BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVII (LXI), Fasc. 6, 2011
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

ANALYTICAL DESIGN, NUMERICAL COMPUTATION AND OPTIMIZATION OF A PERMANENT MAGNET SYNCHRONOUS MACHINE USED FOR ELECTRIC VEHICLE PROPULSION

BY

DANIEL FODOREAN[*] and L. SZABO

Technical University of Cluj-Napoca

Received, May 31, 2011
Accepted for publication: July 26, 2011

Abstract. The paper proposes a study regarding the design, numerical analysis and the optimization of a permanent magnet synchronous machine dedicated for the propulsion of electric vehicles. To be more specific, the concerned application is an electric scooter, but the approach can be adapted for any type of electric vehicle.

Key words: electric vehicleş design-FEM-optimization of an electrical machine.

1. Introduction

One of the greatest problems of modern society, at present, particularly for industrialized countries, is the pollution (Fuhs, 2009; Ehsani *et al.*, 2005; Vogel, 2009; Ceraolo *et al*., 2006; Chenh-Hu & Ming-Yang, 2007; Naidu *et al*., 2005). 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. Even in our country, the pollution effect of is more and more obvious, especially in large cities. Consequently, finding a solution to reduce

[*] Corresponding author: *e-mail*: daniel.fodorean@mae.utcluj.ro

(or eliminate) the pollution is a vital need. If in public transports (trains, buses and trams) were found non-polluted solutions (electrical), for the individual transport, the power solutions can not yet meet the current need in autonomy. Even though historically the electric vehicle precedes the thermal engine, the power/fuel-consumption ratio and the reduce time to refill the tank has made the car powered by diesel or gasoline the ideal candidate for private transport. Although lately there were some rumors regarding the depletion of fossil resources, according to recent studies, America's oil availability is assured for the next 500 years (Ehsani *et al.*, 2005)! So, the problem of breathing clean air remains the main argument of electric vehicle (EV). 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. Thus, 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, every car manufacturer proposes its own version of electric or hybrid car, at *SUPERCAR* standard (s. Table 1 – Fuhs, 2009).

Table 1
"Concept Car" Variants and their Performances

Model	Technical Data	Performances
AUDI quattro	Engine (30 kW); Lithium-ion battery	Autonomy 100 km, in full electric
BMW x5 hybrid SUV	Engine V-8 of 1,000 N.m; electric motor of 660 N.m	20% fuel consumption decrease
CHRYSLER eco	Electric propulsion of 200 kW; FC of PEM type	Autonomy 482 km
FORD hySeries	Lithium-ion battery of 130 kW, and FC of 35 kW	Autonomy 363 km
HONDA FCX	Electric motor of 80 kW, using UC and FC	55% efficiency, autonomy 430 km
HYUNDAI I-blue	FC and electric motor of 100 kW	Autonomy estimated to 600 km
JEEP Renegade	1.5 L engine and 4 motor-wheels of 85 kW	Autonomy 645 km
MERCEDES hybrid	3.5 L (V-6) gas engine and 225 kW electric motor	Acceleration 0…100 km/h in 7.5 s
MITSUBISHI EV	Lithium-ion battery, 4 in-wheel motors of 20 kW	Autonomy 150 km
OPEL flextreme	Series hybrid engine (120 kW); Li-ion battery	1.5 L/100 km; fuel consumption
PEUGEOT hybrid	Diesel-electric engine	Respects the PNGV!requests
TOYOTA 1/X hybrid	Engine 0.5 L, total weight 420 kg (carbon materials)	Reduced weight/fuel consumption
VOLKSWAGEN FC	FC and Li-ion battery; 40 kW electric motor	Autonomy 108 km; V_{max} =125 km/h
VOLVO recgarge	Series hybrid engime with lithium polymer battery	Autonomy in full electric: 100 km

In Table 1 were presented only some of the world's automotive prototypes. 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, an FC of 100 kW would cost 450,000 € (which are practically prohibitive in terms of costs, for series manufacturing).

