# Performances of direct drive and magnetically geared PMSMs with different cooling technologies

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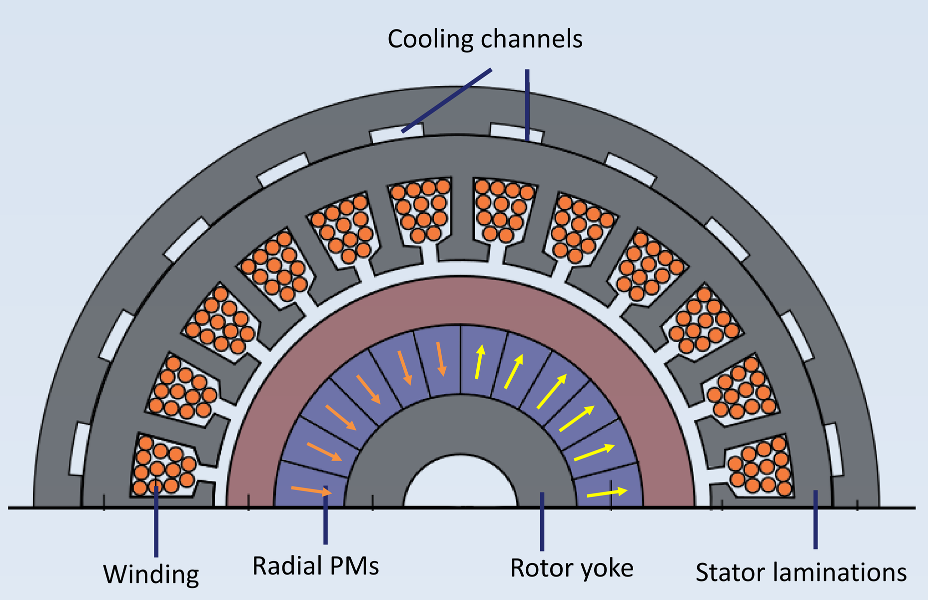
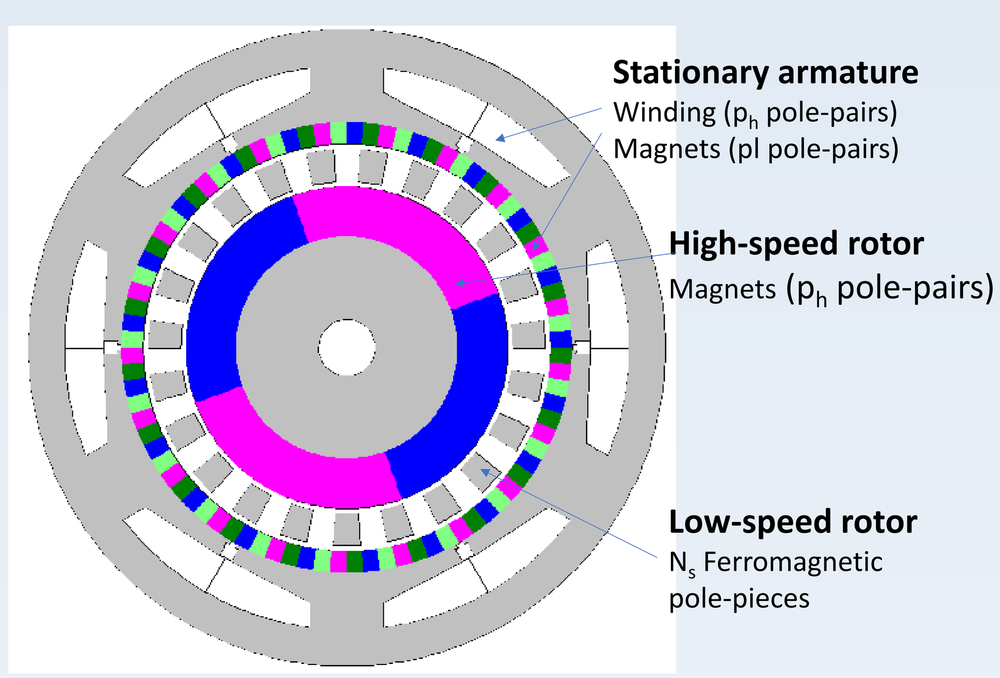
The work deals with the design of surface mounted and magnetically geared PM machines. The aim is to analyze the performances of such machines in the frame of electrified aircraft propulsion. Air and liquid cooled solutions are considered to assess the effectiveness of each propulsion solution regarding torque and power densities. It is shown that for an air cooled machine rated 150 kW - 1000 rpm, the PMSM has an active mass of 250 kg which is 30% higher than the magnetically geared one.

