Study of a High-Speed Motorization for Electric Vehicle based on PMSM, IM and VRSM

D. Fodorean, D.C. Popa, P. Minciunescu, C. Irimia, L. Szabó

***Abstract* – The paper presents the study of a high speed motorization dedicated for electric vehicle (EV). Three types of electrical machines are analyzed: permanent magnet synchronous machine (PMSM), induction machine (IM) and variable synchronous reluctance machine (VRSM). They are studied from the electromagnetic point of view, with closer look on the power density, energetic performances and torque wave (this last parameter being critical while controlling the transients on the EV's motorization). Mechanical aspects will be also treated, since they are influencing the losses and since the presence of centrifugal forces could irreversibly affect the structure of the motors. The best suited variant is constructed and preliminary information on the prototype is given.**

***Index Terms*—high speed motorization, electric vehicle, PMSM, IM, VRSM.**

I. Introduction

THE motorization for electric vehicles (EVs) based on high speed electric machines is not a common topic. Usually, the high speed machines are used for applications with low dynamics, like the ventilation systems, where the load torque does not vary rapidly [1]-[5]. On a contrary, for EV, the transients are the common operation mode and the acceleration/decelerations, accompanied by the sudden high torque demands, are the common operation in such applications. The control in such conditions is a very important task, which depends not only on the power electronic device capabilities, but also on the electrical machines capability to produce very smooth mechanical characteristics, meaning very smooth torque. Smoother torque can be obtained even with iron saturation, meaning that a higher current consumption can be considered to obtain the desired performances. But, by increasing the current the energetic performances will decrease. Moreover, the power density needs to be increased (i.e., by reducing the mass of the machine); otherwise, the cost of the machine will increase. Thus, the goal of the paper is to propose a high speed motorization, with the best power density, with good energetic performances and very smooth mechanical characteristics, thus preparing the high dynamic control needed by the motorization of the EV.

The study presented here proposes the analysis of three electrical machines designed for a high speed motorization of EV. The considered machines are: a permanent magnet synchronous machine (PMSM), an induction machine (IM) and a variable reluctance synchronous machine (VRSM). The same stator will be considered for all the machines, in order to have a better comparison between the studied topologies. (We have intentionally neglected the switched reluctance motor because of its high torque ripples).

Why the use of the high speed motorization? Usually, the traction of an automobile (even a thermal one) is composed mainly from the motor itself and a gear. For the EV, we have the electric machine (EM), its transmission, the control unit (CU) and the power supply (battery, fuel cell and/or ultracapacitor) – see Fig. 1. (We have the possibility to neglect the transmission with an in-wheel motor configuration, but the presence of the machine within the wheel involves extreme mechanical solicitations which could irreversibly damage the motor.)

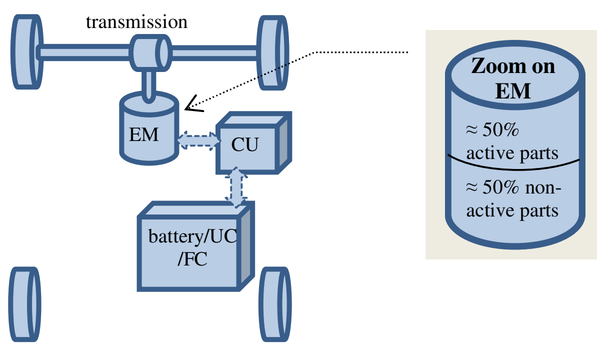

Fig. 1. The layout of an electric traction chain.

From experience we know that the weight of an electric traction is approximately 50% of active parts (stator and rotor iron, armature winding, excitation) and 50% of non-active parts (shaft, bearings, housing, water jacket etc.). It is also clear that the high-speed machine offers reduced weight at the same rated power, which means a very high power density. For example, a 30 kW induction traction motor weights 130 kg, and according to our assumption the active parts weight around approximately 65 kg, which is a lot of weight, which do not really interfere in the torque production. As the reader will see further on, for the constructed high-speed machine we will have a much reduced weight for the non-active parts, which are not involved in the obtained torque. Also, a heavier machine needs much more investment in the active parts. Of course, in this case the big challenge is to design the appropriate gear – but also in the case of the heavier EM, we will still need a transmission. For an EV, such weight decrease is a very important achievement since the weight of the automobile affects directly the autonomy of the EV.

