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Design of a PMSM for the Electric Steering of the Nose Landing Gear

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Abstract— **This paper is focused on the design of a PMSM for the electric steering of a nose landing gear. The traditional hydraulic steering systems utilized in a nose landing gear are usually based on a rack and pinion solution with two hydraulic pistons at the external sides. The main idea proposed in the paper is the substitution of the hydraulic steering system with an electric steering system based on the coupling between an harmonic drive and a three phase double rotor axial flux permanent magnet machine fed by two different three phase inverter.**

Keywords—harmonic drive, double three phase, more electric aircraft, nose landing gear, electric steering

I. INTRODUCTION

The aerospace industry is coming towards the concept of More Electric Aircraft (MEA), in particular the MEA approach affords the utilization of electric power for all non-propulsive systems. Usually these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical. Therefore it is possible to replace on board hydraulic systems with electric actuators systems, in order to decrease operating and maintenance costs, increase dispatch reliability, and reduce gas emissions [1],[2],[3].

This paper is focused on the design of a mechatronic actuator for the electric steering of a nose landing gear. The traditional hydraulic steering systems for a nose landing gear are usually based on a rack and pinion solution with two hydraulic pistons at the external side. The movement of steering is due to the variation of pressure inside the hydraulic system generated by the coordinated control of hydraulic valves positioned in the aircraft. The control of this valves is performed by the pilot with the handling of pedals.

Usually the torque required by a steering application is very high and depends by the weight of vehicle and the friction between the tires and the ground. Therefore, the electric steering is performed with the coupling between the electric motor and the hydraulic steering [4] or a mechanical gear as a ball screw. E.g., in [5] is designed an interior permanent magnet motor for the coupling with a ball screw which allows the steering; the steering system is composed by two motors on the same shaft and the main target of the proposed design is the reduction of a braking torque after a short circuit. The paper [6] describes a proposal of electromechanical actuation for the nose wheel steering system applied to commercial aircraft. The proposed solution provides the control of two dual three-phase motor which are jointed to the steering shaft with a clutch and a mechanical gear.

This paper proposes the design of a surface mounted, double rotor axial flux three-phase, permanent magnet motor coupled with an harmonic drive. This type of mechanical gear allows the possibility to achieve an high mechanical ratio, which is necessary to reduce the torque required and increase the angular speed of the electric motor.

In the following sections the sized permanent magnet motor and the performed finite element analysis are reported: in particular the behavior of obtained motor at different temperature is investigated.

II. FROM HYDRAULIC STEERING SYSTEM TO ELECTRIC POWER STEERING

The hydraulic steering system is usually composed by a rack and pinion mechanical gear which is linked with two different hydraulic piston, as shown in fig.1: the steering occurs [7,8] through the variation of hydraulic pressure inside the piston which governs the movement in the left or right direction. The variation and the control of the pressure of hydraulic system is guaranteed by different valves and hydraulic circuit positioned inside the aircraft. The use of an electric steering system gives the possibility to eliminate all the hydraulic circuits: it is possible to reduce the weight and increase the reliability.

A type of electric steering system can be made similar to the ball screw system utilized in automotive application [5]: the hydraulic pistons are replaced with two ball screw coupled with an electric motor Fig.2:

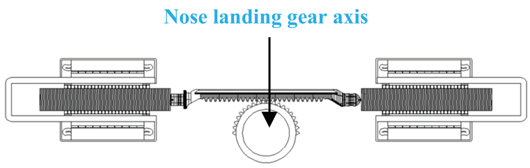

Fig.2 Electric steering actuator based on the ball screws

The rack and pinion system of fig.2 is coupled to the axis of the nose landing gear, and the steering in the right or left

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direction happens through the movement of screw in one of this directions. The two electric motors can be sized or for an half of the required power or for the total required power: in order to guarantee the steering, in the first case is necessary that the movement of the two ball screws are synchronized and both the motors generate torque at the axis; in the latter case, each motor provides to guarantee the necessary mechanical power needs to the steering and the control acts on the left or right motor, depending by the steering direction. The output steering force depends by the pitch of the screw and by the torque of the electric motor: its variation is shown in fig.3.