## PM machine topologies and sizing equations

### Surface mounted PM machine




### Magnetically geared PM machine (PDD)




### Sizing equations of direct-drive PMSM

Torque expression: $\boldsymbol{T = 2.k_w.cos(\psi).(BH).\pi R_a^2 L}$

RMS radial flux density on the stator bore radius $R_a$:

$$\mathbf{B} = \frac{4B_r}{\pi\sqrt{2}}.sin\left(\frac{\beta\pi}{2}\right).\frac{p}{1-p^2}.R_a^{-p-1}.\left(\frac{\frac{2R_a^{2p}}{R_r^{p-1}}-R_m^{p+1}\left(1-p+\frac{R_m^{-2p}}{R_a^{-2p}}.(1+p)\right)}{\left(1-\left(\frac{R_a}{R_r}\right)^{2p}\right)}+(1-p).R_m^{p+1}\right)$$

RMS tangentiel flux density on $R_a$: $\boldsymbol{H} = \frac{NI}{2\pi R_a}$ where $\boldsymbol{NI}$ are the total rms ampere-turns linked to the slot current density

### Sizing of magnetically geared PMSM (Pseudo Direct Drive: PDD)

Torque is transmitted via the low-speed rotor (pole-pieces) of the magnetic gear side of PDD: $\boldsymbol{T = G_r.T_h}$ where the gear ratio $\boldsymbol{G_r = N_s/p_h}$

- The magnetic gear is sized by finite elements

Torque $T_h$ results from the interaction of the high-speed rotor PMs and stationary armature currents (machine side of the PDD)

- Sizing the stator of PDD is similar to that of PMSM, but B is computed when sizing the magnetic gear

### Thermal aspects: losses, heating and cooling methods

Sizing PMSM and PDD allows Joule ($p_j$) and iron ($p_{iron}$) losses evaluation, the total losses are $\boldsymbol{p = p_j + p_{iron}}$

Two cooling methods are considered:

- forced air on the stator outer surface S for both PMSM and PDD: convection coefficient ***h=50-150 W/m²K***
- oil circulation in channels located on the stator outer surface S (only PMSM): convection coefficient ***h=150-400 W/m²K***

The temperature rise of the machines is: $\Delta \boldsymbol{T} = \frac{p}{hS}$, $\Delta\boldsymbol{T}$ is limited to 60°C

## Results

### PMSM design optimazation and performances

Direct drive PMSM rated at **150 kW - 1000 rpm, $\boldsymbol{T}$ =1432 Nm**

Single objective optimization is conducted under openoffice Calc: objective function is the minimization of PMSM active weight

Convection coefficient is varied between 50 and 400 W/m²K

Outer diameter is limited to 0,6 m

The results show that for h=100 W/m²K, the PDD weight is about 190 kg while the PMSM has a weight of about 370 kg

