Comparison between 3-*ph* and 6-*ph* PMSM drives for the electric propulsion of unmanned aerial vehicles

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***Abstract*—The full electric aircraft concept requires accurate design and suitable choice and integration of all the used components. Obviously, the electric propulsion drive is one of the most important on-board equipment. Both power converters and electric motors must have low weight, suitable overload capacity and high reliability. In this paper, two possible solutions of electric propulsion motor for unmanned aerial vehicle are investigated. Sizes, weight and some features of a three-phase PMSM motor are compared to those of a six-phase motor obtained by an appropriate rewinding of the armature, with fixed stator and rotor magnetic circuits. The losses obtained from the numerical analyzes are compared to evaluate the convenience of one solution over the other.**

Keywords — All electric aircraft; Permanent Magnet Motor; Multi-phase motor; UAV propulsion.

I. INTRODUCTION

The electric propulsion of aircraft is becoming an increasingly topical issue, with the growing interest of several research teams and many companies operating in the air transport sector [1]. Recent research programs [2, 3] in this area are focusing on the concept of *all electric aircraft* (AEA), based on the complete electrification of the aircraft' propulsion and on-board actuators (especially for low powered aircraft). The main objective of AEA is the development of new types of aircraft, capable of reducing gas emissions and traffic density within the cities, with the aim of improving their livability.

The success of AEA is made possible thanks to recent advances in electrical machines, power electronics and energy storage equipment. Favorable conditions for the development of fully electric propulsion aircraft are generated by the increase in the power density, safety and reliability of electric power trains, coupled with the reduction of their costs.

Nowadays, the most limiting technology appears to be that of energy storage systems [4]; however, the current trend towards increasing the energy density of batteries or developing high performance fuel-cells will lead to truly lightweight and efficient on-board electrical power sources. As already mentioned, in the aeronautical field there is a particular need for lightness and high reliability of all on-board components and, therefore, also of the propulsion power-trains. In addition, some applications (e.g. VTOL-*vertical take-off and landing* aircraft, small UAV-*unmanned aerial vehicle*) also require good dynamic performance due to the rapid changes in the external load and overload capacity in some particular situations (e.g. take off).

Sometimes, the rules imposed by the regulatory agencies determine the need to investigate configurations capable of satisfying all the constraints required by the application.

At present, full electric propulsion is considered possible and convenient primarily for small aircraft, such as helicopters, light touring aircraft with few seats, unmanned aerial vehicles for civil and military purposes.

This paper deals with electric propulsion of UAVs intended for civil use, such as for example the monitoring of territories. Permanent magnet synchronous motors (PMSM) are considered in the analysis. With the aim of using intrinsically reliable configurations of electric propulsion equipment, the paper analyzes the possibility of using multiphase drives, capable of being reconfigured in the event of a fault in a motor or converter phase, in order to ensure the continuity of the service, albeit with reduced power. In particular, a six-phase drive is analyzed, and its features are compared to those of a three-phase one.

As a first step a 3-phase PMSM motor is sized to meet the different characteristics required by a gear-drive full electric propulsion system. In particular, the angular speed of the motor is assumed constant in different load conditions, because the propeller power is modified through a pitch regulator. The number of slots and poles used for the 3-phase motor are chosen with the aim to be compatible with a 6-phase motor. The armature winding of the latter is suitably designed, without any changes in the electrical and geometric sizes of the reference 3-phase motor. Starting from the two machine configurations and assuming a similar cooling system for them, a comparison in terms of losses is carried out using numerical simulations.

