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A NEW DESIGN OF A ROTOR-AXIAL ACTUATOR BY NdFeB PERMANENT MAGNETS

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ABSTRACT

The paper deals with an original design of an electromechanical actuator suitable for the fulfilment of an integrated system that is able to develop a contemporary motion both of rotation both of axial displacement. The traditional rotational movement, that is continuous, bases itself on a PM DC brushless design characterised by a sector structure with axial magnetisation. The axial motion can be developed by exploiting the original map of the magnetic flux density produced, in the air-gap, by the anisotropy and by magnets allocation. In this note a complete description of the actuator is presented together with the electromagnetic analysis suitable for design indications

1 INTRODUCTION

The large industrial development of the production of high energy permanent magnets has given an interesting impulse to the fulfilment of new geometrical and magnetic structures of electromechanical actuators. In fact the possibility to confine the flux density fields of suitable values ($0.8 \div 1.1$ Tesla) in small elements with a high coercivity allows the ideation of new electromechanical devices that can be adopted in robotics, in automotive applications or in industrial tools, with positive effects with respect to the reliability, the security and the economy of application. In technical literature [1] there are many examples of such new solutions.

During UPEC 93 the same Authors presented a prototypical version of a PM DC brushless motor with axial magnetisation [2] and a mathematical approach for its modelling. Furthermore magnetic field analysis by means of proper FEM technique have been proposed in order to achieve suitable indications about the design of such a machine [3].

The characteristic of this motor is the particular rotor anisotropy that, by means of an axial magnetisation developed by a set of NdFeB permanent magnets, allows an alternative distribution of the flux density in the air-gap. It has been said that the elementary structure of the machine is practically a fusion of two homopolar configurations get by a sector improvement.

This particularity allows a further exploitation of the electrical and magnetic structure in order to add to the rotational motion of the original machine an axial translation. In this way the device can be seen as a very integrated actuator that is able to develop two different and contemporary motions by using the same active parts and the same volume.

The rotor of this new actuator is practically equal to the motor already presented. The stator, on the contrary, presents a double system of windings: a first winding (internal with respect to the axis machine and the nearest to the rotor) represents a typical winding of PM-DC brushless motor; the second winding (external with respect to the previous) has a circular shape, co-axial to the motor and, therefore, with the permanent magnets in the rotor and is composed by a number of coils equal to the number of rotor sectors. Therefore, for each torque unit of the PM-DC brushless motor with axial magnetisation, there are two coils for the axial displacement. In this way a linear stepping actuator is realised and the displacement of the rotor (during the rotation too) with a stroke equal to the sector length can be achieved.

A full presentation of the solution will be proposed together with the analysis of the characteristic electrical and magnetic quantities, suitable for a design too.

The electrical, magnetic and geometrical basic relationships among the different parameters will be found and discussed in order to give a suitable indications about the design and the performances.

Furthermore a full mathematical analysis of the axial motion will be presented by means of the evaluation of the electrical and mechanical

quantities during the displacement of the rotor under the feeding of the added windings.

2 ACTUATOR CONFIGURATION AND MATHEMATICAL APPROACH

Let's consider the configuration in fig.1 in which a four-poles machine is shown and the following meaning of symbols:

h_s	width of circular slot;
i_z	axial winding current;
l_s	length of rotor sector;
v	axial speed;
v_z	axial winding voltage;
x	axial displacement;
z	axial abscissa
B_m	flux density of permanent magnets;
B_δ	air-gap flux density produced by magnets;
R	rotor radius;
R_z	axial winding resistance;
α_s	equivalent polar amplitude of sector;
δ	air-gap under the sectors;
γ	angular abscissa;
ρ	radial abscissa;
σ_m	magnet surface;
ω	volume integration variable.

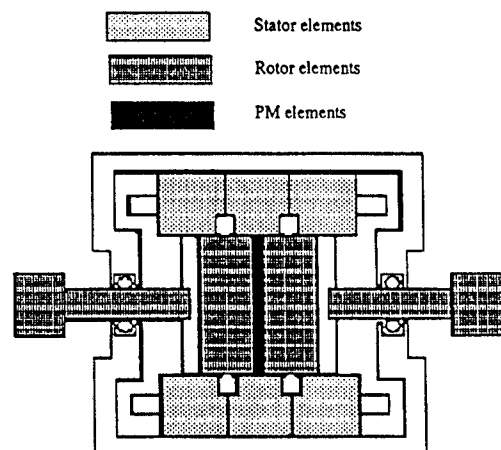


Fig. 1 - Axial machine section: the active stator iron has a length greater than the active rotor in order to develop the suitable stroke.

