Are SRM drives a real alternative for EV powertrain?

Pere Andrada
GAECE-EPSEVG-DEE
UPC-BARCELONATEC
Vilanova i la Geltrú, Spain
pere.andrada@upc.edu

Mark J.Dougan
AMES SA (PM Tech Centre)
Cami de Can Ubach 8
08620 St Vicenç dels Horts, Barcelona, Spain
mjdougan@ames.group

Francisco J. Márquez-Fernández
Div. Industrial Electrical Engineering and Automation
LTH Faculty of Engineering, Lund University
Lund, Sweden
fran.marquez@iea.lth.se

Aritz Egea
Machines and Automatics
Mondragon University-Faculty of Engineering
Arrasate-Mondragon, Spain
aegea@mondragon.edu

Loránd Szabó
Department of Electrical Machines and Drives
Technical University of Cluj-Napoca
Cluj-Napoca, Romania
lorand.szabo@emd.utcluj.ro

I. Introduction

This paper is a summary of the debate that took place in the round tables:

- ✓ What is slowing down the application of SRM drives for road vehicle electrification?
- ✓ Where should research and development focus to boost application of SRM drives to E-traction?

These round tables were the second part of the Workshop SRM an alternative for E-Traction held at the EPSEVG, on February 2, 2018.

Nowadays, although most of the traction drives of electric and hybrid vehicles (EV/HEVs) are permanent magnet synchronous motor (PMSM) drives, many reasons related with the drawbacks of using permanent magnets, advise to consider magnet-less drives [1-4]. Among these drives are: induction motor (IM) drives, synchronous reluctance motor (SyncRM) drives and switched reluctance (SRM) drives.

Despite SRM drives having the following strengths to be a serious candidate for the powertrain of the EV/HEVs:

- ✓ Simple construction
- ✓ Fault tolerant
- ✓ High efficiency and remarkable power and torque densities
- ✓ Match very well the torque speed envelop required for e-traction

and that recent studies have shown with consistent arguments their advantages comparatively to the others alternatives [5, 6], they continue to be just one more option for the propulsion of EV/HEVs, as evidenced by the fact that to date they are not used in any of the commercially available EV/HEVs (notwithstanding the frequent announcements of automakers on the utilization of SRMs in their next models of EV/HEVs).

This paper, the compilation of the discussions of the aforementioned round tables, tries to find out what are the reasons that prevent SRM being a real alternative for E-traction and which are the most advisable research topics to reverse this situation. It, also, includes some concrete promotion actions for the SRMs to become a real alternative for the powertrain of EV/HEVs.

II. Reasons That Slow Down The Application Of SRM Drives In Ev Drives

A. *Reasons concerning the SRM*

Although to a greater or lesser extent, it can be said that all electric motors have torque ripple and are noisy, in the SRM this statement has become a stereotype. Great progress has been made in the research of the causes and in the search for solutions, both in the mechanical design and in the electronic control of the SRMs to reduce the torque ripple and mitigate the audible noise to acceptable levels [7-10]. Nevertheless, these advances seem not to be enough to meet the standards of automotive industry.

As far as power density and efficiency are concerned, SRMs reach values slightly higher than induction motors and are below those attributed to synchronous motors with permanent magnets. However, the use of suitable magnetic materials in conventional SRMs, with very thin laminations (0.1 mm) and high content of silicon (6.5%) has allowed approaching the power density and performance of permanent magnet synchronous motors [11]. On the other hand, the utilization of constructive structures, generally modular, that tend to increase inductance in the aligned position and reduce it in the non-aligned position has helped to improve the performances of SRMs. Specifically, motors with segmented rotor [12], structures with segmented stator [13-16] and motors with double stator [17] or double rotor [18]. Axial flux SRMs are another alternative especially indicated for in-wheel direct drive motors but they are difficult to build using laminations and, therefore, require the use of materials such as SMC (soft magnetic composites) [19-25].

The use of soft magnetic materials different from current silicon-iron laminations can improve the performance of SRM or can make possible its construction but greatly increases its cost.

SRMs structures that increase power and torque density, whether they be of radial or axial flux, clearly penalize the most relevant advantage of SRMs that is its constructive simplicity and robustness, circumstance which has a clear negative impact on costs.