Thus, the main challenges for our high-speed traction system are: to design the best power density traction motor, with very smooth mechanical characteristics and with improved energetic performances. These are the goals that this study is trying to meet.

This work was supported in part by the Romanian National Authority for Scientific Research, CNDI–UEFISCDI, project number PCCA 191/2012.

D. Fodorean, D.C. Popa and L. Szabó are with the Technical University of Cluj-Napoca – Cluj-Napoca, Romania (e-mail: daniel.fodorean@emd.utcluj.ro, dan.cristian.popa@emd.utcluj.ro, lorand.szabo@emd.utcluj.ro).

P. Minciunescu is with ICPE SA – Bucureşti, Romania (pmagnetics@gmail.com).

C. Irimia is with LMS, a Siemens Business – Braşov, Romania (e-mail: cristi.irimia@lmsintls.com).

978-1-4799-4775-1/14/$31.00 ©2014 IEEE

II. The Studied High Speed Motorization Variants

A. *The application's main data*

The main design data of the high speed motorization are given in Table I. All the designed machines (PMSM, IM and VRSM), in radial and inner rotor configuration, will be water cooled, having the same number of stator slots (18) and poles pair (1). The machines will be supplied via an inverter for which the input voltage is 380 Vdc. The output performances are 26,000 r/min and 20 kW.

TABLE I
The Main Motorization's Demands

Parameter	Value	Unit
Power	20,000	W
Speed	26,000	r/min
DC converter voltage	380	V
Number of poles	2	
Number of stator slots	18	
Cooling	Water cooled	

The studied machines will be evaluated in terms of energetic performances and power density, based on analytical and numerical approach. The numerical analysis is employed by using the finite element method (FEM) – the Flux 2D and Flux-Skewed software have been used. The active part materials used in this analysis are: Vacodur 50 for the iron (with sheets of 0.2 mm, stacking factor of 0.93 and saturation at 2.35 T), common copper and, for the PMSM, the magnet is of Sm-Co type, with high temperature stability and remanent flux density of 1.1 T.

(The main performances and the results comparison will be presented at the end of this subchapter, in section II.E. Here, only the main electromagnetic FEM results are depicted.)

B. *The high speed PMSM*

The first analyzed machine, presented here, is the PMSM. Several rotor configurations have been evaluated: with surface mounted, half-inset or buried PMs. For the first two variants the use of a retaining ring is needed; such device can be made of carbon (most commonly and cheap solution, instead, it will limit the temperature operating point of the PMs), or by titan (most expensive, but also more stable at high temperatures, even beyond 150°C). The variant with buried PMs assures a reduced air-gap, but a careful mechanical design should be employed, in order to avoid the iron damage at such high speeds. Here, the second variant has been adopted, thus we have evaluated the mechanical resistance of the used material [6]-[7].

The PMs are unidirectional magnetized and buried into the rotor core in small pieces (5 PM pieces forming one magnetic pole). Between the magnetic poles a flux barrier should be considered to reduce the PMs' leakage flux. In order to avoid the iron irreversible damage, a FEM mechanical analysis was considered, emphasizing that this type of iron can keep its integrity up to 390 MPa. This has imposed also a limitation on the outer rotor radius.

The final configuration of the rotor and the maximum mechanical stress is presented in Fig. 2, while the circumferential speed of the rotor is 83 m/s. The maximum tensile stress developed in the retaining bridges (317 MPa) is below the maximum allowable limit of our material.

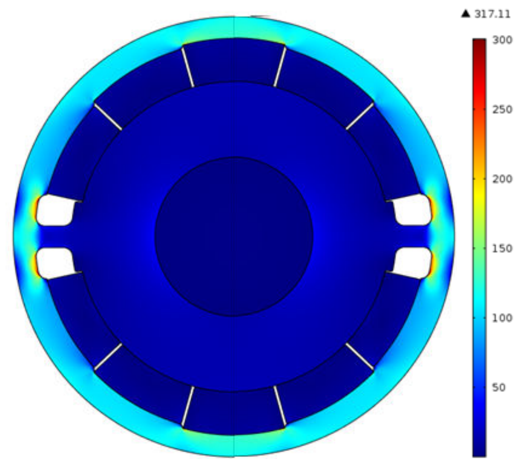

Fig. 2. Von Mises stress distribution (MPa) in final version of rotor with buried magnets

The analytical design is not presented here. Only the electromagnetic behavior of the PMSM will be numerically evaluated.

