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Rotor Shape Influence on Tubular Induction Actuator Force

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***Abstract*—** In this paper we present the inductive force analysis of a tubular induction actuator (TIA) according to its geometrical and physical parameters. The produced force derives from the energy conversion factor witch is a function of the dimensional parameters of this kind of systems. This analysis is done for three kinds of rotors, the massive one, the coated one with a conducting layer and the segmented one. Analysing forces methods are presented. Emphasis has been made on the finite element method using FLUX2D software.

***Keywords*—** Electromagnetic Force, Flux2D Package, Rotor Design, Tubular Induction Machine

I. Introduction

THE tubular induction motors are used as long course actuators. The machine shape is shown on Fig. 1. The primary comprises a three-phase winding and the secondary is a simple steel cylinder. The linear tubular motor can also be regarded as a propulsion system. Its functioning principle is similar to that of the traditional induction linear motor. The propulsion force is the interaction between a sliding field generated by the stator and the rotor induced currents produced by the latter.

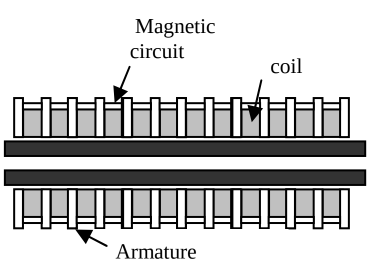

Fig. 1. Architecture of the TIA

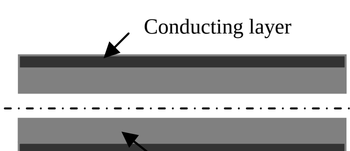

Fig. 2. Coated rotor

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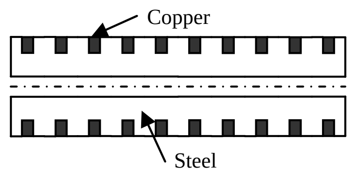

Fig. 3. Segmented rotor

The tubular induction motors are presented as an alternative of the linear flat induction motor in which the stator is rolled up in the form of tube whose axis is parallel to the movement direction.

Recently, a great interest is carried to the use of these systems in the projectiles propulsion [2]-[3]-[5]. In this case, the rotor constitutes the projectile that is accelerated along the stator until leaving it with a high speed. The stator is supplied by an impulse current.

The TIA thrust force depends on the rotor architecture. To this end, we distinguish several types of TIA that are presented on the Fig. 1, Fig. 2, Fig. 3 (Massive rotor, Rotor coated with a conducting layer, Segmented rotor).

II. Force Approching By Simplified Model

The simplified model of the induction motor is shown on Fig. 4. The motor is represented by two magnetic areas separated by an air-gap.

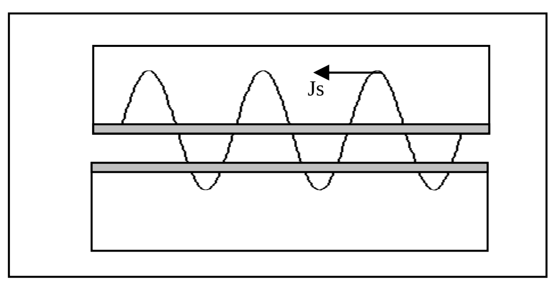

Fig. 4. Simplified representation of the TIA

The stator area is traversed by a sinusoidal wave due to a sinusoidal current density model then the force is given by the following expression [3]:

$$F = \left(J_s^2 \rho_c\right) / \left(t_c V_S \left(1 + \left(1/\tau^2\right)\right)\right) \quad (1)$$

Where, V_S is the speed of the traveling wave 2 τ_p f. The stator current wave Js and τ are given by:

$$\tau = \left(2\tau^2{}_p\mu_0 f t_c\right)/(\rho e)$$
(2)

$$j_s = J_s \sin\left(\left(\pi x/\tau_p\right) + 2\pi f t\right)$$
(3)

The second area is represented by a conducting layer with a surface resistivity equal to ρ_c / t_c where ρ_C is the resistivity of the conducting layer and t_c its thickness. The preceding model, with air-gap e and is a one dimension only, simple to apply and the reactance of the rotor leakages is neglected.

