks can with advantage become DC rather than AC, through adaption of:

i) Turbine Conversion

ii) array cables

iii) offshore substation distribution

iv) offshore substation converter

This report is focusing on item **i) Turbine Conversion.**

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2. Purpose of the selection report

The main purpose is to recommend and provide enough information in order to make the right decision. The report highlights the evidence that marks the differences between different concepts.In order to understand where this document belongs in the process, see Fig. 1. Initially a catalogue of circuits consisting of 35 topologies was arranged. Second a state of the art of demonstrators built by universities and industry was arranged. The selection report will downsize the number of candidates to an optimal topology, based on some metrics.

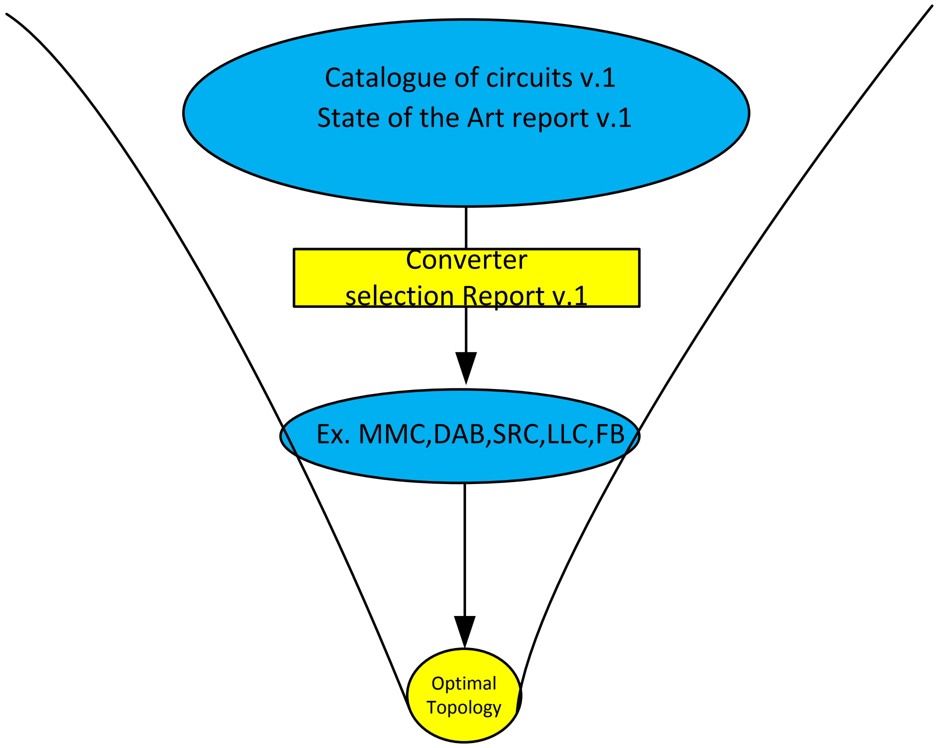

Fig. 1 Where this document belongs to

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3. Preliminary specifications and assumptions

Fig. 2 presents the proposed line diagram of turbine converter and MVDC collection grid

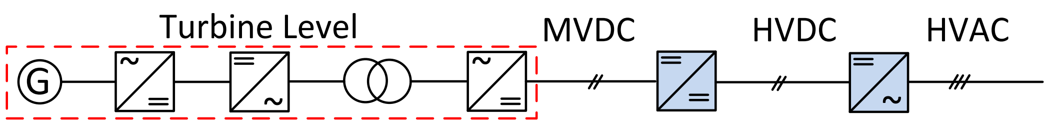

Fig. 2 Line diagram of turbine converter

Following specifications turbine converter are considered:

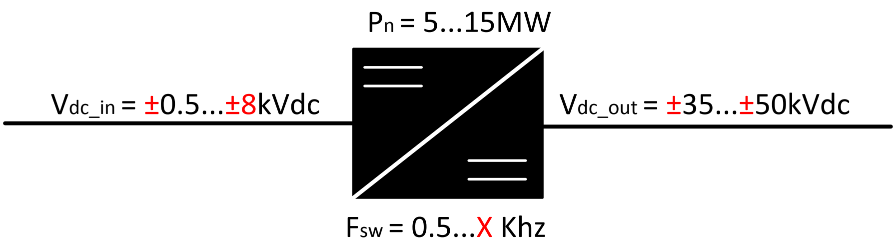

Fig. 3 Specification range for turbine DC/DC converter

So, up to this point, the turbine DC/DC converter is a "black box" that needs to fulfill a set of specifications and functionalities.

Power	10 MVA
Input Voltage	4000 Vdc (±200Vdc)
Output Voltage	100000 Vdc (±50000Vdc)
Switching Frequency	1000hz
Expected switching type	Soft-switching
Transformer	1 monolithic amorphous C-type core 1 primary winding 1 secondary winding 1:25 turns ratio
LV side valve semiconductors	Parallel Valves 4.5KV or 6.5KV IGBTs (power modules)
MV side valve semiconductors	Series connected 6.5KV press pack fast rectifier diodes
Cooling	Oil immersion for transformer and MV valve De-ionized water for LV valve
Auxiliary SMPS	High voltage SMPS connected to MVDC bus

Table 1 Converter preliminary specifications

Assumptions

During the selection process a set of assumptions have been considered:

- the MV is considered to have balanced voltage during conduction and commutation stages
- The transformer core is considered to have ideal flux, without any losses due to fringing effect
- ZCS at turn off is considered to be zero. This will not be the real situation. ZCS depend on two parameters that need to be extracted from semiconductor soft-switching characterization.
- Certainty of core losses depend on k_i, α and β parameters. These parameters need to be extracted from laboratory characterization
- Equal current sharing is considered for parallel converters
- For IGBT it is safe to conduct above datasheet values, but not to switch

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4. Selection process

Different methods can be used to evaluate which converter topology is more suitable then another.

For example, Fig. 4 is presenting an effort vs confidence graph of different methods. For instance, after a solid literature review is done, there are good conclusions of what has been done until now and which are the topologies used in average. A spreadsheet or a table of metrics (like availability, ratings of components, size of transformer, efficiency, etc) can increase the confidence even more on the proper topology.

A lot of time and effort can be spent on simulation model for instance. In order to simulate with non-ideal components some test setups need to be built to characterize the device losses. Afterwards, different topologies can be compared according to voltage and current stress and efficiency.

In our case, considering the time frame and the fact that there is already a preferred converter concept in mind, the selection process should provide enough confidence and a relative small effort.

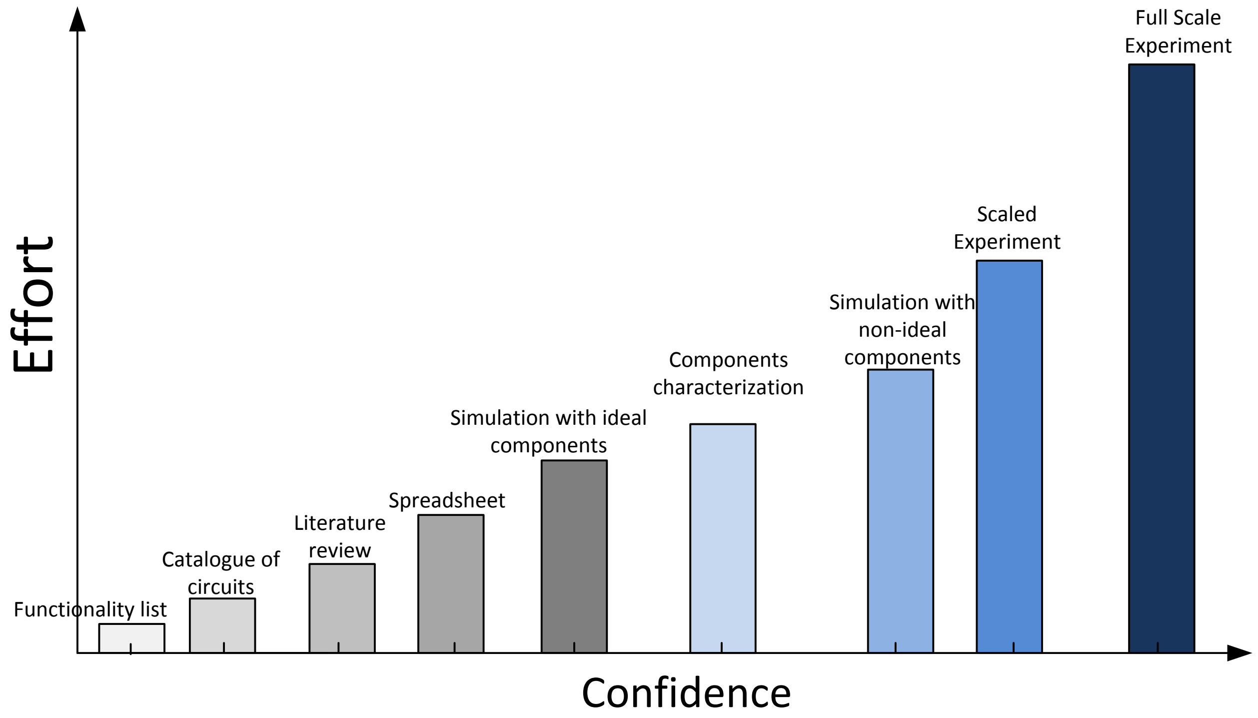

Fig. 4 Effort vs confidence graph

**It should be mentioned that topologies based on Silicon Carbide devices are also very interesting due to the increased blocking voltage and potential in decreasing the number of switches. But the lack of commercial devices will only delay the path to integration so these topologies will not be investigated.*

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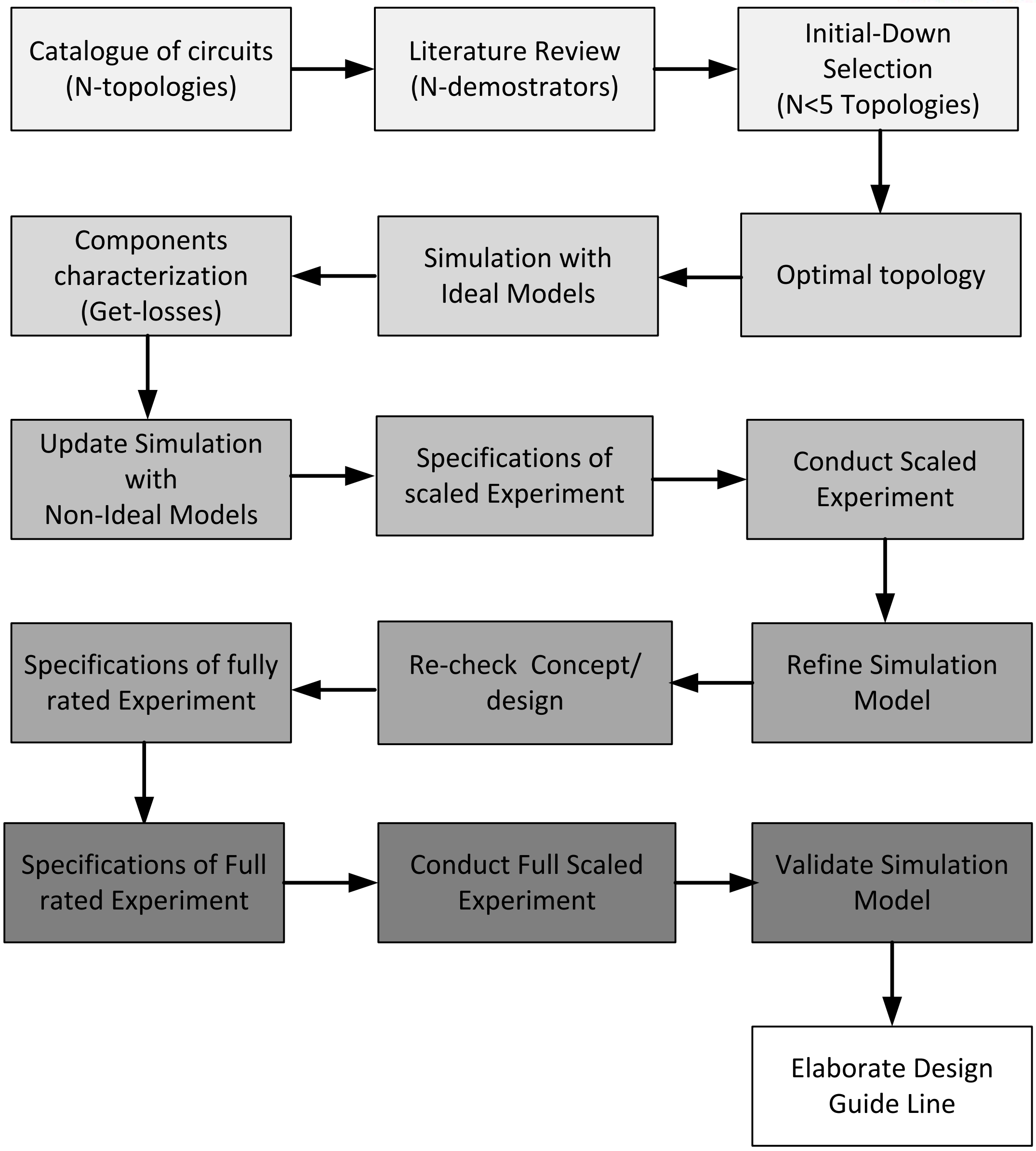

Fig. 5 Path of the project

A catalogue of converter circuits has been arranged, consisting of 35 topologies, arranged in hard switching and soft switching topologies. Fig. 6, Fig. 7 and Fig. 8 show the family tree of high power DC/DC converters.

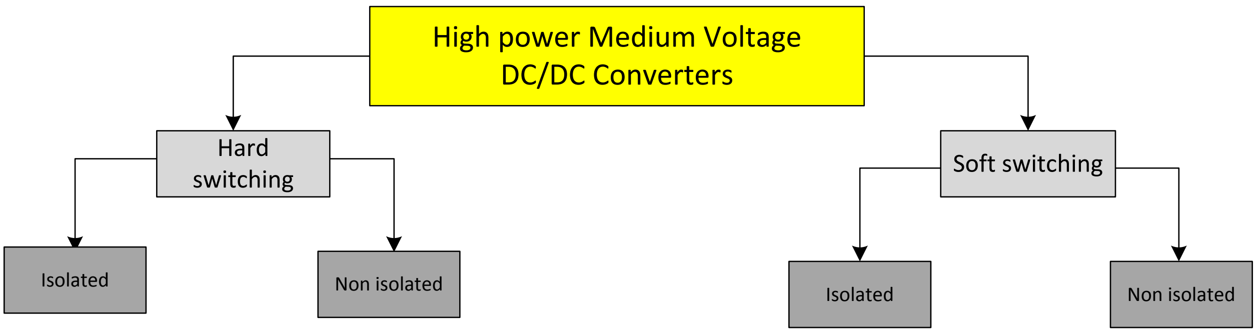

Fig. 6 Family tree of converters

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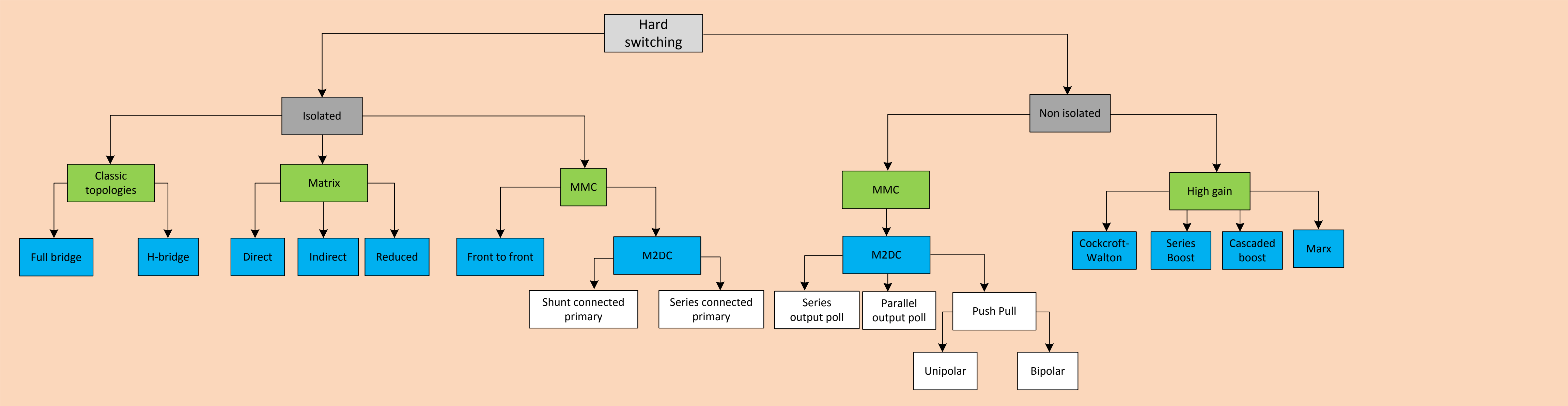

Fig. 7 Hard switching topologies

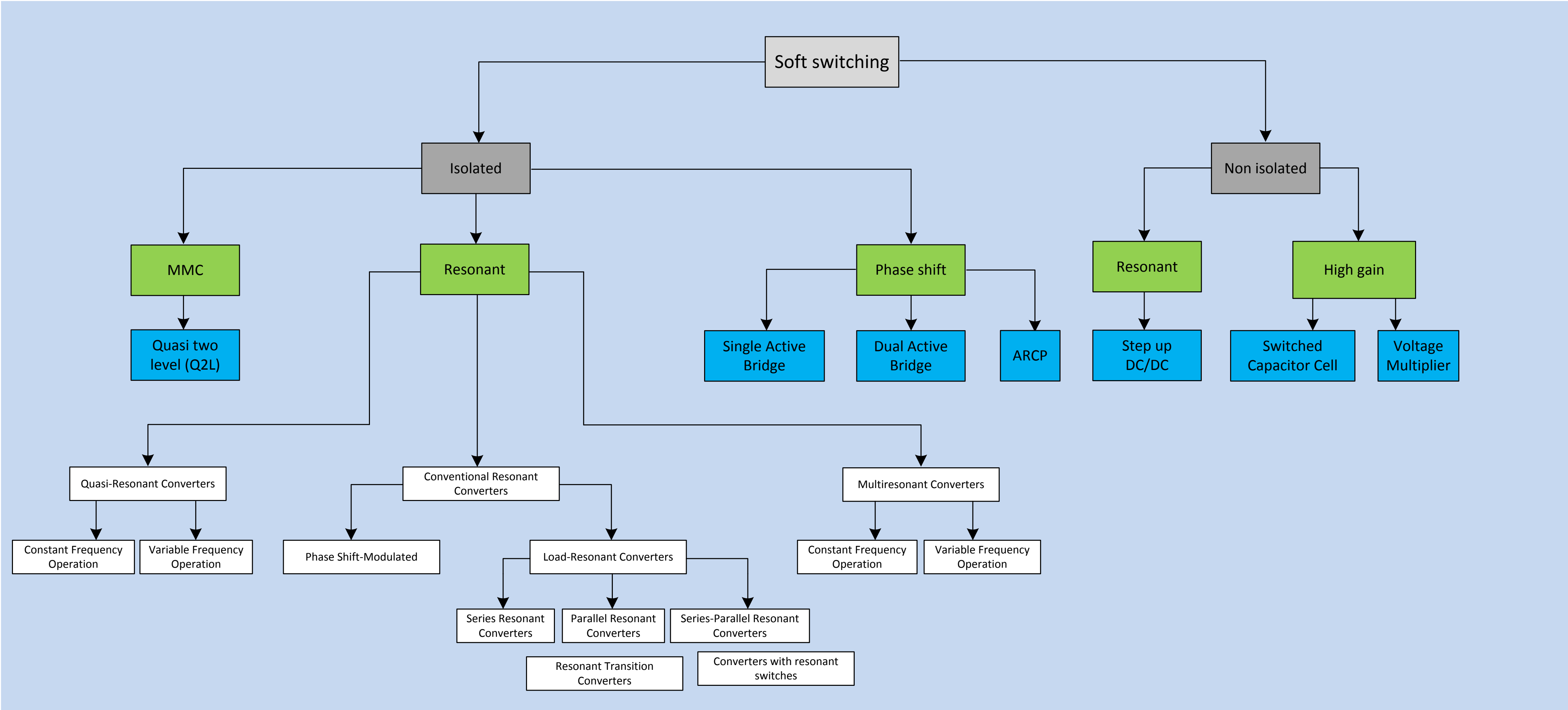

Fig. 8 Soft switching topologies

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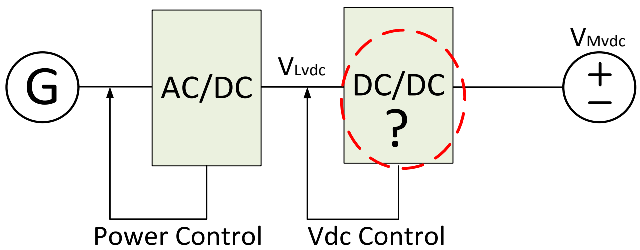
Anyway, regardless of selected topology, the turbine converter needs to fulfill a set of specifications and functionalities, which are determined from network studies.

Considering following objective: ***"Identify, design and develop a unidirectional, single phase, monolithic DC/DC converter (with a nominal power up to 15MW, ±50kV output voltage and galvanic separation), for offshore wind turbines, demonstrating the principal performance indicators of efficiency, functionality, voltage withstand."***

A downsize is performed based on following characteristics:

- Single phase topology
- Unidirectionality
- Galvanic separation
- Monolithic design

So, from this point of view, bidirectional topologies like DAB (Dual Active Bridge) will not be studied. If no transformer is present, no focus continued on high gain topologies. Matrix converters will not be studies, as it has been decided to use a classic PMSG and active rectifier topology, as seen below. It is expected that the generator converter controls maximum output power, while the dc/dc converter keeps V_{LVDC} constant.



Monolithic design, from the project perspective means one transformer, with a single primary and secondary winding, as seen in Fig. 9 and one rectifier, based on a simple full-bridge. One diode in the figure is the equivalent of N series connected diode. Fig. 9 shows the stages that will be present, regardless of the selected topology.

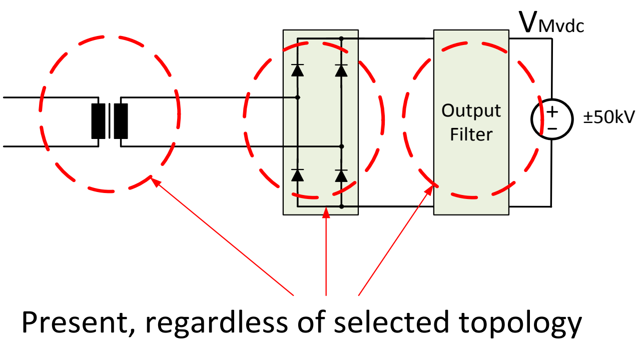


Fig. 9 Monolithic design

Based on above characteristic, the range of 35 topologies is downsized to 4:

- Classic Hard Switched Full Bridge Converter (FB). This will be the base line
- Single Active Bridge (SAB) Converter
- Series Resonant Converter. There will be three different design options that avoid transformer saturation
- LLC Converter.

