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A Direct-Drive Solution for Hydrogen Supplied All-Electric Airplane

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***Abstract*—This paper present a solution for traction motor in Ultra Light Motored (ULM) aircraft applications. A new All Electric Aircraft is here presented with a Hydrogen supplied fuel-cell system and a direct-drive configuration for traction motor. A reverse brushless solution with a distributed winding high pole-pair motor is presented for a 60kW continuous power solution. Materials and geometry have been analyzed with a goal of high torque density and high speed realization. Motor design key points and losses estimation in comparison with the experimental results will be presented.**

I. Introduction

In the field of a more electric aircraft, the "All-Electric Airplain" starts to became interesting as demonstrated by several project at the beginning of this century [1]–[3]. Some big companies have already worked inside this field realizing interesting prototypes in the last years. NASA's Pathfinder, Pathfinder Plus, Centurion and Helios Prototype were an evolutionary series of solar- and fuel cell system-powered unmanned aircrafts as well.

Keyword of the paper is the chosen electric motor solution. Looking at the electric motor in all projects, they are obviously high torque and high power density oriented because weight and volume, together with efficiency and safety, are surely the main issues in flight.

Aircrafts traction power span from some kilowatts to hundreds of megawatts, thus finding a common solution is not a reasonable target. The present project as a target power in the range of some tents of kilowatts, ideal solution for a small aircraft that can be driven by a couple of persons. Smaller solution with novel axial machines [4] or brushless concentrated windings [5], [6] have been developed and recently analyzed. Larger motors need a completely different approach and the cryogenic system proposed in [7] can be surely a valuable solution.

The cost [8] of any drive-line is not the first point dealing with the safety to be grant in aeronautics applications, anyway the consideration on the real feasibility of any project needs to take into account the industrial cost of any proposed solution.

Some attention has been posed in the direction of fault safety [9] without increasing cost and weight.

The goal of the paper is the identification of a distributed windings solution that can be adopted, manufactured and produced respecting the main key issue *weight* and *efficiency*. Cooling and noise will be analyzed too in order to grant for safe and noise free solution.

The paper will briefly introduce the complete airplane project, with a description of the intents. A short summary of the adopted drive-line will be presented. Motor design and its realization will be the core of the paper as well as losses prediction and the experimental validation, on test bench and on air.

II. Project Description

A. The challenge

The proposed study is part of the Skyspark Project (http://www.skyspark.eu) which have the target to place a speed record with a Ultra Light Motor (ULM) All Electric Aircraft.

The principal characteristics of the airplane, shown in Figure 1a, are resumed in Table 1b. The airplane will have a human pilot on board.

B. Energy Storage

Even if the final project has the target of full Hydrogen traction, the project validation flights are divided in three separate phases:

- with a Lithium battery directly connected to the 3-phase converter
- with the same battery divided into two packs and connected to a couple of step up DC/DC converter.
- with a Hydrogen supplied fuel-cells stack.

Firstly in fact the electric drive line will be tested in flights: the 3-phase converter and motor in a direct connection with a purposely designed Lithium polymer battery pack. In the final solution the energy source will be a combination of three 20kW fuel-cell Hydrogen supplied stacks. The hydrogen will

(a) Airplane profile

Total Mass	450kg
Max Speed	300km/h
Estimated autonomy	500km
Person on board	1

(b) Airplane Data

Fig. 1: Skyspark Airplane profile and principal expected characteristics

be stored in high pressure container will ensure 50kW/h that should last for a 500km in cruise flight.

An high power density but small capacity Lithium polymers battery is foreseen in the final solution too, in order to substain the flight if any problem arises to the fuel-cell system so to give the pilot some time to land.

C. Electric Drive-Line

The drive-line have been evaluated in detail and the final configuration is presented in Figure 2 where some indications are given regarding the stored energies and assigned power.

The power converter, supplied by Magneti Marelli Motor Sport, is the (Kinetic Energy Recovery System) KERS Control Unit (KCU) of the automotive F1. The key data of the KCU are summarized in Table I, its characteristics are surely larger that what required by the application but its compactness and oversizing have been considered as a reasonable safety margin.

TABLE I: KCU main data

Total Mass	3kg
Max DC Voltage	450V
Phase rms current	500A
modulation freq.	20kHz

The DC/DC converter, placed between fuel-cells/battery and KCU, is briefly summarized in Table II.

