NEWBORN - NExt generation high poWer fuel cells for airBORNe applications

WP08 – Power line
D8.27
Propulsion Motor and Inverter trade study summary

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REVISION HISTORY

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Draft 2	2023-03-26	Revised based on discussion and feedback on the 2023-03-24
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Table 1: Revision history

INTELLECTUAL PROPERTY

Section/Chapter/Item	Owning Entity	Nature of IP	Comments
Entire document	University of Nottingham	Exclusive Foreground	Logged in March 2023

Table 2: Intellectual property

GLOSSARY

AC	Alternating Current
BEMF	Back ElectroMotive Force
CM	Configuration Management / Configuration Manager
DC	Direct Current
EC	Export Control
Eoff	Turn-off energy
Eon	Turn-on energy
Erec	Reverse recovery energy
EU	European Union
FC	Fuel Cell
GaN	Gallium Nitride
IADP	Innovative Aircraft Demonstrator Platforms
ID	Identifier
IGBT	Insulated Gate Bipolar Transistor
IP	Intellectual Property
MOSFET	Metal Oxide Semiconductor Filed Effect Transistor
MTBCF	Mean Time Before Critical Failure
NEWBORN	NExt generation high poWer fuel cells for airBORNe applications
PC	Project Coordinator
PE	Power Electronics
PF	Power Factor
R_{DS} / R_{DS_ON}	Resistance between drain and source
Tj	Junction temperature
TL	Technical Leader
Si	Silicon
SiC	Silicon Carbide
SPM	Surface Permanent Magnet
UNOTT	University of Nottingham
WP	Work Package

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1 INTRODUCTION

1.1 Objective

The objective of this document is to report on the trade-off studies of the electric propulsion powerline (including DC/AC power converter, electric motor, thermal design, controller, and gearbox options) within the NEWBORN project. Since the project is at its very beginning and many factors which have impacts on the NEWBORN electric propulsion powertrain design are still under discussion at the system level, this report is mainly to provide some initial identified solutions for the propulsion powerline components.

1.2 Scope

This scope of this document is to capture the trade-off studies of power electronic converters, thermal design consideration, gear options, and some limitations of electrical machines.

2 INVERTER

2.1 Main input data inverter

The nominal phase current of the inverter/machine is a function of

- Power (1 MW)
- DC-Link voltage
- Number of phases
- Power factor (PF) of the machine

Different DC-link voltages have been considered in the trade-off studies from 575 V to 1 kV. The phase current and voltages (Machine phase topologies from 3 phases to 12 phases have been considered and studied. Scenarios of phases beyond 12 have been neglected due to practical considerations), DC-link voltages thus can be derived as shown in Table 3. Please note that in Table 3, the DC link voltage represents the minimum operational voltage and for all cases the maximum operating voltage is 1000 V.

Table 3: Phase current and number of phases for different DC Link voltage levels

Power	Minimum DC Link voltages	DC Link currents	PF	Phase Voltage	N_phases	I_phase
W	V	A		Vrms		Arms
1.00E+06	575	1740	0.8	263	3	1585
1.00E+06	575	1740	0.8	263	6	792
1.00E+06	575	1740	0.8	263	**9**	528
1.00E+06	575	1740	0.8	263	12	396
1.00E+06	650	1538	0.8	297	3	1402
1.00E+06	650	1538	0.8	297	6	701
1.00E+06	650	1538	0.8	297	**9**	467
1.00E+06	650	1538	0.8	297	12	350
1.00E+06	700	1428	0.8	320	3	1302
1.00E+06	700	1428	0.8	320	6	651
1.00E+06	700	1428	0.8	320	**9**	434
1.00E+06	700	1428	0.8	320	12	325
1.00E+06	800	1250	0.8	366	3	1139
1.00E+06	800	1250	0.8	366	6	570
1.00E+06	800	1250	0.8	366	**9**	380
1.00E+06	800	1250	0.8	366	12	285
1.00E+06	900	1111	0.8	412	3	1012
1.00E+06	900	1111	0.8	412	6	506
1.00E+06	900	1111	0.8	412	**9**	337
1.00E+06	900	1111	0.8	412	12	253
1.00E+06	1000	1000	0.8	457	3	911
1.00E+06	1000	1000	0.8	457	6	456
1.00E+06	1000	1000	0.8	457	**9**	304
1.00E+06	1000	1000	0.8	457	12	228

From Table 3, a conclusion can be drawn that the configuration with 3 and 6 phases will not be suitable for the NEWBORN application as the currents in those cases are too high to use a single power module per phase for all the considered DC link voltages.

Paralleling of modules has not been considered due to the reduced switching and efficiency performance. The multiphase topologies consist of the same number of power modules necessary as a comparable three phase system as shown in Figure 1 for reference compared to a six-phase system. The basic number of modules will stay the same but with disadvantages due to increased driver and commutation loops.

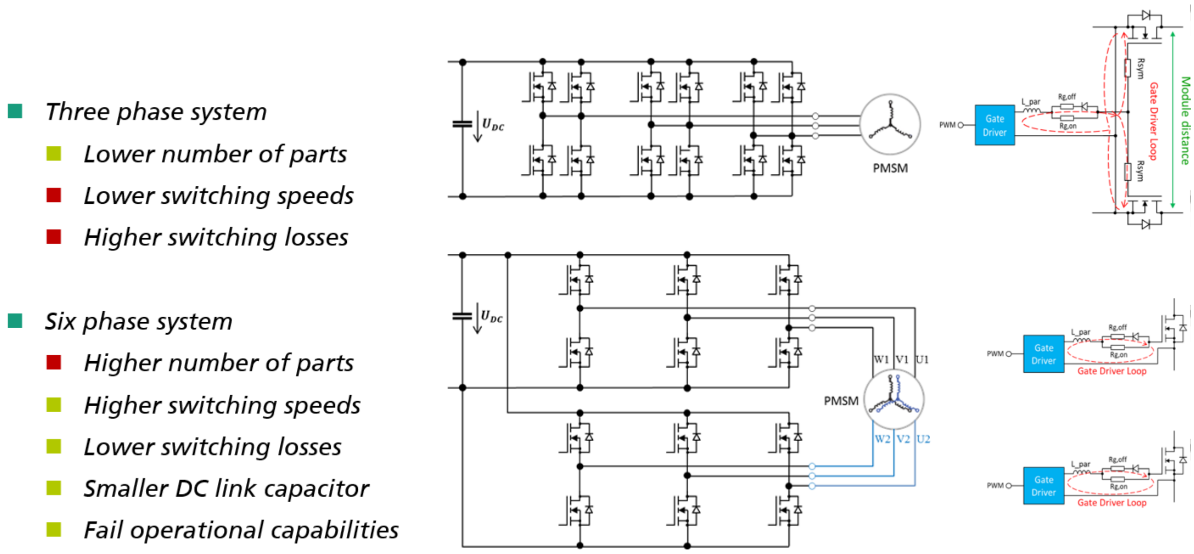


Figure 1: Multiphase topology vs. three-phase system

2.2 Power Module options

Considering visible solutions and their phase currents and DC-link voltages in Table 3, potential power SiC modules available on the market have been identified and shown in Table 4.

Table 4: List of SiC MOSFETs power module.

Power Module	Voltage rated [V]	RDS [mΩ] at 25°C	Extra info
case1	1.2K	2.29	3rd GEN +SiC Schottky DIODE
case2	1.2K	1.33	3rd GEN
case3	1.7K	2.86	3rd GEN +SiC Schottky DIODE
case4	1.7K	2.16	3rd GEN
case5	1.7K	1.42	3rd GEN

During this trade-off study, the Si IGBTs have not been considered due to the much lower performance compared with SiC MOSFETS.

GaN devices also have not been considered due to the lower maximum voltages which requires more complicated topologies for the NEWBORN application (requiring significantly increased device numbers). Furthermore, GaN power modules may not be available in the market at high current ratings required by the NEWBORN converter.

2.3 Losses calculation with fixed DC Link voltage

Analytical model of power converter has been developed in Nottingham to estimate the power losses, junction temperature etc using phase currents, number of phases and DC link voltages. Two types of losses in the power converter have been considered, i.e., the conduction loss and the switching loss. The conduction losses are function of phase currents and junction temperature Tj. The switching losses are function of the junction temperature Tj, phase currents and the DC Link voltage.