We have stated earlier that in order to limit the centrifugal forces and to avoid the rotor iron damage, we have imposed a certain limitation on the outer rotor diameter. Another limitation was imposed on the shaft diameter, because the machine needs to produce the desired torque. Thus, we were forced to accept a certain limitation on the rotor yoke, which involved a partial saturation of the rotor core.

The machine was analyzed in transient operation. The field lines and the flux density distribution within the active parts of the machine are shown in Fig. 3. Here, one can see the partial saturation of the rotor iron. Next, the reader will see how the output performances are influenced by this flux distribution.

The axis torque and the iron loss distribution are plotted in Fig. 4. Based on these results can be concluded that the machine produces the desired performances, but the torque ripple are quite high. Also, since the PMSM works at high speed, the evaluation of the rotor iron loss is important. The motor produces 40 W of losses in the rotor core, 5 times below the stator iron losses (in the yoke and teeth).

In order to obtain a more sinusoidal induced electromotive force (emf), we should incline the stator, or the rotor core, with an angle equal to the tooth pitch (360°/18 slots=20°). We have evaluated numerically the effect of armature incline, by skewing the stator or the rotor sheets. For the constructed prototype we have chosen to incline the rotor (for very thin sheets, the incline is difficult to be employed on the stator armature; the rotor is formed of 5 modules – one module having the length of one magnet piece – which have been then shifted with 20°/5)

The effect of armature skewing can be observed in Fig. 5, where the flux density is also presented, for the stator-skewed PMSM. The induced emf, for the non-skewed and skewed topologies is showed in Fig. 6. The reader can see that the effect of rotor or stator skewing is similar (except a certain shift which will not affect the machines performances).

Thus, we can conclude that the studied PMSM offers the expected results and that the skewing of the machine's armature will produce a smoother and sinusoidal emf.

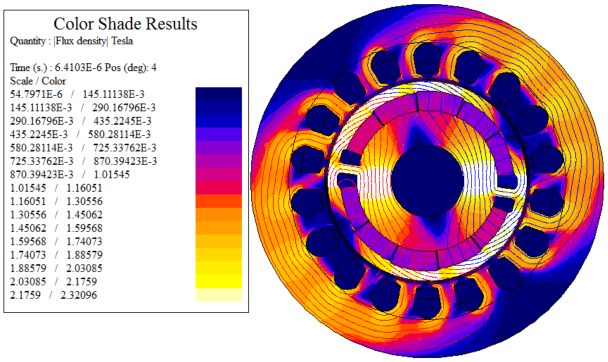

Fig. 3. Flux density and field lines distribution in the high-speed PMSM.

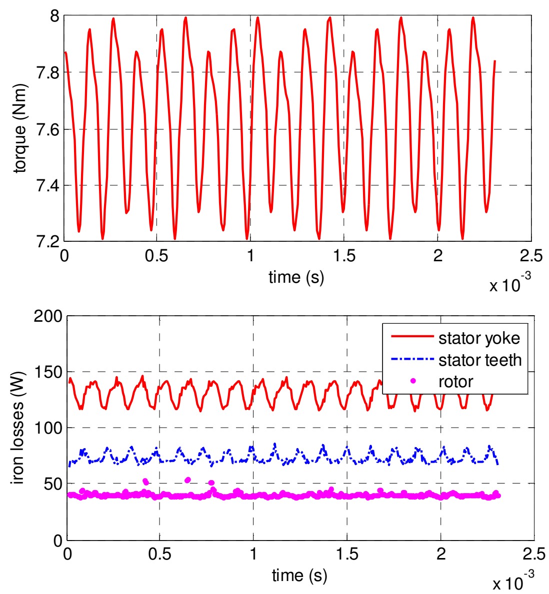

Fig. 4. Torque (top) and iron losses (bottom) FEM results for the studied high-speed PMSM.