TABLE II: Step-up DC/DC main data

Total Mass	2kg
Min DC in voltage	75V
DC out Voltage	450V
Low voltage current	300A

The motor is directly connected to the propeller without any reduction gear and than in front of the aircraft. The principal specifications of the electric machine is summarized in Table III. The difference in the weight depends on the two realized prototypes. As described later the second prototype has an improved stator mechanical structure that has been adopted for safety reason.

TABLE III: Motor specification

Total Mass	$30 \div 35$kg
Nominal Power	60kW
Nominal Torque	210Nm
Max speed	2500rpm

III. Motor Design and Realization

The direct-drive configuration have been considered the most promising solution in terms of ratio total system efficiency towards weight at full power. For this ULM airplain the reduction gear at the propeller has a typical gear-ratio of 2.3. In order to maintain the total expected efficiency at full power above 95%, the geared solution has to consider an electric machine which an efficiency better than 97% stating that the efficiency of the fixed reduction-gear for this class of propeller is roughly 98%. Thus the motor should be lighter because the required torque is lower, but heavier because of the better required efficiency.

The direct-drive solution, in this application, can than have similar torque-to-weight ratio at fixed system efficiency compared with a similar geared solution, but obtained with a simpler and reduction free system.

A. Motor Configuration

As a first fixed point in the design process was posed the number of phase of the motor (three) due to the chosen converter to be adopted. The choice of a distributed winding solution was another fixed starting point and goal of the project. Eventually the cooling system have been fixed to be liquid. The main reason for this last choice is the weight target but some consideration more will be reported in III-D.

In this condition the design process starts with a target to have a magnetic structure (stator, rotor and windings) with a total weight of less than 20kg.

The topology of the rotor is a reverse (rotor-outer) solution in reason of three fundamental factors:

- higher torque density at fixed volume
- easier mechanical connection for the magnet centrifugal stresses
- thermal considerations for the rotor cooling.

B. Electro-Magnetic Design

At fixed motor structure and material exploitation, the torque to weight ratio increases as the number of poles increase leading to ring-shaped motors. From the magnetic point of view, the limitation in increasing the number of poles are:

losses in the active materials, *harmonics* in the realized electromotive force that could lead to a difficult control strategy, and, being the airgap nearly imposed by mechanical considerations, an increase in the number of poles would also leads to larger machine inductances leading to *poor power factor*.

The solution proposed is a 24 poles machine with a 1 slot per pole per phase full-pitch winding distribution. In Figure 3 the polepair 2D view of two realized solutions are reported. Figure 3 refers to no load finite element analysis. It can be appreciated the two different slot topology one designed to have an high filling factor, while the second has been developed to obtain a reduction in the cogging torque.

A furher increase in the polepair number would have lead to a too wide rotor diameter and also some other difficulties in the realization of the stator lamina.

The winding is full-pitch double layer with only two wire per phase. It shows a really short end windings, symmetrical on the both side of the machine. There is no need of end winding connection because start and end of the windings lay on six consequent slots easy to be fixed.

Each wire is realized with a large number of parallel conductor, but still with standard industrial wire, to take into account both fundamental and PWM losses in the copper.

Finally one slot stator skewing has been adopted to reduce the torque ripple and to keep sinusoidal the back-emf. The choice of eliminating the first slot harmonics is due to the physical reliability of the motor. The finite element evaluated waveforms of the torque ripple (Fig. 4) and the back-emf (Fig. 5) are presented with and without the adopted skewing at no load for the first solution.

The chosen stator iron is a NO20 high performance electrical steel from Cogent, then a thin lamination (0.2mm) in order to contain the stator iron losses.

On the contrary the rotor is a bulk iron structure that plays the magnetic joke function for magnets flux and structural for torque transmission.

The chosen magnets are NdFeB capable to work at high temperature [10]. The rotor choices is more in the direction of cost-weight optimization rather then efficiency. Losses into magnet have been evaluated and considered an acceptable compromise.