Following page presents the selected topologies and their corresponding primary winding current and inverter output voltage. The principal waveforms of every topology are shown in **Appendix.**

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Selected Converter topologies

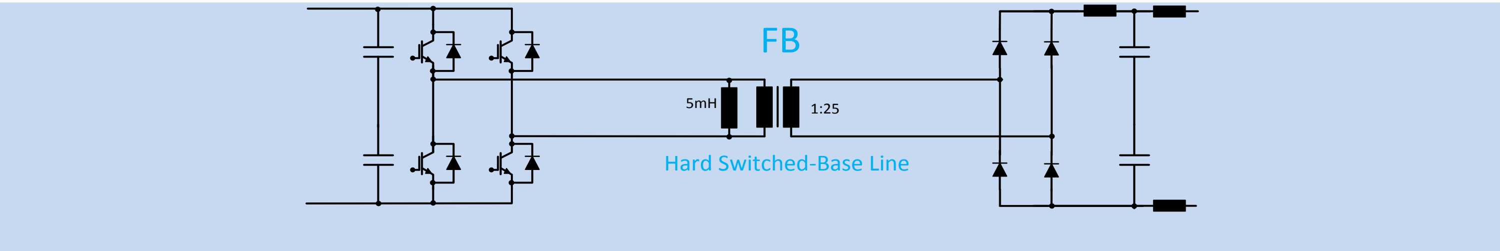

Fig. 10 Hard Switched Full Bridge (FB)

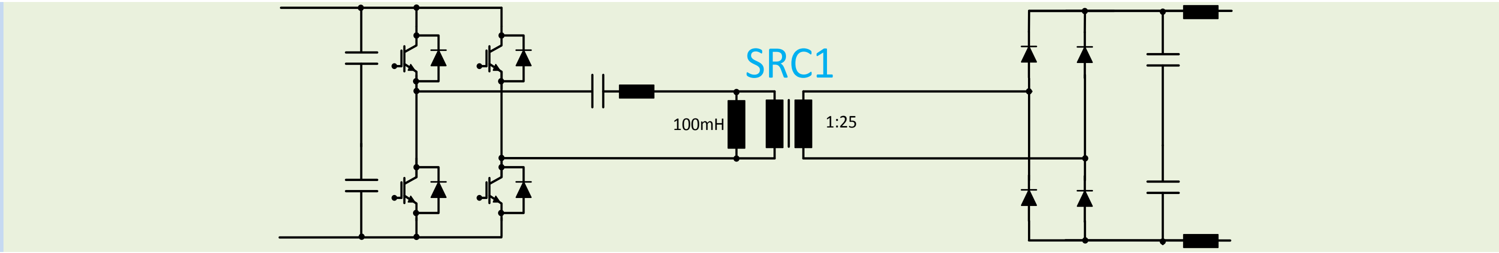

Fig. 11 SRC1-Generous Design

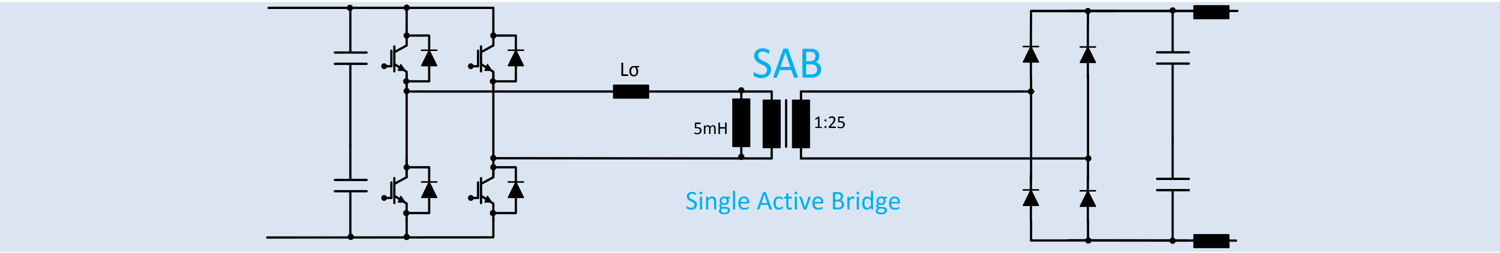

Fig. 12 Single Active Bridge (SAB)

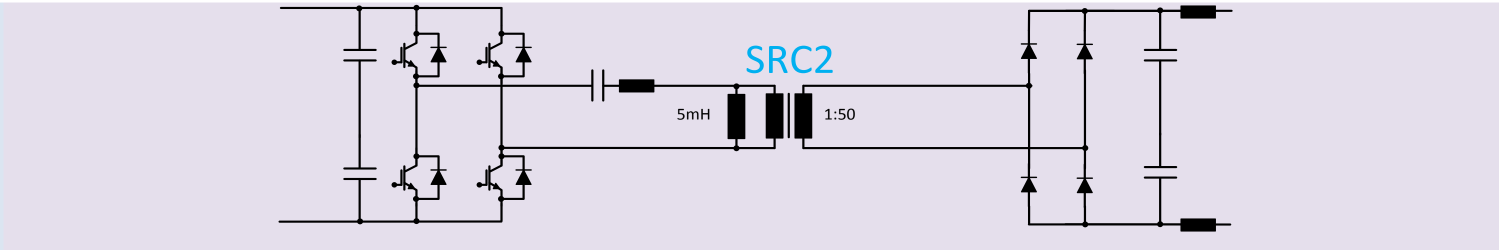

Fig. 13 SRC2-No transformer Saturation

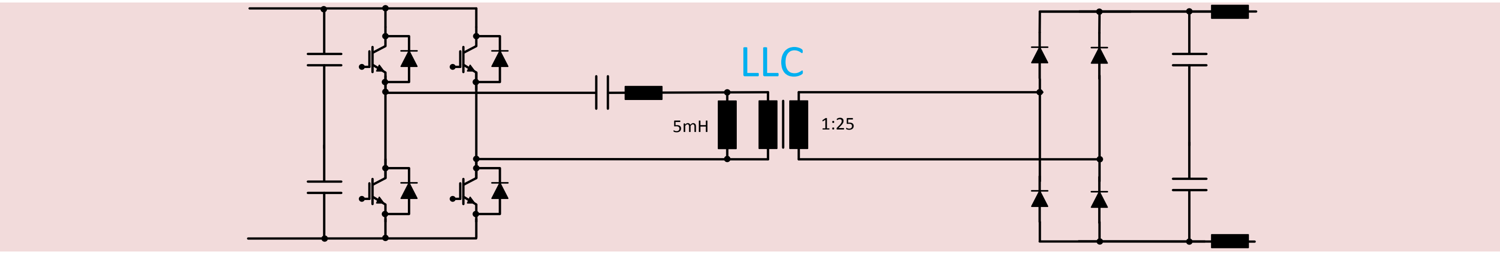

Fig. 14 LLC Converter

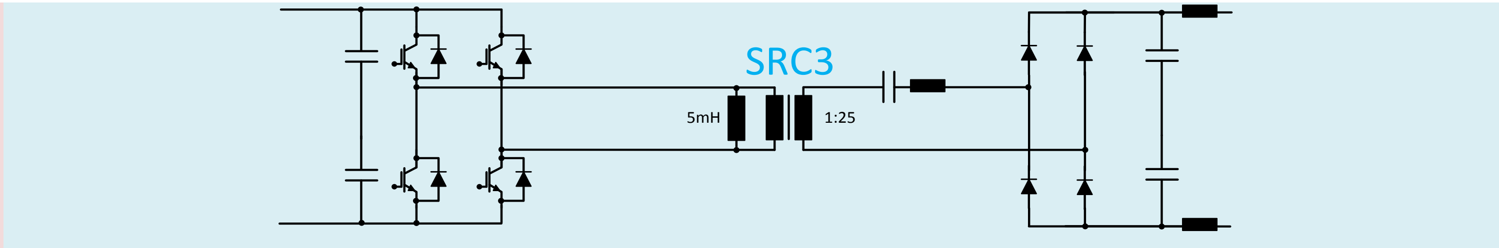

Fig. 15 SRC3-Pulse Removal. Tank on secondary side

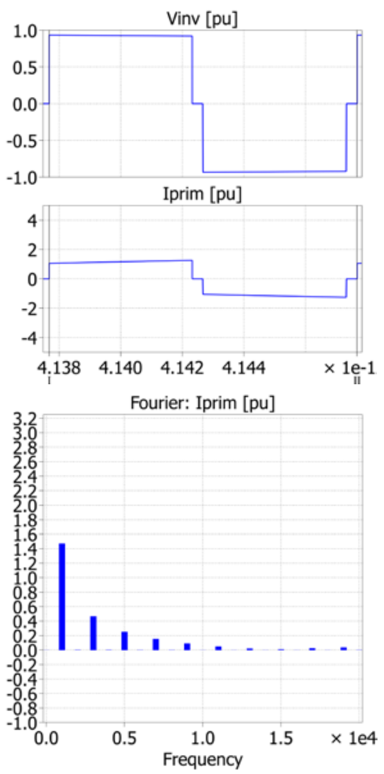

Fig. 16 FB Converter

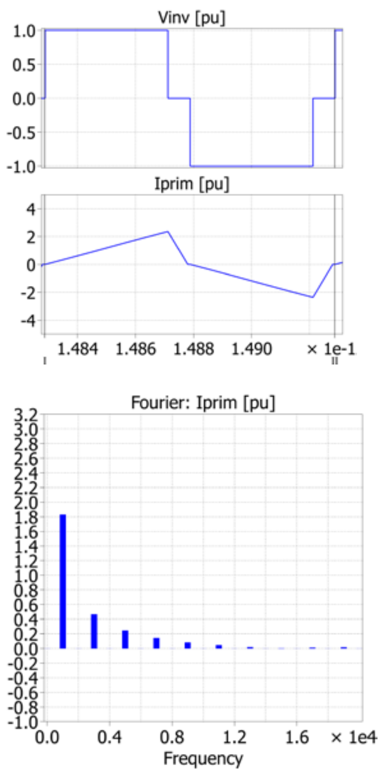

Fig. 17 SAB Converter

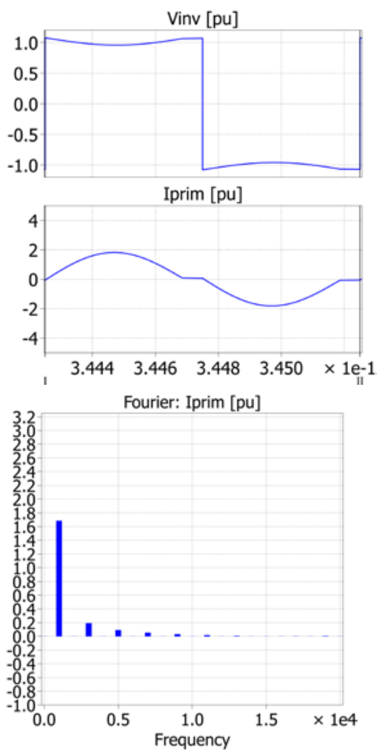

Fig. 18 LLC Converter

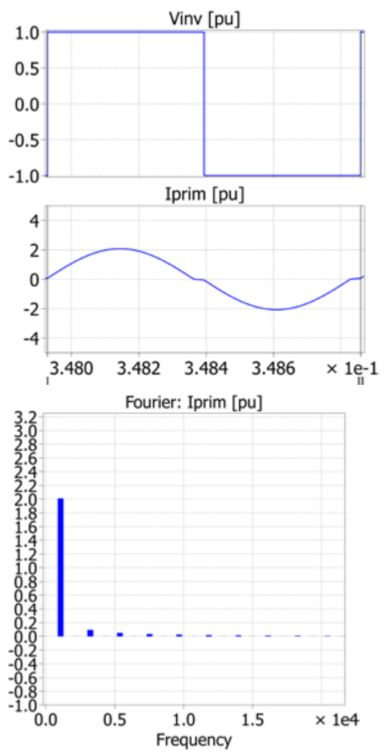

Fig. 19 SRC1

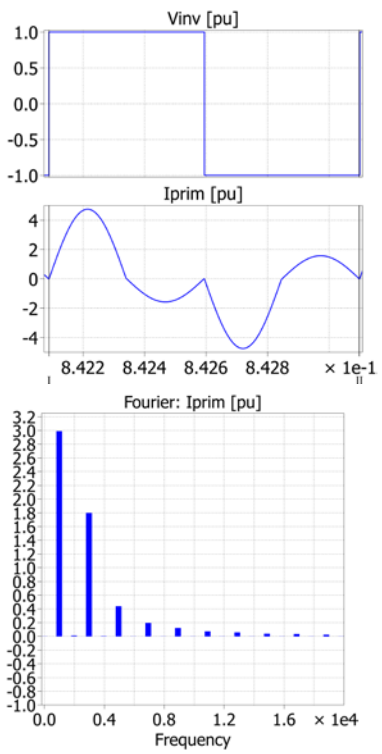

Fig. 20 SRC2

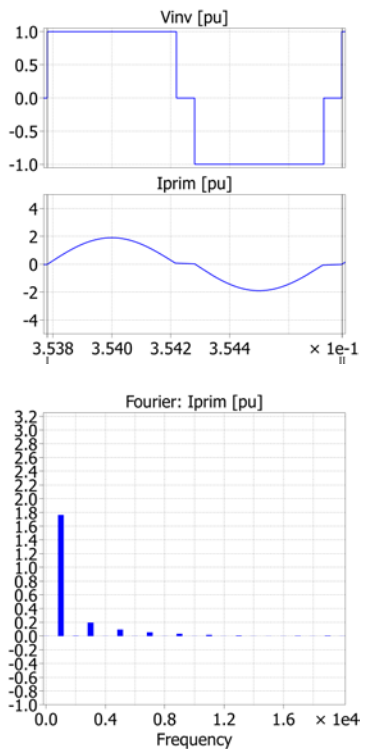

Fig. 21 SRC3

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Considerations for Series Resonant Converter

The Series Resonant Converter is able to control output power either by changing the frequency of applied voltage or it's phase shift. In this case, it has been chosen to use frequency control. This means, the resonant tank impedance is changed during operation. There are three modes of operation: sub-resonant, resonant and super resonant. In this project, the decision has been made to operate in sub-resonant mode, discontinuous current mode, as in this stage there is a linear relation between frequency and output power.

But this comes with a cost: variable frequency in sub resonant mode, means the transformer needs to be designed for the lowest frequency in order to avoid saturation. For this case, three design variants have been proposed:

SRC1.

In this variant, the transformer is designed for 200Hz and operated up to 1000hz. At 200hz, flux density is 1.6T, while at 1000Hz is 0.32T. The main disadvantage is that the converter will not operate below 200hz or 0.2pu operation and another control method should be selected

SRC2

In this design variant, the converter is able to operate from 0 to 1pu, or 0 to 1000hz, because the transformer turns ratio is set in such a way, that Vin/Vout' = 2.

SRC3

In this variant, the tank is on secondary side, while a different modulation is applied, called Pulse Removal. As soon as the primary current reaches zero, Vinv is also set to zero.

5. Selection Criteria

The turbine converter will be selected and designed based on following design drivers:

No	Design driver	Weighted rank
a.	Availability (leading to loss generation [[MW]h]]	5
b.	Electrical losses (efficiency)	4
c.	Ratings (name plate power, voltage, temperature…)	4
d.	Repair costs (excluding scheduled maintenance)	2
e.	Power density (volume and weight)	1

Tabel 1 Ranking of design drivers

At the moment, only following design drivers are possible to be addressed for every converter topology :

- Electrical losses (efficiency)
- Ratings
- Power density (volume and weight)

A loss estimation has been conducted for all topologies, with steps of 0.1pu in output power. Semiconductor and transformer loss model are further explained in **Appendix 8.1 and 8.2.**

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5.1 Semiconductor Losses

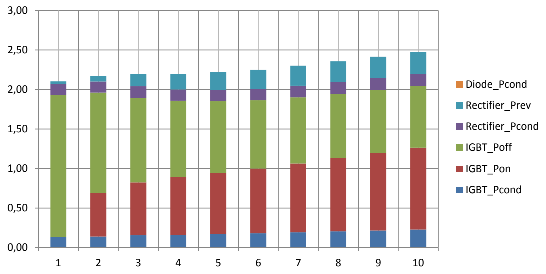

Fig. 22 Hard Switched Full Bridge (FB)

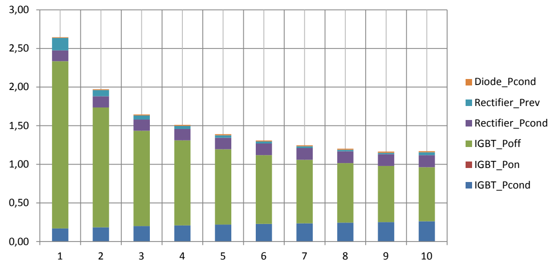

Fig. 23 Single Active Bridge (SAB)

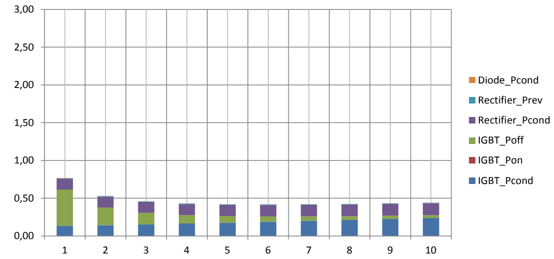

Fig. 24 LLC Converter

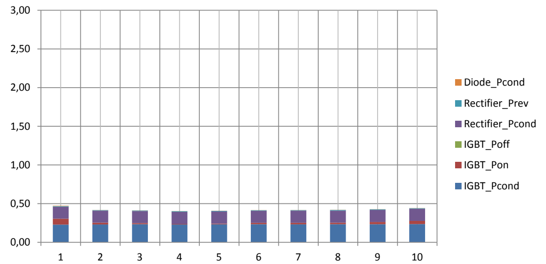

Fig. 25 SRC1-Generous Design

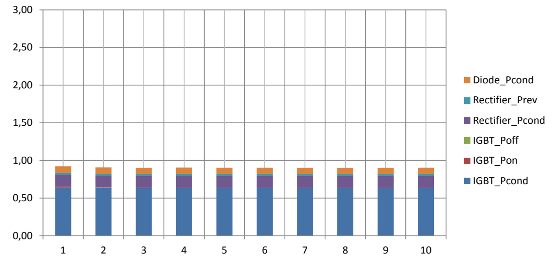

Fig. 26 SRC2-No saturation

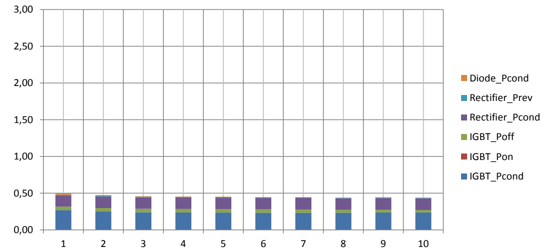

Fig. 27 SRC3-Pulse Removal

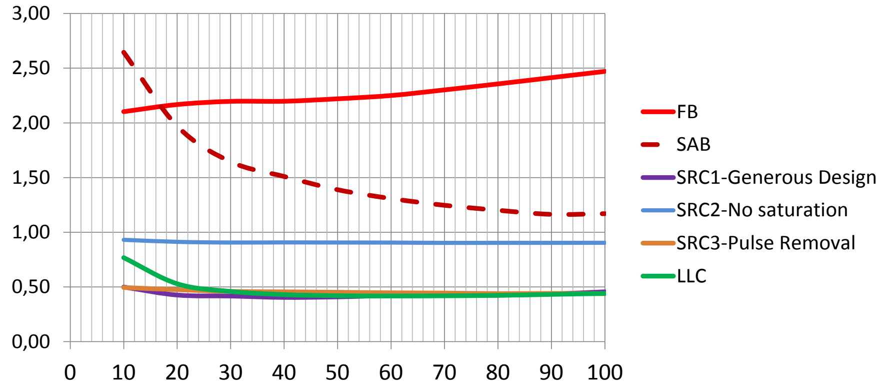

Fig. 28 Semiconductor loss comparison

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5.2 Results interpretation on semiconductor losses

1. Hard switched Full Bridge (FB) - Fig. 22
   - Semiconductor losses are 2.5% at 1pu output power. Switching losses are predominant
   - High turn on and turn off losses, as the converter switches at high current
   - High reverse recovery of rectifier diodes, as the diodes become reversed biased at high current
2. Single active bridge (SAB) - Fig. 23
   - Semiconductor losses are 1.2% at 1pu output power. Turn off losses are predominant
   - Turn on losses are zero, due to ZVS
   - Reverse recovery losses on rectifier side are very small
3. LLC Converter-Fig. 24
   - Semiconductor losses are 0.44% at 1pu output power.
   - Turn on losses are zero, due to ZVS.
   - Turn off losses are small, as the transistors switch at low magnetizing current
   - Reverse recovery losses on rectifier side are very small and close to zero
4. SRC1-Generous design-Fig. 25
   - Semiconductor losses are 0.46% at 1pu output power
   - Turn off losses are zero, due to ZCS
   - Turn on losses are small, as the transistors switch at low current
   - Reverse recovery losses on rectifier side are very small and close to zero
5. SRC2-No saturation-Fig. 26
   - Semiconductor losses are 0.90% at 1pu output power
   - Switching losses are zero due to ZVS and ZCS
   - Reverse recovery losses on rectifier side are very small
   - Conduction losses on inverter side are aprox.3 times higher than SRC1 and LLC
6. SRC3-Pulse removal-Fig. 27
   - Semiconductor losses are 0.44% at 1pu output power
   - Turn on losses are zero due to ZVS
   - Turn off losses are small, as the transistors switch at low current
   - Reverse recovery losses on rectifier side are very small and close to zero
7. Semiconductor loss comparison-Fig. 28
   - Excepting SRC3, inverter and rectifier conduction losses are almost the same for the rest of the topologies. The difference in losses is caused by turn on and turn off losses.
   - The hard switched FB converter has the highest losses as expected, in the range 2 to 2%, from 0.1 to 1pu output power
   - At low output power <0.2pu, SAB as similar losses to FB converter, but above they are 50% lower than the FB.
   - SRC3 has aprox. 0.9% losses in the range 0.1 to 1pu, mostly because of conduction losses
   - LLC, SRC1 and SRC3 show the lowest losses in the range 0.1 to 1pu, with values close to 0.5%.
   - From semiconductors losses point of view, preferred topologies should be SRC1, SRC3 and LLC.

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5.3 Transformer Losses

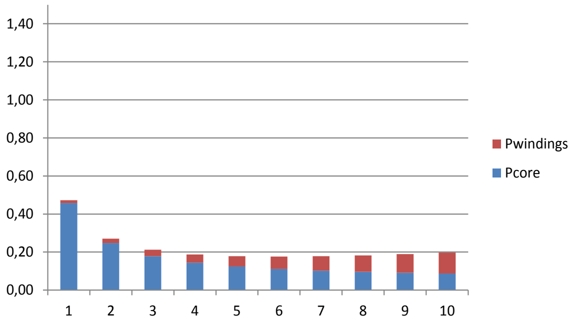

Fig. 29 Hard Switched Full Bridge (FB)

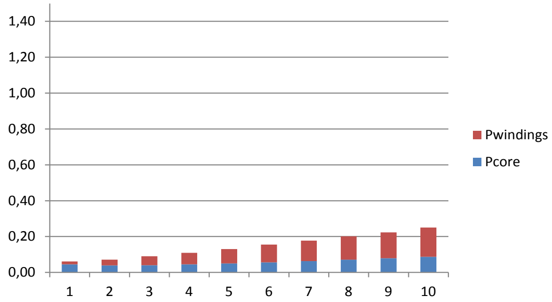

Fig. 30 Single Active Bridge (SAB)

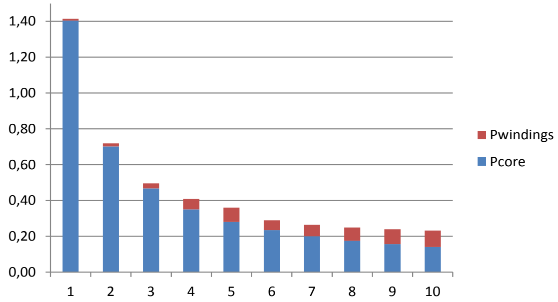

Fig. 31 LLC Converter

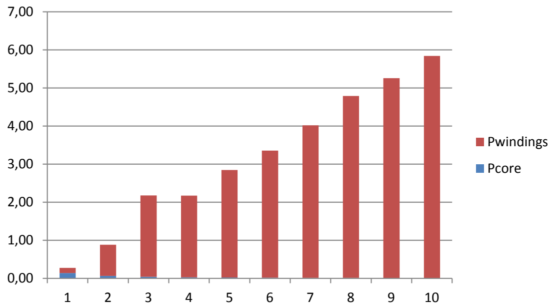

Fig. 32 SRC1-Generous Design

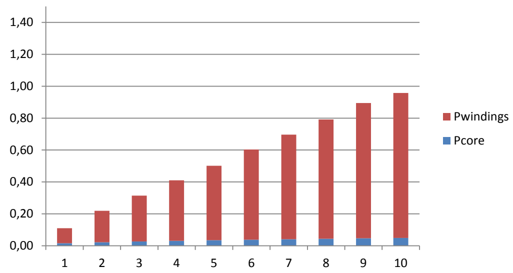

Fig. 33 SRC2-No saturation

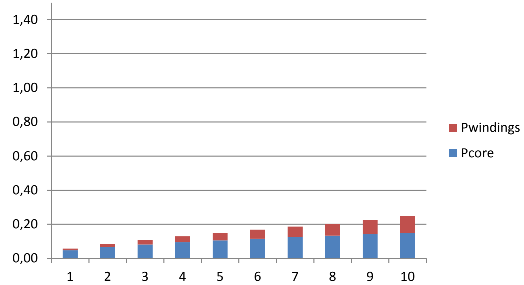

Fig. 34 SRC3-Pulse Removal

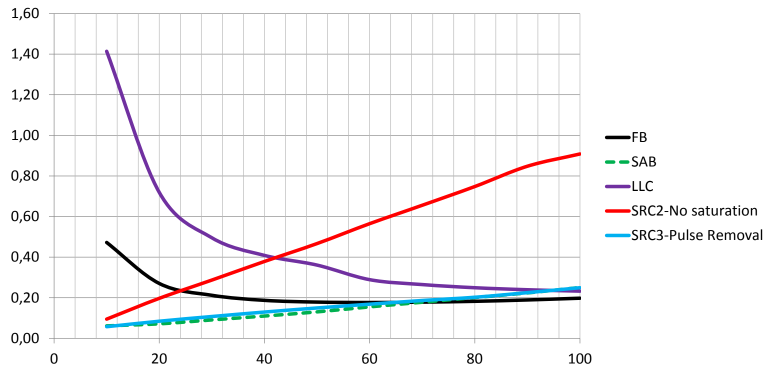

Fig. 35 Transformer loss comparison

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5.4 Results interpretation on transformer losses

