4-MW Class High-Power-Density Generator for Future Hybrid-Electric Aircraft

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Abstract—This article describes the underpinning research, development, construction, and testing of a 4-MW multihouse phase generator designed for a hybrid-electric aircraft propulsion system demonstrator. The aim of the work is to demonstrate gravimetric power densities around 20 kW/kg, as required for multi-MW aircraft propulsion systems. The key design choices, development procedures, and tradeoffs, together with the experimental testing of this electrical machine connected to an active rectifier, are presented. A time-efficient analytical approach to the downselection of various machine configurations, geometrical variables, different active and passive materials, and different thermal management options is first presented. A detailed design approach based on the 3-D finite element analysis (FEA) is then presented for the final design. Reduced power tests are carried out on a full-scale 4-MW machine prototype, validating the proposed design. The experimental results are in good agreement with simulation and show significant progress in the field of high-power-density electrical machines at the targeted power rating.

Index Terms—Aerospace generator drives, high-power generation systems, high-power high-voltage machines design, hybrid-electric aircraft (HEA), more-electric aircraft, multiphase motors, variable speed drives.

I. INTRODUCTION

With air transport being amongst the least green forms of passenger transportation, over the past two decades, the aerospace industry and related bodies have been working intensively on defining aircraft technology roadmaps for the reduction of net carbon emissions [1]. Various ambitious aircraft emission reduction targets are set, such as those within the EU’s Flightpath 2050 program that seeks reductions of CO₂ and NOₓ emissions per passenger kilometer by 75% and 90%, respectively, relative to the year 2000 [2]. In a similar way, NASA, through the Environmentally Responsible Aviation (ERA) work frame, has set targets that include reducing fuel burn by 50% and NOₓ emissions by 75% [3]. The aforementioned programs are tackling the current aircraft emissions problem through different approaches, which involves the improvement of the existing combustion technologies, while looking for new disruptive technologies, among which hybrid-electric and all-electric architectures are gaining increased focus. In the nearer term, targeting the narrow-body aircraft market, which globally consumes over half of the aviation fuel, hybrid-electric solutions have the potential to revolutionize aircraft propulsion and generation systems, combining the advantages of fuel-based systems and battery-powered systems, while offering new degrees of design freedom for efficient aircraft configurations and systemic synergies [4]. One prominent example in this area was the E-Fan X ground demonstrator, which has brought together two key European companies, namely, Airbus and Rolls-Royce, jointly developing a hybrid-electric propulsion system involving a 2-MW electric drive supplied from a 2.5-MW generator that is powered by a gas turbine situated in the fuselage [5]. While the project has been concluded and will not fly as originally planned, ground testing of the Rolls-Royce system will continue. Other programs that have seen the involvement of international consortia comprising industrial, research, and academic institutions are moving in a similar direction by exploring revolutionary aircraft technologies [6], [7]. To make hybrid-electric aircraft fly, the continuous power density and efficiency of the machines used for propulsion and generation both need to be pushed beyond the current state of the art [8]. The challenges in achieving high power densities are compounded by the kV-level insulation requirements at altitude, which demands a sensitive balance between the thermal dissipation and the lifetime. More concepts and case studies for civilian hybrid-electric aircraft have been considered, focusing on both propulsion and generation.
 However, to date, there are a very limited number of MW-class, kV-level demonstrators in the literature, where both power and power density meet the challenging requirements for future hybrid-electric aircraft.

In terms of high-power electrical machines, one of the largest developments is reported in [11], where some preliminary results of a Mark#1 2.5-MW permanent magnet (PM) generator are promising. There is a series of publications recently presented, which investigates various topologies [12], [13], and concepts [14], [15] of electrical machines that could be considered as candidates for the propulsion system of future hybrid-electric aircraft. Taking into account the technology readiness and high requirements for efficiency, power density, and reliability, electrical machines with PMs are a promising topology to fit the criteria for hybrid-electric propulsion systems [16], [17].

This work aims to present and demonstrate the challenges in developing a 4-MW (5-MVA), 15000-rpm, electrical machine suitable for the future hybrid-electric aircraft onboard generating systems, by targeting a record power density of 18 kW/kg (including active and passive components). This article also presents an architecture of a high-speed multiphase machine with an eight-pole PM rotor and multiple isolated three-phase windings in the stator.

