A Novel Concept of Short-Flux Path Switched Reluctance Motor for Electrical Vehicles

Milan DIKO[1], Pavol RAFAJDUS[1], Pavol MAKYS[1], Peter DUBRAVKA[1], Lorand SZABO[2], Mircea RUBA[2]

[1]Department of Power Electrical Systems, Faculty of Electrical Engineering, University of Zilina, 010 26 Zilina, Slovakia
[2]Department of Electrical Machines and Drives, Faculty of Electrical Engineering, Technical University of Cluj-Napoca, 400 020 Cluj-Napoca, Romania

milan.diko@fel.uniza.sk, pavol.rafajdus@fel.uniza.sk, Lorand.Szabo@mae.utcluj.ro

DOI: 10.15598/aeee.v13i3.1309

Abstract. *This paper deals with the design of a novel Switched Reluctance Motor (SRM) with short flux path for electrical vehicles. Design consists of the segmented water cooled stator with the toroidal winding and the rotor with salient poles also in a form of segments. The SRM dimensions have been calculated on the base of input requirements. The static and dynamic parameters of SRM are obtained from simulation models based on Finite element method and torque, power versus speed characteristics are presented.*

Keywords

Electrical vehicles, segmented design, short flux path, switched reluctance motor, traction characteristics.

1. Introduction

At the present time, the discussion about the electrical vehicles (EVs) development and improvement is very extensive. One of the main challenges to overcome is the price of this car. The EV consists of three basic parts: mechanical parts (similar with conventional car, also in the price range), fuel parts (in which the battery pack is the most expensive component of the car) and electrical equipment including electrical drive. The price of the drive depends on the electric motor used and its frequency converter and its control scheme.

As it is known, DC, AC and special electrical drives are used in EVs. Traditionally DC series motors were used because of their mechanical characteristics. These characteristics are suitable from the point of view traction applications requirements. The development of power electronics caused the replacement of series DC machines by separately excited ones, whose field and armature windings are fed from two independent DC controlled sources and the mechanical characteristic can be adapted to traction ones [1]. This type of electrical drive is used in the first Slovak EV [2].

Nowadays, the best electrical drive solution seems to be PMSM because of very high power density to volume ratio. Still, the price of PMs and their limited operating temperature are the main disadvantages of this drive [3]. In many papers, Switched Reluctance Motor is mentioned as a promising drive alternative for EVs [4], [5], [6], [7]. SRM drive is becoming a strong competitor mainly to the conventional drives with IM. SRM has simpler construction, lower production costs, higher robustness and lower maintenance requirements as the IM drives. The SRM can be operated only from the frequency converter and it can operate in wider speed range than IM. The control of the SRM is also simpler as the vector control used for IM drives.

The profile of the SRM torque/speed characteristic looks similar to traction characteristic. This is an important reason for the use of SRM over IM drives. On the other hand, the drawbacks of SRM are its high torque ripple and the need for a rotor position sensor. As mentioned, the SRM construction is very simple. Stator and rotor have salient poles and only stator carries winding coils, which are connected to create a phase of the motor. The magnetic flux is provided by phase current to develop a reluctance torque [8], [9], [10], [11]. The cross-section of the proposed novel three-phase 12/8 SRM design is shown in the Fig. 1.

The aim of this paper is to point out the performance characteristics of this novel SRM design. The

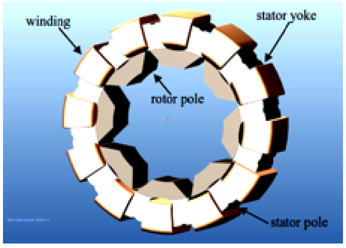

Fig. 1: An illustrative figure of the 12/8 three phase novel SRM design.

mathematical SRM model is described and solved to simulate different operation states to obtain output torque and output power/speed characteristics, which are compared and discussed. The input parameters are: rated power 50 kW, rated speed 5000 rpm, DC voltage 300 V, rated current 250 A and maximum current 400 A.

On the base of this analysis and the suitability of the SRM for EVs a prototype will be manufactured to replace existing DC drive in first Slovak EV.