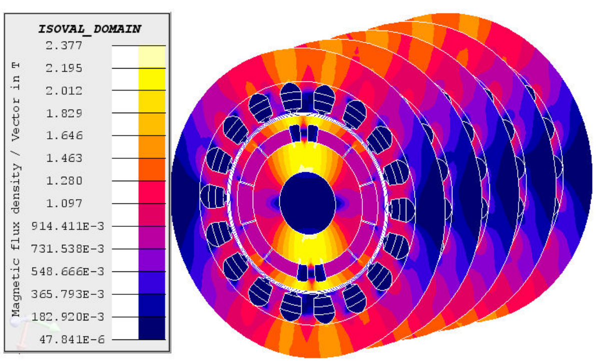

Fig. 5. Flux density and field lines distribution in the stator-skewed high-speed PMSM.

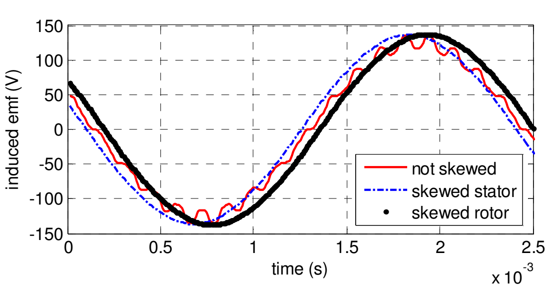

Fig. 6. emf comparison for the studied high-speed PMSM.

C. The high speed IM

The induction machine presented here has the stator identical to the one of the other variants approached in this study. The difference is related however to the length of the machine, which is here 200 mm.

Considering the number of stator slots, the possible solutions for the choice of the number of rotor bars was limited to 13 or 14. With an inverter fed machine it is possible to use relatively shallow bars [8]-[9]. Round bars were used here as pear shape ones would have reduced the height of the yoke, increasing in this way the iron losses. The numerical analysis, performed in Flux 2D in both cases showed that the best results are obtained for the first case mentioned above. The analysis was carried out both in steady state and transient regime.

The flux density in the iron core at a certain position is presented in Fig. 7.

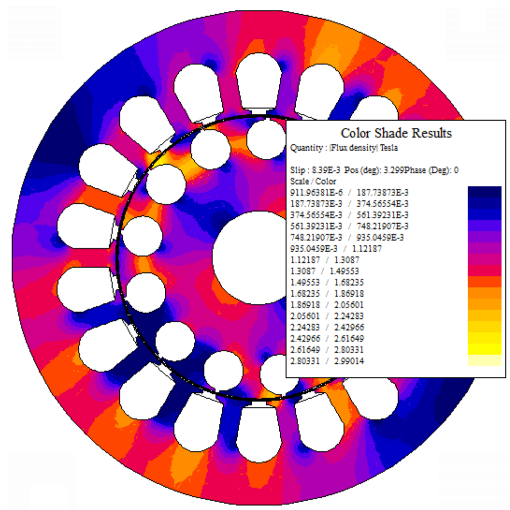

Fig. 7. Flux density map in the stator and rotor iron core.

The torque vs. rotor position and the static characteristic torque vs. slip obtained also in steady state regime are presented in Fig. 8.

The numerical analysis performed in the transient regime focused on obtaining the variation of the electrical and mechanical measures in the starting period of the induction motor.

The currents on the three phases are shown in Fig. 9-top. It can be noticed that the rms value in the steady state regime is around 60 A, which is very close to the one imposed in the design stage. The variation of the induced emf evidences a little higher voltage drop on the coil-s resistance and leakage reactance than at usual speed induction machines, see Fig. 9-bottom. However, this remains at a low value.

The stator and rotor iron losses were limited by designing the machine in such a way that the flux densities in the iron core are not at the highest possible values. This strategy was imposed by the use of a very high frequency. The values obtained in the numerical analysis are smaller than those resulted in the design process as in that case a mean value of the flux density in various parts of the iron core is considered. The separate variations of the losses in the two armatures of the machine are given in Fig. 10, as well as for the dynamic torque.

