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A comparative study of different slot configurations for PM brushless machines used for vehicle traction

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***Abstract*—This work describes the design and optimization process of a direct-drive permanent magnet synchronous machine that is suitable for electric motorcycles. The machine is designed to develop approximately the same power than a conventional 250cc motorcycle internal combustion engine. The main goal of this work is to design an outer-rotor machine that is coupled directly to the wheel (direct-drive or in-wheel motor), so it is necessary to know the dimensions and arrangements of the wheels. The direct-drive systems do not need any gearbox to drive the vehicle, so that the global efficiency is higher than conventional systems employing a gearbox. The design and performance of the machine are assessed by means of simulations using the finite element method. The finite element method is the main tool to optimize the machine's design.**

Keywords—Brushless DC motor, cogging torque, electric vehicle, electromagnetic torque ripple, permanent magnet synchronous machine

I. INTRODUCTION

Along the last years, the green vehicle market has grown thanks to research for sustainable alternative transport, by reducing fossil fuels dependence or looking for a least pollutant solution.

One of the solutions is the employment of full electric vehicles. High efficient motors that comply with excellent operational characteristics as indicated in [1], [2] are very desirable in such vehicles. In this way, engineers have been made many efforts in order to optimize the electric motors.

When it comes to the traction system in electric vehicles, the brushless DC motors appears as the best solution due to its numerous advantages [1], [2]. One of the solutions to increase the traction system efficiency is the employment of the so-called in-wheel motors (direct-drive), eliminating the losses due the gear system [7]-[12].

An outer-rotor permanent magnet synchronous machine is designed and optimized in this paper to be suitable for electric motorcycle. The design optimization process takes into account some novel approach such as similar slot number and pole number [3], unequal teeth width [4], standard and straight teeth [5] and skewed slot.

Although torque ripple is not a critical issue in vehicle traction, as combustion engines have huge torque ripple values, this issue is being considered here because of two major facts: torque ripple increases machine losses, so its reduction implies in losses reduction, and it also increases mechanical stress in transmission systems, as in shafts, gears and bearings.

This paper proposes a comparison between mentioned methods used to reduce cogging torque and, consequently, torque ripple by changing some motor design characteristics. Further, gives some consequences about the choice related with the torque ripple and Back-EMF.

II. GENERAL MACHINE CHARACTERISTICS

The desirable machine characteristics in this work are 75Nm at 1393rpm, approximately 10.9kW, with 1856rpm on no-load speed.

As shown previously, the machine designed is suitable for electric motorcycle (in-wheel motor), so the design process has to take into account some mechanical dimensions to fit the motor properly in the vehicle. These dimensions together with motor dimensions are shown in Table I.

TABLE I. MACHINE DIMENSIONS

Active length (mm)	100
Rotor outer diameter (mm)	300
Rotor inner diameter (mm)	257
Magnet thickness (mm)	10
Air gap length (mm)	1
Stator outer diameter (mm)	235
Slot opening (mm)	2
Tooth height (mm)	30
Slot number	24

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III. MACHINE CONFIGURATION

To achieve the desired characteristics, some design variations have been employed especially concerning tooth shape, tooth width and pole number.

A. *Straight and Standard Tooth*

Almost all motors are designed with standard teeth whereas straight teeth increasing the cogging torque due to a larger reluctance in the air gap. An example of standard teeth and straight teeth is shown in Fig. 1.

However, some projects are done based on straight teeth that give some advantages as in [5], lower total mass, lower iron losses, thinner yoke.

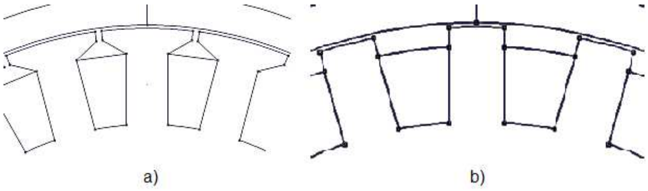

Fig. 1. a) Standard Teeth b) Straight Teeth.

