The Influence of Stator Material on the Power Density and Iron Loss of a High-Performace Starter-Generator for More Electric Aircraft

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Abstract — Maximizing the power density as well as efficiency are two of the main critical aspects for engineers who are designing electrical machines for aerospace applications. Iron losses have a significant impact on the total machine efficiency, thermal state and, eventually, on the final machine design. This impact becomes especially critical for high-frequency machines. Thereby a selection of optimal stator material which allows minimizing the total weight and iron losses is very important.

This paper focuses on the comparison of cobalt-iron alloy and high-grade non-oriented silicon steel materials in terms of influence on the starter-generator iron losses and power density. Analytical and finite element models are used for calculation and optimization of the machine parameters. The optimization of starter-generator design is performed by using genetic-algorithm taking into account thermal state and the estimation of passive mass.

The results of investigation allows for the selection of an optimal stator material based on the machine efficiency, power density as well as the cost considerations.

Keywords—power density, high-speed electrical machine, Iron loss, soft magnetic materials

I. INTRODUCTION

The selection of the most appropriate electrical steel is a very important and critical aspect of electrical machine design. Depending on the application and particular machine requirements there are a lot of properties that should be taken into account for the stator materials: specific loss, density, mechanical properties, BH - saturation curve, cost [1], [2]. Assuming the power density maximization as the main optimization objective for aerospace applications, in this paper the best-in-class(to the authors' knowledge) Cobalt-Iron based alloy Vacoflux48 in a thickness of 0.055mm, and Silicon-Iron based alloy JNEX900 in a thickness of 0.1mm are considered for the stator material.

II. STARTER-GENERATOR DESIGN

The starter-generator is a 3-phase synchronous permanent magnet (PM) machine with inner rotor Halbach array topology Fig. 1. It's an intensively liquid cooled machine [3]. The Oil inlet temperature is 120°C with a flow rate of 15 l/min [4]. The stator region is separated by the oil sleeve from the rotor to prevent oil leaks into the rotor region – Fig. 1. Due to the high operating temperature and high additional rotor loss the Samarium-Cobalt (Sm_2Co_{17}) material is used as a permanent magnets (PM) for the machine, as shown in Fig. 1, following a procedure described in [9].

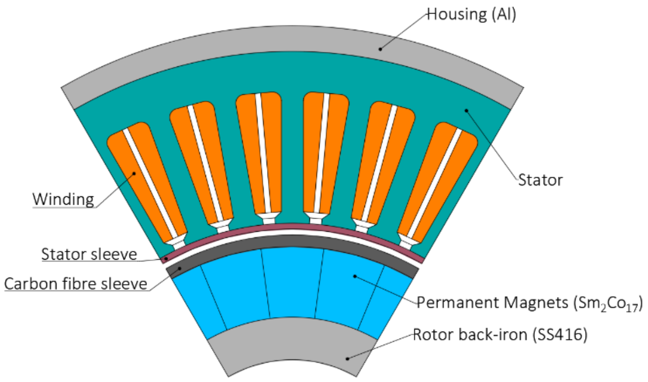

Fig. 1 – The design of 160 kW, 32000 rpm starter-generator

The Halbach PM array is retained by 4 mm carbon fiber sleeve – Fig. 1. The rotor back-iron is made of ferromagnetic stainless steel SS416 that allows for further increasing the flux density in the air gap. To maximize machine power density the housing is made of aluminum.

The main parameters of the starter-generator are given in Table I. The optimization of machine design was performed by using FEA and genetic algorithm [5]. This unique approach allows downsize the machine geometry and total weight taking into account limitation criteria, such us coil temperature, efficiency, voltage THD, power factor, etc. More importantly, since the inactive mass is a big proportion of the total mass, in seeking the highest kW/kg, the inactive mass is considered within the overall optimization. The machine optimization was performed for best in class high-grade silicon steel JNEX900, in a thickness of 0.1mm, and Cobalt-Iron alloy Vacoflux48 in a thickness of 0.055mm.

