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DESIGN OF SWITCHED RELUCTANCE MACHINES FOR INDUSTRIAL APPLICATIONS

Abstract: Switched Reluctance Machines (SRMs) applied in adjustable speed drives are receiving during the last two decades considerable attention from industry since they are characterised by rigid construction, high operation reliability, high efficiency and last but not least low manufacturing costs. The successful realization of a SRM drive for industrial application demands inter alia of the determination of the best motor construction from the point of view of the requirements of considered drive.
A new hybrid design method for SRM drives with application of analytical calculation methods, finite element method and simulation models is proposed in this paper. The calculation/design system is characterised by important effectivity and reliability. The correctness of the proposed design algorithms is verified by laboratory tests made on two motor prototypes manufactured for concrete industrial applications.

1. Introduction

A SRM has salient poles on both stator and rotor. Each stator pole has a simple concentrated winding and there are no conductors of any kind on the rotor. Diametrically opposite windings are connected together either as a pair or in groups to form motor phases. For each phase a circuit with a single controlled switch is sufficient to supply an unidirectional current during appropriate intervals of rotor rotation. For forward motoring, the appropriate stator phase winding must remain excited only during the period when rate of change of phase inductance is positive. Else, the motor would develop braking torque or no torque at all. Fig. 1 shows the typical cross sectional arrangement for a 4-phase SRM having N_s=8 stator and N_r=6 rotor poles ('8/6-SRM').

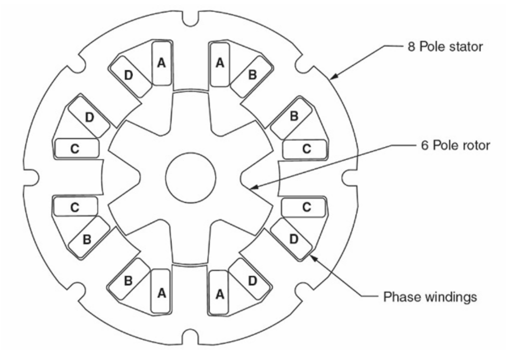

Fig. 1. Arrangement of a 4-phase 8/6-SRM

In recent times, approaches using machine design to influence the machine performance becoming more and more equivalently to efforts at current and hence torque control. The design of SRMs by numeric methods with FEM-programs (Finite Element Method) provides the most precise and proof results. However, calculations by FEM are time consuming and require special, relatively complicated and expensive software. For a complete design of new type series of machines with different dimension's variants the way of using only the FEM is at present not practicable. Therefore software is necessary that can abbreviate considerably the preparation time for the following FEM-calculation. Also the dynamic operational behaviour and the combination of the electric machine with other components like energy storage, converter or mechanical elements must be considered. In that case parameters calculated during the design stage have to be involved in a simulation model.
To meet these requirements for an effective and reliable machine design, this paper proposes a solution to the above mentioned problems in terms of a new hybrid time-economic design-, calculation- and simulation program. This new program developed by author is applied to the design of two different SRM prototypes destined to concrete industrial drives:

(1) a spindle drive in spinning machines for textile industry and
(2) an electrically assisted truck gear.

The correctness of the proposed program will be demonstrated by comparison of the calculation and measurement results made for these two SRM prototypes manufactured by industry.

2. Hybrid design program

2.1. Structure of hybrid design method

Meeting the requirements for an effective machine design requires a new hybrid time-economic design-, calculation- and simulation procedure which is presented in this paper. The structure is shown in Fig. 2 including at first analytical and then numerical calculation methods and finally dynamic simulations. The developed design software can

- abbreviate considerably the preparation time for the following FEM-calculation and
- research the dynamic operational behaviour and the combination of the electric machine with other electrical and mechanical components of the complex drive system.

