EFFECT OF THE POLE NUMBER ON THE PERFORMANCE OF SWITCHED RELUCTANCE MOTORS IN STEADY AND TRANSIENT STATES USING FEA

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This paper presents two usual switched reluctance motor configurations (8/6 and 6/4). The dynamic regime is analyzed using 2D FEM. The aim is to highlight the influence of the number of poles on the characteristics of switched reluctance motors. The study is carried out for steady state and transient state and is based on the comparison between the torques and currents for both SRMs. For the transient state, the starting characteristics are compared based on the speeds, currents and torques. The distribution of induction and flux lines are also shown. For all simulations, the geometric parameters of both motors are the same except for the number of poles and the angles of the supply drive. The aim is to obtain the highest and least rippled torque with the least impact on the performance of the motors.

Keywords: Reluctance, Switched reluctance motor, Finite element method, Coenergy

1. Introduction

Due to their construction simplicity, high robustness, high temperature tolerance and ability to operate over a wide range of speeds at constant power, switched reluctance motors (SRM) have attracted the attention of the researchers. These features make them gain a significant place in various industrial applications, particularly in electric traction and renewable energy [2],[3]. The development of power electronics has also contributed to their growth, since this kind of engine needs electronic drive to operate. However the torque of the SRM is very rippled, what causes mechanical vibrations and acoustic noise. This increases the mechanical losses and affects the performance and the efficiency of the motor.

The magnetic characteristics of this type of motor are highly non-linear. This non-linearity is due to the saturation effect of the material, the salience of the air gap and the position of the rotor. It is therefore necessary to select a reliable

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method to model this kind of problem. Many authors presented different models like analytical, numerical, semi numerical and combined models [1],[3],[8],[9].

In this study we present a 2D planar finite element model for 6/4 and 8/6 SRMs to compare their performances. These two types of SRM are the most popular as they have simple designs and drives. The comparison will be based on inductions, currents and torques. It is carried out for permanent and transient analysis with no load. The two motors have practically the same dimensions, except for the number of stator and rotor teeth. The aim is to minimize torque ripple for the same input power. The idea of comparing two motors with different numbers of teeth is quite complicated. In previous work carried out on a 6/4 motor [1], [4], we have shown that the best torque in terms of value and shape is obtained by having the same dimensions of stator and rotor teeth. In addition, the supply of a phase must take place when the corner of the rotor tooth is placed under the corner of the stator tooth. These conditions still exist for an 8/6 motor. The two models where established using Maxwell 2D for transient analysis.

2. SRM geometry and principle

The motors studied in this paper are 6/4 and 8/6 switched reluctance motors supplied with a constant voltage. Both motors have salient poles in the stator and simple concentric windings as shown in Fig.1.

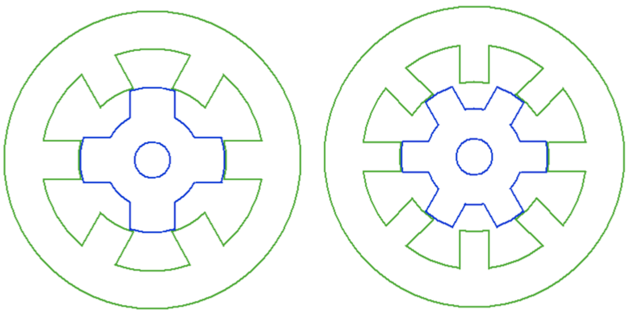


Fig. 1. SRM configurations at non aligned positions

The rotor has no windings and no permanent magnet. It is simply a ferromagnetic piece with salient teeth. The position of non-alignment (N.A) of the axis of the stator and rotor teeth is assumed to be a reference position (0°) [1]. It corresponds to the maximum air gap reluctance hence the rotor pole is far from the stator pole. When a constant voltage is applied at this position, a main magnetic field is generated in the stator pole and the rotor is drawn to minimize the airgap reluctance. To avoid any residual torque that could affect the rotor movement, the supply is generally switched off before the alignment position. Powering up the successive phases causes the rotor to move. However, this supply sequence generates a ripple torque which causes noise and mechanical vibrations as mentioned above.

Switched reluctance motors are supplied by a drive that controls the switching of the phases. Since the torque is independent of the direction of the current, the SRM drive uses unipolar switches. It provides a constant voltage (+V) between switching on and off. The current is quickly reduced by applying an opposite voltage (-V) at the position $\boldsymbol{\theta_{off}}$ and up to $\boldsymbol{\theta_{ext}}$, otherwise it can cause movement disturbances. A phase is formed by connecting two diametrically opposite windings in series, as shown in Fig.2. for 6/4 SRM.

