Design procedure of Switched Reluctance Motor used for Electric Car Drive

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***Abstract*—This paper presents a Switched Reluctance Motor (SRM) design procedure for an electric car drive system. Determination of geometrical dimensions, calculation of static parameters as well as the losses and efficiency is discussed. A dynamic SRM model is outlined and used to calculate the output characteristics of torque and power as functions of the speed. It is shown that the designed SRM satisfies the performance requirements.**

***Keywords*— switched reluctance motor, electric car, finite element method**

I. INTRODUCTION

At present time, the permanent magnet synchronous motor (PMSM) is the most popular electric motor for hybrid electric vehicles (HEVs) as well as electric vehicles (EVs) [1]. The discussion about electrical cars development and improvement is very extensive. One of the main tasks is still the price of such a car, which is at this time relatively high in comparison with other conventional automobiles. The electrical car consists of three basic parts: mechanical (it is very similar with conventional car and also the price can be comparative), fuel part (battery pack, which is the dominant part of the car price) and electrical equipment including electrical drive, which depends on used electrical drive and its converter and control system.

Today, AC induction (IM) and synchronous machines with PM (SMPM) are frequently used in electrical cars. They are very strong competitors to the DC drives due to some features of the IM, such as simple construction, lower production and maintenance costs and total price and higher power density. Vector control of the IM drives also has draw-back, mainly the dependence of control accuracy on the exact knowledge of the IM equivalent circuit parameters, which are very sensitive to changes, e.g. stator and rotor resistance versus temperature.

The best solution seems to be SMPM because of very high ratio of power density per volume. However, it should be noted that the price of permanent magnets and their dependence on the temperature is a disadvantage of this type of drive [3] in comparison with SRM.

In many papers, Switched Reluctance Motor (SRM) is mentioned as a viable alternative for an electric car drive [3], [7], [8], [9]. The drive with SRM is becoming a very strong competitor to the drives with IM. SRM has simpler construction and, therefore, lower production costs, higher robustness and lower maintenance requirements as the IM drives. The SRM can operate only from an inverter, which works in more wide speed range than IM converter. The same can be noticed about the control system and methods. It is also needed for the SRM operation, but it is simpler as the vector control for IM drives.

The profile of the SRM torque/speed characteristic, although it is supplied from converter, looks similar to traction characteristic. This is very important reason, why the SRM is becoming a strong competitor to IM drives. On the other hand, it could be mentioned that the drawback of SRM is the torque ripple and rotor position sensor presence. It is given by basic principle of its construction and operation.

This paper deals with the SRM design for a real electric car application. The main idea is to replace an existing combustion motor by electrical machine – SRM. In the car, the real volume of combustion machine is used for electrical machine. The four phase 8/6 SRM, 20 kW, 5000 rpm is designed and torque/speed, power/speed characteristics are presented.

II. DESIGN PROCEDURE

A. SRM design procedure

The design procedure of SRM consists mainly of the following steps:

- to choose suitable number of phases and number of stator and rotor poles
- to calculate all geometrical dimensions of SRM to determine its preliminary average electromagnetic torque (power)
- to choose the suitable magnetic material for ferromagnetic core of SRM with known B-H curve
- to calculate its static parameters by means of FEM or by means of analytical approach. Static parameters are mainly: flux linkage, phase inductance and electromagnetic torque versus phase current and rotor position for whole operating range
- to input the calculated static parameters to the mathematical model of SRM and to investigate the current, voltage, torque and flux linkage waveforms for different speeds and loads of its operated range

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- to calculate the input power, losses, output power and efficiency based on the simulated waveforms
- to perform the thermal analysis

B. SRM sizing dimensions

Design procedure of SRM is made with the identical outer geometric dimensions of a real combustion motor, mainly outer stator diameter d_s and stack length l_{Fe}, which are chosen: d_s = 250 mm and l_{Fe} = 300 mm, for voltage level of 500 V. The proposed number of phases is m = 4, because lower torque ripple is needed and motor can start up from every rotor position. The number of stator and rotor poles is given as N_s / N_r = 8/6, because the stator slot area for turns is larger than for 16/12 SRM. The SRM design starts usually from output equation given as [5]:

$$T = K d_r^2 l_{Fe} \tag{1}$$

where K is the output coefficient and d_r is the rotor diameter. K is proportional to the product of the electric and magnetic loadings. The range of K is very wide (2.7 - 30 kNm/m^3), therefore FEM calculation of torque is recommended.

