THE DESIGN OF LINIAR INDUCTION MOTORS IN HYBRID CONSTRUCTION WITH BILATERAL TOROIDAL INDUCTORS USED IN LOW SPEED DRIVES

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Abstract. *In the present work the author offer some design solutions of the hybrid motors resulted from the successive transformations of the rotating induction motors, used in low speed drives. The board effect, caused by the finite dimensions armatures and also by the longer air gap, is known and estimated using mathematical relations applied to the linear motors. It has been tested the expression of the secondary plate resistance, for the hybrid construction, with a bilateral toroidal inductor, when the end effect is not neglected.*
Keywords*: design, board effect, hybrid motor, low speed drives.*

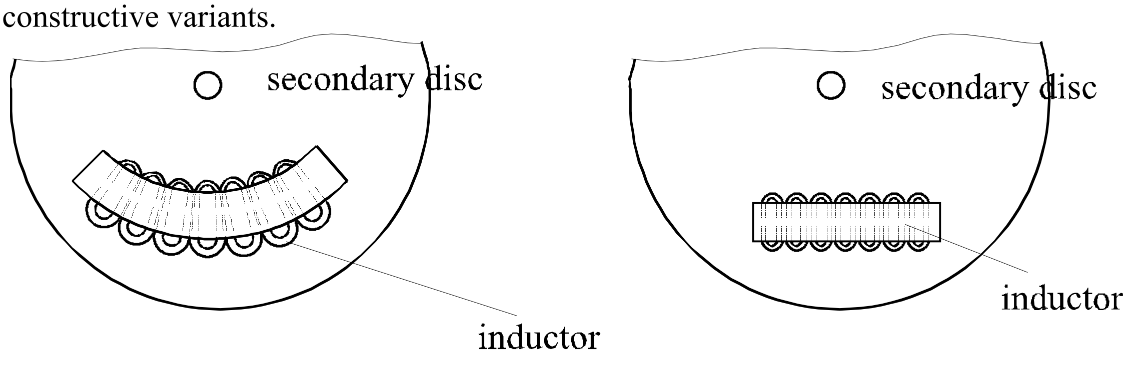
Introduction

The primary winding of a hybrid induction motor is placed on a magnetic circuit of a finite length. The mechanical construction requires a longer air gap than in the rotating induction motors case. This fact will also cause some specific effects in the linear motors, besides the well-known asymmetries caused by some different phase inductance. In case of the hybrid motors the effects mentioned above have a series of characteristic features.

The necessity of the hybrid motors designing imposed an as much as possible correct evaluation of these phenomena, and in this present scientifically work we will focus on the board effect after presenting a couple of hybrid motors constructive variants.

Hybrid Motors Constructions

The hybrid constructions can be obtained through successive stages of the rotating induction motors [1] transformation**.** In the present work we shall analyse the design of the hybrid motors with a toroidal inductor, a plate disc armature and a plane-axial air gap, used in low speed drives. The interest in the hybrid construction is stirred by the essential fact that it is generated a rotary oscillation at reduced speed and thus, the mechanical reducing gear is eliminated. This interest is also owed to the fact that the plate disc armature may be cheaper and permits a radius control of both, the torque and the speed.



a) **b)**

Figure 1

Moreover, if the disc armature has an appreciable radius in comparison to the inductor's dimensions, it can be coupled in a mechanical coupler with a generator, in order to the dynamically test of the linear motor, in the same conditions with these realised in case of the classical linear, progressive and rectilinear oscillations.

This class of the linear motors with an hybrid construction admits varieties with a linear inductor (fig.1.b.), The inductor may be unilateral with one classing path of the magnetic circuit (fig.2.b), or may have two symmetric inductors, hybrid motors called *bilateral* (fig.2.c).