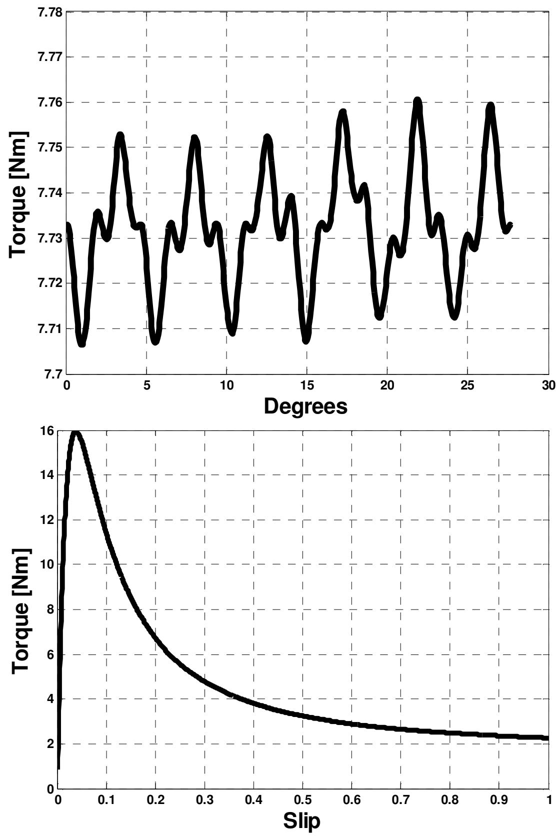

Fig. 8. Mechanical characteristics: torque ripples (top) and the static torque vs. slip (bottom).

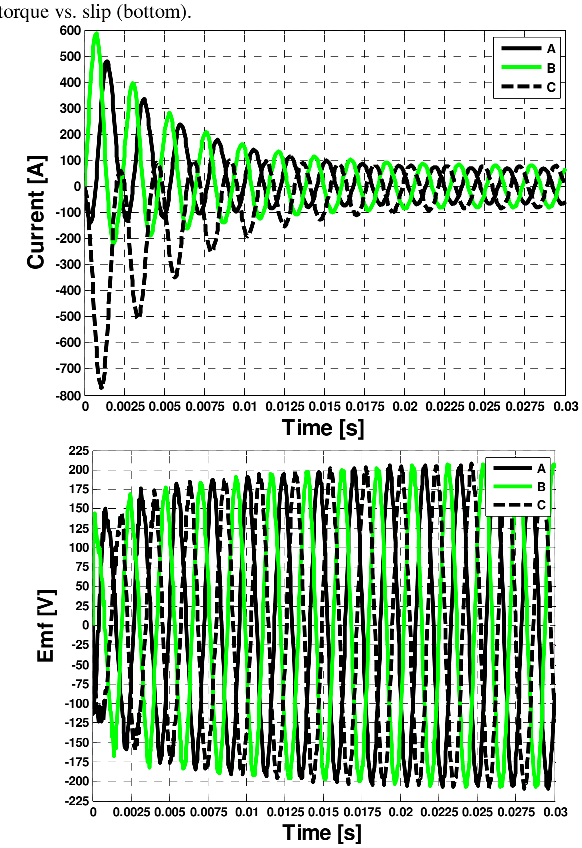

Fig. 9. Electrical characteristics: current (top) and the induced emf (bottom) variation.