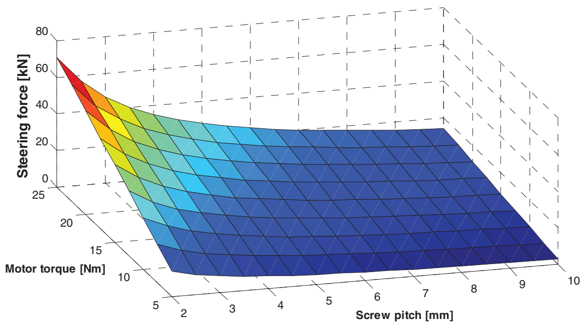


Fig.3 Variation of steering force [kN] with different values of screw pitch[mm] and motor torque [Nm]

The highest values of steering force are reached with the minimum value of screw pitch: this determines that, in order to reduce the required torque by the motor, it is necessary to choice a low value of screw pitch and this can create some strength problem on the ball screw if the steering force necessary is so high.
Considering the scheme of Fig.2, it is possible to note that the separation between the two electric motors can introduce the possibility to increase the reliability of the electrical drives utilizing two different inverters or a more legs inverter, but the limitation of actuator of Fig.2 is that the ball screws are linked to the same rack and pinion system, and this can determine a problem for the control in fault operations. In fact, if a short circuit fault occurs in the stator windings of an electric motor, a brake torque acts on the mechanical shaft of the faulted motor. In this way the correct performance of the steering system can be weakened because the healthy motor has to increase the torque on the mechanical axis in order to exceed both the steering torque and the brake torque due to the fault.
This determines the necessity to size correctly the PMSM, in order to reduce also the brake torque in case of short circuit of the stator windings. Another problem due to the series mechanical system created by the screws can occur with the damage of one of the ball screw: effectively, if one of the ball screw is locked, the steering is not possible.
Another electromechanical actuators which can be used for the electric steering of nose landing gear, is obtained utilizing the harmonic drive.

The harmonic drive based actuator shown in Fig.4, permits to reduce the axial length necessary for the installation and avoid the mechanical series system determined by the actuator based on ball screws.

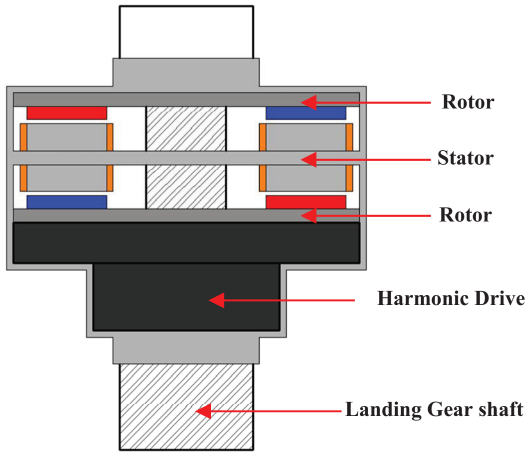


Fig.4 Harmonic drive steering actuator

The stator and the external part of harmonic drive is linked to the fixed upper part of the nose landing gear; the rotors are put in axes with the input part of harmonic drive and the output of harmonic drive is fixed on the nose landing gear and gives the rotational movement for the steering.
The advantage of the use of an harmonic drive is the possibility to obtain an high value of mechanical transmission ratio; in fact are available for sale different harmonic drives whit a mechanical transmission ratio equal or higher than 1:160. An high mechanical ratio permits to reduce the torque required by the electric motor and in this way reduces the main sizes of the motor.
The fig.5 shows the steering force generated by an harmonic drive actuator at different values of mechanical ratio and motor torque.

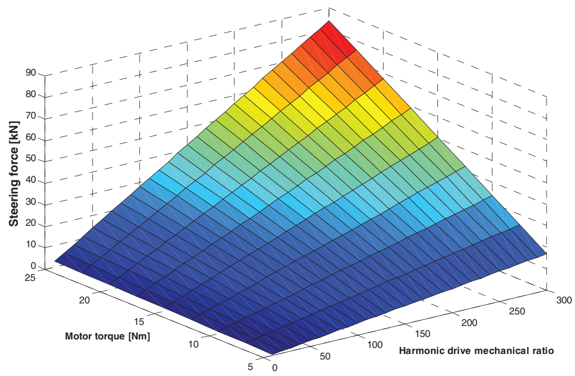


Fig.5 Variation of steering force [kN] at different values of harmonic drive mechanical ratio and motor torque [Nm]

Respect to the actuator based on ball screw, the harmonic drive actuator is based only on the performance of a single electric motor coupled in axis to the harmonic drive. This implies the necessity to design an high reliability electrical drive, with a redundancy of the phases and of the legs of the inverter.
In the following section it is shown the proposed solution based on the use of an axial flux permanent magnet synchronous motor.

III. Axial flux PMSM coupled with an harmonic drive

The utilized permanent magnet motor is a double rotor axial flux permanent magnet motor, with a three phase winding. This kind of machine presents two different windings, each of them associated to a different rotor. The windings can be connected in series (Fig.6a) or in parallel to the same inverter (Fig.6b), or can be fed by two different inverters in order to increase the reliability of the electrical drives as in Fig.6c.