C. Sizing internal dimensions

The internal dimensions are (see Fig. 1): stator and rotor pole arcs β_s and β_r, rotor diameter d_r, stator and rotor pole widths t_s and t_r, stator and rotor yoke thickness y_s and y_r, air gap g, stator and rotor pole length l_s and l_r and shaft diameter d_{sh}. In accordance with [5], the stator and rotor arcs are chosen β_s/β_r=21°/23° for 4 phase 8/6 SRM. The calculated dimensions are summarized in Table 1.

The simplest way to estimate rotor diameter d_r is from typical ratio d_r/d_s. This ratio can typically vary over the range between 0.4 and 0.7, with most designers preferring 0.5-0.55. It also depends on the number of rotor and stator poles. For 4 phase 8/6 SRM the ratio d_r/d_s = 0.53 is recommended. Then, the rotor diameter is d_r = 132.5 mm.

Once the pole arcs have been decided (chosen), the pole widths t_s and t_r are given by equations:

$$t_s = 2\left(\frac{d_r}{2} + g\right)\sin\frac{\beta_s}{2} \tag{2}$$

and

$$t_r = 2\frac{d_r}{2}\sin\frac{\beta_r}{2} \tag{3}$$

The stator and rotor yoke thickness should be sufficient to carry the peak magnetic flux without saturating. In SRM with 2-pole flux pattern, the main flux is divided into two parallel equivalent parts. Then, yoke thickness should be at least t_s / 2 and t_r / 2, but preferably 20-40% more, because during the commutation of two successive phases the overlapping of poles can occur. Then

$$y_s = (1.2 - 1.4)\frac{t_s}{2} \tag{4}$$

$$y_r = (1.2 - 1.4)\frac{t_r}{2} \tag{5}$$

The SRM needs a uniform air gap and good concentricity to maintain phase currents and minimize acoustic noise. It also requires very small air gap, because whole developed torque is reluctance. A rough rule to choose air gap dimension is 0.5% of the rotor diameter, which is g = 0.2 mm or to make it the smallest given by manufacturing technology and possibilities.

The stator pole length needs to be as large as possible to maximize the winding area. The stator pole length has already been determined by choosing other dimensions of stator:

$$l_s = \frac{d_s}{2} - \frac{d_r}{2} - y_s - g \tag{6}$$

The rotor pole length should be at least 20-30 times the air gap length in order to obtain a low unaligned inductance. A useful rule is also to make

$$l_r = \frac{t_s}{2} \tag{7}$$

A large shaft diameter is desirable to maximize the lateral stiffness of the rotor. From this design it is clear, that the shaft diameter has already been determined by others dimensions, then:

$$d_{sh} = d_r - 2(y_r + l_r) \tag{8}$$

The cross-section area of calculated SRM with its dimensions is in Fig.1 and its 3D view in the Fig.2.

D. Number of turns per pole

The calculation of the number of turns 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:

$$\varepsilon = \frac{2\pi}{m N_r} \tag{9}$$

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

$$\psi_{peak} = \frac{V\varepsilon}{\omega} \tag{10}$$

where ω is angular velocity and V is DC supply voltage.

