**Bojan ŠTUMBERGER[1], Miralem HADŽISELIMOVIĆ[1], Tine MARČIČ[2]**

University of Maribor, Faculty of Electrical Engineering and Computer Science (1)
TECES, Research and Development Centre for Electric Machines (2)

# Determination of the adequate split ratio for high-efficiency permanent magnet synchronous motors with surface mounted magnets and concentrated non-overlapping windings

***Abstract**. In the presented study, the influence of the split ratio in 12 slot-14 pole permanent magnet motor with interior rotor on the efficiency and torque capability over a wide-speed range is presented. Results for two motors with the same outer stator diameter and different split ratio are presented in order to demonstrate the influence of split ratio on the motor efficiency and torque capability.*

***Streszczenie.** W artykule przedstawiono wpływ parametrów geometrycznych stojana (stosunek promienia wewnętrznego do zewnętrznego) silnika z magnesem trwałym 12-żlobkowego i 14-biegunowego na sprawność i wydajność momentu w szerokim zakresie prędkości. Wyniki analizy dwóch silników z takimi samymi średnicami zewnętrznym stojana i różnymi wewnętrznymi zostały zaprezentowane w celu zademonstrowania tego wpływu. (**Określenie odpowiednich parametrów geometrycznych stojana w silnikach synchronicznych z magnesami trwałymi o wysokiej sprawności z magnesami umieszczonymi powierzchniowo i nie-nakładającymi się koncentrycznymi uzwojeniami**)*

**Keywords:** synchronous motors, permanent magnets, concentrated windings, split ratio.
**Słowa kluczowe:** silniki synchroniczne, magnesy trwałe, uzwojenia koncentryczne.

## Introduction

Three-phase permanent magnet synchronous motors with surface mounted magnets and concentrated non-overlapping windings having similar slot and pole numbers $2p=N\text{s}\pm1$ and $2p=N\text{s}\pm2$ (where $p$ is number of pole pairs and $N$s number of slots ) has drawn particular attention of the researchers in the last few years. Different selection of slot and pole number mainly depends on the desired shape of back-EMF line-to-line waveform, cogging torque level, torque ripple level, noise level, efficiency and overload capability [1, 2]. Particularly popular are machines with 9 slots ($2p$=8 or $2p$=10) and 12 slots ($2p$=10 or $2p$=14). In such machines however lower and higher order stator magnetomotive force (MMF) harmonics might cause localised core saturation, higher iron core losses and significant eddy current losses in permanent magnets, which limits maximal speed of the machines. Particularly interesting is the design of such machines which exhibit high efficiency over a wider speed range, without increasing overall machine dimensions, typically imposed as design constraints.

It has been long realized that the split ratio (the ratio of the stator bore diameter to the stator outer diameter $D_{\text{sb}}/D_{\text{o}}$) has a significant influence on the torque capability and efficiency of the cylindrical permanent magnet machines [3, 4].

In the presented study, the influence of the split ratio in 12 slot-14 pole permanent magnet motor with interior rotor on the efficiency and torque capability over a wide-speed range is presented. The outside stator diameter dimension $D_{\text{o}}$ (96 mm) and stator and rotor package length dimension $l_{\text{fe}}$ (30 mm) were design constraints. Motor characteristics were calculated by using 2D finite element method software by taking into account copper losses, iron core losses [5-7], eddy current loss in permanent magnets and friction and windage losses as well. For PM material sintered NdFeB magnets were selected, while for iron core material 0.35 mm thick non-oriented electrical steel M250-35A was taken into account. Results for two motors with the same outer stator diameter and different split ratio are presented in order to demonstrate the influence of split ratio on the motor efficiency and torque capability.

## Method of analysis

The calculation of magnetic conditions:

To obtain the field distributions and the loci of local flux density vectors in the motor, a series of magneto-static field calculations for a complete cycle of field variation was computed by 2D FEM, using the basic equation:

$$\text{rot}(\nu\,\text{rot}(\boldsymbol{A})) = \boldsymbol{J}_0 + \text{rot}\boldsymbol{M} \tag{1}$$

where $\nu$ denotes the reluctivity, $\boldsymbol{A}$ is the magnetic vector potential, $\boldsymbol{J}_0$ is the current density and $\boldsymbol{M}$ is the magnetization of the permanent magnets.

