Prediction of efficiency-optimized electrically excited synchronous machines' operating range using a coupled numerical-analytical method

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ABSTRACT

In this paper, a novel method for predicting the torque-speed characteristics of salient-pole synchronous machines (SPSM) is presented. These characteristics are commonly used as the basis for evaluating drives with variable operating ranges, e.g. traction drives for electric and hybrid electric vehicles. Such vehicles are often powered by permanent magnet synchronous machines (PMSM) which contain economically challenging rare earth materials. An interesting alternative to PMSMs are electrically excited synchronous machines which feature conventional materials and offer various advantages over PMSMs, such as lower losses in field weakening operation and the possibility to control the field excitation. To evaluate the use of SPSMs for different areas of application with wide operating ranges, a fast and precise method for prediction of the torque-speed characteristics is needed. For this reason a coupled numerical-analytical calculation method has been developed, combining the advantages of both approaches. The method is implemented into two software tools with different objectives. The calculation results of these two tools are compared to measurements of an industrial SPSM.

INTRODUCTION

The demands for high efficiency and high torque density require an optimization of the design and the operating modes of SPSMs. To consider the use of SPSMs in electric vehicles, a thorough knowledge of the machine's operating characteristics is needed. The prediction is based on a coupled numerical-analytical approach. The main idea of this method is based on a similar approach for PMSMs as presented in [1]. The general advantages of coupled numerical-analytical calculations especially for synchronous machines are published in [2] .The presented method allows a sufficiently accurate calculation of the efficiency and other important characteristics in the design stage of the machine. Additionally, it can be used to identify an efficiency optimal supply of the machine in order to minimize the overall losses for each operation point. Furthermore, the use of the method presented in this paper is not limited to traction drives only but can also be applied for industrial applications with only one or few relevant operating points.

CALCULATION OF TORQUE-SPEED CHARACTERISTICS IN THE OPERATING RANGE

Whereas the steady state operation points for PMSMs are determined by the two stator current components I_d and I_q according to Park's transformation, the steady state operation points of SPSMs are determined by the stator current components I_d and I_q and additionally the field current I_{fd}, leading to an increased computational effort to determine the torque-speed characteristic. In order to identify the machine's characteristics two software tools are developed, named *SPOK* and *SPOK*-Fast. *SPOK*-Fast can be recommended for calculation of the machine's characteristics during the design phase, while *SPOK* is rather suitable for identifying an optimum control strategy of the operating currents to minimize losses by postcalculation.

1.1 NUMERICAL PARAMETER IDENTIFICATION

In the first stage of the method implemented in *SPOK* the numerical calculation of the characteristic quantities of the SPSM is applied using the finite-elements-method (FEM)-based software *FEMAG* (see Fig.1)

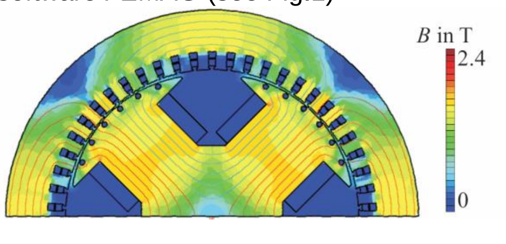

Fig. 1. The (FEM)-model of the test machine in FEMAG

The parameter identification is realized on the basis of steady state field calculations of the (FEM)-model for different vectors $\vec{I}_{\mathrm{SP,ident}}$

$$\vec{I}_{\mathrm{SP}} = \begin{pmatrix} I_\mathrm{d} \\ I_\mathrm{q} \\ I_\mathrm{fd} \end{pmatrix} \qquad (1)$$

within the set of current vectors $I_{\mathrm{SP,ident}}$ (Fig. 2)

