ASUMED – DELIVERABLE

System topology report

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1 Introduction

Air traffic is projected to grow worldwide by 5 % each year in the near future. This steady rise will lead to a highly grown amount of emission. In the *Flightpath 2050* convention, *ACARE (Advisory Council for Aviation Research and innovation in Europe)* targets to reduce the emission of $C0_2$ by 75 %, NO_x and particulates by 90 % and noise by 65 % compared to the year 2000 [1]. The continued incremental improvements of the conventional "tube and wing" aircraft configuration will not be sufficient enough in the future to cover the goals.

With *Distributed Propulsion (DP)* systems seen as a breakthrough-technology to achieve this ambitious goal, the demand for compact, light-weight and highly-efficient electrical machines is set [2]. Normal conductive (*nc*) electrical machines cannot obtain the required values in power density and efficiency. Superconductivity is a key technology to fulfil these requirements.

The consortium of the *ASuMED* (*Advanced Superconducting Motor Experimental Demonstrator*) project will develop, build and test the first fully superconductive motor for aerospace applications. This direct drive motor for aircraft propulsion will prove its potential as an enabler for electric *DP* in large civil transport aircraft.

1.1 Overall topology

To realize *DP* and the electrification of aircraft propulsion systems, different possibilities have been studied and presented, e.g. by the *National Aeronautics and Space Administration (NASA)*. *Figure 1* shows different kinds of system architectures like parallel hybrid, series hybrid, turbo electric and all electric solution. Comparable concepts are already well integrated in the automotive sector, showing their benefits.

With differences in power supply and arrangement of the electrical machine, the requirements for energy-efficient motors with high power-densities are the same.

In this overall topology *ASuMED* focuses on the development of the electrical machine meeting all requirements within the *DP* system for an aircraft application. Beside the first all superconductive motor, a corresponding efficient cryostat as well as a suitable power electric drive system has to be well designed to interact properly.

This document describes the system topology of the *ASuMED* project. It shows different common motor topologies with its properties to choose the best fitting solution for aerospace environment. The cryogenic topology as well as the power electric drive system is presented in further chapters.

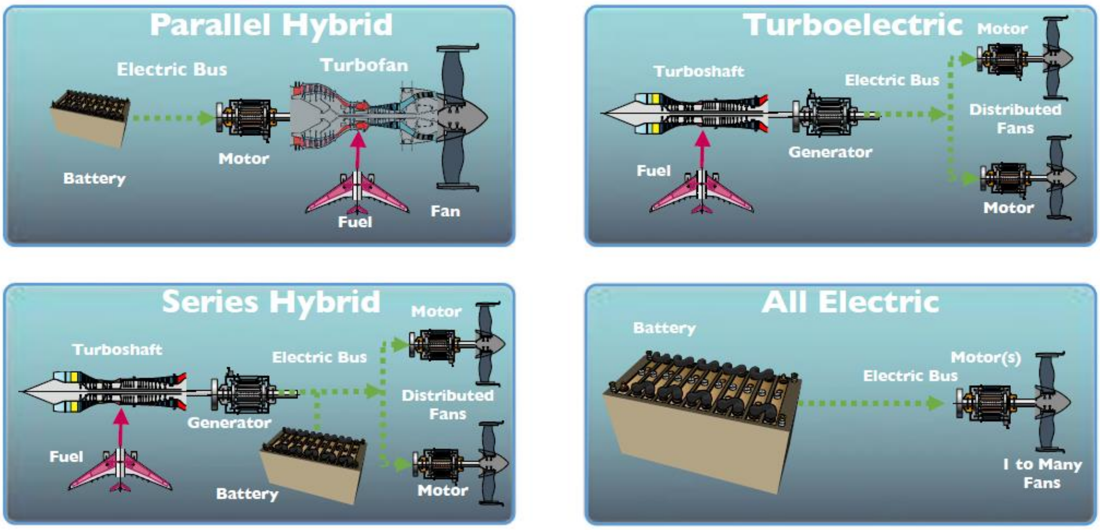

Figure 1: Alternative distributed electrical propulsion configurations (source NASA [3])