To analyse the performance of different NEWBORN power converter using the 5 different power modules show in Table 4, the following assumptions have been considered

- Fixed DC Link voltage. Different levels of DC-link voltages have been considered from (575 V to 1000 V)
- Fixed junction temperature Tj=175 °C
- No conduction on the body diode and/or antiparallel diode, no sharing current between the R_{DS} (max value) channel and the diode are considered in the 3rd quadrant.
- No consideration of the dead time.
- Switching losses linear with the current and extrapolated from data sheet for the voltage (linearization between two point).
- Only the average current will be considered for the switching losses (0.9 rms value).
- Symmetrical modulation with one Eon + Eoff + Erec per cycle per legs.
- Switching frequency: 25k and 35kHz are considered, for a fundamental output frequency in a range of 1 kHz - 1.5 kHz with same safety factor (5 kHz).
- Thermal conductivity of thermal interface material between the power module and heat sinks equal to 10 W/m*K.
- Thermal resistance between the coolant and the heat-sink 0.02 °C/W per module (see section 2.7).
- 10 °C of safety margin

All previous assumptions are conservative the Rds_on loss has been estimated from the available datasheet and considered reasonable safety margins and based on analytical model of a power converter. The NEWBORN is not planned to operate the module with such high junction temperature, but this is mainly for trade-off studies. Behavioural models of power converters will be developed and used for the PDR studies.

Those stress rating are acceptable at the TRL4 stage, as new generation modules with lower losses are in development (e.g., Gen4).

Those assumption are taken here only as a boundary for the design optimization, and the optimization goal is to reduce the temperature gradient for the cooling system.

The efficiency and maximum allowed coolant temperature of different solutions under different DC-link voltage levels and switching frequency are shows in Figure 2 (9-phase scenario) and Figure 3 (12-phase scenario).

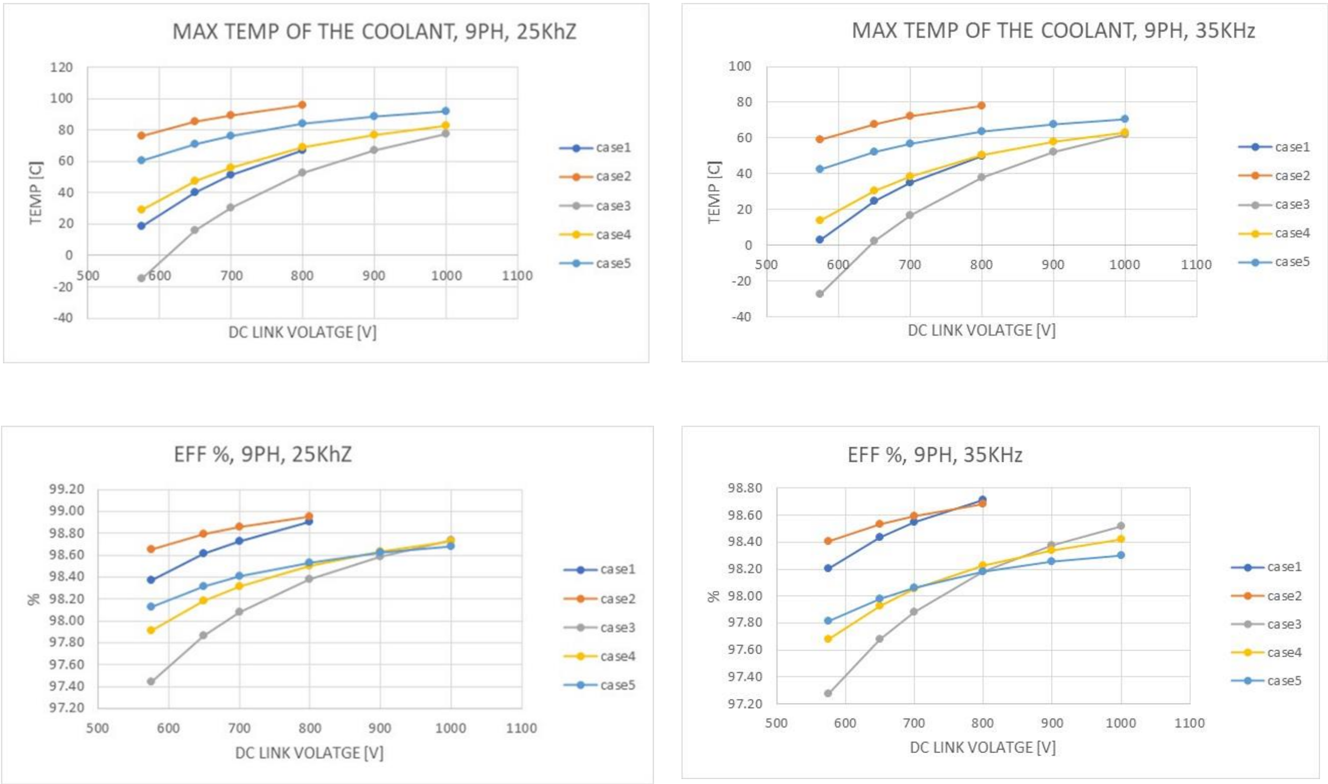


Figure 2: Maximum temperature of the coolant and efficiency comparison with 9-Phase machine with 25 kHz and 35 kHz switching frequency for different DC Link voltage (minimum).

From Figure 2, it can be seen that, for a 9-phase machine scenario, it would preferable to use case2 when the DC-link voltage under 800 V as it has the highest efficiency and less demanding in coolant temperature for the switching frequency at both 25 kHz or 35 kHz.

When the DC-link voltage goes higher and beyond 800 V, it is preferable to use case5 power module as the coolant temperature can be higher and thus ease somehow the thermal design.

When pushing the switching frequency higher to 35 kHz, the efficiency of the power converter reduces and more demanding in terms of coolant temperature. However, this might result in better power quality and less losses in the machine.