The non-linearity of the used iron core material was accounted for with a single-valued $B$-$H$ curve. The magnetic conditions over a complete cycle of magnetic field variation were calculated in 106 discrete equidistant time steps by shifting the rotor position and simultaneously changing the stator excitation.

Terminal voltage and input power calculation:

The discrete time forms of phase voltages were calculated from the average values of the vector magnetic potential in stator slots according to the winding arrangement scheme. The end winding contribution was taken into consideration with the constant value of end winding inductance $L_{\text{e}}$.

The instantaneous value of the phase voltage in the winding of phase a is given by

$$v_{\text{a}}(t) = Ri_{\text{a}}(t) + \frac{p}{c}\frac{d\psi_{\text{ap}}(t)}{dt} + L_{\text{e}}\frac{di_{\text{a}}(t)}{dt} \tag{2}$$

where $R$ is phase resistance, $\psi_{\text{ap}}$ is the instantaneous flux linkage of the a phase winding per pole, $p$ is the number of pole pairs and $c$ is the number of parallel circuit of the phase winding. Terminal line-to-line voltage was calculated from calculated waveforms of phase voltages.

The input power was calculated from calculated time forms of phase voltages and the known form of input current as

$$P_1 = \frac{1}{T}\int_o^T \left[ v_{\text{a}}(t)i_{\text{a}}(t) + v_{\text{b}}(t)i_{\text{b}}(t) + v_{\text{c}}(t)i_{\text{c}}(t) \right] dt \tag{3}$$

The iron loss calculation:

An arbitrary flux density vector variation in each element of mesh was expanded into a Fourier series of elliptical harmonic flux density vectors. For each $k$-th harmonic flux density vector, the major axis flux density $B_{k\text{maj}}$, the minor axis flux density $B_{k\text{min}}$ and the ellipticity ratio $\beta_k = B_{k\text{min}} / B_{k\text{maj}}$ were determined. The total core loss in the element was determined as the sum of total hysteresis losses $p_{\text{th}}$, total classical eddy current losses $p_{\text{te}}$ and total excess losses $p_{\text{ta}}$ as:

(4) $$p_{\text{th}} = \sum_{k=0}^{\infty} k \left[ \beta_k p_{\text{rh}k} + \left(1-\beta_k\right)^2 p_{\text{ah}k} \right]$$

(5) $$p_{\text{te}} = \frac{\sigma d^2}{12\rho} \frac{1}{T} \int_0^T \left[ \left( \frac{dB_{\text{x}}(t)}{dt} \right)^2 + \left( \frac{dB_{\text{y}}(t)}{dt} \right)^2 \right] dt$$

(6) $$p_{\text{ta}} = \frac{C_{\text{ar}}}{(2\pi)^{3/2}} \frac{1}{T} \int_0^T \left[ \left( \frac{dB_{\text{x}}(t)}{dt} \right)^2 + \left( \frac{dB_{\text{y}}(t)}{dt} \right)^2 \right]^{3/4} dt$$

where $p_{\text{rh}k}$ and $p_{\text{ah}k}$ are the rotational and the alternating hysteresis loss with flux density $B_{k\text{maj}}$ at frequency $f$ of fundamental elliptical harmonic, $\sigma$ the conductivity, $\rho$ the material mass density and $d$ the thickness of the laminations. The $B_{\text{x}}$ and the $B_{\text{y}}$ are the x and the y components of $\boldsymbol{B}$. The rotational $p_{\text{rh}k}$, the alternating $p_{\text{ah}k}$ hysteresis loss and the coefficient of rotational excess loss $C_{\text{ar}}$, which appear in above equations, were determined from iron loss measurement and iron loss separation of used magnetic material (0.35 mm thick non-oriented Fe-Si electrical steel M250-35A) under alternating and circular flux conditions [6, 7].