1.2 References

[1] ACARE: Flightpath 2050 Europe´s Vision for Aviation, 2011, doi 10.2777/50266
[2] Berg F, Palmer J, Miller P, Husband M, and Dodds G, 2015 HTS Electrical System for a Distributed Propulsion Aircraft Applied Superconductivity, IEEE Transactions on, 25 1-5
[3] Nateri Madavan, presentation NASA advanced air vehicles program, held during workshop on technology roadmap for large electric machines, University of Illinois Urbana-Champaign, April 5-6 2016

1.3 Acronyms

A	Ampere
AC	Alternate current
approx.	Approximately
$C0_2$	Carbon di oxide
DC	Direct current
DP	Distributed propulsion
etc.	Et cetera
HTS	High-Temperature Superconductor
K	Degrees Kelvin
kg	Kilo-Gramm
kA	Kilo-Ampere
kW	Kilo-Watts
m	Metre
mbar	Milli-bar
mm	Milli-metre
ms	Milli-second
MW	Mega-Watt
NO_x	Nitrogen oxide
NASA	National Aeronautics and Space Administration
nc	Normal conductive
Nm	Newton-metres
sc	Superconductive
T	Tesla
V	Voltage
W	Watt

2 Motor topology

In this chapter the most common and established motor topologies as well as the way to improve their attributes by superconducting technology are described.

The power of an electrical machine can be described by $P \sim (\pi/2) \cdot B \cdot A \cdot D^2 \cdot L \cdot \omega$, where *B* is the average magnetic loading, *A* the average electric loading, *D* the rotor diameter, *L* the rotor length and ω the rotor angular speed. It can be seen that the power is linearly proportional to the air gap field produced by the rotor and the current that can be carried by the stator coils. With the use of superconductive materials both factors can be highly increased compared to conventional conductive motors. Reachable current densities of superconductive tapes (~150 A/mm²) compared to copper wires (~ 2-5 A/mm²) as well as magnetic flux densities achieved by superconductive stacks/bulks (> 2,5 T) compared to the magnets based on rare-earth materials like *NdFeB (neodymium iron boron alloy)* (<1,6 T), are showing potential. Building more compact and lighter motors with the same power than nc motors or reaching higher power with same weight and size leads to power-densities needed for DP in aircraft application.

The following sections present various motor topologies in which superconductivity is used in different ways. The estimated power density compared to nc motors as well as corresponding advantages and disadvantages are described.

All topologies have an AC stator winding system (sc or nc) in common. These coils create a rotating magnetic field inside the machine, the stator field.

2.1 Reluctance Motor

The reluctance motor is based on the principle of magnetic reluctance force. *Figure 2* shows an example of the cross section of a reluctance motor. Sections of high and low magnetic reluctance alternate along the rotor. The magnetic reluctance as equivalent to a magnetic resistance influences the guidance of the magnetic flux. Parts of high reluctance are typically formed by air gaps within the rotor, or in the sc application by sc material (yellow coloured). Low reluctance is obtained by parts of soft iron. Magnetic flux, created by the stator windings, will concentrate in areas of low reluctance causing a reluctance force which moves the rotor in state of lowest energy.

In this topology only the rotor has to be cooled below the critical temperature of the superconductor. The estimated force density compared to a normal conductive permanent magnet motor is approximately 130 % and therefore the advantage of using superconductors in the rotor of a reluctance motor is limited for high power density applications.

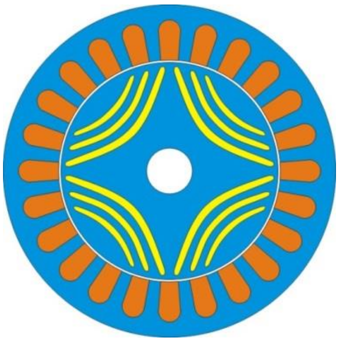

Figure 2: Reluctance Motor

2.2 Synchronous motor

The synchronous motor uses the interaction between the magnetic field of stator and rotor to create a torque. The magnetic field of the rotor can be created by electromagnets or permanent magnets. Some different ways of implementing superconductivity in this topology are presented in the following sections.