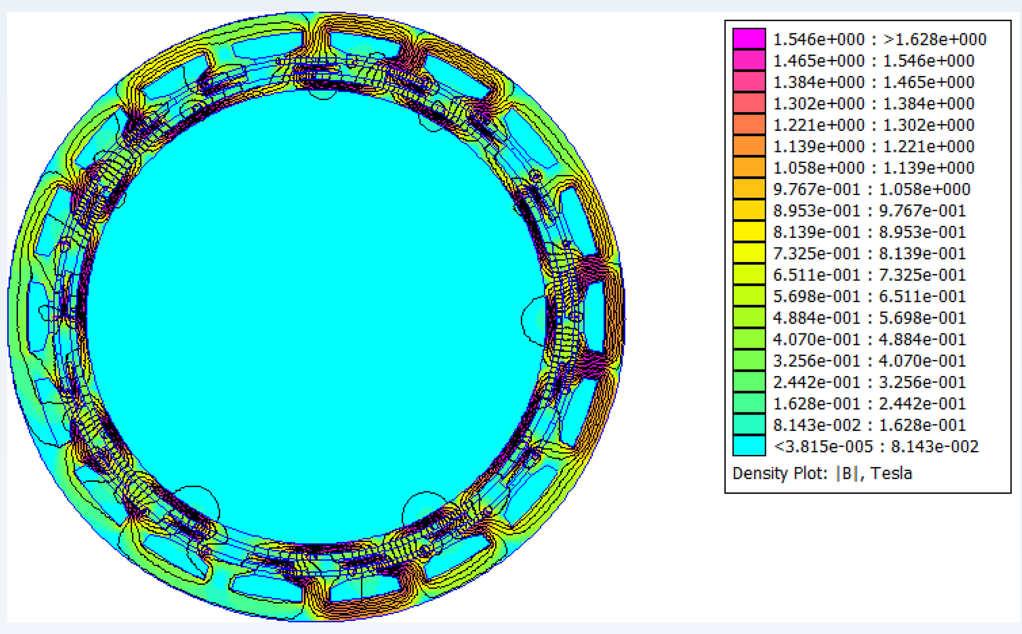
To have the same PDD weight, the convection coefficient for the PMSM is about 200 W/m²K which corresponds to a moderate oil cooling method

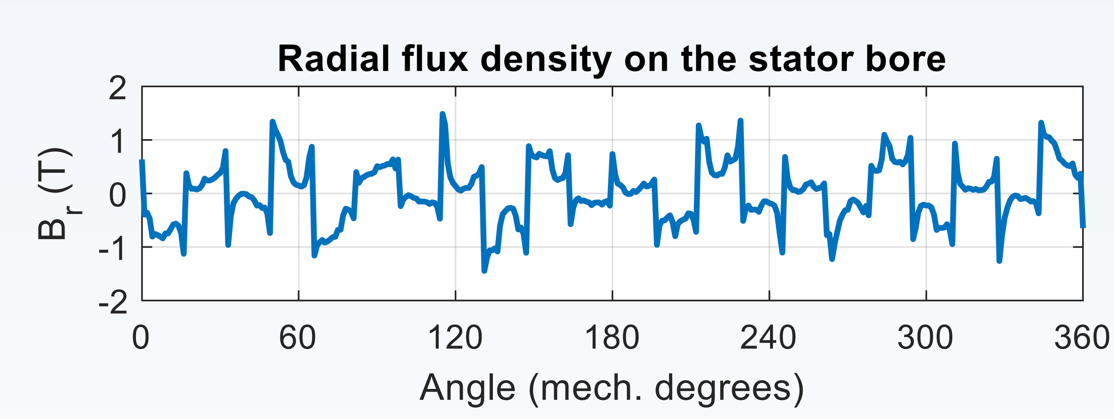
For a more agressive oil cooling with h=400 W/m²K, the PMSM weight is about 120 kg

