Tubular Linear Permanent Magnet Actuator with Fractional Slots

Roberto Di Stefano* Non-member, Fabrizio Marignetti* Non-member

(Manuscript received Jan. 11, 2012, revised July 3, 2012)

This paper presents a design procedure for fractional-slot, three-phase tubular linear permanent magnet machines. The machine has a solid iron mover and stator core, concentrated prewound stator windings, and rare earth annular magnets with axial magnetization. The stator winding interacts with the mover magnets through the fifth harmonic of its magneto-motive force distribution. The proposed design procedure analytically determines the proper dimensions of basic geometry. A finite element method optimization of the air-gap flux density profile focusing on the shape of slots, teeth, and polar expansions completes the design procedure. The study evaluates the effectiveness of the solid iron fractional slot tubular machine for low-speed applications. Experimental verifications are included.

Keywords: linear, magnets, actuator, tubular, fractional

1. Introduction

The recent literature testifies a deep interest for Tubular Linear Permanent Magnet Machines (TLPMMs) for several special applications. The literature on the subject includes quasi-Halbach tubular machines (1) and several advanced three-phase solutions, e.g. the flux-switching permanent magnet (PM) brushless machine, which combines saliency and magnets and presents an alternative stator winding configuration (2). Linear generators, often adopted in marine power plants, offer the advantage of generating power without introducing any conversion crank gear or hydraulic system. The use of a tubular-machine topology allows the electromagnetic thrust density to be improved (3). Recent studies on the analysis and modeling, present machines with square cross sections (4), (5). Reference (6) focuses on iron loss in a single-phase machine for direct-drive linear compressors in domestic refrigeration applications. Optimal performance for a single-phase motor driving a vapor compressor is investigated in (7). This paper deals with the benefits of the adoption of a fractional number of slot per pole and phase in a three phase machine with a solid iron core. The considered machine has solid iron mover and stator core, concentrated pre-wound stator windings, and rare earth annular magnets with axial magnetization, while the polar expansions produce radial air-gap flux density. The stator winding interacts with the mover magnets through the fifth harmonic of its magneto-motive force distribution. The proposed design procedure analytically determines the proper dimensions of the basic geometry. The finite element method is used to optimize the shape of the teeth, and polar expansions. The key point of the work is the evaluation of the effectiveness of the fractional slot three phase tubular machine. The reference application, which determines the optimization goal is as a generator operation for marine power conversion. A prototype was built and subjected to experimental tests in order

to determine its performance in terms of the relationship between generated force and weight of the active section and losses.

2. Design Procedure

Several types of tubular permanent magnet machines can generate high forces with small strokes. Excluding configurations requiring an active mover and fixed magnets, the most frequently used machine structures can be classified according to the magnetization direction of permanent magnets:

- a) Radial magnetized magnets;
- b) Axial magnetized magnets;
- c) Multipole Halbach magnetization;

all types may include both iron or ironless circuits. The presence of iron is essential for actuators to generate high thrusts, however it is very hard to avoid cogging forces. This effect is obviously an important drawback for the dynamic performance, especially for servo applications (8)–(10). Using a large number of slots helps increasing the frequency of the cogging force, although it contrasts with the applications requiring short strokes. In addition, the external geometric constraints imposed to the actuator design by the application, have often a strong influence on the distribution of stator windings, demanding that the windings of each pole were allocated within the least number of slots. Low-speed applications require machines with small pole pitches to increase working frequency and back e.m.f. This suggests a solution with higher order m.m.f. dominant harmonic such as the fifth or the seventh.

In the proposed actuator the stator winding is designed as shown in Fig. 1 where the schematic coils arrangement is reported. Figure 2 shows the exploded view of the actuator according to the Fig. 1 sketch. The slot displacement has been drawn to emphasize the fifth m.m.f. space harmonic. The same figure reports the corresponding stator m.m.f. distribution generated by feeding the actuator with a constant phasor current. Figure 3 shows the theoretical distribution of normalized m.m.f. space harmonics which can be generated. The harmonic distribution was computed for different

* University of Cassino
via Di Biasio 43, 03043, Italy

Fig. 1. Coils layout of phase windings

Fig. 2. Exploded view of actuator layout and corresponding stator m.m.f. distribution

 Fig. 3. FFT diagram of the stator m.m.f. linear distribution as function of ratio γ between the iron thickness and pole pitch

values of the ratio between the iron thickness and the slot pitch: $\gamma = t_{Fe}/\tau_s$ in Figs. 3 and 4. The diagram shows that the amplitude of the fifth harmonic is a monotonically decreasing function of γ . The same diagram suggests to reduce the iron thickness within the limits imposed by the magnetic analysis. In order to verify the cogging force, the FEM analysis has been performed. This design step, which will be further described, allows to optimize the shape of both stator and mover iron circuits.