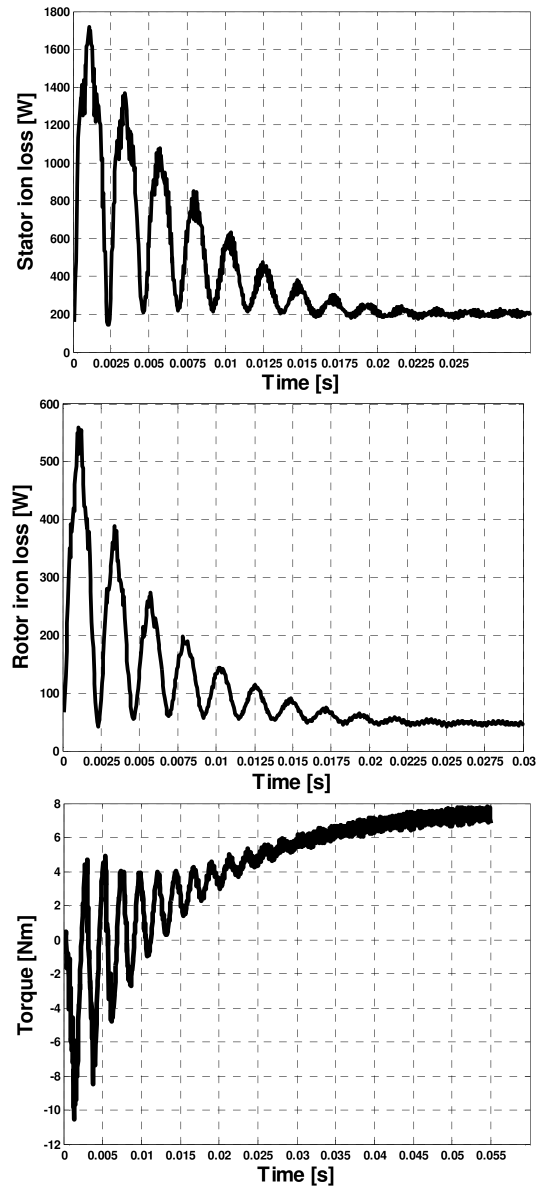

Fig. 10. Dynamic characteristics: stator (top) and rotor (middle) iron losses and the torque (bottom).

However, another advantage provided by the use of the inverter is the possibility to achieve a high starting torque and a low starting current can be achieved, since the supply voltage and frequency are variable.

D. The high speed VRSM

The last studied high-speed machine is the VRSM. The same stator armature was used, like in the case of the PMSM and IM, with the same number of turns per phase. One poles pair for such VRSM has a simple structure, which involves a supplementary friction torque on the rotor (which will act like a fan inside the machine) [10]. To avoid this effect, we will consider a non-magnetic quasi-cylinder which will cover the rotor core. Thus, the whole rotor will look like a tube. Based on the previous analysis, we have tested the non-skewed and the skewed topologies (while the stator was inclined with a 20°), see Fig. 11.

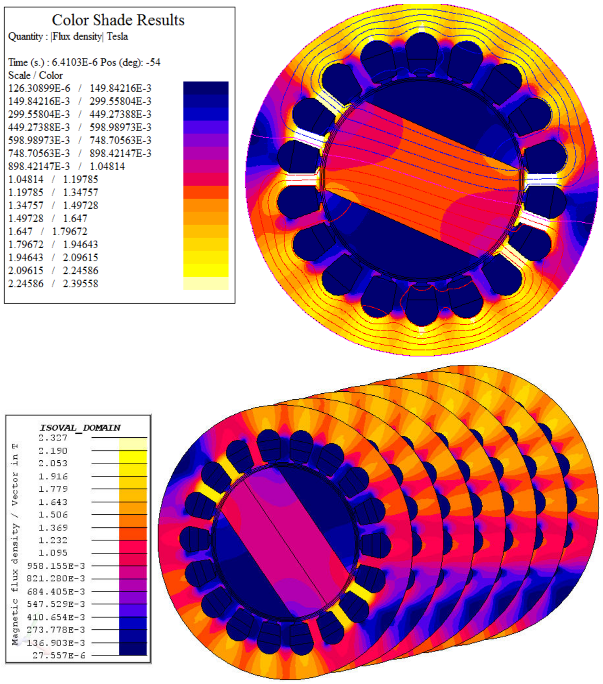

Fig. 11. Flux density distribution in the studied high speed VRSM, with or without skewed rotor.

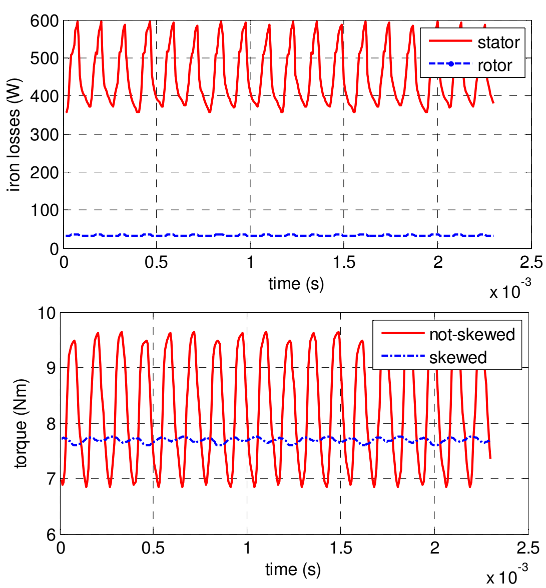

Fig. 12. Torque and iron losses FEM results for the studied high-speed VRSM.