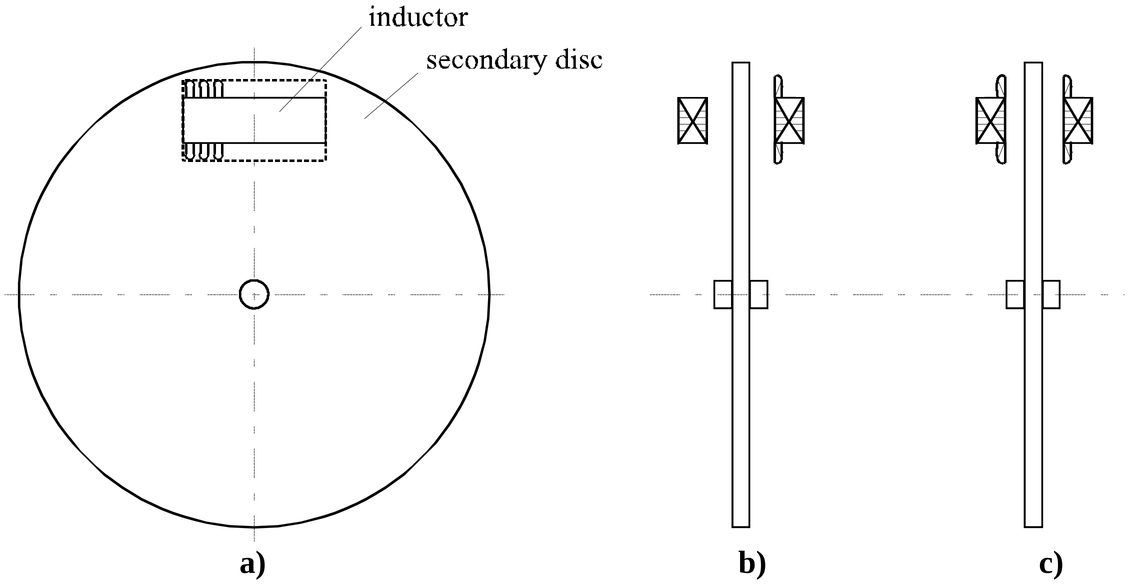


Figure 2.

The toroidal inductor may be with a 270^0 opening (fig.3) when it is necessary to maintain a guard space (such as in the case of the electric traction when the inductor is placed directly on the driving wheel; it is obligatory to hold a guard space to earth), unilateral with the closing path of the magnetic circuit (fig.3.b) or bilateral (fig.3.c).

