DESIGN AND FEM ANALYSIS OF A SPECIAL RELUCTANT MOTOR FOR DRIVING LIGHT ELECTRIC VEHICLES

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Abstract – **The reluctant motor take into study is an inverse radial motor, with a fixed stator mounted on front wheel shaft and an external toothed rotor fixed on the front wheel itself. A short presentation of preliminary design was continued with the FEM analysis in order to provide the optimal geometry of the motor and adequate windings.**

Keywords: *electric bike driving, motor toothed, arrangement, FEM analysis, optimal dimensioning.*

1. INTRODUCTION

Two-wheel urban light electric vehicles-LEVs-include electric bike and scooters. Electric bike are conventional bicycles with an added battery-powered electric motor. An electric bike can maintain a higher average speed than a conventional bicycle, and takes advantage of the same un-congested network of cycle facilities, giving access to routes than cars and motorcycles cannot reach. The result is often a faster door-to-door journey time than any other transport mean.

Electric motor type (within hundred Watts)	Max efficiency [%] *Over* Specific power [kW/kg]	Inverter type	Control strategy	Specific cost [$/kW]
3-phase Induction motor	72 0.04	3 Full bridges, PWM	Vector control, DTC	700
PM Brush DC motor	75 0.028	1 Full bridge, PWM	PI torque control	1000
Brushless DC motor	82 0.2	2-3 Full bridges, PWM	Self-commutated	2000
3-phase PM-synchronous motor	90 0.3	3 Full bridges, PWM	Vector control, DTC	3000
3,4-phase Switched reluctance motor	85 0.15	3,4 Half bridges, PWM or dual voltage	Self-commutated	2500

Table 1: Electric motors for driving bikes.

The main problem encountered in LEV construction is the electric drive motor. Conventional motors of few hundred watts, such as Brushless DC motors or PM Synchronous motors have been adopted so far due to their low cost and easiness of mounting on classic LEVs [1,2]. An overview of main solutions for electrical drives is given in Table 1, taking into account some specifications that could make difference between them.

Significant drawbacks of these motors in case of LEV driving are lead to their particular torque/speed characteristics as electric traction means, which limit drastically mechanical performances of LEV, especially in case of sloped roads.

In this circumstance, the solutions of direct (in-wheel) driving become very attractive, even if they require special construction of the motors. Direct driving motors are of low-speed, high-torque type, to meet the requirements of an efficient electric traction vehicle, capable of satisfying rides on sloped roads, as ususlly appear in case of urban transportation.

The present paper deals with a special electric reluctance motor, of inverse construction, designated for in-wheel gearless driving of LEVs. Two motor variants are considered for comparative study.

2. ELECTRICAL DRIVE OF THE BIKE

The electric bike is an electromechanical device, which converts electric energy provided by battery into mechanical energy for moving its wheels. Away from battery, rider and mechanic structure of the bike, this device consists of an electrical drive system. The main problem encountered with this vehicle refers to the power of electric motor. The power of the motor may be estimated as:

$$P = 1200 \cdot (x + 0.05) \cdot y \ \ [W] \tag{1}$$

where x is the road gradient and y is the running speed in m/s. This expression is written for a total weight of 120 kg (80kg of the rider and 40kg of the bike itself) for a usual friction coefficient of 0.05. For road gradients between 0 (horizontal road) and 0.12 (12%) and running speed from 0 to 10 m/s (36 km/h), the motor output power is presented in Figure 1.

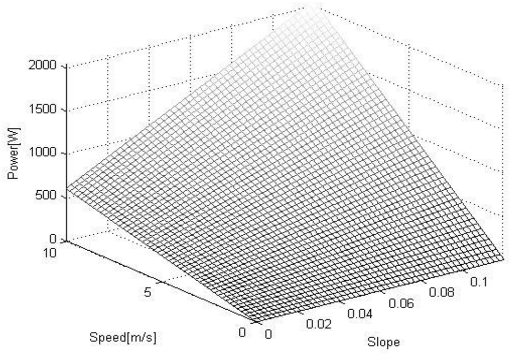

Figure 1: Graphic representation of power/speed/slope relationship.