The hybrid turbo-electric architecture layout considered within this study is sketched in Fig. 1. Starting from the left-hand side of the schematic, a gas turbine (T) is driving an electrical generator (G) connected to an ac/dc converter with two separate isolated channels (BRAVO and ECHO). This project has focused on the combined subsystem highlighted within the orange box.

This article is organized as follows. In Section II, the design choices for a 4-MW (5-MVA) generator are presented, highlighting the pros and cons of different machine topologies. In Section III, the detailed design and proposed three-stage optimization methodology of the selected machine topology are described. The generator is prototyped and experimentally validated, with the results discussed in Section IV. Finally, the conclusions and key outcomes from this work are discussed in Section V. The novelty of this article is a demonstration of a breakthrough power density at the MW power levels reached by using innovative machine optimization methodologies, which exploits improved material properties and advanced thermal management techniques.

II. SELECTION OF THE MACHINE TOPOLOGY

In the earlier stages of this research program, tradeoff studies were conducted with four different topologies of PM machines considered and optimized: outer rotor (OR), inner rotor (IR), double stator (DS), and double rotor (DR) designs, as presented in [18]. In this work, it has been shown, as a case study, that a 1-MW machine with DR topology can enable power densities up to 26 and 34 kW/kg at 14000 and 20000 rpm, respectively. The solutions with IR design resulted in the second-best option, with corresponding power densities around 18 and 23 kW/kg, at the same reference speeds. With the boundaries of the aforementioned study, the optimization results for both OR and DS designs showed comparatively lower power density values compared to DS and IR. Therefore, the OR and DS configurations were not considered as potential candidates to pursue building a higher power prototype. Although the DR machine shows an outstanding power density, the mechanical complexity introduced by the additional rotor and its comparatively lower technology readiness level (TRL) limits its use in high-power systems. For practical reasons and in seeking to develop a higher TRL MW-class demonstrator, the IR configuration with a Halbach array was selected as the topology to take forward for the development of an aircraft ground demonstrator capable of generating 5 MVA (4 MW) of power. The rotor of the IR generator consists of a Halbach cylinder made from samarium–cobalt (Sm2Co17) PMs, as shown in Fig. 2. The samarium–cobalt PMs were selected due to the higher thermal stability compared to neodymium-based PMs.

The material of the stator core is cobalt–iron (49% CoFe) since it exhibits the best-in-class material saturation properties, as well as good specific loss characteristics. It was published in [19] that cobalt–iron steel enables achieving the highest power density at the best efficiency, in comparison with a standard or high-grade silicon electrical steel.
The PMs are retained by a composite rotor sleeve. The rotor core is made from magnetic stainless steel that enhances the air-gap flux density produced by the Halbach magnet array, thereby allowing higher power densities to be reached.

With relatively low iron losses (due to low specific loss characteristics of the core material, optimized winding design, and good current waveform THD) and with high armature current densities, the windings need to be intensively cooled. Cooling channels are located in the middle of the slots allowing delivery of the coolant directly to the heat generation source of the majority of the losses (i.e., the winding). The end windings are cooled by oil jet impingement, while the stator core is cooled by an oil jacket, as shown in Fig. 3. The rotor is separated from the stator by a 1.2-mm glass-fiber sleeve, creating a wet zone (stator) and a dry zone (rotor) in order to keep the windage losses low [20].

### III. DESCRIPTION OF THE MACHINE OPTIMIZATION PROCESS

The technical requirements for the generator are listed in Table I. The requested back-electromotive force (bEMF), phase current, and phase voltage are derived from the power electronic converter to meet the input requirements of its eight three-phase subsystems. In particular, to split the power among the power electronic devices, the three-phase subwindings are fed by series and parallel modules of the converter, respectively, to meet the 3-kV dc-link requirement [21]. A key requirement for this generator is the ability to operate with unbalanced loading across its subsystems, including continuous operation in the event of faults. The generator and converter are cooled by the same fluid (oil) with a maximum flow rate capability of 500 l/min and with an inlet temperature of 90 °C. The generator is designed to be directly coupled to a gas turbine and is designed for a mechanical rotational speed of 15,000 rpm, considering an overspeed capacity of 20% (equivalent to 18,000 rpm).

The machine design optimization procedure comprises three main design stages, conducted sequentially, which are summarized in the flowchart shown in Fig. 4.