By consulting Table 1 it can be noticed the interest of all car manufacturers to get the reduced pollution, with highest autonomy. Nowadays, the hybrid vehicles can be seen on streets. Although the cost of a hybrid car is not much higher than for the classical fuelled one (s. Fig. 1), however, the first one requires maintenance higher costs.

Some predictions on the EV's evolution, given by Fuhs (2009), emphasize that in the nearest future the thermal automobiles number will decrease, while the hybrid ones are taking their place. By 2037 the fully electric vehicle will replace the engine and then, after a fuzzy period (between 2037-2042), all vehicles will be powered based on clean energy sources, when a new philosophy of building and using the cars will be put in place, meaning that the vehicles will be using new materials, new power stations, according to a new philosophy of individual transport.

So, one of the challenges of individual transport refers to finding clean solutions, with enhanced autonomy (Ceraolo *et al*., 2006; Chenh-Hu & Ming-Yang, 2007; Naidu *et al*., 2005). This is the motivation of this research. For that, an electric scooter will be studied from the motorization, supplying and control point of view. Here, only the motorization aspect will be analysed. 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.

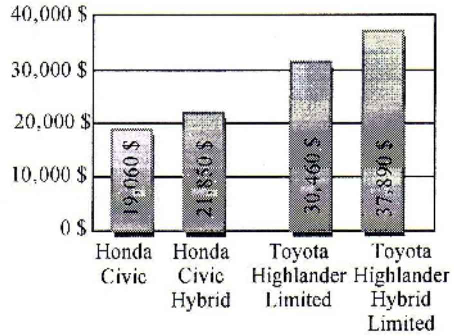

Fig. 1 – Price comparison between thermal – hybrid vehicle (Fuhs, 2009).

2. The Application under Study

From motorization point of view, there are two possible solutions: with inner rotor and transmission belt, or with outer rotor and the motor placed within the wheel. The second variant will be analysed here. Basically, the electric circuit layout of the experimental scooter under study is presented in Fig. 2. Here, the in-wheel motor variant is considered. Thus, a permanent magnet synchronous machine (PMSM) topology seems to be the best choice. (For the inner rotor topology, with transmission belt, it might be used other type of machine, like the induction machine or the dc one excited through PMs.)

The rated data of the designed machine are: 1.5 kW of output power, 420 rpm, 48 V_{cc}.

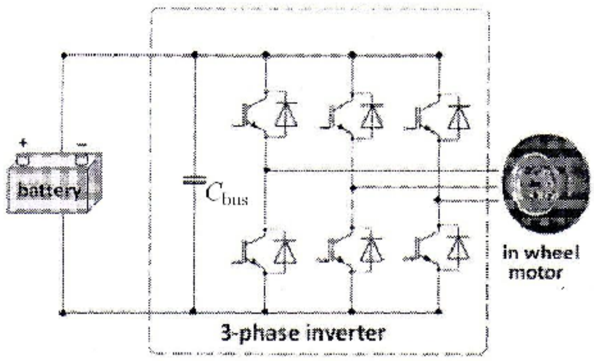

Fig. 2 – Electric circuit layout of the experimental scooter.

3. Design and Numerical Validation of the Studied PMSM

The analytical design is based on magnetic reluctances equivalent circuit (Pyrhonen *et al*., 2008; Chiasson, 2005; Fodorean *et al*., 2007) – not presented here, because of the length limitation of the manuscript. 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 studied PMSM has 17 pair of poles and 39 slots, meaning that the winding is of fractioned type. This will have an important influence on the mechanical torque wave form. For applications with sudden load changes, the torque control technique should be used. In order to have a proper control, the torque wave should be very smooth. An electrical machine with fractioned winding type offers this feature.

Having these supplementary constraints, the PMSM was designed analytically, and the results indicated in Table 2 were obtained. The main results of the designing process (*i.e.*, the air-gap flux density, the output power or axis torque for a specific current supply, the saturation) should be confirmed through numerical computation. This analysis is carried out with the finite element method (FEM), by using the Flux2D software.

In Fig. 3 one should observe the machine's geometry and flux density repartition in the active parts of the machine. Also, the electromagnetic–

mechanical performances (such as the air-gap flux density, the voltage drop for motor operation, the supplied current and the axis torque) are shown in Fig. 4.