II. PRELIMINARY CONSIDERATIONS ON THE ELECTRIC MOTOR FOR UAV

The choice of the electric motor for the full-electric propulsion of an aircraft is a topical issue, influenced by different factors like the high-power density and the reliability. The current trend in electrical machine for aircraft propulsion is mainly going towards the use of rare-earth permanent magnet motors [5], capable of guaranteeing higher power density and efficiency values than other electric motors. It should be noted that the increase in the costs of rare earth magnets and the commercial difficulties in finding them on the market are increasing the interest in other types of electric machines, such as the induction motor [6-8] and the wound-field synchronous machine. The latter is also considered also in the version with a cryogenic cooler for the use with superconductors [9,10]. From a reliability point of view, all the used motor must guarantee the performance also if a fault occurs. As it is well-know, the faults of an electric motor are different: mechanical fault (e.g. the bearings), electromagnetic faults (short-circuit in the windings, demagnetization of permanent magnet, rotor bars broken, etc..) and the loss of the cooling system. The use of distributed propulsion [11,12] determines an increase in the number of electric motors installed with the intrinsic growing in overall reliability. However, for small aircraft or full electric UAVs, configurations with a low number of motors are often adopted preferred; consequently, appropriate solutions must be considered for reducing the effects of faults on the drive.

One of the possible solutions is the use of multiphase motors (greater than 3 phases), which introduce redundancy in the windings with the possibility of ensuring adequate continuity of service even in some abnormal operating conditions. As regards the efficiency of the propulsion motor, it is interesting to investigate the benefits in reducing losses introduced by the use of the multiphase motor instead of the three-phase one. This is particularly interesting when the motor is powered with high frequency values. In fact, the availability of high efficiency and light weight mechanical gears allows to increase the rated angular speed of the motor with a reduction of the overall dimensions of the machine. By combining high speed with an increase in the number of motor pole pairs and the power supply frequency, greater benefits can be achieved in terms of weight and dimensions of the electric motor. Obviously, it become necessary to use materials capable of reducing losses in the magnetic and electrical circuits and to accurately check the thermal behavior of the machine.

In the following, an asymmetric 6-phase motor is considered as a multiphase configuration; the terms of comparison with the reference 3-phase motor are explained in the following paragraph.

III. Three Phase and six Phase configuration

The comparison between the 3-phase propulsion motor and the 6-phase asymmetrical one is made considering an electric machine with tooth concentrated windings [13]. This configuration allows to design an electric motor with a high number of pole pairs, limiting the transversal dimensions of machine (internal and external armature diameters). Furthermore, the use of concentrated tooth windings gives the possibility to choose an appropriate combination of slots/poles, valid for both three-phase and six-phase power supplies. A winding configuration with 24 slots/20 poles is considered; the windings arrangements for the 3-phase and the 6-phase cases are shown in Fig.1*a* and 1*b*.

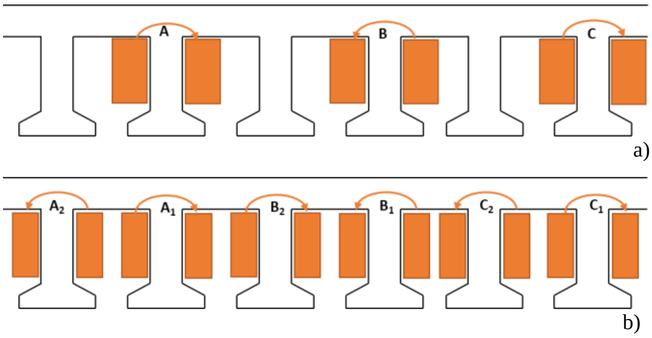


Fig. 1 Machine configurations for 24 slots/20 poles: a) 3-*ph*; b) 6-*ph*.

In the first case (*a*) a single layer distribution is adopted, while a double layer is necessary for the windings of the six-phase motor (*b*).

The number of layers used represents a first difference between the two configurations; in fact, the mutual coupling between the phase coils in the 6-*ph* motor is greater than in the case of a 3-*ph* windings with a consequent worsening of the behavior of the machine in presence of a failure. The comparison between the two motors is carried out respecting the following constraints:

a) the rated current must be the same;

b) no geometric modification of the magnetic circuits of the two motors must be applied: the 6-*ph* motor must be obtained only by means of a rearrangement of the windings; in this way the weights of the two motors are practically the same;

c) the linear current density (Amps per meter) along the air-gap surface of the stator is kept constant; at fixed dimensions of the magnetic circuit, this corresponds to keeping the thermal load constant (W/m^2) on the external surface of the stator.