B. *Pole Number*

The best way to choose slot number NS and pole number 2p to reach lower values of cogging torque has been discussed in [3], [4], where the authors propose the relationship 2p= NS ± 2.

One of the design variations is 22 poles and 24 slots, according with references shown above. In other hand, 8 poles and 24 slots machine has been developed in this paper to make a comparison between torque ripple, cogging torque and Back-EMF.

C. *Equal and Unequal Teeth Widths*

Another way to achieve the desirable characteristics is changing the tooth width. Thus, it is possible to improve the performance of the motor designed based on 2p= NS ± 2. The reason for this improvement is largely explained in [6].

For machines with equal teeth widths in this paper, the tooth width is 13mm for all teeth. For machines with unequal teeth widths in this paper, the wider tooth width is 15.21mm and the narrower tooth width is 10.79mm.

D. *Skewed Slot*

The skewed slot is the wider known way to reduce the cogging torque and torque ripple. In this paper, the skewed slot has been employed, as will be shown later, just for straight tooth in 8 poles and 24 slots machines.

As shown above, two main configurations has been employed, 8 poles 24 slots and 22 poles 24 slots. The configurations that have been tested are:

- Case 1: straight – equal tooth – without skewed slot.
- Case 2: straight – equal tooth – with skewed slot.
- Case 3: straight – unequal tooth – without skewed slot.
- Case 4: straight – unequal tooth – with skewed slot.
- Case 5: standard – equal tooth – without skewed slot.
- Case 6: standard – unequal tooth – without skewed slot.

IV. RESULTS AND ANALYSIS

The finite element method is employed to analyze the machines. The machines are tested and its results are shown below.

A. *8 poles 24 slots*

The flux-linkage waveforms are shown in Fig. 2. As can be seen, there are no significantly changes between standard teeth. Comparing standard teeth and straight teeth (named as "Case 1**" in subtitle) is easy to be noted that the flux-linkage waveforms are different, whereas the straight teeth have lesser surface area, so they link less magnetic flux. To correct this issue, one turn per coil is added for straight teeth configuration (named as "Case 1" in subtitle).

The phase back-EMF waveforms, resulting from the flux-linkage per phase are shown in Fig. 3. Although the back-EMF waveform corresponding to straight teeth shows some oscillation due to the higher amount of flux leakage between adjacent teeth, all back-EMF waveforms present at least 120° (electrical). The Fig. 3 shows that the back-EMF waveform for "Case 1**" has lower value than back-EMF waveform for "Case 1".

The cogging torque of these machines is shown in Table II. As can be seen, the straight teeth (case 1 and case 3) show higher cogging torque thus, as will be shown later, producing a higher torque ripple.

TABLE II. COGGING TORQUE FOR 8 POLES 24 SLOTS

	CASE 3	CASE 1	CASE 6	CASE 5
Max (Nm):	39.32	40.70	4.59	4.29
Min (Nm):	-39.78	-40.76	-4.91	-4.11
(%)	51.8	52.6	6.5	5.6

The cogging torque for straight teeth is approximately 53% of the rated torque, whilst the cogging torque for standard teeth is approximately 6.3% of rated torque. The torque waveforms are shown in Fig. 4.

The values of maximum torque, minimum torque, average torque and torque ripple are presented in Table III. The straight teeth without skewed configurations are not feasible because of the higher torque ripple for 8 poles 24 slots. When it comes to standard teeth configurations, the unequal teeth width gives a higher average torque and lower torque ripple.

Even though the straight teeth configurations (case 1 and case 3) have lower total mass, lower iron losses as shown in [5], the torque ripple for those configurations are higher than other configurations and is necessary to add one turn per coil to link desirable magnetic flux. So it increases the cost of the machine, whereas there is higher amount of copper.