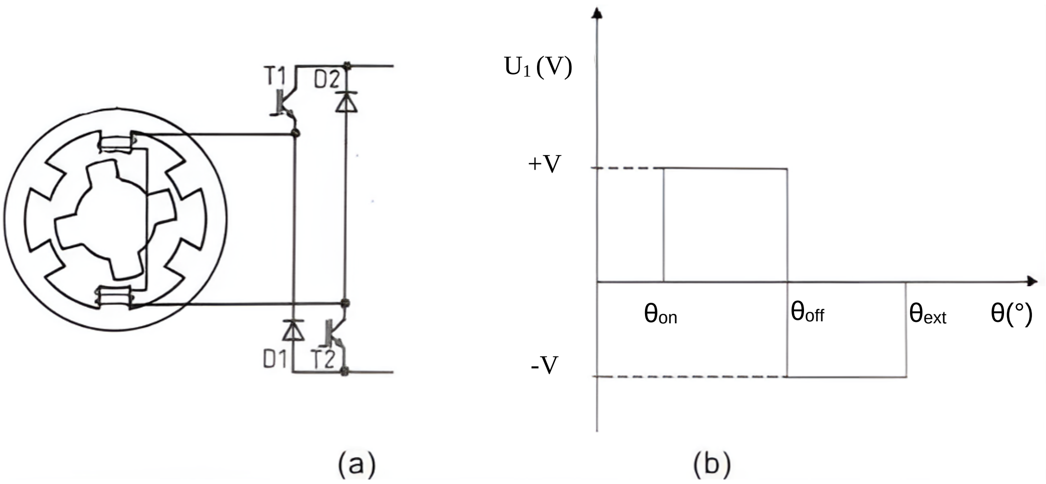


Fig. 2. SRM drive configuration (a) and voltage shape (b).

It should be noted that the 8/6 SRM has four phases and the 6/4 SRM has three phases.

The supply function for one phase for both 6/4 and 8/6 SRM is depicted in eq. (1).

$$U_1(\theta) = \begin{cases} +V & \theta_{on} \le \theta \le \theta_{off} \\ -V & \theta_{off} \le \theta \le \theta_{ext} \end{cases} \quad (1)$$

For the 6/4 motor , $\boldsymbol{\theta_{on}}$=0° and $\boldsymbol{\theta_{off}}$=20°. For the 8/6 motor $\boldsymbol{\theta_{on}}$=0° and $\boldsymbol{\theta_{off}}$=15°. For both motors $\boldsymbol{\theta_{ext}}$ depends on the decrease time of the current.

For the other phases, the supplying angles are switched by 30° for 6/4 motor and 22,5° for 8/6 motor as shown in Fig.3.

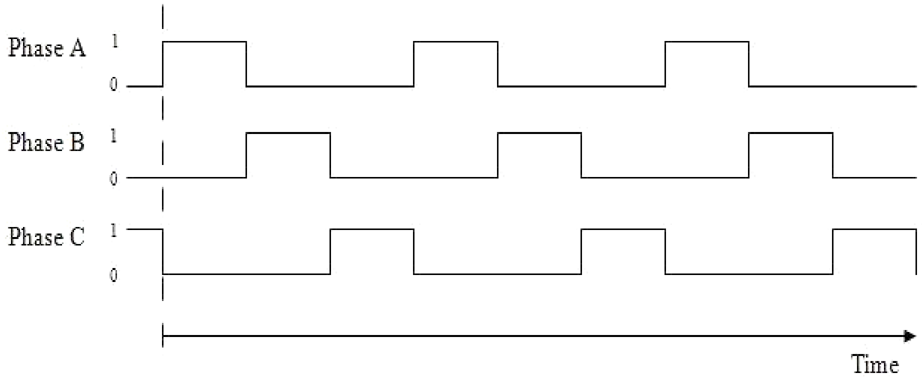


Fig. 3. SRM voltage shape for 3 phases.

The electromagnetic differential equation for phase A is presented by eq. (2):

$$U_1(\theta) = R.i_1(\theta) + \omega.\frac{d\psi_1(i_1,\theta)}{d\theta} \quad (2)$$

Where $\boldsymbol{\omega}$ is the rotor velocity.
R is the winding resistance.
$\boldsymbol{i_1}$ is the winding current.
$\boldsymbol{\Psi_1}$ is the flux linkage of the main stator pole.

