Effect of Permanent Magnet Rotor Design on PMSM Properties

SEKERÁK Peter, HRABOVCOVÁ Valéria, RAFAJDUS Pavol, KALAMEN Lukáš, ONUFER Matúš

University of Žilina, Department of Power Electrical Systems, Žilina, Slovakia

Abstract — **The paper is focused on the permanent magnet location and shape investigation in PMSM. At first, the real PMSM has been modeled by means of FEM which has been verified by experiments. Next step was a creating of two new models with different position of PM: one with surface mounted PM and other one with inset PM. The PM volume and quality have been in all models kept constant . The main goal of this paper is to investigate the influence of the PM design on PMSM properties such as torque ripple, maximum torque, EMF, stator current and winding losses. The investigation has shown, that PM surface design can improve PMSM properties.**

Keywords — Permanent magnet synchronous machine, FEM, design optimization.

I. INTRODUCTION

Many research activities are focused on permanent magnet (PM) rotor design investigation. The different PM position influences machine behavior. In [1], authors created four finite element method (FEM) models for investigation of different rotor structures of PMSM. The FEM models have been used in iron loss calculations and authors carried out the cogging torque calculations. In [2] the authors investigated four models, three with V-shaped PM and one with rectangular placed PM. In [3] the authors have done modifications in rotor structures of interior PMSM in such way that made PM segmentation. In [4], the authors carried out the PMSM parameters investigation by experiments, FEM models and analytical calculations. In [5], the authors investigated stator slot changes on PMSM parameters and torque ripple.

It is known, that PM position in rotor of the machine can significantly change the machine behavior. In this paper three models of PMSM with different PM positions are investigated. If the PMs are surface mounted, PMSM has no saliency in principle. PMSM with surface mounted PM has very easy construction, but the PMs are not protected against mechanical stresses and armature reaction. These unfavorable effects can cause PMSM destruction. The way how to protect the PM is to immerse the PM into the rotor, so the PMs are buried. In this case PMs are protected against mechanical and electrical stresses. The main drawback of this PM configuration is high leakage PM flux, typically a quarter of PM linkage flux [6]. The goal of this paper is comparison of PMSM properties such as torque ripple, maximum torque, winding losses, EMF and stator current in different PM configurations.

II. FEM MODEL VERIFICATION

The real PMSM with buried PM has been investigated in FEM model and verified by experiments and calculations [4]. It is necessary to prove, that the created FEM model represents real PMSM very well. Below you will find basic tests for FEM model verification.

Original PMSM with buried PM

The model of the real PMSM with buried PM has been presented in [4], [5]. The machine nameplate is: 400 V, 8.3 A, 2 kW, 36 Hz, 360 rpm. PM material is N33H. This PM material has been demagnetized in previous operation and in next investigations this demagnetization of PM has been taken in the account (initial residual magnetic flux density B_r = 1.15 T, actual B_r = 0.83 T). The PMs have rectangular shape. The PM dimensions are 32 mm x 4 mm x 35 mm. The cross section area can be seen on the Fig. 1.
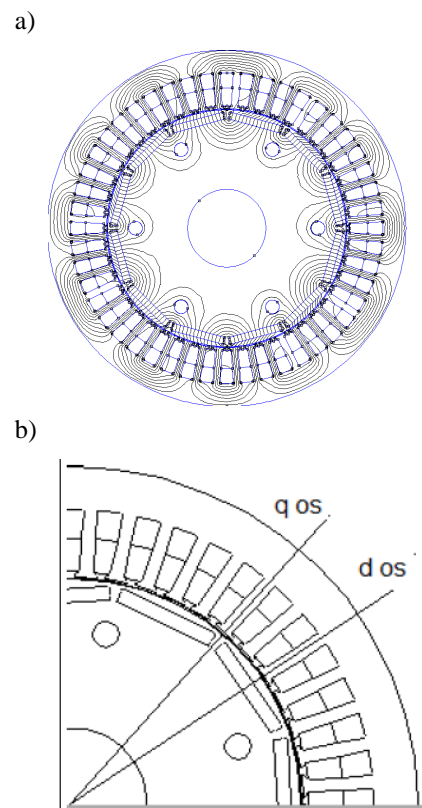
a)

b)

Fig. 1 a) Cross section of PMSM FEM model, b) detail of original PM buried in the rotor