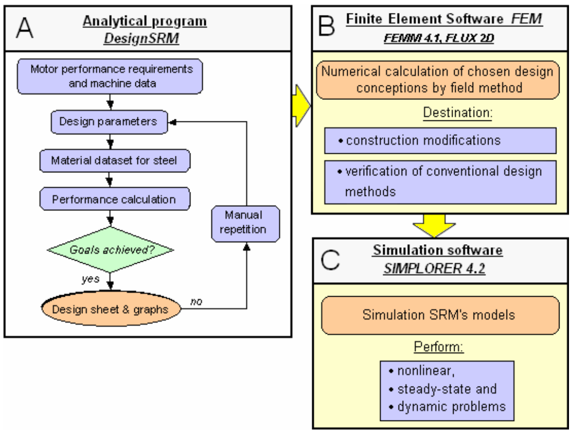

Fig. 2. Structure of the hybrid design program

2.2. Analytical program 'DesignSRM'

In order to fulfil the requirements in a time-effective machine design the analytical computer program 'DesignSRM' was developed by author [3]. That is a special software tool for designing SRMs of various constructions, basing on analytical calculation and design methods proposed in [3]. It is written with the programming language Delphi/Pascal. The program is designed to be fast in operation, with an efficient user interface. Its main use is

- a totally free new machine design or a similar machine design with the same construction starting with a standard geometry proposed by the program;
- winding design;
- calculation of magnetic circuit, considering non-linear magnetization characteristics and saturation effects of the core material;
- calculation of motor and converter losses as well as system efficiency in dependence of different control modes and control parameters;
- calculation and sizing of various steady-state characteristics, e.g. ψ(i,Θ), L(i,Θ), T(i,Θ)
- dynamic calculations, e.g. instantaneous current and torque waveforms;
- studying and learning SRM drives.

Fig. 3 shows a desktop view of the program. Starting from a performance requirement or after loading machine data the computation of all results follows in seconds. A control window shows the program progress and guides the user through the design.

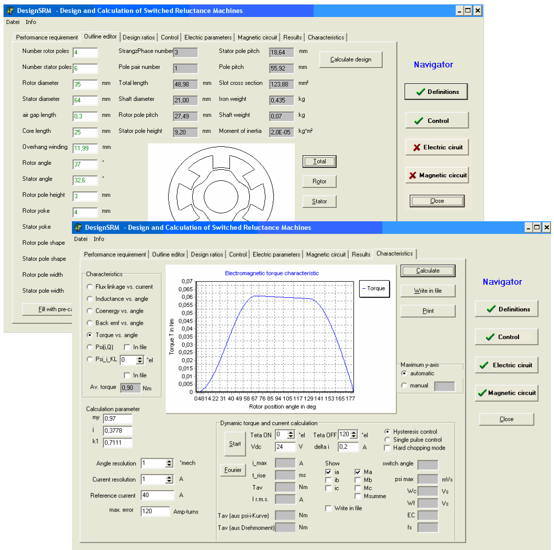

Fig. 3. Analytical program 'DesignSRM'

The motor design is found by calculating its various performance parameters like ψ(i,Θ), L(i,Θ), T(i,Θ) using analytical methods [3]. The process is repeated manually until the design objectives like efficiency or torque-speed-characteristics are achieved. The program provides an outline editor for modifying the cross section. Electrical parameters, control values and many other inputs are considered as well. A material data base includes magnetization and loss characteristics of various steels. Analysis and performance calculations can be either at a specific operating point or over a whole speed-, current-, or torque range to obtain typical machine characteristics. Further, the program contains a discrete time-stepping model to obtain dynamic current and torque waveforms with different control modes.

3. FEM model

The computation of the electromagnetic field is based on Maxwell's equations. By the variable cross-linkage of the space the differential equations are solved numerically. In comparison to the analytical calculation, the FEM offers a number of advantages:

- most accurate and reliable results,
- calculation of any geometry with any field courses,
- real saturation conditions are took into account for each field element and
- steady or dynamic state calculations of any load cases.

Fig. 4 shows the field form of an 8/6-SRM in the case of load run, obtained by the program FEMM 4.2 (Finite Elements Method Magnetics) [4].

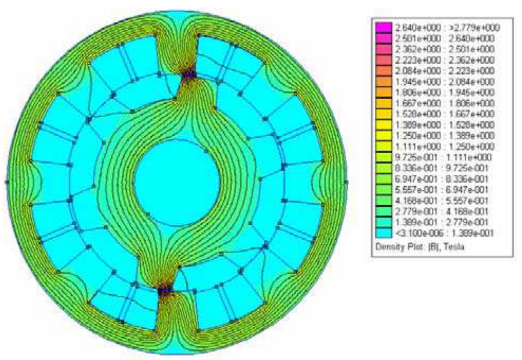

Fig. 4. Field distribution of an 8/6-SRM

FEMM supplies the distribution of the vector potential and the post-processor submits the processing of the data and the calculation of interesting physical values. FEMM 4.2 is free available software for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains [4]. The calculation of the torque vs. rotor position angle characteristics T(i,Θ) requires the calculation of a set of values of electromagnetic torque for given set of angular position of the rotor. Single value of torque T at fixed rotor position angle Θ can be calculated by integrating of Maxwell stress tensor in the air gap region. Assuming constant magnetic flux distribution along the length of the core leads to solution of the two-dimensional magnetostatic problem:

$$T = r^2 \cdot l \int_0^{2\pi} \frac{B_r B_t}{\mu_0} d\Theta \qquad (1)$$

4. Simulation model

The mathematical model of a SRM is highly nonlinear due to magnetic saturation. Assuming that there is no mutual coupling to other phases, the instantaneous voltage of one phase of the SRM windings v_j is

$$v_j = R \cdot i_j + \frac{\partial \psi_j(i_j,\Theta)}{\partial i_j}\frac{di_j}{dt} + \frac{\partial \psi_j(i_j,\Theta)}{\partial \Theta}\frac{d\Theta}{dt} \qquad (2)$$

where j represents the phase number, R is the winding resistance per phase, v_j, i_j, ψ_j are applied voltage, current, and flux-linkage. The electromagnetic torque T_e produced by one phase at constant current can be calculated in terms of the magnetic coenergy W_m:

$$T_e = \left[\frac{\partial W_m(i,\Theta)}{\partial \Theta}\right]_{i=const} \qquad (3)$$

With the load torque T_L, the friction torque T_{Fr}, the rotor pole number N_r, the moment of inertia J and the angular frequency ω the mechanical system is described by

$$T_e - T_L - T_{Fr} - \frac{J}{N_r}\frac{d\omega}{dt} = 0 \text{ with } \omega = {}^{d\Theta}\!/_{dt} \qquad (4)$$

The key to achieve a good simulation of SRM is to use a mythology that permits to take account the non-linearity of its magnetic characteristic while minimizing the simulation time. Such features offers the method using 3-dimensional Look-Up-Tables which approximates the relations L(i,Θ) and T(i,Θ), presented in Fig. 5. They are obtained by previous FEM calculation and alternatively analytical calculations [3].

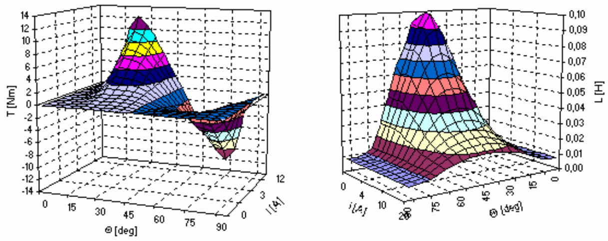

Fig. 5. Torque and inductance characteristics

The simulation model, shown for one phase in Fig. 6, consists of an electrical and a mechanical part. The electrical part represents equ. (2), the phase winding is supplied by an asymmetric bridge converter. The inductance values of each phase are approximated in dependence of actual current and rotor position angle by the 3D-Look-Up-Tables. The mechanical part on the left hand side represents equ. (4).

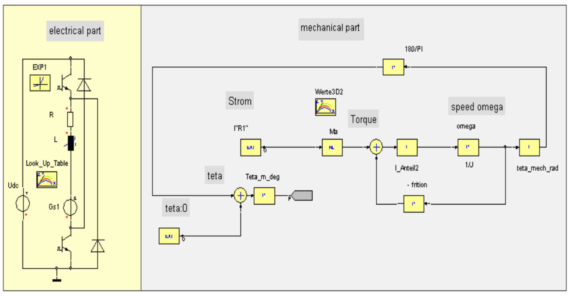

Fig. 6. Simulation model of SRM (1 phase) [3]

5. Industrial prototypes

5.1. 6/4-SRM for textile spindle drive

In cooperation with the German machine construction factory 'Mechanik Leisnig GmbH' and textile machine producer CETEX gGmbH ('Chemnitzer Textilmaschinenentwicklung') a new innovative generation of spindle elements for yarn producing machines as shown in Fig. 7 was developed [1].