2.2.1 SC excited synchronous motor

In the excited synchronous motor topology the rotor magnetic field is created with coils working as an electromagnet (*figure 3*). By using superconductive coils (yellow coloured) instead of normal conductive ones, much higher flux density in the air gap can be created. The benefits of this DC application of superconductivity in the rotor coils are the nearly loss free operation of the superconductors and the possibility to influence the excitation actively during operation. But to obtain a high magnetic flux, high currents have to be supplied to the rotor coils.

A rotatory cryogenic and a cooling system for the rotor coils as well as a high current joint (many kA) are needed. The estimated force density compared to a normal conductive permanent magnet motor is > 200 %.

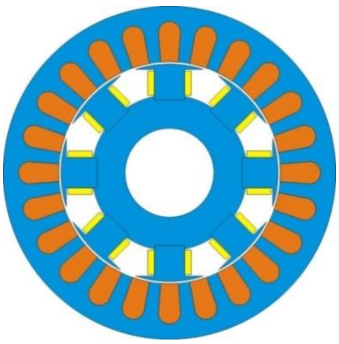

Figure 3: Excited synchronous motor

2.2.2 Permanent Magnet excited synchronous motor

Instead of electromagnets this topology uses normal conductive permanent magnets to create the magnetic field of the rotor (*figure 4*). For a high flux density rare-earth materials such as NdFeB are used. But even these materials are physically limited to a maximum flux density of approx. 1,6 T. To reach a higher power density, the stator coils are superconductive (yellow coloured) which allows a much higher current density compared to copper coils. In this AC application of superconductivity,the superconductive stator coils are not loss free. AC losses like transport current -, hysteresis - and coupling losses make a complex cooling system in the stator necessary.

The estimated force density compared to a normal conductive permanent magnet motor is > 250 %.

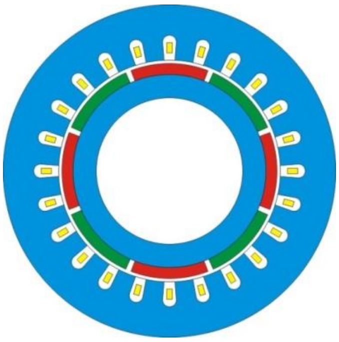

Figure 4: Permanent Magnet SM

2.2.3 Fully SC synchronous motor

The fully superconductive motor topology combines the previous described topologies and result in highest power density values.

With a superconductive stator winding system a high electric load can be obtained. In order to get highest rotor flux values two possibilities can be considered: sc coils (*figure 5*) or sc magnets (*figure 6*).

Although designed to carry transport current, pieces of high-temperature superconductor tapes (HTS) can also sustain persistent currents which correspond to trapped magnetic fields. Stacks of HTS tape can generate fields much greater than rare earth magnets, despite containing less than 2% superconductor by volume. To create sc magnets, so called field trapping technology is used. It allows “the storage” of magnetic flux to superconductive stacks or bulks. Different kinds of field trapping methods can be used and result in a remaining magnetic flux even if the applied field is removed from the sc stack or bulk. The field cooling technique requires the application of steady high magnetic fields only possible with superconducting coils. In pulsed field magnetisation standard technology can be used but this technique only traps a fraction of the field possible by field cooling.

For usage within an electrical machine the stator coils or specific magnetisation coils have to create the magnetic field which should be trapped.