Table 2
Main Performances of the Designed PMSM

Parameter description	Value
Rated torque, [N.m]	34
Supplying frequency, [Hz]	119
Number of phases	3
Number of pole pairs	17
Number of stator slots	39
Outer diameter, [mm]	220
Machine length, [mm]	50
Airgap length, [mm]	1
Airgap flux density, [T]	0.849
Phase resistance, [Ω]	0.0444
Rated current, [A]	20.76
Losses, [W]	89.06
Power factor, [%]	92.03
Efficiency, [%]	94.39
Active part costs, [€]	73.99
Active part mass, [kg]	5.91
Power/mass, [W/kg]	253.5

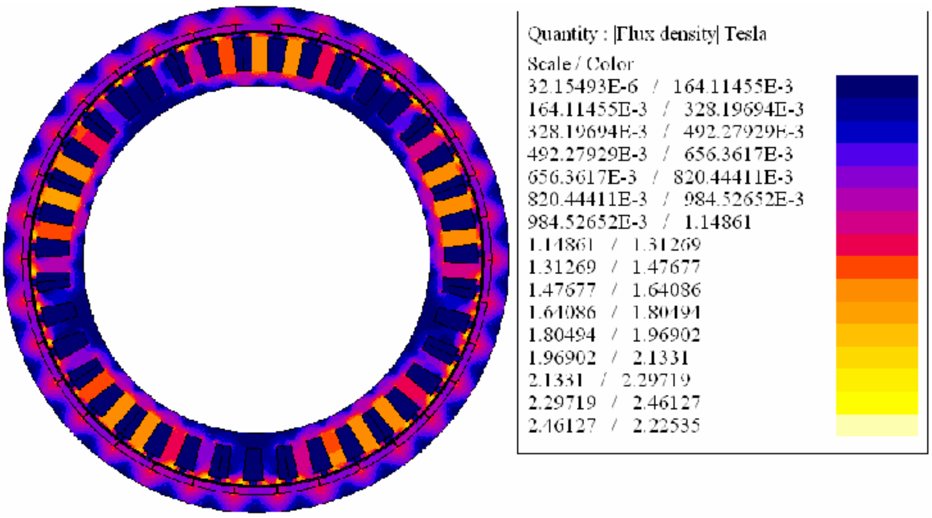

Fig. 3 – The geometry and the steel saturation of the designed PMSM.

Here, it can be observed that the air-gap flux density reaches the value found from the analytical approach. While supplying the 3-phase winding with pure sinusoidal currents, at rated speed (420 rpm), one can see the phase voltage drop in the machine, as well as the obtained torque. The desired torque is reached for the imposed rated current, and the torque wave form is very smooth.

This is the advantage of the fractioned type winding topology which reduces significantly the torque ripples (the torque ripples are 1.88% of rated torque).

