Design and Comparison of Different Switched Reluctance Machines Topologies for Automotive Applications

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***Abstract* — The present paper approaches the comparative design and analysis of 5 SRM topologies for an EPAS application. Different number of phases and different combination of stator and rotor pole number will be considered, keeping the same main dimensions (outer and inner stator diameter, airgap length, stack length, stator pole height, stator yoke width, rotor pole height) and the same winding per phase (number of turns and wire diameter).**

A preliminary sizing of the machine will be carried on, giving the initial geometric data. The key dimensions will be calculated and the winding will be dimensioned. A numerical-based performances analysis will be performed for each case.

***Index Terms* — switched reluctance machine, electrical power assisted steering systems, fault tolerance, conventional and optimization design, numerical field analysis**

I. INTRODUCTION

The automotive industry has in the last years a very high demand for electric, electronic and software components. The demand on new and more complex functions suggests that this development will continue in the foreseeable future. At the same time, the legislative requirements on exhausts and fuel efficiency are getting higher. This, in combination with the development towards electric and hybrid electric drive-trains, demands that many of the auxiliary systems, which traditionally have been driven directly by the combustion engine, need to be replaced with electrically powered systems.

So that, the general worldwide trend in the automotive industry is to increase electrical power, while at the same time, the requirements for reduced fuel consumption and emissions are becoming more restrictive. The customer's demand for safety, comfort, and quality of driving is another reason for explosive growth in electrical power generation capability of automotive electrical systems.

The field of modern and high performance automotive applications covers a broad range including [1]: steering (active, power, power assisted) systems, electromechanical brakes (including brake-by-wire), clutch and shift-by-wire actuators, suspension, damping and stabilization actuators, heating, ventilation, air conditioning, starter-generator (integrated or belt-driven).

The reliability, fault-tolerance and costs of these drive systems are the most important aspects, which should be considered during the design and development process. Most of the automotive applications require high performance motors with a high torque/volume (mass) ratio, low inertia, high dynamics, good field-weakening and high temperature capability. Another important issue is the acoustic behavior (vibrations and airborne noise) of the electric drive system, given by the interaction motor-controller. The analysis of the specification schedule reveals also some other interesting motor challenges: given overall dimension, low voltage feeding supply, wide range of ambient temperature, low motor torque ripple.

Considering the development and the prototype presentations of different electric actuation technologies over the last decades, several electrical machines types were applied: the direct current (DC) machine, the induction machine (IM) and the permanent magnet synchronous machines (PMSM). Both excitation type – trapezoidal or sinusoidal currents - are used depending on application, the selection of the motor structure and topology being influenced by the gearing and mounting in the application. The high torque/volume ratio, high dynamics, high speed due to field-weakening capability, simple motor topology and the low costs are some of the advantages of PMSM. The permanent magnets are susceptible to high temperature complications — a serious consideration in the automotive industry where ambient temperatures are often specified as -40 to 125°C. The PMSM motor also raises concerns about failure modes. For example, the electromechanical brake actuators are typically required to self-release to a very low applied force under fault conditions []. A PMSM winding short circuit would delay or impede such a self-release.

But, in motors of less than 1.5kW rating, the presence of permanent magnets can significantly increase the motor's power density. When space is tight, the energy density of permanent magnets can easily exceed that of a copper winding. This suggests that the PMSM motor should enjoy an advantage around this power level.

Switched reluctance machines (SRMs) are not yet commonly used but have undeniable advantages for automotive applications when compared to more classical machine types. SRMs have simple topology and they are easy to construct. The absence of permanent magnets gives an excellent high-temperature performance and high reliability. Also, SR machines can survive a single-phase failure and keep on moving, which adds a highly desirable level of redundancy to the application. Whether it is possible to benefit from these qualities depends on how well the SR disadvantages can be addressed or at least sufficiently mitigated. This study is a first step in the evaluation of the SRM potential as automotive electric actuator for an electric power assisted steering (EPAS) system. SRM performances are strongly dependent on its control, so that the development of an efficient, reliable, fault tolerant system implies both optimal design of the electrical machine and optimal control strategy development.

Two design methods can be distinguished for electrical machines: conventional and optimization design, respectively.

The conventional design procedure of an electric machine includes the following topics: analysis of the specifications, selection of the topology and of the active and passive materials, dimensioning of the geometry, parameter and performance calculation, choice of the manufacturing technologies and costs prediction.