B. Reasons concerning to electronic power converter

SRM needs an electronic power converter for its operation. There are several alternatives but all have the particularity that have to be unipolar converters since the torque is independent of the sign of the current [26]. Although some efforts have been done to use common inverters for A.C. machines (IM and PMSM), they are not entirely suitable for SRM drives [27-28]. Phase leg commercial modules, containing solid state power switches, can be used in the construction of power converters for SRM but twice as many modules as in an inverter for alternating current machines are required (i.e. only half of the components in each module is employed), implying a significantly higher cost for the electronic power converter. Another drawback of SRM is that both ends of the phase windings have to be accessible unlike A.C. motors where one of the ends can be connected in star or delta. Designs of power trains for special purpose IM or PMSM can take advantage of the use of commercial power controllers (power converters with electronic control unit for traction applications). While in the market there are several commercial controllers for A.C. machines there is none for SRM.

C. Others reasons

There is still no standard for the powertrain of electric vehicles but PMSM and IM start with the advantage that they can adapt the technologies and production processes available in the industrial sector. In addition, nowadays, SRMs are little known among engineers working in automotive industry. Furthermore, in academia, little attention is dedicated to SRMs in the courses about electric drives.

III. Research And Development Trends

In order to boost the application of SRM drives in EV/HEVs, research and development should focus in the following topics:

A. Research on new soft magnetic materials

Improvements in soft magnetic materials, both silicon-iron lamination and SMC, would make it possible to increase the power density and the efficiency of the SRM. In the case of silicon-iron lamination it would be desirable to obtain higher permeability values and lower iron losses at different frequencies, whilst avoiding the fragility of the material. In the case of SMC, the aim would be to achieve higher values of saturation flux density and lower iron losses at different frequencies, all that, with a higher mechanical strength [29]. Obviously, this research would also benefit other types of drives as PMSM and IM drives.

B. Search for new topologies of SRM

Despite, new topologies of SRM, both radial flux and axial flux, increase their constructive complexity they can contribute to improve the power and torque density of SRM drives. Therefore, it is necessary to continue investigating the most promising alternatives and keep on working to develop even better ones.

C. Development of an electronic power converter/controller for SRM

Nowadays, unlike PMSM and IM there is not any commercial controller in the market intended for switched reluctance motors for E-traction applications. The commercialization of a three-phase, universal electronic power converter/controller, which can be used for any type of three-phase SRM, specially designed for EV/HEVs could potentially encourage competiveness and promote new initiatives that facilitate the definitive launch of SRM as a powertrain for EV/HEVs.

D. Introduction of new control strategies to improve the behavior of SRM

Research on new control strategies should not be ignored. Although great progress have been achieved, researchers must continue working to find new control strategies that can improve performance, reduce torque ripple and mitigate acoustic noise [30, 31] in order to be able to accomplish the demands of automotive industry.

IV. PROMOTION ACTIONS

Besides promoting research and development in some topics of SRMs, a greater effort must be made to increase the reputation and knowledge about SRM drives, both in the industrial sector and in the automotive sector. For this, it would be necessary to undertake a neutral, objective comparison between different drives for a given application (say a given vehicle type and drive cycle) including as many aspects as possible (cost of the whole system, size, EMC, NVH, reliability, etc.). This comparative study will help understanding the real potential of SRM drives compared to the other alternatives, and in case it is favorable, will also help promoting them.

In the University, SRM drives should have a more prominent role in the courses about electric machines and electric drives, which requires new ways to teach SRM drives [32] and that a greater number of lectures be devoted to them.

REFERENCES

[1] S. Estenlund, M. Alaküla, A. Reinap. “PM-less machine topologies for EV traction: A literature review”. ESARS ITEC 2016, Toulouse France 1-4, November 2016.

[2] T. Jahns. “Getting rare-earth magnets out of EV traction machines: a review of the many approaches being pursued to minimize or eliminate rare earth magnets from future EV drive trains”. IEEE Electrification Magazine, Issue 1, March 2017, pp. 6-18.

[3] T. Raminosoa, D. A. Torrey, A. El-Refaie, D, Pan, Stefan Grubic, Kevin Grace. “Robust non-permanent magnet motors for vehicle propulsion”. 2015 IEEE International Electric Machines & Drives Conference (IEMDC). pp- 496 - 502,

[4] A.El-Refaie, T. Raminosoa, P.Reddy, S.Galioto, D. Pan, K. Grace, J. Alexander, K.K. Huh.”Comparison of traction motors that reduce or eliminate rare-earth materials”.2016 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1 8.