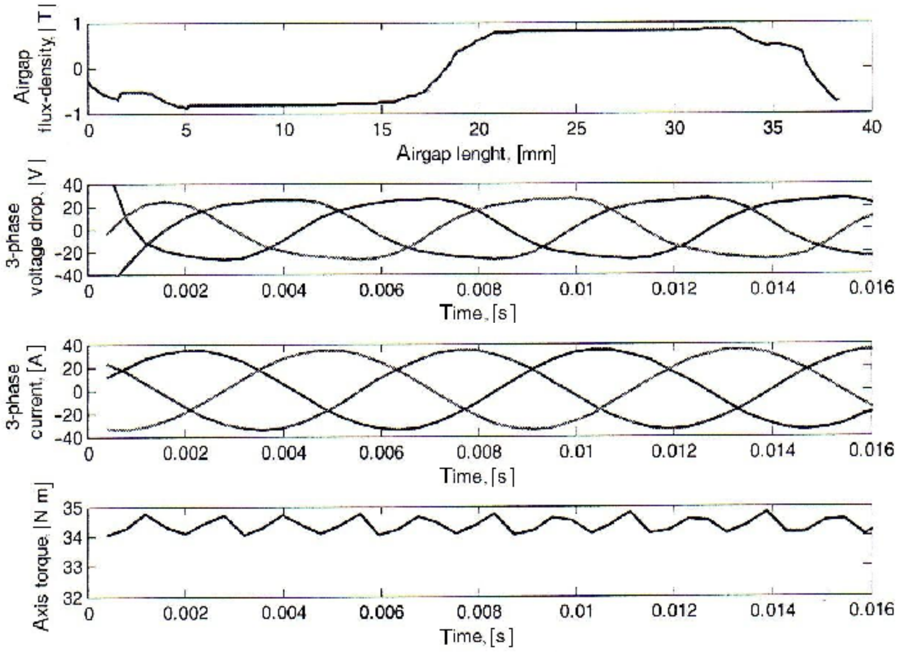

Fig. 4 – The FEM results of the designed PMSM.

Since the numerical results confirmed the analytical ones, the next step is to optimize the PMSM.

4. Optimization of the Designed PMSM

In order to obtain the desired performances, and not overpass the supplying current, it is necessary to impose some supplementary constraints. The objective of the optimization is to increase the power density. Actually, for the least mass of the active part of the machine, we want to get the same output power (and torque). Thus, the objective function will maximize the power/mass ratio. Since, 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 main geometrical parameters (not given here).

There are different optimization algorithms, some of them being simple (like the gradient type, (Tutelea & Boldea, 2007)) or complex (like the genetic type, (Kumar & Bauer, 2009)). Some of them are very complex, and their convergence is very good, while the simple ones are very sensitive to any change in the initial solution (like the gradient type). Anyway, based on their simplicity and satisfactory results, here the optimization method is based on Hook-Jeeves algorithm (Tutelea & Boldea, 2007). This algorithm is of gradient type. Its implementation, for an imposed torque and current, gave the results plotted in Fig. 5. The optimized solution is obtained after 137 iterations.

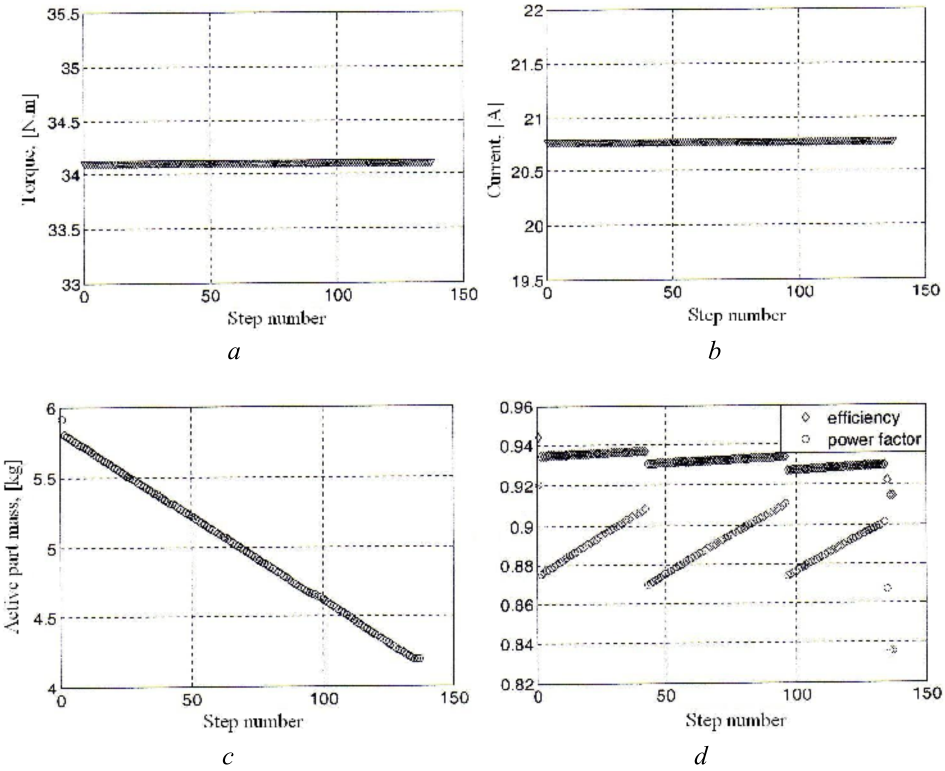

Fig. 5 – The optimization of the studied machine: *a* – motor torque; *b* – source current; *c* – active part mass; *d* – efficiency and power factor.

