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Study of Permanent Magnet Synchronous Machine Topologies for Electric Scooter Application

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Abstract. The paper deals with the study of the motorization for an electric scooter. The motivation of this study is firstly introduced. Next, the application is defined: it is intended to propose a pure electrical traction system for a light electric vehicle, meaning an electric scooter). A short description of the design will introduce the main parameters of the electrical drive system and three topologies of electrical machine will be evaluated. The optimization of the best suited variant will be made based on a gradient type optimization algorithm. Numerical computation, by means of finite element method, will confirm the analytical obtained results, emphasizing the main achievements, performances and drawbacks of the electrical traction system. These performances are evaluated on test bench for validation.

Introduction

One of the greatest problems of the modern society, these days, particularly for industrialized countries, is the pollution [1, 2, 3, 4, 5, 6]. According to several studies, the largest share of pollution from urban areas comes from vehicle emissions and because of this explosive growth of the number of cars. Thus, the problem of breathing clean air represents the main advantage of electric vehicles (EV), while their most important disadvantage is related to the limited autonomy. However, all over the world, one of the current research topics concerns the use of renewable energy sources and EVs.

With regard to automobiles, there have been several attempts to establish a maximum acceptable level of pollution. Several car manufacturers have prepared a declaration of Partnership for a New Generation of Vehicles (PNGV), also called *SUPERCAR*. This concept provides, for a certain power, the performance expected from a thermal or hybrid car. Virtually, today every car manufacturer proposes its own version of electric or hybrid car, at *SUPERCAR* standard. Of course, at concept level, the investment is not a criterion for the construction of EVs, as in the case of series manufacturing (where profits are severely quantified). For example, nowadays the price of 1 kW of power provided by FC is around 4,500 €; thus, a FC of 100 kW would cost 450,000 € (which are practically prohibitive in terms of costs, for series manufacturing).

So, one of the challenges of individual transport refers to finding clean solutions, with enhanced autonomy [4], [5], [6]. This is the motivation of this research work. For that, an electric scooter will be studied from the motorization, supplying and control point of view. Here, only the motorization aspect will be analyzed. The machine's design will be briefly introduced. The expected performances are validated through finite element method (FEM). Finally, the machine is optimized in terms of power density.

The application under study

Basically, the electric circuit layout of the experimental scooter under study is presented in Fig. 1. The motorization is based on a permanent magnet synchronous machine (PMSM) topology with outer rotor (in wheel motor). The rated data of the machine are: 1.5 kW of output power, 420 r/min supplied from a battery of 48 Vcc.

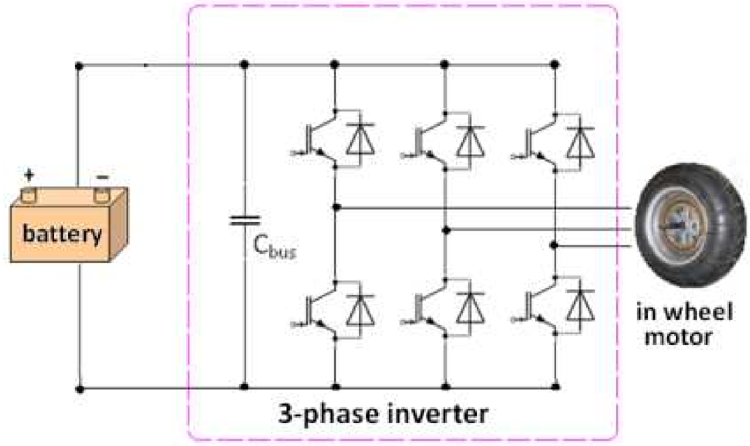

Figure 1 Electric circuit layout of the experimental scooter.

Design and numerical validation of the studied PMSM

The analytical design is based on magnetic reluctances equivalent circuit [7], [8], [9] – not presented here. Since the scooter should be integrated into a wheel, a maximal outer diameter was imposed: 220 mm. Also, the length of the active part of the machine should not surpass 50 mm.

The paper is concentrated on the "heart" of the traction system used for the motorization of an electric scooter. A light and high efficient motorization, with improved energetic characteristic will play an important role with regard to the autonomy problem. Based on these indicators, the achievements of the paper are:

- several motorization variants will be discussed and analyzed to find a proper motorization.
- the best variants will be optimized based on a gradient type optimization algorithm.
- a prototype will be constructed, tested and the obtained performances will be evaluated.