2. Design Procedure

2.1. Motor Dimensions

Design procedure of SRM is made with the required outer geometric dimensions of the existed DC motor. Maximal outer stator diameter d_s and stack length l_{Fe}, were chosen: $d_s = 250$ mm and $l_{Fe} = 200$ mm, for voltage level of 300 V. The number of stator and rotor poles is given as $N_s/N_r = 12/8$, the number of phases is $m = 3$. This topology was chosen due to lower torque ripple and motor ability to start up from every rotor position. A novel concept of SRM consists of segmented stator with concentrated windings and shorted magnetic flux paths. Dimensions of the motor are calculated on the known analytical equations used during common SRM design procedure. It is described in [3], [11] and [16].

2.2. Winding Coil Design

The calculation of the turns number N_p can be made by assuming that at the specified speed the conduction angle of power transistors is equal to the stroke angle ε, which is defined as:

$$\varepsilon = \frac{2\pi}{mN_r}. \tag{1}$$

If there is no current - chopping the peak flux linkage per phase is given by:

$$\psi_{peak} = \frac{V\varepsilon}{\omega}, \tag{2}$$

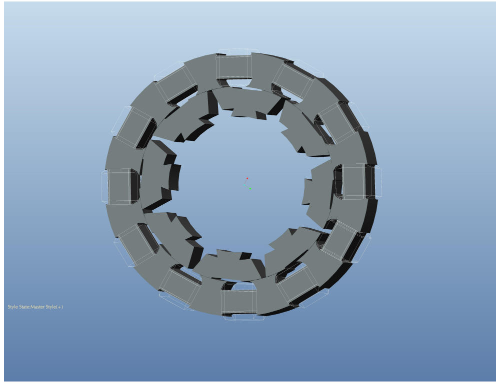

Fig. 2: 12/8 three phase novel SRM design for use in EV.

where ω is angular velocity and V is DC supply voltage. At rated speed ψ_{peak} occurs well before the aligned position, typically when the overlap between the stator and rotor poles is about 2/3 of the stator pole arc. At this moment, it can be assumed that the ampere-turns are sufficient to bring the stator pole to the flux density B_s, then:

$$\psi_{peak} = t_s l_{Fe} B_s n_c N_p. \tag{3}$$

Substituting of Eq. (2) to Eq. (3),

$$N_p = \frac{V\varepsilon}{t_s l_{Fe} B_s n_c \omega}, \tag{4}$$

where n_c is number of coils per phase, l_{Fe} is stack length and t_s is a thickness of stator pole. The flux density of stator pole can be assumed to be 1.6 T. The cross section of coil wire depends on normalized conductor wires available. The calculation is based on constant flux density (1.6 T).

2.3. Static Parameters Calculation

On the base of this design the static characteristics as phase inductance, magnetic flux linkage and torque versus phase current and rotor position have been calculated by means of FEM. The analytical approach is used only for geometrical dimension calculations. The results are in the Fig. 3, Fig. 4 and Fig. 5, respectively.

2.4. Dynamic Analysis of SRM

By using a mathematical model in the dynamic analysis we can calculate phase current, speed, voltage and dynamic torque of the SRM. The electromagnetic torque of SRM can be calculated from:

$$T_e = \frac{\partial \int_0^i \Psi di}{\partial \Theta}. \tag{5}$$

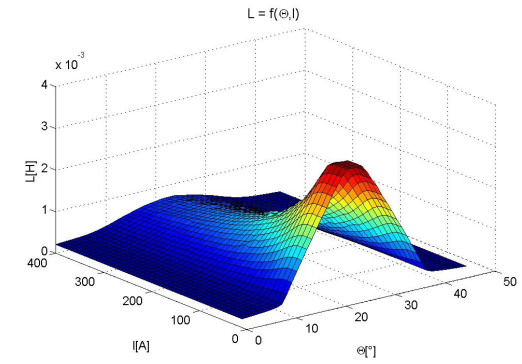

Fig. 3: FEM analysis of inductance for various rotor position and current.

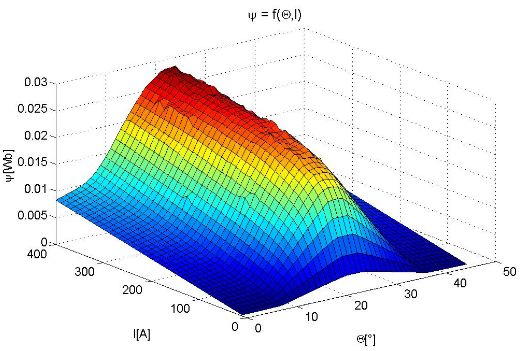

Fig. 4: FEM analysis of flux linkage for various rotor position and current.