TABLE I
INVESTIGATED PARAMETERS OF ORIGINAL PMSM

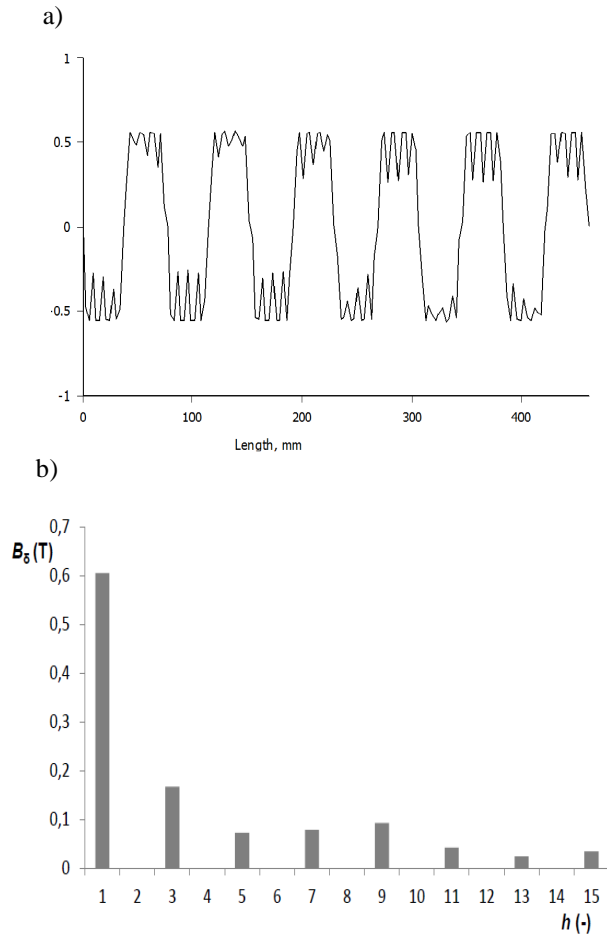| Method	R_s ($\Box$)	$L_{\Box s}$ (mH)	$L_{\Box d}$ (mH)	$L_{\Box q}$ (mH)
Experiments	3.852	28.23	25.59	78.35
Analytical calculation	4.002	23.02	21.1	78.21
FEM	-	-	24.68	76.21

a)

b)

Fig. 2 Air-gap magnetic flux density a) waveform vs. air gap periphery
b) harmonic components

Parameter investigation of original PMSM

The experimental parameter investigation, FEM parameter verification and analytical calculations have been carried out in [4]. Results are in Table I.

It is seen, that 2-dimensional FEM analysis gives quite accurate results of parameters investigation and it can be employed in the renewed models.

Generator operation under no-load condition

This experiment has been chosen to verify FEM model and PMSM behavior in generator mode. The original PMSM has been operated in generator mode under no – load condition. It has been driven at the rated speed.

The voltage waveform has been saved by digital scope (Fig. 3b). The FEM model simulation in generator mode under no-load condition has been performed. In the stator winding the current $I_s = 0$ A due to no - load condition. The air-gap magnetic flux density waveform has been obtained (Fig.2a). By fast Fourier transformation (FFT), the magnitudes of harmonic components have been found out (Fig.2b) and used for calculating of the voltage waveform.
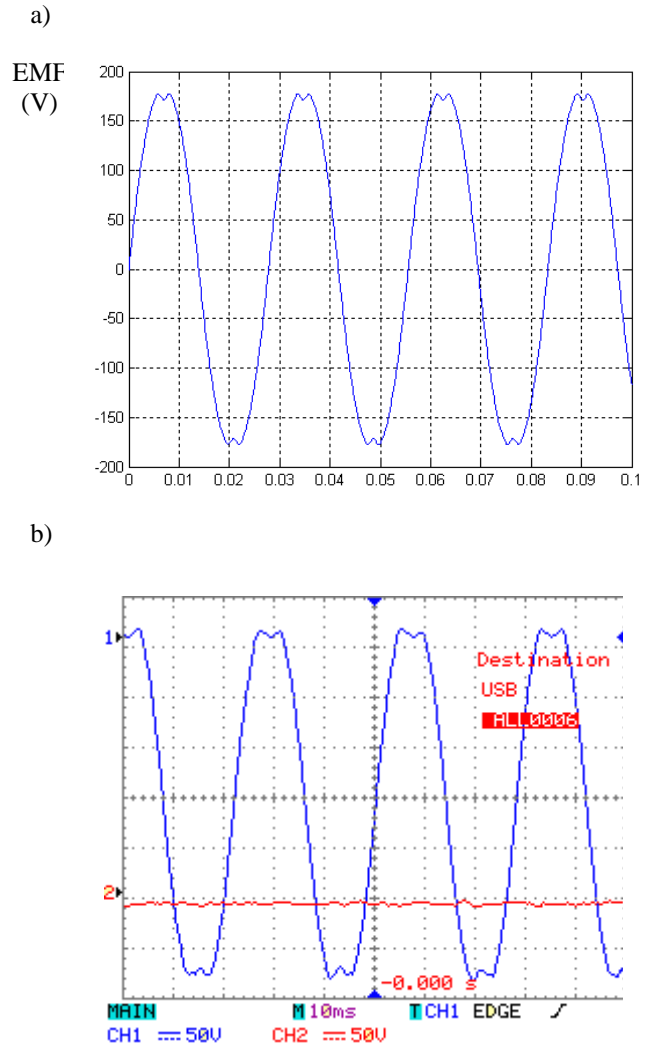
a)