TABLE I STARTER-GENERATOR PARAMETERS

Parameter	**Value**
Power	160 kW
Pole Pairs	3
Max. Fundamental frequency	1600 Hz
Inlet Oil Temperature	120°C
Flow Rate	15 l/min
Number of phases	3
Permanent Magnet Material	Sm$_2$Co$_{17}$ (Br – 1.08 T)

III. ELECTRICAL STEEL COMPARISON

The main physical properties of the considered electrical steels materials which are critical for the holistic design of the machine are compared in this section. Maximizing of power to weight ratio as well as the efficiency are two of the most important requirements for aero-engine starter-generators. The most attractive material should have low mass density, low specific losses and high magnetic permeability properties [6] – [10]. JNEX900 has the lower density - 7490 kg/m^3 compared toVacoflux48 - 8120 kg/m^3.

The CoFe grade Vacoflux48, being approximately 50% cobalt in content, has outstanding characteristics in terms of magnetic permeability – Fig. 2. The value of flux density around 2.1 T can be easily reached at the level of magnetic strength of 360 A/m. Vacoflux48 becomes saturated at the flux density >2.3 T. JNEX900 shows comparatively reduced magnetic permeability properties and reaches saturation at around 1.4 T.

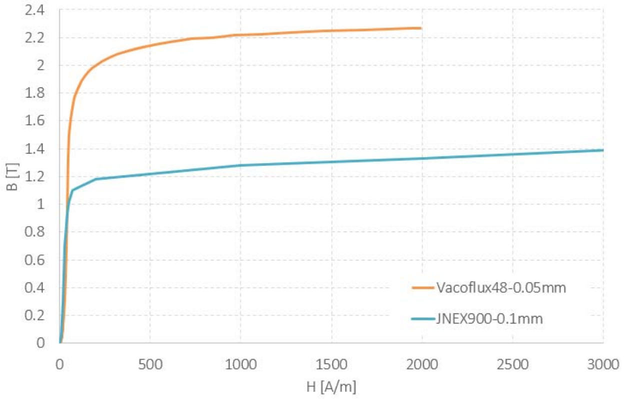

Fig. 2 – Magnetic permeability of electromagnetic steels

A comparison of specific losses for JNEX900-0.1 mm and Vacoflux48-0.055mm at 400 Hz, 1000 Hz and 2000 Hz is given in Fig. 3. At low flux densities and high frequencies the specific losses for both materials similar, however a non-linear increase of specific loss can be observed for JNEX900 for a flux density values higher than 1.2 T – Fig. 3 since the material becomes saturated – Fig. 2.

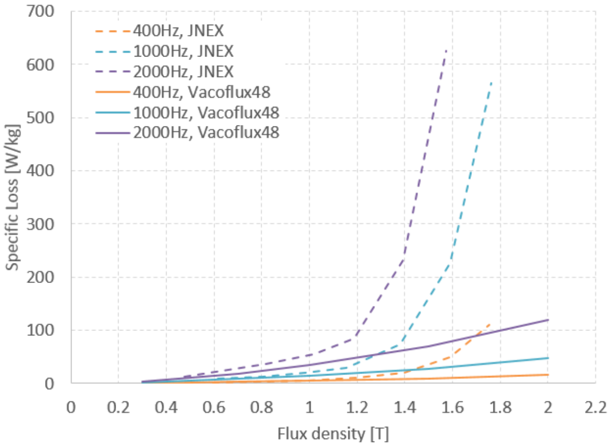

Fig. 3 – Specific loss of JNEX900 and Vacoflux48 at 1 T, 400 Hz, 1000 Hz and 2000 Hz

IV. OPTIMIZATION MODEL

In many classical optimization approaches, the optimization is first done on the electromagnetics, then a housing is designed around the optimized electromagnetic design. However, the housing can be a very significant proportion of the total mass and integrating the housing design with the overall machine kW/kg optimization has significant potential for extra power density entitlement. Appropriate multidomain calculators, which serve as the essential building blocks with which the kW/kg optimization is performed, are required. To this end, electromagnetic, thermal, and mechanical analytical models are developed, as shown in Fig. 4.

The arbitrary SPM machines are defined in terms of their characterising geometries, constituent materials defined by their magnetic, mechanical and thermal properties, as well as the coolant properties which include the coolant temperature and flow rate. The following sections detail the multidomain calculators implemented and used within the optimization tool.