An advanced optimization design process will consider simultaneously the topology and materials optimization and then, if necessary, the shape and sizing optimization. As the design process involves a high number of variables, thus an optimization program will be necessary to reduce the design cycle time and to minimize the number of design iterations. However, the optimization procedure needs powerful optimization algorithms and high computational capacity.

So that, most of the designers are using both conventional and optimization design procedures in order to obtain the better solution for a given application.

The selection of the proper topology for a specific application is the most difficult problem to be solved during the design process. As the implementation of an optimization design procedure is very difficult for topology selection, the experience-based procedure represents even today the most used method.

The present paper approaches the comparative design and analysis of 5 SRM topologies for an EPAS application. Different number of phases and different combination of stator and rotor pole number will be considered, keeping the same main dimensions (outer and inner stator diameter, airgap length, stack length, stator pole height, stator yoke width, rotor pole height) and the same winding per phase (number of turns and wire diameter).

A preliminary sizing of the machine will be carried on, giving the initial geometric data. The key dimensions will be calculated and the winding will be dimensioned. A numerical-based performances analysis will be performed for each case. The comparison of the results will give the best solution for the SRM topology, suited for further analysis and development of a SRM drive for EPAS applications.

II. ANALYSIS OF ELECTRIC POWER ASSISTED STEERING SYSTEM SPECIFICATIONS

First step of the design procedure is the analysis of the specifications. So, the specification data and the demanded torque-speed curve for the electric motor of a column-type EPAS system as described in literature [2] are presented in Table I and Figure 1.

In addition several constraints must be met. These constraints address limited size, lower weight, low torque ripple content, fault tolerance.

TABLE I. SPECIFICATION DATA FOR THE ELECTRIC MOTOR OF AN EPAS SYSTEM

Peak stall torque (T)	7Nm
Base speed (n_N)	500rpm
Maximal speed (n_{max})	2000rpm
DC-bus voltage (U)	12V
Duty cycle	S3-5%
Ambient temperature	-40...125°

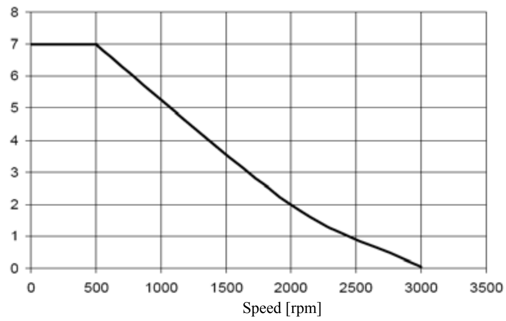

Figure 1. Torque vs. speed curve for an EPAS system.

Following the first constraint, the maximum allowable outer diameter of the machine has to be less than 110mm, and the stack length is constrained to 130-150mm.

Two important aspects to be considered for a low torque ripple high fault tolerant SRM are the number of phases and the proper combination of the number of stator and rotor poles.

Three-phase machines are the most common electrical drives, but, for reducing the torque ripples, a higher number of phases could be considered. Increasing the phase number will also improve the resulting torque and the fault-tolerance of the system. However, a higher number of phases means less space for winding, and a higher level of the current density in the wire.

The relationship between stator and rotor pole numbers (Q_S, respectively Q_R) for regular SRM is:

$$Q_R = Q_S \pm 2 \tag{1}$$

The advantage of a larger Q_R is a smaller stroke angle, and, as a consequence, a lower torque ripples. But the inductance ratio will be lower, and so will be the torque.

The optimal topology for a high torque density, fault tolerant SRM for EPAS applications will be the result of a comparison between five topologies that will be analyzed further: 10/8 five-phase, 8/6 four-phase, 8/10 four-phase, 6/4 three-phase and 6/8 three-phase, as it can be seen in Figure 2.

