Analysis of a Switched Reluctance Machine for EV Application with Torque Smoothening Strategy

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Abstract— **The subject of the paper is focused on the analysis of a 30kW switched reluctance machine for propulsion of electrical vehicle propulsion (EV). The paper details the fundamental steps when developing such an electrical machine, and validates the structure using co-simulation procedures, coupling finite element analysis software (Cedrat Flux2D) with software used to implement the controller (Matlab/Simulink). As the advantages of the SRM are already known, the torque ripples are its main disadvantages. These 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.**

Keywords—SRM, design, modeling, simulation, control, torque smoothening.

I. 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 [1], [2], [3]. However, the issue of price and economical market unbalance, stock limits and political situations, forced researchers to focus their attention to machines that have passive rotors, such as switched reluctance or variable reluctance machines. 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 targets the propulsion unit of a casual small city vehicle, having a power of 30 kW. The speed of the desired SRM is 10krpm at maximum power and the developed torque is about 28Nm. 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 trade-offs 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 Flux2D are presented, followed by a standalone Simulink program, used for simulation of the SRM based on FEA fetched results.

Taking advantage of the fast simulation of the new developed software, 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.

II. THE PROPOSED SRM

Preliminary to the design of the SRM, some parameters need to be established.

TABLE I. 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]

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

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(g) the air-gap flux density in aligned position (B_{gmax}), 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 topology 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.

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 [2].

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

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 [4], [5].

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

TABLE II. 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]

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. 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.

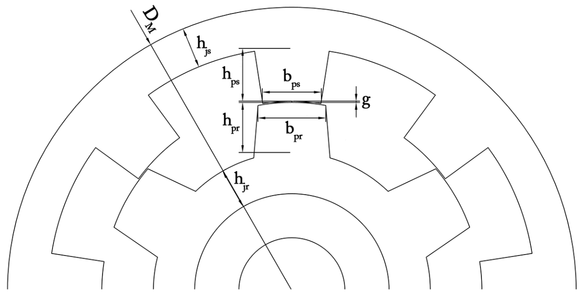

Fig. 1. The designed SRMs main dimensions.

The first validation method 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.

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

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.

III. ANALISYS BY SIMULATION METHODS OF THE SRM

A. *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.

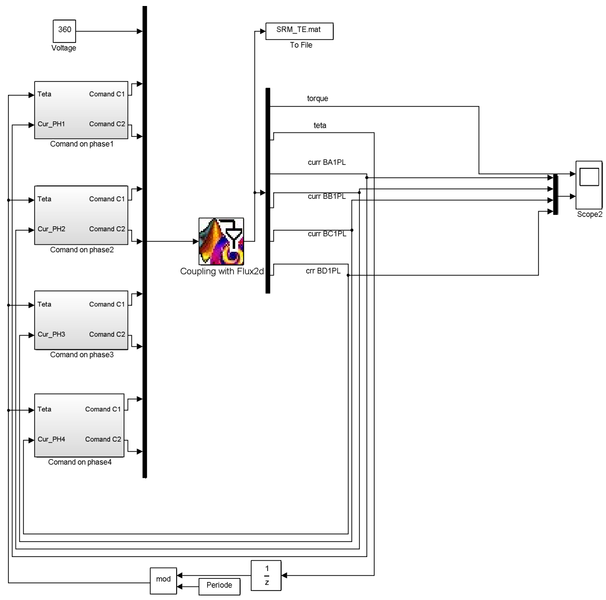

Fig. 2. The Flux 2D to Simulink coupling.

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 Flux2D is coupled to the power converter's controlled, designed in Matlab Simulink (see Fig.2). This way, hysteresis current control can be performed in order to observe the machine's behavior and torque development capability. The current controller is depicted in Fig. 3.

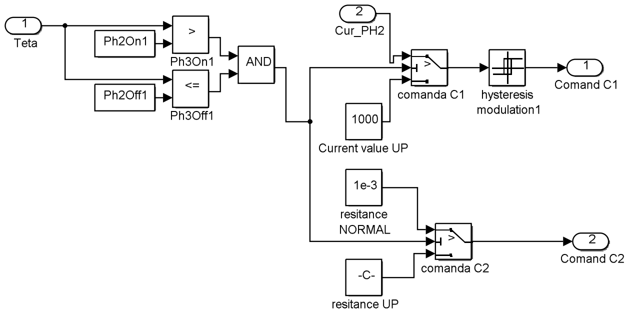

Fig. 3. The Simulink histerezis controller.