The methodology allows calculation of electromagnetic, thermal and mechanical parameters of synchronous permanent magnet machine with Halbach array. An overall structure of multidomain calculator is shown in Fig 4. The electromagnetic calculator has a set of input parameters which describe the machine geometry such as stator inner and outer diameters, active length, magnet height, tooth width, tooth height, etc. Fig 4. The machine active power, speed, material properties and number of turns per phase also should be specified as input parameters. The electromagnetic calculator also estimates copper and iron loss which are then used as input parameters for the thermal calculator Fig 4. The thermal module does a calculation of temperature state of the machine winding, stator back-iron, teeth and Fig 4. Coolant properties as well as flow rate and initial temperature have to be defined as input parameters. The mechanical module estimates active and passive machine mass and also calculates mechanical stress of the retention sleeve Fig 4.

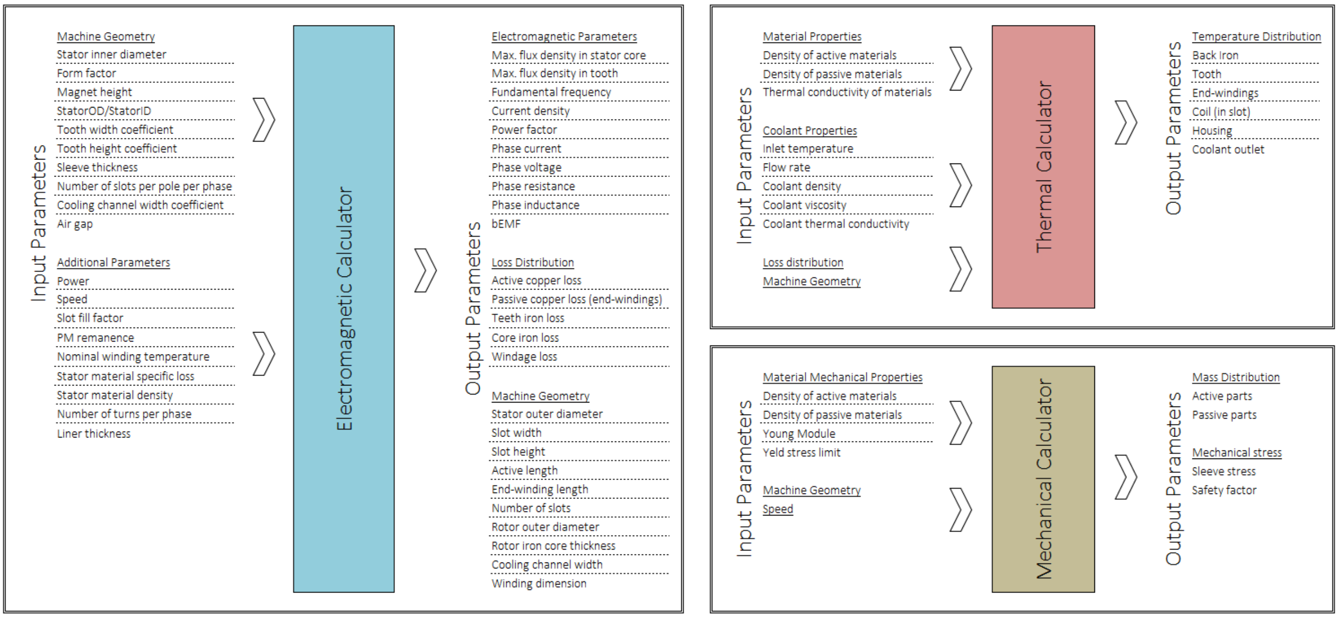

Fig. 4 – Multidomain calculator required for optimization

The model used for optimization was described in [5]. The optimization was performed in modeFrontier by using Matlab as a core for scripting and post processing and Magnet Infolityca for FEA – Fig 5. The input variables for optimization are described in Table 2.