1. Hard switched Full Bridge (FB) - Fig. 29

- Transformer losses are 0.2% at 1pu output power. At low power, core losses are predominant
- Core losses are a function of frequency, Bmax and duty cycle. Duty cycle varies between 0.33% and 0.44%.Bmax varies between 1.1T and 1.37T
- Winding losses influenced by primary current harmonics

2. Single active bridge (SAB) - Fig. 30

- Transformer losses are 0.25% at 1pu output power.
- With a constant frequency of 1000hz and while duty cycle varies between 0.14% and 0.42%, Bmax varies between 0.46T and 1.37T

3. LLC Converter- Fig. 31

- Transformer losses are 0.23% at 1pu output power.
- Core losses are predominat in the whole operating range, as compared to FB and SAB, the LLC runs at constant duty cycle, thus higher flux density
- For every operating point, core losses have the same value, explaining why at lower output power they are predominant
- Windings losses are lower, compared to FB and SAB due to lower rms currents per harmonics

4. SRC1-Generous design- Fig. 32

- Transformer losses are 5.84% at 1pu output power
- Winding losses are predominant. Even if current THD is lower than previous topologies, due to the “generous design”, higher mass of copper leads to higher losses.
- Higher number of turns and parallel layers increase proximity effect, causing the losses
- Core losses are on the other hand very small, due to lower Bmax (varying between 1.6T and 0.32T)

5. SRC2-No saturation- Fig. 33

- Transformer losses are 0.91% at 1pu output power
- Winding losses are predominant in the whole operating range. The main cause is current waveform, with very high 3rd and 5th RMS values
- Core losses are considerably smaller, as Vprimary is decreased to 0.5pu and Bmax is 0.8T

6. SRC3-Pulse removal- Fig. 34

- Transformer losses are 0.25% at 1pu output power
- Compared to SRC1 and SRC2, winding losses are considerably smaller, due to better current THD and lower ac resistance
- Winding losses are load dependent, while core losses are frequency dependent

7. Transformer loss comparison- Fig. 35

- SRC1 has the highest losses, due to higher amount of copper.
- SRC2 has losses almost 4 times higher compared to FB,SAB,LLC and SRC3, due to 3rd and 5th harmonic rms values
- LLC shows higher losses at lower output power, due to constant core losses
- SAB and SRC2 show losses lower than 0.3% in the whole operating range
- From transformer losses point of view, preferred topologies should be FB, SAB and SRC3

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5.5 Total losses

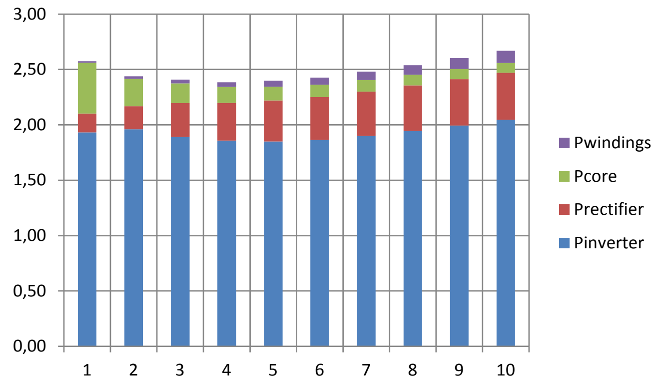

Fig. 36 Hard Switched Full Bridge (FB)

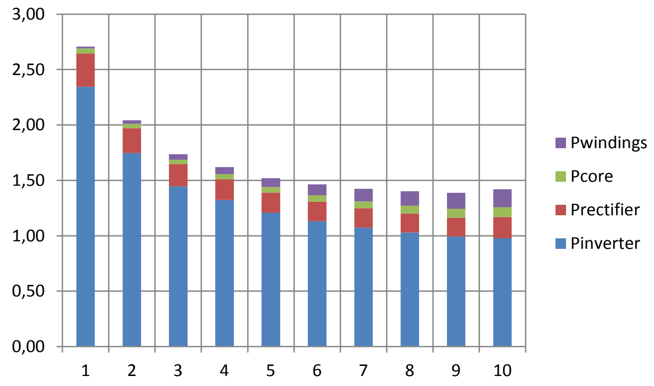

Fig. 37 Single Active Bridge (SAB)

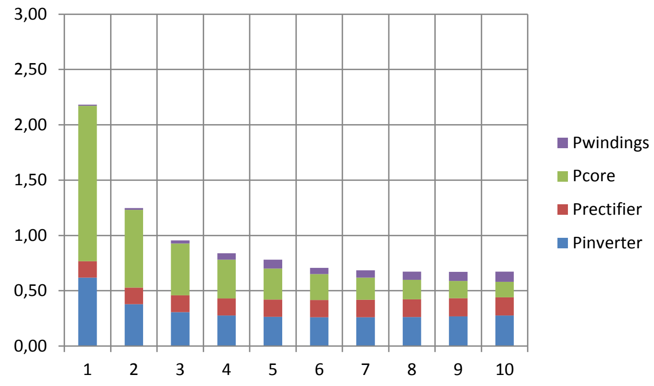

Fig. 38 LLC Converter

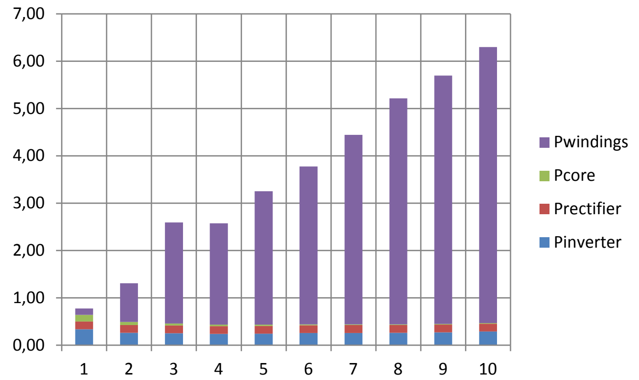

Fig. 39 SRC1-Generous Design

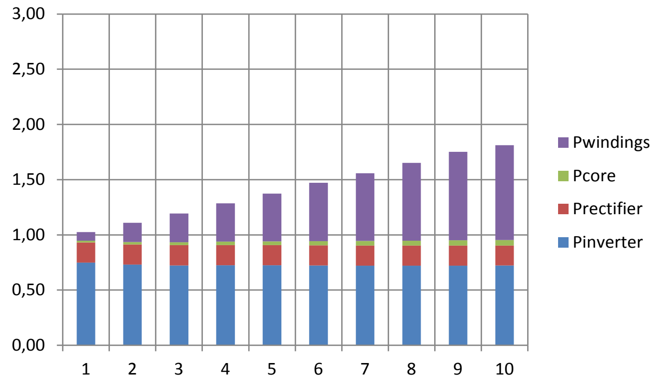

Fig. 40 SRC2-No saturation

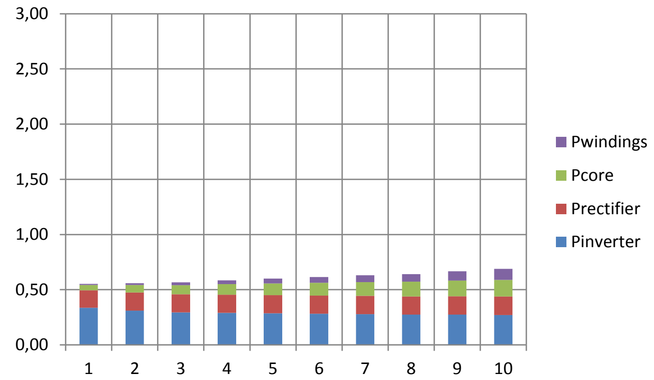

Fig. 41 SRC3-Pulse Removal

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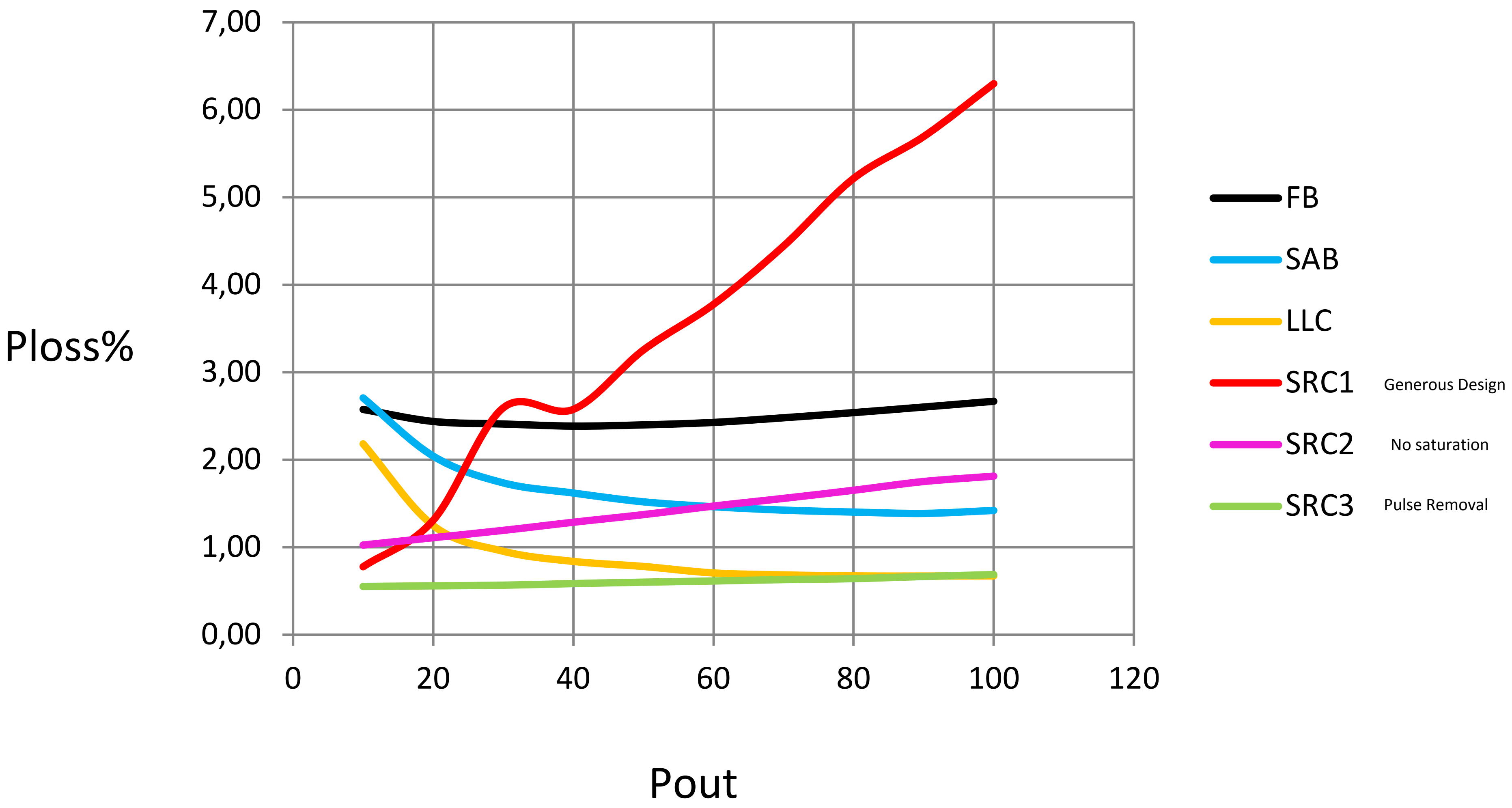

*SRC1-Generous Design: Transformer designed for 200hz. Operational range: 0.2 – 1.0pu
*SRC2-No saturation: Transformer design so Vin/Vou’=2. Tank on primary side
*SRC3-Pulse removal: Tank on secondary side and pulse removal

Fig. 42 Loss comparison of all topologies

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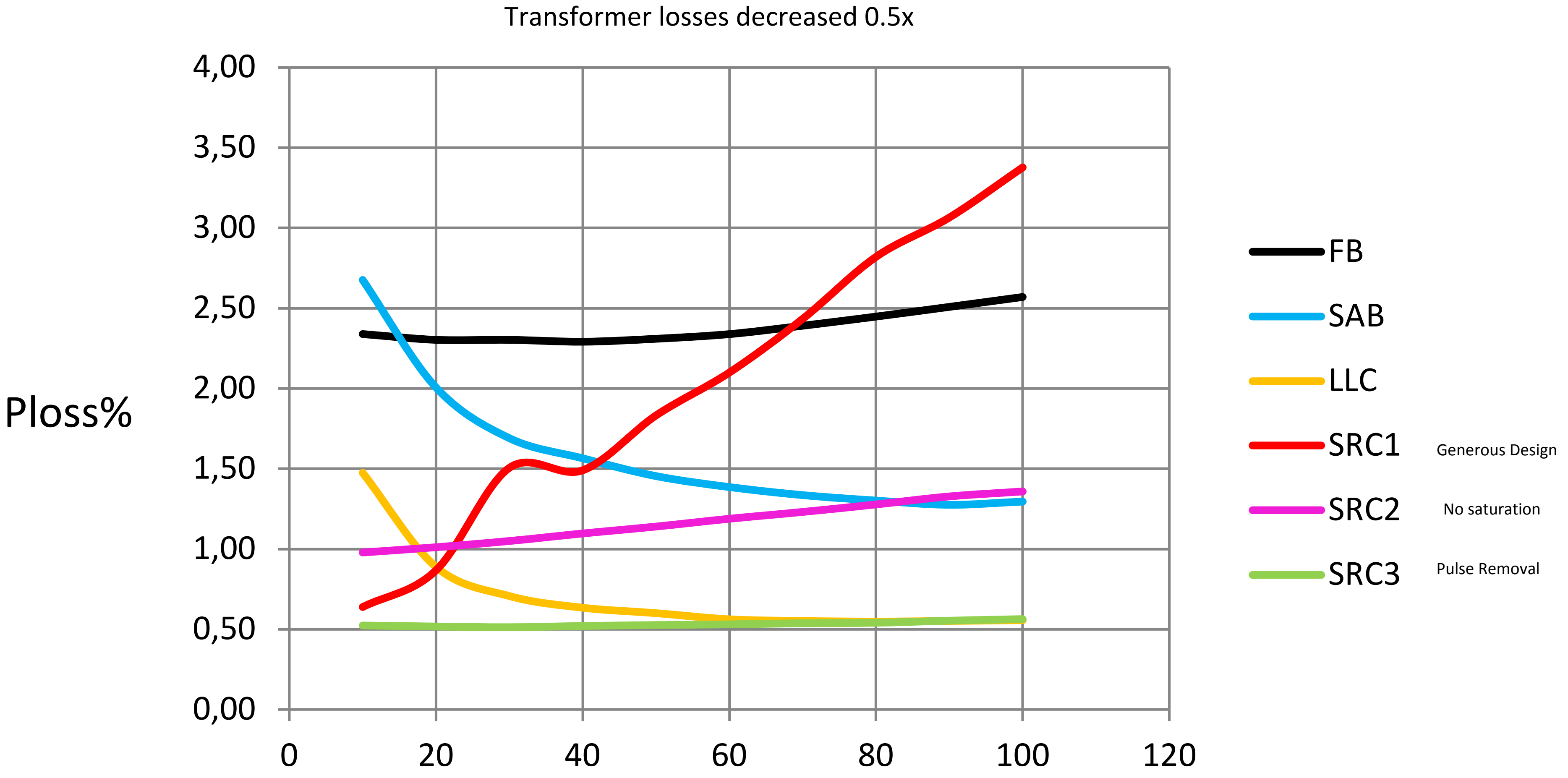

*SRC1-Generous Design: Transformer designed for 200hz. Operational range: 0.2 – 1.0pu
*SRC2-No saturation: Transformer design so Vin/Vou'=2. Tank on primary side
*SRC3-Pulse removal: Tank on secondary side and pulse removal

Fig. 43 Loss comparison of all topologies with transformer losses decresed 0.5x

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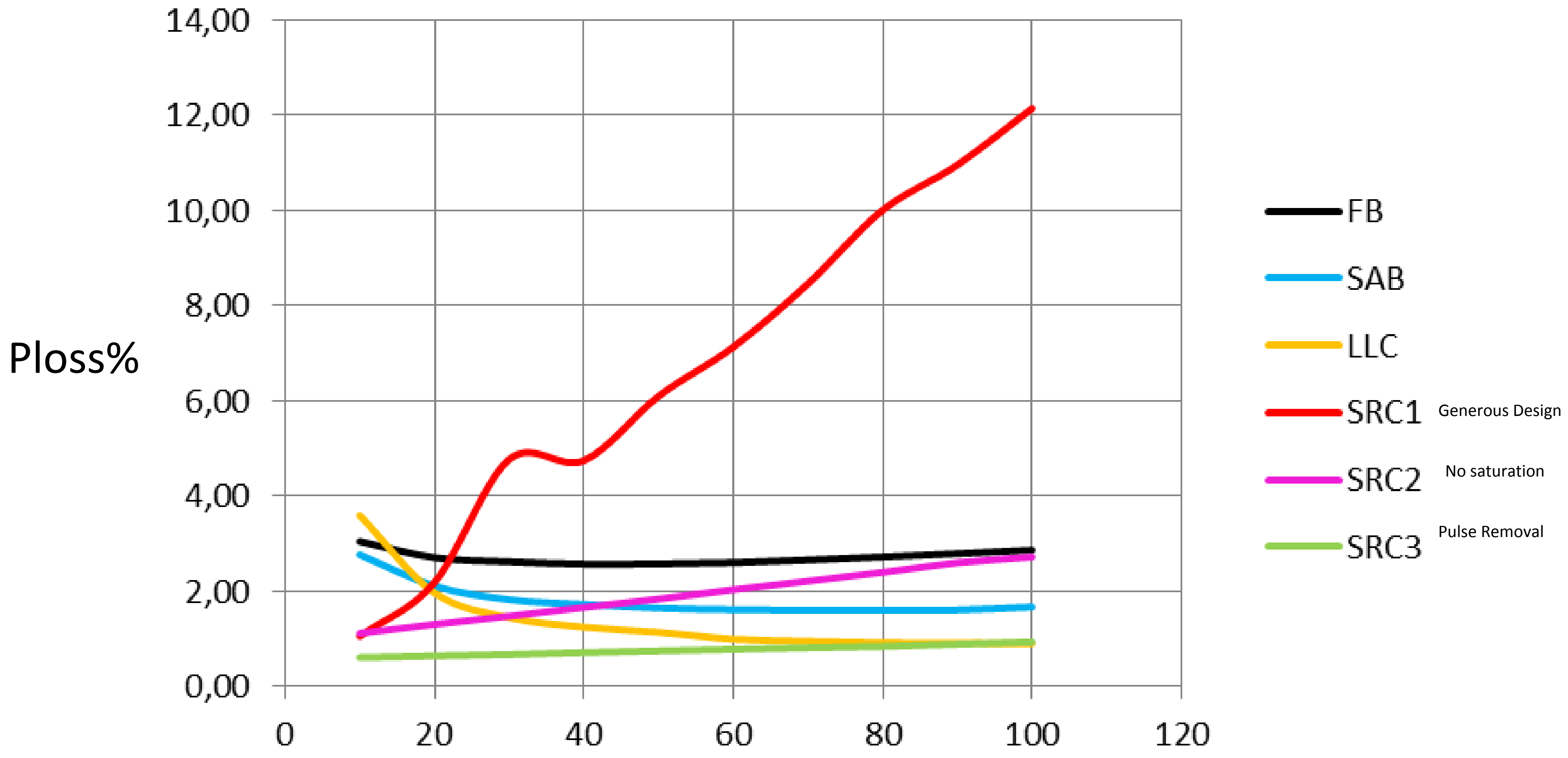
Transformer losses increased 2x



*SRC1-Generous Design: Transformer designed for 200hz. Operational range: 0.2 – 1.0pu
*SRC2-No saturation: Transformer design so Vin/Vou'=2. Tank on primary side
*SRC3-Pulse removal: Tank on secondary side and pulse removal

Fig. 44 Loss comparison of all topologies with transformer losses increased 2x

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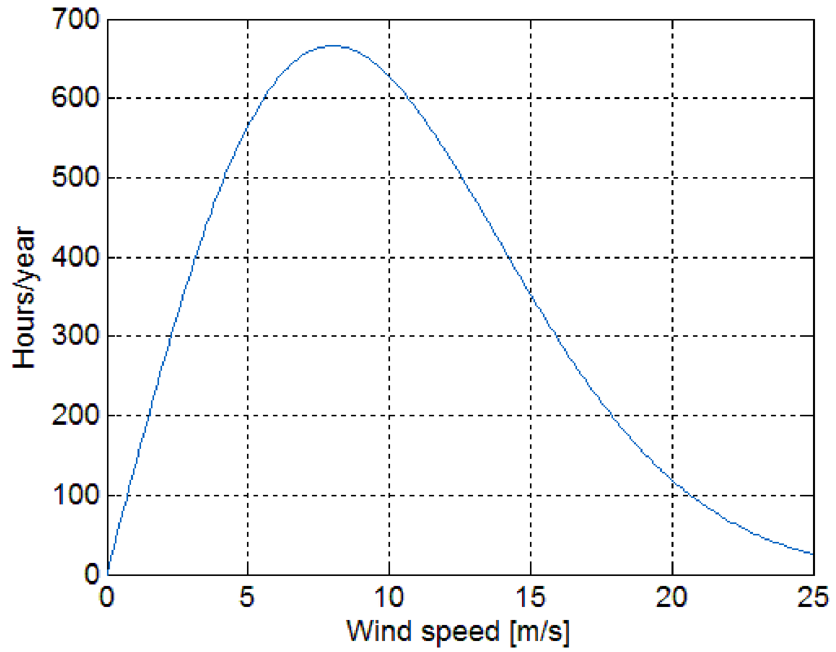