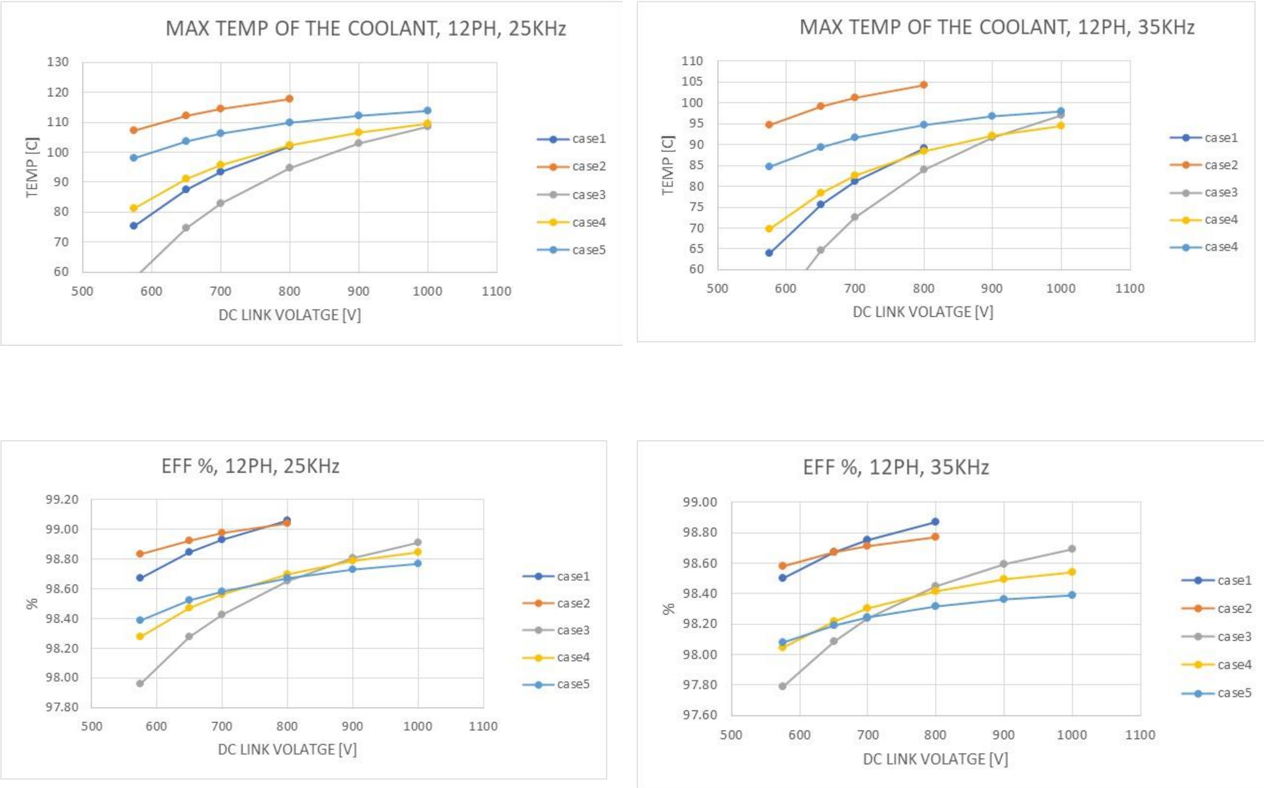


Figure 3: Maximum temperature of the coolant and efficiency comparison of 12-phase machine scenario, considering 25 kHz and 35 kHz switching frequency for different DC Link voltages.

It can be seen from Figure 3 that for the 12-phase machine solution, selection of power modules is similar to the 9-phase case. It would be preferable to use **case2** for DC-link voltage under 800 V. When the DC-link voltage goes beyond 800 V, it is preferable to use **case5** power module as the coolant temperature can be higher.

2.3.1 Discussion

In this study, we only considered losses of the power modules, but there are other losses such DC link capacitor, inductance for EMI, copper bars, gate drive, sensors, and controller. These losses are much less significant compared with those in power modules and thus will not have significant impact on drawing our conclusion. Cases with efficiency higher than 98.5% should be considered.

With 700 V – 800 V, it would be better to go with the 1.2 KV power modules and the best power module is the **case2 (considering the required temperature)**.

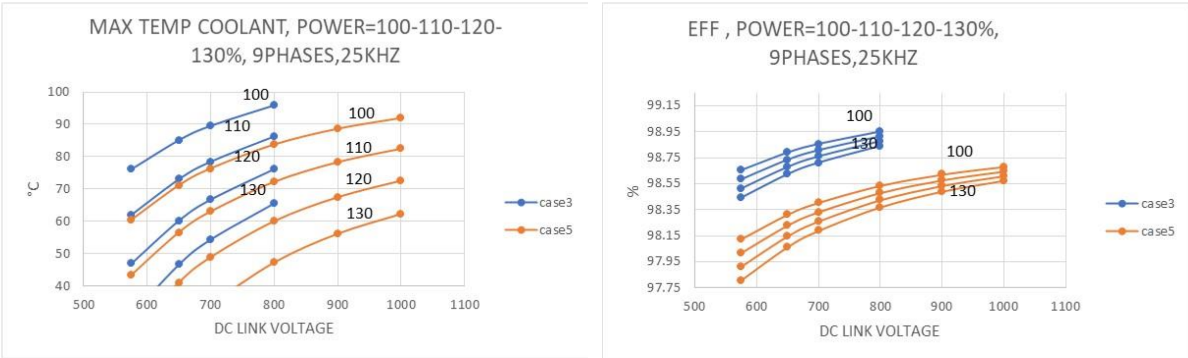
When the DC Link voltage is 900-1000 V, power module of 1.7 kV should be used considering the safety margin and the best option is **case5 considering the coolant temperature requirement.**

Thus, our study is now only focusing on these two power modules **case2 for 700 V – 800 V DC and case5 for 900 V – 1000 V DC.**

The solution with 12 phases will have less restriction on the cooling loop and higher efficiency but the power density will be lower (33% less compared with the 9 phases solution). Although the 12-phase solution seems to be better than 9-phase solutions in terms of efficiency, this will compromise on size, volume, reliability, cost etc

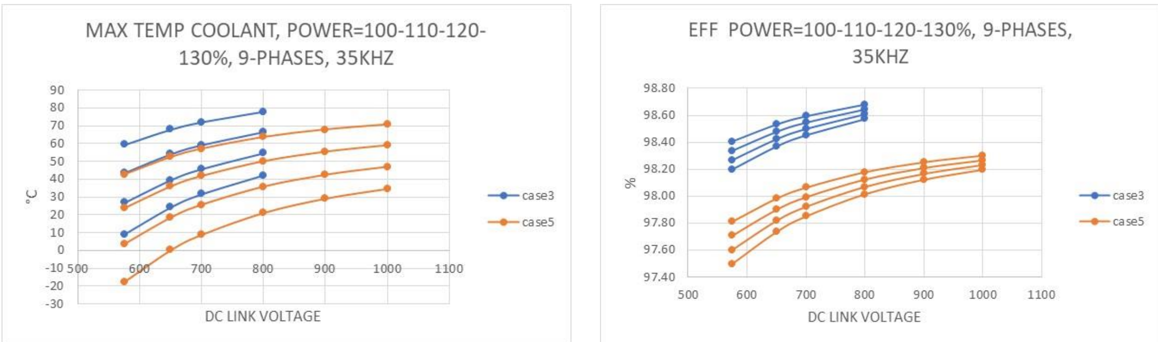
2.3.2 Design margins

The design margins study is mainly to consider the propulsion system’s capability to be of 130%. This study will be focused only on two power modules with 9-phase solution: case2 and case5 and the case of 9-Phases. The results are show in Figure 4 and Figure 5.



a) b)

Figure 4: a) Maximum temperature of the coolant, b) efficiency; 9-Phase machine and 25 kHz switching frequency for different DC Link voltage and power condition 100-110-120 and 130%



a) b)

Figure 5: a) Maximum temperature of the coolant, b) efficiency; 9-Phase machine and 35 kHz switching frequency for different DC Link voltage and power condition 100-110-120 and 130%

As can be seen from Figure 4 and Figure 5, a higher voltage level will result in a higher efficiency and thus can be with a higher temperature coolant. The 9-phase power converter design will have 130% overloading capabilities as long as the coolant is provided is a required temperature. However, when the switching frequency is 35 kHz, the coolant temperature has become unrealistic to around zero degree for 130% overloading. The switching frequency of 25 kHz seems to be a better option to maintain overload capabilities.

2.4 Power line configuration discussed at the kick-off meeting with variable DC Link

For the case that the battery is directly connected to the main DC Link. This means that DC link voltage is not fixed, and the DC-link voltage range of the DC link is between:

VDCmin=575 V VDCmax=800 V

In this case the machine needs to be designed for the minimum DC Link voltage and still with a capability to output 1 MW power. In that case, with voltage changes, the duty cycle changes, and a high voltage will result in more losses. Thus, t**he worst-case scenario is at maximum voltage and machine maximum designed phase current (i.e., torque).**

It is possible to have 3 independent busses.

With 3 independent DC Links the machine can have or 9 phases, but even if there are 3 different DC Link wiring system (i.e. 3 DC/DC converter, 3 batteries, 3 FC stack).

From previous calculation the best choice of the power module iscase2 for this voltage range (voltage is less than 800 V). Here we compared the 9-phase and 12-phase systems for 1 MW rated power consideration.