TABLE II INPUT VARIABLES FOR OPTIMIZATION MODEL

Variable	Description	Input range
k	$\frac{StatorOD}{StatorID}$	1 – 2
k_form	$\frac{L_{active}}{StatorID}$	0.2 – 1.5
$TWcoeff$	$\frac{ToothWidth \cdot N_{slots}}{\pi \cdot StatorID}$	0.3 – 0.8
$THcoeff$	$2 \cdot \frac{TootHeight}{(StatorOD - StatorID)}$	0.3 – 0.8
$StatorID$		60 – 120 mm

Here $StatorOD$ – stator outer diameter; $StatorID$ – stator inner diameter; L_{active} – active length of the machine, k– split ratio, k_form – aspect ratio, $THcoeff$ – tooth height coefficient, $TWcoeff$ – tooth width coefficient, N_{slots} – number of slots. The constraints of optimization are described in Table 3.

TABLE III OPTIMIZATION CONSTRAINTS

Name	Description	Constraint value
PF	Power factor	>0.8
Eff	Efficiency	>0.97
$Jslot$	Current density [A/mm^2]	<30
$Tcoil1max$ $Tcoil2max$ $Tcoil3max$	Coil temperature at different points [°C]	<200
$THD\_Voltage$	Voltage THD [%]	<8%

The single objective of the optimization is the total mass minimization. Fig 5 shows a general structure of optimization model in modeFrontier.

The machine is modeled in motoring mode with sinusoidal phase current, assuming the d-axis current is equal to zero.

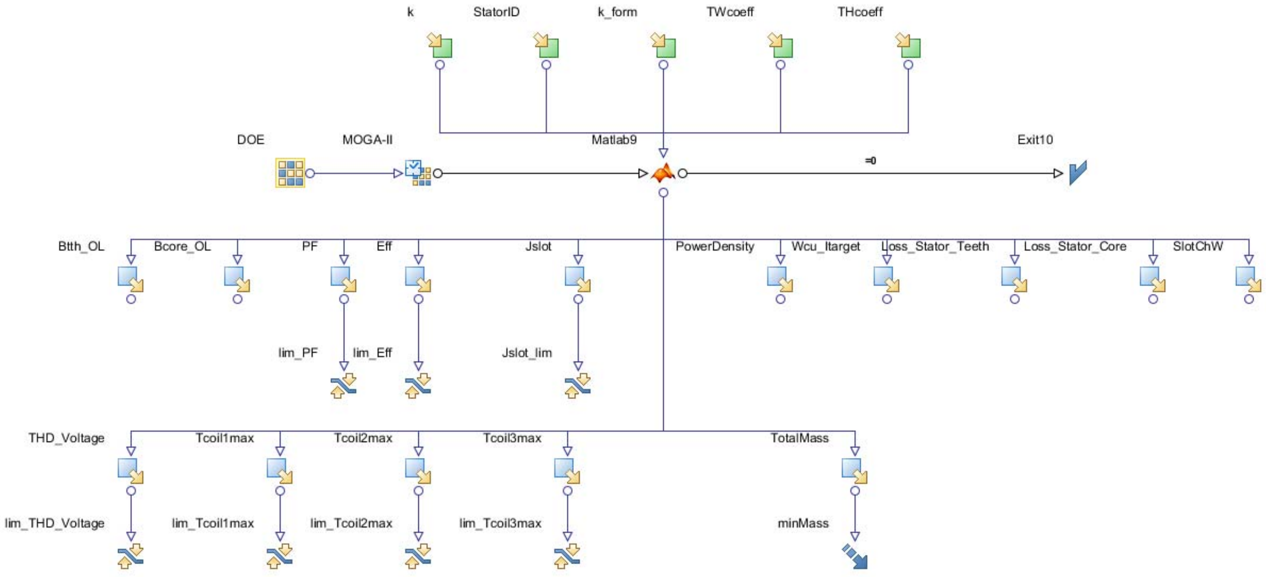

Fig. 5 – Optimization model in modeFrontier

As an example, correlation of machine power density with iron loss is given for feasible designs in Fig. 6 for Vacoflux 48.