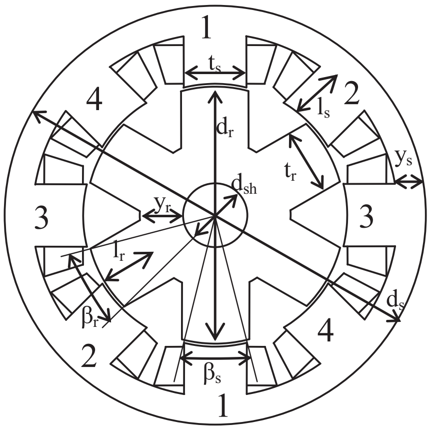

Fig. 1. The cross-section area of calculated SRM with its dimensions

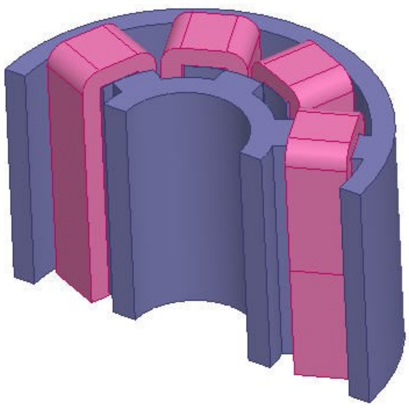

Fig. 2. The 3D volume of calculated SRM

At the 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:

$$\psi_{peak} = t_s l_{Fe} B_s n_c N_p \tag{11}$$

Substituting of eq. (10) to (11),

$$N_p = \frac{V\varepsilon}{t_s l_{Fe} B_s n_c \omega} \tag{12}$$

where n_c is number of coils per phase. The flux density of the stator pole can be supposed to be 1.6T. The cross section of coil wires is depended on normalized wire conductor. The calculation is based on constant flux density (1.6T). All the geometric dimensions are summarized in the Table 1.

TABLE I. SUMMARY OF SRM DESIGN

Parameter	*Symbol*	*Value*	*Units*
Stator diameter	d_s	250	mm
Rotor diameter	d_r	132.5	mm
Stack length	l_{Fe}	300	mm
Air gap	g	0.2	mm
No. of stator poles	Ns	8	-
No. of rotor poles	N_r	6	-
Number of phases	m	4	-
Stator pole arc	β_s	21	o
Rotor pole arc	β_r	23	o
Stator pole width	t_s	21.82	mm
Rotor pole width	t_r	23.08	mm
Stator pole length	l_s	44.72	mm
Rotor pole length	l_r	10.9	mm
Stator yoke thickness	y_s	14.18	mm
Rotor yoke thickness	y_r	15.35	mm
Shaft diameter	d_{sh}	80	mm
Number of turns	N_p	20	turns
Phase voltage	V_{DC}	500	V
Rated power	P_N	20	kW
Rated speed	n_N	5000	rpm

III. FEM ANALYSIS OF SRM STATIC PARAMETERS

There are several methods that can be used to determine the static parameters of the SRM: analytical approach, FEM and measurements. These parameters are input into mathematical model to solve transients and steady state of SRM during its dynamic operation. Very useful and accurate method is based on Finite Element Analysis (FEA), which is used in this paper. For the FEM analysis the following input data are needed: geometrical dimensions of the machine (taken from previous chapter), current density of one phase, material constants (winding conductivity and relative permeability, *B-H* curve of SRM ferromagnetic circuit material) and boundary conditions.

The accuracy of the result depends on the size of FEM mesh and accuracy of the input parameters. The calculation was carried out for each individual rotor position and current under static condition. The rotor position Θ was moved from unaligned Θ_u to aligned position Θ_a with step of 1° and in each rotor position the current was changed within its working range from 0 to 80 A. In Fig. 3 the distribution of SRM magnetic flux can be seen. This analysis has been carried out using ANSYS Maxwell 2D FEM package.

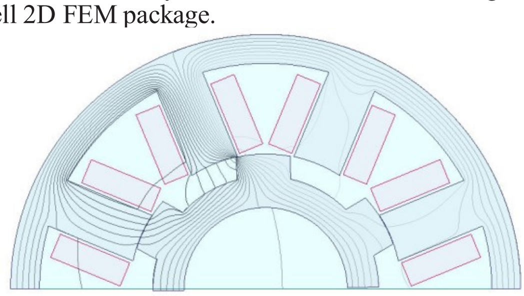

Fig. 3. The distribution of SRM magnetic flux

A. Magnetic flux linkage calculation

The first parameter which has been analyzed is the flux linkage versus phase current for different rotor position $\psi=f(I,\Theta)$. The area bounded by maximal phase current and by both ψ-I curves for aligned and unaligned position is equal to mechanical energy, which is converted to electromagnetic force [13]. The magnetic flux linkage ψ has been calculated as:

$$\psi = n_c N \int BdS \qquad (13)$$

where n_c denotes number of phase coils, N is number of turns of one coil, B is magnetic flux density and S is area of stator tooth in axial direction. In the Fig. 4 can be seen the flux linkage for various rotor position and currents.

