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# Evaluation of axial SRM for electric vehicle application

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**Abstract: In this paper, a study on an Axial Switched Reluctance Motor (ASRM) is provided and comparisons with an equivalent Radial Switched Reluctance Motor (RSRM) are established. A 3D Finite Element (FE) model is used for the ASRM and only 2D FE model for the radial one in order to reduce the computation time. First, a bibliographic review and descriptions of the two motors are given. Secondly, comparisons between both structures are proposed including flux linkages, developed torques, masses, torque-speed curves and cartography of minimum torque ripples. In order to make the comparisons more reliable, optimized control parameters and full operating range for electric vehicle (EV) power train are taken into account.**

***Index Terms*— Switched reluctance motor, axial flux, finite element, torque-speed curve, torque ripples, EV powertrain.**

## 1. INTRODUCTION

The switched reluctance motor is well known for its many advantages, such as simple

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23 manufacturing, robustness, easy maintenance, good efficiency, operating in extreme  
24 conditions, no need to use magnets and low cost. All these advantages make this structure a  
25 serious and an attractive challenger for the electric vehicles traction. However, this motor  
26 presents two major drawbacks: a high torque ripples and an undesirable acoustic noise due  
27 to the stator vibrations caused by magnetic forces on stator teeth.

28 Depending on the magnetic flux path in the airgap, two structures of SRM can be  
29 considered: the radial SRM and the axial SRM (Fig. 1). The second one could be a solution  
30 to limit the last mentioned drawback. Indeed, for the ASRM, the radial efforts, which are  
31 perpendicular to the rotation axis, are insignificant and vibrations that originate from these  
32 efforts, should be more easily mitigable. Previous studies on ASRM highlighted some  
33 advantages such as: adjustable airgap, suitable for applications where the ratio  
34 length/diameter is low, simple cooling and simple process of lamination [1].

35 In order to choose the appropriate structure for electric traction, comparisons between  
36 axial and radial SRM are essentially presented. Except some works like [2]–[4], the  
37 majority of studies on switched reluctance motor for an electric traction has been made by  
38 considering a radial structure [5]–[13]. Therefore, this work focuses on the axial structure  
39 for an automobile application. Two conversion models, from one structure to another one,  
40 have been developed and the comparisons are then performed by considering specifications  
41 of electric vehicle motorization. Furthermore, the two structures are always independently  
42 studied because of their geometrical differences. This is not the case of this work, where  
43 both are studied at the same time.

44

## 2. AXIAL SRM

45

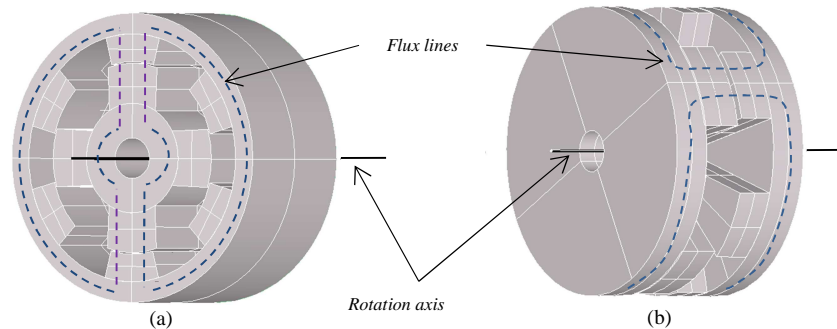
The ASRM is a switched reluctance motor where the magnetic field lines in the airgap

46

are parallel to the rotation axis of the machine (Fig. 1.b). In the RSRM airgap, these lines

47

are perpendicular to the machine axis (Fig. 1.a). There are three main ASRM categories.



48

49

*Fig. 1 SRM structures, (a) radial SRM, (b) axial SRM*

50

### *2.1. ASRM with Single-Stator and Single-Rotor*

51

The first category has a single stator and a single rotor (cf. Fig. 2 a); therefore, it has a

52

single airgap. In this category, the axial magnetic force is unbalanced and important. For

53

this reason, a robust guiding of the rotor is necessary. In [14], a 6/4 and 2.7 kW motor is