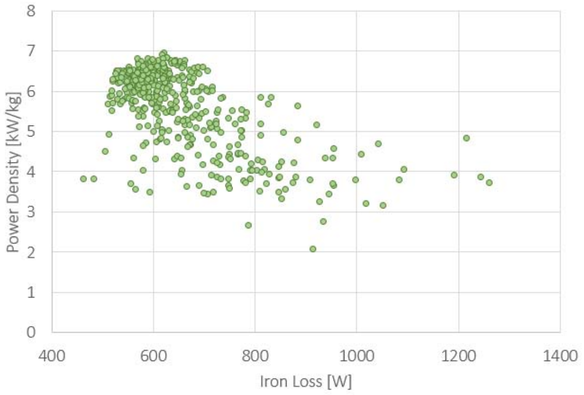

Fig. 6 – Feasible designs for Vacoflux 48

It can be observed that most of optimal designs with high power density are localized within the range of 6 – 7 kW/kg which correspond to iron loss from ~500 W to 700 W

V. POWER DENSITY AND IRON LOSS COMPARISON

The chart of iron loss comparison for optimal designs satisfying the constraints criteria from Table 3 is presented in Fig. 7. The iron loss includes both hysteresis and eddy-current components. Since the compared materials have different saturation points the iron loss characteristics of optimized machines are given against Voltage Total Harmonic Distortion (Voltage THD) for a fair comparison. The optimized machine designs with Cobalt-Iron alloy Vacoflux48 have the lowest loss among the compared materials – 420 W for a given range of Voltage THD from 1.5 to 6.1 – Fig. 7. The machine designs with high grade silicon steel JNEX900 shows significantly higher level of iron loss. It varies in the range from 1650 W to 1900 W for a given Voltage THD range – Fig. 7.

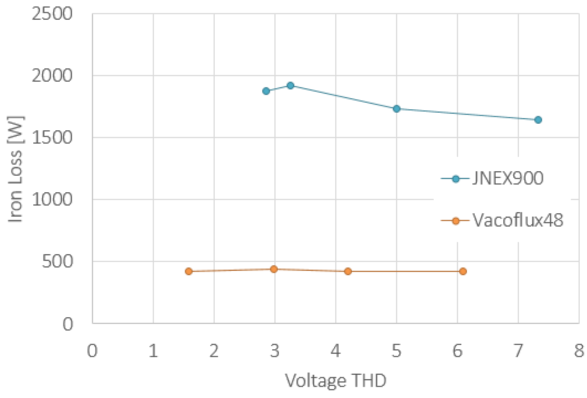

Fig. 7 – Iron loss estimation for 160 kW, 32000 rpm starter-generator

The estimation of the machine power density is presented in Fig. 8. Despite the higher mass-density of Cobalt-Iron alloy the machines with a stator made of Vacoflux48 have the highest power to weight ratio among the compared materials. This is mainly due to the high saturation point which allows minimizing the machine dimension – Fig. 9, Fig. 10 and reaching up to 7 kW/kg of power density. The results of machine optimization for JNEX900 give the power density at around 6.7 kW/kg for a Voltage THD level >7. Both dimensions decrease with increasing of Voltage THD level for all investigated materials.

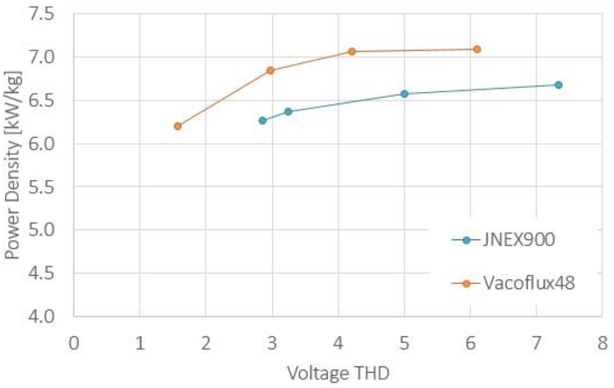

Fig. 8 – Power density comparison for different stator materials

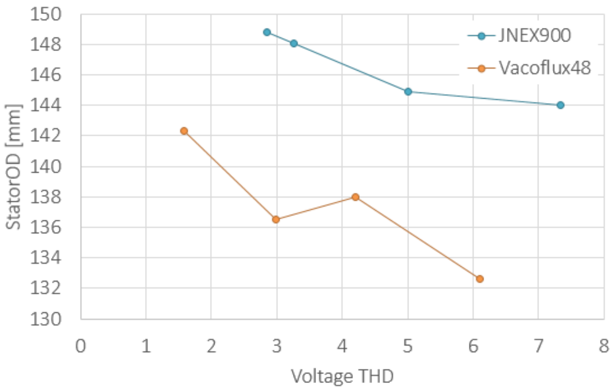

Fig. 9 – Optimal stator outer diameter of 160 kW starter-generator for different materials