Beside the flux-density distribution within the active parts of the VRSM we can see the iron loss distribution and the skewing effect on the torque wave form. In the case of the VRSM, with a longer length on the armature, the stator iron loss is more important than the rotor iron loss, because of the reduced volume of the rotor core. On the other hand, the skewing of the stator will reduce drastically the torque ripples.

More details on the performances of this machine will be presented in the next subsection.

E. Performances comparison

The main performances of the designed high speed motorization variants are given in Table II.

TABLE II
COMPARISON OF THE MAIN PERFORMANCES OF THE STUDIED HIGH SPEED MOTORS

Parameter	PMSM-sk	IM	VRSM-sk
Winding connection	star	star	star
Synchronous frequency (Hz)	433.333	437	433.333
Air-gap length (mm)	1	0.5	1.5
Stack length (mm)	135	210	250
Current per phase (A)	55	60	60
Stator iron loss (W)	203	204	454
Rotor iron loss (W)	40	50	33
Efficiency (%)	95.6	81.5	92.9
Power factor (%)	84.9	92.5	88.4
Torque ripples (not-skewed / skewed) (%)	10.2 / 1.8	11.9	33.7 / 2.1
Mass of the active parts (kg)	8.25	12.4	15
Power density (kW/kg)	2.481	1.612	1.333

Based on the results presented in Table II, one could say that the PMSM has better efficiency, but with a slightly reduced power factor. On the other hand, the IM has the poorest efficiency and a good power factor. Nevertheless, in terms of power density, the PMSM is the most appropriate variant.

(It should be interesting to test experimentally all three machines, to evaluate also the influence of the power converter and the control robustness. Until then, we have decided to construct the PMSM, which offers the best power density.)

III. CONSTRUCTION OF THE HIGH-SPEED PMSM PROTOTYPE

The construction of the PMSM prototype was made by taking into consideration the skewing of the rotor (the reason was indicated earlier in section II.1). As stated previously, we will have five rotor modules shifted with 4°. In this moment only preliminary test have been employed, for the determination of the winding leakage flux, on the constructed PMSM prototype, which one-module rotor and the stator with the water jacket are presented in Fig. 13.

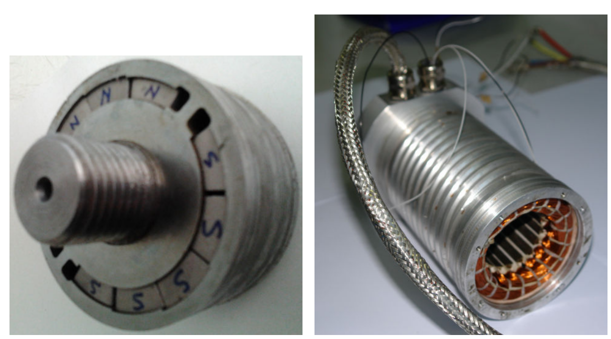

Fig. 13. Constructed high speed PMSM: one rotor module (left) and the stator with the water jacket (right).

IV. CONCLUSIONS

The paper proposes a high speed motorization for electric vehicles. Three motorization variants have been designed: a permanent magnet synchronous machine, an induction machine and a variable reluctance synchronous machine. The performances of these machines have been computed based on finite element method. A special attention was paid to the iron loss calculation and of the mechanical resistance in the case of PMSM with buried magnets. The performances of the three motorization variants have been compared in terms of energetic results and power density. A prototype of a high speed PMSM has been constructed.

V. References

[1] F. Luise, A. Tessarolo, S. Pieri, P. Raffin, M. Di Chiara, F. Agnolet, M. Scalabrin, "Design and Technology Solutions for High-Efficiency High-Speed Motors", *International Conference on Electrical Machines* 2012, Marseille, France, Sep.2012, pp.157-163.

[2] A. Tenconi, S. Vaschetto and A. Vigliani, "Electrical Machines for High-Speed Applications: Design Considerations and Tradeoffs", *IEEE Transactions on Industrial Electronics*, vol.61, no.6, pp.3022-3029, June 2014.

[3] W.L. Soong, G.B. Kliman, R.N. Johnson, R. White and J.E. Miller, "Novel high-speed induction motor for a commercial centrifugal compressor", *IEEE Transactions on Industry Applications,* vol.36, no.3, pp. 706 - 713, 2000.