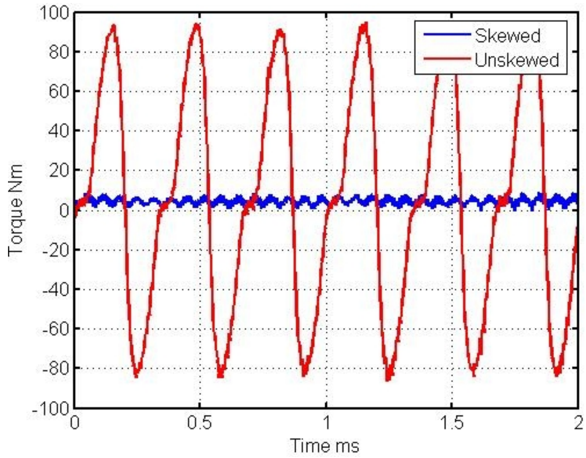


Fig. 4: Simulated torque with and without skewing

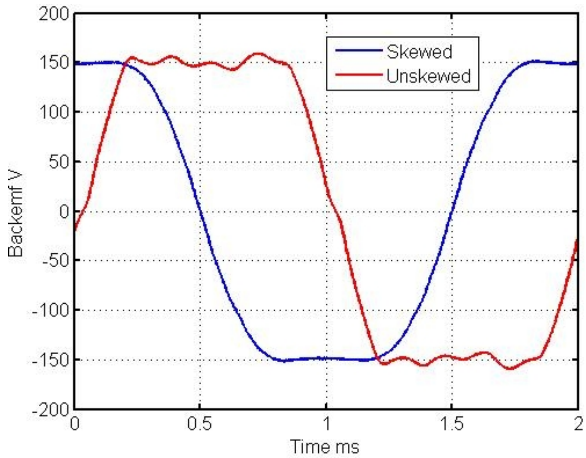
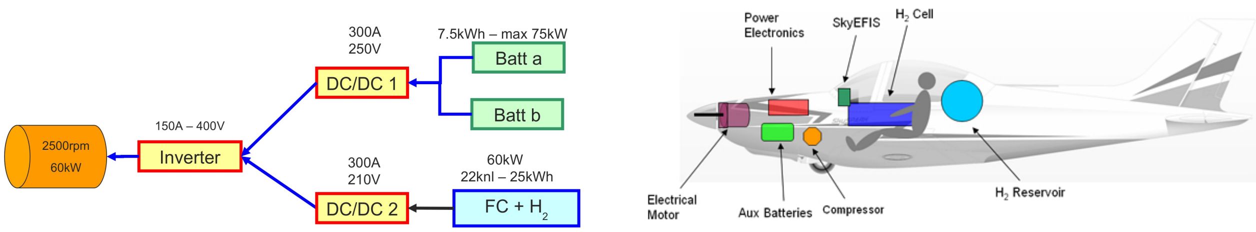


Fig. 5: Simulated phase back-emf with and without skewing

C. Mechanical solution

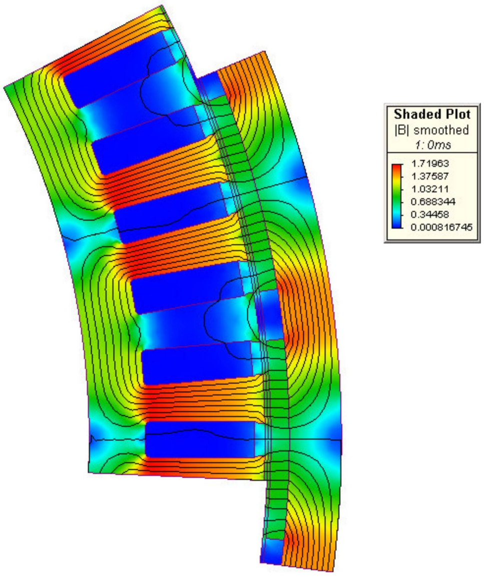
The mechanical evaluations mainly concern the force and stresses in the rotor structure due to the propeller connection and to the axial forces due to traction. For safety reason and due to the intrinsic instable position of the rotor, a brass ring has been posed in the rear part of the motor. The ring is not in contact with the turning rotor surface in normal operations.

Some interesting mechanical resonance in the acoustic range

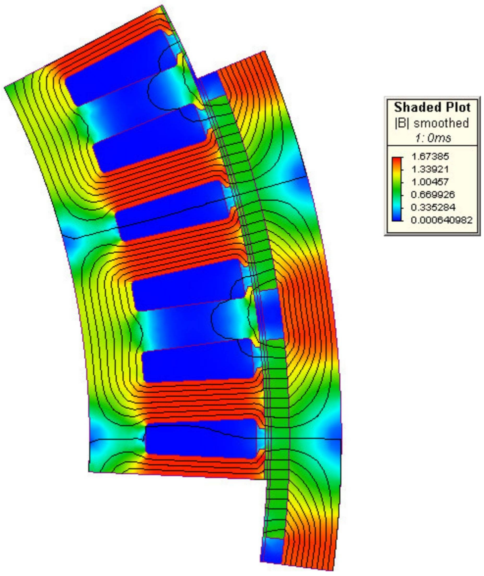


(a) Electric drive line (b) Location of the systems on board

Fig. 2: Electric drive line: a) Power scheme; b) Location of the systems on board



(a) First solution



(b) Second solution

Fig. 3: Finite element analysis in no load: a) High filling factor solution; b) Reduced ripple solution

appears in the first prototype due to the strong cogging. The peculiar structure of the rotor can be appreciated in Figure 6a in a 3D cutted drawing. The second prototype does not present any resonance also thanks to an enforced structure and a more accurate realization.