Expression (1) shows that for the ranges given above, the needed power is in the range of 500-2000W (max power for max speed and max slope). Also, for a given power of 500W, one can reach maximum speeds between 2.5-8 m/s, depending on the road gradient – at a load of 80kg, and 20-30% higher speeds – at a load of 60kg as shown in figure 2.

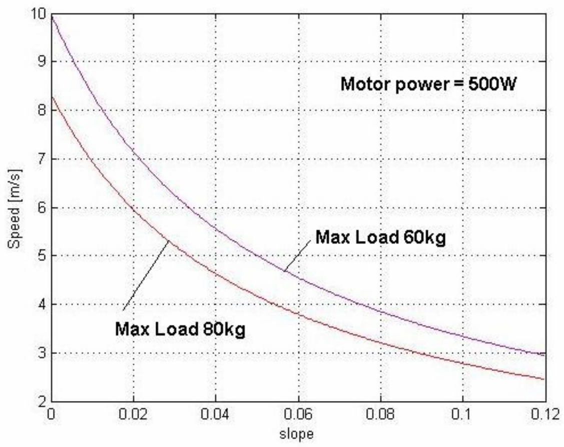

Figure 2: Variation of maximal speed with road gradient.

Preliminary calculus indicates satisfactorily results below 500W, in accordance to existing performances on the market.

3. DESIGNING THE RELUCTANCE MOTOR

In-wheel drive of the bike involves the placement of the electric motor inside the front wheel, which is a direct drive. Accordingly, a high torque-low speed motor is to be designed for this application. An electric reluctant motor of inverse construction (inner stator – fixed on the wheel shaft, and outer rotor fixed on the wheel rim through spokes) have been taken for study.

A 16 pole, 4 phase motor (4 poles/phase) as proposed, is shown in figure 3.

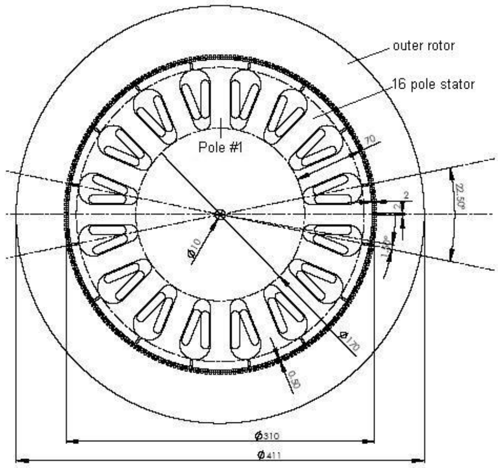

Figure 3: Cross section of the proposed motor.

Each phase is built by 4 series mounted windings, with alternating magnetic orientation.

As a reluctant motor, the structure of the air-gap is similar to the variable reluctance stepping motors. This structure offers the reduction of the rotor movement, to fulfill the requirement of a direct drive. Figure 4 shows a detailed picture of the toothed structure.

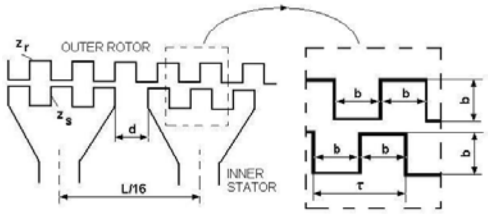

Figure 4: Toothed air gap.

The main results are given in table 2, separately on the two variants of the reluctance motors. Other geometric magnitudes are also calculated.

Parameter	Measure units	Variant I	Variant II
Number of rotor teeth		132	244
Number of steps/rot		528	976
Number of stator poles		16	16
Number of teeth/pole		8	15
Tooth dimension	mm	4	2
Distance between poles	mm	6	3
Air-gap diameter	mm	336	311
Air-gap magnitude	mm	0.2-0.3	0.1-0.15
Active axial length	mm	40	40
Motor diameter	mm	362	319

Table 2: Mechanical parameters.

Toothed structure has been determined using general electromechanical magnitudes, as given in table 3. The two variants are identical in main characteristics, but they differ in internal geometry and needed pulse frequency.