III. Force Approaching by Conversion Factor G

A. The Conversion Factor

The conversion factor G of a system translates its capacity of energy transformation from a given form to another. For an electromagnetic system with the consideration of the air gap flux distribution, conversion factor G can be written in the following form:

$$G = \left(2\tau_p^2\mu_0 f\right)/(\pi\rho e/t)$$
(4)

Where τ_p : the distance between two consecutive poles [m], D: rotor width [m] , t: rotor thickness [m], e: air-gap [m] and ρ : rotor resistivity [Ω. m].

B. Force Analysis Using G Factor

Relation between F and G

As aforementioned, G represents the conversion factor when neglecting the flux leakages. The practical factor of conversion Ga takes into account the leakage reactance X_2.. The force F using the volt-ampere method is given by [3]:

$$F = (1/V_s)\left(G_a/\sqrt{1+G^2{}_a}\right)$$
(5)

With: $G_a = \left(G/\left(1 + G\tan(\phi_2) + \tan^2(\phi_2)\right)\right)$ (6)

ϕ_2: rotor phase angle, G: X_m / R_2 (X_2 neglected)

Fig. 5 shows G_a factor according to G factor or more precisely the effect of the leakage reactance on the conversion factor G_a for the TIA when Fig. 6, shows the force F (Force/volt-Amp) (F/VA) according to G_a factor [6].

The ideal conversion factor G is seldom reached in practice. The presence of a great leakage reactance in the massive rotor induces a small factor G compared to that of the coated rotor for the same value of G.

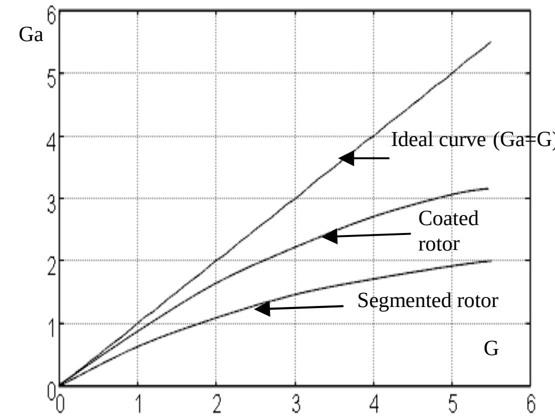

Fig. 5. Conversion factor Ga according to the ideal factor G

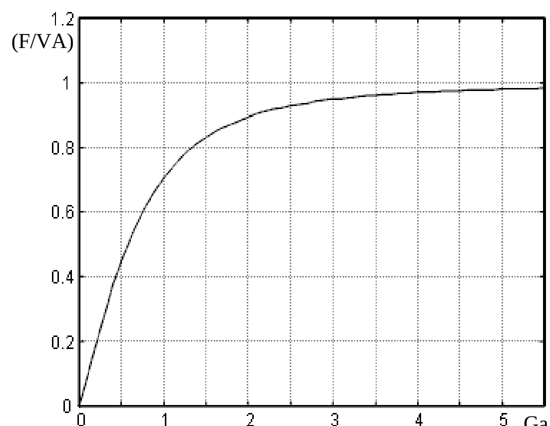

Fig.6. Variation of force with Ga factor

Forces for various types of TIA

It is the force that is used as a fundamental parameter for the comparison between different types of TIA. The study consists finally to compare three types of basic rotors listed below in Fig. 1, Fig. 2, Fig. 3 with the corresponding conversion factors (Gco, Gmass, Gseg):

$$G_{CO} = \left(2\tau^2{}_p\mu_0 f\right)/\left(\pi\rho e_t/t_c\right) \quad (7)$$

$$G_{CO} = \left(2\tau^2{}_p\mu_0 f\right)/\left(\pi\rho(e+t_c)/t_c\right) \quad (8)$$

$$G_{mass} = \left(2\tau^2{}_p\mu_0 f\right)/(\pi\rho e/\delta), \quad (9)$$

$$G_{seg} = \left(2\tau_p^2\mu_0 fwt\right)/(y\pi\rho e) \quad (10)$$

G_{co}, G_{mass} and G_{seg} are the conversion factors of coated, mass and segmented rotors respectively.

e: real air-gap, t_c: thickness of the conducting layer, δ: thickness of skin, e_t: total air-gap = e+t_c, y: rotor pole pitch, w: rotor slot width

The comparison of the ideal factors for the three rotors shows respectively for the three rotors that:

We can improve the conversion factor G by increasing the thickness t_c of the conducting layer. However the total apparent air-gap e_t increases what would thus decrease the air-gap flux density.