Fig. 45 Probability density of a typical offshore location

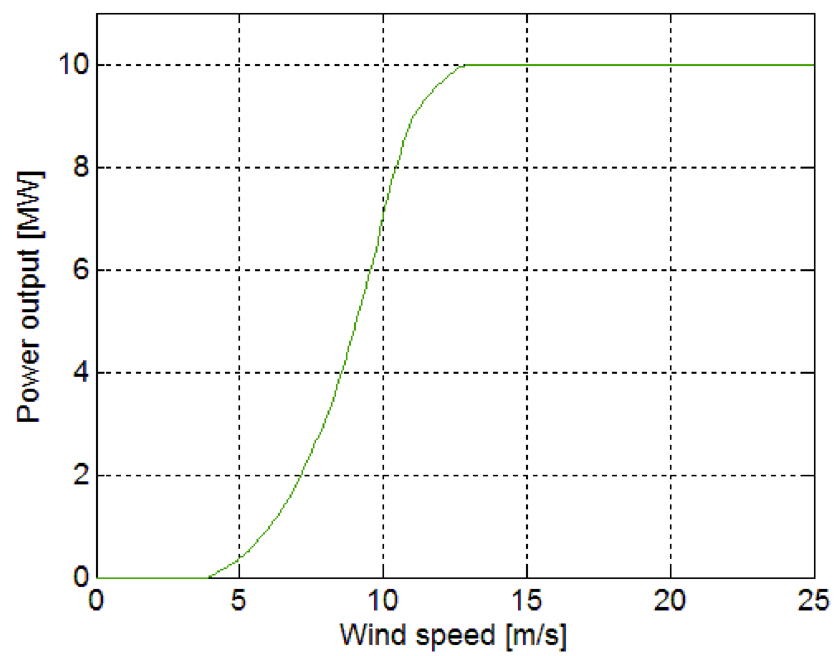

Fig. 46 Power output curve for 10MW turbine

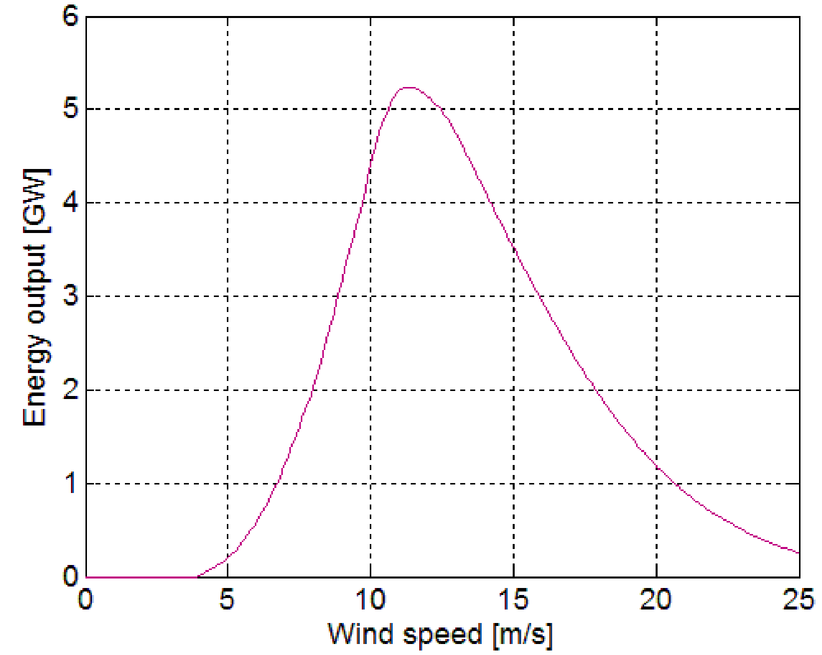

Fig. 47 Energy output for 10MW Turbine

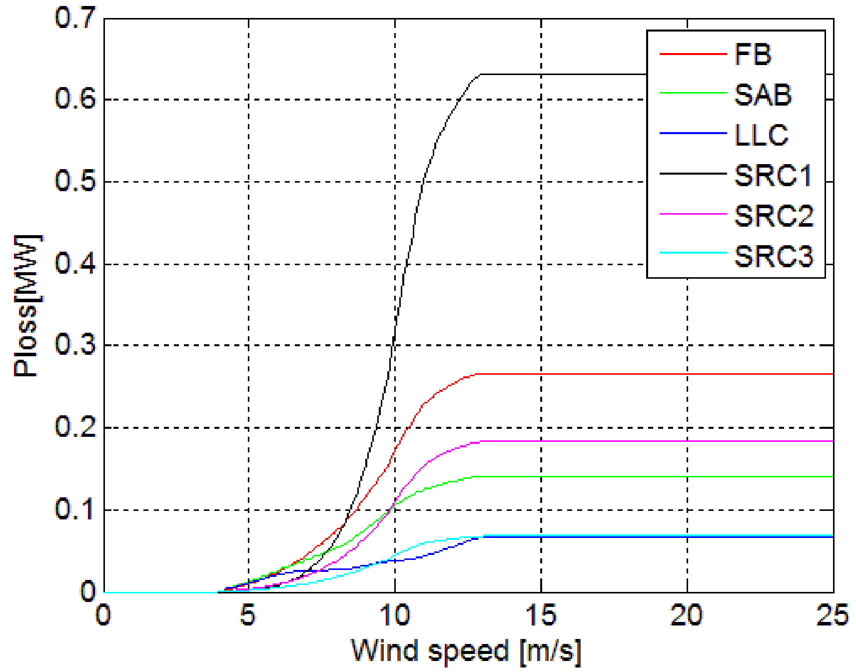

Fig. 48 Losses in absolut value

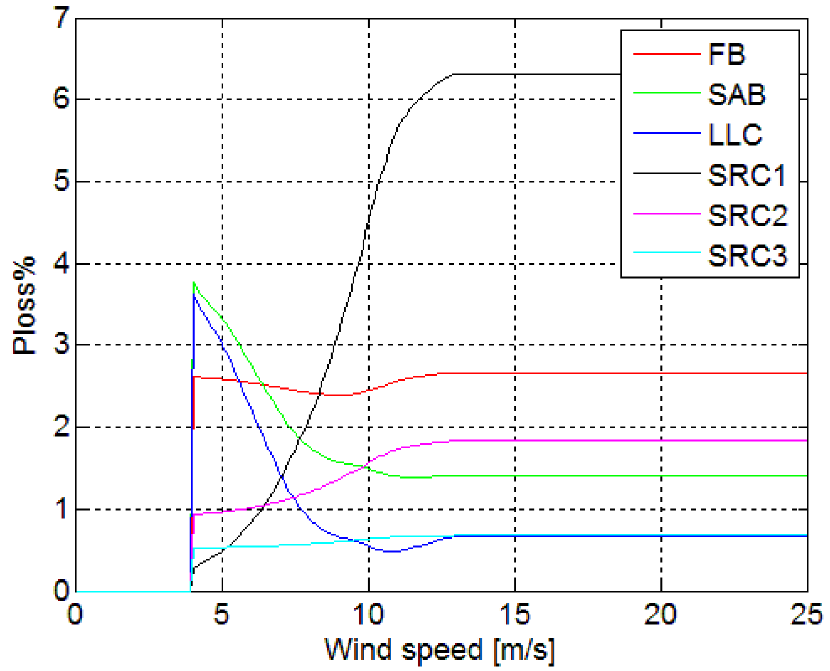

Fig. 49 Losses in percentage

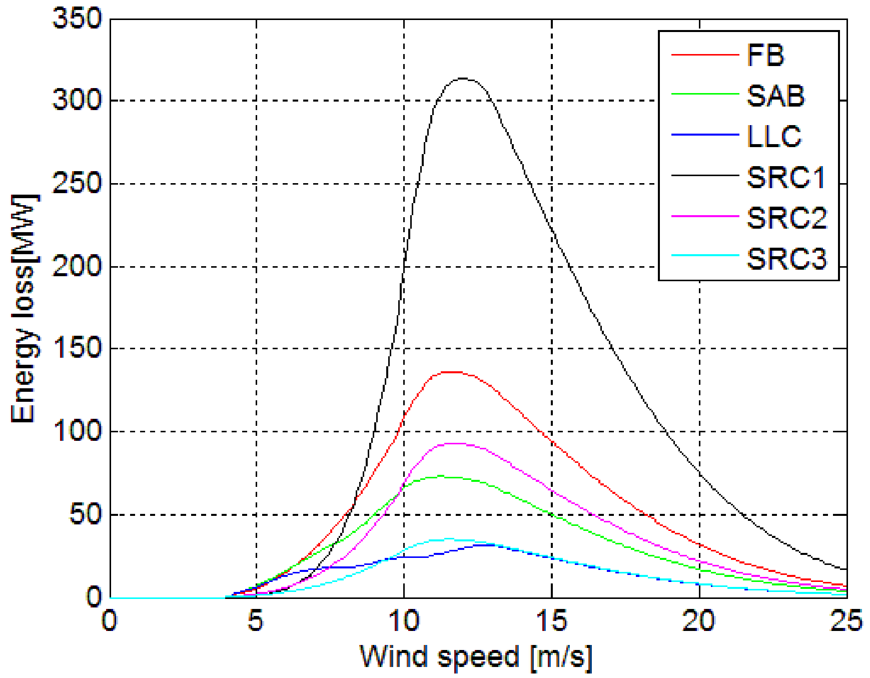

Fig. 50 Annual energy loss distribution

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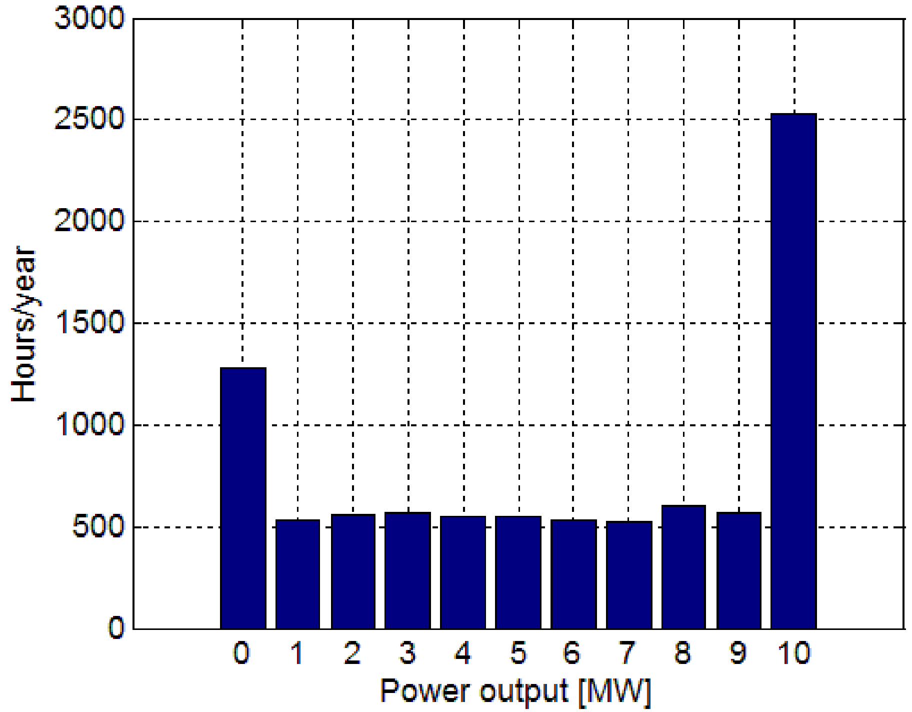

Fig. 51 Power output vs hours distribution

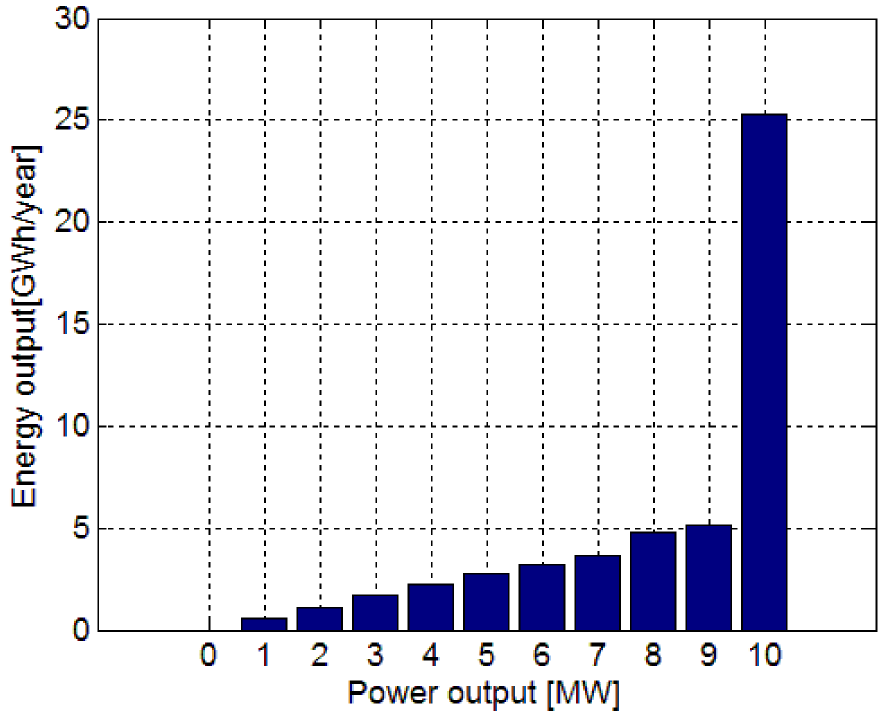

Fig. 52 Power Output vs Energy output

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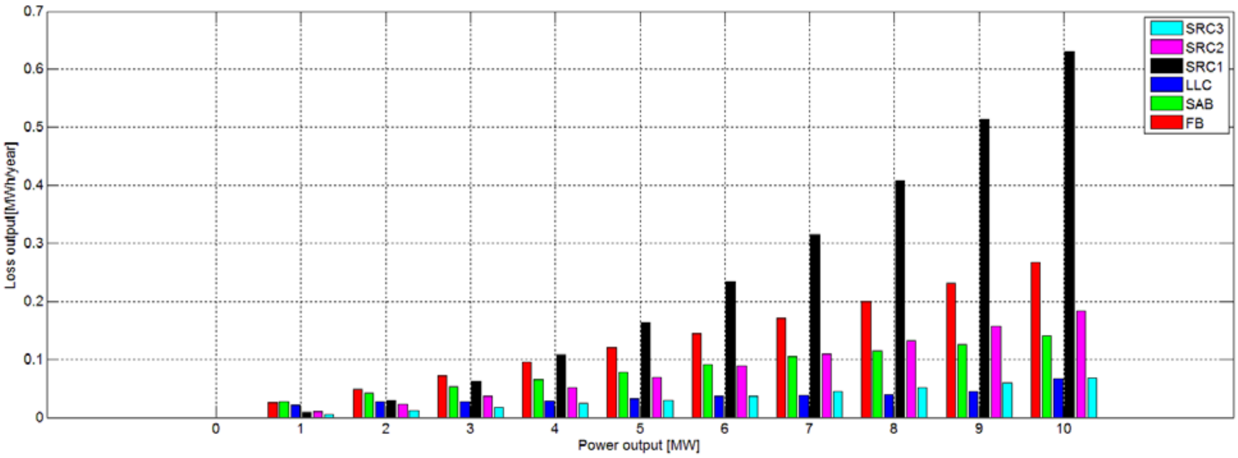

Fig. 53 Power output vs Losses

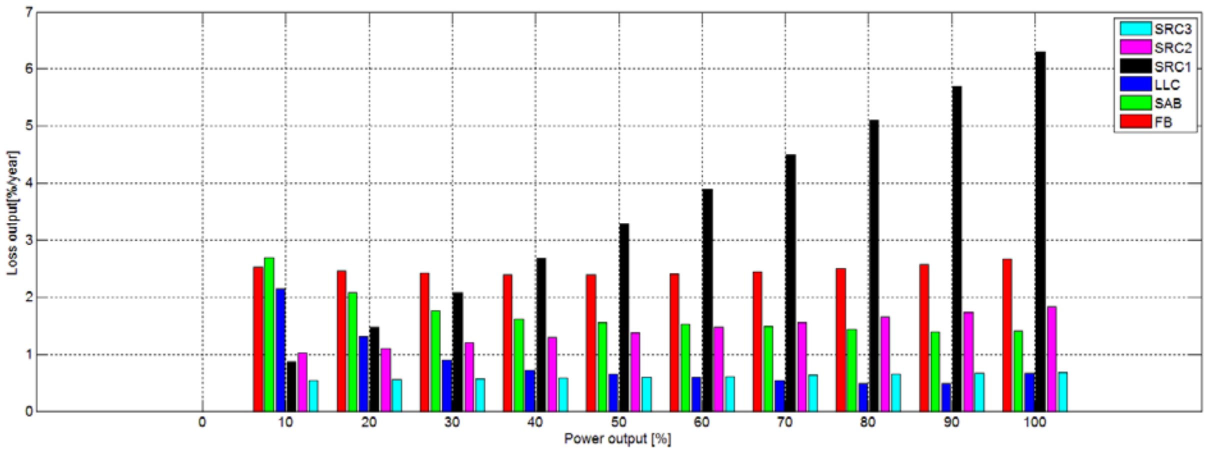

Fig. 54 Power output vs losses %

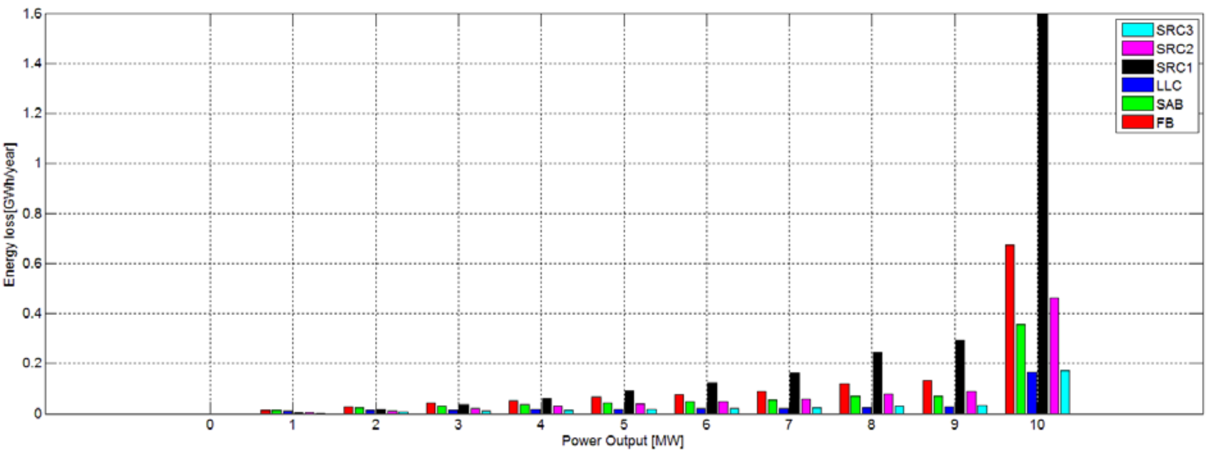

Fig. 55 Power output vs energy loss

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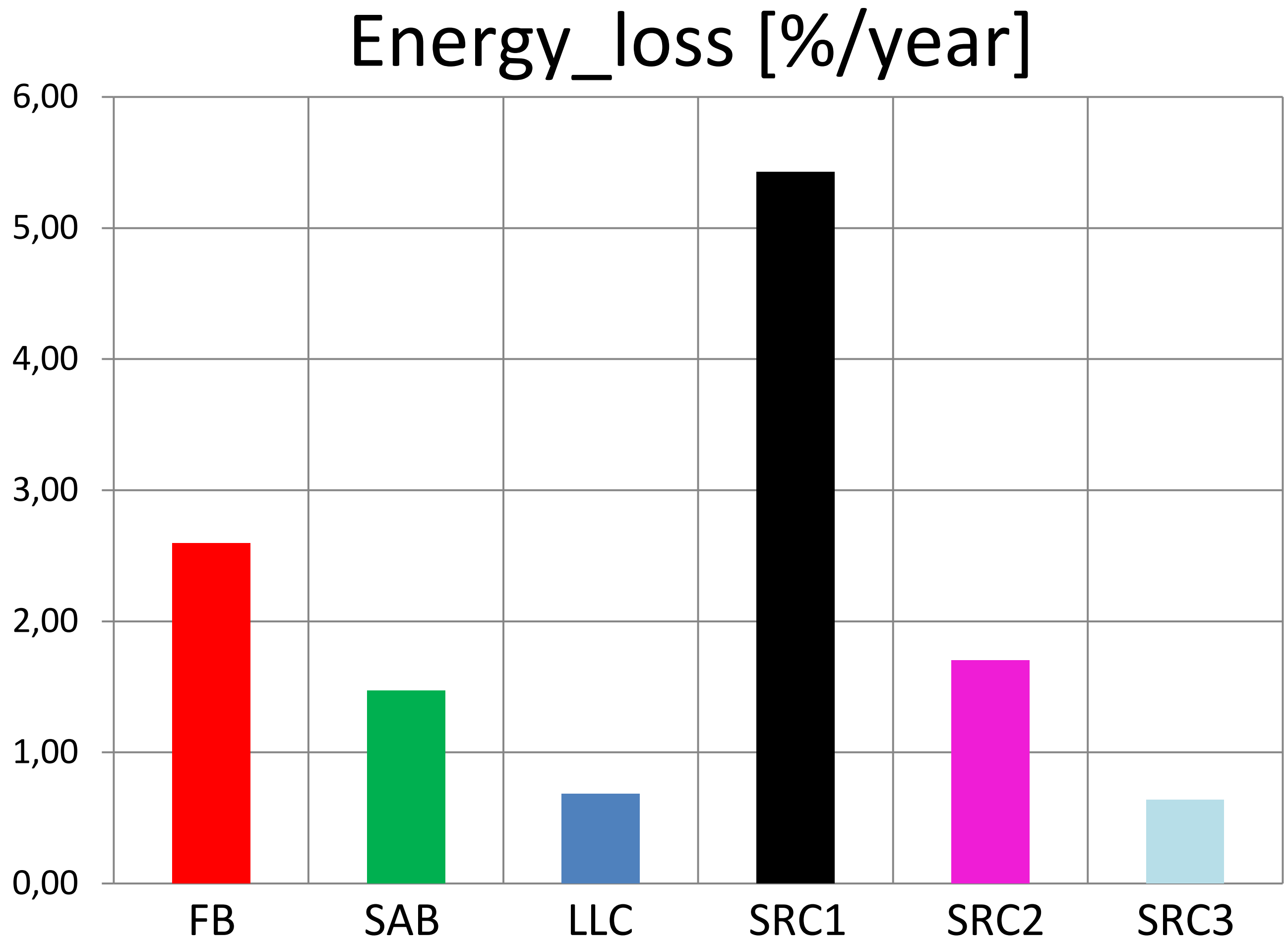

Energy_production = 47 [GW/year]

Fig. 56 Annual energy loss

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An optimal topology from efficiency point of view should take in account the yearly profile of energy losses, rather than minimizing the losses at a specific operating point. In Fig. 45 the probability density of a typical offshore location is shown [1]. The dependency of the output power on the wind speed is presented in Fig. 46. Assuming 100% availability for the wind turbine, the annual WPP energy distribution is depicted in Fig. 47. Energy distribution is a product of the Weibull probability density function and the turbine output power related to the wind speed. The annual energy production is found by integrating the area beneath Fig. 47. 47 GWh/year should be produced by a 10MW turbine. Loss functions for every topology are presented in absolute and percentage values in accordance to the wind speed, in Fig. 48 and Fig. 49. Distribution of annual energy losses for every topology is presented in Fig. 56. Finally, after integrating the area beneath every curve from Fig. 56, total yearly energy loss for every topology is presented in Fig. 56.

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5.6 Conclusion on loss comparison

- The topology with the highest losses (6.3%) at 1pu output power is SRC1. Even if semiconductor losses are 0.44% due to ZCS and low turn off losses and very low reverse recovery, the higher number of primary and secondary windings will lead to a higher number of layers. Proximity effect is influenced by the square number of layers, leading to very high winding losses. Clearly, with this particular transformer design, the topology is not a good candidate.
- The hard switched Full Bridge converter experiences losses in the range of 2.6% in the whole operating area. Semiconductor losses are predominant while transformer losses are only 0.2%.
- SRC2 topology has losses in the range 1% to 1.8%, with mainly conduction and winding losses. The main cause is the current waveform, that has peaks close to 5pu and very high 3^{rd} and 5^{th} harmonics. The SAB has lower losses than SRC2 above 0.5pu output power
- LLC converter has losses smaller than 1% in the operational range 0.3pu to 1pu, while at low output power is around 2.2%
- SRC3 has the lowest losses in the range 0.1 to 1pu, with values between 0.55% and 0.7%.
- From losses point of view, SRC3 has the best performance in the range 0.1 to 1.0pu, followed by LLC converter and SAB
- Topologies like FB and SAB do have higher switching losses, but have almost the lowest losses on the transformer, beside SRC3

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5.7 Weight and Volume comparison

Determining the weight and volume in present assessment was possible for the medium frequency transformer. Assessing size of other components such as: inverter, rectifier, resonant tank, output filter is not so trivial and is also time consuming. Therefore, a different strategy is considered to determine converter weight and volume, where every unit/component is ranked with points. Final volume and weight are proportional to the number of points.

Following assumptions have been considered, based on the fact that exactly same number of IGBTs and diodes we're considered for every topology during loss analysis

- DC/AC converter has same weight and volume for all topologies. DC/AC=1pt
- AC/DC converter has same weight and volume for all topologies. AC/DC=1pt
- All topologies have the same weight and volume for output filter capacitor
- Except SRC1, MF transformer is considered to have same weight and volume for all other topologies. MF transformer=1pt
- Resonant inductor = 0.5pt and Resonant capacitor = 0.5pt, regardless of position
- Filter inductor = 0.5pt and Filter capacitor = 0.5pt.

No	Topology	DC/AC	LV Tank	MF transformer	MV tank	AC/DC	Filter inductor	Filter capacitor	Score
1	FB	1	0	1	0	1	1	0.5	4.5
2	SAB	1	0.5	1	0	1	0.5	0.5	4.5
3	LLC	1	1	1	0	1	0.5	0.5	5
4	SRC1	1	1	3	0	1	0.5	0.5	7
5	SRC2	1	1	1	0	1	0.5	0.5	5
6	SRC3	1	0	1	1.5	1	0.5	0.5	5.5

Discussions:
1. SRC1 has the largest volume and weight, due to a transformer 3 times larger then other topologies
2. FB and SAB will have the smallest volume and weight as no resonant capacitor are employed
3. LLC, SRC2 have the same volume and weight, larger than FB and SAB
4. SRC3 will pay a penalty on placing the resonant cap on MV side. Volume is expected to increase by 50% due to higher volume and mechanical complexity
5. The difference between FB , SAB and LLC,SRC3 will decrease if it's considered that the cooling system for the first two should be designed for higher losses, occupying thus more volume and weight.