D. Thermal Considerations

Cooling a motor for airplane traction applications is surely different than standard industrial drives. Losses in fact typically grows with speed as the required power (roughly with the cube of the rotational speed). Iron losses are surely more than proportional to the rotor angular speed, while copper losses are mainly related to the torque. Consequently when losses are high also air flow is typically high. The availability of a high flow rate of air for cooling could lead to really interesting configurations where air flows directly inside the electric machine.

The choice of a water cooled motor have been done as compromise with the adopted mechanical solution. The inner stator solution makes difficult to let air flow inside the stator especially in a direct drive solution with a standard variable pitch propeller. The pitch variation control system, in fact, is exactly placed where air should flow: along the rotational axis of the propeller itself.

Water is anyway present on the airplane due to the fuel-cell cooling system thus is not an increase in system complexity. Water have been considered at $50°C$ inlet and with $\Delta T = 10°C$ in-to-out at a 8l/min flowrate. In this condition the winding copper should reach $120°C$, a temperature that can still be considered a safe at ground level.

E. Motor Control Considerations

With the adopted KCU converter the limitation in terms of control capability of the motor has been overcome. The electrical characteristics of the motor in fact presents a phase induction of 100μH and a phase resistance of 16mΩ. Ripple current is then high and a fast switching control is needed. In the worst conditions the current ripple at 20kHz modulation frequency is 30A peak.

As angular sensor a Tamagawa Synglyns series resolver has been adopted due to the high poles number in order to ensure precision in the determination of the rotor position.

The electrical frequency at the maximum speed is 500Hz thus the chosen converter can be considered more than suitable for the application.

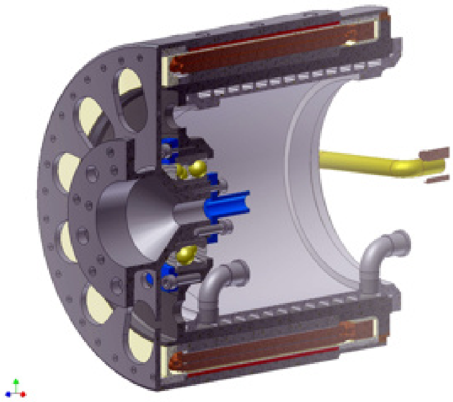
The adopted control technique is a standard dq current control. The torque control dynamics requirement are not so hard in traction application compared with other civil and industrial applications. On the contrary the intrinsic control safety is much more important; the capability to on-the-fly starts has been implemented together with a deep analysis and strategy decision for all the electric and thermal measurement inside the motor and converter itself.

In future work a different control technique to reduce the ripple current and increase the efficiency of the complete system will be proposed.

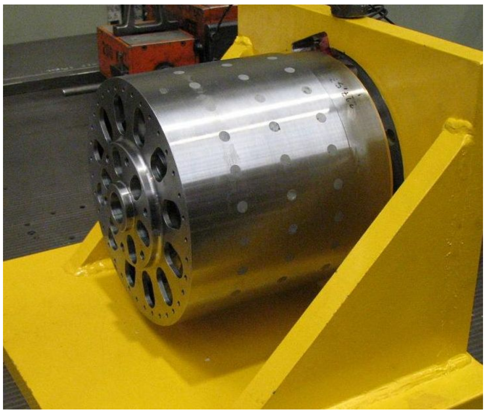
F. The Prototypes

The first prototype developed can be seen in Figure 6b. Some constructive particulars can be appreciated in Figures 7,8,9 where details of the realized windings, rotor and stator are presented.

The principal characteristic of the first prototype (PT1) are summarized in Table IV. The second prototype (PT2) looks



(a) CAD view



(b) First prototype

Fig. 6: Electric Motor: a) CAD view; b) First prototype

Fig. 7: First Prototype: windings particular

Fig. 8: First Prototype: stator complete

Fig. 9: First Prototype: magnet on the rotor inner side

identical to the first one and is the one adopted on the plane. As main magnetic differenced with respect to the first one, the rotor joke has been enlarged and the active pack has been increased. This two actions to ensure a larger power during take-off and to try to fix a speed record. The main characteristics of the second prototype are still summarized in Table IV.