2.1 Stator Design The radial dimensions of the mover and the size of the pole pitch set the minimum radius of coils and its thickness, as shown in Fig. 4, where the basic arrangement of mover is sketched. The Fig. 4 does not reflect the final design of the actuator but it is mainly intended as support in reading the Table 1 which reports the

Fig. 4. Mover and air-gap section with most relevant geometric dimensions before the mover shape optimization

Table 1. Main mover parameters

Name	Value
Total active stator length	$l_a = 180$ mm
Pole pitch	$\tau_p = 30$ mm
Magnet thickness	$\tau_m = 5$ mm
Magnet internal radius	$r_m = 13$ mm
Magnet external radius	$R_m = 30$ mm
Iron internal radius	$r_{Fe} = 13$ mm
Iron external radius	$R_{Fe} = 38$ mm
Iron thickness	$\tau_{Fe} = 10$ mm
Mover diameter	$R = 80$ mm
Actual airgap	$\delta = 3.7$ mm
Stainless steel thickness	$\delta_s = 1.5$ mm

Fig. 5. Coil inductance and resistance versus external diameter

main geometric parameters. The slow mechanical dynamics, required by the application, do not allow to define a rated voltage for the whole phase winding. For this reason only a maximum voltage value has been fixed as a design constraint. Since there are no specific limits on the radial size of the actuator, it is necessary to impose an additional criterion to define the size of each coil. While it is appropriate to increase the depth of slots to generate higher thrust, the corresponding increase of impedance of the phase winding could be harmful to the voltage drop between load and no-load operation. Figure 5 reports the inductance and resistance trends of coils as function of their external diameters. Moreover, as the FEM analysis demonstrates, above a certain value of the coil radius, a further increase does not produce the same contribution to the thrust. For this reason the maximum coil radius is a trade-off between the thrust density of the whole mover and the winding impedance. Considering all these factors the external diameter of coil has been fixed to 170 mm,

Table 2. Slot and coil data

Name	Value
Slot pitch	$\tau_s = 12.5$ mm
Internal diameter	$d = 95$ mm
External diameter	$D = 175$ mm
Wire gauge	$SWG = 19$
Packing factor	$pf = 0.65$
Coil thickness	$\Delta z = 7$ mm
Inductance	$L_c = 180$ mH
Resistance	$R_c = 5.5$ Ω

with a resistance of about 5.5 Ω , and an inductance of about 190 mH. Table 2 reports all the coil and slot data.

2.2 Mover Design Once the stator slot pitch is defined ($\tau_s = 12.5$ mm) the periodicity pitch of the mover poles, is $2 \cdot \tau_p = 30$ mm, as the mover must synchronize to the fifth space harmonic of the stator field. The external diameter of magnets has been chosen smaller than the iron sleeve diameter. This choice depends on two factors: to design a magnetic geometry that allows suitably shaping the pole pieces, and to make room for a magnetic shield to further reduce the flux leakage during the electrodynamic transients. The magnets diameter was chosen equal to 60 mm.

It is possible to find the magnets operating point considering the air-gap pole flux:

$$\Phi_\delta = 2\pi R_{Fe} \frac{\tau_{Fe}}{2} B_0 = \pi (R_m^2 - r_m^2) B_m k = \Phi_m \dots \dots (1)$$

where k is a coefficient that takes into account the leakage between one pole piece and the adjacent one. From relation (1) it is possible to derive the airgap flux density

$$B_0 = \mu_0 H_0 = \frac{(R_m^2 - r_m^2) B_m k}{R_{Fe} \tau_{Fe}} \dots \dots \dots (2)$$

Summing the m.m.f. along the entire path of the magnetic one has

$$H_0 = -\frac{\tau_m H_m}{2\delta} \dots \dots \dots (3)$$

which leads to

$$H_m = -\frac{2\delta}{\mu_0 \tau_m} \frac{(R_m^2 - r_m^2) B_m k}{R_{Fe} \tau_{Fe}} \dots \dots \dots (4)$$

Considering the magnets characteristic $B_m = \mu_r \mu_0 H_m + B_r$ it is possible to derive their operating point at no load condition:

$$B_m = \frac{B_r}{1 + \frac{2\delta \mu_r (R_m^2 - r_m^2) k}{\tau_m R_{Fe} \tau_{Fe}}} \dots \dots \dots (5)$$

Equation (2) can be rewritten now as

$$B_0 = \frac{(R_m^2 - r_m^2) k \tau_m B_r}{R_{Fe} \tau_{Fe} \tau_m + 2\delta \mu_r (R_m^2 - r_m^2) k} \dots \dots \dots (6)$$

Table 3 reports magnetic features of the magnets. Using these data and fixing the most appropriate working point, it is possible to compute the ratio $\frac{\tau_{Fe} + \tau_m}{\tau_m}$. With 5 mm magnets thickness of the mover pieces, the iron pieces will have 10 mm thickness.