A comparison of the topologies, based on their breakdown of components is presented on following page:

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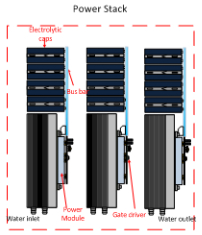
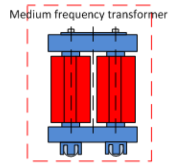
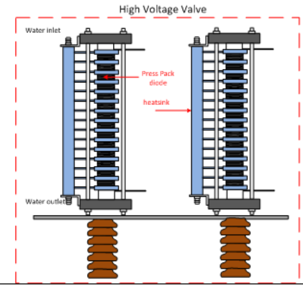
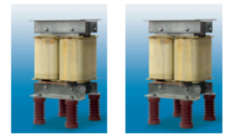
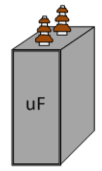
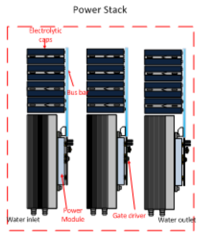
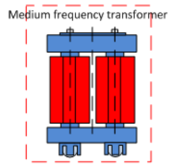
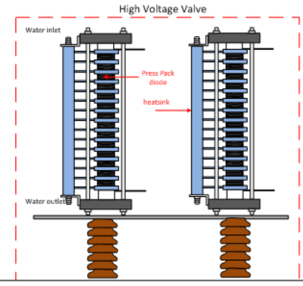
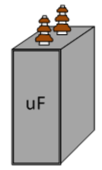
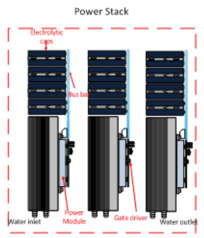
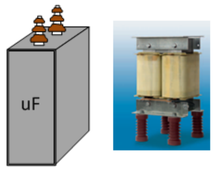
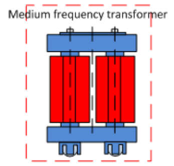
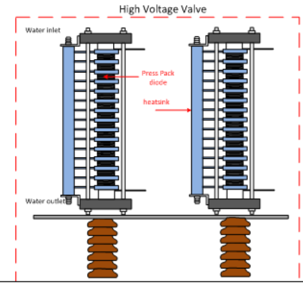
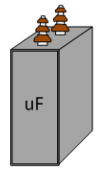
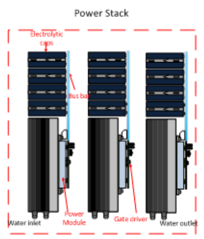
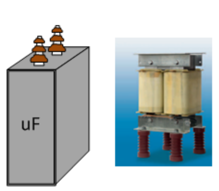
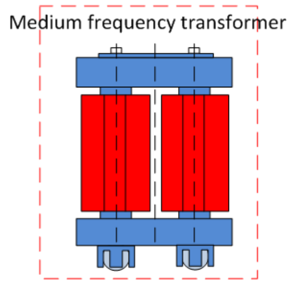
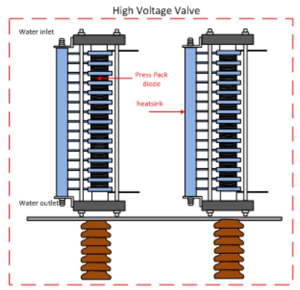
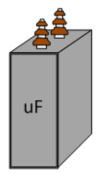
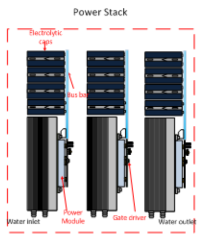
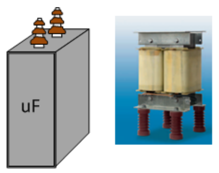
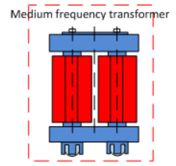
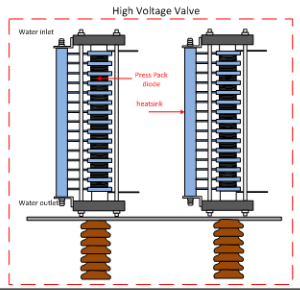
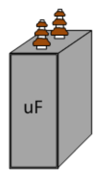
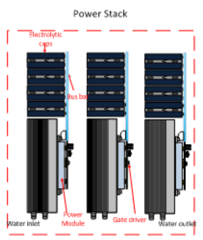
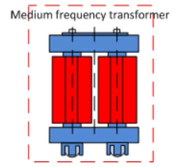
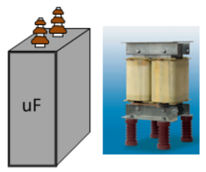
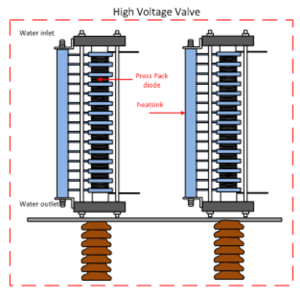
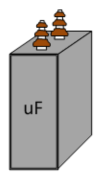
	DC/AC	Tank	MF Trafo	Tank	AC/DC	Filter Inductor	Filter Capacitor
FB							
SAB							
LLC							
SRC1							
SRC2							
SRC3							

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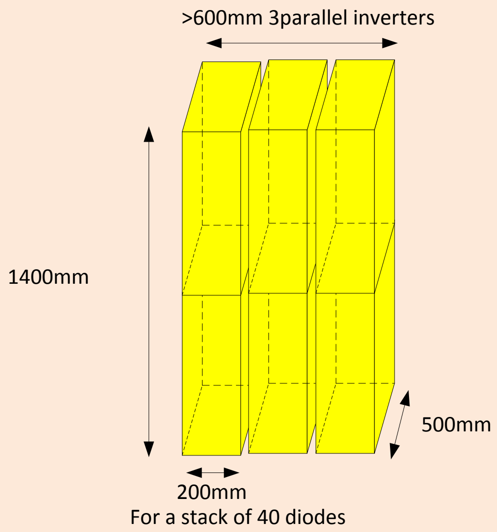
Preliminary Dimensions

Low Voltage Inverter

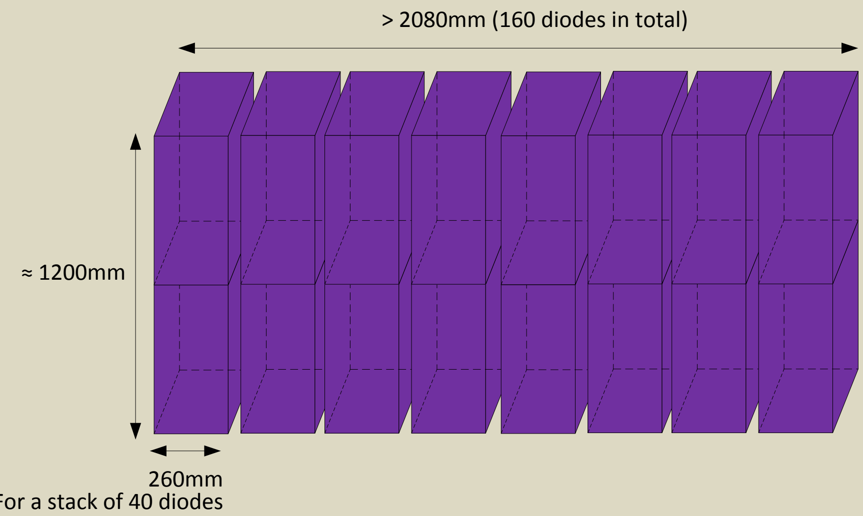


Inspiration

- Infineon power stacks
http://www.infineon.com/dgdl/Infineon-6MS30017E43W34404-DS-v02_01-en.pdf?fileId=db3a3043382e83730138958b66eb1660

- Semikron power stacks
https://www.semikron.com/dl/service-support/downloads/download/semikron-datasheet-sks-b2-140-gd-69-12-u-ma-pb-08800564

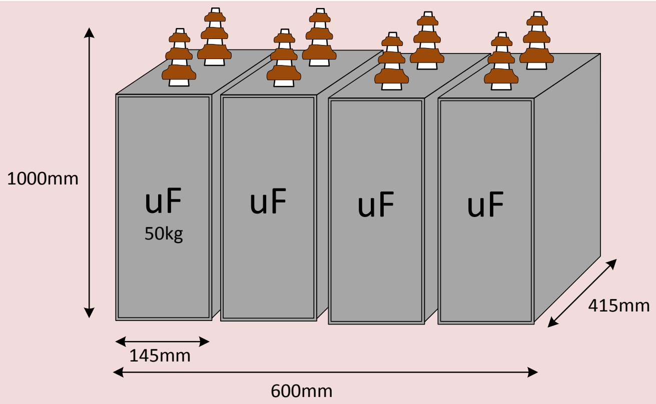
Medium Voltage Rectifier



Inspiration

- Westcode 10kV System Rectifier Valves
http://www.westcode.com/publicity/prod_lit/pub2.pdf

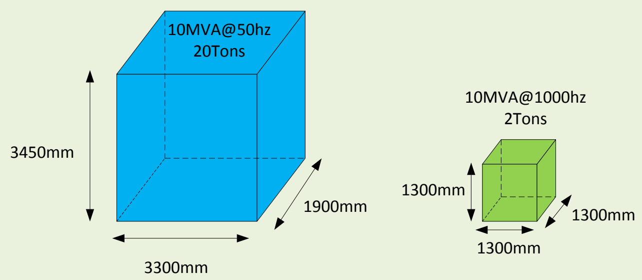
Resonant capacitor tank



Inspiration

-Electronicon medium voltage capacitors
http://www.electronicon.com/en/products/medium-voltage-components/medium-voltage-capacitors/e90-msdtm/

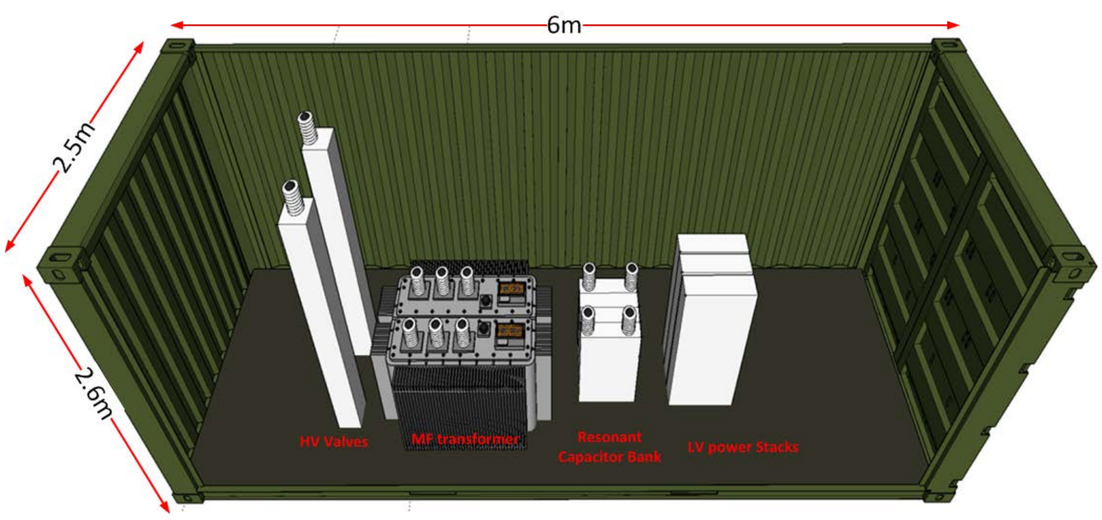
Medium Frequency Transformer



Inspiration

-Siemens 50hz dry cast and oil transformers. Increasing frequency to 1000hz would results in 10x core reduction
http://www.energy.siemens.com/hq/pool/hq/power-transmission/Transformers/Distribution%20Transformers/Oil-filled%20Distribution%20Transformers/Brochure-Liquid-immersed-distribution-transformers-to-13MVA_EN.pdf

Converter dimensions compared to a standard container



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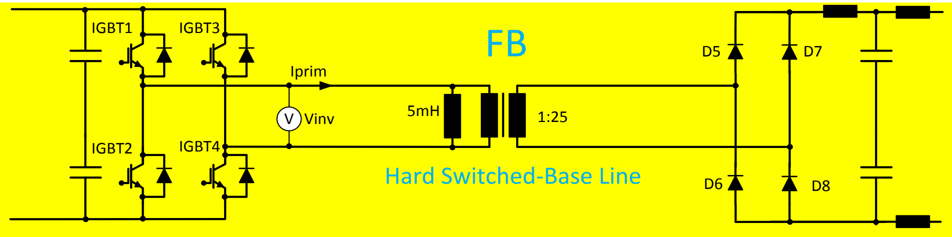
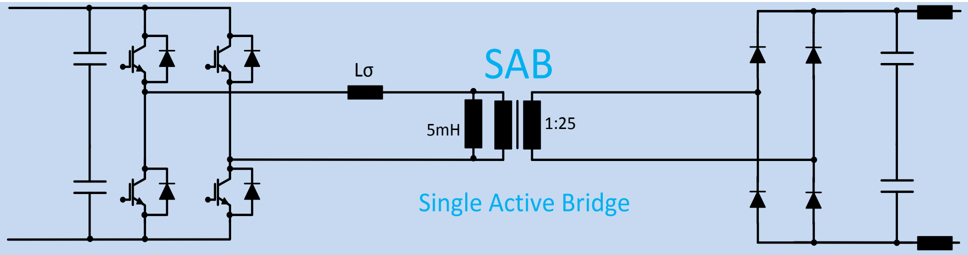
5.8 Advantages and disadvantages of selected topologies



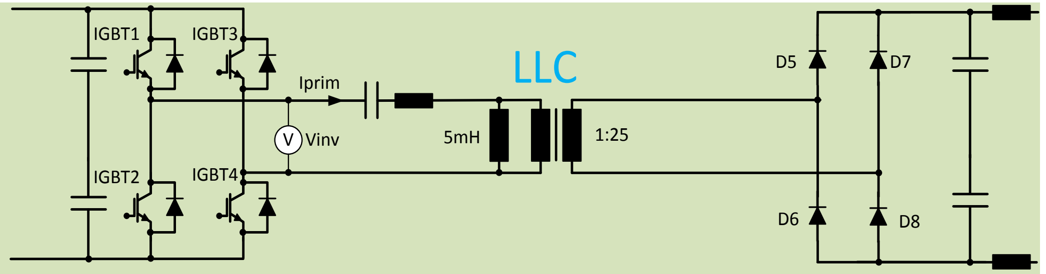
Advantages
1. Constant frequency
2. Low transformer weight
3. Low transformer volume
4. Full operational range
5. Simple control

Disadvantages
1. Highest turn on losses
2. Highest turn off losses
3. Highest reverse recovery losses
4. Requires bulky inductor on MV side
5. Requires more power for cooling semiconductors



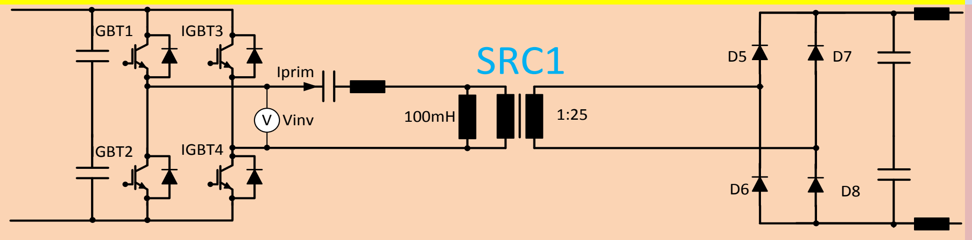
Advantages
1. Constant frequency
2. Low transformer weight
3. Low transformer volume
4. Full operational range
5. ZVS turn on
6. Simple control

Disadvantages
1. High turn off losses
2. Difficult to achieve precise leakage inductance if it's incorporated inside the transformer
3. Requires more power for cooling semiconductors



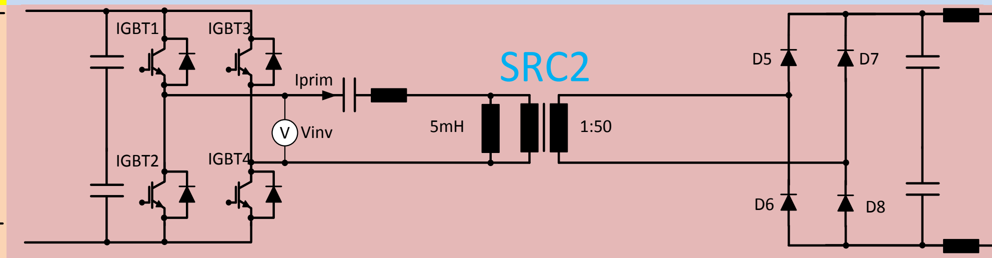
Advantages
1. Constant frequency
2. Low transformer weight
3. Low transformer volume
4. Full operational range
5. ZVS turn on
6. Low turn off losses
7. Very low reverse recovery

Disadvantages
1. Open loop control
2. Highest core losses



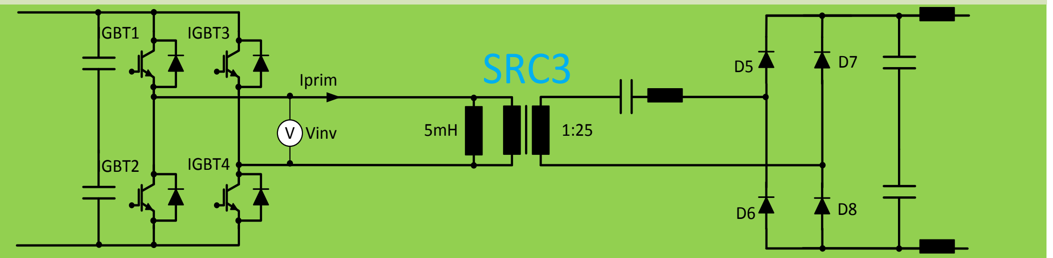
Advantages
1. Lowest semiconductor losses
2. ZCS at turn off
3. No reverse recovery
4. Requires small power for semiconductor cooling

Disadvantages
1. Variable frequency control
2. Largest transformer weight
3. Largest transformer volume
4. Operational range limited to 0.2
5. Highest winding losses
6. Largest cooling system for transformer



Advantages
1. No transformer saturation
2. Low transformer weight
3. Low transformer volume
4. Full operational range
5. Very low reverse recovery

Disadvantages
1. Variable frequency control
2. Highest conduction losses
3. Highest IGBT conduction stress
4. Requires more power for cooling semiconductors



Advantages
1. No transformer saturation
2. Full operational range
3. Very low reverse recovery
4. ZVS turn on
5. Low turn off losses
6. Requires small power for semiconductor cooling

Disadvantages
1. Variable frequency control
2. Tank on secondary side. Requires higher clearance and creepage distance, increases final volume. ESR increases with number of series connected devices, plus extra complexity due to snubbers and different leakage current. Active balancing is required.
3. Risk of transformer saturation due to vols-second unsymetri

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5.9 Ratings

- If following assumptions are considered:
    - the IGBTs are able to withstand larger currents then datasheet values, during conductions states
    - with proper designed cooling system, more heat can be dissipated on the same IGBT
- Exactly the same number of IGBTs and Diodes can be used in all topologies, rated for the same voltage and current levels
- Resonant tanks are rated for LLC, SRC1,SRC2 for 2pu
- Resonant tank for SRC3 is rated for 10pu
- The difference in current and voltage waveshapes for SRC2 will drive different silicon area and different MV capacitor ratings. For the moment this is neglected.
- Output filters are rated for exactly the same specifications for all topologies

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6. Decision

In order to make the decision and increase confidence, the Pugh Matrix will be employed. The most important criteria in the decision are chosen and the alternatives are compared using these criteria. Typically, a Pugh Matrix is used to evaluate various alternatives against a baseline.

The baseline is the Hard Switched Full Bridge converter. 5 criteria (availability, efficiency, ratings, repair cost, power density) are considered with their corresponding weight.

Instead of using a 3 point scale (+1-better, 0-the same, -1 – worser) a 5 point scale will be used. For example:

+2-much better than

+1-better than

0-equal to

-1-worse than

-2-much worse than

Example:

Criteria efficiency has a weighting number of 4. So all the numbers to the right of it are multiplied by 4.

SAB has better efficiency than the FB, so it will receive +1 * 4=4. The LLC has a much better efficiency than the FB, so it will receive +2 * 4 =8.

Availability, ratings and repair costs are considered to be the same for all topologies. Final Pugh Matrix is presented below:

Concept / Criteria	Base line(FB)	Weight	SAB	LLC	SRC1	SRC2	SRC3
Availability	0	5	0	0	0	0	0
Efficiency	0	4	+4	+8	-8	+4	+8
Ratings	0	4	0	0	0	0	0
Repair costs	0	2	0	0	0	0	0
Power density (volume and weight)	0	1	0	-1	-2	-1	-1
Σ+			+4	+7	-10	+3	+7

Conclusion:

LLC and SRC3 have the highest score, followed by the SAB, SRC3, while SRC1 gets the lowest number of points.

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7. Conclusions

- First, topologies that are not suitable for this application are discussed below:
  - Even if the FB has one of the lowest weight, volume and transformer losses, due to hard switching at turn on and turn off, the topology is not suitable for this application. Losses at 1pu are >2.5%
  - Even if the SRC1 has the lowest semiconductor losses, due to the bulky transformer, designed for 200hz and operated at 1000hz, it has the heighest losses, volume and weight. Losses at 1pu are>7%. The topology variant is not suitable for this application
- SRC2 is able to operate with frequency control in full operational range and losses <2%. But, above 0.5pu output power, it turns out that the SAB will have lower losses, making thus this topology also not suitable. Due to higher transformer turns ratio, primary current waveforms will lead to IGBT and conductions losses 3 times higher then the other topologies. Also, the current waveforms exhibits very high rms currents for 3rd and 5th harmonics, leading to higher winding losses
- Remaining topologies for selection are : SAB, LLC and SRC3. From these 3, the SAB has the highest losses(due to turn off losses), but it requires the smallest volume and weight and has very simple control
- LLC and SRC3 have very similar losses, < 0.6% in full operational range. LLC runs in open loop, at constant frequency and 50% duty cycle. Even if the topology is proven in traction application, for dc wind turbines it's not sure it will behave similar, due to different functionality and fault scenarios
- Finally, the SRC3 is able to operate in full operational range, with very small losses (<0.6%), no transformer saturation. The main disadvantage is the location of the resonant tank. Considering that it is energy that rates resonant components and that same energy is used despite of tank location, the increased voltage ratings will lead to higher insulation, clearance and creapage distances. On MV side, it is expected more capacitors will be connected in series, increasing total ESR, snubber complexity and voltage balancing circuits. Differences in tolerances and leakage currents will probably require high engineering complexity. The MV side inductor will lead to a bulky magnetic component, while the capacitor will require a relative small amount of Faradz and it's still not sure how the output secondary stray capacitance will interact with the resonant tank.
- **Therefore, considering advantages and disadvantages, SRC3 is considered a preferred topology, followed by LLC and the SAB. FB, SRC1 and SRC2 are not suitable for this application.**

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8. Appendix

Following topics have been covered in the appendix:

8.1 Semiconductor loss model

8.2 Transformer loss model

8.3 Hard Swiched Full Bridge Converter Principal Waveforms

8.4 Singe Active Bridge Principal Waveforms

8.5 LLC Converter Principal waveforms

8.6 SRC1 Converter Principal waveforms

8.7 SRC2 Converter Principal waveforms

8.8 SRC3 Converter Principal waveforms

8.9 Flux saturation impact on current

8.10 SRC1 Windings loss penalty

8.11 MF Transformer Design and Loss calculation

PLECS simulation models are located under:

\\et.aau.dk\fileshares\DC_distribution\PhD_projects\CGD High Power Medium Voltage DCDC\8. selection report\1.PLECS models

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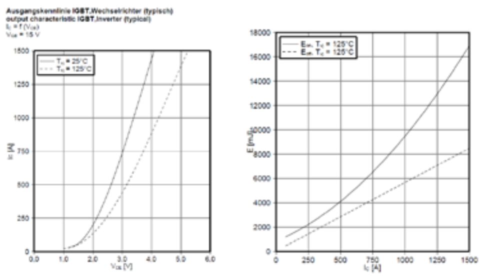
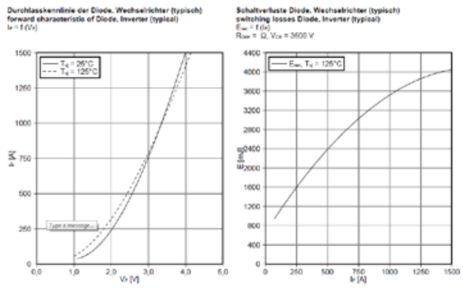
8.1 Semiconductor loss model

Following devices have been used: Infineon IGBT – power module FZ750R65KE3 and Infineon Diode –power module DD750S65K3. Their corresponding conduction, switching and recovery characteristics are presented below:





IGBT FZ750R65KE3

Diode DD750S65K3

Conduction losses

For modeling the losses, [2] and [3] have been used as references. Same methodology has been followed in this report. For both IGBT and diode, output characteristics are present in the data sheet. In case of the IGBT, output current Ic is multiplied with the according voltage Uce directly in the datasheet to get the conduction power loss Pcond. The advantage is the the curves can be approximated with 2nd order polynomial fitting curves. For the present loss model, conduction losses equation was set up temperature-independent for the highest acceptable temperature, e.g. T=125°C. Derived conduction loss function for the IGBT and Diode are shown in Fig. 43 and Fig. 44

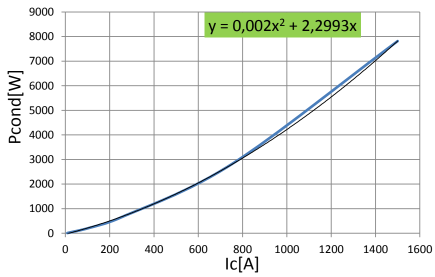


Fig. 57 IGBT Conduction loss

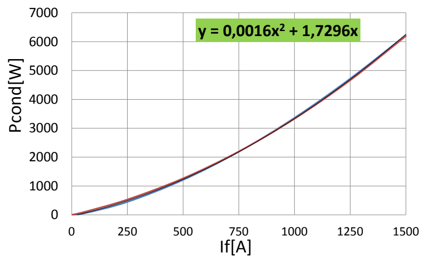


Fig. 58 Diode Conduction Loss

Switching losses

Based on data sheet data, switching losses (turn-on, turn-off and recovery) can also be approximated by a second-order polynomial fitting curve. As discussed with conduction losses, they are considered for a maximum junction temperature Tj = 125°C.