IV. Losses Prediction

In order to define a proper thermal design of the machine in the working conditions, losses prediction capability is mandatory. The estimation of the losses have been firstly done on the basis simple analytical models and consequently refined with finite element analysis. Main losses prediction at full power (60kW) for the two prototypes are divided as shown in Table V.

Magnetic losses are computed a posteriori on the FEA analyses, making reference to the loss theory, evaluating static P_h, classical (or eddy currents) P_c, and excess losses P_e, and

TABLE IV: First and Second prototype Motor data

	PT1	PT2
Total Mass	30kg	35kg
Outer Diameter	240mm	242mm
Total Volume	18liters	20liters
Line to line rms voltage	185V	220V
Phase rms current	195A	165A
Power Factor	0.95	0.95
Continuous Power	60kW	60kW
Maximum Speed	2500rpm	2500rpm
Phase inductance	100μH	115μH
Phase resistance	16mΩ	19mΩ

TABLE V: First and Second prototype motor losses estimation

	PT1	PT2
Stator Iron	210W	210W
Rotor Joke	540W	640W
Magnets	540W	760W
Copper	1650W	1450W

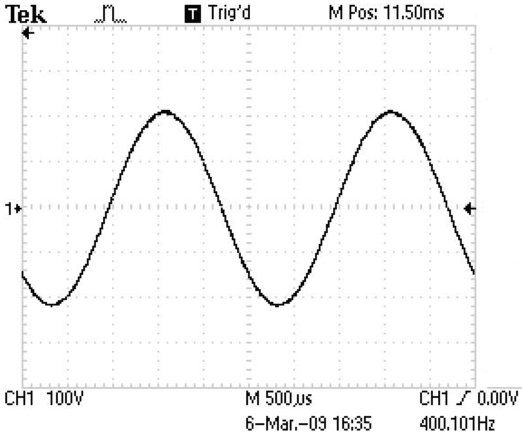


Fig. 10: Test on first prototype: line-to-line back-emf @ no-load 2000rpm

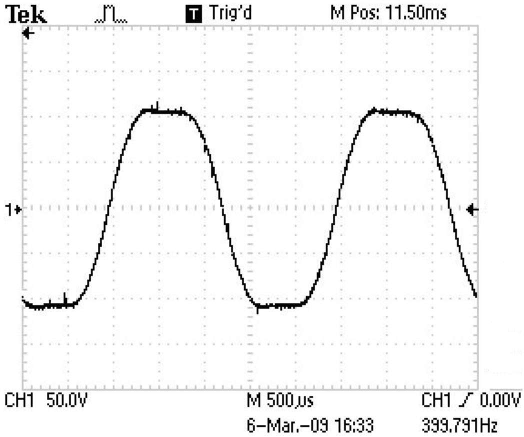


Fig. 11: Test on first prototype phase back-emf @ no-load 2000rpm

in the presence of elliptical flux loci, following the approach proposed in [11].

V. Experimental Validation

The winding distribution and stator slot skew leads to good symmetry in the electromotive force that appears perfectly sinusoidal in Figure 10. The motor design included a good third harmonic in the phase back-emf as can be appreciated in Figure 11.

The prototypes have been tested on bench in static conditions where air-rotor cooling have been simulated by an industrial fun. The motor have been tested in speed loop with regulated load from no load to 220Nm showing good performaces with 95% of maximum efficiency at top speed.

The performances verification on flight were more difficult to ensure due to the difficulties in properly measure torque, currents and power on the plane. Thus the only relevant information is the thermal behavior of motor and converter on the plane. Having flights on a series of hot days ($30°C$) the rotor temperature never goes above $70°C$ (by thermal-strip) and the stator copper reaches at maximum $80°C$ at full power in steady state conditions. In future works a detailed analysis of the thermal performace of the electric machine will be reported.

VI. Conclusions and Future Trends

A conventional solution of reverse-brushless for aircraft traction is here presented. The motor have been analyzed from the mechanical, thermal and electromagnetic point of view. It have been realized in two different solutions: one for high filling factor and a second for a reduced cogging torque. The proposed solution gives the required performance and let think to an integration of the electronics inside the stator hole in order to reduce cabling and emissions. The two prototypes are here presented with detailed results in terms of performance and losses, some important differences in the accuracy of the two realizations do not let an honest comparison but it can be concluded that the reduced torque solution gives a better motor performances. It can be concluded also that a more standard 0.35mm stator iron can still be adopted for a cheaper industrial solution.

Acknowledgment

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