In previous papers the analysis of the motor without the axial windings has been developed. In this section the modification produced by the presence of the linear motion equipment will be discussed only. The axial PM disks are inserted between two rotor sectors that have the aim to give a radial configuration to the flux density. The presence of a no-isotropic shape of rotor sectors develops a restriction of suitable magnetisation area just under the poles that have an axial length l_s and an angular amplitude α_s . Because of the assumption of a small value of the air-gap it is convenient the simplification of the air-gap flux

density in order to consider a mean value of B under the pole defined as:

$$B_0 = \frac{1}{l_r \alpha_r \alpha_s} \iint B_r(\gamma, z, \rho) \Big|_{\rho=R} d\gamma dz \quad (1)$$

By neglecting the magnetic field under the basis of sectors:

$$B_z(\gamma, z, \rho) \Big|_{z=l} = 0 \quad (2)$$

the previous B_0 can be evaluated directly by the PM flux density B_m as:

$$B_0 = \frac{\sigma_m B_m}{2l_r \alpha_r R} \quad (3)$$

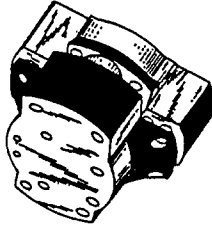


Fig. 2 - Axonometrical view of rotor sectors of considered machine.

The axial winding is confined inside an annular slot with a width h_s . If N_z are the turns of this winding it is convenient the use of the ratio:

$$n = \frac{N_z}{h_s} \quad (4)$$

Therefore the linked flux with the elementary winding $nd\xi$ when the rotor is at the place x produced by the PM elements will be:

$$d\Phi_z = B_0 R \alpha_r (l_r - x - \xi) n d\xi \quad (5)$$

and the total flux linked with the whole axial winding can be evaluated as:

$$\Phi_z(x) = \begin{cases} \int_0^{h_s} d\Phi_z = B_0 R \alpha_r n h_s \left(l_r - x - \frac{h_s}{2} \right) & 0 \leq x < l_r - h_s \\ \int_0^{l_r-x} d\Phi_z = B_0 R \alpha_r n \frac{(l_r-x)^2}{2} & l_r - h_s \leq x < l_r \end{cases} \quad (6)$$

In this way the relevant e.m.f. in this axial winding will be:

$$e_z = - \frac{d\Phi_z}{dx} \frac{dx}{dt} = \begin{cases} B_0 R \alpha_r n h_s v & 0 \leq x < l_r - h_s \\ B_0 R \alpha_r n (l_r - x) v & l_r - h_s \leq x < l_r \end{cases} \quad (7)$$

The axial force F_z , in the case of four rotor poles (two poles for each sector), will be finally:

$$F_z = \begin{cases} 4B_0 R \alpha_r n h_s i_z & 0 \leq x < l_r - h_s \\ 4B_0 R \alpha_r n (l_r - x) i_z & l_r - h_s \leq x < l_r \end{cases} \quad (8)$$

In order to evaluate the reluctance force developed by the axial winding on the no-isotropic rotor sectors it is necessary the computation of the air-gap magnetic tension $\Gamma(z, x)$ between the rotor poles and the stator. Having defined $\Gamma(z, x)$ as:

$$\Gamma(z, x) = \int_r^R H_r dr \quad (9)$$

where P_r and P_s are two opposite points on the rotor and on the stator respectively and H_z the radial magnetic field produced by the axial winding in absence of PM, the result will be:

$$\frac{\Gamma_z(z, x)}{N_z i_z} = \begin{cases} \frac{\left(x + \frac{h_s}{2} - l_r \right)}{l_r} & 0 < z \leq x \\ \frac{z-x}{h_s} + \frac{\left(x + \frac{h_s}{2} - l_r \right)}{l_r} & x < z \leq x + h_s \\ 1 + \frac{\left(x + \frac{h_s}{2} - l_r \right)}{l_r} & x + h_s < z \leq l_r \end{cases} \quad (10)$$

the relevant magnetic energy can be computed as:

$$W_r(x) = \int_{\Omega} \frac{1}{2} \frac{\Gamma^2 \mu_0}{\delta^2} d\Omega \quad (11)$$

with Ω that represents the volume where the field has been restricted. By considering only one sector that consists of two poles the final expression will be:

$$W_r(x) = \frac{\mu_0}{\delta} R \alpha_r \int_{l_r} \Gamma_r(z, x)^2 dz \quad (12)$$

and therefore:

$$W_r(x) = N_z^2 i_z^2 \frac{\mu_0}{\delta} R \alpha_r \left\{ -\frac{x^2}{l_r} + \left(1 - \frac{h_s}{l_r} \right) x + h_s \left(\frac{1}{3} - \frac{h_s}{4l_r} \right) \right\} \quad (13)$$

