Impact of Stator Pole Shape of Synchronous Motor on Torque

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Abstract: - The paper presents pole modelling of small one phase 10 poles synchronous motor with permanent magnets. The purpose of stator pole modelling is to provide a reliable operation of the motor with in advance prescribed direction of rotation with 80 % of the rated voltage. For analysis of magnetic conditions the 2D finite element method was used. Intuitive and trial modelling procedures were used for pole modelling.

Key-Words: - Synchronous motors, Permanent magnets, Magnetic analysis, Finite element methods, Stator pole modeling

1 Introduction

Synchronous motors with permanent magnets present simple drive solution in cases when constant rotational speed needs to be assured. An example of such a drive present drives for watches, drives for hour meters, drives for mechanical counters etc. In such drives the rotational speed is proportional to the frequency of supplied voltage, while the number of revolutions is proportional to the number of periods of supply voltage. The small synchronous motors are usually one phase motors, where the pulsating magnetic field does not generate turning moment in case of perfectly geometrical and magnetic symmetry. By changing (by destruction) of geometrical symmetry, motor is capable of generating the turning moment, while the direction of motor rotation at motor starting is unpredictable. The direction of rotation depends on rotor magnetic poles positions in respect to the stator poles in coherence with the sign of the half-period of supply voltage at motor starting. In practice such a problem is usually solved with a mechanical blockade. However, a mechanical blockade in some cases of unfavourable rotor position prevents motor starting, which can cause standstill rotor vibration.

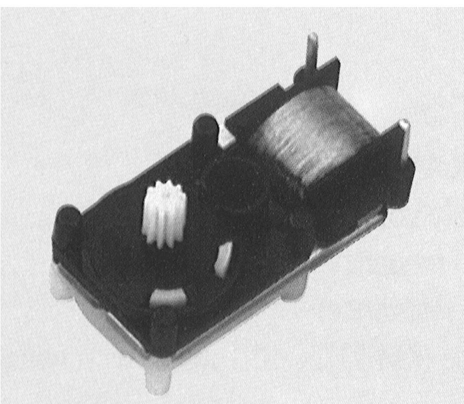

Fig.1: Motor design

In this paper the stator pole modelling of one phase 10 poles synchronous motor with permanent magnets is presented. The purpose of stator pole modelling is to provide a reliable operation of the motor with in advance prescribed direction of rotation with 80 % of rated voltage. This can be achieved by modelling of stator poles in order to achieve appropriate profile of cogging and total electromagnetic torque in dependency on rotor position. The behaviour of the final motor design with the re-designed pole shape was experimentally checked.

2 Motor description

The presented synchronous motor is designed for drives of mechanical counters and hour meters. It consists of two stator segments with salient magnetic poles. Each magnetic pole is assembled from 1.5 mm thick electrical steel. Stator has one phase winding, which is situated at one side of the rotor. Rotor is made from plastic bounded hard ferrite material and it is magnetized in such a way that it exhibits 10 poles structure. The motor design is presented in Fig. 1 and the motor cross-section in Fig. 2. Motor technical data are presented in Table 1. The motor is distinguished by its simple construction and short length, which is very important due to the space limitations.

Table 1: Motor technical data

Supply voltage	24 V (±10%)
Current	5 mA
Frequency	50 Hz, 60 Hz
Rotation speed	600 rpm at 50 Hz, 720 rpm at 60 Hz
Power consumption	0.1 VA

