Experimental characterization and comparison of TLIM performances with different primary winding connections

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This paper presents an experimental characterization and comparison of the performances achieved by a Tubular Linear Induction Motor (TLIM) prototype with different typologies of primary winding connections. More in detail, three different configurations have been considered, analyzed and discussed: full-pitch star, 5/6 shortened pitch star and 5/6 shortened pitch double star. For this purpose, an experimental test bench at the Sustainable Development and Energy Saving Laboratory (SDES Lab), University of Palermo, Italy, has been set-up. The obtained results have allowed the identification of the best winding configuration for different applications intended for the motor. Moreover, in comparison with classic approaches that involve mathematical equations for winding design, the proposed experimental work is suitable for TLIM winding designs: indeed, more accurate results are obtained and approximation coefficients avoided.

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1. Introduction

During the last decades, TLIMs have been widely used in several application fields [1–12]. This is due to the fact that the performances achieved by these electrical machines can be more suitable for specific applications if compared with traditional type ones.

The TLIM is a LIM where the magnetic flux flows, from pole to pole, along the direction of the motion, crossing the air-gap in a radial direction [9]. Moreover, the cross-section of a tubular machine is not always circular, but it can assume square-shape or hexagonal shapes [13]. The most used cross-section configurations are square-shape or circular-shape. In the latest case, the machine is called cylindrical. Moreover, the most used TLIM structure is composed by a short primary, which is fixed to a basement and a secondary longer than the primary. In addition, the lamination of the primary can be either longitudinal or transversal with respect to the direction of motion [14].

TLIMs could have a different stator and slider structure and different winding configurations, in dependence of the specified application. As a matter of fact, the structure of the machine and its winding topology can significantly affect the mechanical performances of the machine, in terms of both thrust and speed, as well as the performances of its electrical drive. Furthermore, the choice of the electrical winding topology affects also the driven current and voltage values of the machine and their harmonic content.

The purpose of this work is to experimentally characterize and compare the performances achieved by a TLIM prototype with different typologies of primary winding connections, in order to define specific fields of applications for each typology of winding configuration. Furthermore, in comparison with a classic analytical approach, which takes into account the use of several formulas, more accurate results without approximation coefficients can be obtained [15–17]. More in particular, this paper is structured as follows: in Section 2 the mathematical model of the TLIM in terms of its energy transfer dynamics is developed; in Section 3 the TLIM prototype used in this work is accurately described and analyzed; in Section 4 three possible typologies of winding configuration are described: full-pitch star, 5/6 shortened pitch star and 5/6 shortened pitch double star; in Section 5, the test bench that has been set-up in order to carry out several experimental tests is presented; in Section 6, the related advantages and disadvantages that occur for each type of winding configuration are reported and discussed.

2. The TLIM dynamic model

Several LIM models have been presented in the technical literature. In particular, some of them are suitable for design purposes, while other models can be more easily applied in the field of elec-
metrical drives. The dynamic model can be conceived either with a “field approach” [18, 19] or with a “circuit approach” [20]. The latter has been chosen for the purposes of this work by taken into account the procedure described in Ref. [21] and by considering the following statements: linearity and isotropy of the magnetic circuit, sinusoidal distribution of the FMM in the air gap, negligibly of eddy current losses and primary and secondary circuits virtually reclosed on themselves, in order to obtain the same structure of the rotating induction motor. Therefore, the TLIM can be studied as an induction machine with rotational movement.