The procedure starts from the first stage, which is analytical and includes electromagnetic analysis and thermal and mechanical calculations. The aim of this step is to define the correlation of the machine power density versus the numbers of poles and slots per pole. At this stage, the winding layout is assumed to be a standard three-phase single layer one, with a single turn per coil. The machine is analyzed in the generating mode with $I_d = 0$, assuming the surface PM (SPM) machine without magnetic anisotropy between $d$- and $q$-axes ($X_d = X_q$).

This is followed by the second stage of optimization, which is performed for a specific pole-slot combination and a winding layout that considers a multithree phase system, made by $8 \times 3$-phase sets, for the case in hand. This is done using the so-called subdomain model (SDM), which is purely analytical, but more accurate than a standard analytical calculator, and allows capture of the slotting effect, the direction of magnetization (DOM) of each PM segment of the Halbach array, the impact of PM segmentation, the winding arrangement, and the coil design [22]. The primary machine dimensions, such as the stator inner diameter, rotor outer diameter, PM height, and rotor sleeve thickness, are defined at this stage, while the range of other input variables, such as tooth width, tooth height, stator outer diameter, and machine length, is narrowed down.

The rotor sleeve thickness was parameterized to get an optimal value and not over or underestimate its dimension. During both first and second optimization stages the mechanical stress...
calculation on the rotor sleeve was carried out analytically at each iteration, taking into account a safety factor of 2. For the final design, the sleeve mechanical stress was refined by FEA. The rotor sleeve prestress condition is not considered during the optimization process; it was later confirmed at the optimization stage 3 using the FEA analysis during the design embodiment phase and confirmed by the rotor manufacturer who has detailed experience with prestressed rotor sleeves.

The final (third) optimization stage, as shown in Fig. 4, is performed by the finite element analysis (FEA) considering the material saturation effect. The stator slot dimensions, the stator outer diameter, and the axial length of the machine are finalized, including manufacturing considerations.

A. First Stage of Optimization

The commercial optimization software “ModeFrontier” is used to allow for a selection of optimization algorithms (Simplex, Multi-Objective Genetic Algorithm-MOGA, Particle Swarm, and so on), which can link to the developed analytical/numerical calculators [18], [23]. The list of input variables and constraints for the first stage of the optimization is given in [18]. At the most fundamental level, the main dimensions of the machine can be described via seven input variables: 1) \( k \) is the stator outer to inner diameter ratio; 2) \( S_{OD} \) the stator outer diameter; 3) aspect ratio \( k_{form} \), expressed as active length to stator inner diameter ratio; 4) PM height; and 5) sleeve thickness \( SL_{th} \) together with tooth width and tooth height coefficients, which defines the tooth dimensions, respectively. The single-objective function is the maximization of the power density of the generator. The constraints to this optimization were set both by the requirements and material limitations (see Table II). A detailed description of how the optimization software ModeFrontier is coupled to the electromagnetic analytical model is given in [18]. At this stage, a hybrid optimization algorithm is utilized. It combines the global exploration capabilities of genetic algorithms with local exploitation guaranteed by Sequential Quadratic Programming (SQP) implementations. About 15 000 designs were evaluated for each pole-slot combination.

In order to limit the fundamental frequency to a maximum acceptable value for the active rectifier, the possible pole-pair number is considered in the range from 2 to 6, with the corresponding fundamental electrical frequency being in the range from 500 to 1 500 Hz. This is also related to the switching-fundamental frequency ratio that was set to 10 as a lower limit. According to the requirements, the PF constraint was set to >0.8, the efficiency constraint to >0.97, and the stator outer diameter to <400 mm. The saturation of the stator material (49% CoFe) is not considered at this stage. To discard nonrealistic designs, the tooth and core flux density constraints were set to <2.1 T. The limit for the coil hotspot temperature was set to 200 °C, which is still a high value of temperature, despite the direct oil cooling of the winding. This is due to the high power density of the machine and the inevitable thermal resistances introduced by the high-voltage turn-to-turn insulation. The thermal boundary conditions are the oil inlet flow rate, and inlet temperature as the heat generated in the machine is removed by the forced oil flow through the machine. The heat transfer coefficients are calculated based on the flow rate, and therefore velocities, of oil impingement and oil forced channel flow in the slot. The list of input variables and constraints is presented in Table II, where the key objective is the maximization of the gravimetric power density with a target power of 4 MW.