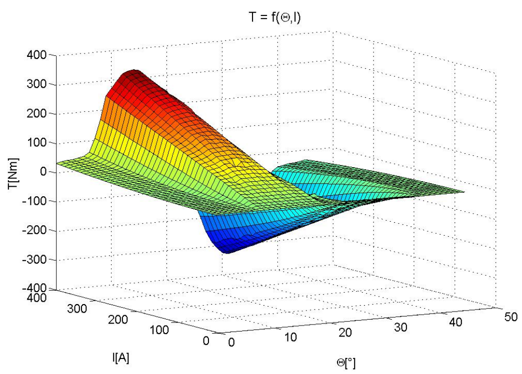

Fig. 5: FEM analysis of torque for various rotor position and current.

The voltage equation of one SRM phase is given as:

$$\nu = Ri + \frac{d\psi}{dt}, \tag{6}$$

where R is phase resistance, i is phase current and ψ is flux linkage. The flux linkage depends on both parameters: phase current and rotor position, $\psi = f(i, \Theta)$. Then:

$$\frac{d\psi}{dt} = \frac{\partial\psi}{\partial i} \cdot \frac{di}{dt} + \frac{\partial\psi}{\partial\Theta} \cdot \frac{d\Theta}{dt}. \tag{7}$$

The phase current can be calculated by combining equations Eq. (6) and Eq. (7) as:

$$\frac{di}{dt} = \frac{\nu - \left(R + \frac{dL(i,\Theta)}{d\Theta}\omega\right) i}{L(i,\Theta)}. \tag{8}$$

The real angular speed is calculated from equation:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{j=1}^{m} T_j(\Theta, i) - T_{load}\right), \tag{9}$$

where J is the moment of inertia and T_{load} is the load torque. The SRM is controlled on the base of rotor position Θ, calculated as follows:

$$\Theta = \int \omega dt. \tag{10}$$

On the base of this mathematical model a simulation model has been created to solve transients for different speeds, loads, switch ON, switch OFF angles to find the optimal dynamic operation of SRM. The dynamic simulation of currents and torque had been done for demanded speed 5000 rpm with the maximum current level of 400 A and 250 A for rated power of 50 kW. The current waveforms for all three phases for speed of 5000 rpm are shown in the Fig. 6 and Fig. 8.

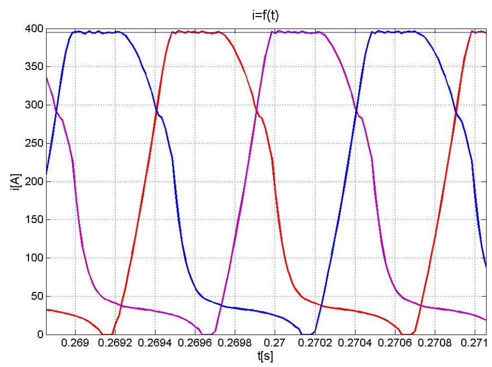

Fig. 6: Phase currents for $n = 5000$ rpm, $I_{max} = 400$ A.

The total torque given by all three phase and the torque ripple detail is in the Fig. 7.

On this base of all required parameters, the output characteristics torque and power versus speed have been obtained from dynamic simulation. These characteristics are shown in the Fig. 10 and Fig. 11 for current up to 400 A.

The losses calculation can be carried out in accordance with [11] and [12]. As it is known, two dominant parts of losses are in electrical machines: winding losses and core losses. In this case both of them have been analyzed and calculated.

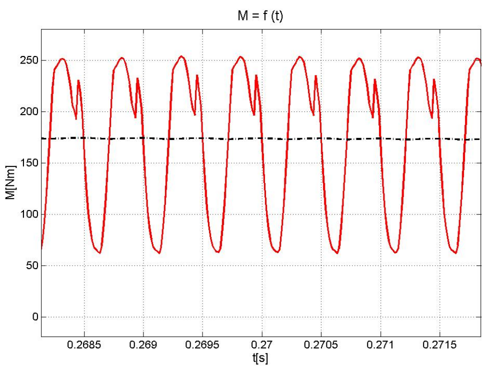

Fig. 7: Total torque ripple detail for n = 5000 rpm, I_{max} = 400 A.