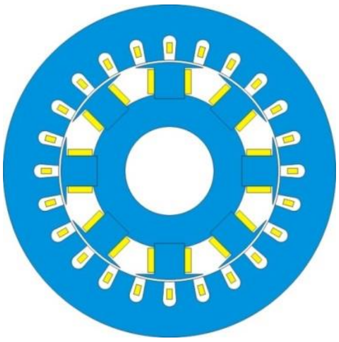

Figure 5: SC motor (rotor sc coil)

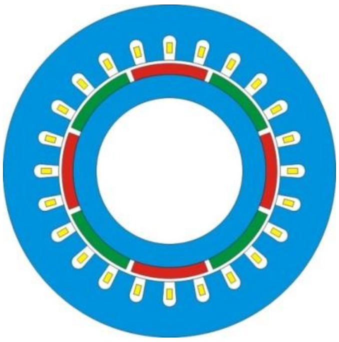

Figure 6: SC motor (rotor sc magnets)

The estimated force density compared to normal conductive permanent magnet motor is > 300 %.

2.3 Summary

Comparing the presented topologies with their different advantages and disadvantages, the most suitable and efficient topology to fulfil the needs in DP and aircraft application and therefore for the *ASuMED* project is the fully superconductive synchronous motor with sc stacks on the rotor. The extreme high current density in the stator coils combined with the flux density trapped by the superconductive magnets will enable the highest power density. The complex cryostat and cooling for stator and rotor as well as the magnetisation of the sc stacks are a challenge for the development but also key points to achieve the ambitious goals.

Besides these first considerations of the overall motor topology, more motor specific details like mechanical power, rated torque and speed are set by the aircraft application. These boundary conditions lead to mechanical and electrical attributes like operating voltage, current, frequency, pole pairs, number of coils and windings per coil, etc.

3 Cryostat

As described in the last chapter, the fully superconductive motor of the *ASuMED* project will consist of sc stator coils and sc permanent magnets on the rotor. To reach a superconductive state, the temperature of the superconductor has to be lower than its critical temperature. To use high temperature superconductors like *YBCO tapes (Yttrium barium copper oxide* compound*)* in the stator and for the rotor stacks, the temperature has to be lower than 93 K. If the temperature is decreased further the critical current density of the tapes will increase, leading to a more efficient and higher power/torque motor. Therefore possible cooling mediums can be nitrogen, neon, hydrogen, helium or an active cooling with coldheads. Depending on the cooling temperature hydrogen and helium can be used liquefied or gaseous. To reach an efficient operation at these extreme low temperatures, high requirements on the design of the cryostat are set. Temperature differences >250 K from surrounding to inner cryogenic area are challenges to the development. Due to this high temperature difference not only the losses of the superconductors itself but also cryostat losses have to be considered. Different thermal isolation methods are used to minimize cryostat losses. Heat conductance, due to contact surfaces of different temperatures, can be lowered by using isolation materials with low thermal conductivity coefficient and a contact area as small as possible. Heat transfer by radiation can be lowered with multi-layer isolation. Multiple layers of reflective films (e.g. silver) are used to reflect the thermal radiation. Vacuum inside the cryostat prevents the heat transfer by convection.

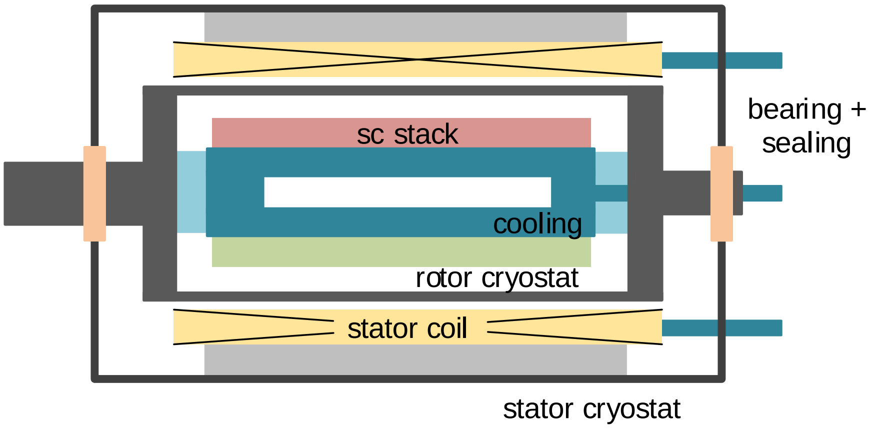

Figure 7: Example of motor cryostat

Figure *7* shows an example of the cryostat for a fully superconducting motor. There are two separated cryostats for stator and rotor giving the opportunity to select different cryostat topologies. This chapter gives an overview of different topologies with individual critical issues.