Within this range, the Halbach PM array is assumed to be sinusoidal with the radial component of fundamental air-gap flux density distribution calculated by using the following equation [24]:

$$ B_{Ir} = B_r \frac{p}{1+p} \left[ (\frac{r}{R_s})^{p-1} \left( \frac{R_m}{R_s} \right)^{p+1} + \left( \frac{R_m}{r} \right)^{p+1} \right] \cos(p\theta) \quad (1) $$

where \( B_r \) is the PM remanence, \( p \) is the pole-pair number, \( R_s \) is the stator bore radius, and \( R_c \) and \( R_m \) are the PM inner and
outer radii, respectively. The parameters $r$ and $\theta$ are the polar coordinates of the point of the field observation.

The results of the first stage optimization are shown in Fig. 5. It should be mentioned that there were no feasible designs found for two pole pairs and one slot per pole per phase (SPP) configuration due to the temperature constraint and the applied cooling technique. Likewise, no feasible designs were found for five and six pole pairs with two SPPs. It can be seen that the power density gradually increases from 7.6 to 14.2 kW/kg for the one-SPP case, while, for the two-SPP design, the power density increases from 5.8 to 15 kW/kg.

When the constraint of slot cooling channel width is set to $S_{Ch,W} > 3$ mm, no feasible results are obtained for two SPPs with five and six pole pairs, since, with the increasing number of slots, the cooling channel constraint leads to machine outer diameter growth, which exceeds the limit of 400 mm.

Fig. 6 shows the trend of the machine efficiencies with respect to the number of pole pairs. This drops from 99.1% to 98.7% for three- and six-pole-pair designs with one SPP, respectively. For a two-SPP configuration, the efficiency drops from 98.8% down to 98.4% when increasing the pole-pair number from 2 to 4.

The loss distribution for the aforementioned optimized set of designs is presented in Fig. 7. The dominant component of the power loss originates from the copper loss, while the iron loss component increases with the pole-pair number due to the rise of the electrical frequency. The total loss in the 5-MVA generator changes from 36.8 to 54.6 kW for the one-SPP designs and in the range from 48.3 to 84.9 kW for the two-SPP designs. Due to the smaller slot dimensions in the machines with a higher pole count, there is a shorter thermal path from the heat sources in the coils, teeth, and core volumes to the coolant. Also, with the increase in the number of poles, the stator core thickness reduces. These characteristics enable increased cooling efficiency and extracting more heat without exceeding the set winding temperature limit of 200 °C. The mechanical calculator part of the analytical model, for an arbitrary active geometry, calculates the inactive mass. This includes consideration of the required torque transmission (for shaft sizing), rotational dynamics, rotor sleeve stress, and bearing mass, together with the mass of the active parts [18], [25]. The passive components comprise the following: housing and endcaps, rotor shaft, rotor balance plates, rotor magnet retention sleeve, bearings, connectors, stator oil sleeve, and bearing housing.

Thus, in the presented approach, seeking the optimal power density (kW/kg), the passive mass is factored into the holistic optimization. This is different compared to traditional approaches where, first, the active mass is minimized, and then, the inactive parts are subsequently added.

Fig. 8 presents the active to total mass ratio, which varies in the range from 0.53 to 0.57 for the investigated designs. It can be seen from the diagrams that, for the lower pole number, the machine’s outer diameter tends to be bigger due to the thicker magnets and larger stator core. This automatically leads to a larger housing outer diameter, which is the main component that contributes to the passive mass of the machine. The results of the described first stage of optimization allow for down selecting the suitable range of the main machine parameters. Considering the factors presented, the four-pole-pair configuration with two SPPs is taken to the next stage of development since it exhibits the highest power density among the considered designs. Also, this solution leads to a
fundamental frequency of 1000 Hz, which is a good match with the power modules to be used within the converter. In fact, a higher value would have required an increase of the switching frequency of the converter, which is limited by the high-power insulated-gate bipolar transistor (IGBT) modules commercially available on the market.

Fig. 9 illustrates the schematic of the architecture of the converter employed for the generator, comprising four parallel layers of two series three-phase neutral point converters (NPCs) each, for a total of $8 \times 3$-phase subwindings. The $8 \times 3$-phase configuration naturally fits the four-pole-pair 48-slot configuration selected [21].