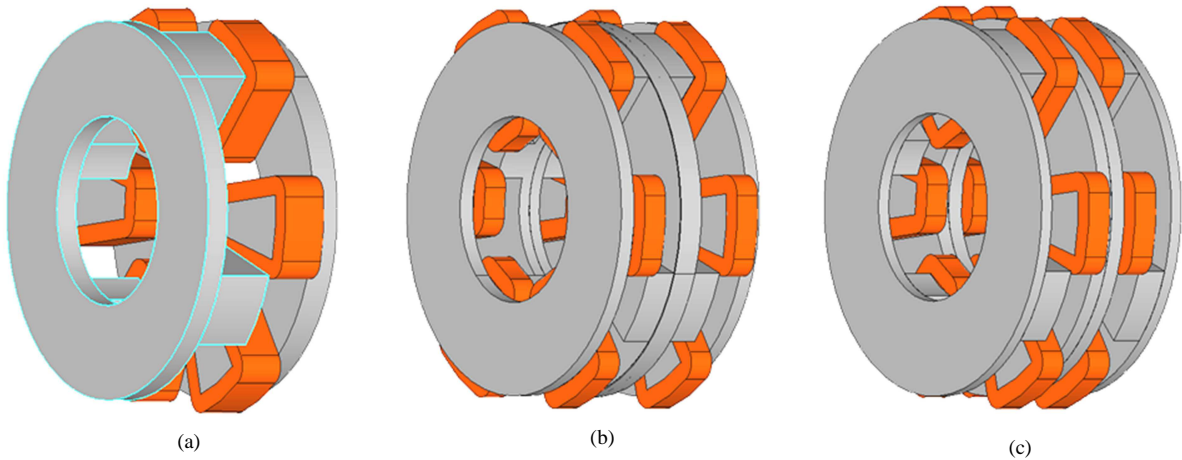
54

presented. Due to the unbalanced axial force, the motor was not tested in its rated speed

55

because "the rotor teeth hit to the stator teeth".

56



57

58 *Fig. 2 ASRM categories, (a) ASRM with single-stator and single-rotor , (b) ASRM with*  
 59 *double-stator and single-rotor, (c) ASRM with single-stator and double-rotor*

60 *2.2. ASRM with Double-Stator and Single-Rotor*

61 In this configuration, the motor comprises a single rotor between two stators (Fig. 2 b), so  
 62 the motor has two airgaps. The main advantage is that the axial forces are balanced. Indeed,  
 63 the axial force of each stator on the rotor is compensated with the force of the other stator.  
 64 The torque ripples can be reduced by an angular shift of stators [15]. However, this shift  
 65 may cause unbalanced axial forces. In patent [1], the inventor presents this structure and  
 66 uses the rolling method for the motor lamination. This lamination requires a variable pitch  
 67 between the teeth in order to use a rolling process. Although, the study is poorly detailed in  
 68 this patent, the inventor announces several advantages namely the reduction of torque  
 69 ripples, noise, vibrations and iron losses... Additionally, the inventor does not propose the  
 70 solution to hold rotor teeth if the rotor yoke is removed. In [16], authors highlight some  
 71 acoustic advantages of this structure.

72 2.3. *ASRM with Single-Stator and Double-Rotor*

73 This configuration has a single stator and two external rotors (cf. Fig. 2 c). The position  
74 of stator in the middle leads to a complicated cooling. In the patent [17], inventors explain,  
75 without calculations, how to adapt radial concept of SRM into axial concept with double  
76 rotor. However, the use of global coils complicates the insertion of winding, and  
77 consequently increases the cost of the machine. In addition, this patent does not provide a  
78 detailed study to verify the announced benefits, like: “high efficiency with lower copper  
79 loss; improved thermal performance; lower torque ripple; higher torque density and lower  
80 costs for mass production”. Authors of [18] have used this motor for automotive traction.  
81 ASRM with segmental rotor for traction wheel is used in [19] and [20]. In [19], authors  
82 propose an original shift which reduces the torque ripples without unbalancing the axial  
83 forces. In [20], the machine has more teeth in the rotor than in the stator in order to increase  
84 the torque density.

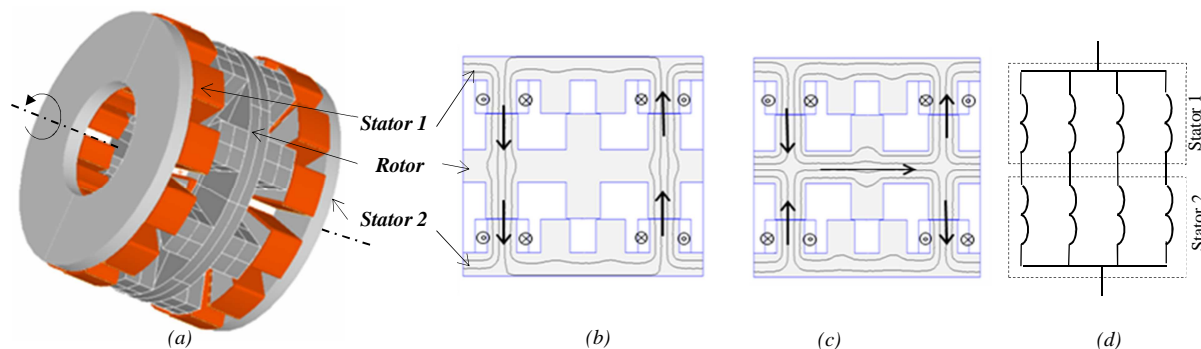
85 3. PRESENTATION OF THE STUDIED AXIAL MACHINE