[4] G. Pellegrino, A. Vagati, B. Boazzo, P. Guglielmi, "Comparison of Induction and PM Synchronous Motor Drives for EV Application Including Design Examples", *IEEE Transactions on Industry Applications*, vol.48, no.6, pp.2322-2332, Nov./Dec. 2012.

[5] D. Gerada, A. Mebarki, N.L. Brown, K.J. Bradley, C. Gerada, "Design Aspects of High-Speed High-Power-Density Laminated-Rotor Induction Machines", *IEEE Transactions on Industrial Electronics*, vol.58, no.9 pp.4039-4047, September 2011.

[6] A. Binder, T. Schneider and M. Klohr, Fixation of Buried and Surface-Mounted Magnets in High-Speed Permanent-Magnet Synchronous Machines, *IEEE Transactions on Industry Applications*, vol.42, no.4, pp.1031-1037, July/August 2006.

[7] K. Sung-Il, K. Young-Kyoun, L. Geun-Ho, H. Jung-Pyo, "A Novel Rotor Configuration and Experimental Verification of Interior PM Synchronous Motor for High-Speed Applications", *IEEE Transactions On Magnetics,* vol.48, no.2, pp. 995 - 998, 2012.

[8] D.P. Marcetic, I.R. Krcmar, M.A. Gecic, P.R. Matic, "Discrete Rotor Flux and Speed Estimators for High-Speed Shaft-Sensorless IM Drives", *IEEE Transactions on Industrial Electronics*, vol.61, no.6, pp.3099-3108, June 2014.

[9] J.F. Gieras, "Comparison of high-power high-speed machines: cage induction versus switched reluctance motors", *IEEE Africon 1999*, vol.2, pp.675-678, 1999.

[10] R.R. Moghaddam, F. Magnussen and C. Sadarangani, Theoretical and Experimental Reevaluation of Synchronous Reluctance Machine, *IEEE Transactions on Industrial Electronics*, vol.57, no.1, pp.6-12, January 2010.

VI. Biographies

Daniel Fodorean was born in Cluj-Napoca, Romania, in 1977. He received the M.Sc. degree in electrical machines and drives from the Technical University of Cluj-Napoca (TUCN), Romania, in 2002, and the Ph.D. degree in electrical engineering from University of Technology of Belfort–Montbéliard (UTBM), France, in 2005. He has been Associate Professor at UTBM between 2007 and 2009. Currently, he is Lecturer at TUCN. His research activities include the design, control, and optimization of electrical machines and drives.

Dan-Cristian Popa was born in Satu-Mare, Romania, in 1978. He received the M.Sc. degree and the Ph.D. degree in electrical engineering, respectively, in 2003 and 2008, from the Technical University of Cluj-Napoca (TUCN), Romania. Currently, he is Lecturer at TUCN. His research activities include the design of electrical machines, planar and tubular motors and numerical field computation.

Paul Minciunescu was born in Ploieşti (Romania) in 1966. He graduated the University "Politehnica" of Bucharest, Faculty of Electrical Engineering (Romania), in 1990. He received the Ph.D. degree in electrical engineering from the University "Politehnica" of Bucharest (Romania), in 1996. He is researcher at ICPE, in Bucharest. His research interests concern design of electrical machines, electro-mechanical devices with permanent magnets, direct drive motors, linear motors and numerical field computation.

Cristi Irimia received the M.Sc. degree in Mechanical Engineering, Automotive Section, from the University Transilvania of Braşov in 1991. He developed a long career in R&D, having a deep education in finite element analysis with high level LMS software. He is serving currently as general manager of LMS Test Division - CAE Division - Engineering Services from Romania. He is Ph.D. candidate within the University "Politehnica" of Bucharest in the field of automotive electrohydraulic remote steering system energy management.

Loránd Szabó was born in Oradea, Romania, in 1960. He received the B.Sc. and Ph.D. degrees in electrical engineering from the Technical University of Cluj-Napoca, Cluj-Napoca, Romania, in 1985 and 1995, respectively. In 1990, he joined the Technical University of Cluj-Napoca as a Research and Design Engineer, where he has been with the Department of Electrical Machines and Drives since October 1999, where he was a Lecturer and then an Associate Professor. Currently he is a Full Professor. His current research interests include linear and variable reluctance electrical machines, fault-tolerant designs, fault detection and condition monitoring of electrical machines.