The main electrical and geometric parameters required by the 3-*ph* motor are listed in Table I:

TABLE I. Main parameters of the considered 3-phase motor

Rated Power, P_n	25 kW
Rated Speed	6000 rpm
Overload at rated speed (max 60 s)	2 x P_n
DC-Link Voltage	270 V_{dc}
Rated Current	120 A_{rms}
External diameter	215 mm
Stator stack length	70 mm
Air-gap length	1.5 mm
Type of magnets	Samarium Cobalt
Soft magnetic material for stator sheets	49 % Cobalt-Iron alloys
Thermal class	C (>220°C)
Type of cooling	Forced Air

The sizing procedure of the motors is based on the optimization algorithm proposed in [14], imposing that the number of conductors per slot must be even (without any consideration about the number of parallel paths for each conductors). In this way, halving the number of conductors per slot for each phase, it is possible to re-arrange the winding in order to obtain a six-phase configuration with certainty of compliance with the constraints a), b) and c).

Once the different parameters of the two motors have been defined, the performance comparison is made taking into account the AC losses in the conductors, the iron losses and the losses in the permanent magnets of the two configurations in the rated operating condition.

The AC losses in the armature conductors are due the Joule effect, skin effect and proximity phenomena; the latter two causes strictly depend on the frequency of the currents. As it well known from literature [15], skin effect and proximity losses can be evaluated starting from the Maxwell equations, modeling the phenomena by means of the following relations:

$$\nabla^2 \mathbf{H} = \sigma \mu \frac{\partial \mathbf{H}}{\partial t} \tag{1}$$

$$\nabla^2 \mathbf{E} = \sigma \mu \frac{\partial \mathbf{E}}{\partial t} \tag{2}$$

which can be particularized in the frequency domain. The solution of the above equations and the use of Ohm's law allows the calculation of the current density **J** in the conductors. Therefore, it is possible to evaluate the total power dissipated in the conductors, integrating the square amplitude of **J** in the volume *V* of the conductors:

$$P_j = \frac{1}{\sigma} \iint_V |\mathbf{J}|^2 \, \mathrm{d}V \tag{3}$$

Using the losses obtained by (3), the AC phase resistance can be correctly evaluated and suitably modified in order to take into account the end-windings.

Usually, the analytical solution of equations (1) - (2) for a generic geometry is rather difficult. Therefore, it is necessary to use a finite element software that can solve the above equations with good accuracy, using detailed geometry. The results of the FE analysis also give the possibility to evaluate the distribution of the losses inside the conductors, with an improvement of the thermal and efficiency analysis of the motor. The calculation procedure is carried out considering the same number of parallel paths in both motors and neglecting the possibility of reducing losses by varying the strands connections.

Iron losses are evaluated using a numerical approach, based on finite element analysis. Using the data of 49% cobalt-iron alloys magnetic sheets, the specific losses [W/kg] dependent on the frequency and magnetic flux-density are considered. Iron losses are evaluated considering the magnetic flux-density values in each centroid of the mesh elements. The approach has a high computational cost but is more precise than simplified analytical methods.

Permanent magnet losses are usually neglected in low-speed rotating machines. Due to the high supply frequency values used in the considered machines, it is also useful to accurately evaluate the eddy-current losses in the magnets in order to reduce the risk of local overheating which could cause partial demagnetizations. The eddy currents induced in permanent magnets [16,17] can be obtained solving the equation:

$$\mathbf{J}_m = -\sigma \frac{\partial \mathbf{A}_m}{\partial t} + \mathbf{J}_c \tag{4}$$

where $\mathbf{J}_m$ is the surface current density, $\mathbf{J}_c$ is an integration constant, σ is the conductivity S/m] of the hard-ferromagnetic material and $\mathbf{A}_m$ is the potential vector inside the magnets.