To have a good controllability, especially in transients (and for a scooter, the transients are the normal operation), the torque characteristics needs to be as smooth as possible, keeping the output performances at the desired level (there are some control technique dedicated for PMSM which could reduce the torque ripples, but they involve performances decrease).

In order to respond to all this constraints, three motorization solutions have been analyzed: the first one with a reduced number of poles and distributed winding type (9 pair of poles and 54 slots, thus the number of slots per pole and per phase is 1), and the other two variants with fractional-slot pitch: a configuration with 17 pairs of poles and 39 slots, and the other structure having 23 pairs of poles and 51 slots.

The resume of the designing results is presented in Table 1.

Table 1
The Design Results of the Studied Variants of PMSM

3-phase machine / **parameter**	**PMSM-9/54**	**PMSM-17/39**	**PMSM-23/51**
Rated torque (N·m)	34	34	34
Number of pole pairs (-)	9	17	23
Number of slots (-)	54	39	51
Outer diameter (mm)	223	223	223
Stack length (mm)	50	50	50
Air-gap flux density (T)	0.828	0.849	0.843
Rated current (A)	21.32	20.76	24.78
Total losses (W)	141.91	131.27	190.82
Power factor (%)	92.27	92.03	80.19
Efficiency (%)	90.53	91.24	87.27
Active part mass (kg)	6.73	5.91	6.25
Power/mass ratio (W/kg)	222.8	253.8	240

In in order to have a clue on the geometry of the designed machine and theirs magnetic behavior one can see the cross references of the studied machines and the flux density repartition within the active parts given in Fig.2.