86 In this part, the work about the ASRM are presented for an electric vehicle application.

87 3.1. *Choice of Axial Typology and Configuration*

88 Double saliency axial switched reluctance motor with single rotor placed between two  
89 stators is chosen for our works (Fig. 2.b; Fig. 3.a). This structure is essentially selected  
90 because of the possibility to use local or transverse magnetic field loops depending on the  
91 coil winding direction (Fig. 3.b.c), compensation of axial forces on the rotor, possibility to  
92 reduce torque ripples by stators shifting [6] and easy cooling. Moreover, the two stators are  
93 mechanically joined, giving better mechanical behaviour. In other words, the axial forces

94 are compensated. In addition, a concentrated winding is here used in order to reduce copper  
 95 losses. Each phase comprises eight coils which are connected as in "Fig 3-d" (serial -  
 96 parallel).



97  
 98 Fig. 3 (a) chosen SRM, (b) cross sectional view of transverse loops, (c) cross sectional view  
 99 of local loops, (d) phase coils connection

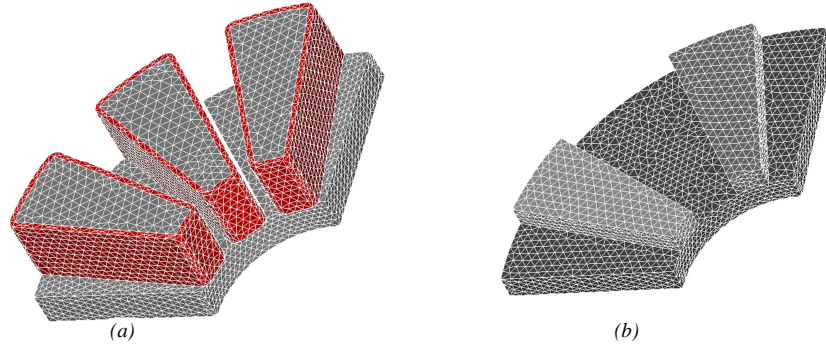
100

101 For confidentiality reasons, the values of the different variables, including rotor position,  
 102 are normalized with respect to the RSRM one, throughout all this work. Furthermore, the  
 103 dimensions and characteristics of motors are not given for the same reasons.

### 104 3.2. ASRM Modelling

105 A half of the chosen axial motor is firstly drawn in 3D and meshed with Platform  
 106 Salome software [21]. The computed mesh (cf. Fig. 4) comprises 388920 tetrahedrons,  
 107 15136 prisms and 84578 nodes. This mesh is then exploited in an electromagnetic  
 108 calculation code "*code\_Carmel\_3D*" of L2EP laboratory (Laboratoire d'électrotechnique et  
 109 d'électronique de puissance de Lille) [22]. This code is used for the establishment of ASRM  
 110 features: torque, flux linkage and axial force as function of rotor position and current.

111



112  
113 *Fig. 4 ASRM mesh, (a) 1/4 stator mesh, (b) 1/4 rotor mesh*

114 "Code\_Carmel\_3D" is used here for 3D finite element magnetostatic calculations with  
115 help of the *overlapping* finite element method [23], which allows to take into account the  
116 rotor displacement. The formulation is based on scalar potential  $\Omega$  and magnetic source  
117 field  $H_s$  (equation (1)). Therefore, conjugate gradient method is used to solve the problem.  
118 The torque is then calculated with virtual work principle.

$$119 \quad H = H_s - \text{grad}(\Omega) \quad (1)$$

120 In order to compute the magnetic ASRM characteristics (torque, flux ...), only one phase  
121 is supplied by constant current and the rotor moves from an unaligned position to an  
122 aligned one.

123 To understand and highlight the advantages, disadvantages and characteristics of the  
124 axial machine, a comparative study is carried out with a radial machine. Therefore, a  
125 prototype of RSRM is used as a reference to design the ASRM. In this work, some passage  
126 rules from radial SRM to axial one are established in the next parts.



127

#### 4. PASSAGE FROM RSRM TO ASRM AT SAME VOLUME

128

Passage rules are developed to transform a reference RSRM into an equivalent ASRM.

129

The radial one is a prototype designed for an electric vehicle. Thus, this prototype has been

130

designed in order to meet the requirements of powertrain specifications.