In classical motors (synchronous, continuous current and induction motors), the torque results from the interaction between stator and rotor currents. For the SRM, the origin of the torque is purely reluctant. It means that it is based on magnetic attraction between an electromagnet and a ferromagnetic piece. It depends only on the variation of the reluctance and the coenergy.

Equation (3) specifies the reluctant torque ***T***, and eq.(4) specifies the coenergy ***W'***.

$$T = \frac{\partial W'}{\partial \theta} \quad (3)$$

$$W' = \int_0^i \psi.di \quad (4)$$

For the transient mode, the mechanical data must be taken in consideration. We mean by mechanical data the weight of the rotor, the moment of inertia and the friction. The mechanical equation is given by eq. (5) :

$$M.\frac{d\omega}{dt} = T_e - T_r - f.\omega \quad (5)$$

Where ***M*** is the moment of inertia of the rotor.

T_e is the electromagnetic torque.
T_r is the resistant torque due to the load.
f is the friction factor.

3. Finite element analysis

The models presented in this section are 2D planar magneto-dynamic model using FEM. To highlight the effect of the number of teeth on the SRMs, the geometrical parameters, the voltage and the output power are similar. However the two motors teeth widths are different.

3.1. Parameters of the studied motors

The construction parameters of the SRMs studied are shown in table (1).

Table 1

Geometrical parameters of the two motors.

Type of SRM	6/4		8/6	
parameters	Stator	rotor	Stator	Rotor
Number of poles	6	4	8	6
Yoke thickness (mm)	10	10	10	10
Length (mm)	150	150	150	150
Teeth height (mm)	10	10	10	10
Outer diameter (mm)	86	46	86	46
Inner diameter (mm)	47	10	47	10

For the 8/6 SRM the rotor pole arc is 22.5°, and the stator pole arc is 22.5°.
For the 6/4 SRM the rotor pole arc is 30°, and the stator pole arc is 30°.
This choice is made to ensure that the rotor and the stator pole width are the same for the two motors.

3.2. Choice of the mesh and boundaries

Meshing is the discretization of a complex domain into multiple domains called elements, in order to simplify solving the differential equations of an electromagnetic system. For our study, the elements have triangular form, to fit the rounded shapes and the complex geometry of the air gap. The mesh is tighter at the crossing areas. To reduce calculation time we take advantage from the symmetry of the motors and the analysis is effectuated for half the machines. Zero potential boundaries conditions and Master slave conditions are applied as shown in Fig.4.

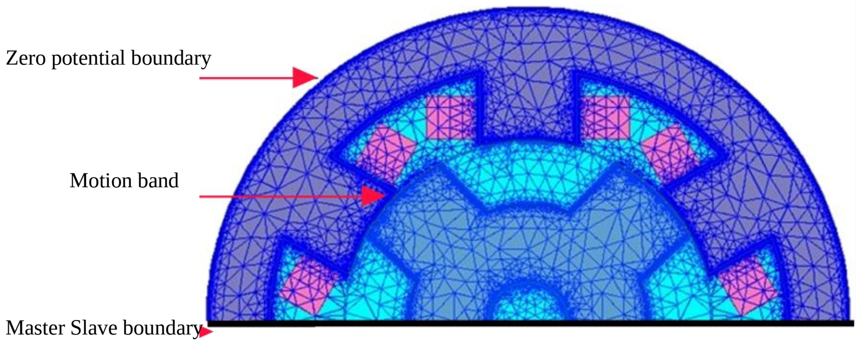


Fig. 4. Mesh configuration for 6/4 SRM.

3.3. Magnetic characteristics

The material used for magnetic parts of the studied motors is steel with high permeability witch the BH curve is shown in Fig.5.