The reluctance force F_s can be evaluated as:

$$F_r = \frac{\partial W_r}{\partial x} \Big|_{x=l_r} \quad (14)$$

so that, on one sector:

$$F_r(x) = N_z^2 i_z^2 \frac{\mu_0}{\delta} R \alpha_r \frac{l_r - h_s - 2x}{l_r} \quad (15)$$

According to the linear trend of F_s with respect to the axial displacement x , the absolute maximum values are developed at the position $x=0$ and $x=l_r-h_s$

$$F_r(0) = -F_r(l_r - h_s) = N_z^2 i_z^2 \frac{\mu_0}{\delta} R \alpha_r \frac{l_r - h_s}{l_r} \quad (16)$$

The total axial force, relevant to only one sector, will have a linear trend and the maximum and minimum values will be:

$$F_{max} = R \alpha_r N_z i_z \left(2B_0 + N_z i_z \frac{\mu_0}{\delta} \frac{l_r - h_s}{l_r} \right) \quad (17)$$

$$F_{min} = R \alpha_r N_z i_z \left(2B_0 - N_z i_z \frac{\mu_0}{\delta} \frac{l_r - h_s}{l_r} \right)$$

The ratio:

$$k_r = N_z i_z \frac{\mu_0}{2\delta} \frac{l_r - h_s}{l_r B_0} \quad (18)$$

gives a suitable indication about the weight of the reluctance force (that in an extreme position of rotor is opposite to the principal force) with respect to the force of interaction between the PM and the axial current.

In order to underline the connection between this ratio and the principal machine dimensions and electrical and magnetic quantities it is possible to express it in terms of magnets flux density:

$$k_r = N_z i_z \frac{\mu_0}{\delta} \alpha_r \frac{l_r - h_s}{\kappa \pi R B_m} \quad (19)$$

where κ represent the ratio between the total permanent surfaces and the rotor cylindrical section,

In order to evaluate the expression of axial inductance, by the assumptions of considering the permanent magnets as ideal flux generators, it is possible to limit the evaluation of the field produced by the axial current under each sector only. This method adopts the same approach used in the thrust evaluation for the no-isotropic structure. By assuming the value of the constant k_w as:

$$k_w = 2N_z^2 \frac{\mu_0}{\delta} R \alpha_r \quad (20)$$

by considering the previous expression of magnetisation energy under one sector, the value of L_z will be:

$$L_z = k_w \lambda(x) \quad (21)$$

with

$$\lambda(x) = -\frac{x^2}{l_r} + \left(1 - \frac{h_s}{l_r} \right) x + h_s \left(\frac{1}{3} - \frac{h_s}{4l_r} \right) \quad (22)$$

this expression gives values positive of λ in the characteristic range of displacement of rotor ($0 \leq x \leq l_r - h_s$).

The expression of emf, produced by the no-isotropic rotor structure with the axial speed v , will be:

$$e_z = k_w \left(i_z \lambda' v + \lambda \frac{di_z}{dt} \right) \quad (23)$$

with:

$$\lambda' = \frac{d\lambda}{dx} = 1 - \frac{h_z + 2x}{l_z} \quad (24)$$

the emf developed by the PM movement in one winding will be:

$$e_B = B_0 R \alpha_z n h_z v \quad (25)$$

and finally the voltage balance equation, for each winding in front of each rotor sector will be:

$$\begin{aligned} v_z(t) &= R_z i_z + e_z + e_B = \\ &= R_z i_z + k_w \lambda(x) \frac{di_z}{dt} + (k_w i_z \lambda' + B_0 R \alpha_z n h_z) v \end{aligned} \quad (26)$$

3 DESIGN GENERAL CRITERIA

In this section a general discussion about the design criteria of the actuator will be developed. Because of the design of the rotor sectors has been already discussed in previous notes [2] and some indications have been given by using particular fem tools too. For this new configuration a fem analysis will be developed in the future. For a first set of suitable indications it is, however, important to fix some general rules on the basis of the constraints established by the design of the sector, for the rotation action. Therefore, in the following, starting from a set of fixed dimensions, some indication about the design of the axial movement arrangement will be given.