131

In this part, the ASRM is designed to take up the same volume as the radial one, i.e. the

132

ASRM has the same diameter and the same length as the RSRM. So, some motors features

133

are considered identical, such as typology (number of poles and phases), material (in the

134

stator and in the rotor), airgap length, axial length, extern radius, current density, specific

135

electric loading, maximum current, DC voltage and arc poles (see Fig. 5, example  $\beta_s = \beta_{sr}$ ).

136

As mentioned, the external radius and the axial length are the same in order to have the

137

same volume (*equations (2) and (3)*).

138

$$D_e = D_s \quad (2)$$

139

$$L_{axi} = L_{rad} \quad (3)$$

140

where  $d_e$  is the extern diameter of ASRM,  $D_s$  is the extern diameter of RSRM,  $L_{axi}$  is the

141

axial length of ASRM and  $L_{rad}$  is the radial length of ASRM.

142

The determination of external diameter gives several choices of the inner diameter of the

143

ASRM ( $d_i$ ), which affects several ASRM dimensions. Thus, to choose the inner diameter

144

( $d_i$ ), a compromise has to be done. In one hand, a small inner diameter ( $d_i$ ) makes the

145

distance " $e$ " (cf. Fig. 5-b) between two stator poles very small and hence the slots are very

146

narrow to place the coils. Moreover, a small inner diameter increases the stator pole section

147

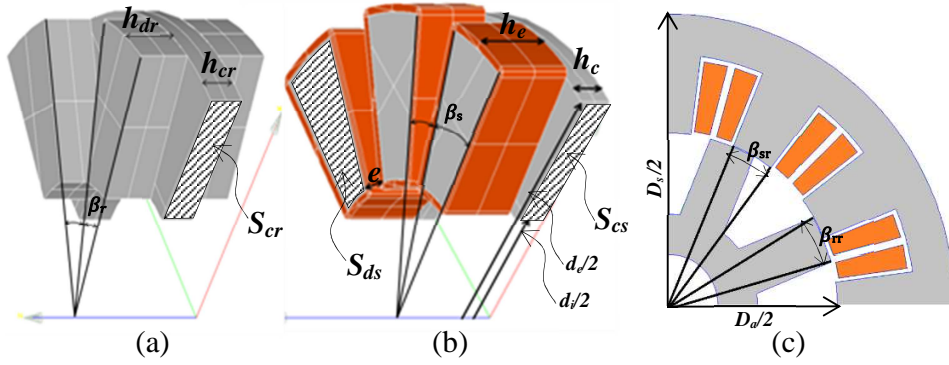
" $S_{ds}$ " (cf. Fig. 5), and so, the yoke section " $S_{cs}$ " must be increased also. The reason is linked

148

to the fact that the two sections are crossed by the same flux. These last increases can lead

149 to a longer axial structure. On the other hand, a great inner diameter reduces airgap surface  
 150 which decreases the developed torque. In order to mount the coils on the teeth, a sufficient  
 151 space is necessary for the slots without increasing axial length, here the chosen value is  
 152  $0.45 D_s$ .

153



154

155

Fig. 5 (a, b) ASRM dimensions, (c) RSRM dimensions

156 To keep the same specific electric loading, the number of turns of the ASRM " $n_a$ " is  
 157 computed by using the RSRM turns number " $n_r$ ". According to Krishnan [24], the specific  
 158 electric loading of radial SRM is defined as in the equation (4).

159 
$$A_{rad} = \frac{2n_{ph}I}{D_a\pi} \quad (4)$$

160 With the same approach, the electric loading of our axial machine ( $A_{ax}$ ) can be computed  
 161 (the bore diameter ( $D_a$ ) is substituted by a quadratic diameter ( $d_q$ ):

162 
$$A_{ax} = \frac{2n_{ph}I}{d_q\pi} \quad (5)$$

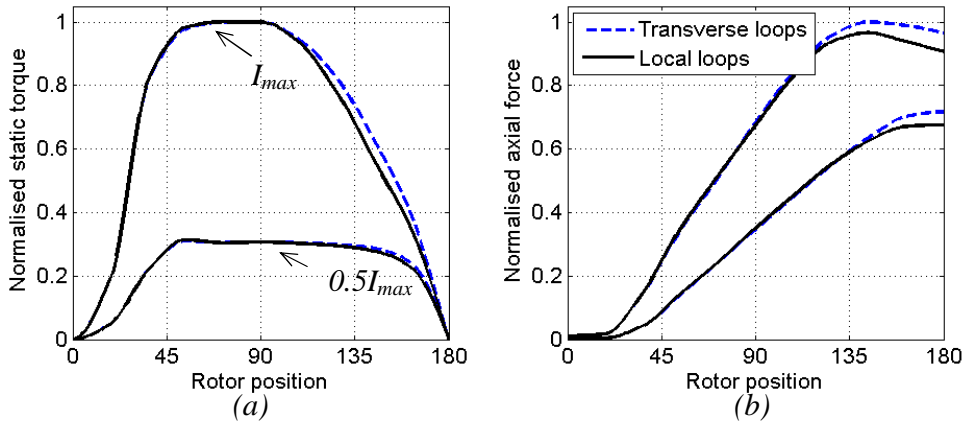
163 with  $d_q = \sqrt{(d_e^2 + d_i^2)/2}$