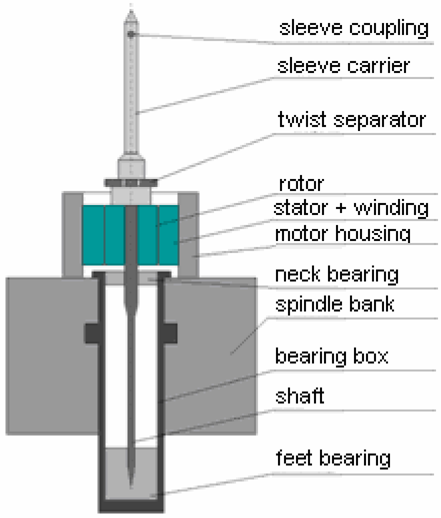

Fig. 7. New spindle element with SRM drive

The new spindle elements include electric single drives which replace the conventional belt drive systems in spinning machines where mechanic components like belts, cogwheels and gears transmit and distribute the mechanic energy from a central energy source.
The technical progress for today's spinning machines is characterized by an increase in performance, quality and ergonomics. Beside the adherence of technological requirements the electrical machines to be developed must fulfil the demand on high efficiency >80% and low manufacturing costs of the entire drive system including converter and control system, since mass production is desired [1]. SRMs are preferred for the application since various advantages of this machine type make them an attractive alternative for ac machines:

- constant speed without mechanic slip due to synchronous operating principle,
- shorter end-windings since concentrated windings can be easily mounted on the stator poles; low manufacturing costs in serial production,
- low moment of inertia, high starting torque,
- easy realization of a holding torque at zero speed, which is a technological need.

Fig. 8 presents the prototype made by industry.

Fig. 8. Manufactured prototype of spindle-SRM

5.2. 8/6-SRM for automatic truck gear

In cooperation with the German gear producer 'ZF Friedrichshafen AG' a SR Motor was developed for the use as a short-time actuator in an electrically assisted automotive gear for cars and trucks. The SRM has to turn the tappet elements in a 6-gear shift for multiples of 45° to choose the lane of a selector fork. The SRM offers similarly to stepping motors pre-defined rotor positions (aligned and unaligned), which can be easily used for an adjusting process. Fig. 9 shows the general arrangement of the automatic gear, consisting of a choice-shaft with several blocking elements, gearwheels and the SR Motor. The gear is much like a classic rack-and-pinion assist gear except that the hydraulic assist function is replaced by a SRM [2].

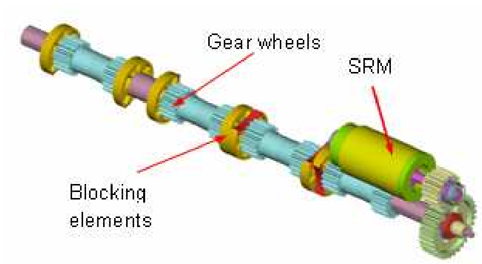

Fig. 9. Electrical assisted gear for trucks [2]

A 4-phase 8/6-SRM was developed with a nominal speed of n_n=1000rpm and nominal torque of T_n=1Nm. The special parameters of the developed machine design in Fig. 9 to achieve maximum torque values are:

- trapezoidal stator and rotor pole profiles to reduce saturation effects and torque ripples,
- larger radius in the stator slots to increase the winding area and
- massive rotor design without laminations; rotor material: 430 Stainless Steel.

Fig. 10. SRM for electrical assisted truck gear

For mounting the winding a 'coil-body' is used on which the stator laminations are pushed on. That is shown on the bottom picture in Fig. 10.

6. Calculation- and Measurement results

6.1. 6/4-SRM for textile spindle drive

Following, results of the laboratory tests including torque vs. rotor position angle T(i,Θ) and copper and core losses vs. rotor speed with constant nominal torque T_n=0.04Nm are presented and compared with analytical calculation results obtained with the program "DesignSRM". Fig. 11 shows the motor on the test bench. Fig. 12 presents the measured torque vs. rotor position angle characteristics for different levels of constant current.