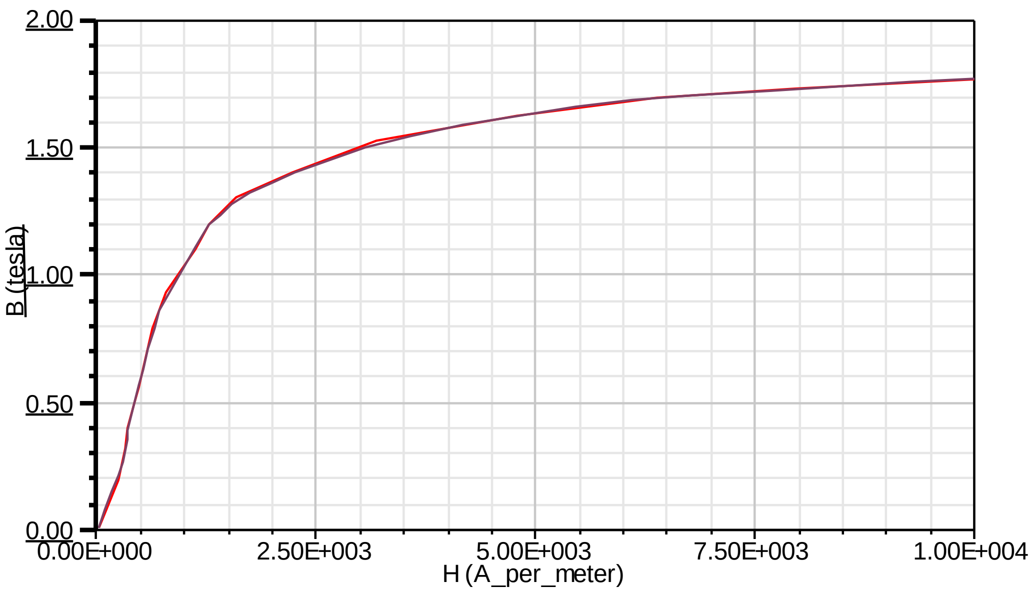
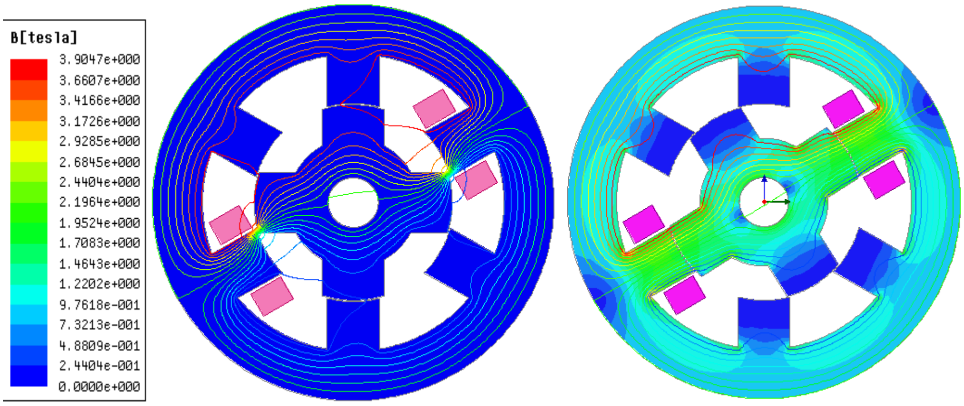


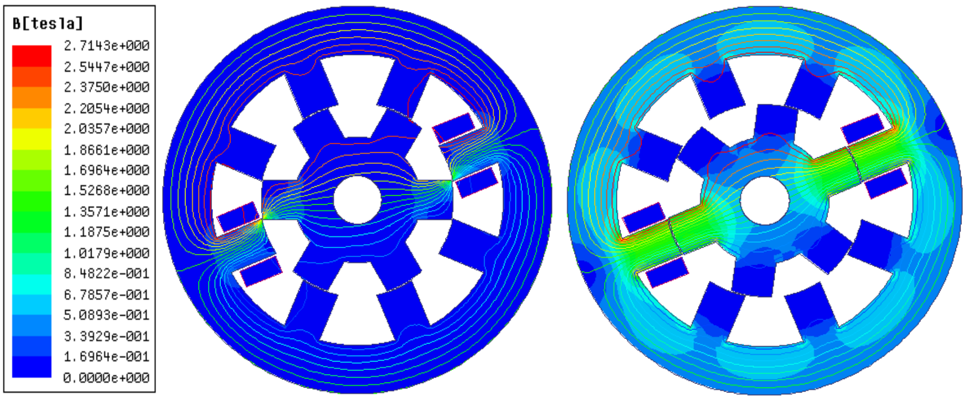
Fig. 5. Material magnetic characteristics.

The two motors have the same output power of 2kW, they are supplied by a voltage source of 80V at 1500rpm speed. Simulations have been established in magnetostatic analysis to determine the magnetic characteristics for aligned and non aligned positions. These results allows to determine the saturation level of the motors.