164 So

$$165 \quad n_a = D_a / d_q \cdot n_r \quad (6)$$

#### 166 4.1. Choice of Transverse or Local Loops

167 Considering that the selected structure can use local or transverse loops, the developed  
168 torques of each loop are compared (Fig. 6). To make this comparison, one phase is powered  
169 by a constant current and the rotor rotates from the unaligned to the aligned position. Two  
170 currents are considered in order to see the influence of magnetic saturation.



171

172

Fig. 6 Torques and axial forces of one stator ASRM

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176

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178

179

180

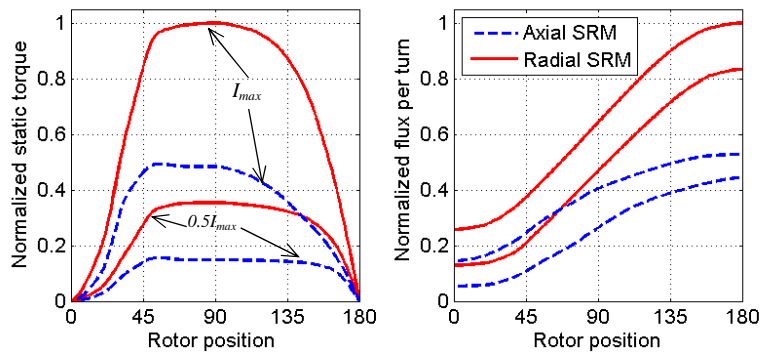
The average torque is higher in the transverse configuration than in the local configuration with an average increase of 2.25% (Fig 6-a). At low current, the difference is negligible, but significant difference appears with the increasing of supply current. This difference is more important near the aligned position (between 100° and 180°).

The figure (Fig 6-b) presents the resultant axial forces applied by a single stator on the rotor. Their behaviour seems similar to the behaviour of the torque. Indeed, the difference between the two configurations is also more noticeable near the aligned position and at high current. These differences are due to the rotor yoke saturation near the aligned position.

181 Indeed, this yoke is fully crossed by flux in the local configuration unlike in the transverse  
 182 one (Fig 3-b-c). This saturation limits the flux in the local loop configuration reducing the  
 183 inductance value in this position and consequently reduces the inductances ratio. For the  
 184 rest of this work, only transverse configuration is considered because of its average torque  
 185 values (+2.25% on average).

186 *4.2. Comparison of ASRM and RSRM at Same Volume*

187 In this part, finite element studies are performed to assess the ASRM and to compare it  
 188 to the RSRM. The static torque and the flux are first compared (Fig. 7). Two currents are  
 189 considered.



190

191

*Fig. 7 Static torque and flux per turn*

192 In all cases of comparison, the radial machine develops more torque than the axial one  
 193 when the same volume is considered. At the same excitation current, the difference can  
 194 reach 52%. Similar differences as in torque comparison are found when comparing the flux.  
 195 For a given current, there is more flux in the RSRM than in the ASRM, whatever the rotor  
 196 position is. These differences are mainly due to:

197 - The use of double stators while keeping the same mechanical airgap length. This  
198 automatically increases the magnetic airgap length. Indeed, a field line crosses the airgap  
199 two times in the RSRM but four times in the axial one,

200 - In electrical machines, airgap is known as the region where the magnetic energy is  
201 concentrated. The airgap area is greater in the radial machine than in the axial one (+10 %),

202 - The flux cross-section (stator pole area) is higher in the RSRM by 55%; which has a  
203 direct effect on the inductances.

