Investigation of Switched Reluctance Machine for EV Propulsion Unit with Torque Smoothening Strategy

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Abstract— The paper deals with the investigation of a 30 kW switched reluctance machine (SRM) designed to be used in the automotive industry, as propulsion unit for electrical vehicles (EV). The paper details the most important steps when designing such an electrical machine, and validates the structure using advanced co-simulation techniques, coupling finite element analysis software (Cedrat Flux 2D) with software used to implement the controller (Matlab/Simulink). As the advantages of the SRM are known, its main drawback, the torque ripples, are reduced as much as possible using a dedicated control strategy, the torque sharing functions (TSF). The solution offered by the paper highlights the possibility of using a cheap, reliable and robust electrical machine for propulsion unit.

1. INTRODUCTION

In general, when an electrical propulsion unit is designed, permanent magnet based electrical machines are involved, having increased power density, reliability and maturity in the field of study. However, the issue of price and economical market unbalance, stock limits and political situations, forced researchers to orient their attention to machines that have passive rotors, such as the switched reluctance or the variable reluctance machines [1, 2]. Serious competitors to these machines are the induction machine (IM) or the DC machine, but the latter one has some disadvantages regarding the issue of the sliding contact on the collector. The induction, machines on the other side, are robust, reliable, but their control is not so simple due to the slip, that is quite difficult to be estimated precisely.

To be used as a propulsion unit, the electrical machine has to be reliable, low cost, hence simple design and building and able to reach high speeds of rotation. One machine that reaches all these expectations is the switched reluctance machine (SRM). One such machine is involved in the study of the present paper.

The SRM studied in this paper regards the propulsion unit of a casual small city vehicle, having a power of 30 kW. The speed of the desired SRM is 10 krpm at maximum power and the developed torque is about 28 Nm. The DC supply is ensured by a battery of 360 V. The phase current of the SRM is 150 A at rated power and rated speed.

The present paper will detail the design procedure of the SRM highlighting important aspects regarding compromises that are to be considered to reach increased reliability of the machine. Finite element analysis (FEA) will validate the theoretical studies with regards to the design and control of the SRM. Details regarding the building of the coupled simulation task between Matlab Simulink and Flux 2D are presented, followed by a stand alone Simulink program, used for simulation of the SRM based on FEA fetched results.

Taking advantage of the fast simulation of the new developed program, the linear torque sharing function control method is applied to smoothen the torque of the machine, to fulfill the requirements of the automotive industry with regards to the torque ripple of the propulsion unit.

2. THE PROPOSED SRM

Preliminary to the design of the SRM, some parameters need to be established. The main parameters (given in Table 1) that will guide the sizing process are: the rated current (I), the number of phases (m), the machine's rated power (P_{2N}), the mechanical air-gap (g) the air-gap flux density in aligned position ($B_{g\max}$), the rated speed (n_N) and the rated torque (T_N).

When sizing a SRM it is important to have a proper selection of the stator to rotor number of poles ratio. Lower number of phases, hence lower number of stator poles, will return a structure with increased torque ripples. This represents a serious disadvantage for automotive applications. However, increasing the number of phases and increasing the number of stator poles will decrease the torque ripples. The drawback here is the size of the machine that increases with the number of phases. A second drawback is the complexity and price of the power converter.

Table 1: The SRM's specifications.

Parameter	***Value***	***Unit***
Battery voltage	360	[V]
Imposed current	150	[A]
Output power	30	[kW]
Rated torque	28	[Nm]
Rated speed	10000	[r/min]
Number of stator poles	8	-
Number of rotor poles	6	-
Rated efficiency	0.8	-
Maximum airgap flux desity	1.9	[T]
Airgap length	0.4	[mm]

Hence, the compromise is taken for a 8/6 structure, a four phase SRM.

The main and maybe the most important step when designing the machine is a proper sizing for the mean diameter (D_g) that will have a direct impact on the torque development [3].

$$D_g = \sqrt[3]{\frac{P_{2N} \cdot Q_s \cdot k_\sigma}{Q_R \cdot \pi^2 \cdot k_L \cdot \frac{n_N}{60} \cdot B_{g\max} \cdot \left(1 - \frac{1}{K_{cr}}\right) \cdot A_S}} \tag{1}$$

Based on the size of the mean diameter, the rest of the stator and rotor dimensions can be easily computed, based on geometric models for the poles and the slots of the machine [3].