Fig.4 shows the distribution of induction in ferromagnetic and non magnetic areas at unaligned position of the 6/4 SRM (Fig.6.a) and the 8/6 SRM (Fig.6.c).The saturation is very low at this position for the two motors because the current is very low and the airgap reluctance is maximal. The flux lines passes from the stator to the rotor via the airgap. They are concentrated in the excited stator poles.



(a) (b)



(c) (d)

Fig. 6. Flux lines and induction in 6/4 and 8/6 SRM.
(a)and (c) non aligned position
(b) and (d) aligned position

For the aligned position Fig.6.(b) and Fig.6.(d), the magnetic circuit is more saturated. It reveals clearly the source of magneto-motive force in the stator poles that are excited. At this position the airgap reluctance is minimal.

The induction is higher in the main pole and reaches 2.7Tesla for 6/4 SRM and 1.7 Tesla for 8/6 SRM.
The maximal values of the induction have been noticed at the boundaries areas between the stator poles and the stator yokes.
The shape of the inductance according to electrical angle of the two motors are depicted in Fig.7. The maximum inductance is reached at aligned position. The 8/6 SRM inductance (in dotted line) is lower than the 6/4 one (in solid line) for this position. The minimal inductance at the unaligned position has the same value.

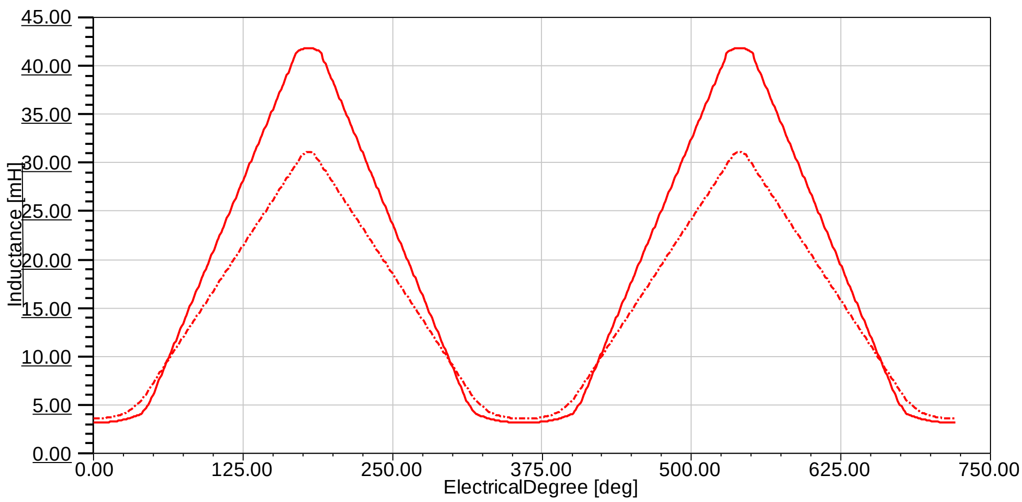


Fig. 7. Inductances of the 6/4 SRM (solid line) and 8/6 SRM (dotted line).

4. Results and discussions

The comparison of the performances of the two structures will be done firstly for steady state to compare currents and torques and finally for starting mode to compare torques and speeds, taking into account the mechanical characteristics.

4.1. Steady state analysis

We first compared the two motors in steady state with no load. The currents as function of time of the 8/6 SRM are shown in Fig.8 and Fig.9. For the 8/6 SRM, the maximum value reaches 18.66A per phase but this value is not harmful because the power supply only lasts 4 ms. The winding does not have time to heat up. The rms current value is 8.9 A for phase A.

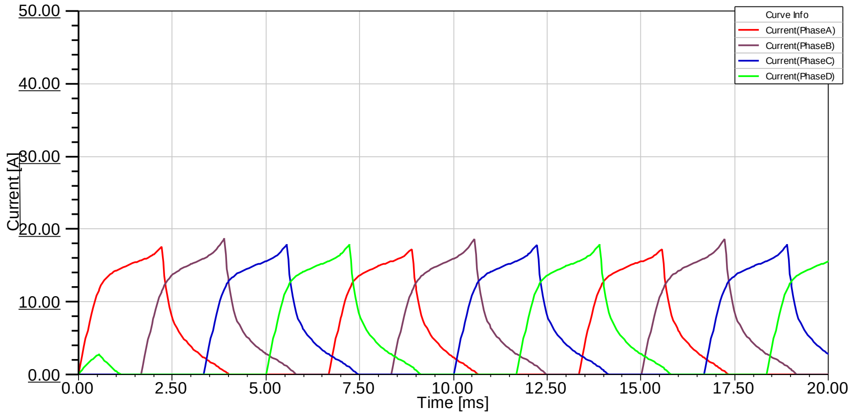


Fig. 8. Evolution of current in the 3 phases of 8/6 SRM in steady state.