b)

Fig. 3 EMF waveforms gained by a) FEM, b) measurement

When the harmonic components of the air-gap magnetic flux density B_δ are known, the induced voltage EMF can be calculated by formula EMF = $\sqrt{2}\pi f \phi_{PM} N_s k_{ws}$, where f

is frequency, Φ_{PM} is PM magnetic flux, N_s is number of stator turns and k_{ws} is stator winding factor. This calculated EMF waveform (Fig. 3a) is compared with measured one, see Fig. 3.

The magnitude of simulated voltage waveform is 175 V, and of measured one is 171 V, what is quite good coincidence.

The FEM model provides very good results, which are confirmed by experiments. Therefore the next research will be carried out by means of FEM models with different PM position in the rotor. All investigated data will be compared with original PMSM.

III. NEW PMSM DESIGN

For effect of the rotor design, two new FEM models have been created. These new models have the same stator as the real machine, so it is possible to assume that stator resistance and leakage inductance is the same as in the real machine shown in Table I. The PM volume has been kept constant. The PM quality is represented by the same BH – curve in all three models: $B_r = 0.83$ T and $H_c = 626$ kAm^{-1}.
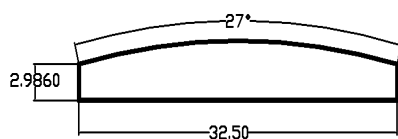
a)
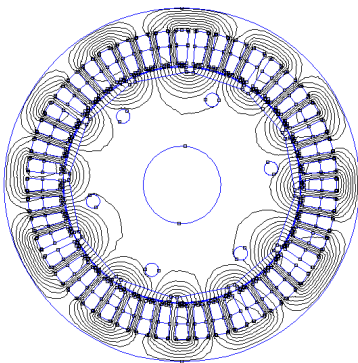
b)
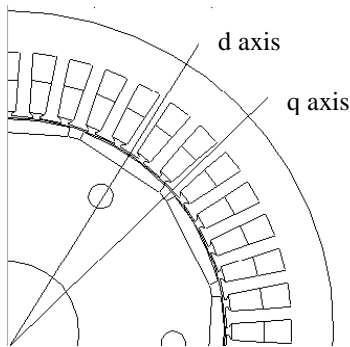
c)

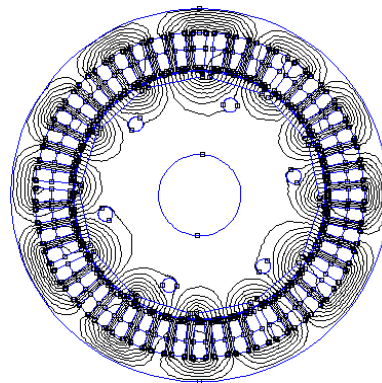Fig. 4 a) Cross section area of FEM model b) detail of surface mounted PM, c) detail of PM shape

PMSM with surface mounted PM

This model has been created with surface mounted PM (Fig. 4). The PM quality and PM volume has been kept as in the original machine. The PM shape has been modified to create a constant air-gap length. Therefore PM has not a rectangular shape more (see Fig. 4c) what can mean a higher cost.