204 The ASRM is less heavy than the radial one (20% of reduction), in addition, it uses less  
205 copper (43 %) and less iron (17 %). Furthermore, the torques densities, namely the  
206 maximum torque per the total weight and the maximum torque per the copper mass, are  
207 more important respectively by 37% and 15% in ASRM

## 208 5. PASSAGE FROM RSRM TO ASRM AT SAME TORQUES

209 This part concerns a design of the ASRM to fulfil similar torque specifications as the  
210 radial one.

### 211 5.1. Pre-Design Equation of Radial SRM

212  
213 The reference [24] gives a pre-design equation of SRM similar to those of conventional  
214 machines. This equation gives the torque as a function of some machine parameters.

$$215 \quad T = \eta(1 - \lambda)B.A_{rad}\pi\left(\frac{D_a}{2}\right)^2 L \quad (7)$$

216 Where  $T$  is the torque,  $\eta$  is the efficiency,  $\lambda$  is the inductances ratio,  $B$  is the airgap  
217 magnetic density,  $A_{rad}$  is the specific electric loading,  $L$  is the axial length and  $I$  is the  
218 current amplitude.

219 In this equation, several machine parameters appear, in particular, the airgap volume.  
220 Indeed, the torque depends on bore radius ( $D_a$ ) and the length of the machine called “active  
221 length”. Furthermore, the torque depends on the magnetic density in the airgap, the ratio of  
222 inductances and the specific electric loading. The reader can refer to the reference [24] for  
223 more information. The last parameter is chosen according to the cooling and to the  
224 maximum number of turns. It must be determined for a given current.

## 225 5.2. *Pre-Design Equation of the Axial SRM*

226  
227 Similarly to Krishnan approach [24], a pre-design equation of the ASRM is here  
228 proposed.

$$229 \quad T = \eta(1 - \lambda)BA_{ax} \frac{1}{2} \pi \left( \frac{d_e^2 - d_i^2}{4} \right) \left( \frac{d_e + d_i}{4} \right) \quad (8)$$

230 The ASRM torque depends directly on mean radius " $(d_i+d_e)/4$ ", the area of a single  
231 airgap, magnetic induction and inductances ratio. Unlike the RSRM, the axial length of the  
232 ASRM does not appear in this equation. So, the torque is directly independent of the axial  
233 length (if we do not take into account the influence of this variable into the magnetic  
234 saturation).

235 5.3. *Identification of the Pre-Design Equations*

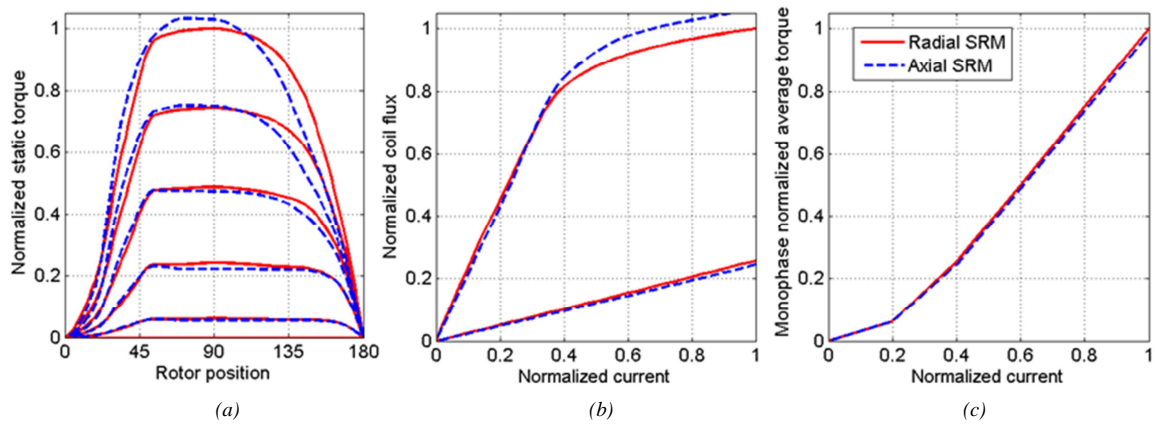
236 As mentioned, the purpose of this conversion is the rapid design of ASRM. Thus, it is  
237 considered that the specifications of the axial machine are the same as the radial one. In  
238 addition, some assumptions are adopted. The motors have the same features like:  
239 efficiency, induction in the airgap, inductances ratio and specific electric loading.  
240 Furthermore, a constraint on axial length is considered, i.e. the machines must have the  
241 same axial length. Seen that the inner diameter ( $d_i$ ) is limited by the slot area, there is only a  
242 choice for outer diameter ( $d_e$ ). By identification of the two pre-design equations, we obtain  
243 the next passage equation:

244 
$$\frac{1}{8}(d_e^2 - d_i^2) \cdot (d_e + d_i) = D_a^2 L \quad (9)$$

245 Several values of  $\{d_i, d_e\}$  give an equivalent ASRM to the reference RSRM. So, if  $d_i$  is  
246 known, the equation (9) has three solutions, two imaginary numbers (not acceptable) and  
247 one that is real.