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.

As prospective, the machine has to be build, for the final validation of the design and optimization approach.

Acknowledgment. This paper was supported by the project “Development and Support of Multidisciplinary Postdoctoral Programmes in Major Technical Areas of National Strategy of Research – Development – Innovation” 4D-POSTDOC, contract no. POSDRU/89/1.5/S/52603, project co-funded by the European Social Fund through Sectoral Operational Programme Human Resources Development 2007-2013.

REFERENCES

Ceraolo M., Caleo A., Campozella P., Marcacci M., *A Parallel-Hybrid Drive-Train for Propulsion of a Small Scooter*. IEEE Trans. on Power Electron., **21**, *3*, 768-778 (2006).

Chenh-Hu C., Ming-Yang C., *Implementation of a Highly Reliable Hybrid Electric Scooter Drive*. IEEE Trans. on Ind. Electron., **54**, *5*, 2462-2473 (2007).

Chiasson J.J., *Modeling and High Performance Control of Electrical Machines*. IEEE Press Series on Power Engng., John Wiley & Sons, West Sussex, 2005.

Ehsani M., Gao Y., Gay S.E., Emadi A., *Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory, and Design*. CRC Press, Boca-Raton, 2005.

Fodorean D., Djerdir A., Viorel I.A., Miraoui A., *A Double Excited Synchronous Machine for Direct Drive Application – Design and Prototype Tests*. IEEE Trans. on En. Conv., **22**, *3*, 656-665 (2007).

Fuhs A.E., *Hybrid Vehicle and the Future of Personal Transportation*. CRC Press, Boca-Raton, 2009.

Kumar P., Bauer P. *Progressive Design Methodology for Complex Engineering Systems Based On Multiobjective Genetic Algorithms and Linguistic Decision Making*. Soft Comp., **13**, *7*, 649-679 (2009).

Naidu M., Nehl T.W., Gopalakrishnan S., Würth L., *A Semi-Integrated, Sensorless PM Brushless Drive for a 42-V Automotive HVAC Compressor*. IEEE Trans. on Ind. Appl. Mag., **11**, *4*, 20-28 (2005).

Pyrhonen J., Jokinen T., Hrabovcova V., *Design of Rotating Electrical Machines*. John Wiley & Sons, West Sussex, 2008.

Tutelea L., Boldea I., *Optimal Design of Residential Brushless d.c. Permanent Magnet Motors with FEM Validation*. Internat. AGEAN Conf. on Electr. Machines a. Power Electron., Istanbul, Turkey, Sept. 2007, 435-439.

Vogel C., *Build Your Own Electric Motorcycle*. McGraw-Hill Co., New-York, 2009.

DIMENSIONAREA ANALITICĂ, ANALIZA NUMERICĂ ŞI OPTIMIZAREA UNEI MAŞINI SINCRONE CU MAGNEŢI PERMANENŢI UTILIZATĂ LA ANTRENAREA UNUI VEHICUL ELECTRIC

(Rezumat)

Se prezintă dimensionarea, analiza numerică, prin metoda elementelor finite, şi optimizarea unei maşini sincrone cu magneţi permanenţi, utilizată la antrenarea unui scuter electric. Din punct de vedere constructiv maşina este de construcţie inversată, rotorul fiind la exterior. Rezultatele dimensionării sunt validate cu ajutorul analizei numerice prin metoda elementelor finite. Optimizarea maşinii dimensionate este realizată prin două metode, de tip gradient şi evolutiv, pentru a valida confruntarea metodelor, dar şi pentru a confirma performanţele maşinii optimizate. Parcurgând toate etapele necesare dimensionării, se pregăteşte soluţia de antrenare a scuterului electric, înainte de realizarea unui model experimental ce urmează a fi testat pe standul de încercări.