Jordan S, Baker NJ.

[Air-Cooled, High Torque Machines for Aerospace Applications.](#)

In: 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016).

19-21 April 2016, Glasgow, UK: Institute of Engineering and Technology (IET).

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DOI link to published paper:

<http://dx.doi.org/10.1049/cp.2016.0236>

Date deposited:

27/07/2016

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Abstract:

With the increased electrification of aircraft, the use of motors to replace traditionally mechanical or hydraulic auxiliary systems has increased. Aerospace motor design has the rather unique characteristics of mass and torque density being extremely important, whereas cost is less so. For low maintenance, non safety critical components, which are only used for short durations of the flight cycle, efficiency also becomes less important whilst eliminating an external cooling circuit and gearbox can look very attractive.

To achieve maximum torque in a constrained space for minimum active mass, the designer has the choice between selecting a high torque density topology or stripping the design back to its basic active components. In this paper, an aerospace application is considered against a backdrop of these design priorities. Two extremes of machine design are compared – a transverse flux machine (TFM) and a double rotor air cored design. The paper considers how to achieve a rated and three fold larger overload torque whilst retaining the limits imposed by the current airframe design, converter limits, stringent mass restrictions and safety aspects of aerospace. The desire for no external cooling circuit imposes limits on current density for rated torque but can sustain high current densities for short periods of time in order to provide a low-duty peak torque requirement. It is shown that the design problem is essentially driven by thermal and mass constraints, where loss simulation results are used to inform the thermal model of Joule and hysteresis losses and heat transfer boundary conditions are set by the application.

The TFM is well known for its torque dense properties and, as such, is ideal for an application where an external cooling is not an option and mass is limited. Due to the three-dimensional flux paths it is common to construct such a machine from soft magnetic composite (SMC) materials. However, these materials tend to have a poor permeability and lower saturation point when compared with silicon or cobalt steels. Here, a high pole (64), flux concentrated rotor with laminated cobalt iron stator teeth and SMC stator coreback has been designed. The flux concentration of the magnets is used to provide a high air-gap flux density and remove the need for a rotor core-back, thus keeping mass to a minimum.

Figure 1: Thermal performance of models with (left) copper and (right) aluminium windings

The desire for low mass drove the design to consider aluminium for the winding material. Whilst a mass saving of 0.3 p.u. is achievable, there is a considerable increase in Joule loss, 0.65 p.u.: the higher resistivity proving to be inhibitive in its use due to thermal concerns at high current densities, detrimentally affecting the performance of the high dysprosium content neodymium iron boron (NdFeB) magnets. After half an hour at rated torque conditions, the isotropic thermal model, depicted in Figure 1, shows that the rotor temperature for the aluminium windings is approaching the Curie temperature of these magnets, leading to permanent demagnetisation. Samarium cobalt (SmCo) can be used in extreme environments, however at some reduced torque output. Copper windings provide a suitable working environment for NdFeB.

Overload torque production is limited in TFMs as the teeth of a well designed mass limited machine are on the point of saturation at rated torque. As shown in Figure 2, rated torque is achieved at a modest current density but overload torque is limited by saturation and converter constraints. The high pole number results in a high voltage and, whilst paralleling the phase coils can remedy this, the problem is

replaced by hitting the current limit of the converter. Furthermore, the voltage quality for TFMs is notoriously poor and, as depicted in Figure 3, the sinusoidal waveforms are distorted by third and fifth harmonics. Tooth pitching can reduce the spatial harmonics, producing a more sinusoidal back-emf and satisfying the converter requirements.

Figure 2: Torque production of TFM

Figure 3: Open-circuit back-emf of TFM

The requirement for a large overload torque led the authors to consider a second machine topology which reduces the machine to its fundamental torque producing parts, removing the stator laminations and producing a double rotor air-gap machine – Figure 4 (*r*). This ironless machine has no saturation effects and the potential overload torque is thus not limited by saturation - Figure 4 (*l*). Although lower in pole number, a relatively large pole-arc helps maximise the flux density from the internal and external flux concentrated rotor topologies.

There are no slots due to there being no teeth. However, the effective area that the windings can encompass is limited by the pole-arc length. The winding circumferential width is limited by this and the inclusion of a support structure. Furthermore, since the reluctance of the air-gap is high, the radial length must be kept to a minimum. End-windings are now a consideration and methods of ensuring cooling air passes these surfaces must be taken into account. The support structure becomes an integral mechanism in removing heat since there is no longer active material to interface and soak heat from the windings.

Figure 4: Torque production (*l*) simplified 2D model section (*c*) and full 3D model (*r*) for air-gap machine

The peak torque can be met by an extremely high current density, which, with adequate cooling air, can be sustained for the short period required with winding temperatures reaching approximately 230 °C, approaching the limits of class H insulation. In this design, it is thermal performance at rated torque which leads to excessive temperature rise, especially around the end-winding region. The end-windings are encapsulated in resin interfacing a cold plate to reduce the heat. However, this limits the cooling air passing across the exposed coil faces and also doesn't consider the potential cooling provided by the support structure.

The full paper will detail the design process and thermal performance for both topologies in the face of strict application constraints. The final selection process and details of the laboratory prototype will also be included.