Each phase of the machine is compound of two coils placed on diametrically opposed stator poles. The coils are connected in series, hence the same current will pass through them. The calculations around the number of turns per coil are based on the relation of the magneto-motive force H and the geometrical details of the machine [3, 4].

$$\Theta = H_{Fe} \cdot (l_s + l_r) + H_g \cdot l_g \tag{2}$$

Hence, the number of turns per coil is computed as ratio between the magneto-motive force and the rated current of the machine. The proper cross section area has to be chosen function of the rated current. Here, about 9.37 was chosen. The height of the stator and rotor poles can be computed now, knowing the final dimensions of the coils. Table 2 contains the data regarding the dimensions of the SRM designed. Their correspondence on the machine's blueprint are depicted in Fig. 1.

The first method to validation is to analytically compute the developed torque of the newly design SRM. This can be accomplished function of the MMF and the machine's mean diameter.

$$T_v = k_{unal} \cdot (N_f \cdot I)^2 \cdot \frac{D_g}{2} \cdot \mu_0 \cdot \frac{l_a}{2 \cdot g} \tag{3}$$

Table 2: The SRM's geometry dimensions.

Parameter	***Notation***	***Value***	***Unit***
Height of stator pole	h_{pS}	18	[mm]
Height of rotor pole	h_{pR}	17	[mm]
Height of stator yoke	h_{jS}	14	[mm]
Height of rotor yoke	h_{jR}	14	[mm]
Width of stator pole	b_{pS}	20	[mm]
Width of rotor pole	b_{pR}	23	[mm]
Active stack length	l_S	100	[mm]
Air-gap length	g	0.4	[mm]

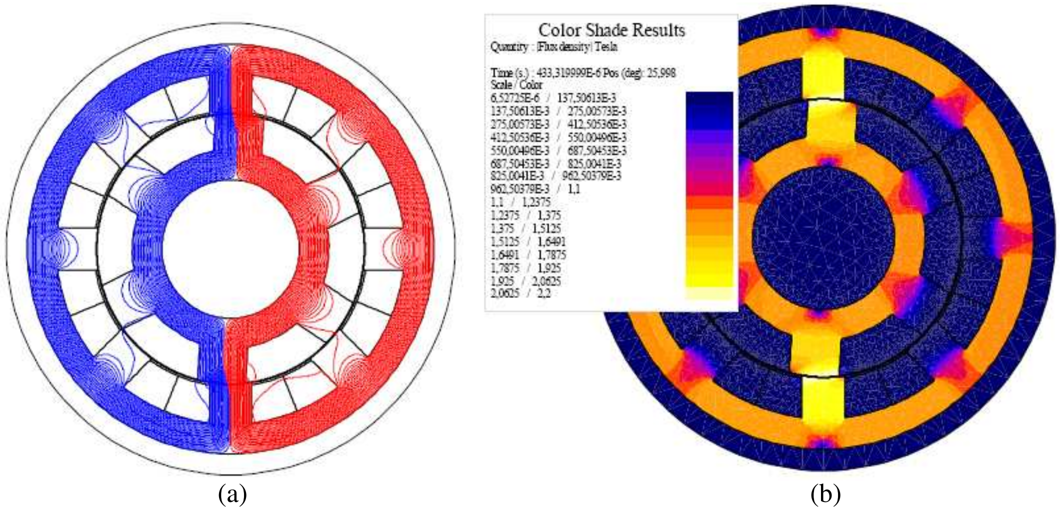


Figure 1: (a) The magnetic flux paths and (b) the flux distribution in the aproached SRM.

where k_{unal} is a constant that considers the contribution of the magnetic flux in un-aligned position. The developed torque, computed analytically with (3) is 28.2 Nm, quite close to the value imposed at the beginning of the design procedure.

3. ANALISYS BY SIMULATION METHODS OF THE SRM

3.1. The Coupled FEA Model for the SRM

Finalizing the sizing process of the SRM, the next step is to validate the results using FEA methods. For this a dedicated software was used, Flux 2D. The model is built considering the possibility to simulate the machine's operation controlled with its power converter [4].

The FEA model of the machine, designed in Flux 2D is coupled to the power converter's controlled, designed in Matlab Simulink [5]. This way, hysteresis current control can be performed in order to observe the machine's behavior and torque development capability.

As it can be seen in Fig. 1, the magnetic flux developed by the SRM closes in the correct paths, involving poles from diametrically opposite directions. However, there is flux that leaks out of the structure, but the ratio of the usable to leakage flux is about 0.9, hence, nearly all the magnetic flux is used for torque development.

Another important aspect to be verified is the flux density in the machine. As depicted in Fig. 1(b), the values of the flux density does not reach hazardous values. Peak values, such as 2T in the edges of the poles, are acceptable and usual for SR machines. From this point of view, the machine is sized correctly.