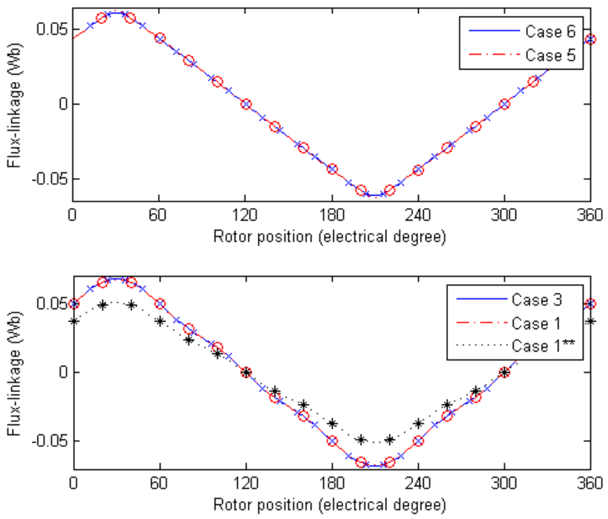

Fig. 2. Flux-linkage waveforms per phase.

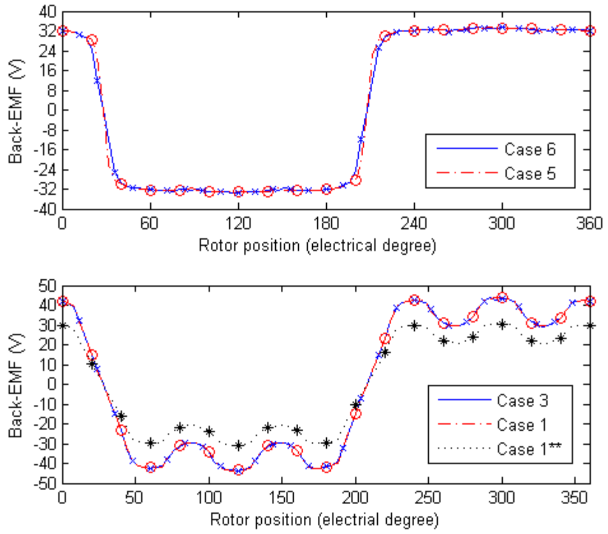

Fig. 3. Back-EMF waveforms per phase

Therefore, to produce the desirable electromagnetic torque it is necessary to supply the motor with lower current. Whilst the machines with standard teeth require 3 turns per coil and 4 coils supplied with 230 A to produce 75Nm, the machines with straight teeth require 4 turns per coil and 4 coils supplied with 200 A to produce 75Nm.

For straight teeth with 4 turns per coil, the copper losses are approximately 1% higher.

To improve the performance of the machines with straight teeth and reduce torque ripple they were designed with skewed slot with an inclination of one slot pitch. This method has been employed for machines with straight teeth and the results for flux-linkage are shown in Fig. 5.

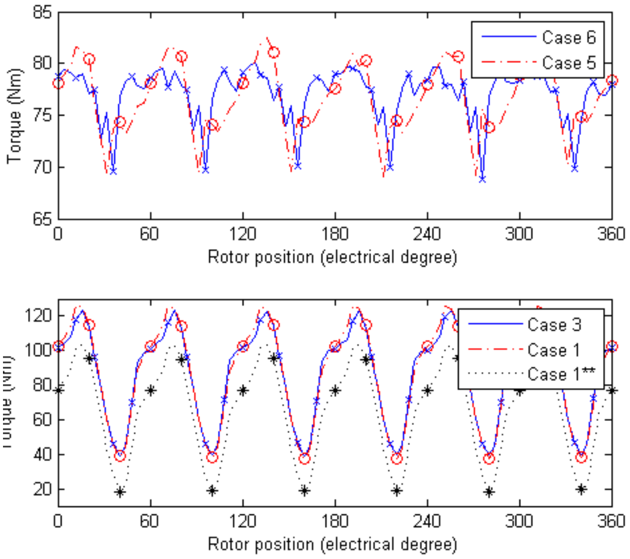

Fig. 4. Torque waveforms.

TABLE III. TORQUE FOR 8 POLES 24 SLOTS

	CASE 3	CASE 1	CASE 6	CASE 5
Max (Nm):	112.38	113.66	80.17	82.82
Min (Nm):	28.98	27.31	68.82	69.00
Average (Nm):	75.29	75.97	77.13	76.69
Ripple (%):	55.38	56.83	7.36	9.01

Employing the skewed slot method in the straight teeth machines, the oscillations in the flux-linkage waveforms disappears. Unequal teeth (case 4) and equal teeth (case 2) show, practically, the same flux-linkage waveforms. Therefore, the back-EMF for both will be, practically, the same, as can be seen in Fig. 6.