IV. Comparative Numerical Results

A first comparison between the two machines is made considering the electromagnetic torque evaluated through the finite element analysis with reference to the steady state rated operating condition. The result (Fig. 2) is known and shows the convenience in terms of mean value and torque ripple of the 6-phase motor compared to the 3-phase one.

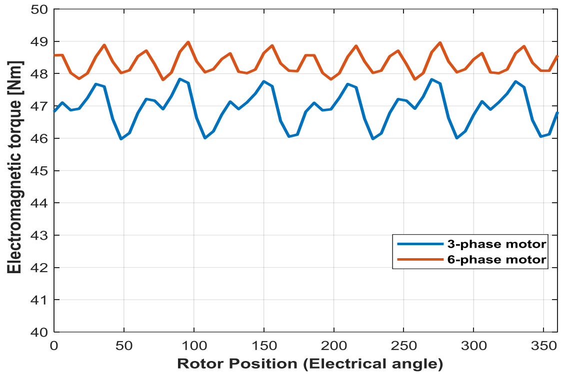
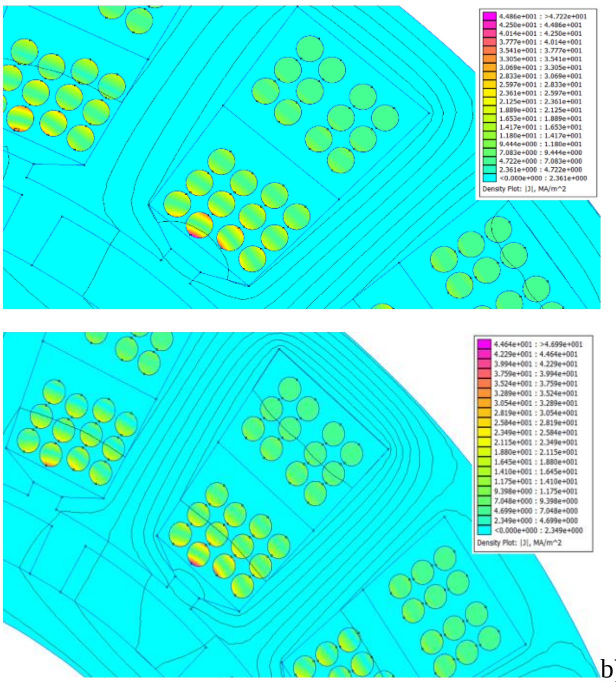


Fig. 2 Electromagnetic torque versus rotor position in the steady-state rated operating condition: 3-*ph* motor (blue); 6-*ph* motor (red).

A further comparison between the two motor types concerns the losses in the active materials. All the losses are calculated using the software FEMM 4.2 [18]. The results inherent the AC losses in the armature conductors are shown in Fig.3.



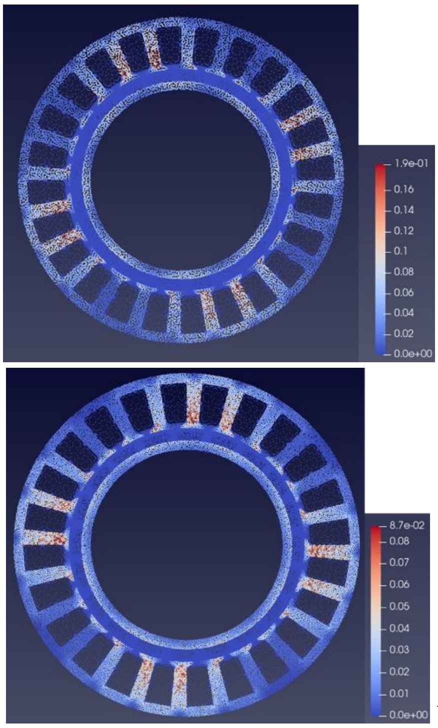
a)

b)

Fig. 3 Current density distribution with a frequency of 1000 Hz: a) 3-ph motor; b) 6-ph motor.