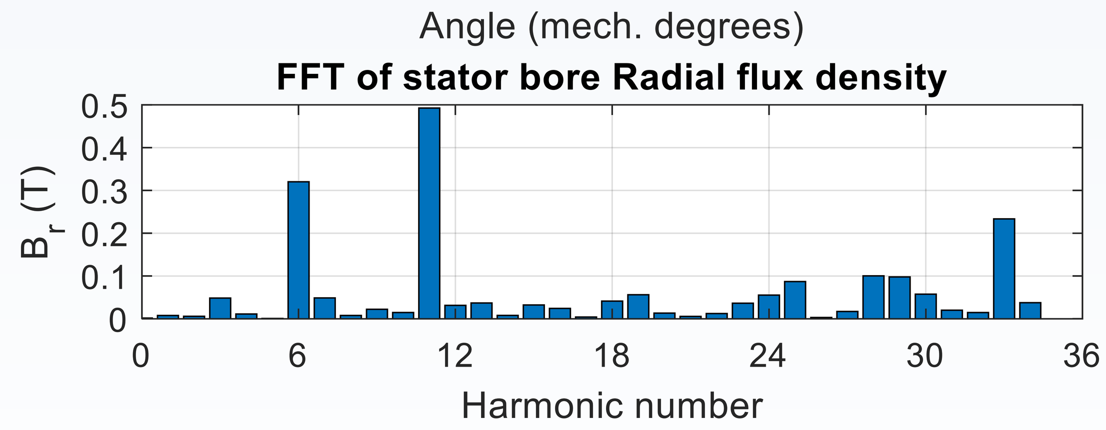
### PDD design and performances

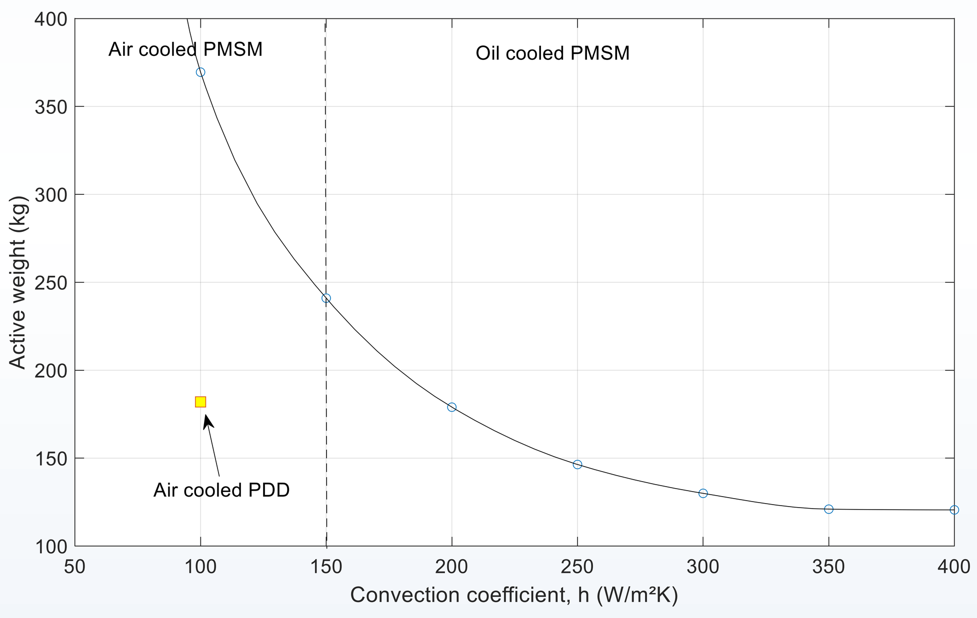
| Name | Value |
|---|---|
| $p_h$ | 6 |
| $p_l$ | 11 |
| $N_s$ | 17 |
| $G_r$ | 2,833 |
| Outer diameter | 0,6 m |
| Active length | 0,23 m |
| Active weight | 190 kg |
| Rated torque | 1432 Nm |
| Maximum torque | 1690 Nm |
| RMS current density | 2,4 A/mm² |
| efficiency | > 95% |