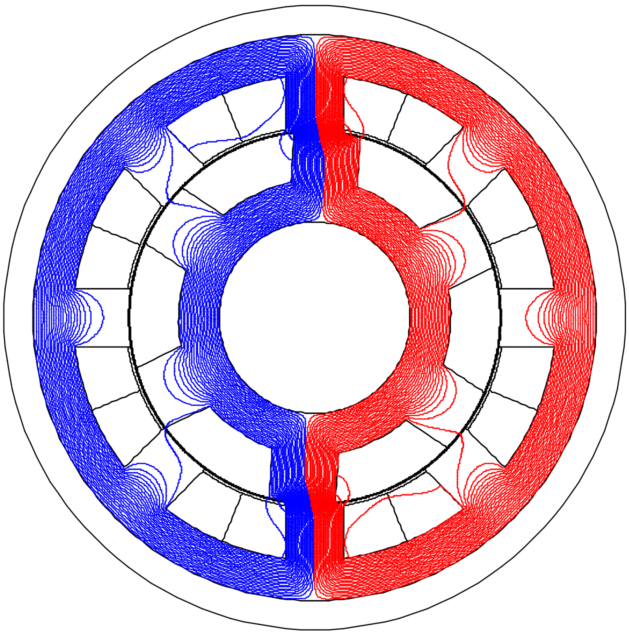

Fig. 4. The magnetic flux paths in the aproached SRM.

As it can be seen in Fig. 4, 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. 5, the values of the flux density do not reach hazardous values. Peak values, such as 2 T 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 co-simulation 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. 6 the evolution of the currents and of the torque function of time is depicted.

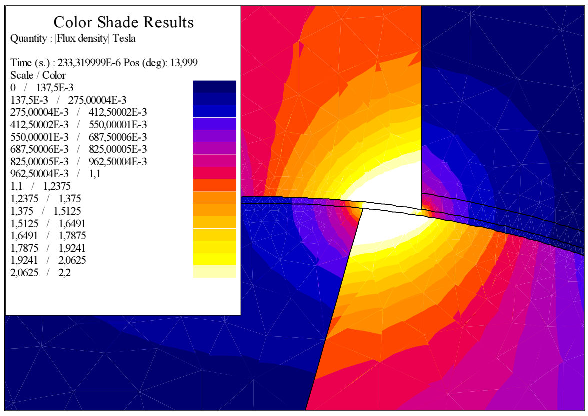

Fig. 5. The magnetic flux density in the aproached SRM.

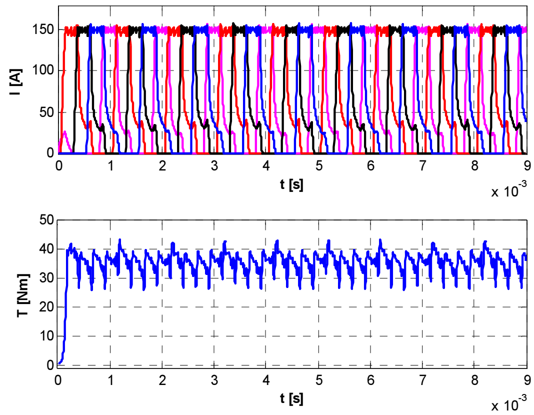

Fig. 6. The currents (top) and the developped torque (bottom)

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. 6, 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.