By referring to a d-q coordinate system fixed to the stator, the mathematical model of the motor can be summarized by the following dynamic equations:

\[ v_{1d} = R_1 i_{1d} + \frac{d\psi_{1d}}{dt} \]  
(1)

\[ v_{1q} = R_1 i_{1q} + \frac{d\psi_{1q}}{dt} \]  
(2)

\[ v_{2d} = R_2 i_{2d} + \frac{d\psi_{2d}}{dt} + \omega_r \psi_{2q} = 0 \]  
(3)

\[ v_{2q} = R_2 i_{2q} + \frac{d\psi_{2q}}{dt} = 0 \]  
(4)

\[ i_{2d} = \frac{\psi_{1d} - (L_1 + A) i_{1d}}{A} \]  
(5)

\[ i_{2q} = \frac{\psi_{1q} - (L_1 + A) i_{1q}}{A} \]  
(6)

\[ i_{1d} = \frac{\psi_{2d} - (L_1 + A) i_{2d}}{A} \]  
(7)

\[ i_{1q} = \frac{\psi_{2q} - (L_1 + A) i_{2q}}{A} \]  
(8)

\[ A = L_m (1 - f(Q)) \]  
(9)

\[ f(Q) = \frac{1 - e^{-Q}}{Q} \]  
(10)

where \( v_{1d} \) and \( v_{1q} \) are the primary voltages along the direct-axis and quadrature-axis, respectively; \( v_{2d} \) and \( v_{2q} \) are the secondary voltages along the direct-axis and quadrature-axis, respectively. The terms \( i_{1d} \) and \( i_{1q} \) are the primary currents along the direct-axis and quadrature-axis, respectively, whereas \( i_{2d} \) and \( i_{2q} \) are the secondary voltages along the direct-axis and quadrature-axis, respectively. In addition, \( \psi_{1d} \) and \( \psi_{1q} \) are the primary fluxes along the direct-axis and quadrature-axis, respectively, \( \psi_{2d} \) and \( \psi_{2q} \) are the induced fluxes along the direct-axis and quadrature-axis, respectively. \( R_1 \) and \( R_2 \) are the primary and secondary resistances, respectively, \( L_1 \) and \( L_2 \) are the primary and secondary leakage inductances, respectively, and \( L_m \) is the magnetizing inductance. Finally, \( \omega_r \) is the angular frequency, \( A \) is a parameter that takes into account the end effect and \( Q \) is a parameter that takes into consideration the length of the secondary. The equation that represents the mechanical equilibrium is given by:

\[ F = F_r + Bv + m \frac{dv}{dt} \]  
(11)

where \( F \) is the tension force, \( F_r \) is the resistance force, \( B \) is the coefficient of viscous friction, \( m \) is the mass of the movable element and \( v \) is the related speed.

3. The TLIM prototype

The TLIM prototype described in this work is shown in Fig. 1 and it is available at the SDES Laboratory of the University of Studies of Palermo.

This three-phase machine has been designed according to Ref. [22]. The motor is composed by a short primary, a long bimetallic secondary and two pole pairs. Furthermore, this prototype has been designed in order to produce 150 N at 2 m/s. The generated mechanical power P is 300 W at its rated voltage of 400 V and its rated frequency of 50 Hz. The primary and secondary structures are described with more details in Subsections 3.1 and 3.2, respectively.

3.1. TLIM primary

The primary core is composed by 24 slots and it is realized with 5 mm width laminates, which guarantee a transversal lamination with respect to the motion. The iron sheets shown in Fig. 2 have been used for the construction of the iron parts of the TLIM primary.

By assembling eleven iron sheets of the A-type and sixteen of the B-type, it is possible to obtain the slot/tooth alternative sequence, as shown in Fig. 3. In fact, the overall thickness of both teeth and slots is determined by the number of sheets of the same type used for the assembling of either teeth or slot. In addition, the tightening of the sheets is guaranteed from the hubs located into the holes, which are realized in correspondence to the edges of the sheets (see Fig. 3a). The terminals of the winding pass through a cut, which has been realized in each of the sheets used for the TLIM primary construction. In particular, 264 A-type and 400 B-type iron sheets have been assembled for the stator prototype realization. The primary winding is composed by coils with circular shape, which can be wrapped in order to achieve either a single layer or a double layer.

![Fig. 1. The TLIM prototype.](image1)

![Fig. 2. Schematic representation of the iron sheets used for the primary core.](image2)
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