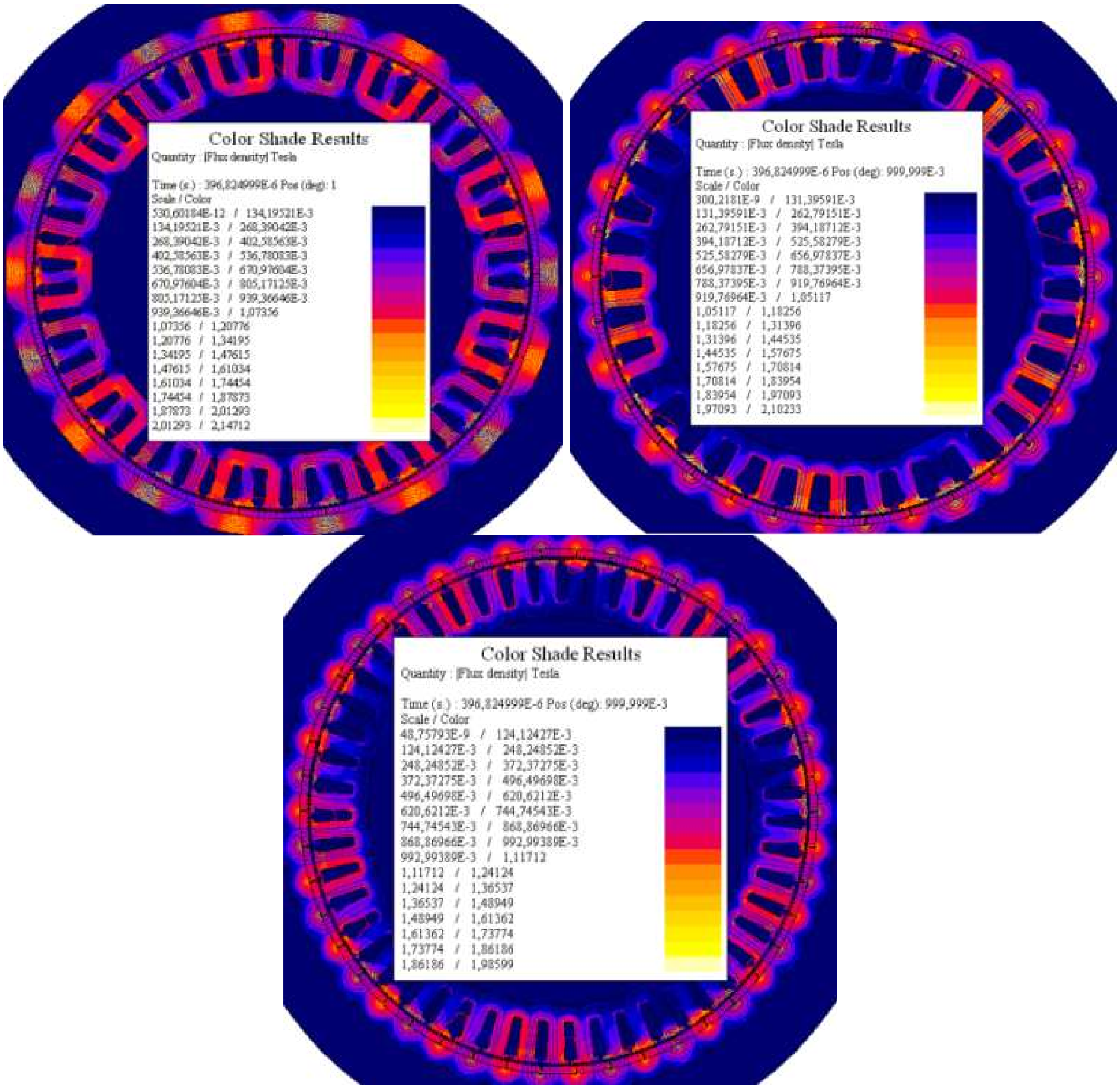

Figure 2 The cross section and the flux density repartition within the active parts of the studied machines: PMSM-9/54 (top), PMSM-17/39 (middle) and PMSM-23/51 (bottom).

PMSM-9/54: The first analyzed variant for the motorization of the electric scooter is based on a PMSM with 9 pair of poles, while on the stator there is a polar pitch three phase winding and 54 slots. (Using a reduced number of poles – to get a reduced frequency and iron loss – is not possible for such a structure, where a high number of poles mean improved power/mass.)

Since the geometry of this machine is not very special, no geometrical details are given at this stage (more information will be given in the numerical analysis section).

PMSM-17/39: The second analyzed machine has 17 pairs of poles and fractional pitch on the stator winding, the coils being distributed on 39 slots. At 420 r/min, the rated frequency is of 119 Hz. Compared to the previously topology with 18 poles (which has 56 Hz) practically the frequency is doubled. Later on, one will see how the frequency will affect the machine's operation (efficiency).

PMSM-23/51: The third studied topology of PMSM has 23 pair of poles and 51 slots on the stator, with a fractional winding pitch. The idea of testing this variant is to study the limit of using the fractional slot topology related to the smoothest possible torque, with good energetic performances (i.e., efficiency and power factor). For 46 poles, the rated frequency of the supply will be 161 Hz. Is this increase in frequency acceptable in terms of reduced torque ripples against a weakened efficiency? The answer will be given in the next section.

The studied machines have been analyzed numerically by using the finite element method (FEM). For that, the Flux2D software has been used.

All machines were simulated in motor operation. A sinusoidal current was injected into the winding. The comparison of the studied machines is made based on torque ripples, iron loss, power density and energetic performances.

The iron losses are computed and plotted for comparison, Fig. 3-a. The iron loss is about 42 W for the PMSM-9/54. For the other two machines, the iron loss is quite high (due to frequency increase): 73.8 W for the second PMSM, and 81 W for the third PMSM. Based on this analyze it could be said that the first variant offers the best result. But, in order to produce the desired torque, a much important current and copper is needed for the first PMSM. This explains the fact that the efficiency is better for the second variant, PMSM-17/39.

The other important criterion which helps us to decide which machine is best suited for the scooter application is the torque wave form. The lowest ripples were obtained for the third variant, PMSM-23/51, see Fig. 3-b.