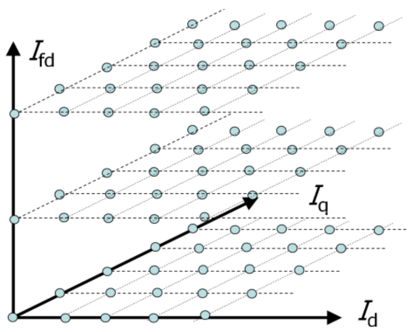

Fig. 2. The set $\boldsymbol{I}_{SP,ident}$ of the current vectors

To consider the influence of saturation effects, the air gap torque, the flux linkages, the inductances and the iron losses are obtained in dependence of the current vector $\vec{I}_{\mathrm{SP,ident}}$.The FEM calculation in *SPOK* is carried out for numerous rotor positions. All identified parameters are than averaged over one rotor revolution. The routine *SPOK*-Fast goes one step further in pursuing the idea of eliminating the need for calculating all electric parameters for every rotor position. Instead, it is assumed that evaluated ripple factors of electromagnetic torque and back-electromotive force (back-EMF) voltage U_{i} remain fairly constant throughout the machine's operating range. Therefore, two so-called ripple factors are calculated for rated operation by evaluating both parameters for a complete electric period.

$$k_T = \frac{T(\gamma=0)}{\bar{T}},\ k_U = \frac{U_i(\gamma=0)}{\bar{U_i}}, \qquad (3)$$

Once these ripple factors are determined, the electromagnetic behavior of the machine can be calculated for all other current vectors $\vec{I}_{\mathrm{SP,ident}}$ without evaluating more than one rotor position. The identification been performed, the density of the $\vec{I}_{\mathrm{SP,ident}}$-grid has to be increased in order to increase the quality of the torque-speed characteristic prediction. Therefore the identified parameters are interpolated in all three dimensions.

1.2 ANALYTICAL CALCULATION OF OPTIMIZED TORQUE-SPEED CHARACTERISTICS

The following losses occurring in the SPSM are considered when calculating the operating range:

- current losses in windings of stator $P_{\mathrm{cu,1}}$ and rotor $P_{\mathrm{cu,2}}$,
- iron losses: hysteresis $P_{\mathrm{fe,hyst}}$ and eddy current losses $P_{\mathrm{fe,eddy}}$
- friction losses P_{frict}
- losses of the inverter P_{inv}
- losses in excitation system P_{brushes}

For a calculation of the torque-speed characteristics, all aforementioned losses are estimated as function of the current vector $\vec{I}_{\mathrm{SP,ident}}$ and of the rotor speed *n*. The recalculation of the iron losses for the different values of the rotor speed *n* is performed according to Steinmetz' equations. The friction losses are considered by means of quadratic interpolation of the values obtained by measurements. The inverter losses are estimated according to [3]. The calculation of the limiting torque-speed curve of the motor is performed considering the limitations of the inverter as well as the temperature limitations of the motor winding insulation system. In order to calculate the maximum torque for a certain speed, it is analyzed if the load torque corresponding values satisfy the following requirements:

$$\begin{cases} U_1 \leq U_{1,\max} \\ I_1 \leq I_{1,\max} \\ I_{\mathrm{fd}} \leq I_{\mathrm{fd,max}} \end{cases} \qquad (2)$$

In the first stage of the operating range calculation, the new sets of all interpolated current vectors that result in an identical torque are evaluated. An example of the iso-surface of current vectors for a given torque demand $\boldsymbol{I}_{\mathrm{SP,ident}}^{T=\mathrm{const}}$ is shown in Fig. 3.

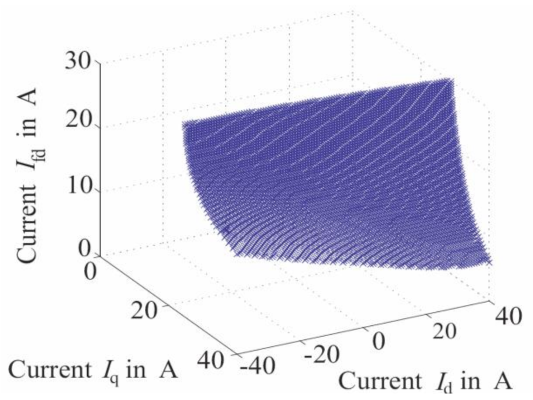

Fig. 3. Iso-torque surface $\boldsymbol{I}_{SP,ident}^{T=const}$

This procedure is repeated for all discrete torque steps in the range from T_{δ}=0 to T_{δ}= $T_{\delta,\max}$ for the specified rotor speed. In the second stage, the total losses for every current vector $\vec{I}_{\mathrm{SP,ident}}$inside of the corresponding set $\boldsymbol{I}_{\mathrm{SP,ident}}^{T=\mathrm{const}}$ are calculated and compared to find the efficiency-optimized current vector $\vec{I}_{SP,opt}$ which provides minimum total losses. The summation is performed using the weighting coefficients $G_{part,i}$ to provide desired weighting of different kinds of losses