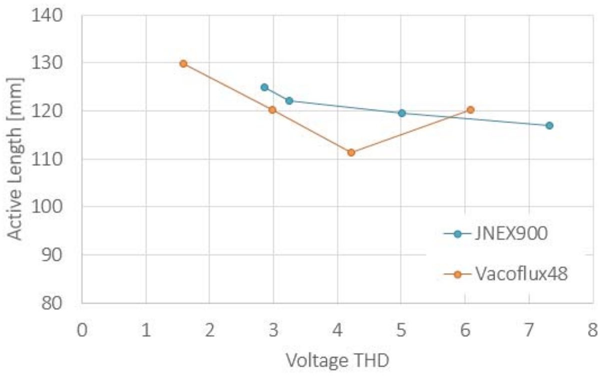

Fig. 10 – Optimal active length of 160 kW starter-generator for different materials

A correlation for stator mass is given in Fig. 11. Despite the high mass-density of Vacoflux48 the amount of required material is significantly less than for JNEX900– Fig. 11. For a high Voltage THD level (>5) the mass of stator is 3.7 kg compared to 4.6 kg for JNEX900 In general the machine stator mass gradually decreases with increasing of Voltage THD for the investigated materials. From 5.2 kg to 4.6 kg for JNEX900 and from 6.2 kg to 3.7 kg for Vacoflux48.

The machine efficiency has been estimated including both copper and iron losses. It is varied in a narrow range for Vacoflux48: from 0.987 to 0.985 and remains close to 0.98 for JNEX900 – Fig. 12.

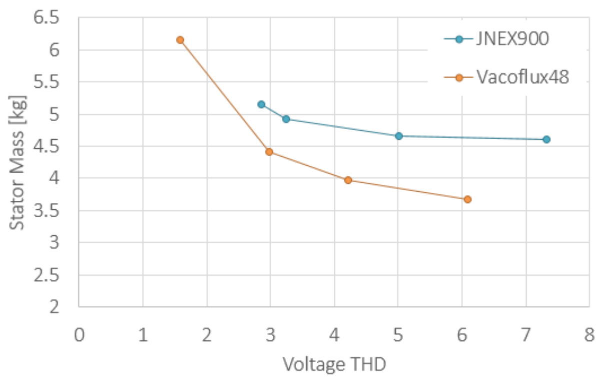

Fig. 11 – Stator mass against Voltage THD for different materials

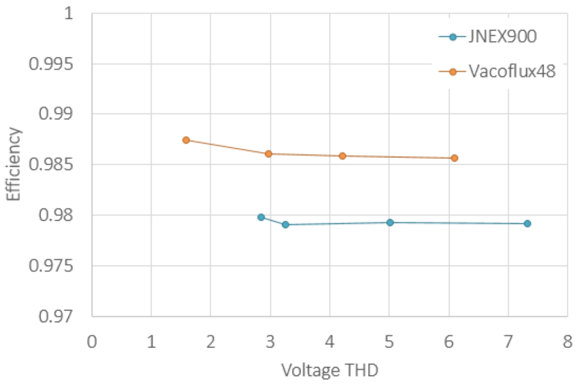

Fig. 12 – Starter-generator efficiency for different materials

VI. CONCLUSION

The influence of stator materials on the output parameters of a high-performance, high-frequency aerospace machine were investigated in the paper. Best-in-class Cobalt-Iron alloy Vacoflux48, and high-grade silicon steel JNEX900 were considered for the stator material and the impact on machine power density, machine dimensions and iron losses were compared. The Cobalt-Iron material has a 30% higher saturation flux density, albeit also having an approximately 8% higher mass-density.

In general in seeking the best kW/kg, Cobalt-Iron material Vacoflux48 yields an overall better power density despite the higher mass-density. If however, a higher THD is acceptable within the application, the power density of the JNEX SiFe based design is comparable despite the lower efficiency. The overall decision should also take into consideration other important factors, such as the cost, with the CoFe grades being an order of magnitude costlier.

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