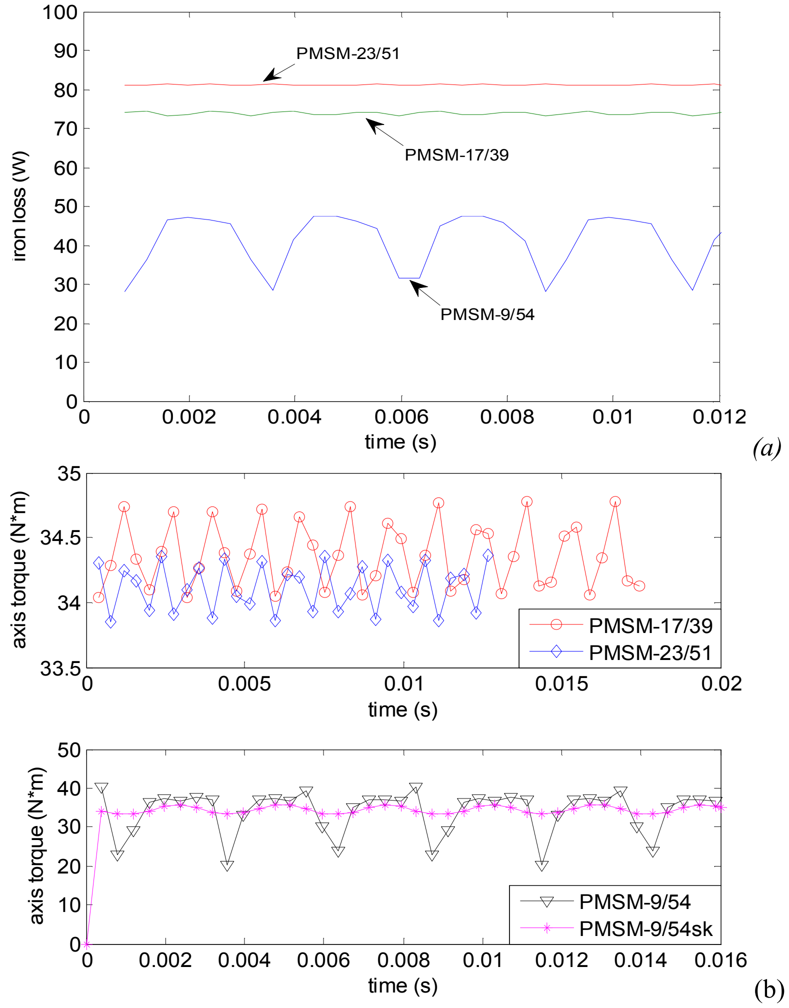

Figure 3. Torque wave characteristic from the FEM analysis for the studied machines.

Furthermore, the current should have a similar profile, with reduced ripples. This is shown in Fig. 4-right-top, where the torque for the second and third variant are presented. It is clear again than the fraction-slot topology, with the highest number of poles gives us the better performances in terms of torque wave. But this is a sensitive difference between these last two variants. On the other hand, since the lowest iron loss level was obtained with the first topology, having a reduced number of poles (18), one should take advantage of this improvement.

Thus, the idea is to try to find a solution which could reduce the torque ripples (to have the best controllability) based on this variant which works at the lowest frequency level. For that, the skewing effect of the PMSM-9/54 was studied, by skewing the stator with one tooth pitch.

Another solution could be to control the direct and quadrature current, but it is known that acting on the current component which reduces the torque ripple, will reduce the torque, too.

The torque wave, for the skewed and un-skewed PMSM-9/54, is presented in Fig 4-right-bottom. One can see that the torque ripples have been drastically reduced, but the desired torque has been obtained at an increased current (25 A). Practically, by skewing the machine, the output performances are reduced, too. In order to be able to obtain the rated torque, one should consider a much higher current. In conclusion, this skewed variant has reduced ripples, but a higher current is needed to get the desired output performances (thus, increasing the loss and decreasing the efficiency of the machine).

In Table 3 a comparison of torque and iron loss results is presented. Related to this results and the ones related to Table 2 & 3 it is clear that the PMSM-17/39 is best suited for our application.

Table 2

The Torque and Iron Loss Comparison for the Studied Machines

machine / parameter	PMSM-9/54	PMSM-9/54sk	PMSM-17/39	PMSM-23/51
torque ripples (%)	55.8	7.35	1.88	1.23
iron loss (W)	42	41	73.8	81

Optimization of the designed PMSM

In order to obtain the desired performances, and not overpass the supplying current, it is needed to impose some supplementary constraints. The objective of the optimization is to increase the power density, meraning that the desired outoput is obtained with the lowest possible mass. Thus, the objective function will maximize the power/mass ratio. Usually the optimization supposes the minimization of a function: in order to attain our goal we well minimize the 1/(power/mass) ratio. The mass variation is established within the limits of the geometrical parameters (not given here).