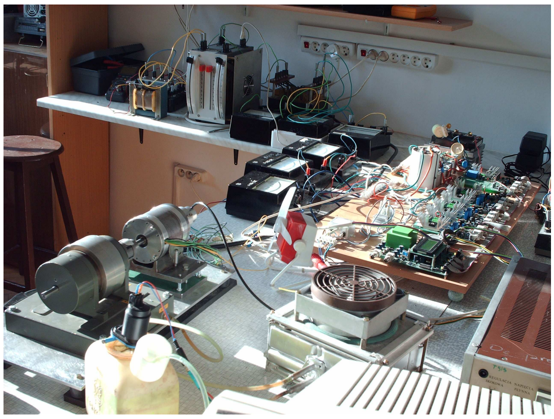

Fig 11. Spindle-SRM on test bench

The analytically predicted values are given with broken lines. The measured and pre-calculated values match very well, however the error between them slightly increases with the current since the saturation effect of the iron material leads to a stronger decrease of torque then predicted. Particularly the narrow rotor yoke saturates even at low currents (5-6A). However, the calculation error is in the range of 3-5% [3].

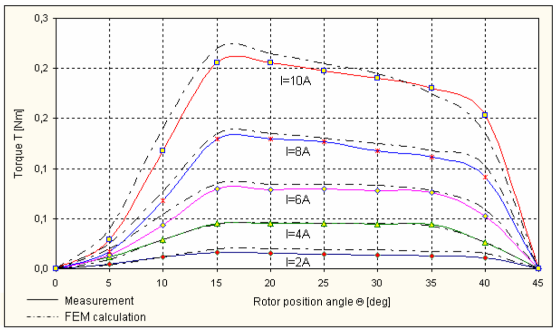

Fig. 12. Measured and predicted T(i,Θ)-curves

Copper- and core losses P_{Cu} and P_{Fe} shown in Fig. 13 have been measured as well as friction losses to obtain the motor efficiency η_{Mot}. The maximum calculation error for copper losses is between 5-7%; for core losses the error is in the range of 10-17%. That is a quiet good result considering that the analytical calculation of core losses is one of the most difficult jobs for SRM designers due do the non-sinusoidal flux-waveform and iron-saturation effects. In order to obtain the core losses by an analytical approach, a modified STEINMETZ-equation extended to non-sinusoidal problems was used [3]. The measured efficiency is 80.3% compared to 79.8% which was calculated, satisfying the demand of industrial application.

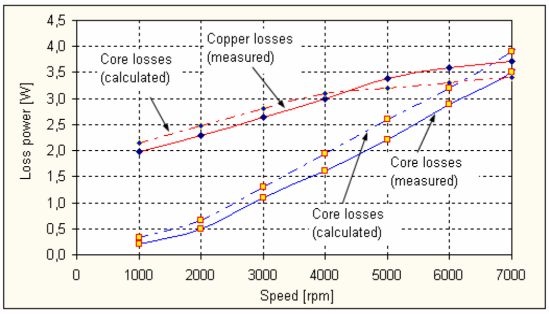

Fig. 13. Measured and calculated motor losses

6.2. 8/6-SRM for automatic truck gear

Fig. 14 shows the SRM prototype on the test bench for measuring torque characteristics.

Fig 14. Gear-SRM on test bench

Measured and analytically predicted torque characteristics for small currents in Fig. 15 are approximately identical. The calculation error increases with current values higher than I=30A. Nevertheless, comparing the characteristics for the investigated current range it is found that the maximum calculation error is less than 10% which is a very good result.

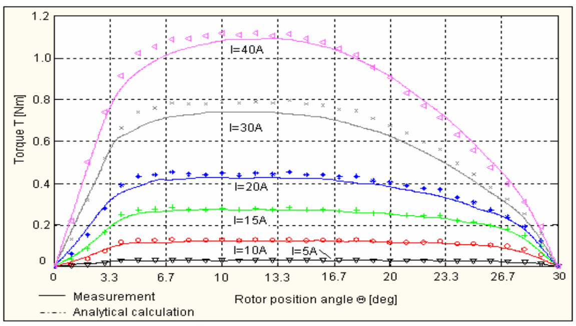

Fig. 15. Measured and predicted T(i,Θ)-curves

7. Conclusions

A new time-effective hybrid design-and calculation program for SRMs was presented including at first analytical and then numerical calculation methods and finally dynamic simulations. The correctness of the proposed design algorithms is verified by laboratory tests made on two SRM prototypes manufactured by industry: a 6/4-SRM for a high-speed electric textile spindle drive and an 8/6-SRM desired as short-time actuator in an electrically assisted gear for cars and trucks. The comparison of both analytical calculation and experimental results were made, proving the high accuracy of the proposed design program. All prototypes fulfil the strong demands of their industrial application what demonstrates that SRMs are a serious solution in the industrial drive marked.

8. Bibliography

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