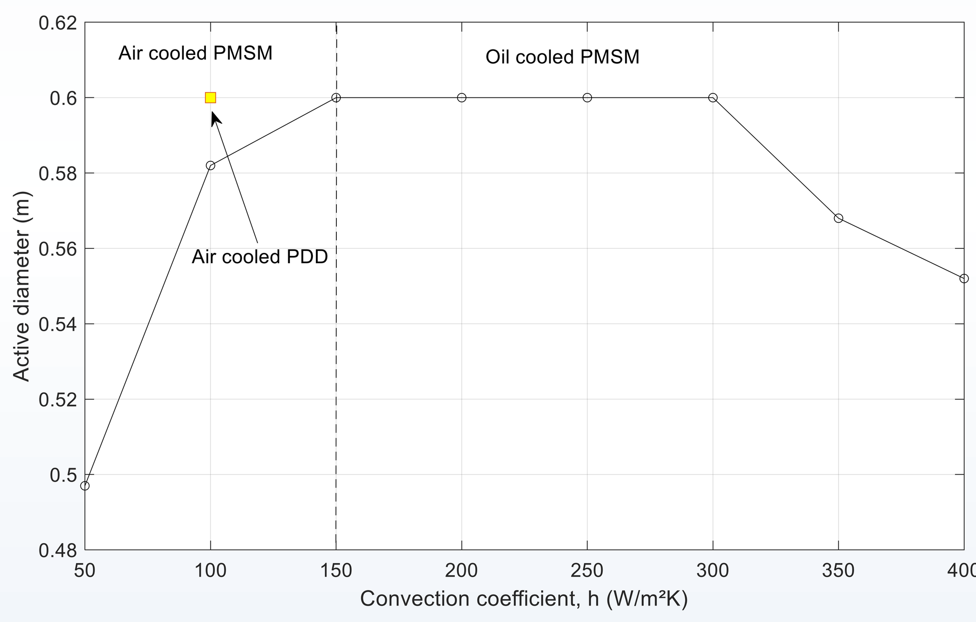
- PDD is designed for a max torque 20% higher than the rated torque for stability during transient operation
- Convection coefficient h=100 W/m²K is enough to maintain the temperature rise of the PDD under 60°C
- A max torque density of about 26 Nm/l is achieved

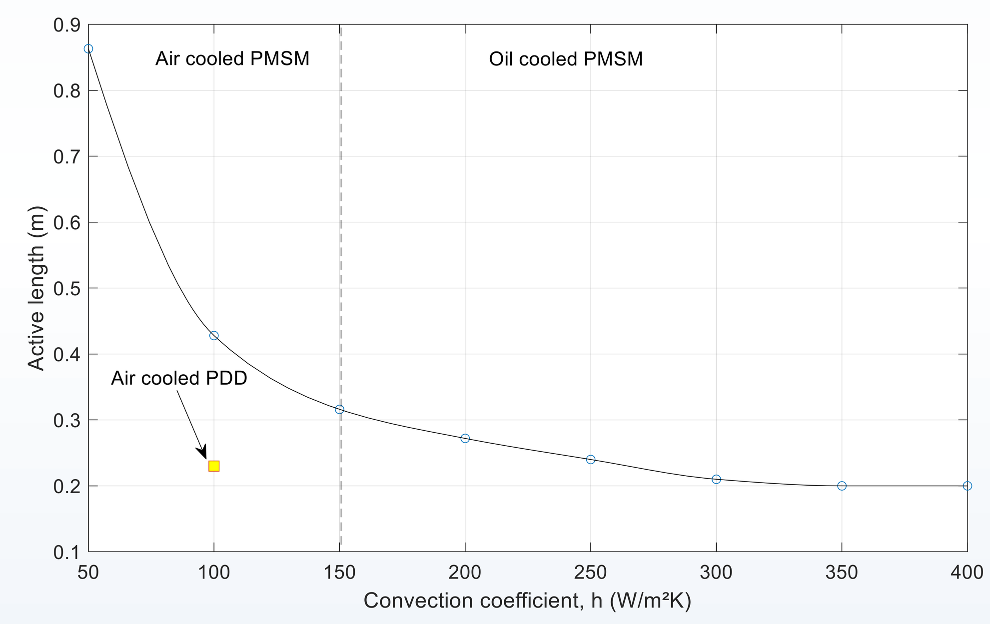



## Conclusion

- ❖A comparison of direct drive and magnetically geared PMSMs is achieved for various air and liquid cooling methods
- ❖The PDD solution is more compact than PMSM for air cooling solution with a convection coefficient lower than 100 W/m²K
- ❖Liquid cooling allow an important reduction of PMSM weight and better performances than the air cooled PDD

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