There are different optimization algorithms, some of them being simple (like the gradient type, [10]) or complex (like the genetic type, [11]). Here, the optimization method based on Hook-Jeeves algorithm was employed. This algorithm is of gradient type. Its implementation gave the results plotted in Fig. 4. The optimized solution is obtained after 137 iterations. We want to mention that the optimized variant is obtained for a constant torque, at the same rated current. Here, the geometry is reduced, meaning that the mass of the machine is decreased. A 28.8% of the geometry mass decrease was obtained with the employed algorithm, while the energetic performances are maintained within the acceptable values. This mass value is obtained with a specific geometry configuration, which has been validated again through FEM analysis.

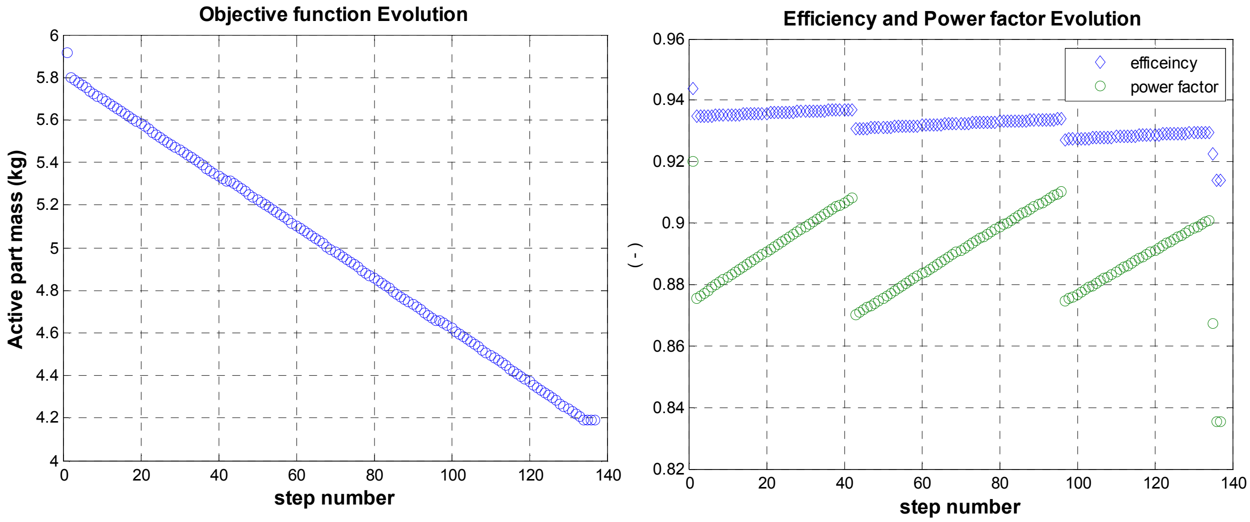

Figure. 4 The optimization of the best suited motorization variant.

Experimental validation

A prototype of the studied and optimized PMSM-17/39 was constructed. Next, a test bench of the electric scooter was installed, containing: the PMSM-17/39 and its power converter, an electrical machine as a load, a power source which emulates the battery, a programmable load to consider the load torque, voltage-current transducers, the torque-speed transducer and a control unit based on dSPACE1103 board, see Fig .5.

The characteristics of the PMSM-17/39 are presented in Fig. 6. The load current at rated operation reaches 21.05 A. From the input/output power characteristic one could get the efficiency of the studied motor, at the bottom of Fig. 6.

The rated efficiency of the studied motor is 0.901, which is very close to the calculated value (see Table V). Also, the power factor is 0.91.5, meaning that the designed-optimized-constructed machine corresponds to the application’s needs.

When the PMSM-17/39 operates in motor regime we can see the chopping effect on the torque characteristic, see Fig. 7.

Figure 5. The experimental bench.