A simplified version of the winding layout is also presented in Fig. 9. The phases $A_1B_1C_1$ and $A_2B_2C_2$ have an electrical phase shift of $30^\circ$ and belong to adjacent phases of BRAVO and ECHO. All the other three-phase winding systems are identical to $A_1B_1C_1$ and $A_2B_2C_2$.

**B. Second Stage of Optimization**

The second stage of optimization is performed by using a subdomain analytical modeling (SDM) technique [26]–[28]. The SDM model is based on the direct solution of Laplace’s and Poisson’s equations within the four domains of the machine, as shown in Fig. 10, namely, the PM, air gap, slot opening, and slot regions. These can be represented by the following equations:

$$\Delta A_{so} = 0, \quad \Delta A_s = 0$$

for air-gap and slot opening (2)

$$\Delta A_s = -\mu_0 J$$

for the slot (3)

$$\Delta A_{PM} = \mu_0 \nabla \times \mathbf{M}$$

for the PMs. (4)

The detailed solution of (2)–(4) is described in [26] and [28].

The set of input variables for this second stage optimization is listed in Table III. The variables’ range is narrowed down compared to the first stage of optimization.

At this stage, the machine is optimized for the selected $8 \times 3$-phase winding layout. There are $4 \times 3$-phase systems that are controlled by ECHO, while the other $4 \times 3$-phases are controlled by the BRAVO channel of the converter.

The independent control of the current in the channels with the phase shift of $30^\circ$ between ECHO and BRAVO three-phase systems allows increasing the torque by 3.4% compared to the solution without phase shift between three-phase systems.

The main assumption of the SDM model is the linear behavior of the materials. However, due to the high-efficiency requirement and the use of CoFe lamination material, the design is not expected to have significant iron saturation, leading to reasonable use of this approach for an “intermediate” design optimization.

The feasible designs of the second stage of optimization with the target function of the machine power density

| Symbol | Input Range | Optimal Value |
|--------|-------------|---------------|
| $k$    | 1.2–2       | 1.42          |
| $S_{sp}$ | 235–285 mm | 273 mm        |
| $k_{form}$ | 0.85–1.1   | 0.915         |
| $M_{sat}$ | 27–30 mm   | 29 mm         |
| $T_{W_{eff}}$ | 0.35–0.45 | 0.41          |
| $T_{H_{eff}}$ | 0.55–0.7  | 0.6           |
| $SL_{so}$ | 6.8–8.3 mm | 7.4 mm        |
maximization for the case of two- and four-PM segments per pole pitch are given in Fig. 11, which shows the correlation of power density, efficiency, and current density. About 10 000 designs were evaluated at this stage for each case of PM segments. The optimal machine design selected at this stage has the four-PM per pole, a power density of 16.1 kW/kg, and an efficiency of 98.5%. The comparison of the main parameters of the optimal designs for the case of two- and four-PM segments per pole is presented in Table IV.

It can be seen from Table IV that the design with four magnet segments has both higher power density and efficiency: 16.1 kW/kg against 15.7 kW/kg and 98.5% against 98.4%, respectively. For two magnet segments, only radial and tangential DOMs of PM in the rotor have been taken into account, whereas magnets with 45° DOM are introduced for the four-segment layout. The latter allows increasing the flux density in the air gap, achieves a more sinusoidal field distribution, and improves the power density without sacrificing the efficiency of the machine.

C. Third Stage of Optimization and the Machine Design Finalization

As investigated in [29]–[31] at a high fundamental frequency, the ac copper losses can be significant and very sensitive to the type and position of the wire. In the case of bulk (thick) conductors, such as Roebel bars or hairpin wires, the proximity effect causes eddy current circulation in the copper, which leads to additional heat generation. On the other hand, using conventional round wires with a suitable diameter requires connecting several strands in parallel within a bundle. As described in [32] and [33] employing parallel strands causes additional ac loss due to the circulating current between the strands. In addition, these ac losses are quite difficult to predict since they are very sensitive to the strands and bundle arrangements within each slot. To suppress proximity effects and circulating currents within the winding, the Litz wire is selected and considered in this work.

Before the third stage of optimization, several winding trials were made to check the technical feasibility of the coils and the dimension of the end-winding overhang, together with the practical implementation of the winding procedure. The decision to make an open slot design was taken at this stage since it allows for preforming the coils and then inserting them into the slots.