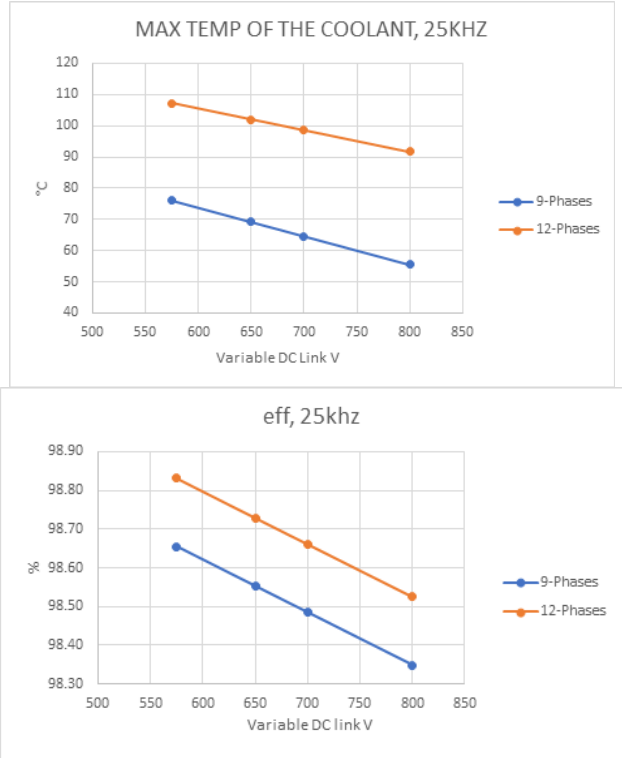


Figure 6: a) Maximum temperature of the coolant, b) efficiency; 25 kHz switching frequency for variable DC Link voltage.

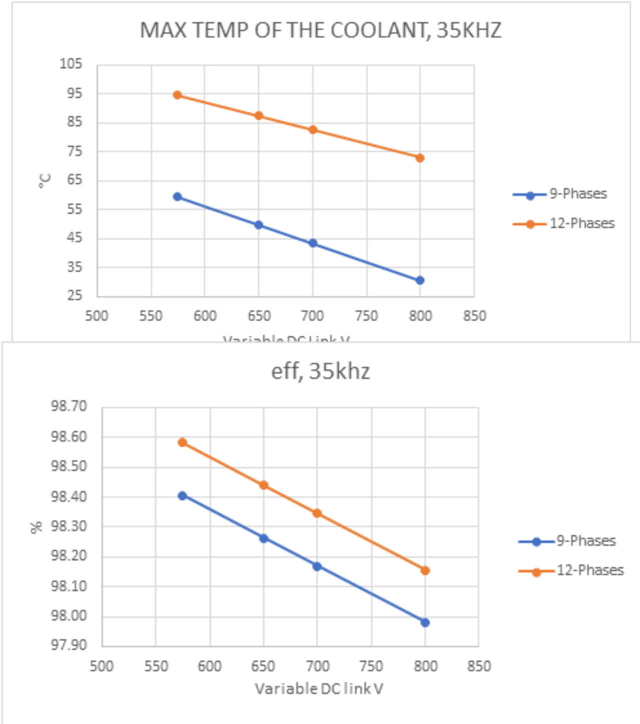


Figure 7: a) Maximum temperature of the coolant, b) efficiency; 35 kHz switching frequency for variable DC Link voltage.

From Figure 7, for 9-phase solution, if the DC-link voltage is equal to 800 V, it is clear that the converter can be operated with 35 kHz switching frequency since under these switching frequency, the maximum temperature of the coolant is required to be as low as ~35 °C.

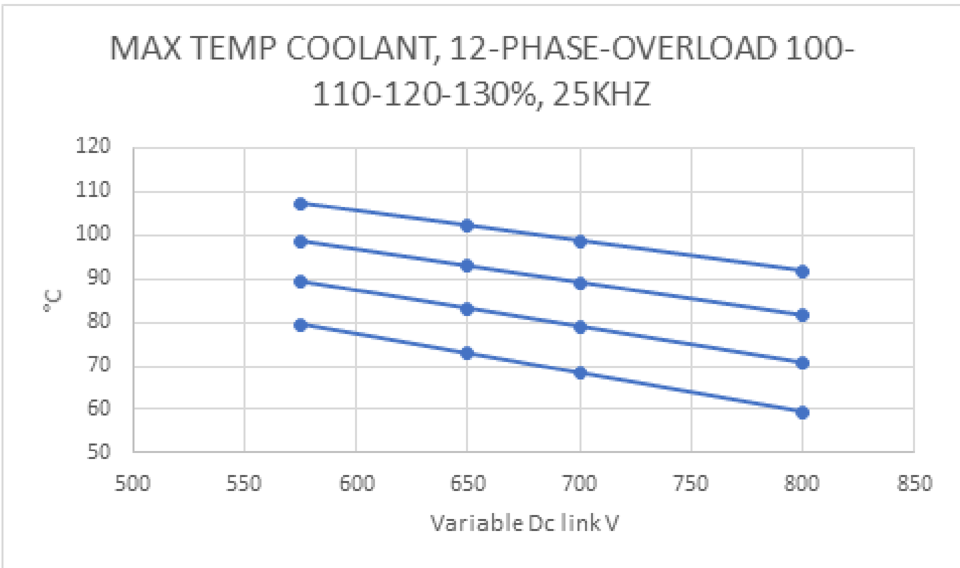


Figure 8: Maximum temperature of the coolant, at 25 kHz switching frequency for variable DC-link voltage in overload (100-110-120-130) from top to bottom.

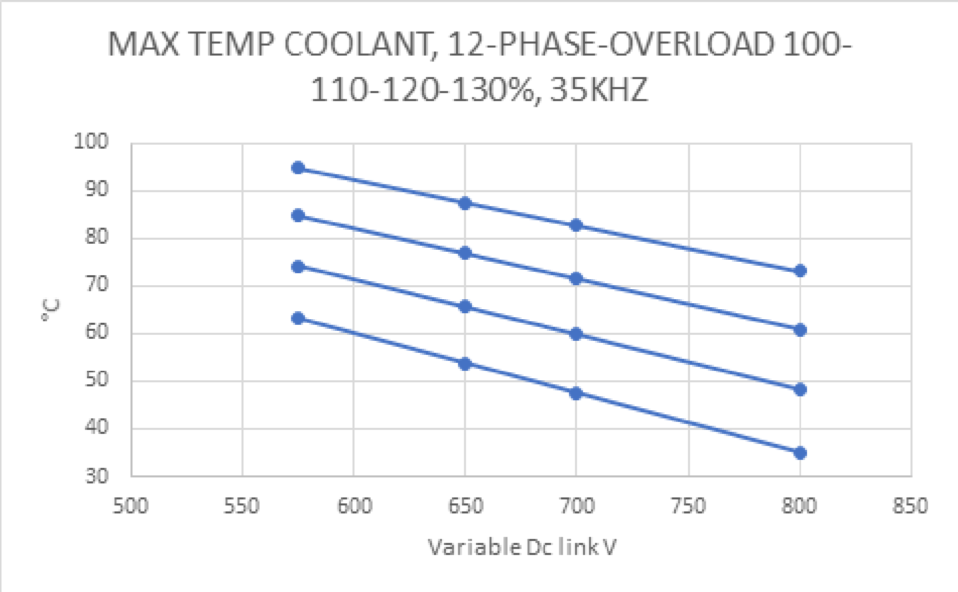


Figure 9: Maximum temperature of the coolant, at 35 kHz switching frequency for variable DC-link voltage in overload (100-110-120-130) from top to bottom.

It can be seen from Figure 8 and Figure 9 that the 12-phase solution will be a better option for overloading capabilities.

With the 9-phase solution, the switching frequency must be limited to 25 kHz to allow 130% overload capabilities. This in return limit the fundamental frequency of the machine to be less than 1 kHz. In this case there are no overload capability assuming the maximum temperature of the coolant equal to ~50 °C.

For the 12-phase scenario with 35 kHz switching frequency, and a coolant temperature of 50 °C it is possible to have an overload of 20%.