248 5.4. *Comparison between ASRM and RSRM at the Same Torques*

249  
250 In order to limit the volume, the values of  $\{d_i, d_e\}$  are chosen to give the minimum  
251 volume. As mentioned above, the inner diameter ( $d_i$ ) was chosen to have a sufficient space  
252 in the slot which allows housing coils ( $d_i=0.45 D_s$ ). Once the inner diameter is determined,  
253 the extern diameter is computed by solving analytically the equation (9) ( $d_e=1.2 D_s$ ). In  
254 others words, to have the same torque, the volume of the axial machine must be increased  
255 and the number of turns must also be increased from  $1.3n_r$  to  $1.55n_r$  (cf. equation 6).



256  
257

Fig. 8(a) Static torques, (b) flux linkages, (c) average torques

258 The 3D computations show that the new axial machine can reach the torque of the radial  
 259 one, whatever the considered current (Fig. 8.a and Fig. 8.c). The linkage flux is almost the  
 260 same for both (Fig. 8.b), so they should have the same envelope curve. Indeed, the torque is  
 261 directly related to conversion surface of energy which is delimited by flux linkage and  
 262 magneto-motive force (MMF,  $nI$ ).

263 The increase of extern diameter affects directly the ASRM mass; this is why the axial  
 264 SRM is here heavier than the radial one (about +23 %). However, ASRM develops the  
 265 same torque as its rival with less amount of copper (-8%). Concerning the torque densities,  
 266 the maximum torque per the total mass is better in the RSRM (+23%), but the maximum  
 267 torque per the copper mass is better in the ASRM (+8.5 %).

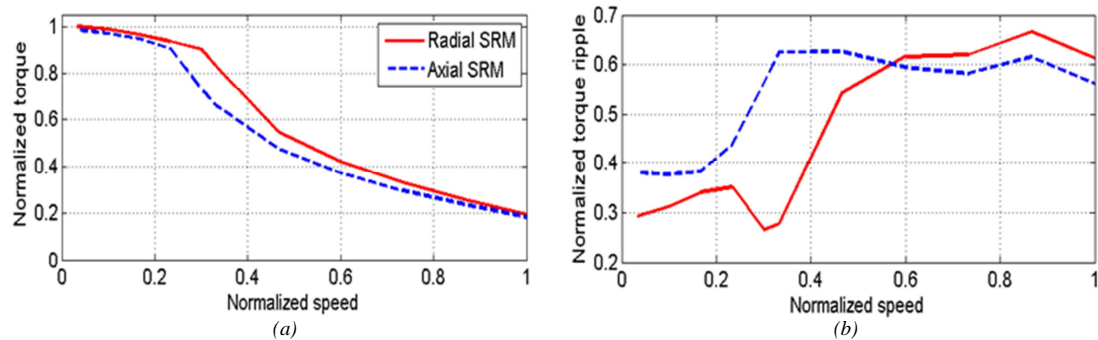
268 The increase in ASRM mass presents a disadvantage for this SRM. To remedy this  
 269 problem, we propose to remove the rotor yoke which has no electromagnetic interest  
 270 (transverse loops are here used). After this modification, the masses of magnetic structures  
 271 are almost the same (+2.6%). In addition, less copper is used in the axial machine (-  
 272 8.4%). Thus, ASRM can compete with the RSRM because of only -2.5% deficit in ratio of



273 the torque per the total mass. For the ratio of the torque per copper mass, the axial motor is  
274 still better (+8.5%). The fact of removing the rotor yoke allows also reducing the axial  
275 length of ASRM by 16%. However, this might complicate the rotor teeth fixation and then  
276 the motor manufacturing.

#### 277 5.5. Comparison at Operating Mode

278  
279 In this comparison, speed-torque curves and corresponding torque ripples of the two  
280 machines are considered (cf. Fig. 9). In automotive applications, one of the specifications is  
281 the compliance to a defined torque-speed-curve. Last is defined as the maximum average  
282 torque developed when the machine is supplied by the maximum current and the maximum  
283 voltage for given speed [25]. The optimization of the control angles is taken into account by  
284 our software "*MRVSIM*" [26]. *MRVSIM* is a calculation code under MATLAB<sup>®</sup> used for the  
285 design of radial SRM. This tool uses analytical and/or numerical model of SRM and its  
286 control parameters optimization takes into account the machine and the associated  
287 converter. First, finite element model is employed for accurate computation of  
288 cartographies (flux and torque as function of current supply and position). By exploiting  
289 these features and by optimizing the turn-on and turn-off angles, the torque-speed curve of  
290 SRM can be calculated.