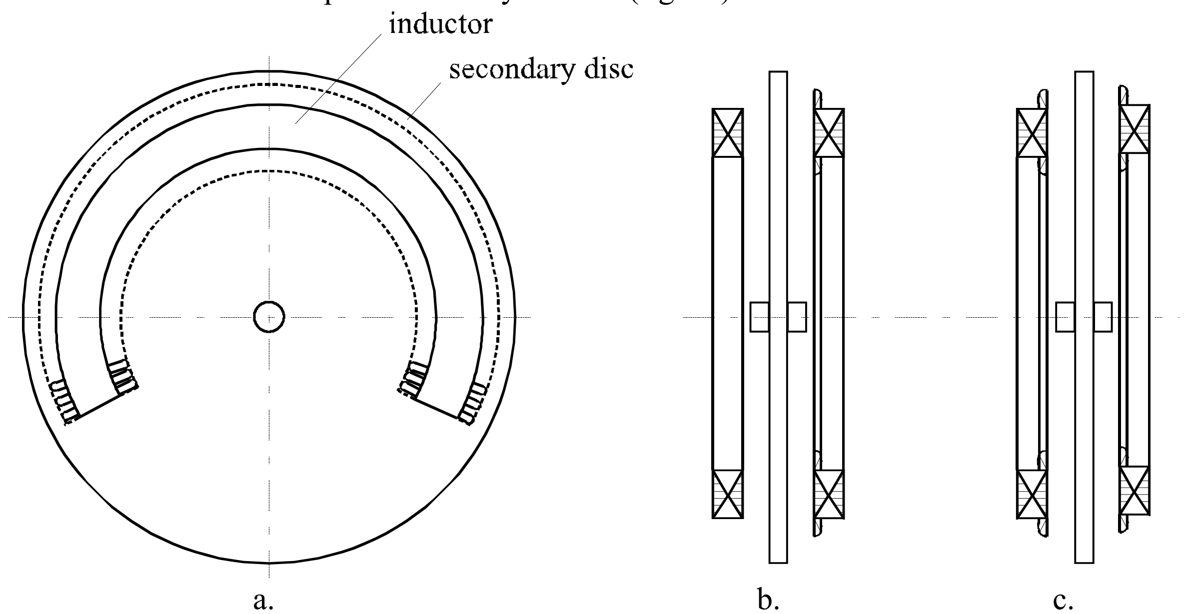


Figure 3

The toroidal inductor may be fully closed, and, in this situation, the unfavourable specific effects of the linear motors are much improved. The machine transforms itself into an asynchronous induction one, with a plate disc armature.

The hybrid induction motor with an axial air gap and magnetic armature

The mobile armature may be a sandwich armature (fig.4.a) with a disc made of low-board resistivity (copper, aluminium or brass) and plated at the exterior of the magnetic core, or in the double variant (fig.4.b)

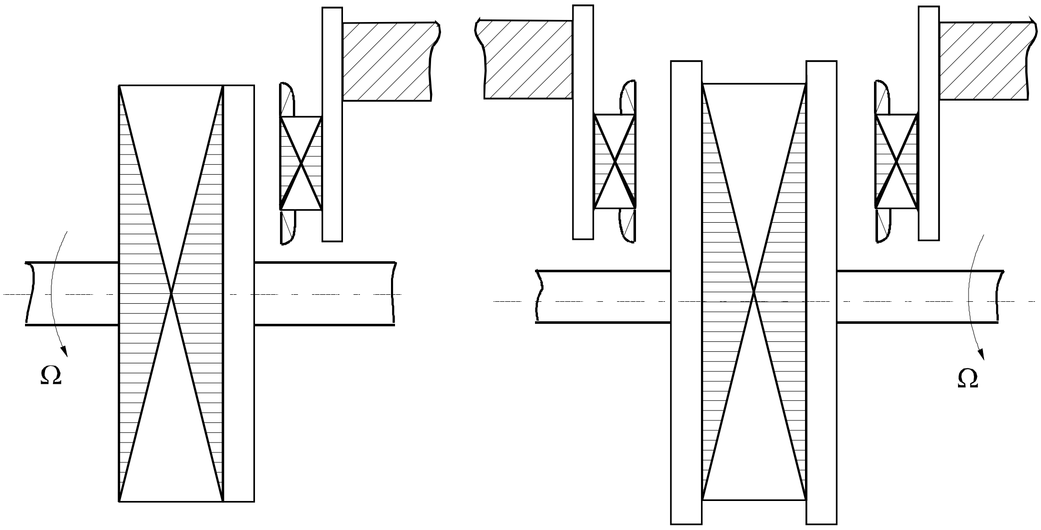


Figure 4

The motor may be with only one sandwich armature (fig.4.a), without any magnetic circuit, but with one path far coming back of the inductor magnetic flux (fig.2.b, 3.b), or with two sandwich armatures (fig. 4. b).In order to increase the efficiencies, the linear and the hybrid motors are rarely constructed in variants with only one inductor and any magnetic circuit closing path.

Foucault' currents in the armature plate

Considering one of the previous constructive solutions, such as the toroidal inductors one (fig.3), the main features to be taken into consideration (fig.5) for this class of motors are:

d - the thickness of the armature plate;

ρ - the resistivity of the secondary circuit;

R_a - the resistance of the current path in a radial direction, useful for the oscillation,

$$R_a = \rho \frac{r_1 - r_2}{a \cdot d}; \qquad (1)$$

a, a_1, a_2 - the widths of the current tube on a radial direction, for a radius r_1 at the exterior, and for the interior one r_2;

u - the electromotive force in the conductor elementary with an i current;

i - the current in the elementary circuit;

The board effect also evaluated in the linear motors [2] suffers transformations through the particularisation of the construction in the hybrid motor [3]. The essential element is the angular opening $d\alpha$ of a primary inductor of a width (r_1 - r_2). The induced current tube has the appropriate dimensions, and it is closing on a circuit as in the 5 figure. The induced currents close then arcs at a short radius r_2 on a margin level with $d\alpha$, inside, and outside at r_1 radius on the longer arc $(r_1/r_2)d\alpha$. The constructive variants require a larger number of pole for reducing the end effects.