2.5 Losses-efficiency summary

Table 5: Summary of the most reasonable inverter solutions.

cases	power	Tmax pk coolant	VDC	IDC	fout	N phases	Phase current	power module	Overload capability	eff at 100%	
	MW	C	V	A	kHz		Arms	name	%	%	NOTE
1	1	50	700	1429	1	9	434	CAB760M12HM3	~30%	98.86	**possible solution 2**
2	1	50	700	1429	1	12	325	CAB760M12HM3	>30% (or 30%with Tcoolat at ~90C)	98.97	not possible for a 3x3 system
3	1	50	700	1429	1.5	9	434	CAB760M12HM3	~10%	98.59	**possible solution 4**
4	1	50	700	1429	1.5	12	325	CAB760M12HM3	>30% (or 30%with Tcoolat at ~70C)	98.71	not possible for a 3x3 system
5	1	50	1000	1000	1	9	304	CAB650M17HM3	>30% (or 30%with Tcoolat at ~65C)	98.68	**possible solution 1**
6	1	50	1000	1000	1	12	228	CAB650M17HM3	>30% (or 30%with Tcoolat at ~90C)	98.77	not possible for a 3x3 system
7	1	50	1000	1000	1.5	9	304	CAB650M17HM3	~15	98.3	**possible solution 3**
8	1	50	1000	1000	1.5	12	228	CAB650M17HM3	>30% (or 30%with Tcoolat at ~90C)	98.39	not possible for a 3x3 system
9	1	50	575-800	1739	1	9	528	CAB760M12HM3	0	98.35 to 98.65	not overload capability, **possible solution 5**
10	1	50	575-800	1739	1	12	396	CAB760M12HM3	~30%	98.52 to 98.83	not possible for a 3x3 system
12	1	50	575-800	1739	1.5	12	396	CAB760M12HM3	~20%	98.58 to 98.16	not possible for a 3x3 system

- The switching frequency of power converter is preferable to be 25 kHz and the machine maximum fundamental frequency should be limited to 1 kHz.
- Regarding the solution with fixed DC link there are two options: 700 V and 1000 V with two different modules (**case2 module for 700 V, case5 module for 1000 V)**.
- The solution with 1000 V is probably better for the DC/DC converter (battery side) to reduce the weight of the cables.
- With variable DC link, there are only one possible solution with a coolant temperature of 50 °C, and the system will not allow any overload condition for 9-phase solution.
- The 12-phase solution will be with good overload capabilities but will come with higher cost.

The maximum coolant temperature (temperature margin) allowed for all case studies is shown on the section 2.7 for power of 1 MW and 1.2 MW.

2.6 Power density estimation

The required power density for the converter is 18 KW/kg that means for 1 MW inverter 55 kg limit. If the power of the converter is 1.2 MW the weight limit is 67 kg.

Majority of the data are extrapolated from previous projects. At this stage this those number are just indicative.

Three case study are considered: all with 9-phases, and different DC link voltage, 700 V, 1 kV and variable DC Link voltage 575-800 V

In this study no overlord capability of an inverter is assumed because the power electronics typically have very short time thermal time constant of ~1-2 sec. **The maximum power is also the nominal value.**

DC capacitor consideration

The size of the DC-link capacitor is function of voltage, current and life expectancy set to 20000 h.

A possible choice is the C4AQ DC link (Automotive grade) series [X10], made by KEMET. T_{am} (temperature inside the box) have been assumed to be 80 °C.

In the case of 1000 V to get the 20000 h the capacitor must be rated at 1500 V and the temperature of the hot spot is ~87 °C.

In the case of 700 V to get the 20000 h the capacitor must be rated at 1100 V and the temperature of the hot spot is ~95 °C.

In the case of variable dc link (575-800 V) the capacitor must be rated at 1100 V and the temperature of the hot spot is ~95 °C.

Table 6: DC Link capacitor current requirement

Cases: DC Link	**Capacitor part number**	**Imax (for temp and life time) [Arms]**	**Dimension BxHxL [mm]**	**Weight [Kg]**	**Required current [Amrs] For 100% and 130% Power**	**Ncap** (must be a multiple of 6)	**Total weight [kg]**
1000	C4AQUBW5150A3OJ	14.6	35x50x42	.1047	381-480	36-36	3.6-3.6
700	C4AQQBW5250A3OJ	19	35x50x42	.1051	552-660	36-36	3.9-3.9
575-800	C4AQQBW5250A3OJ	19	35x50x42	.1051	660-810	36-54	3.6-5.7
575-**800**	C4AQQBW5250A3OJ	19	35x50x42	.1051	960-1125	54 - 72	5.7-7.5

In Table 6, we have been analysed two separate cases for the variable voltage cases, because the different duty cycles generated different current requirement, worst case scenario at high DC Link due to lower duty cycles.

<u>**Estimated Volume: 860 x 380 x 120 mm, ~40 l, "planar solution"**</u>

Table 7, Table 8, and Table 9 compare the weight of the main parts of the converters for the three different configurations of DC-link voltage, 1000 V, 700V, and a variable voltage of 575 V and 800 V. The best power resulting inverter density is for the cases with fixed and higher DC Link voltage.

Table 7: inverter weight - 9-phases with fix DC Link voltage at 1000 V.

9-PHASES 1000 VDC				
part	QTY	kg	tot kg	note
control board	1	0.30	0.30	Estimation from previous project
sensor board	1	0.30	0.30	Estimation from previous project
CURRENT SENSOR (HASS-400)	9	0.07	0.63	Data sheet + cables
copper bar output	9	0.10	0.90	Estimation from previous project
copper bar dc link	6	0.15	0.90	Estimation from previous project
gate drive	9	0.12	1.08	Estimation from previous project
Power PCB	3	0.40	1.20	Estimation: 2 layers with ~0.4mm thickness
power module	9	0.17	1.50	Data sheet
DC link cap	1	3.78	3.78	Data sheet
heat sink (for 3 module)	3	1.50	4.50	Estimation from previous project
power connectors	15	0.30	4.50	Estimation from previous project
differential inductor -DC side 20uH	1	10.29	10.29	Based on Metglass soft tool
box	1	12.80	12.80	Estimation: aluminium with 5 mm thickness
			42.68	Total weight [kg]

Table 8: inverter weight - 9-phases with fix DC Link voltage at 700 V.

9-PHASES 700 VDC				
part	QTY	kg	tot kg	
control board	1	0.30	0.30	Estimation from previous project
sensor board	1	0.30	0.30	Estimation from previous project
CURRENT SENSOR (HASS 500-S)	9	0.07	0.63	Data sheet + cables
copper bar dc link	6	0.15	0.90	Estimation from previous project
gate drive	9	0.12	1.08	Estimation from previous project
copper bar output	9	0.13	1.16	Estimation from previous project
power module	9	0.18	1.61	Estimation from previous project
Power pcb	3	0.60	1.80	Estimation: 2 layers with ~0.75mm thickness
DC link cap	1	3.76	3.78	Data sheet
heat sink (for 3 module)	3	1.50	4.50	Estimation from previous project
power connectors	15	0.45	6.75	Estimation from previous project
differential inductor -DC side 12uH	1	10.8	10.80	Based on Metglass soft tool
box	1	12.80	12.80	Estimation: aluminium with 5 mm thickness
			46.41	Total weight [kg]

Table 9: inverter weight - 9-phases with variable DC Link voltage at 575-800 V.

9-PHASES At Variable DC Link 575-800 V				
part	QTY	kg	tot kg	
control board	1	0.30	0.30	Estimation from previous project
sensor board	1	0.30	0.30	Estimation from previous project
CURRENT SENSOR (HASS 600-S)	9	0.07	0.63	Data sheet + cables
gate drive	9	0.12	1.08	Estimation from previous project
copper bar dc link	6	0.17	1.03	Estimation from previous project
copper bar output	9	0.14	1.28	Estimation from previous project
power module	9	0.18	1.62	Estimation from previous project
Power pcb	3	1.89	5.67	Estimation: 2 layers with 1.3mm thickness
DC link cap	1	5.67	5.67	Data sheet
heat sink (for 3 module)	3	1.50	4.50	Estimation from previous project
power connectors	15	0.55	8.25	Estimation from previous project
differential inductor -DC side10uH	1	12.00	12.00	Based on Metglass soft tool
Box	1	14.72	14.72	Estimation: aluminium with 5 mm thickness
			57.06	Total weight [kg]

For 9-phase the inverter, the mass is summarised as

- **42 kg for the 1000 V DC-Link case**
- **46 kg for the 700 V DC-Link case**
- **57 kg for the variable DC-link case (575 V - 800 V)**

In cases of 12-phase the inverter weight will be increase of ~30%:

- **55 kg for the 1000 V DC-Link case**
- **60 kg for the 700 V DC-Link case**
- **74 kg for the variable DC-link case (575 V - 800 V)**

2.7 Inverter cooling Loop

Heat sink reference: Microcool CP009 [ref. X11] for 3-phase system, or three power modules.