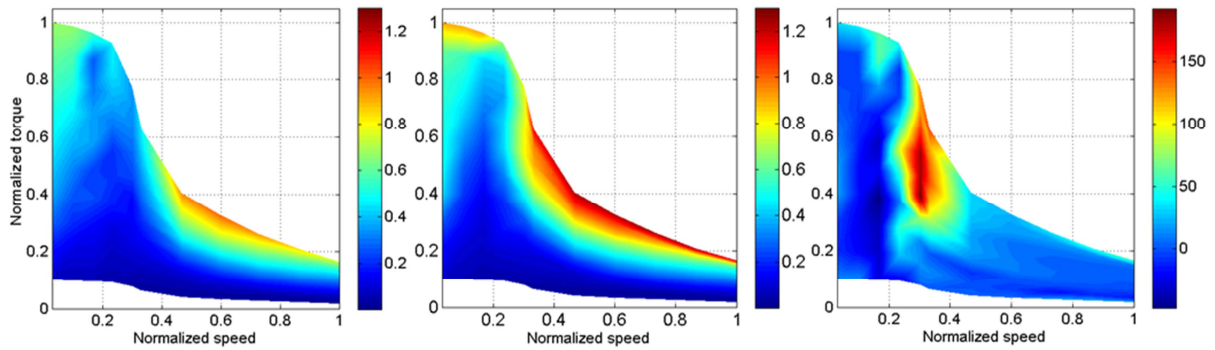


291

292 Fig. 9 (a) Maximum torque vs. speed curves, (b) torque-ripple vs. speed curves

293 By increasing the motors speeds, the electromotive force (EMF) increases and limits the  
 294 supply current that reduces thus the average torque for both machines. At low speed, the  
 295 two machines develop almost the same torque (-2%). Indeed, the equation passage was  
 296 established in static mode with constant current and these conditions are observed when the  
 297 motor is operating at low speed. Nevertheless, when increasing the speed, the RSRM  
 298 develops more torque compared to ASRM, in particular near the rated speed, where the  
 299 difference can reach -20%. Besides this, the RSRM is more suitable to this specific point  
 300 which is the rated speed than the axial one, because the first one was directly designed and  
 301 sized for this point. At high speed, the EMF prevents to achieve the reference currents in  
 302 the two SRM. In this operating range, the difference between the torques is low, because  
 303 the two SRM have almost the same coils flux, which is directly related to EMF.

304 According to the torque ripples (Fig. 9.b), no SRM can be considered advantageous for  
 305 all speed range. So, the minimum torque ripple cartographies are computed in the next part  
 306 (cf. Fig. 10). These cartographies consist to look for the optimal control parameters that  
 307 allow minimum torque ripples across the entire operating range [27].



308

309 *Fig. 10 Cartographies with minimum torque ripples, (a) RSRM (b) ASRM, (c) Differences*

310

*(ASRM minus RSRM [%])*

311

The results of this comparison do not allow retaining one conclusion on the all entire

312

operating range because those results change from an operating point to other.

313

Nevertheless, it can be noticed that the axial machine has generally less ripples at low

314

speeds. This can be considered as an advantage, because at these speeds, it is more difficult

315

to mechanically filter ripples than at high speeds.

316

## 6. CONCLUSION

317

ASRM with double stator and single rotor has been chosen for automotive application.

318

Equations to pass from the reference radial machine to the axial one have been detailed.

319

Firstly, the passage was at same volume but it shows that ASRM cannot reach torque

320

performances of RSRM. Secondly, the passage was at same torque, where the axial SRM

321

had to satisfy the same specification as the radial one. For this, the extern radius has been

322

increased. In this configuration, ASRM gives similar torque compared to RSRM with

323

smaller copper volume. However, this axial SRM was heavier than the radial one. In order

324

to have the same mass of magnetic structures, it was proposed to withdraw the rotor yoke.

325 Concerning the speed-torque curves, there was almost the same curve except around the  
326 rated speed. The study of the minimum torque ripple cartographies has shown that axial  
327 machine had less torque ripples at low speed, presenting here an advantage of this structure  
328 for EV application and comfort criterion.

329 This paper has proved that, despite some advantages presented by the axial SRM, the  
330 radial SRM seems finally to be the most adequate structure for the specifications in the  
331 automotive application. Indeed, the designed axial structure is not able to reach all  
332 operating points of the speed-torque curve, unlike the radial one. Furthermore, the mass and  
333 volume of axial machine are more important than in the case of the radial ones. The  
334 solution of axial SRM without rotor yoke limits these drawbacks, but also complicates the  
335 manufacturing. For all these reasons, it has been decided to stop the works on this axial  
336 structure without the prototype manufacture. Ongoing works will then focus on the design  
337 of the radial structure for electric vehicle motorization.

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