In a nod of an electrical equivalent circuit (fig. 5 b) the continuance equation is:

$$i + di = i + I \cdot d\alpha \quad \text{with} \quad \frac{di}{d\alpha} = I \qquad (2)$$

The physical quantity *I* is the useful angular charge, and *i* is the return current in the board path. In these conditions, in the electric network mesh in fig. 5 b it is possible to apply the Kirchhoff's law for an arbitrary chosen direction, if it is admitted an electromotive force *du* on the current track

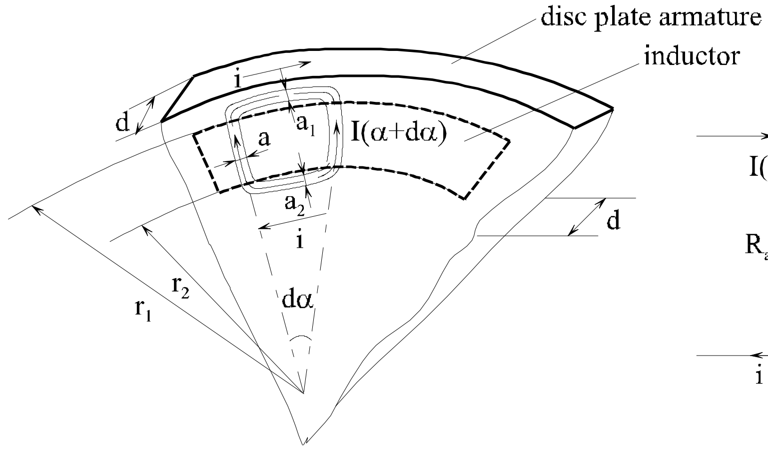
$$R_a \cdot I(\alpha + d\alpha) \cdot a - i\frac{\rho \cdot d\alpha}{a_2 \cdot d} - R_a \cdot I(\alpha) \cdot a - i\frac{\rho \cdot r_1 \cdot d\alpha}{r_2 \cdot a_1 \cdot d} = (r_1 - r_2) \cdot du \quad (3)$$

The primary inductor winding is supplied with a tree-phase, sinusoidal, symmetric voltage system.

In the absence of the harmonic components, that could disturb the waveform of the secondary quantities, it is admitted that the useful angular charge of the current *I* and the electromotive force *u* are both sinusoidal quantities of the following form:

$$I \cdot e^{j\left(\omega t - \frac{\pi}{\tau}\alpha\right)} \qquad U \cdot e^{j\left(\omega t - \frac{\pi}{\tau}\alpha\right)} \qquad (6)$$

where the inductive phase difference may be neglected because we have admitted that the secondary plate is only a resistive plate disc.



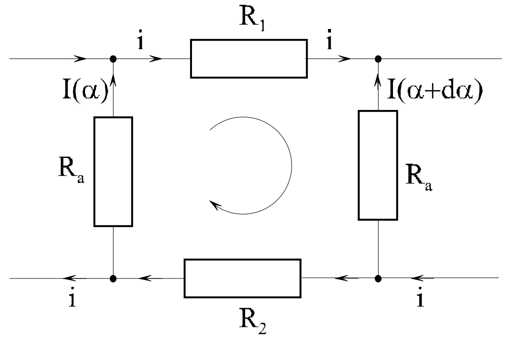


Figure 5

The derivatives of the second rang in comparison with the elementary angle, with $d\alpha$ opening, are:

$$\frac{d^2 I}{d\alpha^2} = -I\frac{\pi^2}{\tau^2} \quad \text{respectively} \quad \frac{d^2 U}{d\alpha^2} = -U\frac{\pi^2}{\tau^2} \quad (4)$$