The initial range of input variables for FEA optimization is listed in Table V. These variables fully define the stator geometry. The other input variables, such as the sleeve thickness $S_{SL}$, the PM height $M_{height}$, and the stator inner diameter $S_{ID}$, which determine the rotor dimensions, were fixed after SDM optimization. About 2500 designs were evaluated at the third stage of optimization. It should be noted that the thermal model used for the third stage is the same as for stages 1 and 2. A more detailed CFD analysis was performed as a separate investigation for the final machine design.

### Table IV

| Basic Output Parameters | 2 PMs per pole pitch | 4 PMs per pole pitch |
|------------------------|----------------------|----------------------|
| Total mass [kg]        | 255                  | 248                  |
| Active mass [kg]       | 130                  | 126                  |
| Passive mass [kg]      | 125                  | 122                  |
| Power density [kW/kg]  | 15.7                 | 16.1                 |
| Efficiency             | 0.984                | 0.985                |
| Current density [A/mm²] | 24.4                | 23.5                 |
| Coil temperature [°C]  | 200                  | 200                  |
| Power factor           | 10.0                 | 10.9                 |
| Iron loss [kW]         | 56                   | 51                   |
| Total loss [kW]        | 66.0                 | 61.9                 |

### Table V

| Symbol     | Input Range | Optimal Value | Description |
|------------|-------------|---------------|-------------|
| $TW_{eff}$ | 0.36 – 0.4  | 0.37          | Tooth width coefficient |
| $TH_{eff}$ | 0.6 – 0.7   | 0.65          | Tooth height coefficient |
| $k$        | 1.33 – 1.47 | 1.38          | $\frac{M_{height}}{S_{ID}}$ |
| $k_{form}$ | 0.7 – 1     | 0.77          | Aspect ratio $\frac{S_{SL}}{S_{ID}}$ |

Fig. 11. Comparison of the optimal design layouts—correlation of power density against efficiency and current density.
TABLE VI
MAIN OUTPUT PARAMETERS OF THE FINAL DESIGN

| Basic Output Parameters | Value       |
|-------------------------|-------------|
| Phase current [RMS]     | 414 A       |
| Phase Voltage [RMS]     | 491 V       |
| Phase bEMF [RMS]        | 404 V       |
| Power                   | 4 MW        |
| Torque                  | 2558 Nm     |
| Power Factor            | 0.82        |
| Current Density         | 27.5 A/mm²/mm² |
| Power Density           | 17.3 kW/kg  |
| Iron Loss               | 8.8 kW      |
| Copper Loss             | 60.3 kW     |
| Total Electrical Loss   | 69.1 kW     |
| Efficiency              | 0.983       |
| Iron Mass               | 56.4 kg     |
| Magnet Mass             | 34.7 kg     |
| Copper Mass             | 21.8 kg     |
| Active Mass             | 113 kg      |
| Passive Mass            | 119 kg      |
| Total Mass              | 232 kg      |

The feasible designs are presented in Fig. 12, in the key power-density versus efficiency correlation. The design with the highest power density of 17.3 kW/kg, with the optimal input variables listed in Table V, was chosen for manufacturing a full-scale prototype. The main parameters of the final machine design are provided in Table VI.

The generator has a stator outer diameter of 378 mm and a stator bore diameter of 273 mm, while the axial length of the stator stack is $2 \times 10^5$ mm, as shown in Fig. 13, considering the cooling channel in the midaxial section of the core, as shown in Fig. 3.

From Fig. 13, it can be noted that the PM array has a flat bottom for mechanical and practical manufacturing purposes. The flat bottom simplifies the assembly procedure since three magnet segments can be stacked and glued to the rotor core together as a single pack. It should be mentioned that the PMs are axially segmented in 2-mm sections in order to prevent additional eddy current losses in the magnets. The PM design has been validated against demagnetization against both currents and high-temperature effects. The insulation system comprises the Nomex material that is used as a phase-to-ground liner and the Kapton tape wrapped around the Litz wire bundles, as shown in Fig. 13. The gap in the middle of the slot provides a path for the coolant flow.

IV. EXPERIMENTAL VALIDATION

It should be noted that the stator core of the first prototype presented in this work is made from SiFe electrical steel grade M235–35A. This is to avoid the unpredictable challenges and risks related to the manufacturing and assembly procedures and minimize the risk of damaging an expensive CoFe core material. All the experiments described hereafter were performed with a SiFe stator core in the machine. The assembly of the second prototype with the CoFe stator core is in progress, and it will be tested in the near future.