Component	Symbol	Measure units	Variant I	Variant II
Phase current	I	A	8.7	8.7
Output torque	M_o	Nm	33	33
Battery voltage	U	V	3x12	3x12
Pulse frequency	f	pls/sec	1260	2330
Linear speed	v	m/s	4.5	4.5
Angular speed	Ω	rad/sec	15	15
Output power	P_o	W	500	500

Table 3: Electromechanical parameters.

The variant I is of medium shape toothed structure (tooth dimension a=4mm), but variant II is of fine one (tooth dimension a=2mm). Variant II needs higher pulse frequency for switching the phases, than variant I.

4. MOTOR GEOMETRY

Classical electromagnetic design of the motor [4] directs towards stator geometry as shown in figure 5. In this purpose the following parameters are first calculated: permeances, ampere-turns, inductivities, number of wires/pole, wires arrangement inside stator slots. This minute calculus is compulsory in case of any type of motor and precedes the FEM analysis.

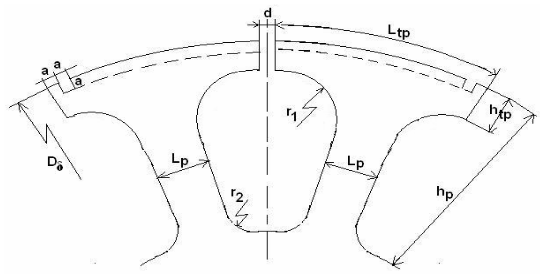

Figure 5: Stator poles geometry.

Additionally to the tooth data given in table I, the rest of geometry design is partially given in table 4.

Parameter	Symbol	Measure units	Variant I	Variant II
Pole width	L_p	mm	18.73	39
Pole height	h_p	mm	120	83
Polar sole length	L_{tp}	mm	60	58
Polar sole height	h_{tp}	mm	12	6
Big circular radius	r_1	mm	10	10
Small circular radius	r_2	mm	3	3

Table 4: Dimensions for stator poles of the motor.

Geometry design helps also to calculate electromagnetic characteristics of the motor, very useful for the next step of motor design using FEM analysis. Part of these electromagnetic characteristics is given in table 5.

Magnitude		Variant I	Variant II
Ampere-turns		6867	3447
Number of wires/pole		789	396
Phase inductivity [mH]	average	20.8	11.2
	amplitude of variation	10.4	5.61

Table 5: Electromagnetic characteristics.

The variant I is of little more copper consumption.

5. FEM ANALYSIS

First, the 2D geometry of the stator/rotor is created. Points, lines and several transformations are made in order to obtain a complete base geometry. Figure 6 indicates a part of the geometry in the case of variant I (8 teeth per pole).

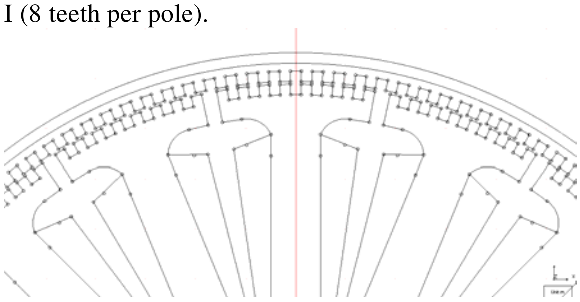

Figure 6: Stator/rotor geometry of the motor I.

As observed, pole #1 – in the center of the figure – is in aligned position, while subsequent poles are shifted respectively with multiple of (½ a) (see table I for a).
The study is of outspread volume, as it is based on iterative process starting with new modified geometry and coils and completing it with corresponding solving process, until the desired construction will be reached. Flux density, as main goal of the FEM, may indicate some saturated regions, but other regions seem to be over-dimensioned.

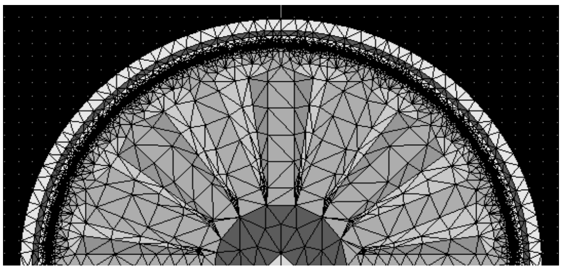

Figure 7: Mesh points and lines.