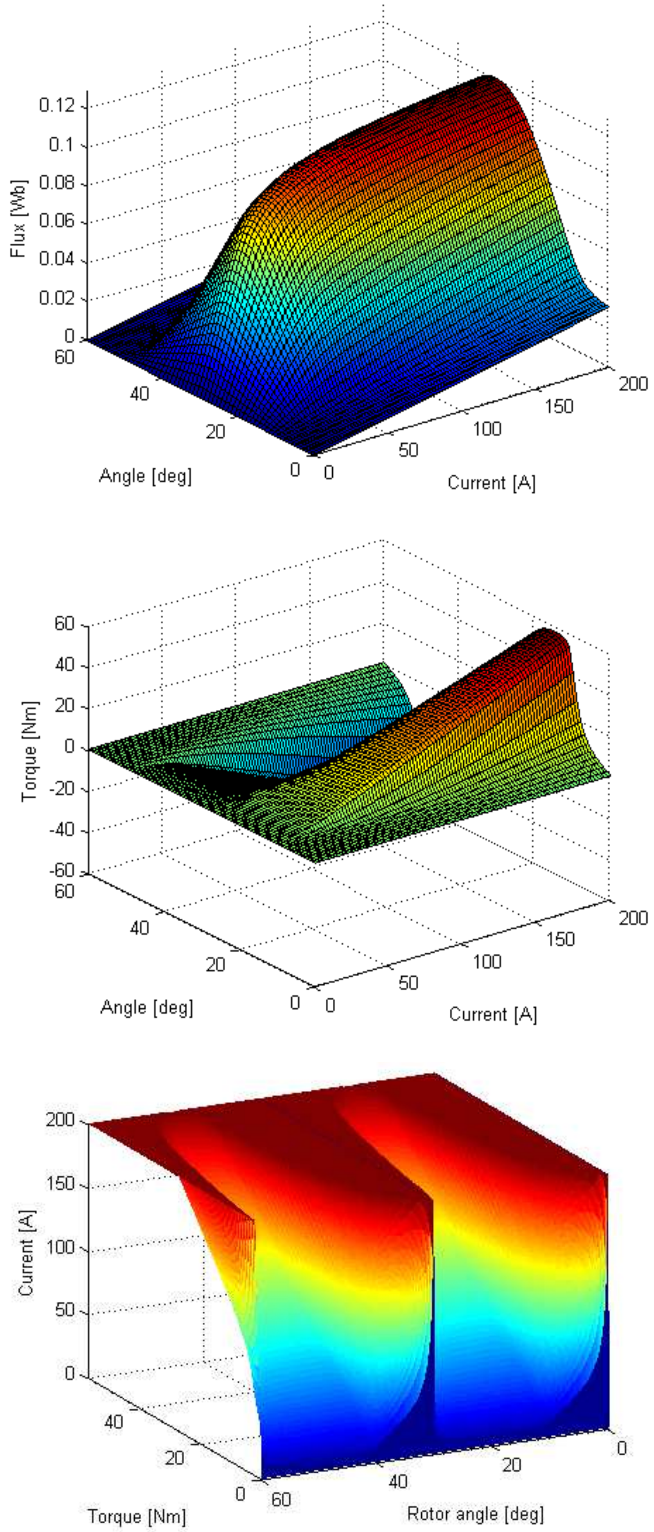

Fig. 7. The magnetic flux (on top) and magnetic torque (in middle) variations vs. current and rotor postion and the current (on bottom) vs. torque and rotor position.

B. 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 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.

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. This way one can offer highly accurate results for any simulation scenarios.

It can be seen that each LUT is very smooth as there is a quite high number of values involved. Each matrix contains about 100000 values. A third matrix, necessary for the LSTF contains data about the current vs. torque and rotor position. All these are depicted in Fig. 7.

The actual machine model based on the LUT's is depicted in Fig. 6. 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 torque for the same rotor position.

$$\Psi = \int \left(u - R_f \cdot i\right) \cdot dt \qquad (1)$$

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.

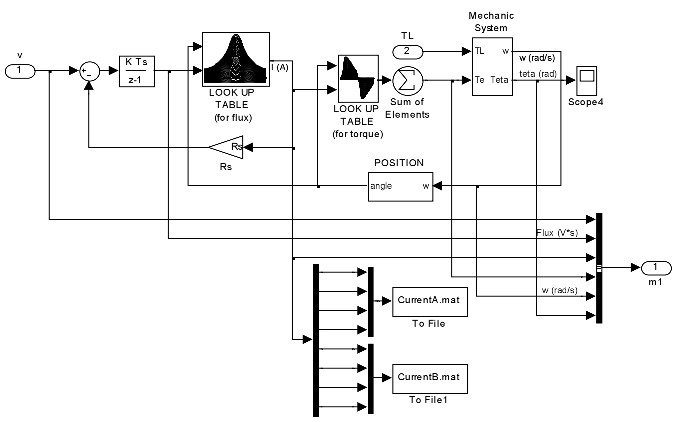

Fig. 8. The machine model based on LUTs

The results of the Matlab Simulink Simulation program are depicted in Fig. 9. There were obtained at 10krpm at rated torque and with simple hysteresis controller in order to validate the operation of the simulation tool. It can be seen that the currents reach the rated value as expected and the torque has the shape of the one obtained from the FEA model. Some minor differences are present due to different simulation time step and interpolation errors.