With the skewed slot, the top flat is almost 120° (electrical) and the value of the back-EMF is slightly higher than the back-EMF for standard teeth, therefore, to produce desirable torque in above machines (with skewed slot), it is necessary to supply them with 200 A.

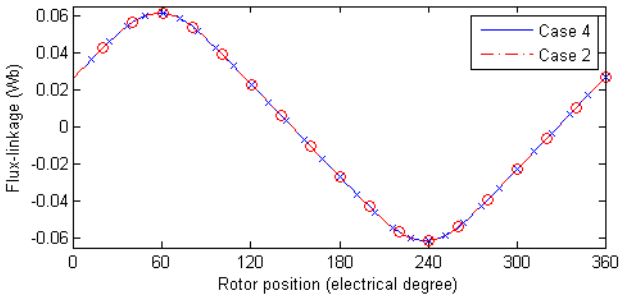

Fig. 5. Flux-linkage waveforms per phase.

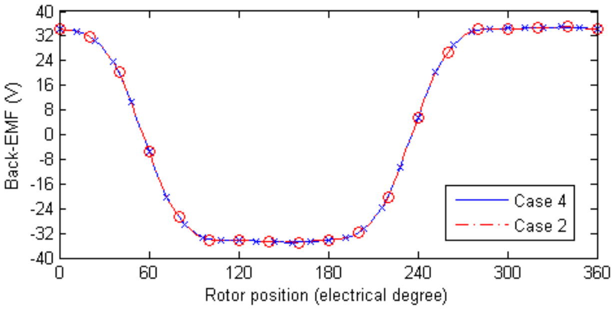

Fig. 6. Back-EMF waveforms per phase.

A reasonable result appears in the cogging torque value. For both machines (unequal and equal), the cogging torque values are shown in Table IV.

The values of maximum torque, minimum torque, average torque and torque ripple are presented in Table V. With the skewed slot method, the machine with equal teeth has approximately the same average torque that machine with unequal, whilst machines without skewed slots show higher torque for unequal teeth configuration.

TABLE IV. COGGING TORQUE FOR 8 POLES 24 SLOTS – STRAIGHT WITH SKEWED SLOT

	CASE 4	CASE 2
Max (Nm):	0.16	0.07
Min (Nm):	-0.59	-0.17

TABLE V. TORQUE FOR 8 POLES 24 SLOTS – STRAIGHT WITH SKEWED SLOT

	CASE 4	CASE 2
Max (Nm):	75.59	76.02
Min (Nm):	74.75	75.72
Average (Nm):	75.18	75.86
Ripple (%):	0.56	0.19

The torque waveforms are shown in Fig. 7.

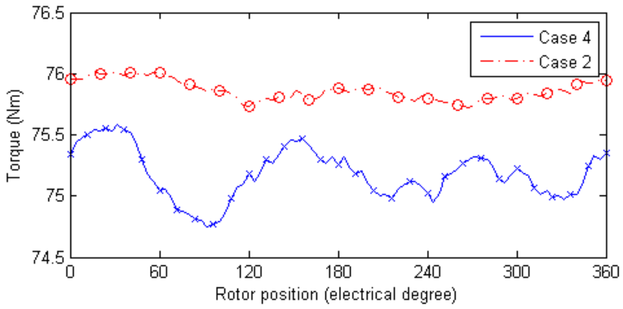

Fig. 7. Torque waveforms.

B. 22 poles 24 slots

The second configuration tested employs 22 poles in a 24 slot machine, which is based on 2p= NS ± 2 [3], [4]. The flux-linkage waveforms are shown in Fig. 8. For straight teeth (case 1 and case 3), it is necessary to increase one turn per coil in order to link approximately the same flux that the standard teeth and achieve the desirable results for back-EMF waveform. As can be seen in Fig. 8, the flux-linkage waveforms for straight teeth are more sinusoidal than flux-linkage waveforms for standard teeth configuration (case 5 and case 6).