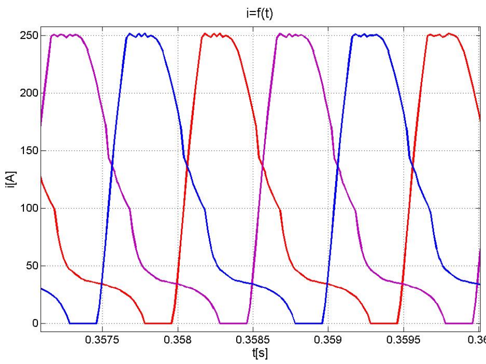

Fig. 8: Phase currents for n = 5000 rpm, I_{max} = 250 A.

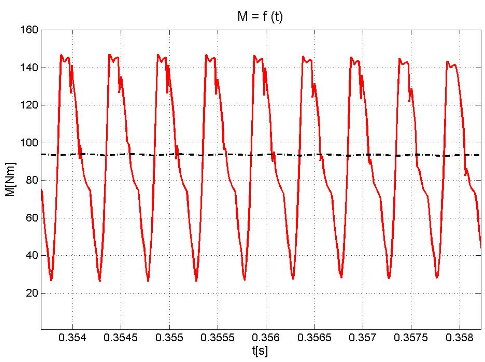

Fig. 9: Total torque ripple detail for n = 5000 rpm, I_{max} = 250 A.

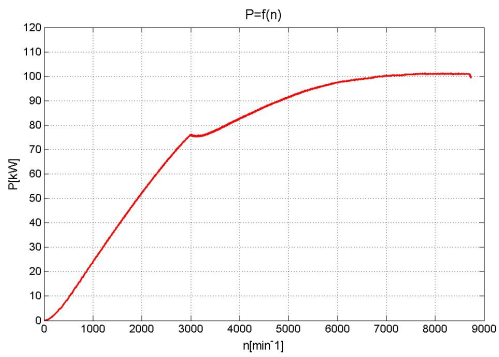

Fig. 10: Output power versus speed for working range of proposed novel SRM design.

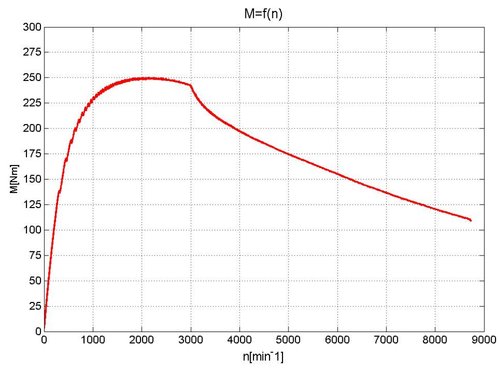

Fig. 11: Total torque versus speed for working range of proposed novel SRM design.

To calculate the efficiency, the input power is needed. It could be given from known equation for instantaneous power. On this base, the efficiency of designed SRM for various speeds from 1000 to 5000 rpm has been calculated. The results are from 89 % to 94 %, what are acceptable values for SRM.

This SRM design described above has been calculated on the base of analytical calculation and FEM without its optimization. The prototype model of this novel SRM design with segmented stator is shown in the Fig. 10 and Fig. 11. Table 1 shows the total mass of the active parts of a novel SRM design. In the future, the thermal analysis will be carried out and some recommendations will be given for manufacturing process.

Tab. 1: Total mass of the active parts of a (the) novel SRM design.

Stator mass	21.5 kg
Rotor mass	11.8 kg
Winding mass	6.9 kg
Total mass	40.2 kg

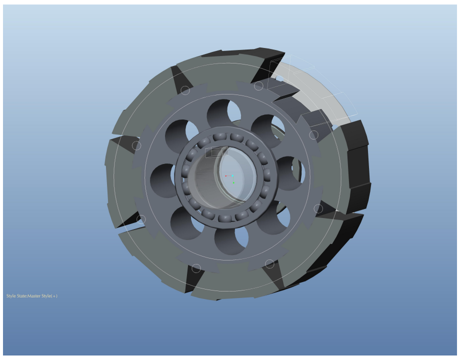

Fig. 12: Rotor assembly of novel SRM design.