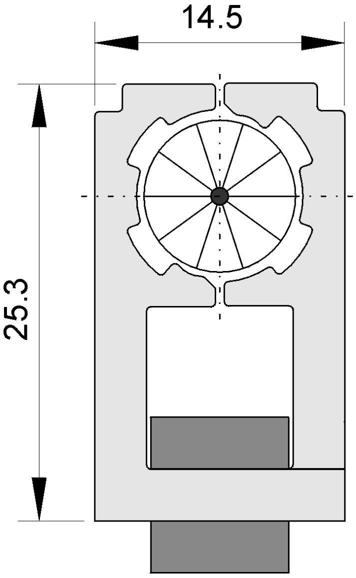

Fig.2: Motor cross-section

3 Calculation of magnetic conditions

For the calculation of magnetic conditions 2D finite element method was used. First order triangular elements were used for cross-section disretization. For each triangular element of rotor discretization, the direction of magnetization in the element should be given for calculation of magnetic conditions. The direction of magnetization from one element to another can vary substantially due to the 10 poles rotor structure. Therefore the direction of magnetization, the depth of magnetization and the degree of rotor magnetization present the main uncertainty at magnetic field calculation. The real conditions in the rotor magnet material can be accounted for only with the detail simulation of magnetic behaviour of rotor material during the magnetization process. Necessary data for detail simulation of magnetic behaviour of rotor material during the magnetization process usually are not accessible to the users, while the magnetization process is accomplished at the manufacturer. Therefore some assumptions at determination of magnetization directions are necessary. These assumptions are:

- Magnetization curve of rotor material at magnetization is linear,
- Relative permeability of rotor material approximately equals 1,
- Magnetization is accomplished with the magnetization device as presented in Fig. 3.

Each bar of magnetization device generates magnetic field with magnetic field intensity H_i

$$H_i = \frac{I_i}{2 \cdot \pi \cdot r} \cdot \operatorname{sgn} I_i \tag{1}$$

I is current in the bar and r is distance between the bar and the observed point in the magnet. Resulting field in the observed point of the magnet is the sum of contributions of all bars. The number of bars is equal to the number of magnetic poles n.

$$H_x = \sum_{i=1}^{n} H_i \cdot \cos\alpha_i, \quad H_y = \sum_{i=1}^{n} H_i \cdot \sin\alpha_i \tag{2}$$

The angle of magnetization direction φ in freely chosen point of the magnet can be determined by (3).

$$\varphi = \arctan\frac{H_y}{H_x} \tag{3}$$

The centre of gravity of the discretization elements was chosen as a point in which the direction of magnetization is prescribed.

Magnetic field distribution for initial motor design without the stator current is presented in Fig. 5a and for rated current in Fig.5b. For both presented cases the rotor is in the same position.

4 Torque calculation

The torque is calculated by Maxwell stress method. This method is based on the distribution of the magnetic field on the closed surface in the air gap around the rotor. For a 2D field solution, the torque is:

$$T = \left[\frac{r}{\mu_0} \oint_C B_n B_t \, \mathrm{d}C \right] L \tag{4}$$

where r is the distance from the integration path to the axis of rotation of the rotor, C is the closed integration path, B_n and B_t are the normal and the tangential components of the magnetic induction on the integration path and L is the axial length of the motor. B_n and B_t are obtained with the transformation of the components B_x and B_y. At presented motor design the relation between the rotor length in respect to the stator length is 2.67, therefore the length L is difficult to define correctly. The length L has influence only on the magnitude of the torque, and does not have influence on the shape of the torque variation in dependency on rotor position, which is the main object of our investigation.

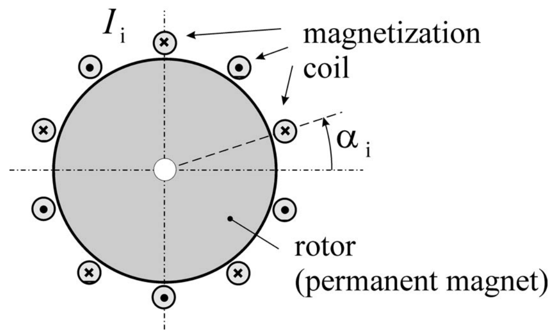

Fig.3: Principle of rotor magnetization

5 Stator pole modelling

The aim of stator pole modelling is to provide a reliable operation of the motor with in advance prescribed direction of rotation with 80 % of the rated voltage. While the quality of different pole shape design can be estimated on the basis of electromagnetic torque characteristic variation in dependency on rotor position, the use of automatic optimisation methods was quite impossible. Therefore intuitive changing of the stator pole shape was used for pole modelling. The initial design of stator pole shape S1 is presented in Fig.4a, while the final design of stator pole shape S2 is presented in Fig. 4b. The final design of stator pole shape S2 was estimated as the most satisfactory design. The analyses were performed also on other pole designs, however these designs gave less satisfactory results than the final design S2.