[5] I.Boldea, L. N. Tutelea, L. Parsa,D. Dorrell. “Automotive electric propulsion systems with reduced or no permanent magnets: an overview”. IEEE Transactions on Industrial Electronics, vol. 61, no. 10, October 2014, pp 5696-57711

[6] J. D. Widmer, R. Martin, M. Kimiabeigi. “Electric vehicle traction motors without rare earth magnets”. Sustainable Materials and Technologies, 3 (2015), pp.-7–13

[7] I.Husain. “Minimization of torque ripple in SRM drives”. IEEE Transactions on Industrial Electronics, 2002, Volume: 49, Issue: 1, pp 28 - 39

[8] J. Ye, B. Bilgin, A.Emadi. “An extended-speed low-ripple torque control of switched reluctance motor drives”. IEEE Transactions on Power Electronics, 2015, Volume: 30, Issue: 3, pp 1457 – 1470.

[9] M.N.Anwar, I.Husain.S. Mir, T. Sebastian, “Evaluation of acoustic noise and mode frequencies with design variations of switched reluctance machines”. IEEE Transactions on Industry Applications, Vol 39, May-June 2003. pp 695 -703.

[10] D. E. Cameron, J. H. Lang, S.D. Umans. “The origin and reduction of acoustic noise in double salient variable - reluctance motors”, IEEE Transactions on Industry Applications, Vol 28, Nº 6, November/December 1992, pp 1250-1255.

[11] A. Chiba. “Recent development of switched reluctance motors for hybrid electrical vehicles”. IAS Webinar Series., 16 june 2017

[12] J.D.Widmer, R.Martin, B.C.Mecrow. “Optimization of a 80 kW segmental rotor switched reluctance machine for automotive traction.” IEEE Transactions on Industry Applications. Vol.51, No 4, July/August 2015, pp. 2990-2999.

[13] C.Hancock and J.R. Hendershot.”Electronically commutated reluctance motor”. US Patent 5015903, 1991

[14] T.Burress, C. Ayers. “Development and experimental characterization of a multiple isolated flux path reluctance machine”. 2012 IEEE Energy Conversion Congress and Exposition (ECCE), pp 899 – 905.

[15] M. Ruba, I. A. Viorel, L. Szabó. “Modular stator switched reluctance motor for fault tolerant drive Systems”. IET Electr. Power Appl., 2013, Vol. 7, Iss. 3, pp. 159–169..

[16] S. R. Mousavi-Aghdam, M. Reza Feyzi, N. Bianchi, M. Morandin, "Design and analysis of a novel high-torque stator-segmented SRM". IEEE Transactions on Industrial Electronics, Vol. 63, pp. 1458-1466, 2016.

[17] M. Abbasian, M. Moallem, B.Fahimi. “Double-Stator Switched Reluctance Machines (DSSRM): Fundamentals and Magnetic Force Analysis”. IEEE Transactions on Energy Conversion, Vol. 25, No. 3, September 2010, pp. 589-597

[18] Y. Yang, N. Schofield, A. Emadi. “Double-rotor switched reluctance machine design, simulations and validations”. IET Electrical System in Transportation. Vol 6, issue 2, 2016, pp. 117-125.

[19] L. E. Unnewehr and W.H. Koch. “An Axial Air—Gap reluctance Motor for Variable Speed Applications,” Jan./Feb. 1974, IEEE Transactions on Power Apparatus and Systems.

[20] H. Arihara and K. Akatsu.”Characteristics of axial type switched reluctance motor”. IEEE Energy Conversion Congress and Exposition 2011, pp 3582-3589.

[21] A. Labak, N.C. Kar. “Designing and prototyping a novel five-phase pancake-shaped axial flux SRM for electric vehicle application through dynamic FEA incorporating flux-tube modeling”. IEEE Transactions on Industry Applications, Vol. 49, No 3, May/June 2013.

[22] R. Madhavan and B.G. Fernandes. “A novel axial flux segmented SRM for electric vehicle application”. XIX ICEM 2010, Roma, pp. 1-6.

[23] H.J. Potgieter, F.M. Márquez-Fernández, A.G.Fraser, M.D.McCulloch. “Design optimisation methodology of a high-speed switched reluctance motor for automotive traction applications”. 8th IET International Conference on Power Electronics, Machines and Drives. Glasgow Scotland, UK, 2016, pp. 1-6.

[24] P. Andrada, E. Martínez, B. Blanqué, M. Torrent, J.I. Perat, J.A. Sánchez. “New axial-flux switched reluctance motor for E-scooter”. ESARS ITEC Toulouse(France), 2-4 November 2016.