III. PRE-SIZING OF THE SWITCHED RELUCTANCE MACHINE

SRM design is a multi-disciplinary subject, involving electromagnetic, thermal, mechanical and acoustic design. In the industrial practice, technological and cost aspects are also issues to be taken into account. The motor design problem is to find a set consisting of topology, materials and geometry, following the design constraints of this specific

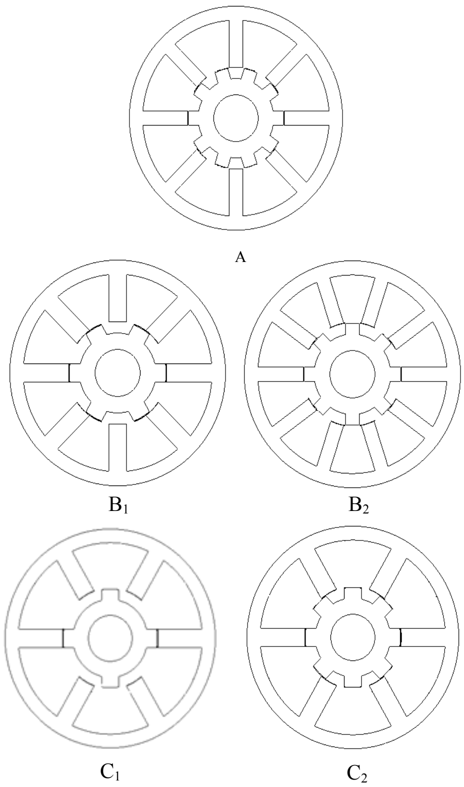

Figure 2. Analyzed SRM topologies

application, as: size, weight, low torque ripple content, fault tolerance.

The preliminary sizing will give the main dimensions of the machine. The main sizing equation is the usual $D_g^2 l_s$ equation, named the output power equation, relating the machine dimensions to the magnetic and electric loading. Thus, the output power for an electrical machine is proportional to the product of specific electric and magnetic loadings, airgap diameter and effective stack length [5]:

$$P_{out} = \eta K_I K_e \frac{Q_R}{Q_S} \frac{\pi^2}{60} n_N A_S B_{g\,max} D_g^2 l_s \tag{2}$$

with the required output power of the machine given by:

$$P_{out} = T \frac{\pi n_N}{30} \tag{3}$$

and η – the machine efficiency, A_S – the stator electrical loading (25000-90000 At/m), B_{gmax} – the maximum value of the airgap flux density (1.2…1.8T as a function of lamination quality), D_g – the machine airgap diameter, K_I – the current waveform factor [4], K_e – emf factor, l_s- effective stack length.

The stator and rotor pole arcs are important variables in the SRM design. Two important aspects to be considered are the self-starting requirement and the shaping of static torque vs. rotor position characteristics [2]. The pole pitch, pole width and yoke height for both stator and rotor are given by [5]:

$$\begin{aligned} \tau_{pi} &= \pi \frac{D_i}{Q_i} \\ b_{pi} &= (0.8...1)\frac{\tau_{pi}}{2},\ i = S, R \\ h_{yi} &= (0.8...1)\frac{b_{pi}}{2} \end{aligned} \tag{4}$$

It is desirable that stator and rotor pole width should be equal or almost equal. The optimum pole widths must be chosen considering the maximization of the aligned phase inductance, increased slot area, high inductance ratio, and mechanical stiffness.

The stator pole geometry has to allow the insertion of the coils after winding them and to provide enough slot area for the stator winding. The number of turns per phase (N_{ph}) results from the emf expression:

$$E = k_e \frac{\pi}{30} \frac{Q_R}{Q_S} N_{ph} n_N B_{max} D_g l_s \tag{5}$$

Considering the maximum allowable outer machine dimensions, the value of the stator outer diameter is 96mm, and the length of the active part of the machine is 100mm. The airgap diameter of the machine will result from (2) as:

$$D_g = \sqrt{P_{out} \frac{60 Q_S}{\eta K_e K_I \pi^2 n_N B_{max} A_s l_s Q_R}} \tag{6}$$

The resulted main dimensions of the topologies which were analyzed are presented in Table II.

TABLE II. MAIN DIMENSIONS OF THE ANALYZED TOPOLOGIES

	5-phase	4-phase		3-phase	
	10/8	8/6	8/10	6/4	6/8
Outer stator diameter	96mm				
Inner stator diameter	44mm				
Stack length	100mm				
Airgap length	0.4mm				
Shaft diameter	20mm				
Stator pole height	20mm				
Rotor pole height	4.6mm				
Stator yoke width	6mm				
Stator pole width	6mm	8mm	6mm	8mm	8mm
Rotor pole width	6mm	8mm	6mm	8mm	8mm

Table III presents the slot area and the slot fill factor for each topology.