Table 3. Magnets properties

Name	Value
Material	<i>NdFeB sintered</i>
Remanence	$B_r = 1.210$ T
Coercivity	$H_c = 892$ kA/m
Max energy product	$BH_{max} = 279$ kJ/m ³

Fig. 6. FEM diagram for the geometry defined by the basic analytical approach. The image shows how the shape of polar expansion, slots, and teeth influence the field map

Fig. 7. Radial flux density diagram for shape defined by first analytical approach. The data were collected on a line parallel to the z axis of the inner surface of the armature

2.3 FEM Analysis The analysis leads to the preliminary definition of the characteristics of the magnetic circuit. The geometric profiles of the magnetic sections are not yet optimized, therefore, in order to increase the magnetic flux linkage and to reduce the leakage flux, a FEM analysis must be performed. Figure 6 shows the flux density map of the magnetic section, while Fig. 7 reports the diagram of the radial component of flux density of inner stator core surface.

Starting from the preliminary design, several simulations were carried out. Leading to taper the magnetic poles with a significant reduction of the flux leakage and a corresponding increase of the air gap flux, this geometry also helps to keep the flux density constant in this section. A further change was made on the openings of the armature circuit. In fact the adopted shape allows to improve the magnetic coupling between the armature and magnets.

2.4 Armature Reaction Further FEM analysis is

Fig. 8. Effects of a different pole shape. Diagram of the radial flux density collected on the surface crossing the necks of armature slots (red line)

Fig. 9. FEM data for final shape. Diagram of the radial flux density collected on the surface crossing the necks of armature slots (red line)

Fig. 10. Permanent magnets demagnetization curve

needed to verify the effect of the armature currents on the magnetic voltage of magnets. In fact, the choice of the operating point of permanent magnets depends on the minimum value of flux density in the magnets. As shown in the Fig. 10, the minimum value is higher than B_k , to avoid any irreversible demagnetization.

This calculation must be performed on the magnetic circuit considering the worst conditions, both in terms of the supply current and the mover position. The mover position should exhibit the slightest reluctance. Under these conditions, assuming one phase current at maximum value I_1 , the others will be $I_2 = -\frac{1}{2}I_1$ and $I_3 = -\frac{1}{2}I_1$. Figure 11 reports the magnetic voltage across the the permanent magnets. The computed values are well below the defined safety limit.

Fig. 11. Permanent magnets demagnetization voltage, the data were collected on the cylindrical surface crossing the magnets (red line)

Fig. 12. Coil between two iron discs

Fig. 13. Isometric sketch of the actuator

2.5 Iron Losses Even if the motor is designed for very low speed, or standstill operation, the iron losses cannot be neglected because the stator core is made of solid steel. Eddy currents that are generated in this case can be very intense and can affect the thermal conditions of the motor. However, as described in (11), the iron losses can be considerably reduced by few radial cuts on the discs. In this way the path of the eddy currents is longer resulting in a better thermal behavior.

3. Hardware Setup

The motor armature was made by assembling solid steel discs shaped for housing the coils. The discs are kept locked by threaded rods. The Fig. 12 shows a coil between two iron discs. The mover is aligned to the armature by means of linear ball bearings SKF LBBR80. The magnets and the pole of the mover are inserted into a stainless steel tube and secured

by a 32 mm threaded bar. The whole arrangement is shown in the Fig. 13 where a perspective view of some sections of the actuator are drawn.

4. Experimental Results

The first experiment performed on the machine was the measurement of no load voltages during generator operation. This measure was performed on two phases of the armature when the mover of the tubular motor is driven by another actuator. Figure 14 reports the voltages diagrams. The relationship between voltage and speed can be inferred from this diagram, the voltage constant is about 1000 Vs/m. The actuator is fed by means of a three phase inverter. The tests were performed by feeding the motor with a current of 1.3 A. In order to measure the thrust as a function of the mover position a load cell was bolted to the shaft. The load cell is connected to the stator via a mechanical system shown in Fig. 15. The thrust was measured along 70 mm. Figure 16 shows in detail the collected data. The presence of the cogging thrust along the z axis can be remarked, but this ripple remains within a very small range of about 10%.

The fundamental component of the m.m.f. harmonic distribution is counter-rotating respect to the fifth. The interaction between the harmonic distribution of the magnet field and

Fig. 17. Prototype

the fifth harmonic distribution of the stator m.m.f. generates a parasitic alternative force. This effect is however of limited importance. Larger effects can be seen on translator iron losses, which are, however, outside the scope of the present paper. Considering the thermal limits conditions and a maximum current density of 4 A/mm^2 the thrust/volume ratio is about $1.2 \cdot 10^5 \text{ N/m}^3$. In order to evaluate the ratio between thrust and weight of the actuator, only the active components of stator and mover should be considered. In particular, iron sections affected by main magnetic field, copper and magnets have been taken into account. The output-weight ratio is about 30 N/kg.