Assuming water-glycol 50/50.

Extrapolation per single power module:

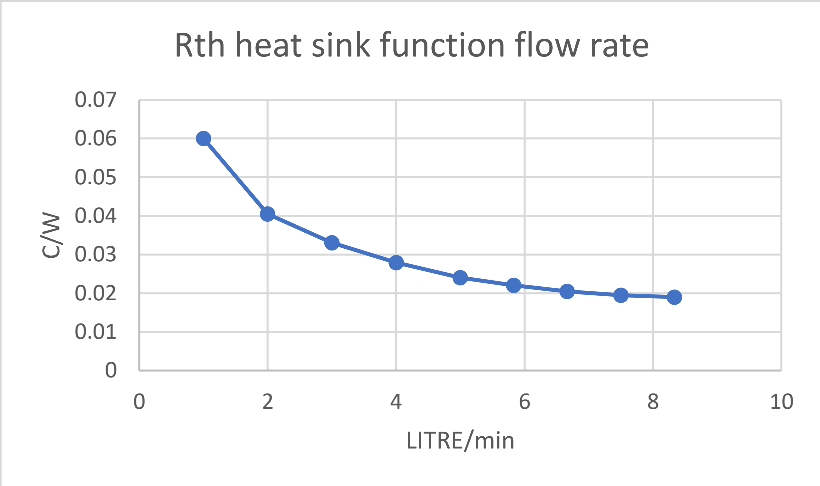


Figure 10: Thermal resistance of the heat sink for a single power module.

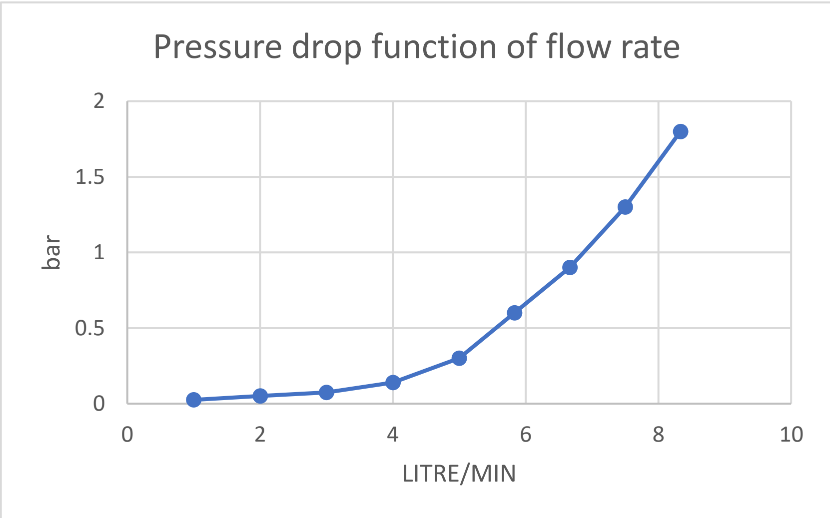


Figure 11: Pressure drop of the heat sink for a single power module.

The thermal resistor used in this study is 0.02°C/W, that means a flow rate of ~8.3 l/min and a pressure drop ~ 2 bar.

For a 9 Phase system the total flow rate is ~72 l/min, and pressure drop of ~2 bar, while for the 12-Phase the pressure drop still the same and the flow rate is ~96 l/min.

The ΔT of the coolant between inlet and outlet is ~8 °C

Table 10: Cooling requirement for all cases input power 1 MW.

Power	DC link	Phase	Fundamental phase frequency	Losses single module	Total losses	Flow rate water glycol	T inlet max	Pressure drop
MW	**V**	**N**	**kHZ**	**W**	**W**	**l/min**	**°C**	**bar**
1	700	9	1	1287	11583	72	89	2.0
1	700	9	1.5	1584	14356	72	72	2.0
1	700	12	1	863	10356	96	114	2.0
1	700	12	1.5	1086	13032	96	101	2.0
1	1000	9	1	1485	13365	72	92	2.0
1	1000	9	1.5	1919	17271	72	71	2.0
1	1000	12	1	1038	12456	96	114	2.0
1	1000	12	1.5	1362	16344	96	98	2.0
1	575-800	9	1	1866	16794	72	55	2.0
1	575-800	12	1	1248	14976	96	92	2.0
1	575-800	12	1.5	1566	18792	96	73	2.0

Table 11: Cooling requirement for all cases input power 1.2 MW.

Power	DC link	Phase	Fundamental phase frequency	Losses single module	Total losses	Flow rate water glycol	T inlet max	Pressure drop
MW	V	N	kHZ	W	W	l/min	°C	bar
1.2	700	9	1	1675	15075	72	67	2.0
1.2	700	9	1.5	2031	18279	72	46	2.0
1.2	700	12	1	1109	13308	96	100	2.0
1.2	700	12	1.5	1377	16524	96	84	2.0
1.2	1000	9	1	1880	16920	72	73	2.0
1.2	1000	9	1.5	2398	21582	72	47	2.0
1.2	1000	12	1	1353	16236	96	98	2.0
1.2	1000	12	1.5	1689	20268	96	82	2.0
1.2	575-800	9	1	Not considered				
1.2	575-800	12	1	1606	19272	96	71	2.0
1.2	575-800	12	1.5	1988	23856	96	48	2.0

Table 10 and Table 11 show the comparison for all different cases, for a power level of 1 MW and 1.2 MW.

Note those tables are useful to see the difference between the cases, they do not give the input for the coolant system.

Also note that the maximum temperature of the cases of the power module should not exceed 125 °C.

The input data for the cooling system are the follow:

20 kW heat losses, maximum inlet temperature of 70 °C, flow rate 72 l/min for the 9-phase and 96 °C for the 12-Phase cases.

Note to the outlet temperature: this heat sink with a 7 l/min per module has a thermal impedance between inlet and outlet coolant of ~0.0023 K/W. The delta T between inlet and outlet in case of 2000 W losses per module is 4.6 °C.

3 MACHINE AND GEARBOX

The electromechanical drivetrain (machine and gearbox) are designed at 1 MW rated power with a 20% overload capability. Different propeller speeds were considered to allow for a trade-off with the propellor properties including noise.

The choice of direct-drive machine or a geared version is an important decision in the NEWBORN project since it effects not only the power density, but also other important aspects including the number of components, the mean time between critical failure (MTBCF) as well as the overall packaging.

Within this work-package UNOTT investigated the geared vs. direct-drive with a focus on reducing the total mass whilst accounting for efficiency, volumetric constraints, power electronics limits as explained in the previous section and drivetrain complexity.

For any electrical machine, the size and power density are dependent on the product of the magnetic loading and the electrical loading. High power density electrical machines can be in general classified as (i) electrically loaded machines, i.e., machines which use a higher electrical loading or (ii) magnetically loaded machines, i.e., machines which use a higher magnetic loading. Topologies with a higher magnetic loading include, but are not limited to, Vernier Machines and Transverse Flux Machines.

In general, in this exercise, the machines are designed to match the PE converter with a fundamental frequency limited to around 1 kHz. A premium material recipe, summarised in Table A, is employed for the motors which includes the use of thin (0.05 mm) cobalt-iron laminations, high grade Samarium Cobalt Magnets, and the use of winding technologies which mitigate effectively winding AC effects.

Table 12: Materials used within the electrical machine studies

Component	Material
Iron Core	Cobalt Iron laminations, 0.05mm
Magnets	Samarium Cobalt, Halbach arrangement

Figure 12 summarises UNOTT's studies on mass estimation of the electrical machine and gearbox (for the case of high-speed machines with a step-down gearbox), considering different machine type solutions.

The blue line within the aforesaid figure represents the direct-drive surface permanent magnet (SPM) machine with a high electrical loading and with an efficiency in the range of 97-98%. The mass of the machine in this case varies from 250 kg down to just below 140 kg across the speed range 1000-2000 rpm. With more intensive cooling such a machine topology can be made more compact and lightweight, while accepting higher losses (i.e. a lower efficiency). For an efficiency of 95-96% the direct drive SPM-machine, represented by the green lines achieves a total mass of 170 kg down to 90kg across the speed range of interest, which is as much as 30% less mass with respect to the case with higher efficiency.