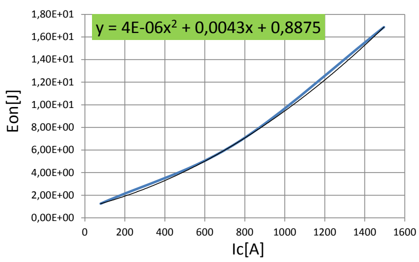


Fig. 59 IGBT Turn-on loss

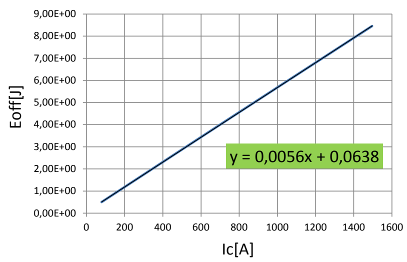


Fig. 60 IGBT Turn-off loss

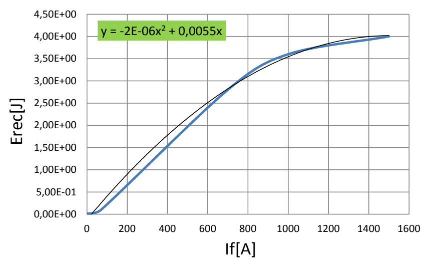


Fig. 61 Diode Reverse recovery loss

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The implementation of the scheme calculating the conduction and switching losses for both IGBT and diode is shown in Fig. 48 and Fig. 49.

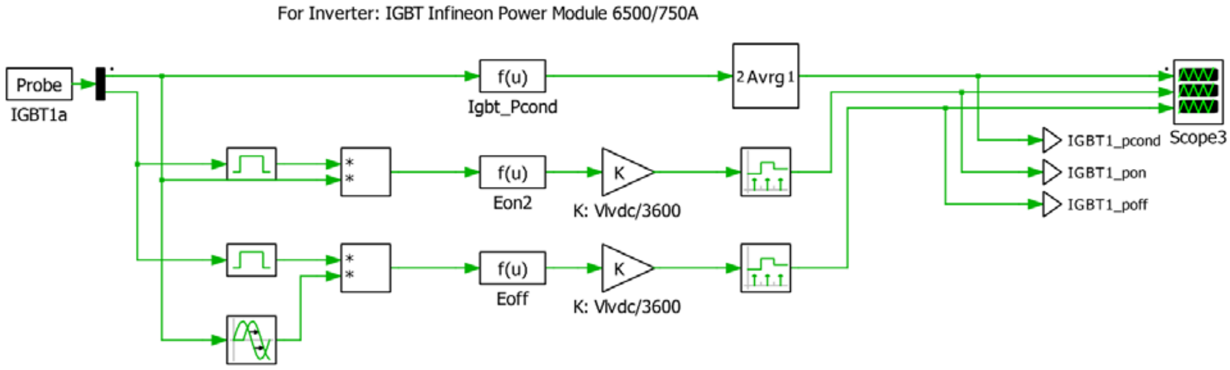

Fig. 62 IGBT loss model

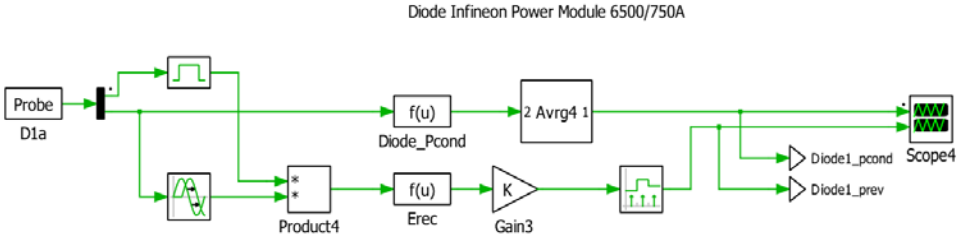

Fig. 63 Diode loss model

By applying the actual current through the device to the 2nd order polynomial curve, the time behavior of the conduction loss Pcond can be directly calculated, while the simulation is running. For switching losses, the current is sampled only at turn on and turn off behavior.

Fig. 50 shows an example of IGBT loss calculation. Conduction losses are averaged for one switching cycle, while turn on and turn off losses are fed through a Periodic Impulse Average block, which has an averaging time of 100ms. The block periodically averages Dirac impulses over the specified time and the output is updated at the end of each averaging period.

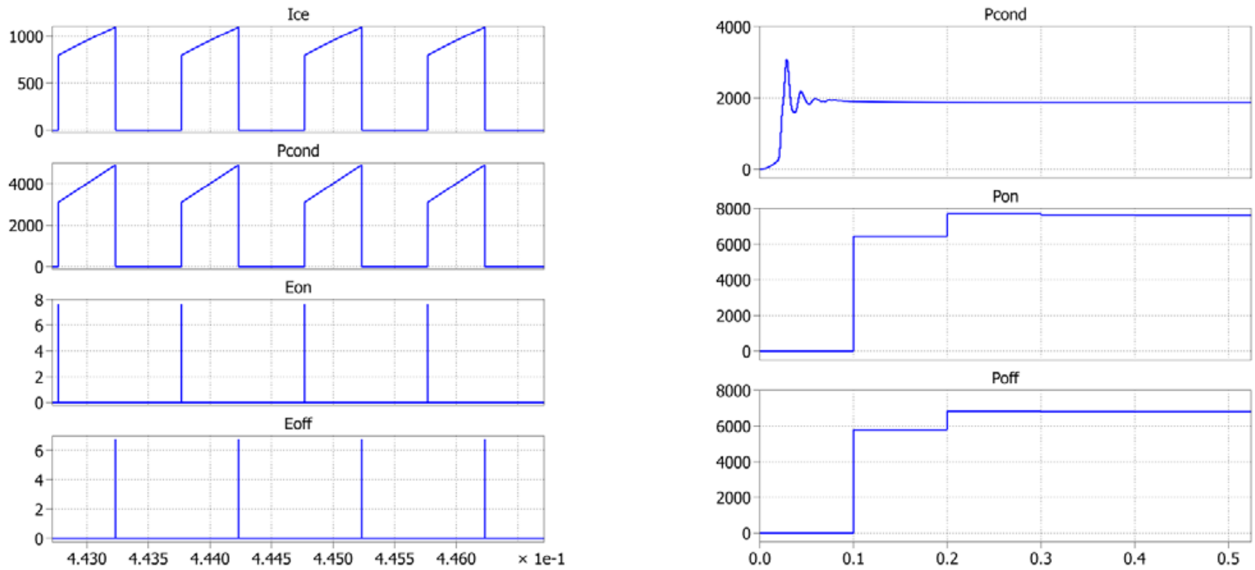

Fig. 64 Example of IGBT loss calculation

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8.2 Transformer loss model

For calculating the transformer losses, [4], [5] and [6] have been used and their methodology was implemented.

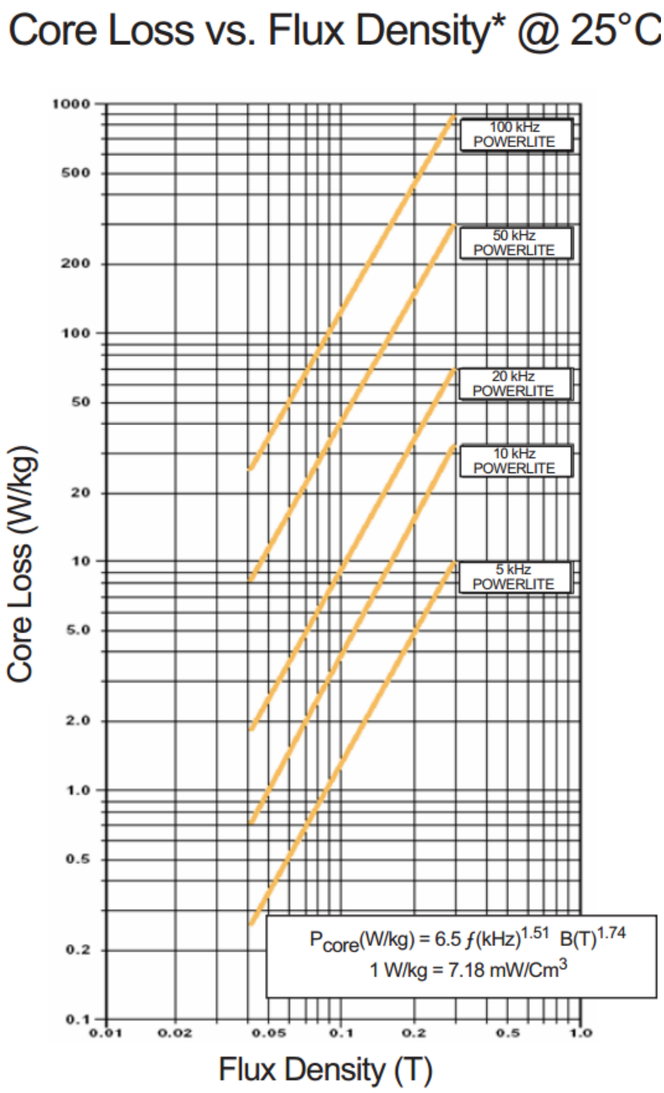
Core losses

For calculating core losses (P_V), based on above reference's recommendations, the *Improved Generalized Steinmetz Equation IGSE* was employed. This method is an improved equation of the the empirical method normally used to calculate core losses in transformers, the *Original Steinmetz Equation OSE,* which is basically a curve fitting expression of measured data under sinusoidal excitation. The corresponding equations of OSE and IGSE are presented below:

OSE: $P_V = K \cdot f^{\alpha} \cdot B_m^{\beta}$, where *K, α and β* are normally provided by the manufacturer

IGSE: $P_V = 2^{\alpha+\beta} \cdot k_i \cdot f^{\alpha} \cdot B_{sq}^{\beta} \cdot D^{\beta-\alpha+1}$, where D is the square wave duty cycle.

For amorphous core material 2605SA1, losses are provided by the manufacturer for sinusoidal excitation link.



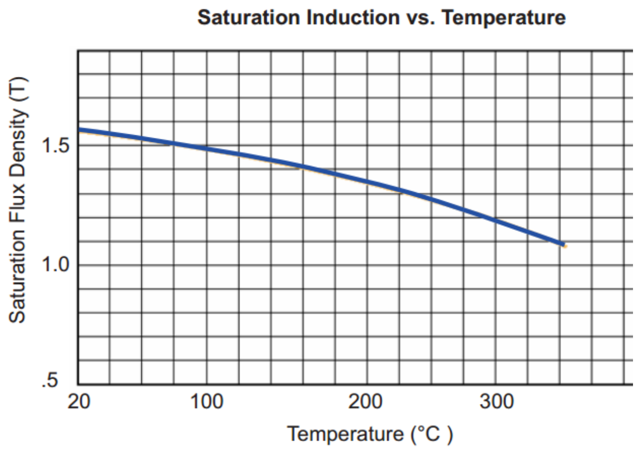


Fig. 65Core losses vs Flux Density (K=6.5,α=1.52,β=1.74)

Fig. 66 Saturation Induction vs Temperature

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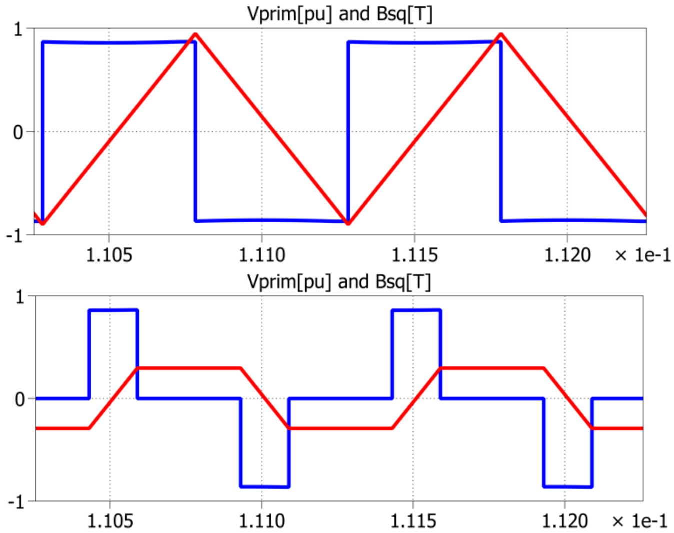
Acording to **IGSE** , flux density is dependent on the duty cycle. Therefore, when calculating core losses, it's important the use the actual Bsq, otherwise errors will be introduced.



$B_{sq} = \frac{1}{2}\frac{V_n}{NA_c}\left(\frac{T}{2} - T_0\right)$ with $T_0 = \Omega\frac{T}{2\pi}$,where Ω is the 0 voltage vector period.

Fig. 67 B influence of different duty cycles

For present core losses, α = 1.5, β = 1.6 and k_i = 2. Now, it's important to mention that these values should be evaluated based on transformer characterization measurements performed on an actual core. The values from here are taken from other phd works [7] and [8], which have done exactly the same thing on same core material.

Winding losses

In very simple terms, the winding losses are an expression of ac equivalent resistance and the rms current:

$$P_{winding} = R_{ac} \cdot I_{rms}^2$$

The equivalent ac resistance is dependent on the dc resistance of the wire and the so called Dowell factor:

$$R_{ac} = F_r \cdot R_{dc}$$

Now, the interesting part is that the Dowell factor is just an expression that specifies the influence of skin and proximity effects:

$$F_r = f(Skin\_effect, \Pr oximity\_effect)$$

Skin effect is a function of frequency and thickness of the winding, while proximity effect is a squared function of number of layers.

The final expression for winding losses is:

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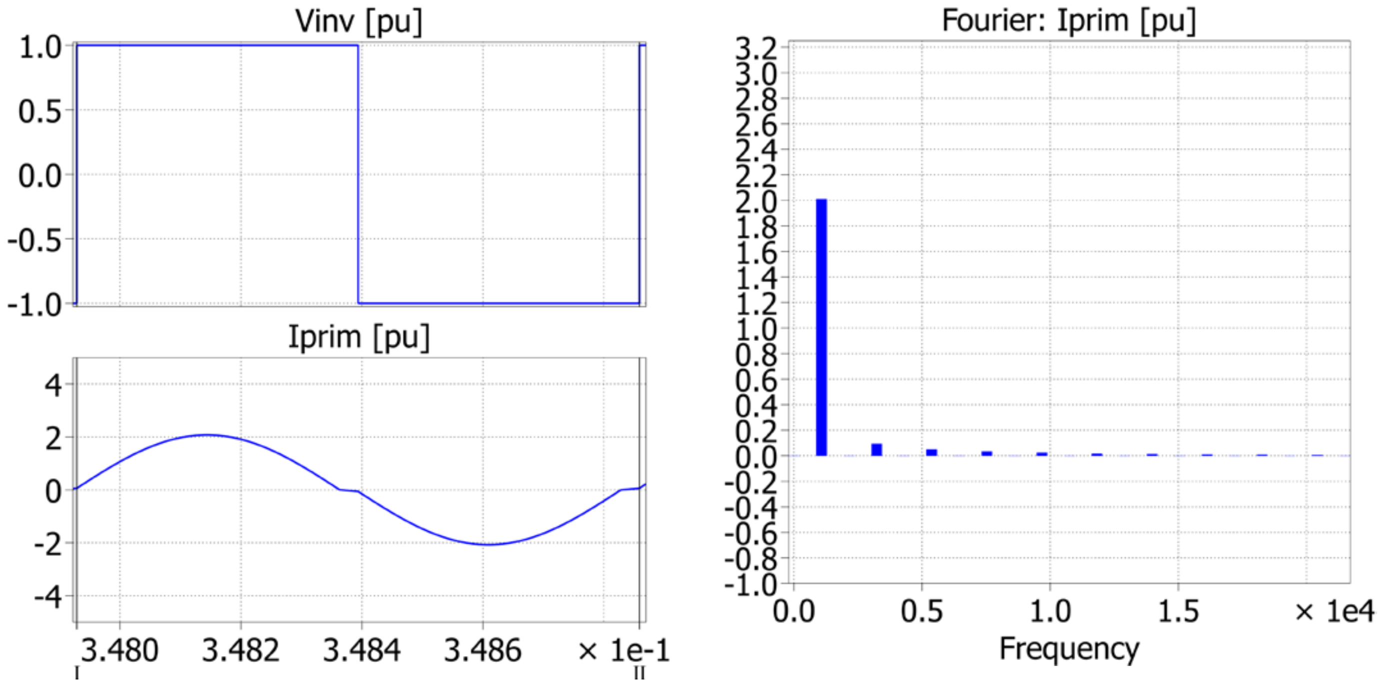
$$P_{Winding} = R_{DC} \cdot \frac{D}{\delta}\left[\frac{\sinh\left(\frac{D}{\delta}\right)+\sin\left(\frac{D}{\delta}\right)}{\cosh\left(\frac{D}{\delta}\right)-\cos\left(\frac{D}{\delta}\right)} + \frac{2\cdot(m^2-1)}{3}\frac{\sinh\left(\frac{D}{\delta}\right)-\sin\left(\frac{D}{\delta}\right)}{\cosh\left(\frac{D}{\delta}\right)+\cos\left(\frac{D}{\delta}\right)}\right]\cdot I_{rms}^2$$

Now, for a certain current waveform, FFT needs to be applied to identify the current harmonics, with their corresponding frequencies and rms values.



Example for above graph

For above current wave form, harmonics at 1000hz, 3000, 5000,7000 and 9000 are identified. The corresponding rms values are 2pu, 0.1pu, 0.05pu, 0.025pu and 0.01pu. For every frequency, the ac resistance needs to be calculated with Dowell's formula and afterwards multiplied with the square of the rms current. Finally, the windings losses are a sum of every harmonic

$$P_{winding} = \sum_h R_{ach} \cdot I_{rmsh}^2$$

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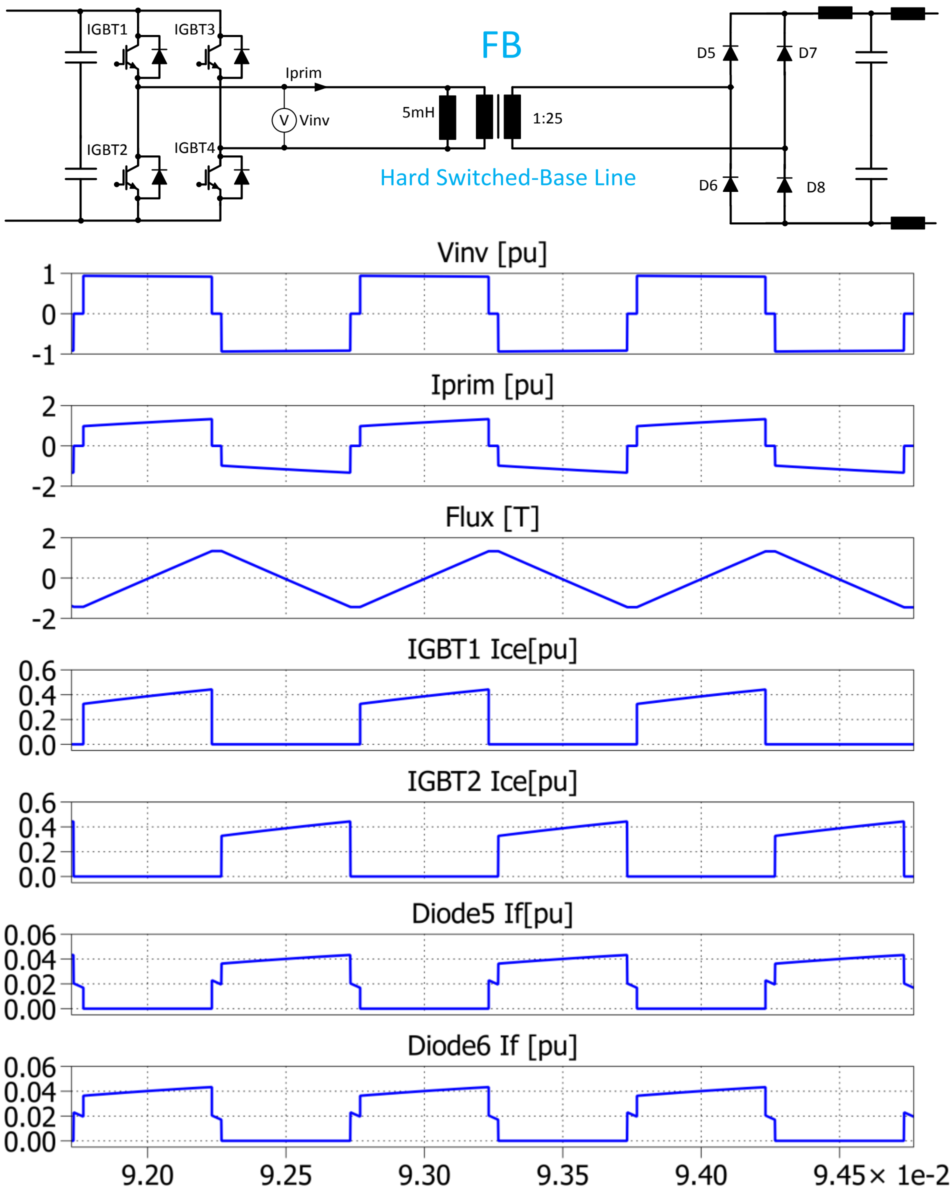
8.3 Hard Switched Full Bridge Converter Principal Waveforms



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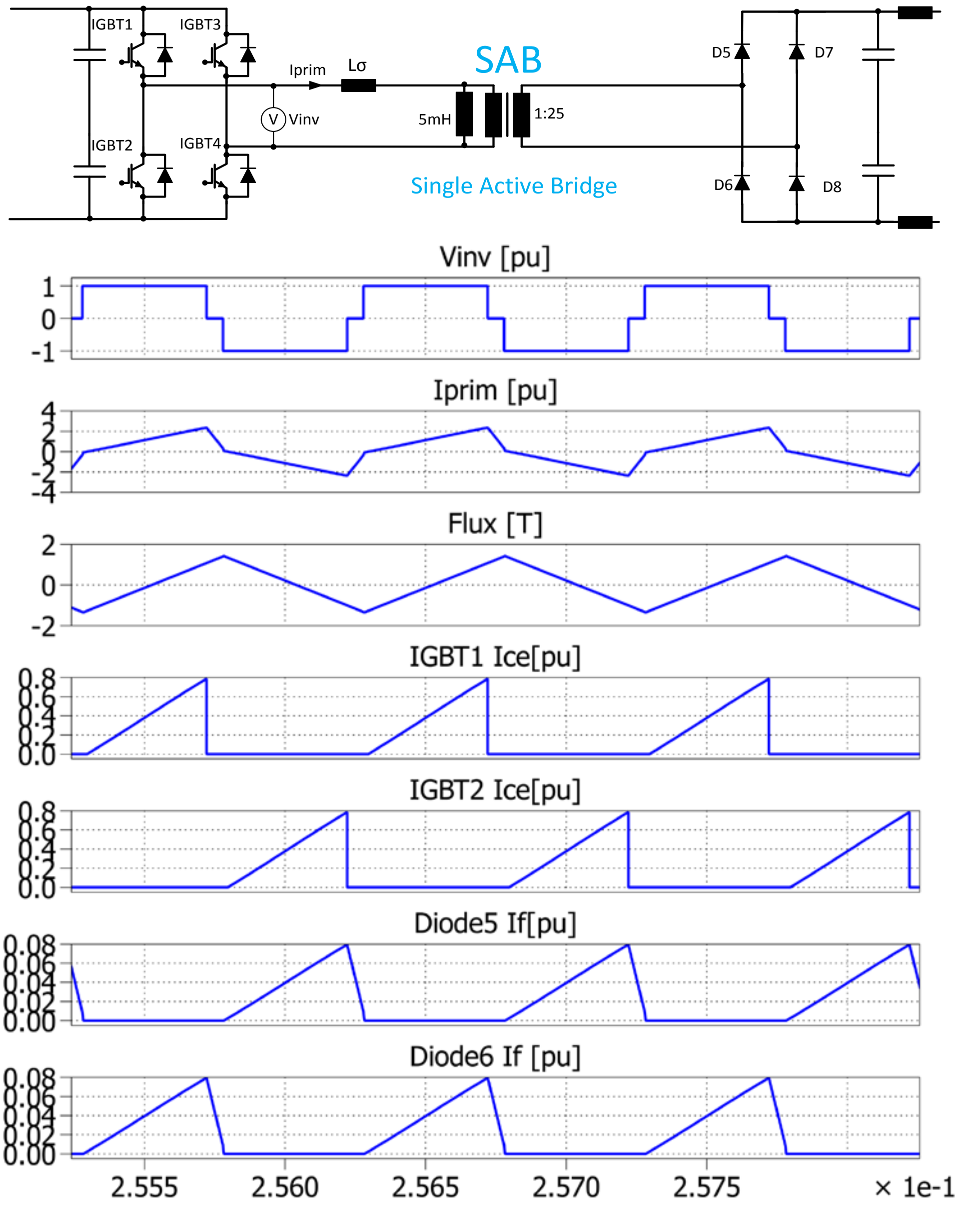
8.4 Single Active Bridge Converter Principal Waveforms

[8], and [9] have been used as reference to design and operate the SAB.