5. Conclusions

The analysis and design of TLPM actuator has been presented highlighting the different design steps. The generator has been designed for high thrust and low speed. The special shape of the armature of this machine has suggested to adopt a fractional slots winding. The validity of this choice has been demonstrated by both FEM analysis and experimental tests.

Acknowledgment

This study was supported, in part, by the Italian National Research Program PRIN 2008, prot 20085BP47Z004.

References

- (1) J. Wang, Z. Lin, and D. Howe: "Analysis of a short-stroke, single-phase, quasi-halbach magnetised tubular permanent magnet motor for linear compressor applications", *Electric Power Applications, IET*, Vol.2, pp.193–200 (2008-5)
- (2) J. Wang, W. Wang, K. Atallah, and D. Howe: "Design considerations for tubular flux-switching permanent magnet machines", *IEEE Trans. Magnetics*, Vol.44, No.11, pp.4026–4032 (2008)
- (3) V. Colli, P. Cancelliere, F. Marignetti, R. Di Stefano, and M. Scarano: "A tubular-generator drive for wave energy conversion", *IEEE Trans. Industrial Electronics*, Vol.53, No.4, pp.1152–1159 (2006)
- (4) X. Chen, Z. Zhu, and D. Howe: "Modeling and analysis of a tubular oscillating permanent-magnet actuator", *IEEE Trans. Industry Applications*, Vol.45, No.6, pp.1961–1970 (2009)
- (5) S. Boroujeni, J. Milimonfared, and M. Ashabani: "Design, prototyping, and analysis of a novel tubular permanent-magnet linear machine", *IEEE Trans.*

Fig. 14. Phase voltages measured when the motor is acting as generator

Fig. 15. Load cell to measure the thrust

Fig. 16. Measured thrust

Magnetics, Vol.45, No.12, pp.5405–5413 (2009)

- (6) J. Wang, T. Ibrahim, and D. Howe: "Prediction and measurement of iron loss in a short-stroke, single-phase, tubular permanent magnet machine", *IEEE Trans. Magnetics*, Vol.46, No.6, pp.1315–1318 (2010)
- (7) J. Wang, D. Howe, and Z. Lin: "Design optimization of short-stroke single-phase tubular permanent-magnet motor for refrigeration applications", *IEEE Trans. Industrial Electronics*, Vol.57, No.1, pp.327–334 (2010)
- (8) J. Wang, G. Jewell, and D. Howe: "A general framework for the analysis and design of tubular linear permanent magnet machines", *IEEE Trans. Magnetics*, Vol.35, pp.1986–2000 (1999-5)
- (9) N. Bianchi, S. Bolognani, D. Corte, and F. Tonel: "Tubular linear permanent magnet motors: an overall comparison", *IEEE Trans. Industry Applications*, Vol.39, No.2, pp.466–475 (2003)
- (10) N. Bianchi, S. Bolognani, M. Pre, and G. Grezzani: "Design considerations for fractional-slot winding configurations of synchronous machines", *IEEE Trans. Industry Applications*, Vol.42, No.4, pp.997–1006 (2006)
- (11) I. Boldea and S. A. Nasar: *Linear Electric Actuators and Generators*. Cambridge University Press (1997)

Roberto Di Stefano (Non-member) received the Laurea degree in

Electrotechnical Engineering from the University of Naples, Naples, Italy. From 1993 to 1997, he was with the Research Group of Electrical Machines and Converters, University of Naples. In 1996, he joined the Electrical Machines and Drives Research Group, University of Cassino, Cassino, Italy. Since 1996, he has been the Director of the "Giovanni D'Angelo" Industrial Electronic Laboratory, University of Cassino, where, since December 2004, he has been an Asso-

ciate Professor of power electronics and electrical drives. His research interests include power electronics converters, soft switching converters, digital control of electrical drives and special electrical machines.

Fabrizio Marignetti (Non-member) received the Laurea degree with

honors and the Ph.D. degree in Electrical Engineering both from the University of Naples 'Federico II' in 1993 and in 1998 respectively. In 1998 he joined the University of Cassino, Italy, where he is currently an associate professor of power electronic converters, electrical machines and drives. Since 1996 he lectures at the University of Cassino in electrical machines, electric vehicles, generators and converters for renewable energies. In 1998 he has been bestowed a scholarship in Rational Mechanics by the University of Cassino. His Research areas are in design, analysis and digital control of electrical machines, renewable energies, power converters. Prof. Marignetti is the author and/or coauthor of more than 100 publications in his research field and three patents. Dr. Marignetti received one IEEE prize paper award in 2008. Dr. Marignetti received also one prize paper at the 2008 Comsol Conference.sDg