Figure 6 shows the flux density in case of variant I, for one phase.

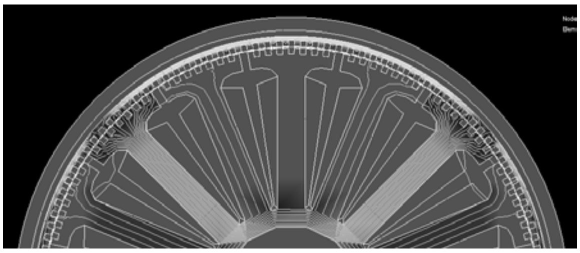

Figure 8: Flux density in case of variant I.

As observed, some mutual flux exists in the vicinity of reference pole, but little saturation.
Theoretically there are no mutual fluxes in the motor [3] and thus for unaligned position (tooth per slot) very little flux density is calculated, as shown in figure 9.

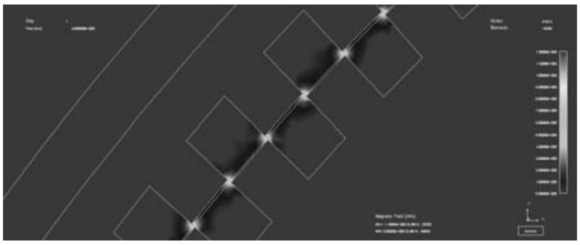

Figure 9: Flux density for unaligned position (var. I).

The study is repeated with the variant II of the motor (15 teeth/pole) and the results can be compared. Figure 10 shows the flux density calculated in the case of the variant II of the motor.

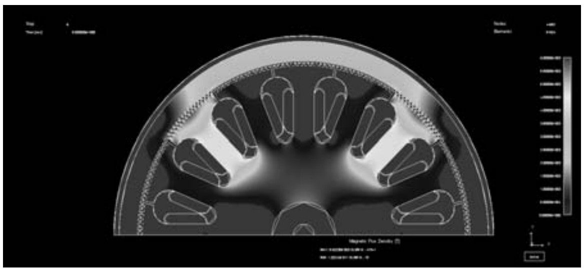

Figure 10: Flux density for variant II.

Similar qualitative results are obtained and so, comparative study is achieved. Also, proper and mutual fluxes can be observed.
Similar study is made for various rotor positions and figure 11 shows flux density for unaligned position. Little mutual flux exists, may be greater than in the case of variant I.
As result of this comparative study, the main features of the two variants of reluctance motors may be deduced, as shown in table 6.

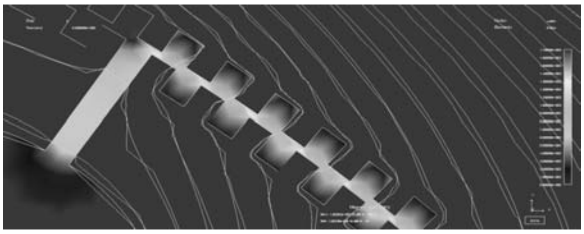

Figure 11: Flux density for variant II.

Item	Variant I (7 teeth/pole)	Variant II (15 teeth/pole)
Resolution of movement	medium	high
Control pulse frequency	medium	high
Copper consumption	significant	medium
Technological accuracy	medium	fine

Table 6: Parameters and theirs values.

The variant I of the motor is easier to construct, but needs more copper and consequently is more expensive than variant II. In reply, the variant I may be cheaper, but involves more technological accuracy.

6. CONCLUSIONS

The study of an inverse reluctance motor, in two variants, has been presented, in a short form due to the large amount of chapters to be taken into consideration. Classical design is a preliminary study for FEM approach, compulsory for any case of motor. Both classical and modern approach leads to an optimal design of the motor, very suitable in case of new models for special applications, as LEVs driving.
FEM analysis offers a large palette of results, but the user must adopt an iterative calculus for achieving optimal design of the motor. Research will be focused on 3D analysis in order to develop advanced studies.

References

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