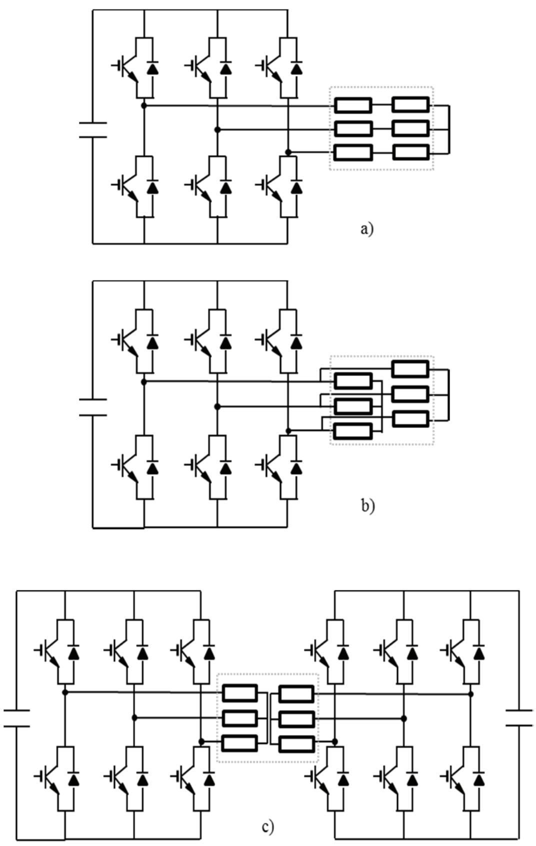


Fig.6 Configurations of the two windings of the stator: a)series connection; b) parallel connection; c) separated connection.

The considered configuration is shown in fig. 6c): if a fault occurs on a single phase of the motor, e.g. is considered that the phase is open after the fault, the post-fault configuration is shown in Fig. 7.

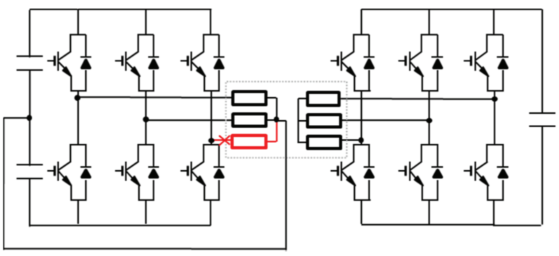


Fig.7 Post fault configuration: open fault of a single phase (red)

While, if a fault occurs on two phase of the two different motors, each motor is fed as a two phase PMSM motor with the common star point connected to the middle point of the dc-link of each inverter, as shown in Fig.8.

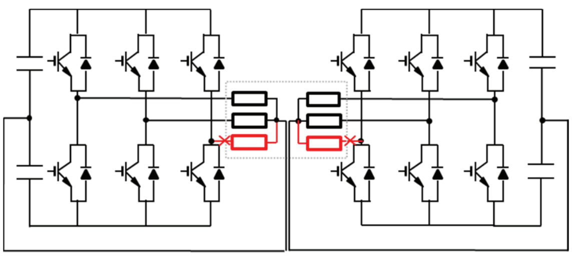


Fig.8 Post fault configuration: two open faults of a single phase (red) of the two different windings

The advantages of the proposed solution is the possibility to use a three phase motor with a well know control algorithm and with the possibility to obtain a satisfactory level of redundancy; also, the use of harmonic drive permits to avoid the use of two mechanical gears in series as occurs for the actuator based on ball screw. A limit of the proposed solution is due to the fact that the two rotors are linked on the same shaft and this implies that speed and torque performance are limited by the control of the faulty winding.

IV. Design of double rotor axial flux PMSM for the electric steering

The torque needs to the steering depends by different factors: type of wheel, length of the wheels shaft, friction between wheels and road, weight of the aircraft. This factors are influenced by the type of aircraft considered.
The characteristics required for the steering actuator analyzed in this paper are reported in the Table I:

TABLE I. STEERING CHARACTERISTICS

Steering angular speed	5 rpm
Steering torque	1200 Nm
Harmonic drive ratio	1:160

The chosen harmonic drive has a mechanical ratio of 1:160: through this value and the geometric sizes are calculated the torque and the speed required by the PMSM (Table II):

TABLE II. PMSM CHARACTERISTICS

Motor angular speed	5 rpm
Motor torque	1200 Nm
Maximum External Diameter	0,210 m
Minimum Internal Diameter	0,058 m