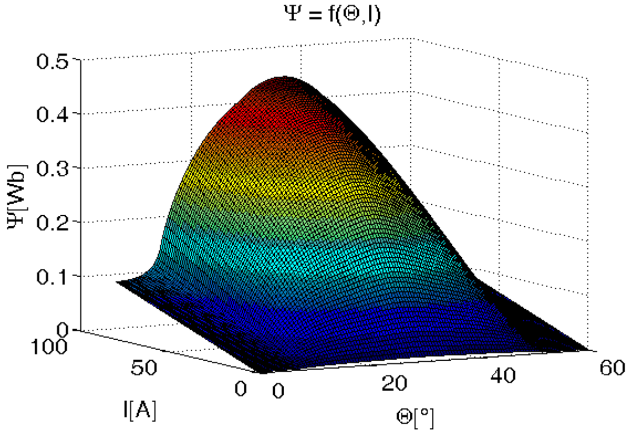

Fig. 4. FEM analysis of the SRM, flux linkage for various rotor position and current

B. Phase inductance calculation

The phase inductance $L=f(I,\Theta)$ versus rotor position for whole current range is a static parameter which is needed in SRM mathematical model for dynamic simulations. The analysis was made for the whole working range. The phase inductance profiles are shown in the Fig. 5. The results are obtained by means of FEM for SRM in accordance with the equation $L = \Psi / I$, where I is the phase current.

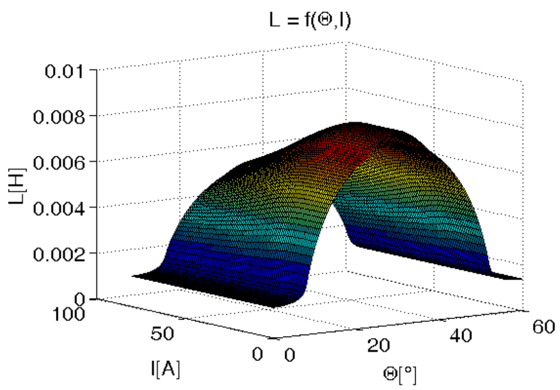

Fig. 5. FEM analysis of inductance for various rotor position and current

C. Electromagnetic torque calculation

For torque calculation is needed to know coenergy W' which is calculated as:

$$W' = \iint (BdH)dV \qquad (14)$$

where H is intensity of magnetic field and V is volume. Then static electromagnetic torque T_e is given:

$$T_e = \left[\frac{\partial W'}{\partial \Theta}\right]_{i=const} \qquad (15)$$

In the Fig. 6, there is shown the static electromagnetic torque of one phase for various rotor positions and various phase currents obtained from FEM.

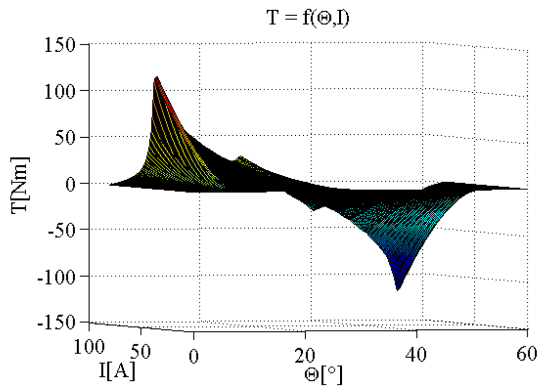

Fig. 6. FEM analysis of torque for various rotor position and current

The SRM design has been carried out for various stack length l_{Fe} to obtain better volume using in the car as small as possible. Therefore, three stack lengths have been calculated 300, 250 and 200 mm. The comparison of static parameters is shown in the Fig. 7., Fig. 8 and Fig. 9 for current 100 A.