The useful current *I* results from (3) and for that, the terms are grouped and derived, in comparison with an α angle:

$$R_a \cdot a \cdot \frac{d^2 I}{d\alpha^2} - \frac{\rho}{d} \cdot \left(\frac{1}{a_2} + \frac{r_1}{r_2 \cdot a_1}\right) \cdot \frac{di}{d\alpha} = (r_1 - r_2) \cdot \frac{d^2 U}{d\alpha^2} \quad (5)$$

The useful current value results from the formula:

$$I = \frac{U(r_1 - r_2)\frac{\pi^2}{\tau^2}}{R_a \cdot a \cdot \frac{\pi^2}{\tau^2} + \frac{\rho}{d} \cdot \left(\frac{1}{a_2} + \frac{r_1}{r_2 \cdot a_1}\right)} \qquad (7)$$

Or if in (6) the counter and the denominator are multiplied with the factor $\frac{\tau^2}{\pi^2(r_1-r_2)}$ then:

$$I=\frac{U}{R_a\cdot a\cdot\frac{\pi^2}{\tau^2}\cdot\frac{\tau^2}{\pi^2(r_1-r_2)}+\frac{\rho}{d}\cdot\left(\frac{1}{a_2}+\frac{r_1}{r_2a_1}\right)\cdot\frac{\tau^2}{\pi^2(r_1-r_2)}} \quad (8)$$

The previous formula represents a current, for the counter is a voltage, and the denominator is an equivalent resistance.

The armature plate disc resistance

If in the previous relation of the useful current tube, with an *a* width, which is closing in the plate on the radius direction, the resistance R_a is replaced:

$$R_i=\frac{\rho(r_1-r_2)}{a\cdot d}\cdot\frac{a}{r_1-r_2}+\frac{\rho}{d}\frac{1}{\pi^2}\left(\frac{1}{a_2}+\frac{r_1}{r_2\cdot a_1}\right)\frac{\tau^2}{(r_1-r_2)} \quad (9)$$

The relation (9) may be essentially simplified, and in this case, the expression of the equivalent resistance R_i takes the form possibly to be analysed:

$$R_i=\frac{\rho}{d}\cdot\left[1+\frac{1}{\pi^2}\left(\frac{1}{a_2}+\frac{r_1}{a_1\cdot r_2}\right)\frac{\tau^2}{(r_1-r_2)}\right] \quad (10)$$

The second member in the squared parenthesis is nondimensional one, so it is a constant quantity. We agree on noting it:

$$K_P=\frac{1}{\pi^2}\left(\frac{1}{a_2}+\frac{r_1}{a_1\cdot r_2}\right)\frac{\tau^2}{(r_1-r_2)} \quad (11)$$

It is considered in this stage, that a_1 and a_2 are equal and consequently the substitution is possible $a_1 = a_2 = a_{cr}$ and then (11) becomes:

$$K_P=\frac{1}{\pi^2\cdot a_{cr}\cdot r_2}(r_2+r_1)\frac{\tau^2}{(r_1-r_2)} \quad (12)$$

Or if we go back to (8), the value of the inductive current will be
:

$$I_2=\frac{U_2}{R_{u_2}}=\frac{U_2}{\frac{\rho_2}{d}(1+K_P)} \quad (13)$$

The limits of the coefficient of increase the resistance of the plate disc armature K_P

It is possible to estimate the limits of variation of the coefficient K_P of the resistance increase (5) for the hybrid motors.

1. The width of the inductor is always determined by the difference (r_1-r_2). This sum is positive, as it is shown in (fig.5); consequently, the term K_P is always positive and the secondary plate disc resistance of the hybrid motor is increasing. From this observation, two limits may be deduced. When r_1 increases more and finally tends to the infinite ($r_1 \to \infty$), the case becomes that one of a linear motor. The second limit value is in the case when r_1 is closer near r_2 value, as a secondary plate of small dimensions opposes infinitely to the transition of the secondary currents.