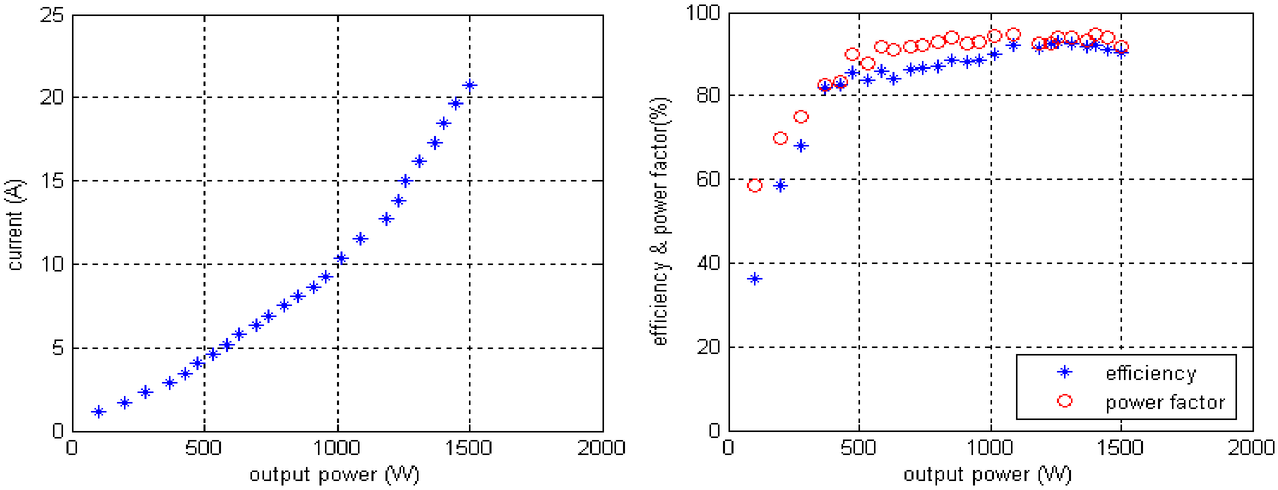

Figure 6. The characteristics of the constructed machine.

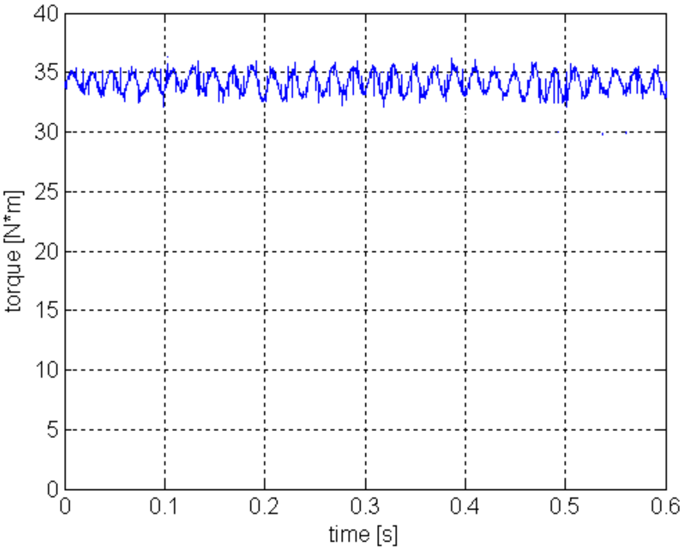

Figure 7. The measured results: current and torque of the constructed prototype.

The rated torque is reached at the rated current. Apart some spikes coming from the transducers/acquisition devices, the torque ripples are below 6%. This result is very good for a PMSM, but there is quite a difference with the torque wave computed via the FEM software. One of the reasons could be the fact that in the FEM analysis the machine was fed with purely sinusoidal currents, while in practice, this will never be possible. Nevertheless, the desired torque was obtained, thus validating the calculated (results from Table 2) and computed (Fig. 4) results.

Conclusions

The paper presents the performances of a permanent magnet synchronous machine designed for scooter applications. First of all the applications demands are stated. Next, three topologies of electrical machines are proposed and their performances are evaluated. Numerical analysis via finite element method was employed in order to validate the calculated results. The best variant was chosen after the numerical analysis and then was optimized it. Next, a prototype of the scooter motorization was constructed and tested. The experimental expected results were obtained, thus validating the study.

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