The back-EMF waveforms for each phase are shown in Fig. 9. For the standard teeth configuration, the top flat is almost 120° (electrical). However, for the straight teeth configuration, the back-EMF waveforms seems to have a narrower top flat that will produce a higher torque ripple when fed by a conventional three-phase inverter in six-step mode.

For these machines, the cogging torque values are presented in Table VI. As discussed in [3], [6], the use of unequal teeth increases the winding factor which increases the average torque. However, the cogging torque in machines employing unequal teeth is higher than in those using equal teeth, whereas the unequal teeth change the airgap permeance.

A reasonable result appears in the cogging torque for Case 1, which is the lowest value.

Even though Case 1 shows the lowest cogging torque, the final torque is a combination of the back-EMF waveform, cogging torque and current in the coil in magnetostatic analysis by means of finite element method. Therefore, the torque value for this configuration shows a higher torque ripple when it is compared with standard teeth configurations as can be seen in Table VII.

The Table VIII shows normalized values for average torque and torque ripple, 75 Nm and 5.39% respectively, i.e., the lowest values are equal to 1. One must note that values for machines with straight teeth have more turns per coils in order to balance the magnetic flux linkage due to dispersion.

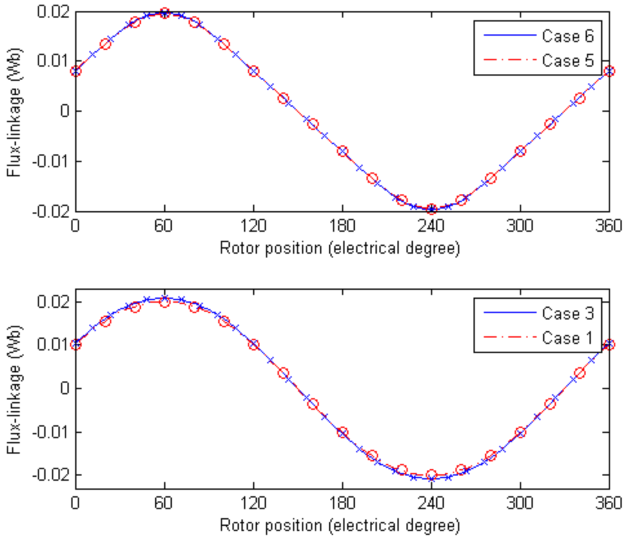

Fig. 8. Flux-linkage waveforms per phase.

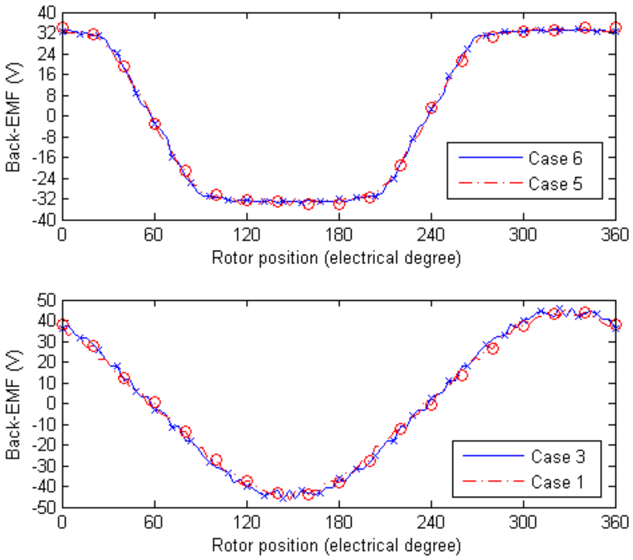

Fig. 9. Back-EMF waveforms per phase.