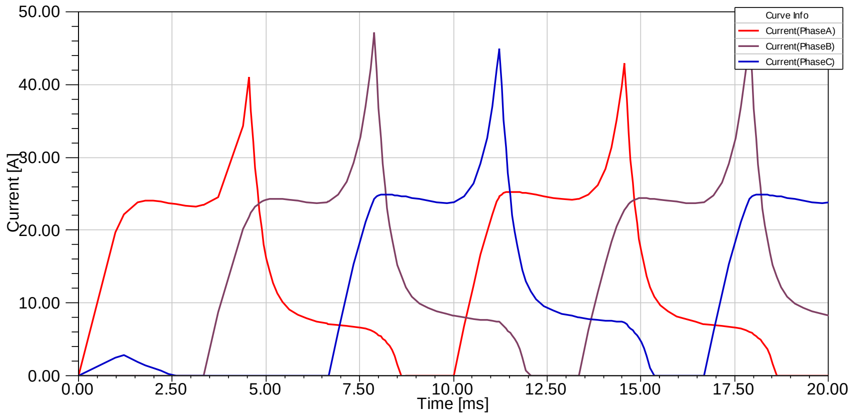


Fig. 9. Evolution of current in the 3 phases of 6/4 SRM in steady state.

The currents of the 6/4SRM in Fig.9 are very high in appearance but have a rms value of 16.28A. A very acceptable value given the supply duration. Current peaks appear also at switching times like the 8/6 SRM.

For the 8/6 motor (Fig.10. in blue line), the torque increases rapidly at the beginning and stabilizes at an average value of 5.84 Nm. It presents ripples which correspond to the moments of extinction of one phase and the supply of the next phase as shown in the current characteristics figure. Maximum torque reaches 7.35Nm.

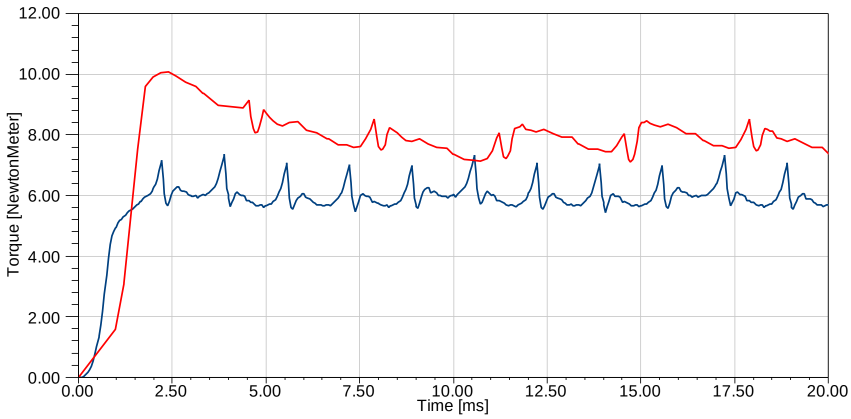


Fig. 10. Torque for 6/4 SRM(red line) and 8/6 SRM(blue line) in steady state.

For the 6/4 SRM (Fig.10. in red line), the torque seems less rippled and higher with an average value of 7.17Nm and a maximum value of 8.4Nm.

Table 2 shows the principal differences between the two motors in steady state.

Table 2

Comparison of performances in steady state.

	8/6 SRM	6/4 SRM
Average induction (Tesla) (at aligned position)	Around 1,6	Around 2,5
Maximum inductance (mH)	31	43
Minimum inductance (mH)	3,5	3,5
Rms current (A)	8,9	16,28
Mean torque (Nm)	5,84	7,17
Max torque (Nm)	7,35	8,4

4.2. Transient state analysis

In this case we take into account the mechanical characteristics such as ***M*** the moment of inertia of the rotor, and ***f*** the friction factor.

For 6/4 SRM, ***M***=2,76 .10^{-4} Kg/m2 and for 8/6 SRM ***M***=2,75.10^{-4} Kg/m2. The friction factor ***f***=0,01 N.m.sec/rad.

The simulation showed that the starting current (Fig.11) is very high in phase A specially and reaches a maximum of 77A for the 8/6 SRM. This current is maintained until 120°. The other phases of currents are lower at the beginning and increase gradually. The currents maintain their stable shape towards the position of 140°.