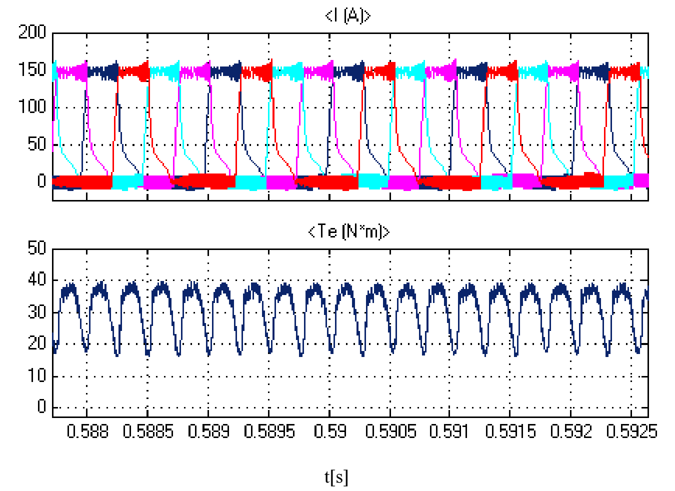

Fig. 9. The results of the Matlab Simulink program with hysteresis controller

C. *The linear torque sharing function (LTSF) control strategy*

In the literature there are many types of torque smoothening strategies developed, but in order to keep as simple and as efficient as possible the machine and its controller, the linear torque sharing function was engaged to smoothen the torque characteristic [7] [8].

Using this strategy while phase commutation, the current in the incoming and outgoing phases is profiled. It is important to mention that each phase must conduct for precisely 15 mechanical degrees with an overlap angle θ_{ov} in the range:

$$\theta_{ov} \leq \frac{\theta_{rot}}{2} - \theta_{off} \tag{2}$$

where, θ_{rot} denotes the period of the rotor and θ_{off} the turn off angle; with θ_{on} the turn on angle of the phase is denoted.

The operation of the LTSF follows the conditions imposed in (3) [8].

$$LTSF(\theta) = \begin{cases} 0 & 0 \leq \theta \leq \theta_{on} \\ f_{inc}(\theta) & \theta_{on} \leq \theta \leq \theta_{on} + \theta_{ov} \\ T_{ref} & \theta_{on} + \theta_{ov} \leq \theta \leq \theta_{off} \\ f_{dec}(\theta) & \theta_{off} \leq \theta \leq \theta_{off} + \theta_{ov} \\ 0 & \theta_{off} + \theta_{ov} \leq \theta \leq \theta_{p} \end{cases} \tag{3}$$

Eq. 3 denotes that there are five stages of control for each phase of the machine, and in two of them the LTSF is null while the phase is out of its conducting region. For the incoming phase the LTSF becomes $f_{inc}(\theta)$ while for the outgoing phase is $f_{dec}(\theta)$. An important issue that needs to be mentioned here, is that the current that needs to be profiled in the machine has to be computed function of the desired torque. Hence, it is necessary to invert the torque vs. current and rotor position matrix, using cubic interpolation methods. The result will be a 3D matrix with current vs. torque and rotor position, such as the one depicted in Fig. 7.