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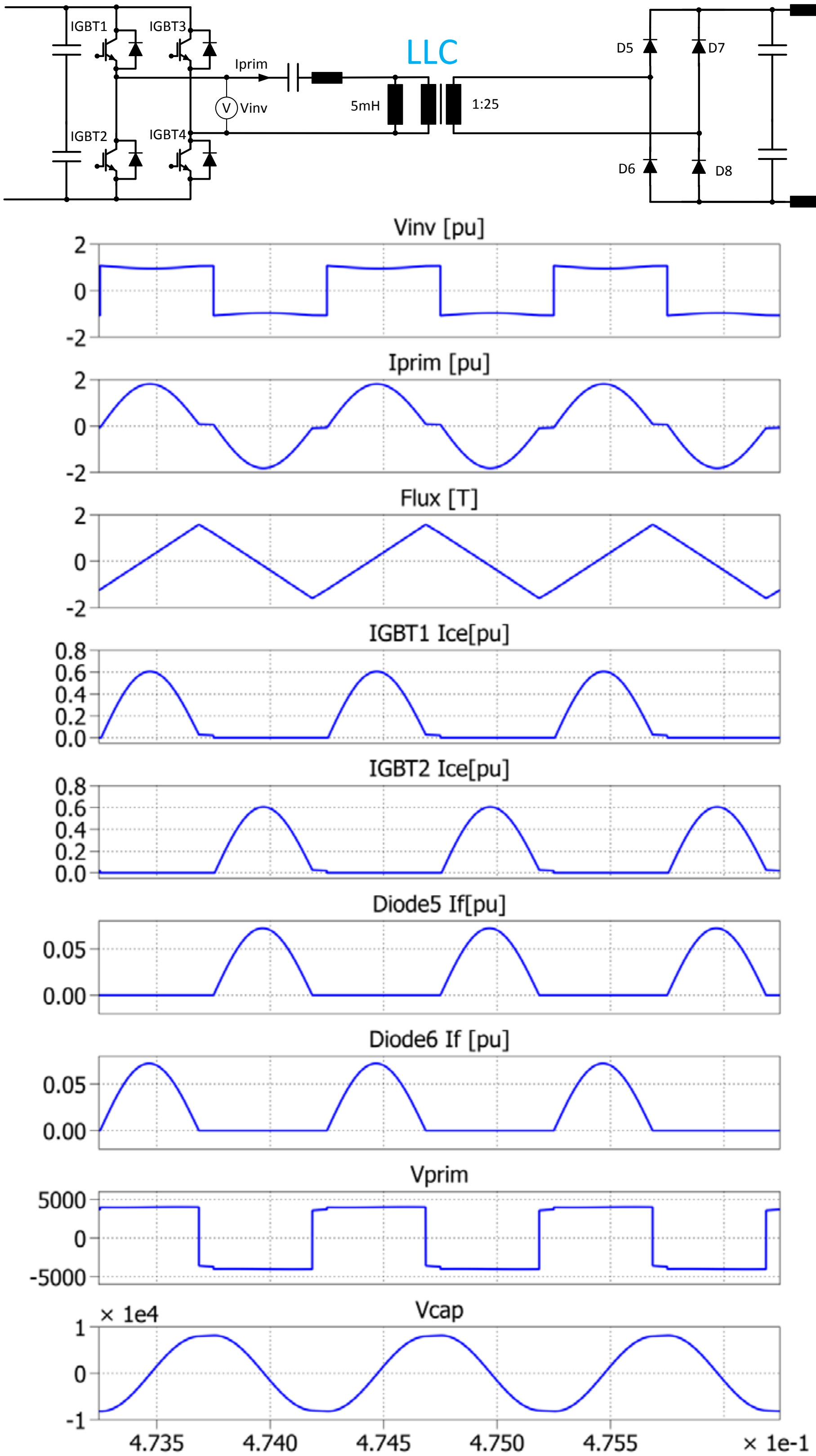
8.5 LLC Converter Principal Waveforms

[11]–[15] are the main references to evaluate the efficiency, control and hardware construction of a traction prototype.



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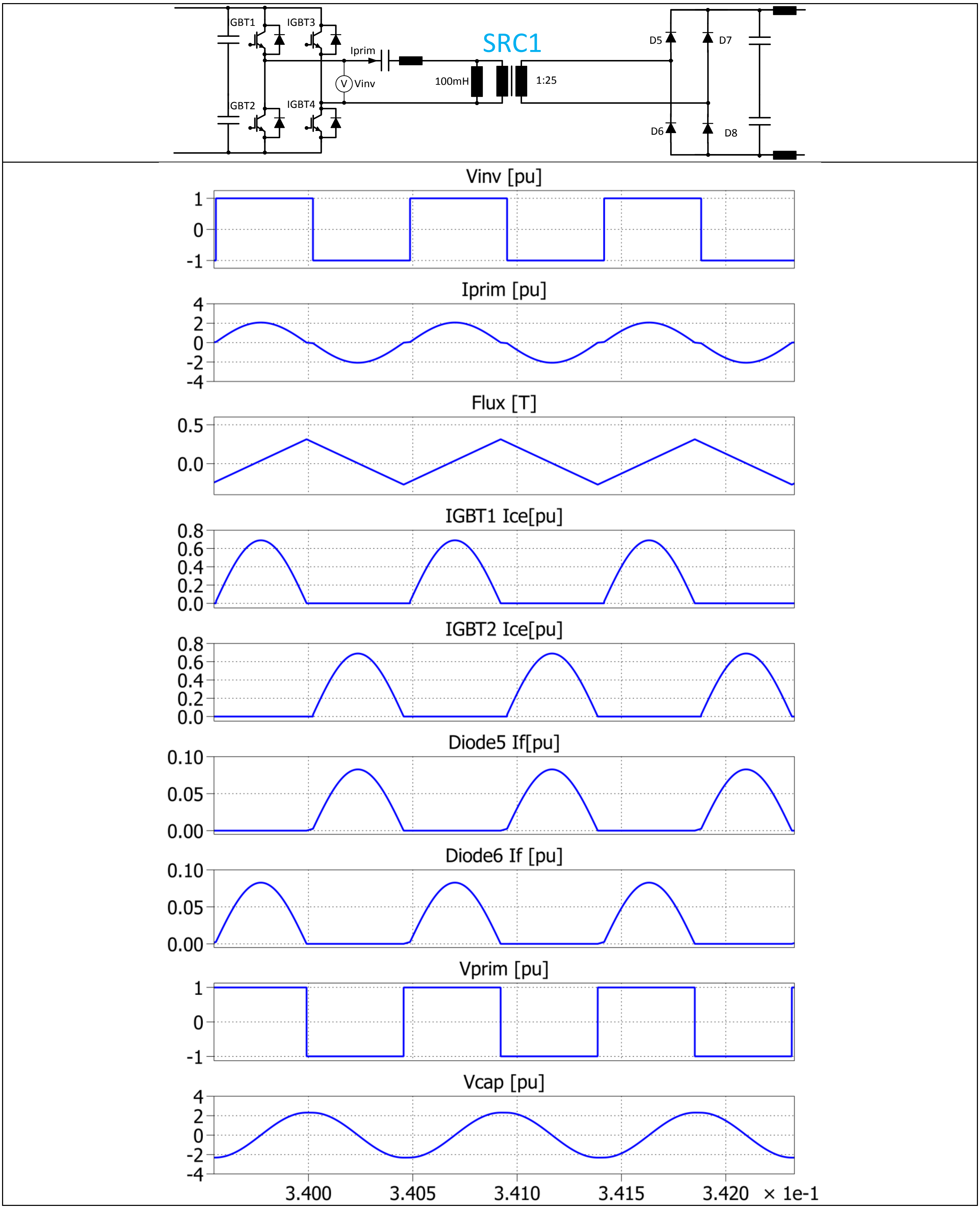
8.6 SRC1 Principal Waveforms



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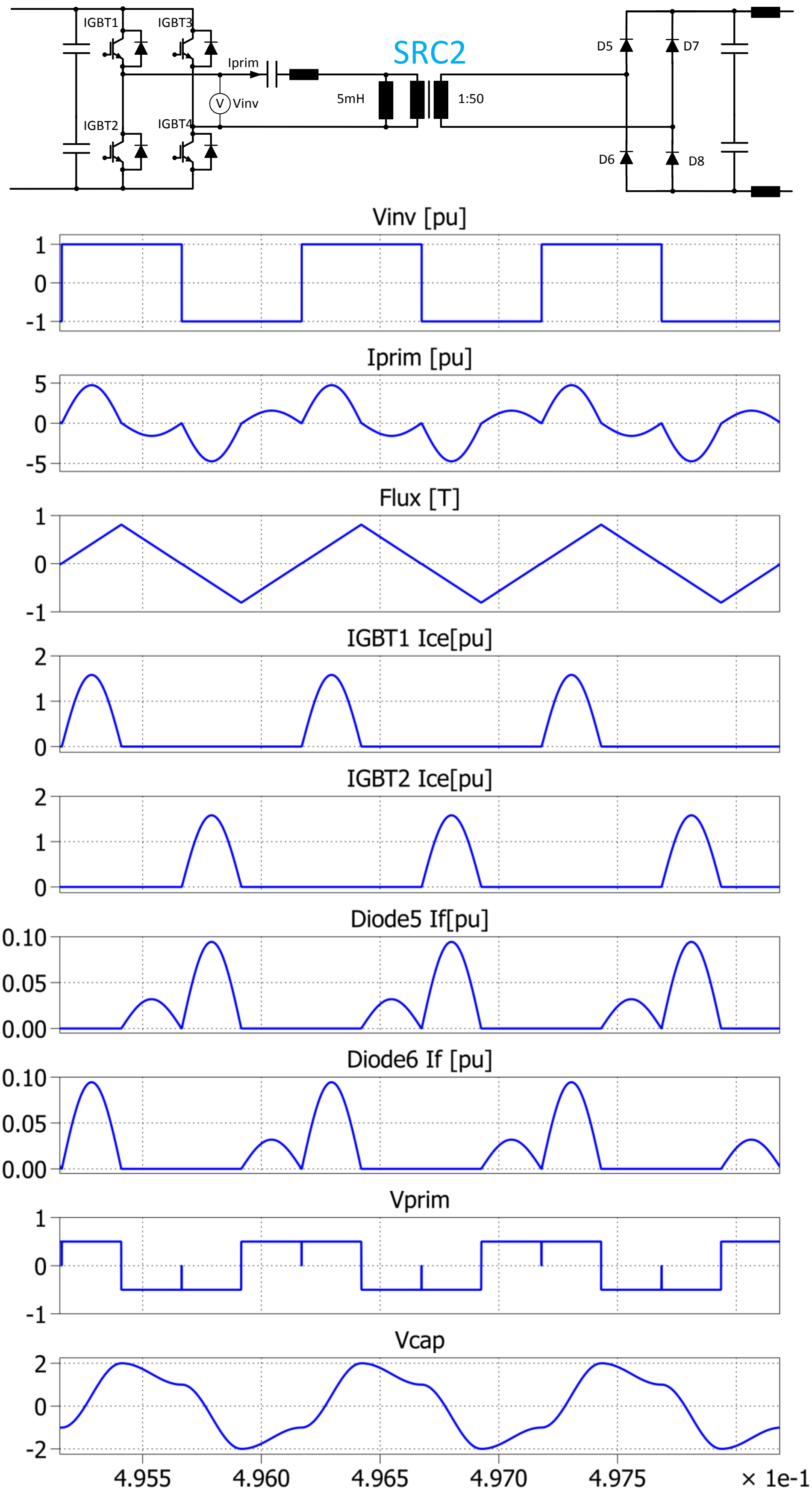
8.7 SRC2 Principal Waveforms



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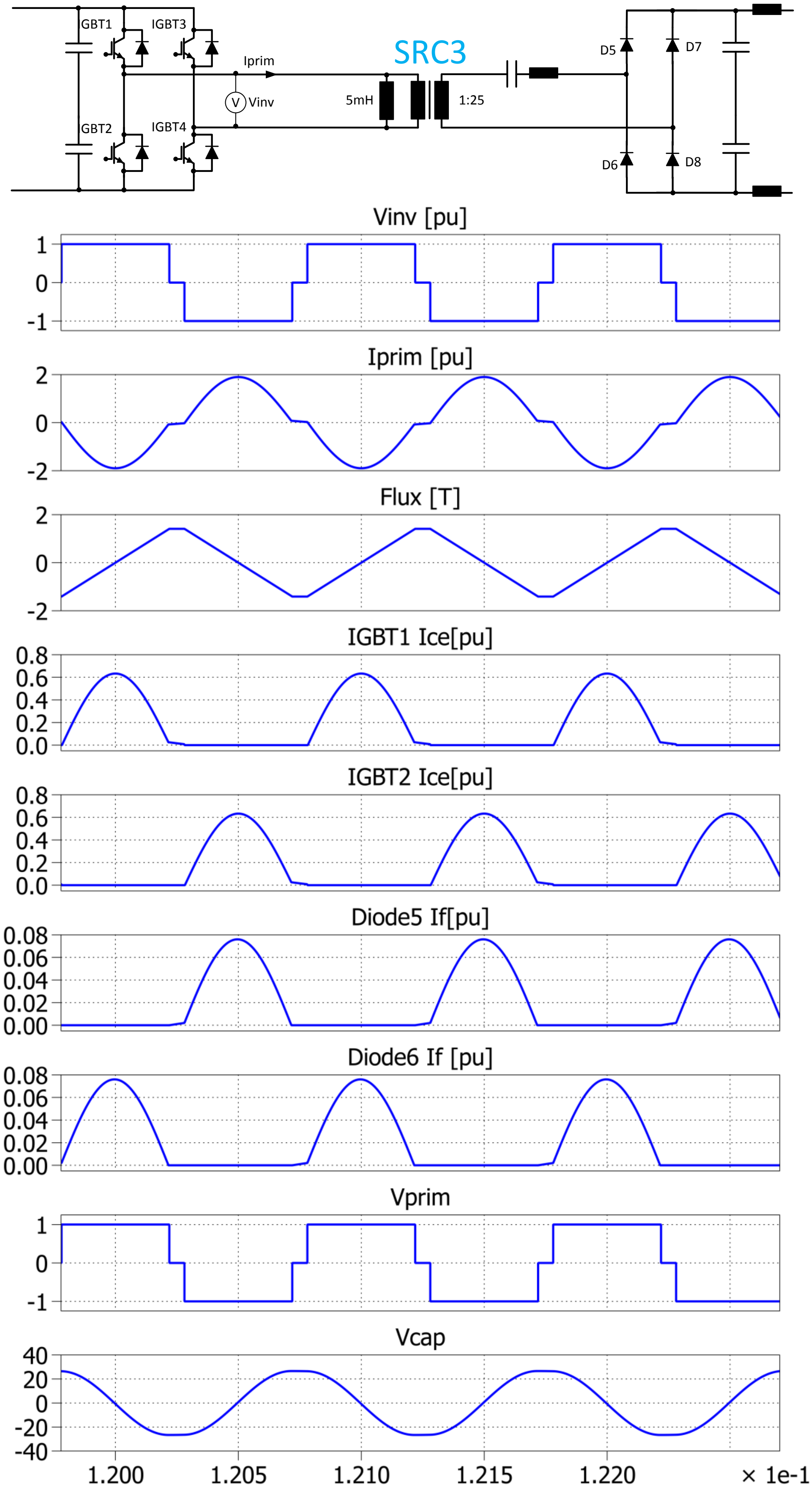
8.8 SRC3 Principal Waveforms



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8.9 Flux saturation impact on current

Flux saturation was investigated on SRC1 and FB converters.

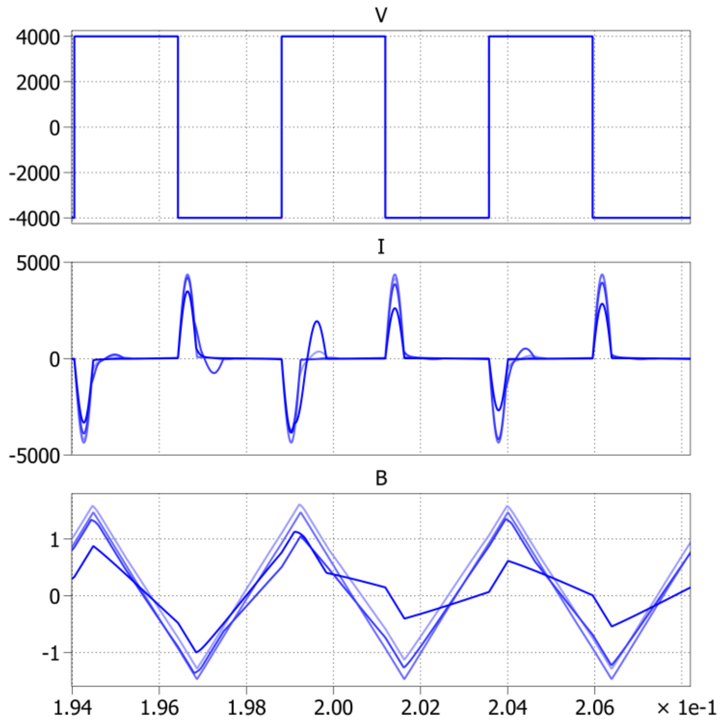

Fig. 68 SRC1 Flux saturation

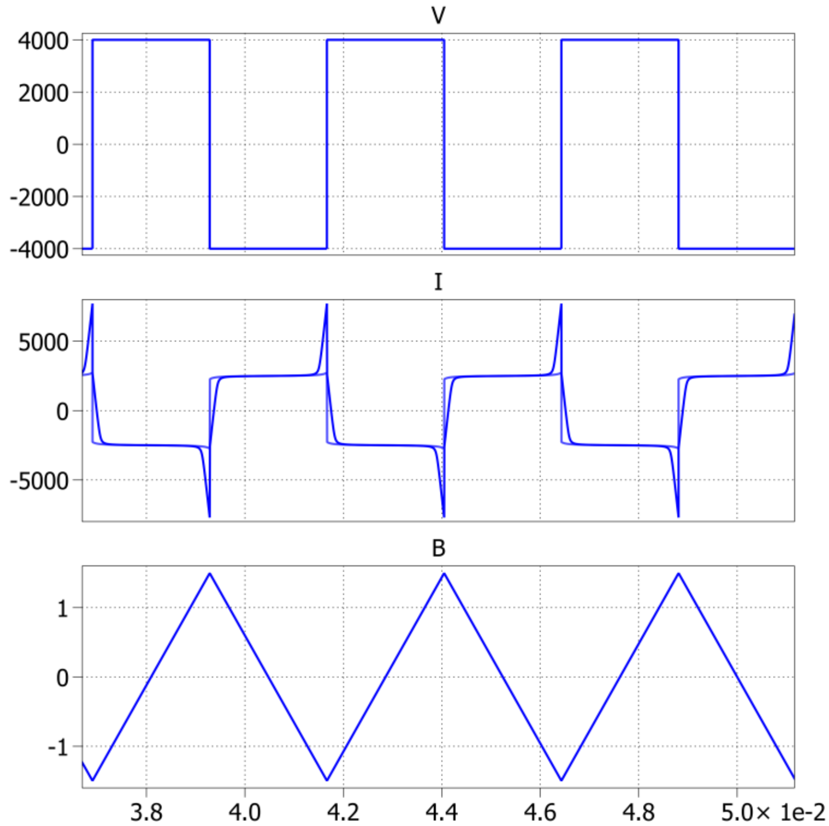

Fig. 69 FB Converter Flux Saturation

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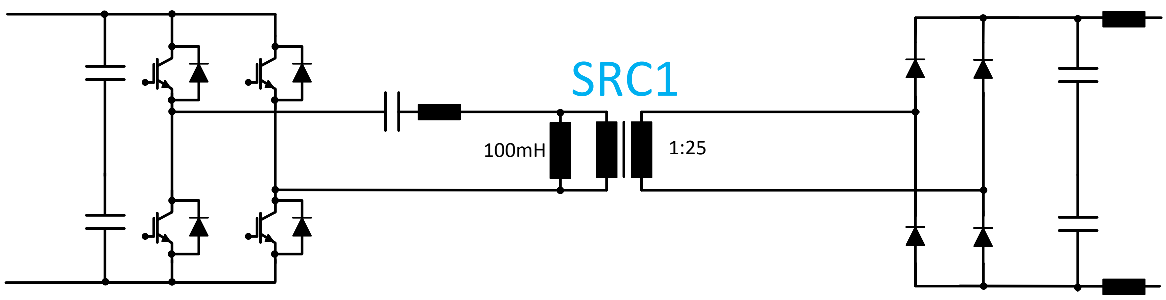
8.10 SRC1 winding loss penalty

Fig. 54 should be interpretated as following. In order to avoid transformer saturation, the SRC transformer should be designed for the lowest frequency. Considering that the main goal is to deliver 1pu output power at 1000hz, the next question is how big the losses are going to be for that particular design when operated at 1000hz. For example, if the transformer is designed for a frequency of 200hz, according to Fig. 54, winding losses will be around 6% of total output power, while when designed for 600hz and operated again at 1000hz, they are 0.25%. Offcourse, higher the specification for frequency design, the lower the losses will be. But the operation range will be limited according that this design frequency.



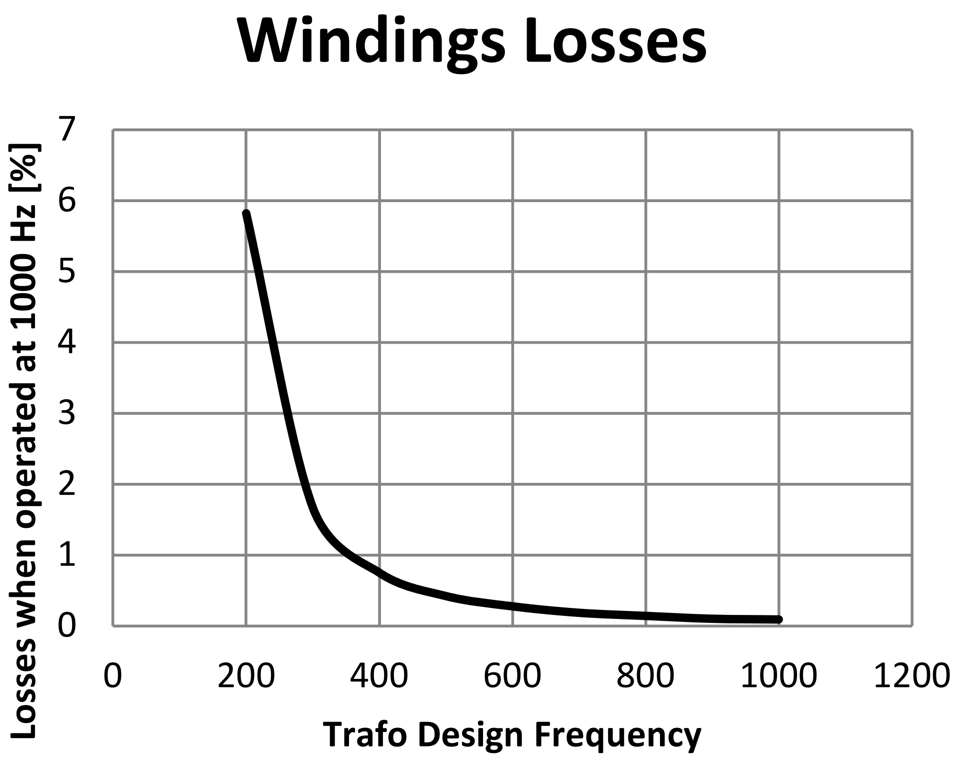


Fig. 70 SRC Windings losses

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8.11 Control block

Controller structure is shown in Fig. 69. As the turbine's generator rectifier maximizes the wind energy extraction, the dc/dc converter controls the dc-link voltage. Changes in captured wind power disturb the dc-link voltage, in turn requiring changes to the dc/dc converter power transfer. In the case of sub-resonant frequency control, output power is dependent on the amount of energy transferred to the MVDC link. For a given frequency and duty cycle, output power is a function of number of energy pulses transferred to the output. DC link voltage control is achieved by transferring a certain integral number of pulses to the output. In this case two controllers are used. P_{ref} comes from the dc/dc converter's own dc-link voltage controller and when divided by the measured V_{MVDC}, provides the current reference $I_{MVDC.}$ This current is the output state variable, which is measured and averaged. The feedforward controller equation is determined by the mode of operation, while the PI feedback controller complements the feed-forward controller by correcting its inaccuracies. For frequency control, the output control signal for modulator block is frequency, while for phase shift, it is duty cycle. In case of dual control, both frequency and duty cycle are control variables.