For the 6/4 motor the maximal current of phase A(Fig.12) is also high, about 69A and still maintained until position 200°. The other phases have a mean current of about 15A. The steady state is reached at position 210°.

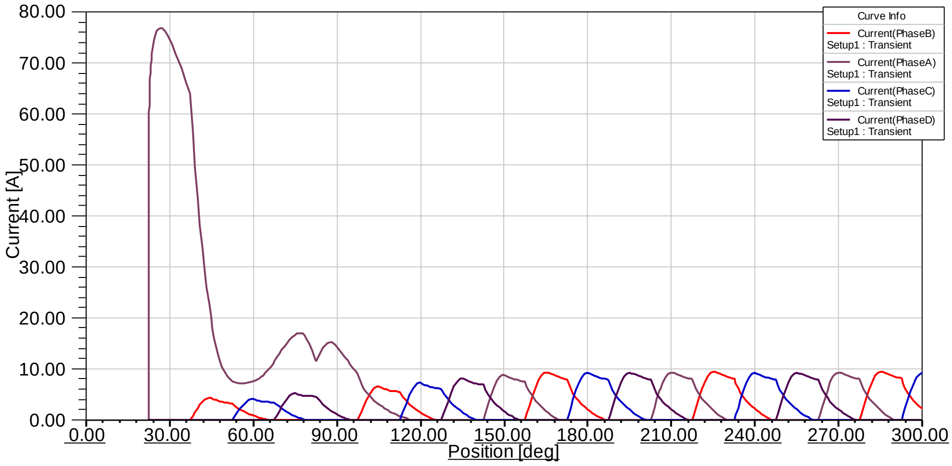


Fig. 11. Evolution of current in the 3 phases of 8/6 SRM for starting mode.

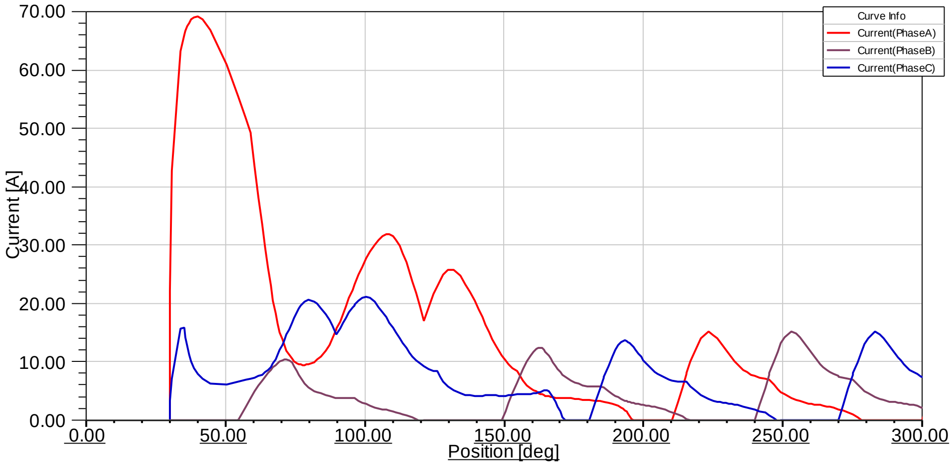


Fig. 12. Evolution of current in the 3 phases of 6/4 SRM for starting mode.

Fig. 13 shows the shape of the torque for 8/6 SRM (in blue line) and 6/4 SRM (in red line).

The starting torque is very high for the two motors. We notice an inversion of the torque at position 70° for the 6/4 SRM and at position 52°for the 8/6 motor, due to the residual current in phase A. The torque is inverted once again. The steady state is reached after position 140° for 8/6 and 170° for 6/4 which means that the two motors torque becomes stable in less than half a turn. The mean torques of the two motors have almost the same value.