The relationships (8) and (15)...(20), in particular, allow a general discussion about the choice of the main design parameters of the axial actuator.

In fact it is evident that the main component of the thrust depends on the inter-activity between the permanent magnet and the winding current; on the contrary the thrust produced by the no-isotropic geometry, because of the alternating trend around the central position of the rotor sector with respect to the winding, is a component that in half a stroke is in accordance with the previous component and in the other half is in opposite. Therefore it is suitable a choice of machine parameters that minimises the ratio k_F . This ratio depends on the PM flux density, the ampere turns of the axial winding, the air-gap, the stroke of the rotor and the sector length.

A good design should provide a full exploitation of the available space between the rotor sector for magnets allocation. Furthermore the rotor should have a large radius and the stroke should be reduced. Usually the stroke is a constraint and than the only possibility to improve the performances, with an assigned type of magnets, is the increasing of the radial dimension. Then if the magnetic stability is assured, in all the heating operating conditions, it is convenient the increasing of the air-gap. Following this indications the axial equipment of the PM DC motor, with an inter sector disk magnets allocation, has been designed and the results are summarised in tab.I.

With a stroke of 21 mm and a current of 5 A the value of F_{max} for one sector is 36 N and the maximum peak of reluctance thrust is equal to 16 N.

$$\begin{aligned} N_z &= 100 \text{ turns} & \alpha_z &= \pi/3 \\ R &= 37.5 \text{ mm} & h_z &= 5 \text{ mm} \\ \delta &= 0.5 \text{ mm} & l_z &= 26 \text{ mm} \end{aligned}$$

Tab. I - Electrical arrangement for the axial-rotor actuator

4 SIMULATION RESULTS

The previous mathematical model, developed in order to evaluate the axial motion characteristic, has been integrated by considering the electrical arrangement in tab.I presented. For this computation it is not considered a resistance force so that the evaluation is referred to a no-load condition. On the contrary a friction force has been taken into account by a parameter $b_f = 0.04 \text{ N s}^2/\text{m}^2$. During the axial displacement no-current has been considered in the windings for rotating motion. However the presented model does not take into account the iron saturation so that the armature currents cannot produce a modification of the performances in the axial windings. Furthermore the de-magnetisation effect of the axial windings current on the permanent magnets, in the worst de-magnetisation condition developed by the other standard windings too, does not

succeed to compromise the magnetic stability of PM elements inside the range of admissible temperatures.

The feeding system of the axial windings can be arranged by considering a voltage impressed or a current impressed supply. The first case is surely the most chip arrangement because the control devices are only two end-stroke transducers. In the case of impressed current feeding, on the contrary, a current control loop, for a chopper supply, must be implemented.

The mechanical behaviour during the axial motion neglects the oscillating trend of the speed after the crash of the rotor on the terminal restraints. Therefore, when the equipment has achieved the final position, a brake stops the motion. The inertia of the rotor has been fixed to 1kg for all the considered cases.

Fig. 3 shows the trend of current and thrust when an impressed current is considered and a maximum switching frequency of static devices is 5 kHz. As it is possible to notice in this figure the value of current is quite constant and equal to the fixed value of 5 A. The ripple in the force is produced by current controller. The mean value of force decreases with the displacement because, in the first half of stroke the component F_z is positive while in the second one is negative. When the brake stop the running after a time-stroke minus then 30 ms, the current controller and the supply should be turned off.

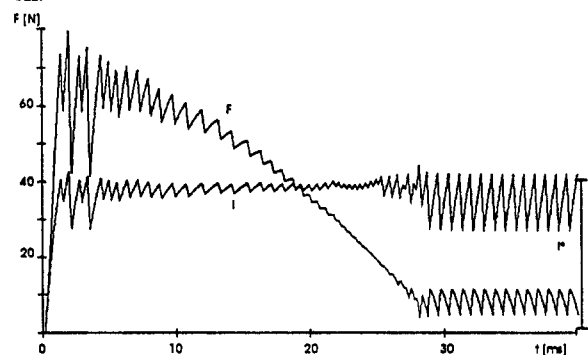


Fig.3 - Total axial force and current when a 5 kHz current controller is adopted.