In detail, the Fig.3 shows the current density distribution inside the conductor of the 3-*ph* (top) and 6-*ph* (bottom) with a supply frequency of 1 kHz. In the simulative analyses four parallel strands in a turn have been considered for both the machines. The distribution of the current-density is similar in the two cases shown in the figure, with a slight increase in the maximum value of the current density in the 3-*ph* configuration.

The maps of the iron losses of the two motors are depicted in fig.s 4*a*,*b*. A slight difference between 3-*ph* and 6-*ph* motors is highlighted by the maximum value of the losses: in fact, the difference in the number of turns in series per poles and per phase of the 6-*ph* motor causes a reduction in the magnetic flux-density inside the iron paths.



a)

b)

Fig.4 Maps of iron losses: a) 3-*ph* motor; b) 6-*ph* motor.

The different loss components of the two motors are listed in Table II in relation to the rated operating conditions; AC losses in the conductor are referred to a temperature of 180 °C.

TABLE II. LOSSES AT RATED OPERATING CONDITIONS

	3-phase motor	**6-phase motor**
AC conductor losses	337 W	328 W
Iron losses	531 W	516 W
Magnet losses	57.9 W	52.7 W

The results obtained show a reduction of conductor and iron losses of about 2.5÷3% for the 6-*ph* motor. A greater reduction in percentage terms (~ 9%) occurs for the losses in the magnets, but the influence of this term on total losses is low. Another important consideration on the two motors concerns overloadability. In the electric propulsion of UAVs, the need for overload operations for a few minutes is often required by the vehicle's mission. Regarding overload operation, Table III reports the losses occurring under the overload conditions indicated in Table I.

TABLE III. LOSSES IN OVERLOAD CONDITIONS

	3-phase motor	**6-phase motor**
AC conductor losses	707 W	690 W
Iron losses	635 W	569 W
Magnet losses	73.4 W	57.6 W

In particular, the difference in iron losses is 10% while the greatest increase is in the magnet losses (with a percentage difference of ~20%). This difference can be charged to the presence of high saturated parts in the magnetic circuit of 3-*ph* motor.

Under the considered overload conditions, the losses in the 3-*ph* motor reach values higher than those of the 6-*ph* configuration; in particular, the difference in iron losses is ~10% while the greatest increase is in the losses of the magnet (with a percentage difference of ~20%). This difference is due to the presence of very saturated parts in the magnetic circuit of the 3-*ph* motor.

If we do not consider the reduction in efficiency of the entire electric drive and the thermal problems, one of the most limiting variables affecting overloadability are the limited DC-Link voltage values usually adopted on board. By means of the rewinding procedure carried out, a reduction of the counter-emf constant (V/rpm) in the 6-*ph* motor is obtained. This leads to an improvement in the overload capacity of the machine from an electrical point of view.

V. CONCLUSIVE REMARKS

In the paper a comparison was made between some performances of a a 3-*ph* and 6-*ph* PMSM used for the electric propulsion of UAVs. The two machines were compared considering a slots/poles combination compatible with both 3-*ph* and 6-*ph* windings, without any variation in the geometric dimensions of the motor. In addition to a higher intrinsic reliability, the 6-*ph* solution also allows a small reduction in losses compared to the 3-*ph* motor. Arguably, this small reduction alone may not justify the increased cost of using a six-leg inverter (or two separate three-leg inverters). An important role is to be attributed to the overload capacity, which in the cases examined was higher for the 6-*ph* motor.

Future work will focus on the following developments:

- energy performance of the inverter included in the comparative analysis;
- overcoming of the constraints imposed in paragraph III for the comparative sizing of two different three-phase and multi-phase motors.

Furthermore, different configurations of multiphase motors may be suitable for increasing the overall reliability of the electric drives. In particular, the use of a suitable slot/pole configuration with a single-layer winding would improve the reliability of the electric drive. In fact, this type of windings can reduce the possibility of fault propagation and the effects of mutual coupling among phases during operation in the presence of a failure.

ACKNOWLEDGMENTS

This research was financially supported by "*PRIN 2017 - Advanced powers-trains and -systems for full electric aircraft* - 2017MS9F49".

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