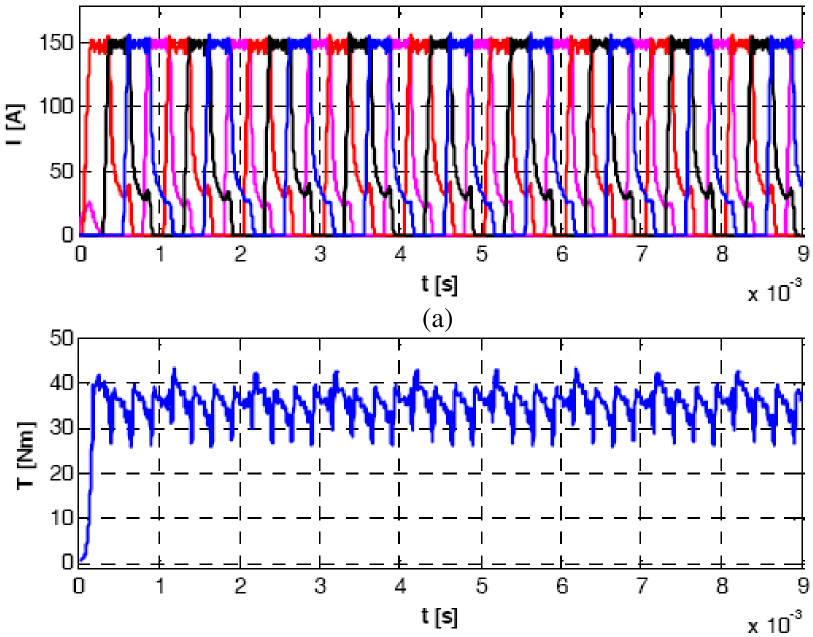
The test via cosimulation of Matlab Simulink with Flux 2D was performed at rated speed, 10000 rpm and rated currents, 150 A. It needs to be mentioned that classical hysteresis controller was involved to maintain the currents at their rated value. In Fig. 2 the evolution of the currents and of the torque function of time is depicted.

The mean developed torque is about 28 Nm, the value desired from the design process, and at the DC voltage of 360 V, the machine is able to form the currents even at the rated speed. It is important to mention that several tests were performed in order to find the proper switching angle. For a so wide range of speeds, from 0 to 10 krpm the switching angle cannot be kept constant. Hence, in the controller, it is important to create a look up table containing the ON and OFF angles function of the speed of the machine.

However, analyzing Fig. 2, the torque characteristic has increased ripples. In this condition, the machine cannot operate as propulsion unit for domestic vehicles. Hence, a dedicated torque smoothening procedure is required to diminish as much as possible these ripples. For this, the linear torque sharing function (LTSF) is engaged in study.

3.2. The LUT Based Matlab/Simulink Model

Studying the LTSF control strategy of the SRM directly on the FEA model is quite difficult and time consuming. However, building a particular model of the machine, based on the classical equations combined with results fetched from the FEA model, proved to be the proper solution. This new



(a)

(b)

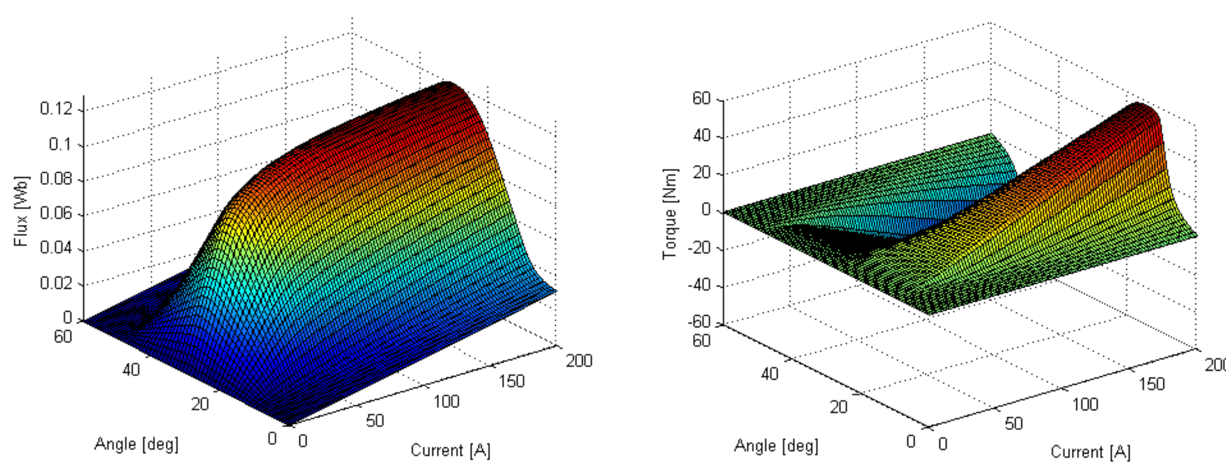
Figure 2: (a) The currents and (b) the developed torque.

model was created in Matlab Simulink based on 3D matrixes from the FEA model containing data regarding data for the magnetic flux and magnetic torque vs. currents and rotor positions [6].