In the same plot high speed machines with high electrical loading and employing a gearbox are represented by the brown line (two examples are also given in Figure 14 (a) and (b)). Due to the compact nature of high-speed machines the losses, especially in the iron, tend to be lower due to the lower iron mass, which can partly describe the good observed efficiencies. At propeller speeds of around 2000 rpm the mass of the geared system is similar to the direct-drive machines of comparable efficiencies. It could be concluded that at such higher propeller speed, the use of a geared drive does not bring any particular advantage and only results in a more complex system with an additional component to qualify and maintain. This could also lead to a reduced MTBF; gearboxes are however very reliable as long as they are maintained. At lower propeller speed the mass of the geared system follows closely that of the direct-drive SPM with lower efficiency. Justification of either system i.e. lower efficiency direct-drive SPM or higher efficiency geared version requires further careful system-level considerations including the maintainability, qualification aspects, additional impact of the thermal management on weight as well as aircraft drag.

The trend with the direct-drive magnetically loaded machines is represented by the red line (an example machine design for the NEWBORN project is shown in Figure 14.(c)). Generally, these topologies achieve lower mass, around 10-15% less with respect to the more-traditional direct-drive SPM machines of comparable efficiency. However as can be seen in Figure 13, due to their higher V*A requirements, these topologies result in more converter mass, and within the speed range investigated translate to a higher overall e-drive mass with respect to the conventional topology. Such machines tend to perform better in case of direct air cooling.

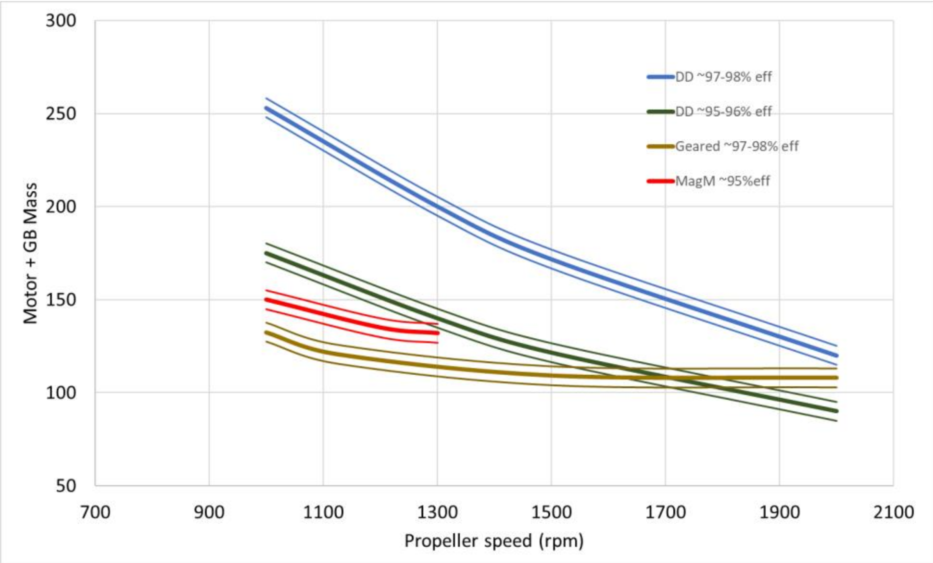


Figure 12: Estimated Motor+Gearbox mass across the propeller speed range of interest

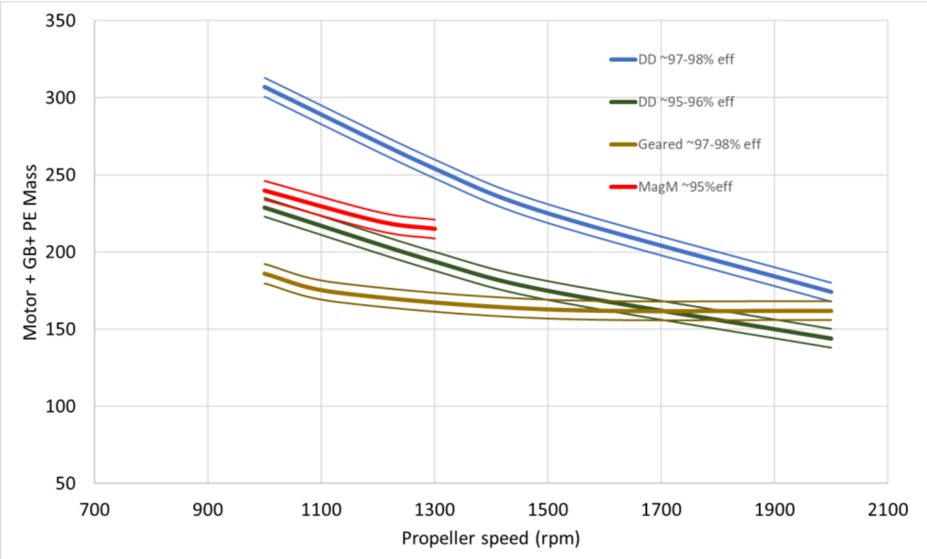
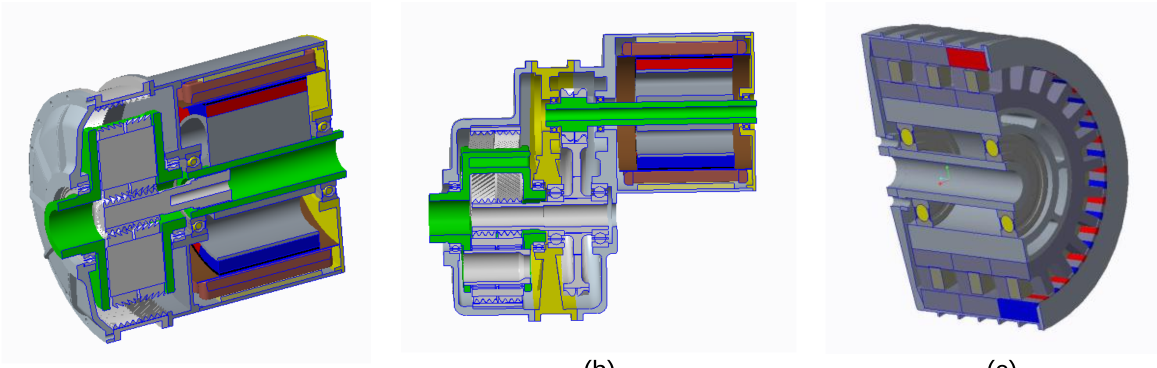


Figure 13: Estimated Motor+Gearbox+PE mass across the propeller speed range of interest

From the foregoing discussions it can be summarised:

(i) For high-speed propellers, (above ~1,800 rpm), a direct-drive electrically loaded machine is the best solution. For a given efficiency its power density is similar to the geared solution with the added advantage of higher reliability and lower maintenance. Furthermore, it gives ample flexibility to maximise the power density by further handling extra losses.

(ii) For propellers with lower speeds (speeds lower than 1,800rpm), both the geared solution and the direct-drive electrically loaded machine could be viable solutions. Geared machines give the best weight-efficiency compromise at the expense of higher maintenance. Further detailed studies will be required to quantify the efficiency vs. reliability aspects between the aforesaid solutions.



(a) (b) (c)

Figure 14: Examples of some of the investigated concepts (a) 9 krpm motor + 8:1 gearbox, (b) 20 krpm motor + 20:1 gearbox, (c) transverse flux motor

4 COOLING TRADEOFF

For the NEWBORN propulsion cooling system, two independent cooling channels will be used as shown in Figure 15.