PMSM with inset PM

The third model has been created with an inset PM (Fig. 5). As in previous case, the PM quality and PM volume has been the same as in the original machine. The same PM shape has been used as in Fig. 4c due to constant air-gap length.
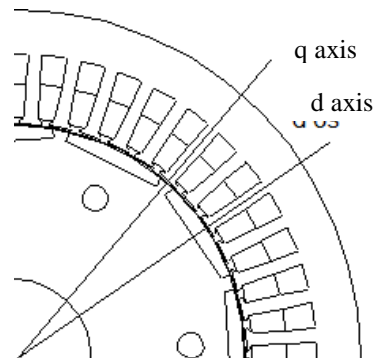
a)

b)

Fig.5 a) Cross section area of FEM model b) detail of inset PM rotor

IV. FEM MODELS INVESTIGATION

Firstly, the magnetizing inductances $L_{\mu d}$, $L_{\mu q}$ of new PMSM designs have been calculated by FEM models. These parameters can be used in mathematical models. Secondly, the induced voltage EMF is calculated on the base of B_δ created by PM. EMF has important influence on the stator current, which is calculated on the base of difference between EMF and terminal voltage (see eq. 2). Next, the maximum torque and torque ripple is calculated for all three FEM models. All three FEM models are

simulated at the rated terminal voltage and rated frequency.

Parameters identification

The new designs of PMSM rotors require currying out the parameters investigation - magnetizing inductances in d and q axes $L_{\mu d}$, $L_{\mu q}$ by FEM [4]. Parameters of PMSM with surface mounted PM are in Table II and with inset PM are in Table III. The stator resistance R_s and leakage inductance $L_{\sigma s}$ are the same for all three models and can be seen in the Table I.

TABLE II

PARAMETERS OF PMSM WITH SURFACE MOUNTED PM

Method	$L_{\mu d}$ (mH)	$L_{\mu q}$ (mH)
FEM	23.97	19.27

TABLE III

PARAMETERS OF PMSM WITH INSET PM

Method	$L_{\mu d}$ (mH)	$L_{\mu q}$ (mH)
FEM	24.37	58.37

a)

b)

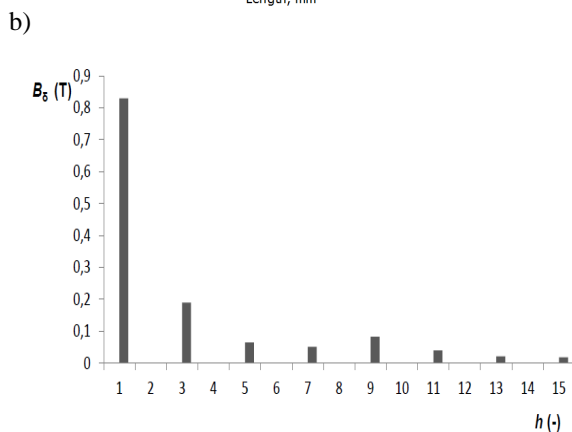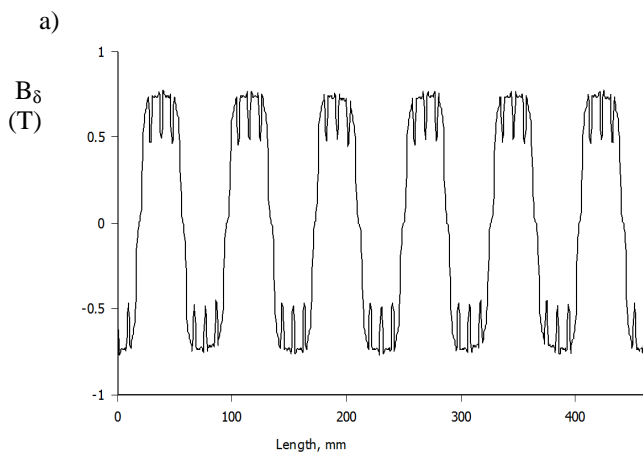Fig. 6 Surface mounted PM a) B_δ waveform b) harmonic components of B_δ ($B_{\delta 1}$ = 0.8302 T)