Eddy current loss calculation in permanent magnets:

The eddy current loss in permanent magnets was calculated from the variation of average value of the vector magnetic potential in each element of the permanent magnet material discretization over one electrical cycle as:

(7) $$p_{\text{eddyPM\_e}} = \sigma_{\text{PMeff}} l_{\text{e}} \Delta_{\text{e}} \frac{1}{T} \int_0^T \left( \frac{dA_{\text{e}}(t)}{dt} \right)^2 dt$$

where $p_{\text{eddyPM\_e}}$ is average eddy current loss over one electrical cycle in the element, $\sigma_{\text{PMeff}}$ is the equivalent PM material conductivity [8, 9] (taken into account end effect), $l_{\text{e}}$ length of the PMs in the axial direction, $\Delta_{\text{e}}$ surface of element of discretization and $A_{\text{e}}$ average value of magnetic vector potential in the element.

For the determination of equivalent PM material conductivity the following correction formula is used [9]:

(8) $$\sigma_{\text{PMeff}} = \sigma_{\text{PM}} \frac{3}{4} \frac{L^2}{w^2 + L^2}$$

where $\sigma_{\text{PM}}$ is electrical conductivity of PM material, $L$ is length and w is width of permanent magnet segment.
In the used method for the determination of eddy current loss in PM material following assumptions are made:

- the eddy currents in PMs are resistance limited, i.e. magnet segments dimensions are less than skin depths;
- the eddy currents flow only in one plane;
- PM segments are electrically isolated from each other.

**Results and discussion**

Results for two motors with the same outer stator diameter, the same active motor length and different split ratio are presented in order to demonstrate the influence of split ratio on the motor efficiency and torque capability. Motor with the higher split ratio (called Motor A) has more PM material and less copper material than motor with lower split ratio (called Motor B). The Motor A has also wider slot opening than Motor B. Both motors have the same one side air-gap length and are designed to produce similar electromagnetic torque at the same RMS value of phase current. All presented characteristics are determined for the case of pure sinusoidal current supply, when the vector of stator current has only q-axis current component. The same variation of friction and windage losses for both motors in dependency on speed was taken into account (friction and windage losses were obtained from the experiments on the similar size motor).

Fig. 1 and Fig.2 show cross-sections of two motors with different split ratio used in the analysis (Motor A and Motor B). In Fig. 3 the influence of magnet axial segmentation on eddy current loss in permanent magnets is presented. In following figures, Fig. 4, Fig. 5 and Fig. 6 variation of iron core loss, input power, output power and shaft torque in dependency on motor speed is presented. In determination of output power and shaft torque the segmentation of magnet material in six pieces along axial direction is taken into account.

From the presented results it can be seen that Motor A exhibits higher eddy current loss in permanent magnets than Motor B. This effect is mainly caused by the wider slot opening, especially at no-load [10].