TABLE III. SLOT AREA AND SLOT FILL FACTOR

	5-phase	4-phase		3-phase	
	10/8	8/6	8/10	6/4	6/8
Slot area [mm^2]	282.12	342.65	382.65	510.21	510.21
Slot fill factor	0.73	0.60	0.53	0.404	

Performances analysis can be done by analytical approach, numerical computation, usually by the finite-element (FE) method, and/or experimental techniques. Experimentation can be performed only after manufacturing a prototype motor. Therefore, there is considerable advantage and interest in using numerical methods.

IV. NUMERICAL CALCULATION FOR PERFORMANCES ANALYSIS

Using the preliminary sizing results, a model of each proposed topology was developed, and analyzed for different phase current values and different rotor positions, using a FEM-based software. The simulations were done for 500 rpm and 30 current values (from 2 to 60A). For the rated current (48A) the stator poles magnetic field density distribution, the developed electromagnetic torque and the phase flux linkage are depicted in the following pictures.

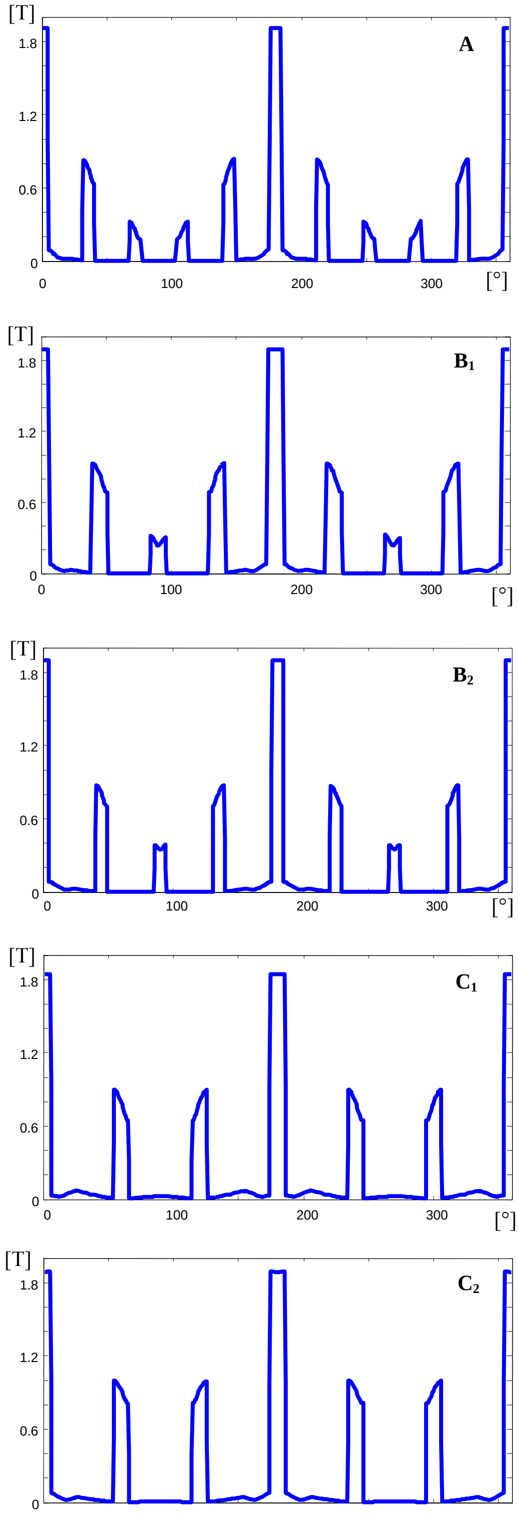

Figure 3. Stator poles magnetic field density distribution.