Factor G for the massive rotor is proportional to the skin effect thickness δ that depends on the air-gap maximum flux density Bg, on the magnetic pole saturation flux density B_0 and on the pole pitch τ_P [1].

The advantage of the massive rotor lies in the simplicity of its realization and its aptitude for varying G through the increase of the penetration depth in order to increase the emf E. The segmented rotor combines the advantages of the above rotors (the coated rotor and the massive rotor) to give finally:

This allows a greater flexibility in the choice of rotor slot width w, y and t to get the desired value of G. Thus, in this case, we can improve the factor G by:
- increasing the width of the rotor slot
- decreasing the rotor slot pitch
- decreasing the air-gap
- decreasing the resistivity.

IV. Force Approaching By Coupled circuits method

The stator winding of TIA consists of an arrangement of series-connected coils supplied with a sinusoidal power source. The rotor is a conducting metal cylinder.

The rotor can be divided into conducting rings in which the current density is supposed uniform. Each ring is regarded as an electric circuit of the same form as that of the stator [9]. The equivalent electric circuit of the rotor obtained using coupled circuits method is short-circuited; however, the stator circuit is feed [5]-[9].

The $L_{rj,\,si}$, mutual inductance between the rotor ring j_{ht} and the stator coil i_{ht}, depends on the linear displacement of the rotor along z coordinate. This permits to write the mechanical equations governing the TIA [7]:

$$F_Z - F_F = M\left(d^2 z / dt^2\right) \quad (11)$$

$$F_z = I_s^{\,T} G_{rs} I_r, \quad (12)$$

$$G_{sr} = \partial L_{sr} / \partial z = G_{rs}^T \quad (13)$$

$$L_{rs} = L_{sr}^T = \begin{bmatrix} L_{r1,s1} & L_{r1,s2} & L_{r1,s3} \\ L_{r2,s1} & l_{r2,s2} & L_{r2,s3} \\ L_{r3,s1} & L_{r3,s2} & L_{r3,s3} \end{bmatrix} \quad (14)$$

V. Finite Elements Modelling

The model of the inductive tubular actuator by the finite element method is governed by equation (15):

$$\text{rot}\,\frac{\mathbf{1}}{\mu}\,\text{rot}A = J \quad (15)$$

By applying the Galerkin technique we obtain:

$$\int N\left(\text{rot}\,\frac{\mathbf{1}}{\mu}\text{rot}A - J\right)d\Omega = \mathbf{0} \quad (16)$$

In the axisymmetric case the volume integral is reduced to a surface integral:

$$\mathbf{2}\pi\int rN\left(\text{rot}\,\frac{\mathbf{1}}{\mu}\text{rot}A - J\right)d\Gamma = \mathbf{0} \quad (17)$$

N is the 2D form function.

A study with the software FLUX2D of a TIA prototype allowed predicting the evolution of the force according to other determining parameters. This component decrease rapidly when the air-gap value exceeds 2 mm. The maximum value of B_N is about 0.6 Tesla for an air-gap of 2 mm (Fig. 7) and it reaches a very low value, 0.3 10^{-6} Tesla, for an air-gap of 4mm.

Studies undertaken on the tubular motor and discussing the comparison of the results obtained by the simplified model, used in [4], and the finite element method (FEM) (Fig. 7, Fig.8) with taking into account the effects of the extremity show that:

- The theory of the simplified model gives reasonable results in consideration of various simplifying assumptions.
- Better results are obtained by the FEM and mainly in the case of the infinitely long model where the boundary effects are neglected.

- A difference in the force values exists between the finite and infinite length models what confirms the importance of the boundary effects for this type of motor.

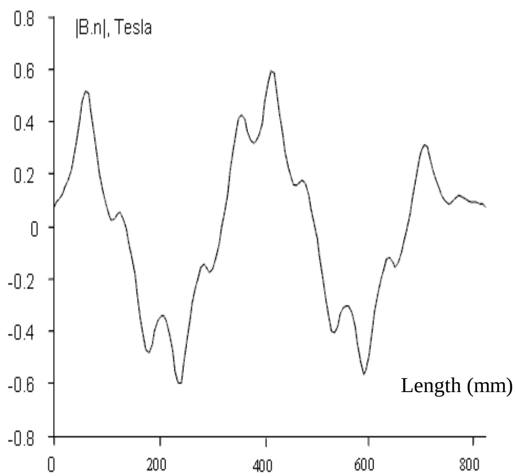

Fig. 7. Normal component of flux density Bn for an air-gap of 2 mm.