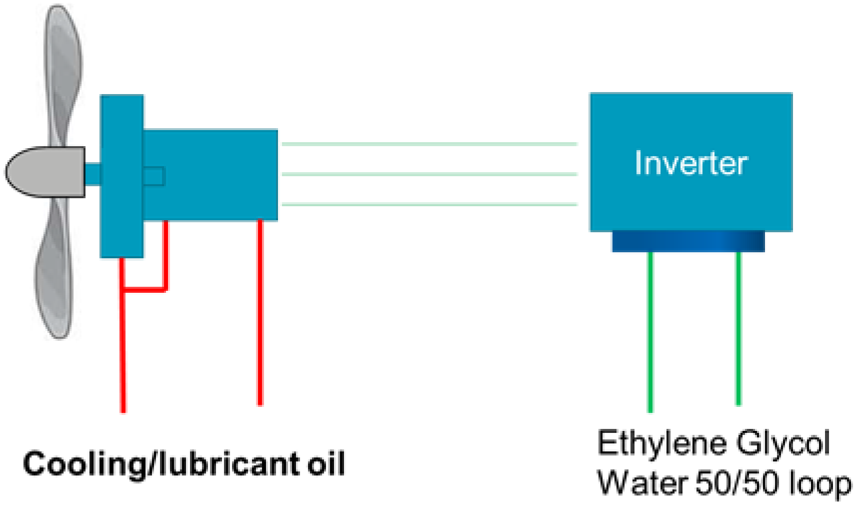


Figure 15: NEWBORN propulsion motor system cooling system high-level plan

The propulsor machine will be oil-cooled and the inverter will use water cooling. During the initial trade-off studies, the cooling design is based on the assumption that the machine achieves 98% efficiency. The selected oil can also be applied for gearbox lubricant (if the geared option is selected) and cool the gearbox. A total of 40 kW cooling capacity is needed for the machine cooling loop (considering some safety margin).

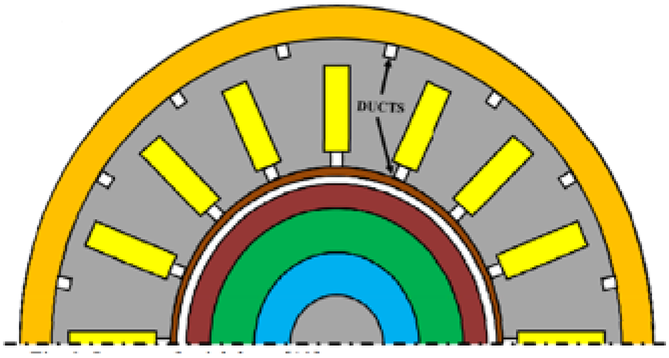
BP2389 oil is assumed as coolant for initial studies, and several cases of machine power and efficiencies listed in Table 13 are selected for oil cooling loop initial design. At the rated power, 1 MW and 98% efficiency, about 100 l/min oil flow is needed to cool the machine with an oil temperature rising of 7 degree and able to remove the heat from electrical machine. The pressure drop is approximately 2 bar. For the case of 97% machine efficiency at a peak power of 1.2 MW, flow rate of 180 l/min is needed to be able to cool down the machine efficiently. To achieve high power density with directly drive machine the efficiency could be dropped down to 94.9% and total loss of machine will be as high as 51 kW, in this worst case, total 255 l/min oil flow rate is needed to cool the machine efficiently.

For the inverter, the coolant flow rates needed can be found in the previous section of this report.
Case 1: the machine is considered machine is working 1 MW (geared option)
Case 2: the machine is considered machine is working 1.2 MW (geared option)
Case 3: the machine is considered machine is working 1 MW (direct option, High efficiency design)
Case 4: the machine is considered machine is working 1.2 MW (direct option, High efficiency design)
Case 5: the machine is considered machine is working 1 MW (direct option, Low efficiency design)
Case 6: the machine is considered machine is working 1.2 MW (direct option, Low efficiency design)

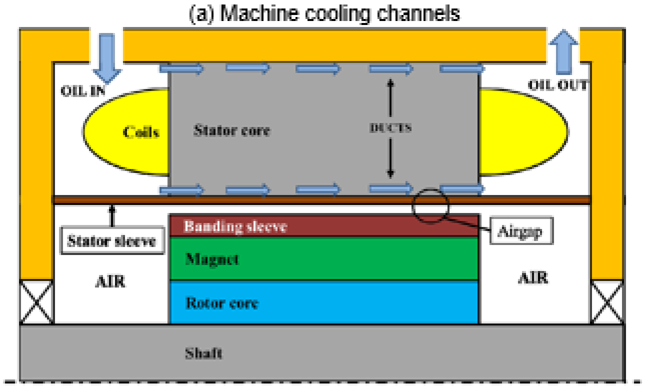
Table 13: Electrical machine oil cooling capacities

Items	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Machine power (kW)	1000	1200	1000	1200	1000	1200
Efficiency	98%	98%	98%	98%	95.0%	95.0%
Loss in EM (kW)	20	24	20	24	50	60
Gearbox loss efficiency	99.60%	99.60%	N/A	N/A	N/A	N/A
Loss in GB (kW)	4	4	0	0	0	0
Total loss (kW)	24	28	20	24	50	60
Oil flow rate (L/min)	116	135	97	116	242	292
Temperature rising (°C)	7.0	7.0	7.0	7.0	7.0	7.0
Tinlet (°C)	90	90	90	90	90	90
Toutlet (°C)	97.0	97.0	97.0	97.0	97.0	97.0
Pressure drop (bar)	2	2	2	2	2	2

A **semi flooded oil cooling concept** will be considered for NEWBRON electric propulsor motor and has been applied to all the considered machine solutions investigated in the trade-off study. This cooling concept has been used for several high-speed machines developed in UNOTT and proven to be a good solution that provides very effective cooling performances especially for cases with high loss density. Figure 16 shows an example of the cooling concept where cooling channels are created inside the slots of the machine and back iron of stator core. An oil sleeve is fitted in the air gap of machine to separate the machine into an oil flooded stator chamber and a dry rotor chamber. The major loss of the machine concentrated in machine windings and stator core can be directly removed by the oil flow through the machine while in the rotor chamber, high windage loss on high speed rotating rotor surface can be avoided due to oil free of rotor chamber.



(a) Machine cooling channels



(b) Machine cooling flow through

Figure 16: A semi-flooded cooling concept for machines.

Initial cooling performances of all machines developed have be investigated at the similar cooling flow rate and boundary conditions. BP2389 turbine oil is applied to cool the machine with constant inlet temperature of 90 °C, the flow rate of oil is set up to 100 l/min and the ambient temperature is set up at 50 °C.

5 SUMMARY

This report summarizes the trade-off studies of NEWBORN propulsion motor drive system. Different DC bus voltages have been considered and a few conclusions can be drawn below

- A higher voltage DC bus is beneficial to improve the efficiency of the electric propulsor drive systems. Thus 1 kV DC bus voltage is recommended from the point of view of the propulsion system, out of the assumed options. The second-best option would be a fixed 700-800 V DC-link voltage.
- The DC-link voltage is dominating the module selections. From this trade-off studies, it is clear that module case2 fits best the 700 V or 800 V DC-link voltages, and case5 the 1000 V DC-link applications.
- The 9-phase machine system will have no overload capability with variable DC-link voltage 575 V – 800 V. If a variable DC-bus voltage is selected, the NEWBORN propulsor electric drive system needs to be 12-phase to accommodate 130% overload capabilities. This will result in a higher cost and weight on the machine drive side (by saving a DC/DC converter at the battery side).
- For thermal management, the electrical machine will be using oil cooling and power converter will be water cooled.
- The solution of electric machines and gear options is dependent on the constraints to the propeller speed:
    - i) For high-speed propellers, (above ~1,800 rpm), a direct-drive electrically loaded machine is the best solution. For given efficiency, its power density is similar to the geared solution with the added advantage of higher reliability and lower maintenance. Furthermore, it gives ample flexibility to maximise the power density by further handling extra losses.
    - ii) For propellers with lower speeds (lower than ~1,800 rpm), both the geared solution and the direct-drive electrically loaded machine could be viable solutions. Geared machines give the best weight-efficiency compromise at the expense of higher maintenance.

6 REFERENCES

ID	Reference	Title	Revision
X10	**Data Sheet**	**C4A Q** https://content.kemet.com/datasheets/KEM_F3114_C4AQ.pdf	
X11	**Data Sheet**	**CP3009** https://www.microcooling.com/wp-content/uploads/2015/05/CP3009-data-sheet.pdf	