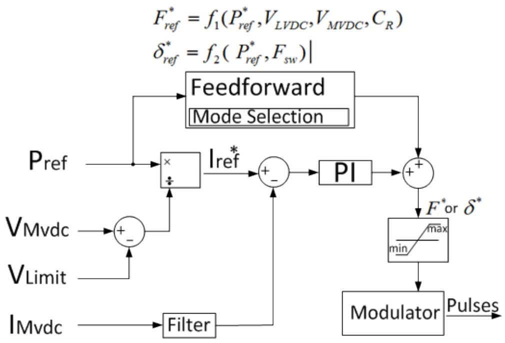

Fig. 71 Controller structure

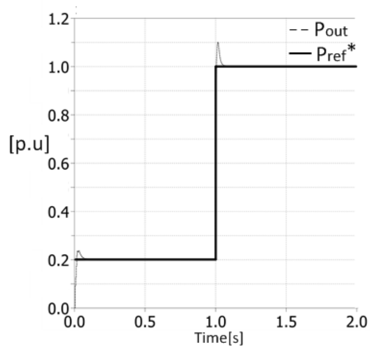

Fig. 72 Output power step response

Fig. 70 shows the output power step response for frequency control, operating in sub-resonant mode. Further on, in Fig.6 and Fig.7, the function of output power to frequency and duty cycle is presented. Two phenomena related to frequency control are noteworthy: as the converter is designed to operate in discontinuous mode in sub-resonance, output power can easily be controlled by frequency in a linear mode. On the other hand, in sub resonance mode, the frequency range is from 1160 to 1200Hz for operation between 1 pu and 0.2 pu output power, and it's not a linear characteristic. Fig.7 indicates that output power can indeed be controlled at constant frequency, by changing the duty cycle of the applied inverter voltage, but in a very limited range. Considering that a change in duty cycle from 0 to 0.225% changes output power from 1 to 0.2pu, the sensitivity of the modulator's impact on output power is a challenge.

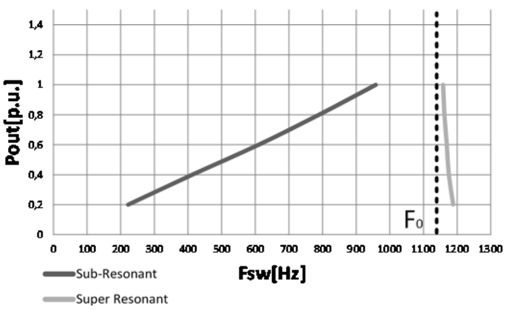

Fig. 73 Pout = f(Fsw)

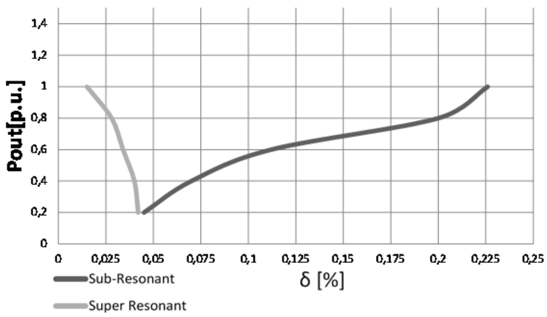

Fig. 74 Pout = f(δ)

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8.12 LLC Control block

A preliminary control block for the LLC Converter is given in Fig. 75.

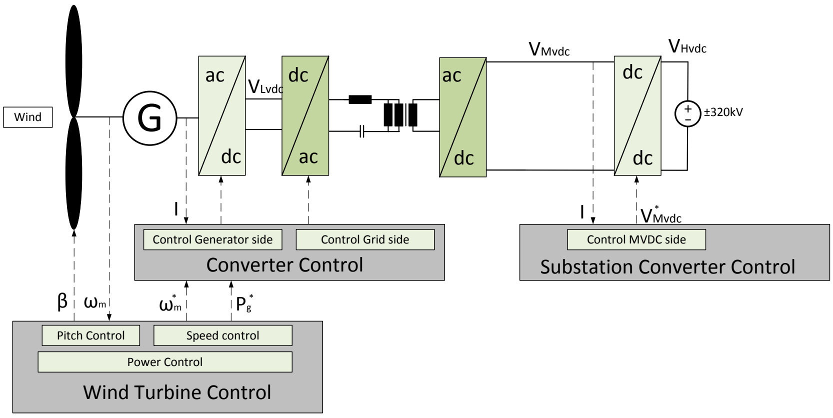

Fig. 75 LLC Control block

- Pitch control modifies the angle of attack of the rotor blades so that the output power of the wind turbine can be controlled.
- The generator side converter controls the speed of the rotor so that the power is maximized.
- MV side voltage is kept constant by substation converter
- The grid side converter should control the DC link by means of PWM or frequency control. But, due to the characteristics of the LLC tank, a load independent operating point exists near the resonant frequency. Therefore, a simple 50% duty cycle at fixed switching frequency is used for control, which does not depend on the dc gain of the LLC converter, and the input to output voltage relation is mainly determined by the transformer turns ratio. In other words, VLvdc is kept constant due to the natural characteristic of the LLC converter and constant VMvdc.

Challenges

- Considering a ±10% variation of V_{Mvdc}, how will the LLC tank respond to it?
- What is the behavior of multiple DC wind turbines with open loop grid side converters connected to same collection grid?
- In case of overvoltage or short circuit, how fast can the LLC converter react?

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8.13 MF Transformer Design and loss calculation

```
%%%% Medium Frequency Transformer %%%%%%%%%%%%
%%%% Catalin Dincan, february 2016 %%%%%%%%%%%
%%%% Design constraints: C-Core and Foil windings only%%%%%%%
%%%% For simplicity Primary and secondary foils have same thickness,
%%%% including insulation


clear all;
clc;

%1)Initial electrical parameters:
V_lvdc = 4e3; %Primary nominal voltage [V];
V_mvdc= 100e3; %Secondary nominal voltage [V];
Fsw = 900 ; %Design frequency [Hz];
Bmax = 1.6; %Amorphous Material Maximum Field Density [T];
K = 1;
Nt = K*V_mvdc/V_lvdc; % Turns ratio;
Irms_p = 3000; %Primary RMS current 1.1*In;
Irms_s = Irms_p/Nt; %Secondary RMS current 1.1*In;
J = 4*1e6; %Current density [A/m];
uo=1.25664e-6;
ur=1000;

%2)Initial insulation, clearance and creepage parameters:
Vins = 150e3; %Insulation voltage between primary and secondary
kf = 0.3; %Safety factor for insulation distance;
Dielectric = 20e3; %Oil + paper insulation dielectric strength;
Dins = round(Vins / (kf * Dielectric))*1e-3; %insulation distance between primary
and secondary;
Dins_p = Dins; %Primary winding clearance distance to core [m];

%3)Initial dimensions , based on Hitachi core data sheet
X = 1; %maximum window height [m];
%Y = ? maximum window width [m] will be calculated based on windings size;
T2 = 0.160; %maximum core build - to calculate core cross section [m];
W = 0.213; %maximum ribbon width - to calculate core cross section [m];
Ac = T2 * W; %core cross section [m^2];
rho_fe  = 7800;     % specific mass of iron
rho_cu  = 8900;     % specific mass of copper
sigma_cu = 5.8108*1e7; %copper conductivity [S/m];
miu_cu = 1.256629*10^-6; %copper permeability [H/m];



%4)Primary and secondary number of turns
Np_total = round (V_lvdc / (Fsw * Ac * Bmax * 4));
Ns_total = Np_total * Nt;

% Final construction will have on each side of the C-core 1primary and 1
% secondary winding with half of the nominal turns, in series connection
Np = Np_total/2;
```


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```
Ns = Ns_total/2;

%Primary winding (Copper foil)

Np_layer = Np; %Primary winding number of layers
Np_turn_per_layer = Np_layer / Np; %Primary winding number of turns per layer
Hp = X - 2*Dins ; %Primary winding height [m];
Dp = round(1000*Irms_p/ (J * Hp))*1e-3; %Primary winding foil thickness [m];
INSp = 0*2e-3; %Primary winding foil insulation [m];
Wp = Np_layer * (Dp + INSp); %Primary winding width [m];

%Secondary winding (Copper foil)

Hs = Hp; %We want same height like primary winding
Ns_layer = K*Np_layer; %Selected Number of Layers;
Ns_turn_per_layer = Ns / Ns_layer ; %Number of turns per layer;
Hs_layer = Hs / Ns_turn_per_layer; %Height of one layer
%Ds = Irms_s / (J * Hs_layer); %Secondary winding foil thickness [m];
Ds = Dp;
INSs = 0*2e-3; %Secondary winding foil insulation [m];
Ws = Ns_layer * (Ds + INSs); %Secondary winding width [m];

%Window area
Y = 2*(Dins_p + Wp + Dins + Ws )+ 50e-3;
% 50e-3 is the distance in the middle of the transformer, between two
Lint=2*(X+Y);%Interior magnetic path
Lext=2*(X+Y+4*T2);%Exterior magnetic path
Le=(Lint+Lext)/2; %Mean magnetic path
Lprim=uo*ur*Np_total^2*Ac/Le; %Magnetizing inductance;

%Core Volume and mass
V_core = (X + 2*T2)*(Y+2*T2)*W;
V_window = X*Y*W;
V_fe = V_core - V_window;
M_fe = V_fe * rho_fe;

%Windings Volume and core

%Primary Volume and mass
V_p1 = Hp * (T2+2*Dins+2*Wp) * (W+2*Dins+2*Wp);
V_p2 = Hp * (T2+2*Dins) * (W+2*Dins);
V_p = 2*(V_p1 - V_p2); %We have 2 x primary windings in series
M_cu_p = V_p * rho_cu;

%Secondary Volume and mass

V_s1 = Hs * (T2+2*Dins+2*Wp+2*Dins+2*Ws) * (W+2*Dins+2*Wp+2*Dins+2*Ws);
V_s2 = Hs * (T2+2*Dins+2*Wp+2*Dins) * (W+2*Dins+2*Wp+2*Dins);
V_s = 2*(V_s1 - V_s2); %We have 2 x secondary windings in series
M_cu_s = V_s * rho_cu;

V_cu = V_p + V_s;
```


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```
M_cu = M_cu_p + M_cu_s;

M_transformer = M_fe + M_cu;
V_transformer = (X + 2*T2)* (Ws+2*Dins+Wp+Y+2*T2)*(Ws+2*Dins+Wp+W);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Drawing area%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Window area
x1 = [0 0 Y Y 0];
y1 = [0 X X 0 0];

%Core size
x2 = [-T2 -T2 Y+T2 Y+T2 -T2];
y2 = [-T2 X+T2 X+T2 -T2 -T2];

%Primary winding

x3 = [Dins_p  Dins_p Dins_p+Wp Dins_p+Wp Dins_p];
y3 = [Dins Dins+Hp Dins+Hp Dins Dins];
x4 = [-T2-Dins_p  -T2-Dins_p -T2-Dins_p-Wp -T2-Dins_p-Wp -T2-Dins_p];
y4 = [Dins Dins+Hp Dins+Hp Dins Dins];

x5 = [Y+T2+Dins_p  Y+T2+Dins_p Y+T2+Dins_p+Wp Y+T2+Dins_p+Wp Y+T2+Dins_p];
y5 = [Dins Dins+Hp Dins+Hp Dins Dins];
x6 = [Y-Dins_p  Y-Dins_p Y-Dins_p-Wp Y-Dins_p-Wp Y-Dins_p];
y6 = [Dins Dins+Hp Dins+Hp Dins Dins];

%Secondary winding

x7 = [Dins_p+Wp+Dins  Dins_p+Wp+Dins Dins_p+Wp+Dins+Ws Dins_p+Wp+Dins+Ws
Dins_p+Wp+Dins];
y7 = [Dins Dins+Hs Dins+Hs Dins Dins];
x8 = [-T2-Dins_p-Wp-Dins  -T2-Dins_p-Wp-Dins -T2-Dins_p-Wp-Dins-Ws -T2-Dins_p-Wp-
Dins-Ws -T2-Dins_p-Wp-Dins];
y8 = [Dins Dins+Hs Dins+Hs Dins Dins];

x9 = [Y+T2+Dins_p+Wp+Dins  Y+T2+Dins_p+Wp+Dins Y+T2+Dins_p+Wp+Dins+Ws
Y+T2+Dins_p+Wp+Dins+Ws Y+T2+Dins_p+Wp+Dins];
y9 = [Dins Dins+Hs Dins+Hs Dins Dins];
x10 = [Y-Dins_p-Wp-Dins  Y-Dins_p-Wp-Dins Y-Dins_p-Wp-Dins-Ws Y-Dins_p-Wp-Dins-Ws
Y-Dins_p-Wp-Dins];
y10 = [Dins Dins+Hs Dins+Hs Dins Dins];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Winding losses%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%!!!!!Remember there are two primary and two secondary windings in
%%%%% series

%%%%%%%%%%%%Primary winding skin and proximity losses%%%%%%%%%%%%%%%%%
```


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```
L=250e-6;
C=78e-6;
fres=1/(2*pi*sqrt(L*C));
tres=1/fres;

%%%%%%%%%%%%%%%%Sub_resonant_frequency_control @ 1pu
%Hard Switched Full Bridge
%Harmonic_p = [1000 3000 5000 7000 9000 11000 13000 15000 17000 19000]; %Harmonic
frequencies for primary winding;
%Current_p = [3600 984 360 100 160 245 270 250 188 114]; %Peak Primary current
vector per harmonic;
%Harmonic_p = [1000 3000 5000 7000 9000 11000 13000 15000 17000 19000]; %Harmonic
frequencies for primary winding;
%Current_p = [4500 1200 650 400 270 170 106 60 40 40]; %Peak Primary current vector
per harmonic;
Harmonic_p = [978   2950    4900    6900    10800]; %Harmonic frequencies for
primary winding;
Current_p = [4200   550 254 140 32]; %Peak Primary current vector per harmonic;

Ploss_p = [0 0 0 0 0];
Rac_p = [0 0 0 0 0];
Duty_cycle = Harmonic_p(1)/fres;
%Duty_cycle = 1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Sum_ploss_p = 0;
for i = 1:5
skin_depth = sqrt(2/(2 * pi * Harmonic_p(i) * miu_cu * sigma_cu));
delta_p = Dp/skin_depth;
MLT_p = 2 * (T2 +W) + 4 * (Np_layer*Dp + 2*Dins); %Primary winding Mean-Length-
Turn;
Rdc_p = Np_layer * Np_turn_per_layer * MLT_p/(sigma_cu * Dp * Hp); %Primary DC
resistance;
Skin_p = (sinh(2*delta_p)+sin(2*delta_p))/(cosh(2*delta_p) - cos(2*delta_p));
%Primary winding losses due to skin effect
Proximity_p = 2/3*(Np_layer^2-1)*(sinh(delta_p)-sin(delta_p))/(cosh(delta_p) +
cos(delta_p)); %Primary winding losses due to proximity effect
Fr_p = delta_p * (Skin_p + Proximity_p);% Dowell resistance factor for primary
winding;
Ploss_p(i) = 2 * Rdc_p * Fr_p * (Current_p(i)*sqrt(Duty_cycle/2))^2; %Losses per
harmonic
%%%Factor 2 is because we have two windings in series and sqrt(2) in
%%%current is due to RMS value. I am not sure if this is correct. It might
%%%be we have to include also influence of D..period where Current is zero.
Sum_ploss_p = Sum_ploss_p + Ploss_p(i); %Total sum of losses per harmonic
Rac_p(i) = Fr_p * Rdc_p; %Primary winding AC resistance

end;


% %%%%%%%%%%%%Secondary winding skin and proximity losses%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%Sub_resonant_frequency_control @ 1pu
```


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```
Harmonic_s = Harmonic_p; %Harmonic frequencies for secondary winding;
Current_s = Current_p/Nt; %Peak Secondary current vector per harmonic;
Ploss_s = [0 0 0 0 0];
Rac_s = [0 0 0 0 0];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Sum_ploss_s = 0;
for i = 1:5
skin_depth = sqrt(2/(2 * pi * Harmonic_s(i) * miu_cu * sigma_cu));
delta_s = Ds/skin_depth;
MLT_s = 2 * (T2 +W) + 4 * (Ns_layer * Ds + 2*(Dins + Np_layer * Dp + Dins));
%Secondary winding Mean-Length-Turn;
Rdc_s = Ns_layer * Ns_turn_per_layer * MLT_s/(sigma_cu * Ds * Hs_layer); %Secondary
DC resistance
delta_s = Ds/skin_depth;
Skin_s = (sinh(2*delta_s)+sin(2*delta_s))/(cosh(2*delta_s) - cos(2*delta_s));
%Secondary winding losses due to skin effect
Proximity_s = 2/3*(Ns_layer^2-1)*(sinh(delta_s)-sin(delta_s))/(cosh(delta_s) +
cos(delta_s)); %Primary winding losses due to proximity effect
Fr_s = delta_s * (Skin_s + Proximity_s);% Dowell resistance factor for secondary
winding;
Ploss_s(i) = 2 * Rdc_s * Fr_s * (Current_s(i)*sqrt(Duty_cycle/2))^2; %Losses per
harmonic
%%%Factor 2 is because we have two windings in series and sqrt(2) in
%%%current is due to RMS value. I am not sure if this is correct. It might
%%%be we have to include also influence of D..period where Current is zero.
Sum_ploss_s = Sum_ploss_s + Ploss_s(i); %Total sum of losses per harmonic
Rac_s(i) = Fr_s * Rdc_s; %secondary winding AC resistance
end;

Ploss_cu = Sum_ploss_p + Sum_ploss_s; %Total Transformer Losses

%%%%%%%%%%%%%%%%%%%%%%%%%%%%Core losses%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Core = [2000 0.4 0.5]; %Core(1) is frequency, Core(2) is B and Core(3) is Duty
Cycle.

%%%%%Improved generalized Steinmetz equation (IGSE) was used%%%%%%%%%%%
%Bellow parameters are from I.Villar PhD Thesys. They seem to give quite
%low core losses.
%alfa = 1.51; %Frequency parameter
%beta = 1.74; %Field Density parameter
%Ki = 0.65;
%K = 6.5;
%D = 0.5 %Duty cycle
%Ploss_fe = 2^(alfa + beta) * Ki * (Fsw/1e3) ^ alfa * Bmax ^ beta * 0.5^(beta-
alfa+1) * M_fe;

%Original Steinmetz equation OSE %%%%%
%Ploss_fe = K * (Fsw/1e3) ^ alfa * Bmax ^ beta * D^beta %*M_fe;
%Bellow parameters are from measurements done on METGLAS2605A1 by Jacobs
%from Aachen
alfa = 1.5;
beta = 1.6;
```


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```
Ki = 2;
D = 0.5
Ploss_fe = 2^(alfa + beta) * Ki * (Fsw/1e3) ^ alfa * 1.37 ^ beta * 0.42^(beta+1-
alfa)*M_fe;
%Plot
plot(x1,y1,'k');
hold on;
plot(x2,y2,'k');
hold on;
plot(x3,y3);
hold on;
plot(x4,y4);
hold on;
plot(x5,y5);
hold on;
plot(x6,y6);
hold on;
plot(x7,y7,'r');
hold on;
plot(x8,y8,'r');
hold on;
plot(x9,y9,'r');
hold on;
plot(x10,y10,'r');

grid off;
hold off;
title(['M_f_e = ',num2str(M_fe,4),' kg.  M_c_u = ',num2str(M_cu,5),' kg. Volume =
',num2str(V_transformer,3),' m^3. Ploss_c_u = ',num2str(Ploss_cu,8),' W. Ploss_f_e
= ',num2str(Ploss_fe,6),' W.']);


str1 = 'Electric parameters';
text(1.5,1.3,str1);
str1 = 'Vp = ';
str2 = num2str(V_lvdc);
text(1.5,1.2,str1);
text(1.65,1.2,str2);
str1 = 'Vs = ';
str2 = num2str(V_mvdc);
text(1.5,1.1,str1);
text(1.65,1.1,str2);
str1 = 'Fsw = ';
str2 = num2str(Fsw);
text(1.5,1,str1);
text(1.65,1,str2);
str1 = 'Bmax = ';
str2 = num2str(Bmax);
text(1.5,0.9,str1);
text(1.65,0.9,str2);
str1 = 'Nt = ';
str2 = num2str(Nt);
text(1.5,0.8,str1);
text(1.65,0.8,str2);
```

```
str1 = 'I_r_m_s_p_ = ';
str2 = num2str(Irms_p);
text(1.5,0.7,str1);
text(1.65,0.7,str2);
str1 = 'I_r_m_s_s_ = ';
str2 = num2str(Irms_s);
text(1.5,0.6,str1);
text(1.65,0.6,str2);
str1 = 'Magnetic parameters';
text(1.5,0.5,str1);
str1 = 'Ac =';
text(1.5,0.4,str1);
str2 = num2str(Ac);
text(1.65,0.4,str2);
str1 = 'Wa width =';
text(1.5,0.3,str1);
str2 = num2str(Y);
text(1.75,0.3,str2);
str1 = 'Wa height =';
text(1.5,0.2,str1);
str2 = num2str(X);
text(1.75,0.2,str2);
str1 = 'Core height =';
text(1.5,0.1,str1);
str2 = num2str(X+2*T2);
text(1.75,0.1,str2);
str1 = 'Core width =';
text(1.5,0.0,str1);
str2 = num2str(Y+2*T2);
text(1.75,0.0,str2);
str1 = 'Primary windings ';
text(-1.5,1.3,str1);
str1 = 'Np =';
text(-1.5,1.2,str1);
str1 = num2str(Np);
text(-1.4,1.2,str1);
str1 = 'Turns per layer =';
text(-1,1.2,str1);
str1 = num2str(Np_turn_per_layer);
text(-0.65,1.2,str1);
str1 = 'Np layers=';
text(-1.5,1.1,str1);
str1 = num2str(Np);
text(-1.3,1.1,str1);
str1 = 'Foil Thickness[mm]=';
text(-1,1.1,str1);
str1 = num2str(Dp*1e3);
text(-0.65,1.1,str1);
str1 = 'Secondary windings';
text(-1.5,1,str1);
str1 = 'Ns =';
text(-1.5,0.9,str1);
str1 = num2str(Ns);
text(-1.4,0.9,str1);
```


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```
str1 = 'Turns per layer =';
text(-1,0.9,str1);
str1 = num2str(Ns_turn_per_layer);
text(-0.65,0.9,str1);
str1 = 'Ns layers=';
text(-1.5,0.8,str1);
str1 = num2str(Ns_layer);
text(-1.3,0.8,str1);
str1 = 'Foil Thickness[mm]=';
text(-1,0.8,str1);
str1 = num2str(Ds*1e3);
text(-0.65,0.8,str1);
str1 = 'Area product';
text(-1.5,0.7,str1);
str1 = 'WaAc =';
text(-1.5,0.6,str1);
str1 = num2str(X*Y*Ac);
text(-1.3,0.6,str1);
str1 = 'Rac_p =';
text(-1.5,0.5,str1);
str1 = num2str(Rac_p,1);
text(-1.3,0.5,str1);
str1 = 'Ploss_p =';
text(-1.5,0.4,str1);
str1 = num2str(Ploss_p,5);
text(-1.3,0.4,str1);
str1 = 'Rac_s =';
text(-1.5,0.3,str1);
str1 = num2str(Rac_s,2);
text(-1.3,0.3,str1);
str1 = 'Ploss_s =';
text(-1.5,0.2,str1);
str1 = num2str(Ploss_s,5);
text(-1.3,0.2,str1);
str1 = 'Lprim =';
text(-1.5,0.1,str1);
str1 = num2str(Lprim,3);
text(-1.3,0.1,str1);

axis([-2 2 -0.5 1.5]);
%axis equal;

% str1 = 'Ns =';
% text(-1,1.1,str1);
% str1 = num2str(Ns_total);
% text(-0.9,1.1,str1);
clc;

,
```


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