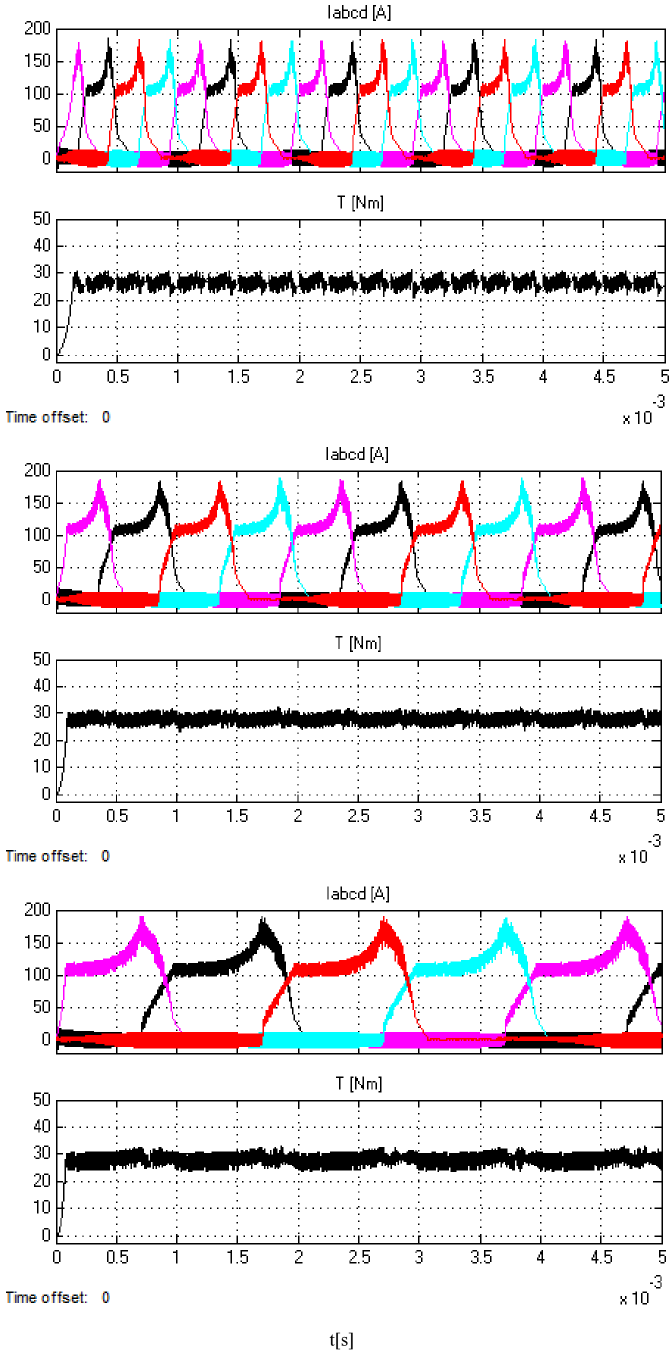

Fig. 10. The results of the Matlab Simulink program with LTSF controller for 10000rpm (top), 5000rpm (middle) and 2500rpm (bottom)

The concept of LTSF [9] refers to the fact that the torque produced during phase commutation varies linearly with the rotor position. The LTSF for the incoming phase is given by (4).

$$f_{inc}(\theta) = \frac{T_{ref}}{\theta_{ov}}(\theta - \theta_{on}) \tag{4}$$

while for the outgoing phase the LTSF will be:

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

As it can be seen in Fig. 10, the LTSF is able to perform torque linearization quite well in order to place the machine in the field of usage in the automotive industry. It can be observed that the currents vary in order to keep the torque around the reference value of 28 Nm. However there are some ripples while phase commutation, but these can be even more smoothened using optimized torque sharing functions with optimized switching angles [10] [11].

The efficiency of the machine with the LTSF was computed, and for 10 krpm it reaches 0.89 decreasing to 0.63 at 2500 rpm.

It is important to mention that using torque sharing functions, it is also possible to minimize the noise and the vibrations of the SRM. Hence, investigation of this aspect it is also important as for propulsion units, the noise level has to be as low as possible [12].

IV. Conclusions

The present paper details the design steps of a 30kW SRM focused for automotive traction applications. Some of the main steps in sizing the machine are presented in order to lead the reader to size a machine able to reach the requested torque at the rated speed.

Several FEA based simulations are performed on the final machine structure. These validate the analytically obtained design breviary. Even more, the flux density distributions are measured to make sure that no hazardous values are reached in the machine.

Preliminary, from the FEA model the torque is computed when controlling the machine with classical hysteresis strategy, imposing the rated current in the windings. The torque ripples are quite high, making the machine impossible to be used in the field of automotive industry. However, applying dedicated torque control strategies to smoothen its characteristic, it is possible to offer the comfort required by an electrical vehicle, equipped with an SR machine. For the study of the SRMs operation with LTSF using a Matlab Simulink program.

This new program is built up using FEA extracted values for the flux and torque versus current and rotor position combined with the classical voltage and flux equations of the switched reluctance machine.

The results proved that the machine can be controlled to reach a linear torque and it can be used in the automotive industry as propulsion unit, having in the same time a good efficiency.The torque ripples are diminished quite well, the only remaining ripples being generated by the switching frequency of the currents. Future investigations regard noise and vibration analysis of the machine and also optimization of the functions in order to find the best ON and OFF angle combinations for the phase switching.

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