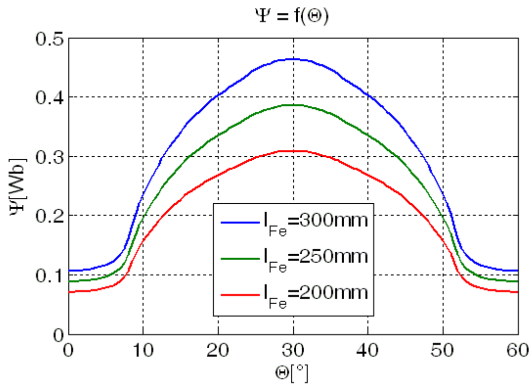

Fig. 7. Comparison of flux linkage for various stack length for current 100 A

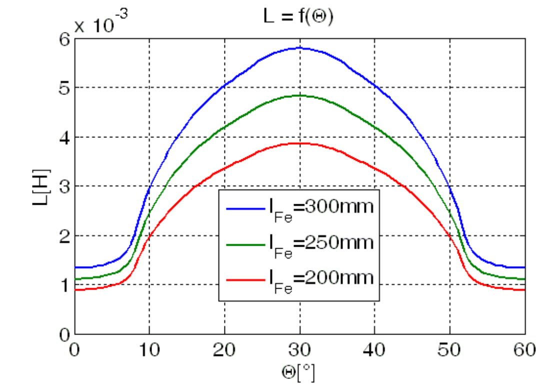

Fig. 8. Comparison of inductance for various stack length for current 100 A

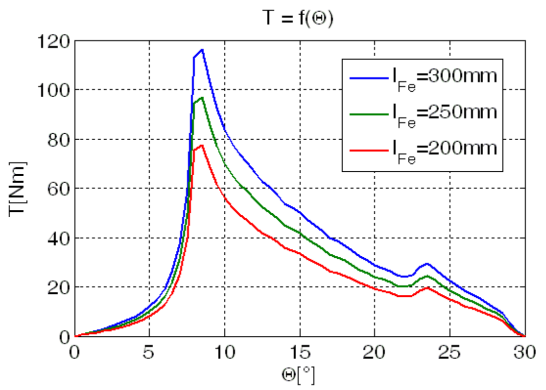

Fig. 9. Comparison of torque for various stack length for current 100 A

IV. Mathematical Model of SRM

By using mathematical model we can calculate phase current, speed, voltage and dynamic torque of the SRM.

The electromagnetic torque of SRM can be calculated from:

$$T_e = \frac{\partial \int_0^i \Psi di}{\partial \Theta} . \tag{16}$$

The voltage equation of one SRM phase is given as:

$$v = Ri + \frac{d\psi}{dt} . \tag{17}$$

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

$$\frac{d\psi}{dt} = \frac{\partial \psi}{\partial i}\frac{di}{dt} + \frac{\partial \psi}{\partial \Theta}\frac{d\Theta}{dt} . \tag{18}$$

The phase current is calculated from combination of (17) and (18) as:

$$\frac{di}{dt} = \frac{v - \left(R + \frac{dL(i,\Theta)}{d\Theta}\omega \right) i}{L(i,\Theta)} . \tag{19}$$

The real angular speed is calculated from equation:

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{j=1}^{m} T_j(\Theta, i) - T_{load} \right) . \tag{20}$$

where J is the moment of inertia and T_{load} is load torque.

The SRM is controlled on the base of rotor position Θ, therefore it is as following

$$\Theta = \int \omega dt . \tag{21}$$

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 optimal dynamic operation of SRM. The simulation of currents, speed and torque waveform has been done for demanded speed 5000 rpm. In the Fig. 10 is shown speed waveform during startup to 5000 rpm and in time $t = 0.6$ load 30 Nm is connected.