Induced voltage EMF

The induced voltage EMF has been investigated for new rotor configurations. The waveform of magnetic flux density in air gap B_δ is obtained by FEM model for the surface mounted PM (Fig. 6) and inset PM (Fig. 7). Both waveforms have been analyzed by FFT to get their harmonics. Note increasing of B_δ in both new models in comparison with the original one.
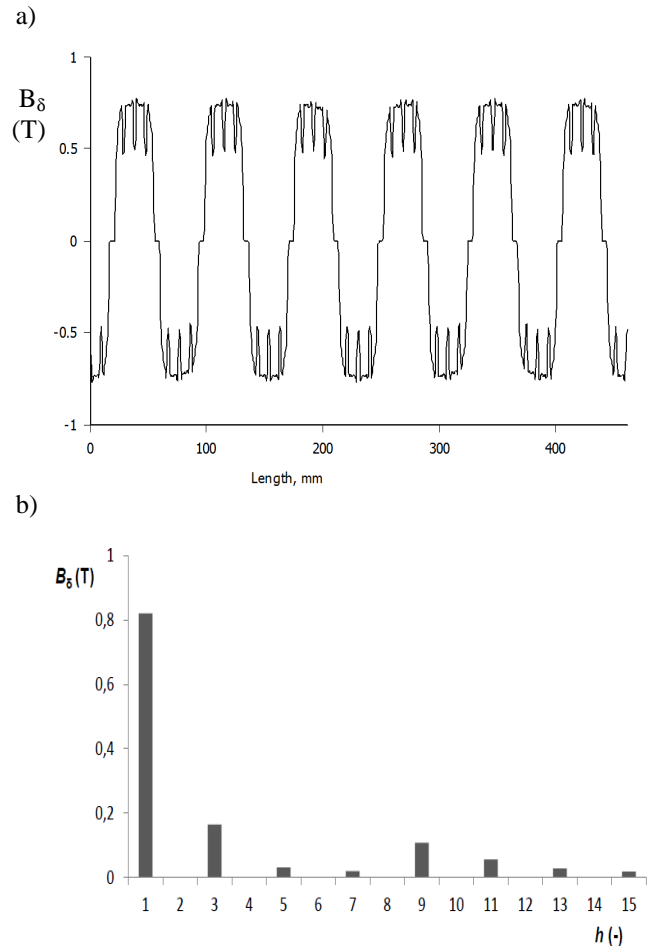
a)

b)

Fig. 7 Inset PM a) B_δ waveform b) harmonic components of B_δ ($B_{\delta 1}$ = 0.8205 T)

By using harmonic components of magnetic flux densities in Fig 6b, 7b, the voltage waveforms are calculated by well known procedure. By formula given above each harmonic component is calculated and then by inverse FFT an EMF waveform is gained. The EMF waveform for surface mounted PM is shown in Fig. 8a and for inset PM in the Fig. 8b.

The RMS value of EMF has been calculated for all machines, see Table IV. The reason of low EMF_{RMS} in case of the original machine with buried PM is: the iron bridges over PM are saturated and behave as a diamagnetic material, which enlarges effective air gap.
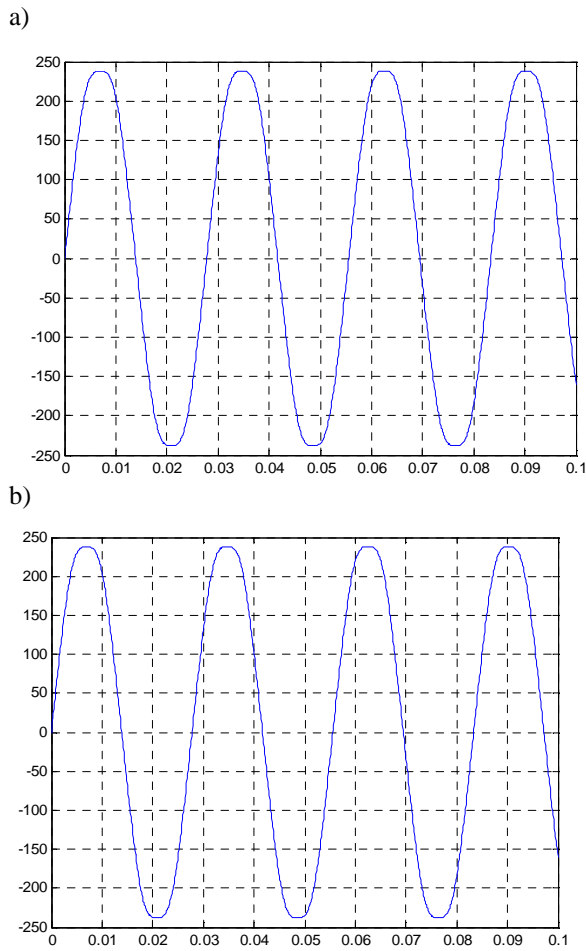
a)

b)