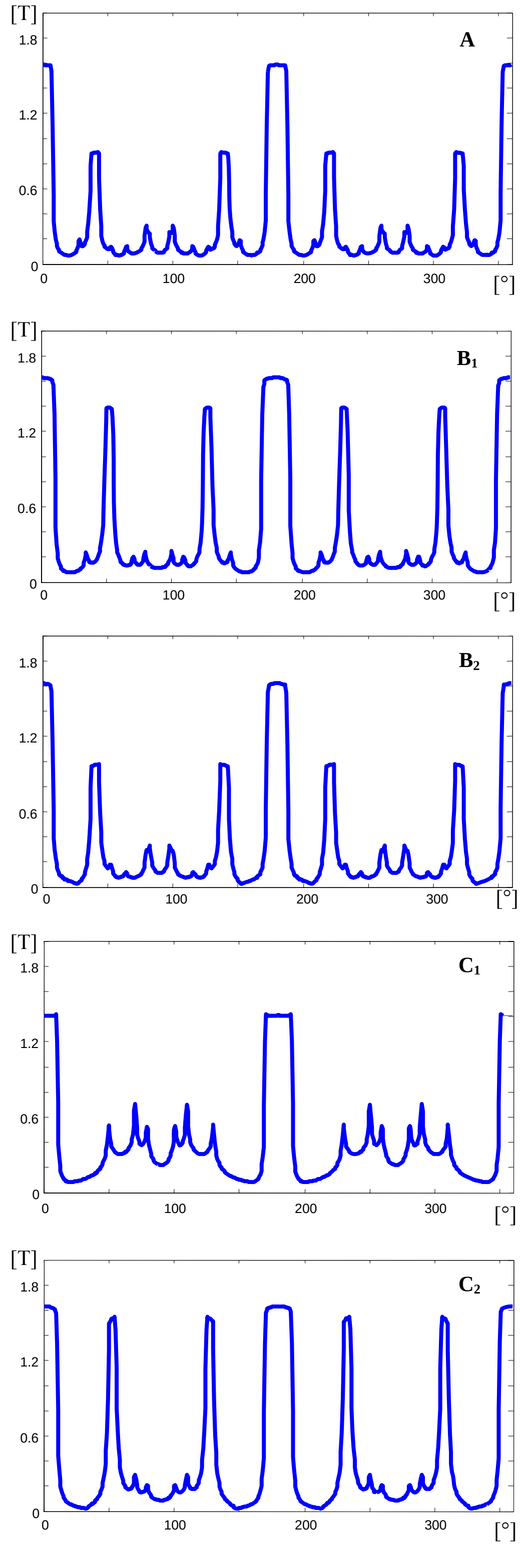

Figure 4. Airgap magnetic field density distribution.

Table IV presents the maximum values of the stator pole and airgap magnetic flux density for the aligned position and for the rated current.

TABLE IV. MAXIMUM VALUES MAGNETIC FLUX DENSITY

	5-phase	**4-phase**		**3-phase**	
	A	B_1	B_2	C_1	C_2
Stator pole [T]	1.91	1.89	1.90	1.84	1.89
Airgap [T}	1.59	1.63	1.62	1.42	1.63

The maximum value and the harmonic content of the magnetic flux density are very important in determining the losses in the core of the machine and, so, the efficiency of the machine. The highest harmonic content corresponds to B_2 and C_2 topologies, so the highest level of the iron losses will corresponds to these topologies too.

The average value and the harmonic content of the airgap magnetic flux density are important in the average and ripple level of the developed electromagnetic torque. The lowest ripple content corresponds to B_2 topology, but the average torque value developed by this topology is lower than those of A and B_1 topologies.