2. The increase of the inductor resistance is proportional to the square of the pole pitch.

The design parameters

Parameters used to describe an induction motor are of severals types, are *design parameters* which describe how the motor is manufactured, these parameters are interesting to the design engineers and build elctrical engineering.

Parameters used to describe induction motors

I. Design parameters

1. Rotor radius;
2. Active stack lengh;
3. Number of laminations in stack;

4. Air gap;
5. Number of pole pairs;
6. Wire diameter;
7. Series coil turns;
8. Stator slot geometry;
9. Number of stator slots;
10. Shaft radius;
11. Number of rotor bars;
12. Back iron depth;
13. Coil throw.

II. Performance parameters

A. Attributes

1. Cost;
2. Efficiency;
3. Power factor;
4. Starting torque;
5. Mass;

B. Characteristics

1. Power;
2. Speed;
3. Supply voltage;
4. Frequency;
5. Thermal constant.

Examples of such parameters are the air gap dimension and the width of the stack slot and others geometrics elements.

These parameters are ***performance parameters*** wich describe the operation motor, and are the primary concern of the customer. Examples of performance parameters are power, efficiency and mass.

Performance parameters fall into two categories: *atributes* and *characteristics*. **Atributes** are those parameters that are to be optimised. For example, the atribute *efficiency* should always be maximized, all else being egual. Similary, the atribute *cost* is not maximized, it is minimized. On the other hand, **characteristics** are those performance parameters that define a class of motors. Examples of characteristics are speed and power. In general, it makes sense only to compare attributes, among motors that have the same characteristics. For example, it does not make sense to compare the efficiency of a 1kW motor to the efficiency of a 100 kW motor.

Results

Often, it is difficult to precisely specify the relative importance of two or more attributes. Therefore, the optimisation of a single performance criterion involving all atributes is usualy difficult to justify and curry out. Alternatively, trade-off curves describing the possibilities offer a more useful approach.

Through program run have been obtained, for a micromachine with inductor wide of

l =125 mm, a number by 40 elementary micromachines. The characteristic sizes for first and last elementary micromachine are presented just down :

- the number one micromachine: l = 4.5 mm; v_s = 8.5 m/s; k_{pd} = 1.06; q = 5.14; a = 7471 A/m ;
- the number forty micromachine: l = 2.04 mm; v_s = 3.91 m/s; k_{pd} = 1.14; q = 0.98; a = 162432 A/m.

Conclusions

The secondary radial currents in the plate (fig.5) are useful for the electric drive. The longitudinal currents that are closing in the margin levels, because of the board effect, are not favourable for the useful force. For the linear motors, Wiart proposed a relation [2], according to which it can be estimated the increase of the resistance. We considered it useful to specify, analytically, this phenomenon in the particular case of the hybrid motor.

We have taken into account the angular oscillation, and also the radial dimensions of the motor. The increase coefficient of the resistance which has been first dimensioned to the hybrid motors, has an expression justifying entirely the previous statements. It is true that also the previous results of the final relation - for example the expression of a resistance (4) or of a current (3) make us to be sure that manners of proceeding was physically correct. The observations above, concerning the factor K_P impose important consequences:

a. The inductor is preferably to be as much wider as possible.

b. It is possible to built hybrid motors with diminished I^2R losses. if the pole pitch is narrower.

The results is that the performance hybrid motors are those with a high capacity, with an increased active surface of the inductor. If the speed is low or medium, with the inductive winding tightly disposed on the pole pitch, the influence of the longitudinal margin currents is , consequently, reduced. In the some way, the I^2R loses are reduced, too. In parallel, the inductive field uniformity is improving. For the some motor length - for a small pole pitch - the number of the poles that reduce the unfavourable margin effects will grow.

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