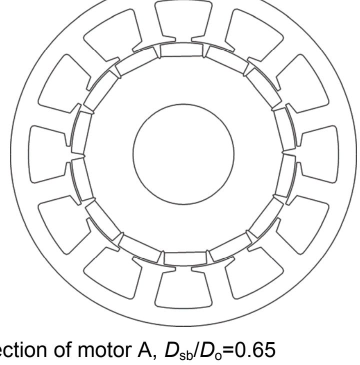

Fig. 1. Cross-section of motor A, $D_{\text{sb}}/D_{\text{o}}$=0.65

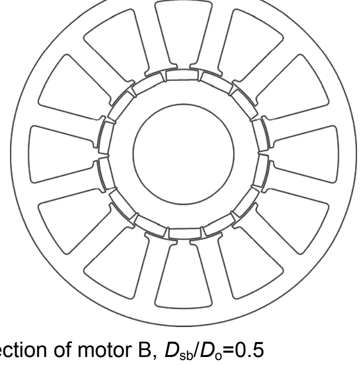

Fig. 2. Cross-section of motor B, $D_{\text{sb}}/D_{\text{o}}$=0.5

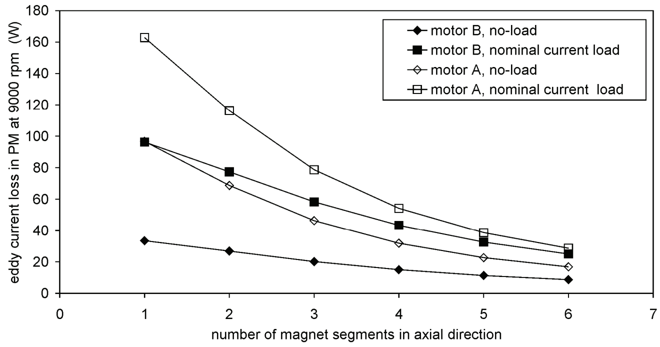


Fig. 3. Eddy current loss in permanent magnets at 9000 rpm

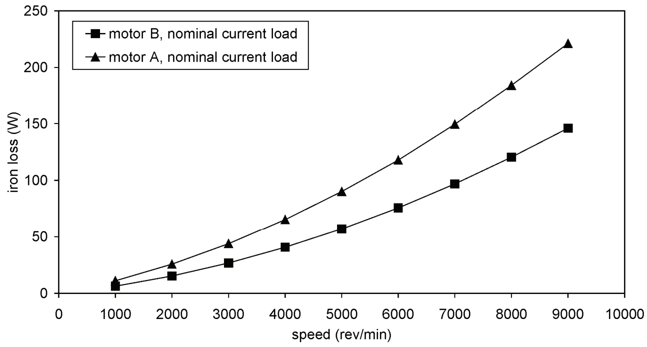


Fig. 4. Iron loss in iron core in dependency on rotor speed and nominal current load

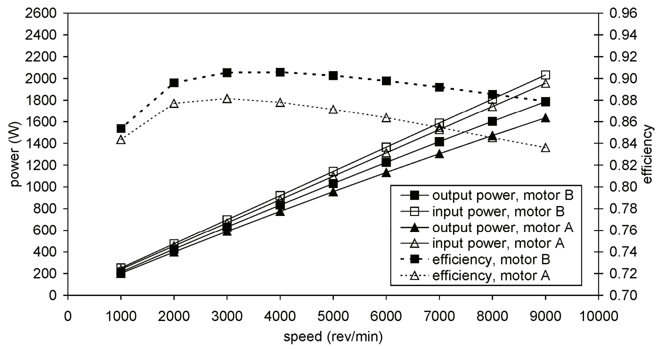


Fig. 5. Efficiency, input and output power of motors A and B in dependency on speed at nominal current load

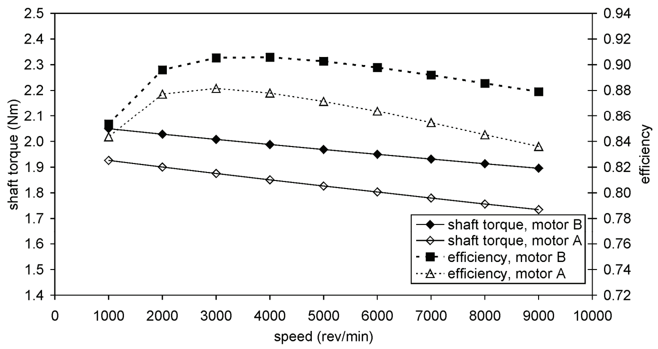


Fig. 6. Efficiency and shaft torque in dependency on speed at nominal current load

At load conditions the difference between eddy current loss in PMs for motor A and Motor B slowly diminished with the increasing of number of magnet segments in axial direction.

In spite of the higher needed ampere-turns number in the Motor B, for the similar value of the electromagnetic torque as it is in the Motor A, at the same RMS value of stator current, the Motor B exhibits the lowest value of iron losses.

Higher number of turns in the Motor B demands higher value of supply voltage for the same level of stator current as it is in the Motor A. This higher number of turns causes higher phase inductance and lower power factor of the Motor B.

## Conclusion

The results presented in the paper clearly show a significant influence of split ratio on the efficiency and output power capability in the permanent magnet synchronous motors with the surface permanent magnets and concentrated windings. The accuracy of the used eddy current loss calculation in the PMs by the modified electrical conductivity warrants an additional experimental verification.

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***Authors:*** *Bojan Štumberger, Miralem Hadžiselimović, University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, 2000 Maribor, Slovenia,*
*Tine Marčič TECES, Research and Development Centre for Electric Machines, Pobreška cesta 20, 2000 Maribor, Slovenia,*
*E-mail: bojan.stumberger@uni-mb.si.*