3.1 Stator cryostat

Using superconductors in the stator leads to remarkable thermal losses due to the AC application, up to 1% of the system power. A well designed cooling system with a high cooling capacity is necessary. The cryostat made of metal should have a small surface in the active motor parts to minimize eddy currents or should be set up with non-conductive material (e.g. plastic). The advantage of a static cryostat is the mechanically simple vacuum isolation and cryogenic supply. So far only small number of systems including superconductors in AC application in the stator have been tested.

3.1.1 Liquid cryogen bath

Filling the stator area complete with a liquid cryogen like nitrogen is a reliable concept to cool the stator winding system. This concept also means additional losses due to iron losses and makes a cryostat in the airgap necessary. Having such a cryostat increases the airgap by a few millimetres and reduces the system power.

3.1.2 Cooling circuit

In this cryostat concept a more flexible design of the cryostat is possible, so the additional iron losses and a cryostat in the airgap can be avoided. In a closed cooling circuit the cooling medium should be a gas with good heat conductivity like helium and depending on the stator losses a high recooling capacity is needed. For circulation a vent is necessary. In an open circuit all cryogenics can be used but it is recommended to use a liquid medium due to the advantage of evaporation cooling. For economic issues helium and neon should be avoided in an open cooling circuit.

3.2 Rotor cryostat

Having a superconducting rotor is the common way of developing superconducting electric machines. The needed cooling capacity is very low due to the DC application. The challenge in this cryostat concept is the rotating system and the needed mechanical connection to distribute the torque from the motor at cryogenic temperatures to the application at room temperature. At least parts of the cryostat are rotating including some kind of cryogenic supply joint for the cooling medium. Bearings and rotating sealing only work at room temperature and should be very well thermally isolated from the cryostat, maybe additional heating is necessary.

3.2.1 Thermosiphon (closed cooling circuit)

Cooling with the thermosiphon effect is well known and the major tasks like sealing, bearing and coolant supply are solved. The liquid cryogen evaporates in the rotor, rises through a heat pipe to the recooling device, gets liquefied and goes back to the rotor. On today’s market there is no recooling device suitable for operation in an aircraft.

3.2.2 Direct active cooling

In this concept a coldhead is integrated in the rotor and in contact with the cold parts (coils or stacks/bulks) through a coldbus. The coldhead is rotating and the compressor is static. Solutions for working gas feedthroughs are available on the market. The advantage of this concept is the operation without a cooling medium, thus there is no need for a cryostat, only a vacuum chamber at room temperature is necessary.

3.2.3 Open cooling circuit

There is no system with an open cooling circuit in the rotor on the market. Such a cryostat is only useful if the stator is cooled with a suitable cooling medium. Otherwise it is more economic using a coldhead. But using the cryogenic from the stator also for the rotor leads to a very lightweight rotor cooling concept, fitting to the demands of the aviation industry.

3.3 Summary

A fully superconducting motor is a new investigation but combining two separated cryostats for stator and rotor give the opportunity to select each cryostat topology independently with demand to the individual critical issues. Depending on the expected losses in stator and rotor, the availability of different cryogenics and economic issues a suitable overall cryostat topology will be chosen.

4 Power electronics

The function of the power electronics is not only to supply the motor with the electrical energy but also to control the motor operation and to protect the system. A superconducting motor requires a specific inverter, since superconductors behave differently from normal copper windings. Therefore specialized hardware and software has to be developed.

4.1 Overall topology

The overall electrical system of DP consists of a power source (e.g. generator or battery) a distribution grid, the inverter and motor.

Generally the output stage of an inverter is supplied by a DC voltage link. This DC link can be connected directly to a superior DC source, a DC/DC converter if connected to a DC source of different voltage level or an AC/DC converter if connected to an AC grid (*figure 8*). In an aircraft application with *DP*, a common DC grid which connects all the inverters would perfectly fit to the sc technology to obtain lowest power losses during energy transfer within the complete system.