Fig. 14 shows the manufactured 4-MW generator, assembled in-house. The total mass of the designed generator, including passive components, is 249 kg, which is close to the modeled value of 232 kg. The active mass of the prototype is 117 kg, approximately 47% of the total mass, while the passive mass is 132 kg or about 53% of the total mass.

A series of experiments were performed to validate the machine characteristics. The experimental test rig includes the dynamometer drive with a nominal power of 860 kW, the modular 4-MW multiphase-multilevel converter, a 256-kW bidirectional dc power supply, and the cooling system. Fig. 15
The first test was the no-load bEMF measurements. The machine was coupled with the induction motor and spun up to 3000 rpm, while the bEMF waveforms of four different lines were recorded. The measured bEMF is in good agreement with the simulation. The measured and simulated line-to-line bEMF harmonic spectra at 2000 rpm are shown in Fig. 16. The acquired bEMF waveform is sinusoidal without the significant contribution of high-order harmonics (see Fig. 17). The total harmonic distortion (THD) is 1.88%.

The torque characteristic was measured at a constant speed of 500 rpm, with the power supply input dc voltage of 800 V, as shown in Fig. 18. The \( I_q \) current was gradually increased from 100 to 600 A for all \( 8 \times 3 \)-phases, while the dynamometer speed was kept constant via a speed control loop. The nonlinear behavior of the torque curve, due to the stator core saturation effect, can be observed at a higher current. The measured torque deviation from the simulation result at the maximum load was 5.3%.

The acquired current waveforms related to the motoring mode with the load torque of 2400 Nm are presented in Fig. 19.
A recirculating power test was performed as described in detail in [21]. For the recirculating power of 350 kW, the efficiency of the overall system, machine plus converter, reached the maximum of 92.5% (see Fig. 20). The test was carried out at 7500 rpm, with a dc-link voltage of 1.5 kV and a reference torque varying from 100 to 500 Apk. For the highest power test, the total losses of the series drive system are about 85 kW. The split of the losses, according to the simulation results, is 53.9 kW (64.7% of the total) in the machine. A series of thermal tests will be carried out in the near future to segregate the machine and converter losses by using a colorimetric method and assess the efficiency of the machine and converter separately.

V. CONCLUSION

The presented work contains a description of the optimization procedure and key steps in the development of a 4-MW class high-power-density generator. The optimization procedure comprises three stages: 1) simple and fast analytical calculator; 2) SDM; and 3) FEA. At the first stage, a broad range of possible number of pole pairs (from 2 to 6) and slots (one and two slots per pole per phase) was considered, seeking the configuration with the highest power density while meeting the converter requirements together with the efficiency, mechanical, and thermal constraints. As the result of the first stage of optimization, the configuration with four pole pairs and two SPPs that predicted a power density of 15 kW/kg and the efficiency of 98.4% was selected and taken to the next stage of optimization. The output of the second stage was the improved machine design with four PM segments per pole pitch and with the corresponding power density of 16.1 kW/kg and an efficiency of 98.5%. At the third and final stages of optimization, the slot dimensions together with the stator outer diameter and the active length were refined by an FEA optimization considering the stator core saturation effect. As a result, the final machine has a predicted power density of 17.3 kW/kg that corresponds to 232 kg of total mass and an efficiency of 98.3%.

The experimental campaign confirms the key machine characteristics. The measured line-to-line bEMF has a deviation within 1.2% compared to the simulation at the tested speed range from 1000 to 3000 rpm. The load test was performed at a low speed (500 rpm) and shows a 5.3% difference compared to the simulation at the maximum load.

It should be mentioned that the test results presented in this work were done for the first prototype with the SiFe stator core. The second prototype with CoFe stator core material is under development, and improvements of the output characteristics of the generator compared to the first version are expected, which will be reported in subsequent publications.

ACKNOWLEDGMENT

The authors would like to thank Mykhaylo Filipenko and Rolls-Royce Electric Team for the great research collaboration. They would also like to thank John Hinchcliffe (Senior Technical Manager), Kevin Last, Matthew Cooper, and all the electrical and mechanical technical teams from the Power Electronics Machines and Control (PEMC) Research Group, Faculty of Engineering, University of Nottingham; their continued support with the planning, manufacturing, assembly of the prototypes and test rigs has been fundamental. They would like to thank Andrew Plummer and the Mechanical Team at the Central Engineering Workshop (L2), Faculty of Engineering, University of Nottingham, for their great technical support. They would also like to thank their industrial partners on the project for their financial and technical support.