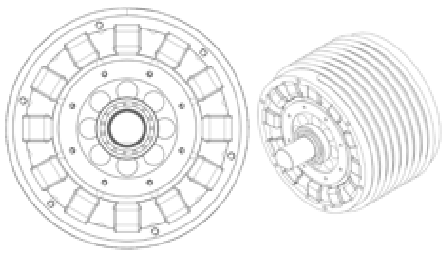

Fig. 13: Top assembly of novel SRM design with the spiral for water cooling.

3. Conclusion

The paper deals with the SRM novel design and static and dynamic parameters investigation from the point of view of its application and using in electrical cars. In the future, the optimization of this concept will be carried out to minimize materials and losses and to improve the efficiency of this motor. On this base a prototype of SRM will be manufactured and used in the real car.

Acknowledgment

This work was supported by the Slovak Research and Development Agency under the Contract No. SK-RO-0028-12 and by Slovak Scientific Grant Agency VEGA No. 1/0940/13. This paper is (was) supported also by the following project: University Science Park of the University of Zilina (ITMS: 26220220184) supported by the Research&Development Operational Program funded by the European Regional Development Fund.

References

[1] BOLDEA, I. Control issues in adjustable speed drives. *IEEE Industrial Electronics Magazine.* 2008, vol. 2, iss. 3, pp. 32–50. ISSN 1932-4529. DOI: 10.1109/MIE.2008.928605.

[2] JUHA PYRHONEN, T. J. *Design of Rotating Electrical Machines.* Chichester: John Wiley, 2009. ISBN 978-047-0740-088.

[3] MILLER, T. *Electronic control of switched reluctance machines.* Boston: Newnes, 2001. ISBN 07-506-5073-7.

[4] GAO, J., H. SUN, L. HE, Y. DONG and Y. ZHENG. Optimization design of Switched Reluctance Motor based on Particle Swarm Optimization. In: *2011 International Conference on Electrical Machines and Systems.* Beijing: IEEE, 2011, pp. 1–5. ISBN 978-1-4577-1044-5. DOI: 10.1109/ICEMS.2011.6073525.

[5] XUE, X. D., K. W. E. CHENG, T. W. NG and N. C. CHEUNG. Multi-Objective Optimization Design of In-Wheel Switched Reluctance Motors in Electric Vehicles. *IEEE Transactions on Industrial Electronics.* 2010, vol. 57, iss. 9, pp. 2980–2987. ISSN 0278-0046. DOI: 10.1109/TIE.2010.2051390.

[6] RAHMAN, K. M., B. FAHIMI, G. SURESH, A. V. RAJARATHNAM and M. EHSANI. Advantages of switched reluctance motor applications to EV and HEV: design and control issues. *IEEE Transactions on Industry Applications.* 2000, vol. 36, iss. 1, pp. 111–121. ISSN 0093-9994. DOI: 10.1109/28.821805.

[7] KAMALAKANNAN, C., V. KAMARAJ, S. PARAMASIVAM and S. R. PARANJOTHI. Switched reluctance machine in automotive applications - A technology status review. In: *2011 1st International Conference on Electrical Energy Systems.* Newport Beach: IEEE, 2011, pp. 187–197. ISBN 978-1-4244-9732-4. DOI: 10.1109/ICEES.2011.5725326.

[8] KRISHNAMURTHY, M., C. S. EDRINGTON, A. EMADI, P. ASADI, M. EHSANI and B. FAHIMI. Making the case for applications of switched reluctance motor technology in automotive products. *IEEE Transactions on Power Electronics.* 2006, vol. 21, iss. 3, pp. 659–675. ISSN 0885-8993. DOI: 10.1109/TPEL.2006.872371.

[9] NUCA, I., P. TODOS and V. ESANU. Urban electric vehicles traction: Achievements and trends. In: *2012 International Conference and Exposition on Electrical and Power Engineering.* Iasi: IEEE, 2012, pp. 76–81. ISBN 978-1-4673-1172-4. DOI: 10.1109/ICEPE.2012.6463948.