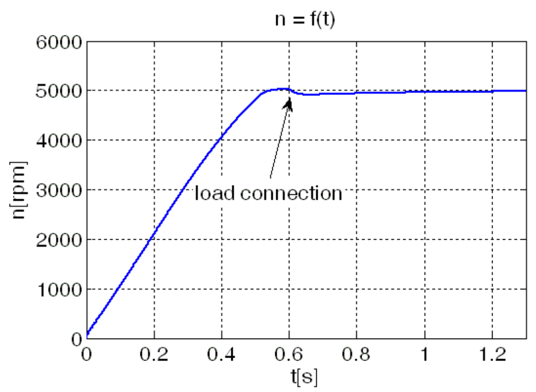

Fig. 10. Speed waveform with $n = 5000$ rpm

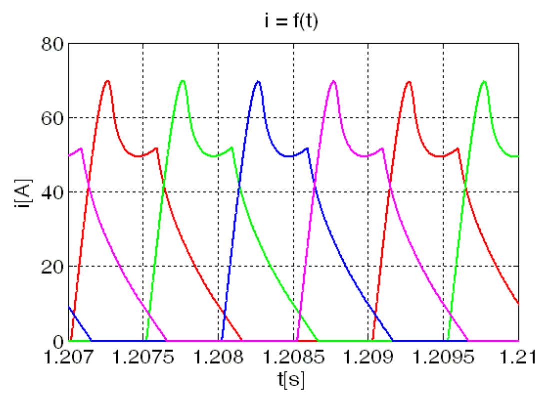

Fig. 11. Phase currents for $n = 5000$ rpm

The output characteristics torque and power versus speed have been obtained from dynamic simulation. These characteristic are shown in the Fig. 12 and 13 respectively for various stack lengths.

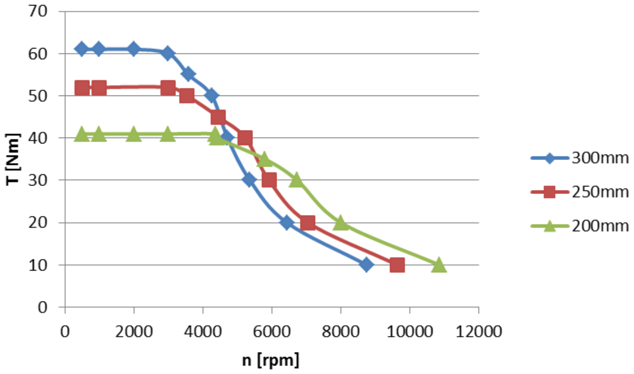

Fig. 12. Torque versus speed characteristics for various stack length

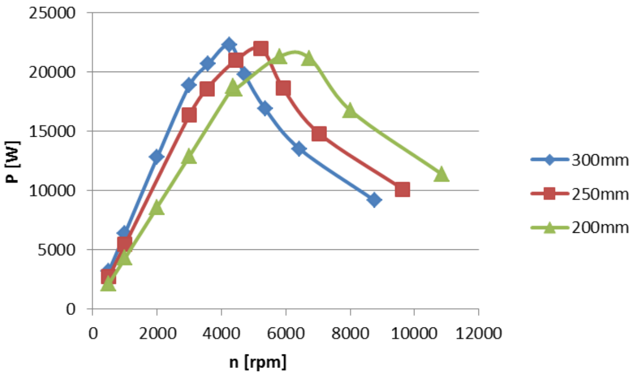

Fig. 13. Output power versus speed characteristics for various stack length

Finally, the losses and efficiency calculations are needed to have the SRM design. Also a thermal analysis is very important task, but it will be published in the next paper.

The losses calculation can be carried out in accordance with [4] or [11]. 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. To calculate the efficiency, the input power is needed. It could be given from known equation for instantaneous power [11]. On this base, the efficiency of designed SRM for various stack lengths, speeds (from 1000 to 5000) has been calculated. The results are from 89 % to 92 %, what are acceptable values for SRM.

V. Conclusion

The paper deals with the SRM design procedure and static and dynamic parameters investigation from point of view of its application and using in electrical cars instead of combustion machine in a real car or vehicle. The SRM dimensions have been calculated. Static and dynamic parameters have been investigated and output power and torque versus speed have been presented for several SRM stack lengths. On this base an optimization will be made in future.

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