The forces are calculated by the finite element method (FEM) via the integral of **J**x**B** [7]-[8].

To obtain acceptable forces, only the air-gaps going up to 2 mm are acceptable, beyond this value the force decrease considerably. Optimal force is obtained for frequencies varying between 20 Hz and 40 Hz (Fig. 8).

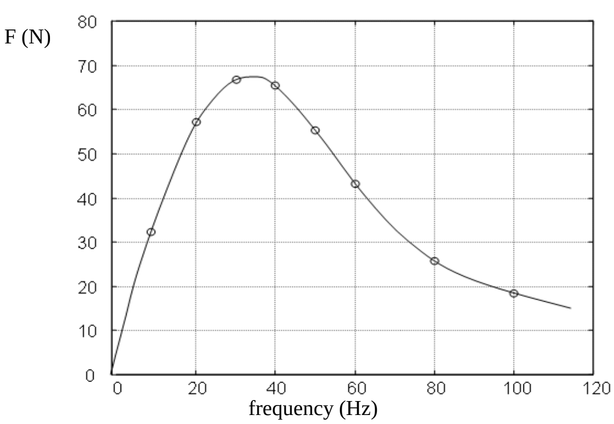

Fig. 8 Thrust force for different supplying frequencies

VI. Conclusion

The analytical approach of the thrust forced by the means of the conversion factor proves to be interesting insofar as it makes it possible to clarify the principal parameters necessary to the design of the linear tubular motor. This approach makes it possible to carry out a first analysis of the thrust force according to the choice of the various parameters that determine it. Thus, the thrust force for different types of TIA (massive rotor, coated rotor, segmented rotor) was discussed. This approach makes it possible to get the first values of the studying parameters and the design of TIA by the finite element method. Owing to the latter, results were obtained namely the behaviour of the force according to the choice of the air-gap, the frequency, as well as the behaviour of the normal component of the air-gap flux density which is at the origin of the thrust force.

References

[1] E. R. Laithwaite, *Induction machines of special purposes*, *George. Newnes Limited,* London, p.155, (1966)

[2] J. L, He, Z. Zabar, E. Levi, L. Brienbaum ,’’Transient performance of linear induction launchers fed by generators and by capacitor banks,’’ *IEEE Transactions on Magnetics*, Vol. 27, N°1, January 1991.

[3] J. F. Easthman, R. Akmese, D. Rodger, R. J. Hill-Cothingham’’ Prediction of thrust fore in tubular induction machine,’’ *IEEE Transactions on Magnetic*s, Vol. 28, N°2, March 1992.

[4] S. Williamson, P. J. Leonard, ‘’ Analysis of air-cored tubular induction motors,’’ *in Proc. IEE Conference*, Great Britain, Vol. 133, N°4, July 1986.

[5] M. Abdellah, A. Hammel, A. Zaoui, H. Mohellebi, “Study of the feeding mode effect on the linear induction launcher (LIL) performances,’’ *in Proc*. *WSEAS Transactions On Systems,* Issue 10, Vol. 4, pp. 1798-1804, October 2005.

[6] W. G. Grover, *Inductance_Calculations,* New York, Dover publications, 1946.

[7] M. Zaouia, F. Hocini, M. Abdellah, H. Mohellebi, “Electric-magnetic-mechanical coupled model for transient analysis of three phases-axisymmetric electromagnetic launcher,’’ in *Conf. Rec. 2003*. *European Conference NUMELEC*’2003, *Communication,* pp. 189-190.

[8] M. Zaouia, H. Mohellebi, M. Abdellah,’’Electric-magnetic-mechanical coupled model for analysing dynamic characteristics with feeding effects of linear induction launcher,’’ *in Proc*. *WSEAS IASME Transaction,* Issue 2, Vol. 1, pp. 235-240, April 2004.

[9] M. Abdellah, K. Challal, H. Mohellebi,’’ Influence of Rotor Design on Variable Reluctance MachineTorque,’’ *in Proc. Wseas Systems Theory and application,*Vol. 2, Crete Island, Greece, July 23-28, pp. 288-293, 2007.