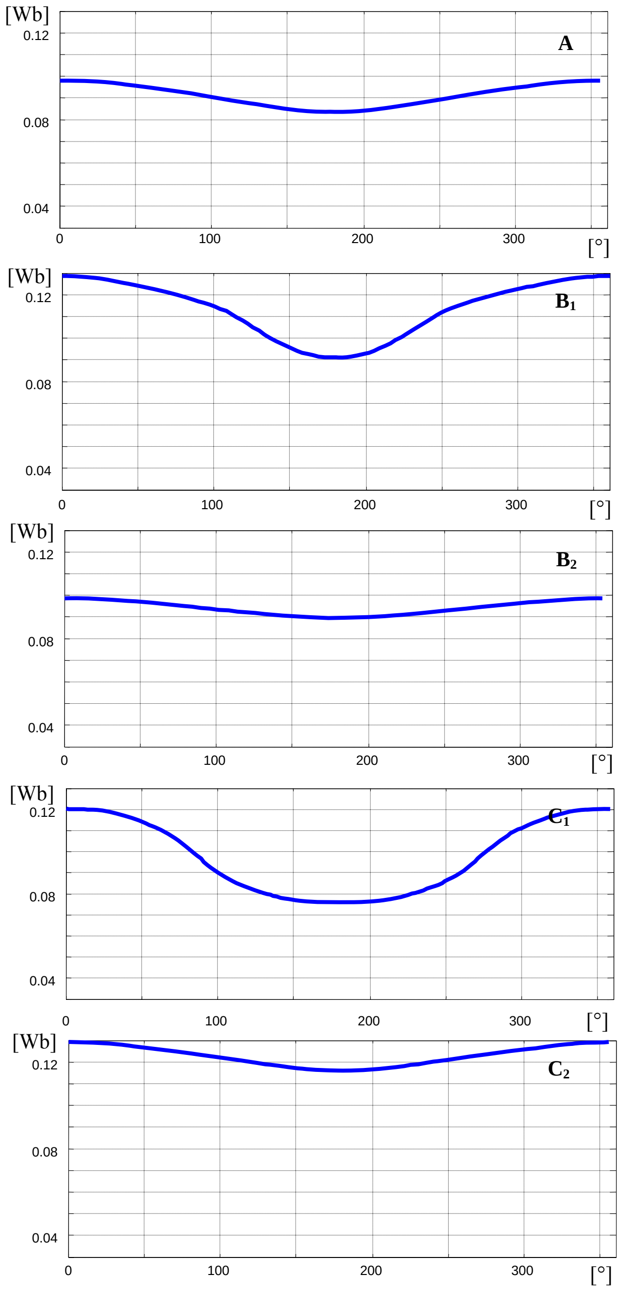

Figure 5. Phase flux linkage vs. rotor position.

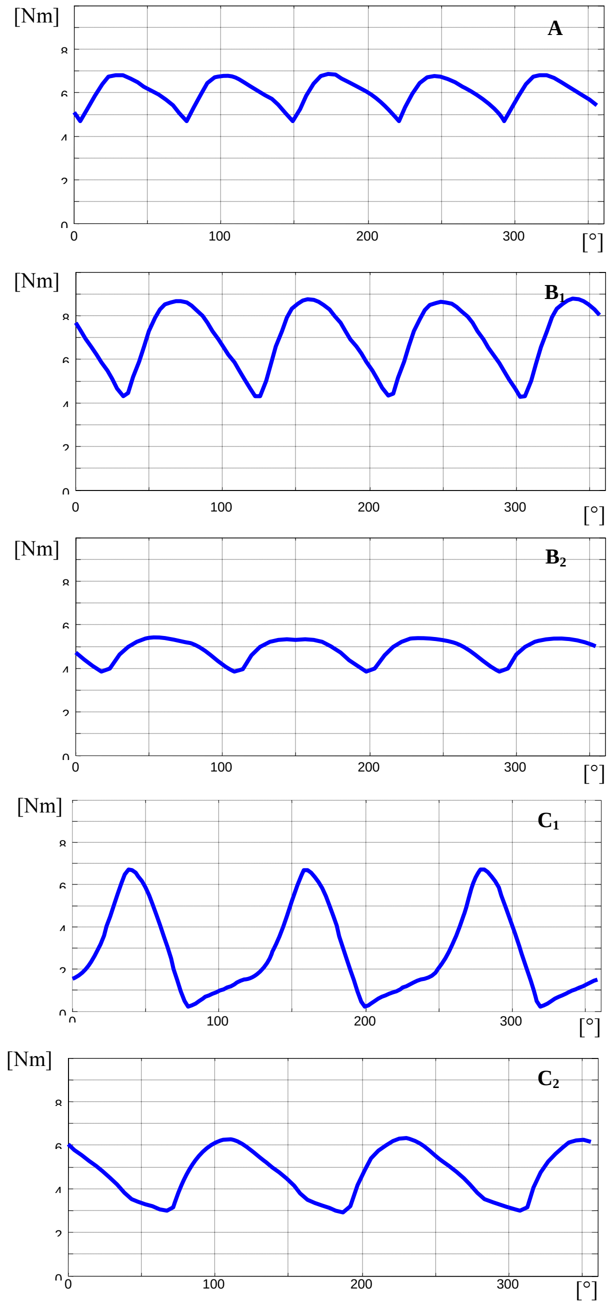

Figure 6. Developed electromagnetic torque vs. rotor position

Another important factor in the development of the electromagnetic torque is the phase inductance. The phase inductance results from the magnetic flux linkage per phase, presented in Figure 5 for each considered topology.

The developed electromagnetic torque vs. rotor position (given in electrical degrees) is depicted in Figure 6, and Table V presents the average value and the ripple given by each analyzed topology.