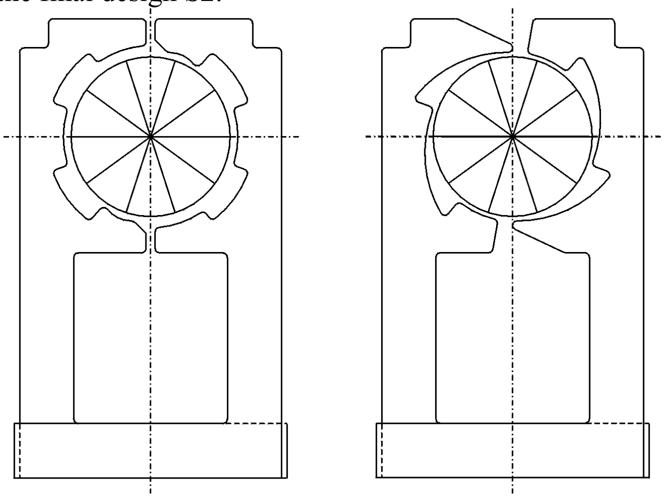

Fig.4: Stator pole shapes: a) initial design S1, b) final design S2

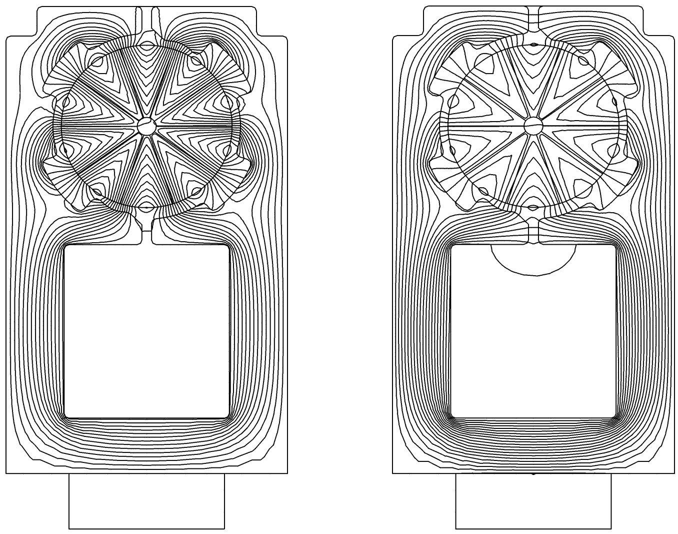

Fig.5: Magnetic field distribution for initial design S1: a) without stator current, b) at rated current

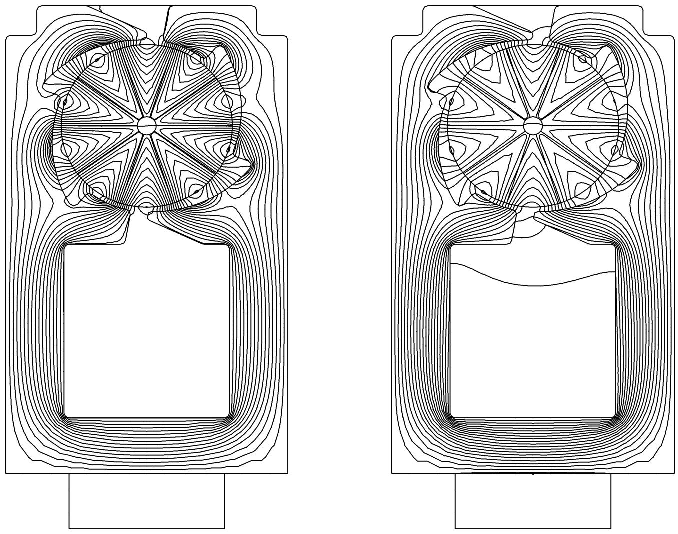

Fig.6: Magnetic field distribution for final design S2: a) without stator current, b) at rated current

Magnetic conditions in the motor for initial design S1 are presented in Fig.5. In this figure it can be seen that almost 30% of total magnetic flux presents leakage magnetic flux, which directly proceeds between adjacent stator poles. Leakage magnetic flux does not generate useful torque, but only increases the impedance of the excitation coil together with the necessary supply voltage. At final design S2, the portion of leakage flux is smaller than for initial design S1. The amount of leakage flux is about 10 % of total magnetic flux (Fig.6.), which has a consequence that for normal motor operation, lower excitation current together with the lower supply voltage is needed.