[10] KRISHNAN, R. *Switched reluctance motor drives: modeling, simulation, analysis, design, and applications.* Boca Raton: CRC Press, 2001. ISBN 08-493-0838-0.

[11] RAFAJDUS, P., V. HRABOVCOVA and P. HUDAK. Investigation of Losses and Efficiency in Switched Reluctance Motor. In: *12th International Power Electronics and Motion Control Conference.* Portoroz: IEEE, 2006, pp. 296–301. ISBN 1-4244-0121-6. DOI: 10.1109/EPEPEMC.2006.4778416.

[12] TAKENO, M., A. CHIBA, N. HOSHI, S. OGASAWARA, M. TAKEMOTO and M. A. RAHMAN. Test Results and Torque Improvement of the 50-kW Switched Reluctance Motor Designed for Hybrid Electric Vehicles. *IEEE*

Transactions on Industry Applications. 2012, vol. 48, iss. 4, pp. 1327–1334. ISSN 0093-9994. DOI: 110.1109/TIA.2012.2199952.

[13] SKALA, B., J. HRUSAK, D. MAYER and M. STORK. On Strongly Nonlinear Phenomena in Electrical Machines, New aspect of systems. In: *Proccedings of the 2008 WSEAS International Conference. Mathematics and Computers in Science and Engineering (No. 12)*. Heraklion: WSEAS Press, 2008, pp. 120–125. ISBN 978-960-6766-83-1.

[14] SZABO, L. and M. RUBA. Segmental Stator Switched Reluctance Machine for Safety-Critical Applications. *IEEE Transactions on Industry Applications*. 2012, vol. 48, iss. 6, pp. 2223–2229. ISSN 0093-9994. DOI: 10.1109/TIA.2012.2226857.

[15] KANUCH, J. and Z. FERKOVA. Design and simulation of disk stepper motor with permanent magnets. *Archives of Electrical Engineering*. 2013, vol. 62, iss. 2, pp. 281–288. ISSN 0004-0746. DOI: 10.2478/aee-2013-0022.

[16] RAFAJDUS, P. *Switched Reluctance Motor*. Zilina: EDIS, 2010. ISBN 978-80-554-0836-1.

About Authors

Milan DIKO was born in Martin, Slovakia. He received his M.Sc. from University of Zilina in 2014. His research interests include design of special electrical machines and FEM analysis.

Pavol RAFAJDUS was born in Trnava, Slovakia, in 1971. He received the M.Sc. degree in electrical engineering and the Ph.D. from University of Zilina, Slovakia, in 1995 and 2002, respectively. At present he is an associate professor at the Faculty of Electrical Engineering, University of Zilina. His research is focused on the electrical machines, mainly switched reluctance motors and other electrical machine properties.

Pavol MAKYS was born in 1980, in Banovce nad Bebravou, Slovakia. He graduated from University of Zilina. He obtained his Ph.D. degree in power electronic and electrical drives at University of Zilina in 2006. Actually he works as a teacher and researcher at University of Zilina where his activities are oriented on specific domains of electrical drives like sensorless control of AC drives, different types of control of AC/DC drives by using of digital signal processors.

Peter DUBRAVKA was born in Povazska Bystrica, Slovakia in 1988. He received M.Sc. degree, in field of Electric Drives, at University of Zilina, Slovakia in 2012. He is currently a Ph.D. student at the same university. His research interests include electrical machines and drives, control of variable electric drives, fault diagnosis and fault tolerant control. Currently, he is mainly focused on the analysis and development of fault tolerant control techniques for switched reluctance motor drives.

Lorand SZABO was born in Oradea, Romania, in 1960. He received the B.Sc. and Ph.D. degree from Technical University of Cluj, Romania in electrical engineering in 1985 and 1995, respectively. Since October 1999 he is with the Department of Electrical Machines and Drives of the same university, where by now 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, etc.

Mircea RUBA was born in Satu Mare, Romania. He received the M.Sc. and Ph.D. degree in electrical engineering from the Technical University of Cluj-Napoca, in 2007 and 2010. Now, he is an assistant with the Department of Electrical Machines and Drives at the same university. His research is focused on the automotive electrical propulsion units with SRMs and three phase ac machines.