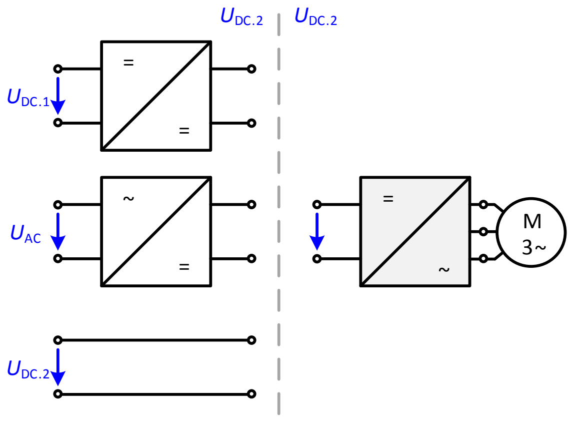

Figure 8: overall power electronic architecture

4.2 Semiconductors and inverter topology

In *figure 9* a common inverter topology to feed a 3-phase electrical machine is shown. Two semiconductor switches (e.g. IGBT modules) form a so called half-bridge which is connected to one phase of the electrical machine.

Depending on the rated current and voltage of the motor, best fitting semiconductors will be chosen. The investigation and comparison of semiconductor materials e.g. silicon or gallium nitride will lead to best performance results. The behaviour at cryogenic temperatures will influence the choice as well.

The inverter topology will be chosen considering the number of phases, semiconductor switches per phase, the usage of several inverters in parallel or series. These techniques can bring benefits in number and height of creatable voltage levels, redundancy, electromagnetic compatibility and power sharing possibility. Tailored driver electronics enable fast and efficient switching of the semiconductors.

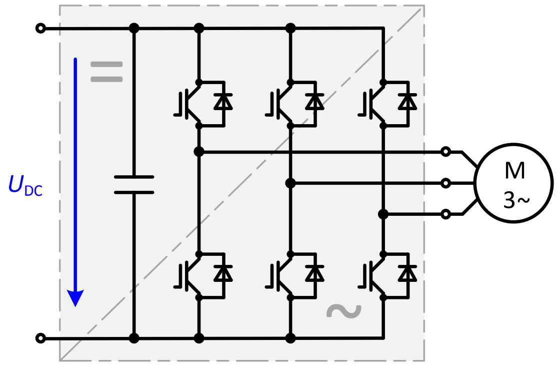

Figure 9: common 3 phase inverter topology

4.3 Control strategy

Depending on the state of the semiconductor switches (open or closed) the positive or negative potential of the DC link is supplied to the motor windings. Pulse width modulation technique can be used to control the phase currents by adapting the corresponding phase voltages as a mean value within a switching cycle. The switching frequency has an impact on the current ripple, switching losses and motor losses due to harmonics.

The control strategy will take modern methods known from conventional motor operation into account. In view of high dynamic speed and torque control, as well as energy optimised operation and the different behaviour of superconductive windings, a novel strategy will be developed and implemented. Furthermore, a special current waveform can decrease the AC-losses of the superconductor even more and will be considered as well.

4.4 Safety concept

The high safety requirements in aircraft applications demand a specialized protection system. In case of system failures (e.g. short circuit) the fail safe strategy for the power electronics has to protect the inverter itself and all connected components. To avoid further damage, the voltage has to be switched off immediately. With a continuous measurement of the different system variables (e.g. winding current, temperature) and comparison with critical values a real time system protection is realizable. Furthermore detection methods for sc quenches will be developed and implemented.

4.5 Summary

The development of a power electronics drive system for superconductive machines within an aircraft system is a challenge for the hardware and software. High power, compact and lightweight structure as well as the choice of best semiconductors and electronic circuits defines the hardware layout. Fast data acquisition to ensure high dynamic motor control needs the development and implementation of novel control algorithm. Redundant output stages and safety concepts in software and hardware ensure fail safe operation and protection of the overall system.