$$P_v(\vec{I}_{SP}) = \sum_i G_{part,i} P_{part,i}(\vec{I}_{SP}) \qquad (4)$$

The described procedure is repeated for all discrete torque-speed values in the operating range which meet the requirements (2). Additionally, the friction torque T_{frict} is calculated for each speed and then subtracted from the air gap torque in order to identify the shaft torque. As an example of the result of an operating range calculation, an efficiency map is shown in Fig. 4 for the test machine (Tab. 1)

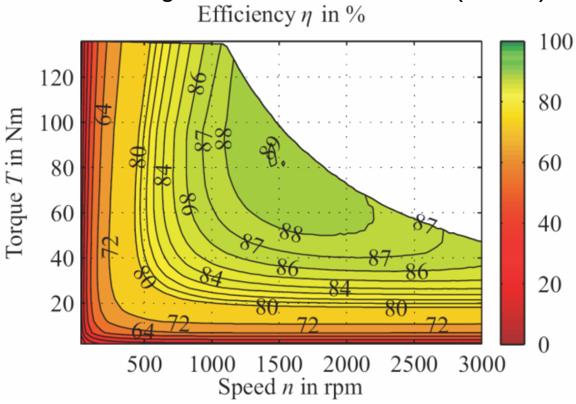

Fig. 4. Efficiency map of the test machine

Rated torque	95 Nm
Rated power	15 kW
Rated speed	1500 rpm
Rated current	21.7 A
Rated field current	18 A
Maximum phase voltage	238 V
Number of slots/poles	54/4

Tab. 1 Data of the test machine

For a quick estimation of the influence of different design and material factors (such as laminated core length, number of turns of stator and rotor winding, operating temperatures, iron loss coefficients etc.) on the torque-speed characteristics, post-processing functions are provided in *SPOK* what can be useful during the design stage of the machine

1.3 VALIDATION OF THE METHOD BY MEASUREMENT

The two described software routines *SPOK* and *SPOK* -Fast have been used to calculate the characteristics of the test machine under different load conditions. The SPSM is supplied directly from the mains with a system frequency of f_1=50 Hz and is coupled with a DC load machine. For different load conditions, the field current of the SPSM is varied, the stator current as well as the electrical power are measured in dependence on the field current I_{fd} and subsequently compared with the results of the calculation (Fig.5).

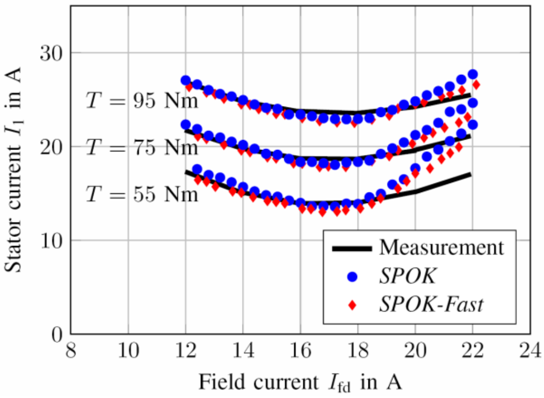

Fig. 5. Comparison between calculation and measurement

CONCLUSION

The paper presents a new method for calculating the operating range of SPSMs which is implemented in software tools named *SPOK* and *SPOK*-Fast. Both software tools were validated by measurements on a test machine. The results show a satisfactory correlation of calculation results and the measurements in a wide range of operating points, exhibiting small deviations for over-excited operation due to a simplified geometry used for the FEM model.

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