TABLE V. AVERAGE ANDF RIPPLE VALUES FOR THE CONSIDERED TOPOLOGIES

	5-phase	4-phase		3-phase	
	10/8	8/6	8/10	6/4	6/8
Average torque [Nm]	5.97	6.86	4.77	2.81	4.64
Ripple [Nm]	2.17	4.49	1.57	6.4	3.4

V. CONCLUSIONS AND FURTHER WORK

Analyzing the results of the work, the best solutions for a SRM for an EPAS system seem to be A and B_1 topologies. The main disadvantages of the first one are the high value of the slot fill factor and the higher number of needed converter phase units that will increase the complexity of the control and the overall cost of the drive. The second topology's main disadvantage consists of the higher level of torque ripple. This problem could be though solved using a proper control technique, including a torque ripple strategy.

Next step of the work will approach the development of an accurate model and precisely estimation of the parameters for the successful implementation of the control system.

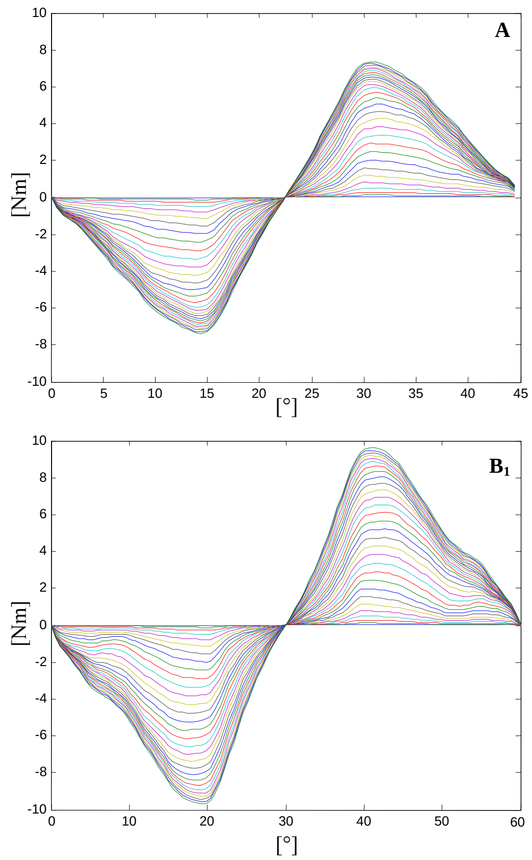

Figure 7. Electromagnetic torque vs. rotor position.

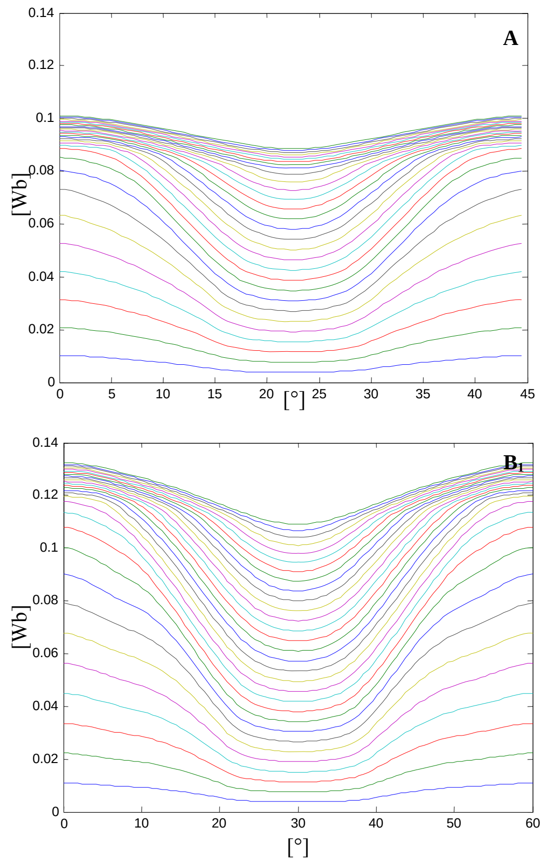

Figure 8. Flux linkage vs. rotor position.

The torque and flux linkage characteristics vs. rotor position for 30 values of the phase current for both A and B1 topologies are presented in the following figures.

These characteristics will be implemented in the Matlab-Simulink environment for further work on the analysis of SRM drive for EPAS systems performances.

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