[25] P. Andrada, E. Martínez, M.Torrent, B.Blanqué, J.I. Perat. “Novel in-wheel axial-flux segmented switched reluctance motor” EPE 2017 Warsaw (Poland), pp 1-8.

[26] Vukosavic, Stefanovic. "SRM inverter topologies: a comparative evaluation".IEEE Transactions on Industrial Applications. Vol. 27, Nº 6, November-December 1991, pp 1034-1047.

[27] A.C. Clothier and B.C. Mecrow. “The use of three phase bridge inverters with switched reluctance drives”. Eighth International Conference on Electrical Machines and Drives, 1997, pp. 351-355.

[28] T. Celik. “Segmental rotor switched reluctance drives”. Phd Thesis. University of Newcastle upon Tyne. School of Electrical, Electronic and Computer Engineering. August 2011.

[29] A.Krings, M.Cossale, A.Tenconi, J.Soulard, A.Cavagninio, A.Boglietti. “Magnetc materials udsed in electrical machines”. IEEE Industry Apllications MagazinVl 23,No 6, November/December 2017, pp. 21-28

[30] Q.Yu, B.Bilgin, A.Emadi."Design considerations of switched reluctance machines with high power density". 2016 IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1 – 5.

[31] B.Burkhart, A.Klein-Hessling, I.Ralev, C.P.Weiss, R. W.De Doncker. "Technology, Research and Applications of Switched Reluctance Drives". CPSS Transactions on Power Electronics and Applications, Vol 2, No 1, March 2017, pp. 12-26.

[32] P. Andrada, M. Torrent, F. Martínez. "Introducing reluctance motors in electric machines and drives courses: a new approach". EPE 2017 Warsaw (Poland), 2017.

Pere Andrada was born in Barcelona (Spain) in 1957. He received the M.Sc. and the PhD. degrees in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1980 and 1990 respectively. In 1980 he joined the Department of Electrical Engineering, Universitat Politècnica de Catalunya UPC, where he is currently Associate Professor in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drive Group (GAECE). His teaching activities and research interests include design, modelling and control of electrical machines and drives.

Mark J. Dougan was born in Watford, England in 1968. He received his B.Sc. and Ph.D. in Metallurgy from the University of Manchester in 1991 and 1995 respectively. He worked as a Research Assistant in the Thermal Spray Centre in the University of Barcelona, and in the Department of Metallurgy in the University of Leeds before joining AMES, SA in Barcelona in 1999. He is currently Chief Metallurgist in the AMES PM Tech Centre, working on material and process development, failure analysis, and with special responsibility for soft magnetic materials.

Aritz Egea received the degree in electrical engineering from the University of Mondragon, Mondragon, Spain, in 2009 and the Ph.D. degree in electrical engineering in 2012. Currently he is an Associated Professor in the Faculty of Engineering, University of Mondragon. His current research interests include electrical machine design and control and electromagnetic actuators.

Francisco J. Márquez-Fernández was born in Huelva (Spain) in 1982. In 2006 he graduated as a M.Sc. on Industrial Engineering with a major in Industrial Electronics from the University of Seville (Spain). He received his Ph.D. in Electrical Engineering in 2014 Lund University in Sweden. Between 2014 and 2016 he was appointed as Post-doctoral Research Assistant at the Energy and Power Group, University of Oxford, UK. Since 2016 he is a Post-doctoral Researcher at the Industrial Electrical Engineering Group, Lund University, and the Swedish Electromobility Centre. His research interests are design and control of new topologies of electrical machines and power electronic drives, applied to either renewable energy systems or electric vehicles, electrical machine characterisation methods, energy management in EVs and HEVs and their interaction with the power grid.

Loránd Szabó was born in Oradea, Romania, in 1960. He received the B.Sc. and Ph.D. degree from Technical University of Cluj-Napoca (Romania) in electrical engineering in 1985 and 1995, respectively. He joined in 1990 the Technical University of Cluj-Napoca (Romania) as a research & design engineer. Since 1999 he is with the Department of Electrical Machines and Drives, where he was a lecturer, associate professor, and by now is full professor. He is also director of Centre of Applied Researches in Electrical Engineering and Sustainable Development (CAREESD) in the frame of the same university. Prof. Szabó's current research interests include linear electrical machines, variable reluctance machines, fault tolerant designs, fault detection and condition monitoring of electrical machines, etc. He published more than 260 papers. He received the 2015 Premium Award for Best Paper in IET Electric Power Applications. He is member of IEEE since 2005, and in 2017 he was elevated to Senior member.