Cogging and electromagnetic torque have the main influence on the successful start and direction of motor rotation at motor starting. Cogging torque can be directly calculated with rotating rotor without the stator excitation. Variation of cogging torque in dependency on rotor position is presented in Fig. 7, for pole shape presented in Fig. 4. Period of the cogging torque is equal to the rotor pole pitch, that is 36 degrees. The main feature of cogging torque at motor starting is that the standstill rotor position is exactly determined with cogging torque. In Fig. 7 it can be seen that standstill rotor position is about 18 degrees for initial pole design S1 and about 21 degrees for modified final pole design S2 in respect to the presented rotor position in Figs.4-6. The cogging torque has the influence also on the total electromagnetic torque. Variation of total electromagnetic torque in dependency on rotor position at constant rated current of 5 mA is presented in Fig. 8. In this case the period of the total electromagnetic torque is equal to the two rotor pole pitches. At the initial pole shape design S1 the electromagnetic torque dependency on rotor position is almost mirror symmetrical, therefore the probability for both directions of rotation are equivalent. However, this cannot be observed for final pole shape design S2, where is the above mentioned symmetry more destructed, which increases the probability that the motor will turn in the chosen direction at the motor starting.

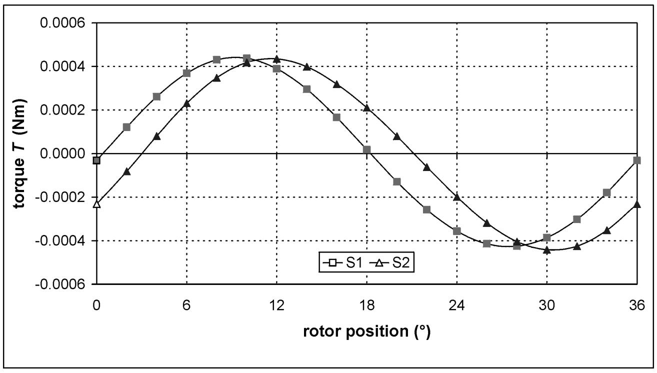

Fig.7: Variation of cogging torque in dependency on rotor position

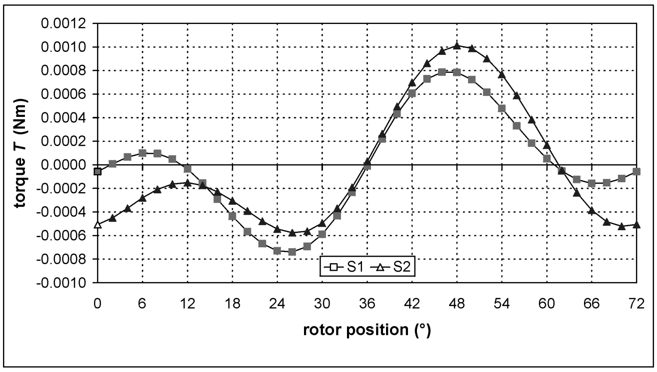

Fig.8: Variation of electromagnetic torque in dependency on rotor position at rated current $I = 5$ mA

6 Conclusion

Searching for optimal stator pole shape is a pretentious and time consuming process, which cannot be fully automatized due to the need for torque calculation in more rotor positions over one period. The FEM can be a very useful tool, which helps us, together with experience and intuition to decrease the number of necessary prototypes. The biggest problem at the use of FEM for analysis of magnetic conditions in small motors presents the material characteristics. In presented motor design dimensions of all motor parts are very small, therefore the huge influence of mechanical treatment on the magnetic properties of used magnetic materials can be observed. From this reason in almost all cases the heat treatment is necessary after the mechanical treatment of the materials. The rotor magnetization can present a serious problem at calculation of magnetic conditions in the motor, while depth, degree and direction of rotor magnetization cannot be accurately defined.

Presented motor analysis shows that it is possible to obtain with modelling of stator poles advance prescribed direction of rotation with higher probability of successful starting at reduced supply voltage. This statement was experimentally checked on prototypes. Unfortunately, the measurement results are not presented, for at the time we do not have the measurement equipment for measurement of such small torque values.

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