Fig. 8 a) EMF waveform for surface mounted PM, b) EMF waveform for inset PM

For quality of EMF waveform it is necessary to define total harmonic distortion THD:

$$THD = \frac{\sqrt{A_2^2 + A_3^2 + A_4^2 + ... + A_n^2}}{A_1} \qquad (1)$$

where A is harmonic order amplitude. Calculated THD values for all machines are in Table IV. All comparisons are done at rated frequency 36 Hz. It is seen that the position of PM has significantly influence on the value of EMF and its quality.

Torque investigation

The rated torque of original PMSM is $T_N = 53$ Nm. All three models have been simulated in FEM under this rated load (Fig. 9 a, b, c). The goal of this investigation is to investigate influence of rotor design on the torque ripple and maximal torque (Fig. 9d).
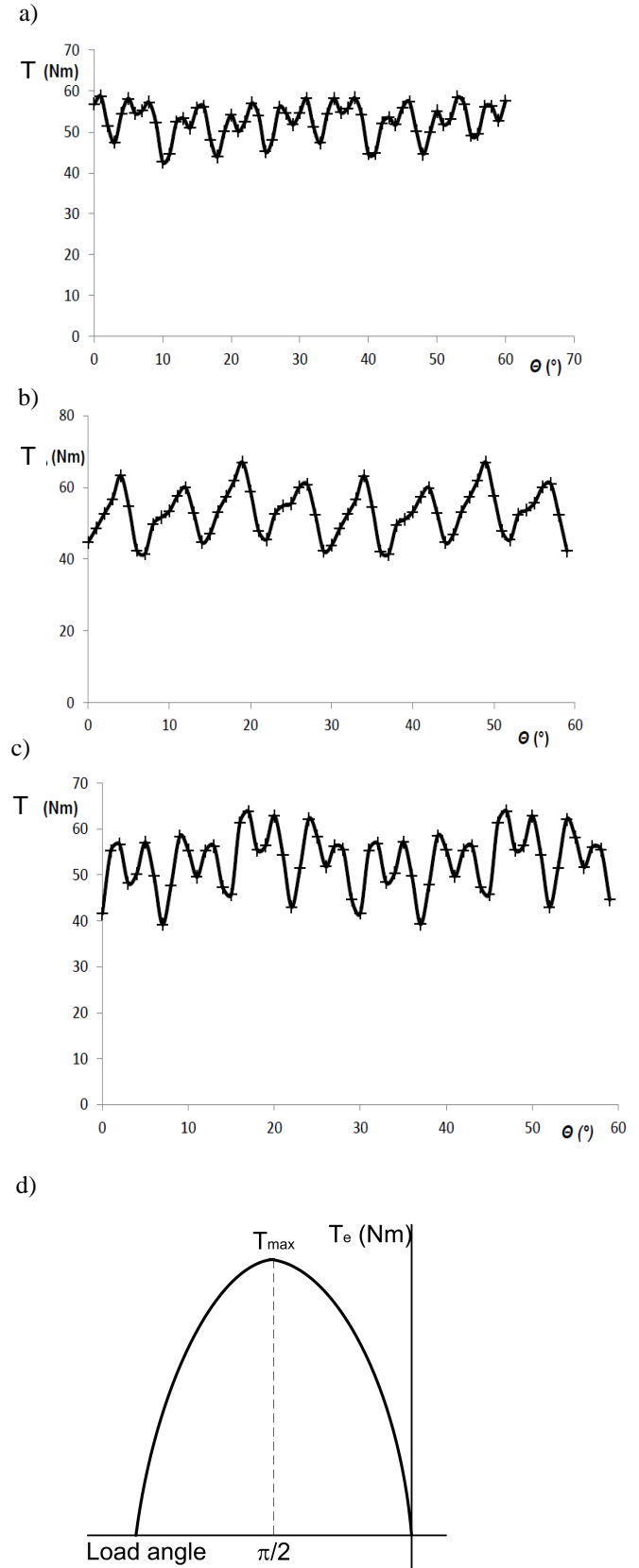
a)

b)

c)

d)