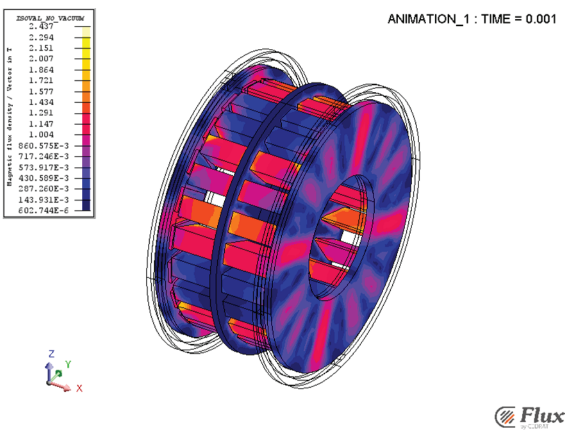
The designed motor is composed by two windings arranged in 24 slots and two rotors with 20 poles; for the iron parts of motor is utilized the magnetic steel M800-50A. Usually, the stator of axial flux machine is realized with powered soft magnetic materials; in this case also the stator and the tooth are realized with the magnetic steel and in particular the tooth are obtained by laser cutting a magnetic sheet core.

The main sizes, the electrical and mechanical parameters of the designed motor are reported in the Table III:

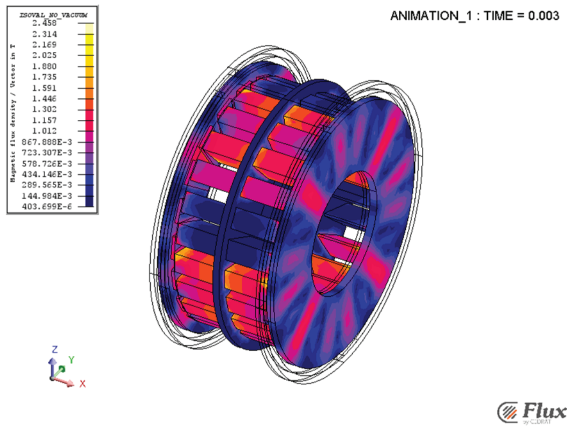
TABLE III. MAIN SIZES AND ELECTRICAL PARAMETERS

External Diameter	0,180 m
Internal Diameter	0,090 m
Rated current	5 A_{rms}
Rated voltage	110 V_{rms}
Rated Torque	7,5 Nm
Rated Speed	800 rpm

The Fig.9 a) and b) show the magnetic flux density obtained by the post-processing of the finite element analysis:



a)



b)

Fig.9 Isovalues map of magnetic flux density for two different instants of transient simulation

Due to the particular application, the electric motor can be designed in order to satisfy the required specifications for the steering and the possibility to operate in all the environmental conditions.

In fact, the performance of the PMSM utilized in aerospace applications are influenced by the variation of environment temperature. Usually it is required that the temperature range varies from -55°C to +75 °C and this makes a variation of residual magnetic flux density B_r [T] and of coercivity magnetic field H_c [A/m]: B_r and H_c can be assumed constant at low temperature, while as is well known, their values decreases at high temperature.

Therefore the verify of the torque expressed by the designed motor is checked through a finite element analysis at both temperatures, supposing that the initial temperature of the magnets are both -55°C and +75 °C.

The electromagnetic torque produced by the motor is reported in Fig.10.

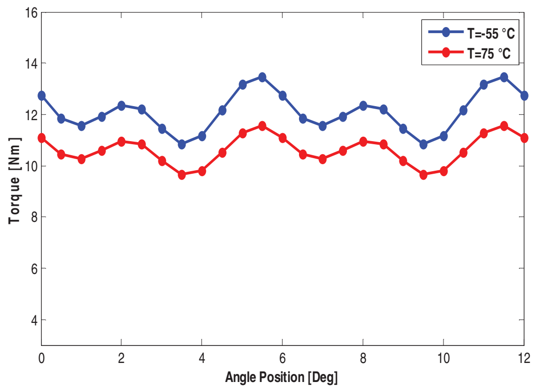


Fig.10 Torque characteristic of designed axial flux PMSM for two different initial temperatures: blue line indicates the torque at T=-55°C, red line indicates torque at 75°C

As it is possible to note, the torque calculated with the finite element analysis satisfies the required torque for the steering.

V. Conclusion

In the paper has been proposed the application of an axial flux double rotor PMSM for the coupling with an harmonic drive utilized for the electric steering of nose landing gear.
The utilized axial flux permanent motor is composed by a double rotor and two separate three phase windings, in order to increase the reliability of the system. The use of harmonic drive as mechanical gear permits to obtain high mechanical ration and avoid the realization of a series mechanical system. In the paper possible fault configurations have been considered and analyzed.
Finite element analysis have been performed in order to verify the correct sized of the axial flux machine.

Acknowledgment

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