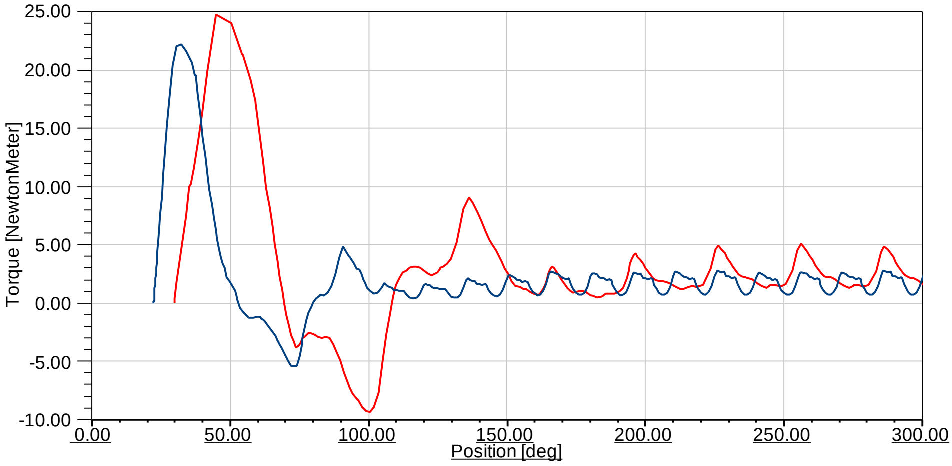


Fig. 13. Torque for starting mode (8/6 SRM in blue line and 6/4 SRM in red line).

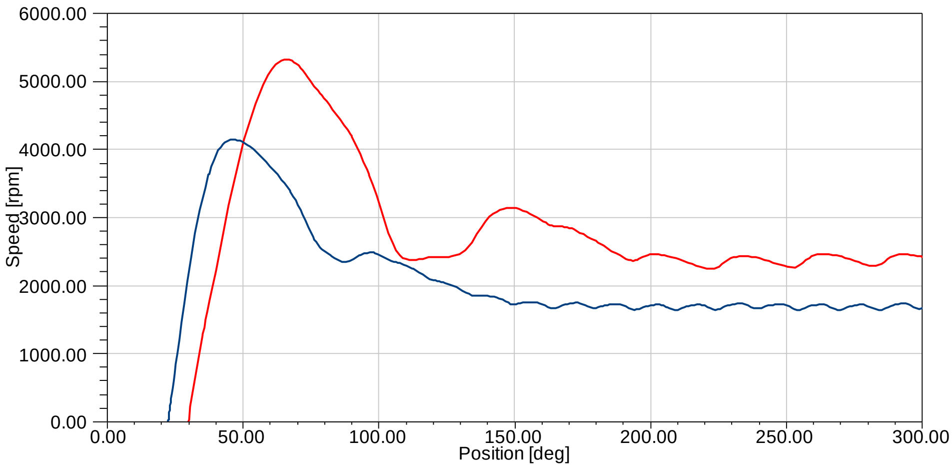


Fig. 14. Speed for starting mode (8/6 SRM in blue line and 6/4 SRM in red line).

The speed is represented in Fig.14. The 8/6 SRM begins from 0 to 4140 rpm and decreases until reaching the steady state mean speed of 1703 rpm. For the 6/4 SRM the maximum speed is 5314 rpm and the final mean speed is about 2352 rpm. Both speeds are rippled and might cause vibrations and noise.

The following table gives a summary of the principal differences between the two motors for the starting mode.

Table 3

Comparison of performences in starting mode

	8/6 SRM	6/4 SRM
Maximum starting current (A)	76,75	69,07
Final rms current (A)	3,18	8,95

Maximum starting torque (N.m)	21,96	24,71
Maximum starting speed (rpm)	4140	5314
Final mean speed (rpm)	1703	2352
Final mean torque (N.m)	2.25	2.45

5. Conclusion

A comparison between an 8/6 and a 6/4 switched reluctance motors have been presented in this paper. The two models are based on 2D planar FEA and have exactly the same geometrical parameters except the number and the widths of stator and rotor teeth. This study highlighted the effects of changing the number of teeth on the performances of the SRMs. The study was divided in two parts, steady state and transient state analysis. Firstly, for the steady state, the two motors have the same supply voltage and the same speed. The 6/4 motor presented a higher but less rippled torque than 8/6 motor. However, it presented a higher rms current and a higher saturation. These two consequences may lead to thermal losses and excessive heating.

Secondly, for the transient state, the currents of 8/6 motor are higher than 6/4 ones at the starting time, but the final values are slightly lower. The speed of the 6/4 is about 1.38 times higher than the 8/6. And hence the output power is the same value for the two motors, the torques are almost the same.

The starting torque is about 10 to 12 times the final torque for both motors.

This investigation has demonstrated that the number of teeth of the srm have an effect on torque, speed and current characteristics. Other comparisons can be done in the future, with a 12/8 SRM for exemple to support these results.

R E F E R E N C E S

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