Fig. 9 The torque ripple vs. rotor position of investigated machines: a) original PMSM with buried PM, b) PMSM with surface mounted PM, c) PMSM with inset PM, d) torque vs. load angle with T_{max}

Table IV contains results of simulations for maximum torque and torque ripple by FEM analysis. Torque ripple T_{ripp} is calculated as difference between maximum value and minimum value of the developed torque. It is seen that the torque ripple is worse in both new models in comparison with original one.

TABLE IV

MAXIMUM TORQUE AND TORQUE RIPPLE VALUES FOR DIFFERENT ROTOR PMSM DESIGN

	Original PMSM	Surface mounted PM	Inset PM
T_{ripp} (%)	30.07	48.42	46.56
T_{max} (Nm)	129	150	143
EMF_{RMS} (V)	131.1	179.8	177.65
THD (%)	6	4.77	4.07

Stator current investigation

The induced voltage EMF has high influence on the stator magnetizing current. Lower EMF causes higher stator current then in case of higher EMF, at the same stator terminal voltage. Lower EMF means under-excitation, therefore higher magnetizing current is required from the source. In no-load condition the stator current I_{s0} can be calculated by (2) if stator resistance can be neglected:

$$I_{s0} = \frac{V_{sph} - EMF}{X_d} \qquad (2)$$

where X_d is the synchronous reactance in d axis and V_{sph} is the phase terminal voltage. In Table V there are shown the results of calculated stator currents I_{s0} and current at rated load I_{sN}, which were obtained by FEM simulations. Joule losses ΔP_{jsN} calculated at the rated load are shown in the Table V to illustrate how the position of PM will influence PMSM efficiency.

TABLE V

CALCULATED STATOR CURRENTS AND WINDING LOSSES

	Original PMSM	Surface mounted PM	Inset PM
I_{s0} (A)	6.83	4.337	4.458
I_{sN} (A)	8.3	4.695	4.632
ΔP_{jsN} (W)	880	309.68	301.42

V. CONCLUSION

The research has shown that different rotor designs can change machine properties significantly by keeping PM volume and quality. PM mounted on surface or inset PM can improve maximum torque and induced voltage EMF, however the torque ripple is increased. The stator current is lower than in buried PM, which results in lower Joule losses in the stator winding. The main disadvantages of surface mounted or inset PM are special shape of PM, which can increase costs and there is a danger of PM damage by centrifugal forces.

ACKNOWLEDGEMENT

REFERENCES

[1] Z. Q. Zhu, G. W. Jewell, D. Howe: Finite Element Analysis in the Design of Permanent Magnet Machines, IEE Seminar Current Trends in the Use of Finite Elements (FE) in Electromechanical Design and Analysis, 2000

[2] P. Salminen, J. Pyrhonen, H. Jussila, M. Niemela: Concentrated Wound Permanent Magnet Machines with Different Rotor Designs, International Conference POWERENG 2007, ISBN: 978-1-4244-0895-5

[3] Pouramin, A.; Madani, S.M.: New Interior PM Rotor Design with High-Flux Weaking Capability, IEEE Conference IEMDC, 2009, ISBN: 978-1-4244-4251-5

[4] Sekerák, P., Hrabovcová, V., Rafajdus, P., Kalamen, L.: *Interior Permanent Magnet Synchronous Motor Parameters Identification,* ISEM 2010, Prague, ISBN: 978-80-01-04621-0

[5] Sekerák, P., Hrabovcová, V., Rafajdus, P., Kalamen, L.: *Empty Slot Effect in Interior Permanent Magnet Synchronous Motor,* LVEM 2010, Brno, ISBN: 978-80-214-4178-1

[6] Pyrhonen, J., Jokinen, T., Hrabovcová, V.: Design of Rotating Electrical machina, Wiley, 2008, ISBN: 978-0-470-69516-6

The contribution was presented on the conference ISEM 2011, PRAGUE, CZECH REPUBLIC