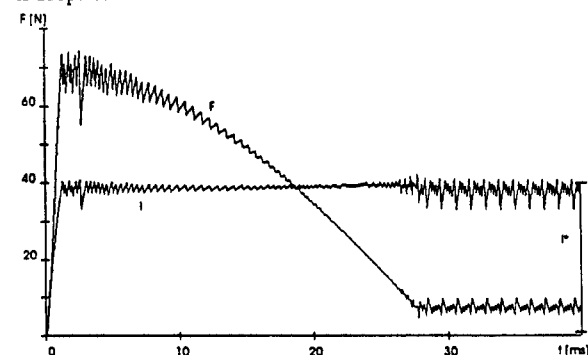


Fig.4 - Total axial force and current when a 10 kHz current controller is adopted.

Fig. 4 shows the trend of current and thrust when an impressed current is considered and a maximum switching frequency of static devices is 10 kHz. In this case the ripple has decreased very much both in the current and in the force.

Because the reference value of current is equal for previously considered cases the mechanical behaviour on the speed is quite coincidence. In fig.5 this trend has been shown together with the relevant axial displacement.

In the case of constant voltage supply the trend of current and thrust is represented in fig.6. When x displacement produces a positive value of reluctance force, for the higher values of uncontrolled current, the total thrust gives a significant starting acceleration as sketched in fig 7 where position and speed versus time are drawn.

Therefore the stroke is completed in a lower time with respect to previous cases. Unfortunately, the ending position is reached with a very high value of current so that the reluctance thrust, that assumes negative sign, overcomes the main thrust. In order to avoid a dangerous increasing of current after the intervention of the brake a null value of voltage has been imposed to axial windings.

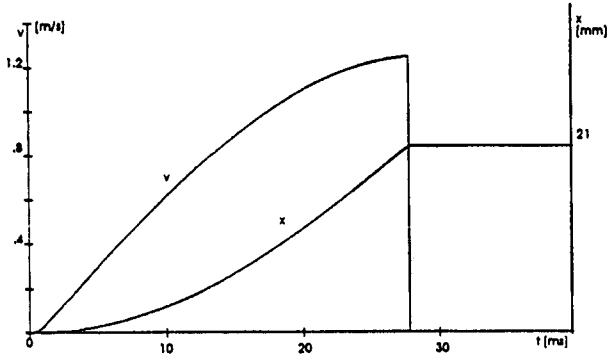


Fig. 5 - Speed and axial position when a current controller is adopted.

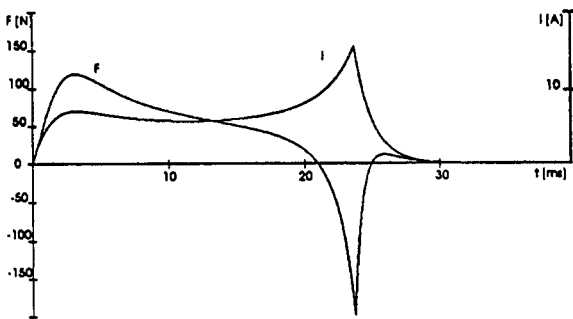


Fig. 6 - Total axial force and current when an impressed voltage supply of 30V for winding is adopted.

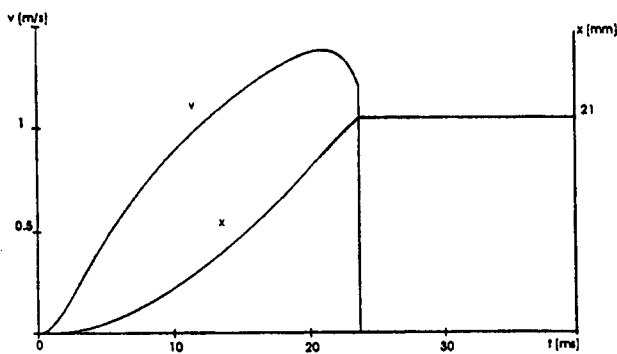


Fig. 7 - Speed and axial position when a constant voltage (30V) is adopted.

5 CONCLUSIONS

The original structure of the presented actuator has allowed the integration of two different types of motion by adopting a very compact solution. The first design has demonstrated the good capability of this solution of developing an axial motion (as a two levels linear stepping motor) superimposed to the standard rotation of a PM DC motor. After this preliminary study of feasibility a fém analysis will be requested in order to improve the electromagnetic

and mechanical performances of the actuator by means of the optimisation of the design and the full exploitation of used material. Furthermore a re-definition of mechanical requirements must be done when the final allocation of such an actuator will be decided in machine tools, in the field of automotive devices, and so on.

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