REFERENCES

[1] IATA. Technology Roadmap, 2018. Accessed: 2018. [Online]. Available: http://www.iata.org and https://www.iata.org/en/programs/environment/technology-roadmap/
[2] European Commission, Flightpath 2050 Europe’s Vision for Aviation Report of the High Level Group on Aviation Research, Directorate-General for Mobility and Transport. Accessed: 2011. [Online]. Available: https://ec.europa.eu/transport/sites/transport/files/aviation2050.pdf
[3] K. Suder, “Overview of the NASA environmentally responsible aviation Project’s propulsion technology portfolio,” in Proc. 48th AIAA/ASME/SAE/ASEE Joint Propuls. Conf. Exhib., Jul. 2012.
[4] R. D. Rosario, “A future with hybrid electric propulsion systems: A NASA perspective,” in Proc. Turbine Engine Technol. Symp. (TETS), 2014.
[5] (2017). Airbus, Rolls-Royce, and Siemens Team up for Electric Future Partnership Launches E-Fan X Hybrid-Electric Flight Demonstrator. [Online]. Available: https://www.airbus.com/newsroom/press-releases/en/2017/11/airbus-rolls-royce-and-siemens-team-up-for-electric-future-par.html
[6] (2018). Clean Energy Wire. Emission-Free Aviation is Technically Feasible—DLR Researcher. [Online]. Available: https://www.cleanenergywire.org/news/emission-free-aviation-technically-feasible-dlr-researcher
[7] Zunum Aero. Accessed: 2018. [Online]. Available: https://www.aerospace-technology.com/projects/zunum-aero-hybrid-electric-aircraft/
[8] W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett, and D. J. Atkinson, “Overview of electric motor technologies used for more electric aircraft (MEA),” IEEE Trans. Ind. Electron., vol. 59, no. 9, pp. 3523–3531, Sep. 2012.
[9] D. F. Finger, C. Braun, and C. Bil, “Case studies in initial sizing for hybrid-electric general aviation aircraft,” in Proc. AIAA/IEEE Electric Aircraft Technol. Symp., Cincinnati, OH, USA, Jul. 2018.
[10] C. L. Bowman, T. V. Marien, and J. L. Felder, “Turbo- and hybrid-electric aircraft propulsion for commercial transport,” in Proc. AIAA/IEEE Electric Aircraft Technol. Symp., Cincinnati, OH, USA, Jul. 2018.
[11] S. Øvrebø, “Test and validation of the mark 1 (2.5 MW) E-fan X generator,” in Proc. NATO AVT-RSY-323 Res. Symp. Hybrid/Elec. Aeroprops. Syst. Mil. Appl., 2019.
[12] E. Ganee, “Selecting the best electric machines for electrical power-generation systems: High-performance solutions for aerospace More electric architectures,” IEEE Electrific. Mag., vol. 2, no. 4, pp. 13–22, Dec. 2014.
[13] X. Zhang, C. L. Bowman, T. C. O’Connell, and K. S. Haran, “Large electric machines for aircraft electric propulsion,” IET Electr. Power Appl., vol. 12, no. 6, pp. 767–779, Jul. 2018.
[14] M. Filipenko et al., “Concept design of a high power superconducting generator for hybrid electric aircraft,” Supercondenscr Sci. Technol., vol. 33, no. 5, May 2020, Art. no. 054002.
[15] A. Perez, R. R. van der Woude, and R. Dekker, “Rotor cooling concept for the ASuMED superconductive motor,” IOP Conf. Ser., Mater. Sci. Eng., vol. 502, Apr. 2019, Art. no. 012139.
[16] A. El-Refaie and M. Osama, “High specific power electrical machines: A system perspective,” CES Trans. Electr. Mach. Syst., vol. 3, no. 1, pp. 88–93, Mar. 2019.
[17] M. van der Geest, H. Polinder, J. A. Ferreira, and M. Christmann, “Power density limits and design trends of high-speed permanent magnet synchronous machines,” IEEE Trans. Transp. Electrific., vol. 1, no. 3, pp. 266–276, Oct. 2015.
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