TABLE VI. COGGING TORQUE FOR 22 POLES 24 SLOTS

	CASE 3	CASE 1	CASE 6	CASE 5
Max (Nm):	4.69	2.62	3.20	2.50
Min (Nm):	-4.74	-1.98	-3.77	-2.55

TABLE VII. TORQUE FOR 22 POLES 24 SLOTS

	CASE 3	CASE 1	CASE 6	CASE 5
Max (Nm):	84.75	78.45	79.50	78.01
Min (Nm):	65.63	62.19	69.25	69.92
Average (Nm):	76.35	73.88	75.92	75.01
Ripple (%):	12.52	11.00	6.75	5.39

The torque waveforms are shown in Fig.10

V. CONCLUSIONS

Ten machines have been designed and simulated in order to find the best solution for the given application.

A good view is given by means of Table VIII, since it shows normalized values for main machine characteristics as cogging and average electromagnetic torque. The machines with straight teeth have higher copper amount, whereas those machines need more turns per coil to link the same amount of magnetic flux. So that increases the material costs (more copper) but increases only 1% in copper losses for the configuration tested in this paper.

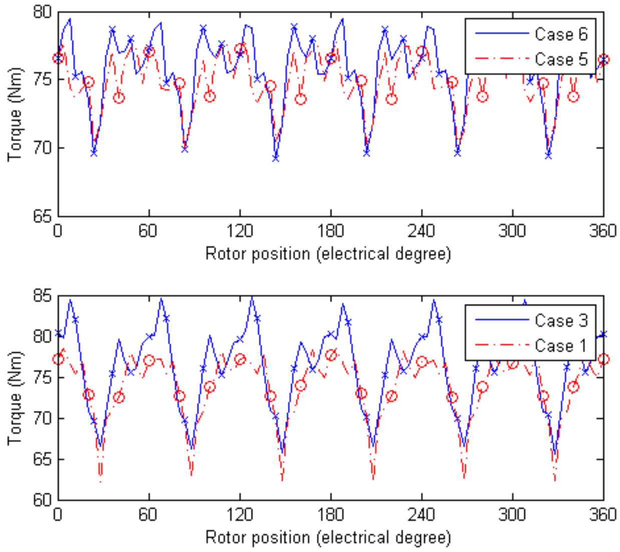

Fig. 10. Torque waveforms.

TABLE VIII. COMPARISON BETWEEN CONFIGURATIONS TESTED

		Straight		Standard		
		Unequal	Equal	Unequal	Equal	
8p 24s	Average Torque:	1.004	1.013	1.028	1.023	No Skewing
	Torque ripple:	10.275	1.544	1.365	1.672	
22p 24s	Average Torque:	1.018	0.985	1.012	1.000	
	Torque ripple:	2.323	2.041	1.252	1.000	
8p 24s	Average Torque:	1.002	1.011	x	x	Skewed
	Torque ripple:	0.104	0.035	X	x	

The machines with straight teeth having the same turns per coil than machines with standard teeth produce lower average torque than the others, approximately, 65 Nm of average torque.

Even though the straight teeth have higher ripple, this configuration has lower magnetic losses, lower mass and becomes the winding process easier. That configuration can be improved with the skewed slot method, showing the lowest cogging torque, the lowest torque ripple.

Machines with 8 poles and 24 slots without skewed slots have been tested with numerous variations and shown lower cogging torque values for standard teeth. When it comes to machines with 22 poles and 24 slots without skewed slots, the cogging torque values are approximately the same for all variations.

Indeed, unequal teeth widths give a higher average torque though the torque ripple is slightly higher than torque ripple for equal teeth widths. However, when employed skewed slots, unequal teeth and equal teeth show approximately the same average torque and cogging torque values as shown in Table IV and Table V.

VI. ACKNOWLEDGMENT

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VII. APPENDIX

The winding schemes for one phase of the machine with 8 poles and 24 slots is [-, 0, 0, +, 0, 0, -, 0, 0, +, 0, 0, -, 0, 0, +, 0, 0, -, 0, 0, +, 0, 0]. The winding schemes for one phase of the machine with 22 poles and 24 slots is [-, +, 0, +, -, 0, -, +, 0, +, -, 0, -, +, 0, +, -, 0, -, +, 0, +, -, 0].

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