These results are obtained by imposing in one phase of the machine increasing currents from 0 to a current above the rated one (200 A) and for each current moving the rotor from unaligned to aligned, and again to unaligned positions. In order to increase more the accuracy of the model, the characteristics obtained are multiplied for more currents and positions than those imposed using interpolation functions [7–9]. This way one can offer highly accurate results for any simulation scenarios.

The LUT's used in the model are depicted in Fig. 3. In order to compute the flux in the machine, as the input for the first LUT, the analytical expression of the flux function of the voltage is involved (1).

Having the flux and rotor position as input in the LUT, the actual current in the machine can be determined. This will be used then in the second LUT to define the value of the developed



(a) (b)

Figure 3: (a) The magnetic flux and (b) magnetic torque variations vs. current and rotor postion.

torque for the same rotor position.

$$\Psi = \int (u - R_f \cdot i) \cdot dt \quad (4)$$

This approach has the benefit of high accuracy and very fast solving, reducing the computation time from tens of hours with the FEA model to few minutes.

4. RESULTS OF THE ANALYSIS

The LTSF used in the model is based on two different equations that compute the current shape reference function of the torque and of the rotor position. One function is with respect to the increase of the current and one is with respect to the decreasing slope of the current (2). Hence only when phase commutation occurs, the functions are engaged. When one phase conducts, the reference of the controller is the desired torque.

$$f_{inc}(\theta) = \frac{T_{ref}}{\theta_{ov}} (\theta - \theta_{on}) \quad f_{dec}(\theta) = T_{ref} - \frac{T_{ref}}{\theta_{ov}} (\theta - \theta_{off}) \quad (5)$$

As it can be seen in Fig. 4, the LTSF performs well smoothening the torque characteristic as desired both at rated and under rated speeds. The θ_{on}, θ_{off} and θ_{ov}, the ON, OFF and overlap angles can be computed in order to reach even better performances to smoothen even more the developed torque. Also, adding other functions, such as exponential or cubic TSFs can improve the control of the torque characteristic of the machine [10, 11].

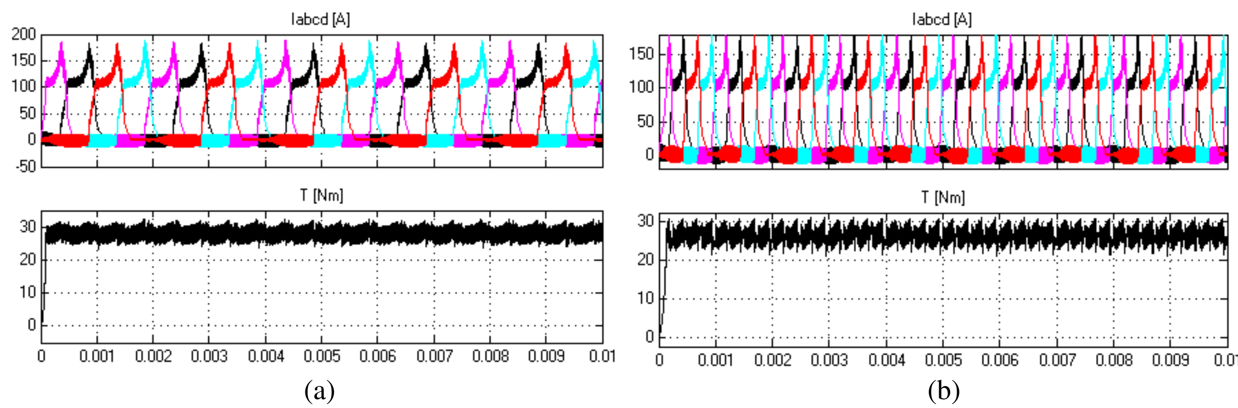


Figure 4: The developed torque and currents for (a) 5000 rpm and (b) 10000 rpm.

5. CONCLUSIONS

In the paper it was detailed the design procedure of a SRM for traction applications followed by FEA based analysis. The torque ripple issue was solved using linear torque sharing function as method of control, smoothening the torque characteristic even at rated speed of 10000 rpm. Hence it was proved that the SRM is a serious candidate to be used as propulsion unit in the automotive industry.

Future investigations regard implementation of several other control strategies combined with noise and vibration analysis.

ACKNOWLEDGMENT

This work was supported by a grant of the Romanian National Authority for Scientific Research, CNDI-UEFISCDI, project number PCCA191/2012.

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