Synchronous Motor of Permanent Magnet compared to Asynchronous Induction Motor

Vasilija SARAC[1], Dejan ILIEV[2]

[1]University "Goce Delecev", Faculty of Electrical Engineering, P.O. Box 201, 2000 Stip, Macedonia
[2]Feni Industries, Vozarci, 1430 Kavadarci, Macedonia

Abstract

Asynchronous induction motors are large consumers of electric energy. They are widely used in different industrial applications although their usage is often limited by low power and efficiency factor. Often they are replaced by synchronous motors especially in applications with wide range of speeds and high dynamic performance is required. Model of the asynchronous squirrel cage motor for calculating parameters and characteristics is derived and obtained results from this model are compared with experiments. The synchronous motor with surface mounted permanent magnets is constructed from the asynchronous motor without changing the stator configuration and for the constant power application. Parameters and characteristics of both motors are calculated, compared and analysed leading to the conclusion of improved characteristics of the synchronous motor in terms of the efficiency for the same power rating. Cogging torque of the synchronous motor is calculated and parametric analysis of the motor is set resulting in the improved model of the synchronous motor with decreased cogging torque and improved dynamic response. All motor models are analysed with Finite Element Method and magnetic flux density in cross-section of the motor models is obtained as well as transient performance characteristics. FEM models verify the accuracy of the proposed motor designs.

Keywords: synchronous permanent magnet motor, induction motor, efficiency factor, cogging torque, FEM models

Received: March 29, 2017

To cite this article:
SARAC V., ILIEV D., "Synchronous Motor of Permanent Magnet compared to Asynchronous Induction Motor", in *Electrotehnica, Electronica, Automatica (EEA)*, 2017, vol. 65, no. 4, pp. 51-58, ISSN 1582-5175

1. Introduction

Three-phase induction motors (IM) are one of the most significant electric energy consumers due to their wide application in the industry. The conventional three-phase induction motor is a constant speed motor, which can be easily used in variable speed applications usually with reduced efficiency. The recent progress on the field of permanent magnet materials, their reduced cost, the use of the inverters for on-line starting of the permanent magnet synchronous motors (PMSM) and their increased efficiency, has made the synchronous motors very attractive replacement of the three-phase squirrel cage motors in applications where higher efficiency is required [1]-[2].

The synchronous motors have been recognized for their efficiency, but also for the limitations in terms of the control. Magnet limitations (costs and performance) have restricted their use. Advancement in the magnet technologies allows operations at higher temperatures without the loss of permanent magnetization [3].

There are not many variants of the stator construction for the synchronous motors. Two main design of the stator are used these days: slotted and slotless. The slotted geometry has the advantage of the reduction of the permanent magnet material. On the contrary, there are many different possibilities for the construction of the rotor [4]. Magnets can be placed on the rotor surface, which is a ferromagnetic material (steel) with the direction of magnetization aligned to the shaft (surface permanent magnet motors). They are attached to the rotor surface with adhesive material and wrapped with high strength fibre wrap necessary to keep them in place at high speeds. This is one of the design approaches to attach magnets to the rotor. The second one is to place them inside the rotor (embedded design). This design limits the motor speed and restricts the magnet circuit [5]-[8].

The paper investigates the replacement possibilities of squirrel cage rotor of the asynchronous motor by the surface permanent magnet rotor, known for its robust and easy constriction. Analytical models of IM and PMSM suitable for computer aided design and calculation of steady-state performance characteristics are derived [9]-[12]. The obtained output characteristics from both motor models are compared. Steady-state characteristics of PMSM model have for the same output power increased efficiency compared to the characteristics of IM model.

Cogging torque is one of the most important parameters to be incorporated in calculating the performance of the synchronous motor. It is a pulsating torque occurring because of the interaction of stator teeth and rotor magnets [13]. In good design of PMSM, the cogging torque should be kept as low as possible. Reduction of the cogging torque is gained by parametric analysis of PMSM, i.e. by varying the coverage of the rotor with magnets and magnet shaping.

This new improved model of the synchronous motor (IPMSM) resulted in the reduced cogging torque and increased efficiency compared to the IM model. Finally, Finite Element Method (FEM) verifies design of the motors.

2. Analytical and numerical motor models

Asynchronous induction motor type 2AZ 155-4, product of company Koncar–Zagreb is analysed. Analytical model of asynchronous motor is derived based on the data from the producer of the motor, given in Table 1.

Table 1. Parameters of IM

Parameter	Value
nominal power	P=2.2 kW
number of poles	2p=4
nominal voltage Δ/Y	220/380 V
nominal current Δ/Y	8.7/5 A
power factor	cosφ=0.81
nominal speed	1410 rpm
number of stator slots	Z_1=36
number of rotor slots	Z_2=40
stator winding resistance per phase	R1=2.76 Ω
stator outer diameter	D_{sa}=152 mm
stator inner diameter	D_{si}=97mm
radial air gap length	g=0.6mm
stack length	l_{FE}=100
nominal frequency	f=50 Hz

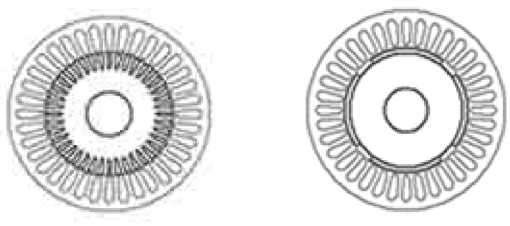
Laminations of stator and rotor remain unchanged with respect to manufacturer model. The derived model is suitable for computer-aided design. The computer-aided design allows fast and accurate design of the electric machines although good definition of the starting problem is necessary for comprehensible results [14].

Stator winding is calculated as number of conductors per slot (Table 2).

Table 2. Stator winding parameters

Parameter	Value
winding layers	2
parallel branches	2
conductor per slot	N_c=97
coil pitch	7

Also, stator and rotor laminations of the induction motor are modelled in a way that is applicable for computer aided design and PMSM is designed for constant power application (Figure 1).



(a) IM (b) PMSM

Figure 1. Cross-section of analysed motors

PMSM is designed with the same stator lamination and the winding of the IM. Only the rotor is redesigned with surface permanent magnets acting as a rotor winding instead of the aluminium cage.

Calculation of rotor windings is done for both motor models. For IM, the aluminium cage bars and end rings are calculated. For PMSM, the height of the magnets and pole coverage with magnets is calculated. Their data are presented in Table 3.

Table 3. Rotor winding parameters for both motors

Parameter	Value
IM bar conductor	cast aluminium
IM end ring width	8 mm
IM end ring height	19 mm
PMSM magnet pole embrace	0.8
magnet thickness	h_m=3.4 mm

Another important issue in the design of the PMSM is a permanent demagnetization of the magnets. Demagnetisation fault may occur especially in high load or due to the armature reaction [15]-[17].

In addition, demagnetization fault is also caused due to magnetic fields in opposite direction that occur as a result of current passing through stator windings [14].

The maximum permitted steady-state current before the reverse field exceeds Hd, the field intensity vector on the demagnetization curve where magnetic vector collapses, is calculated from [18]:

$$I_{dgmrm} = \frac{p\pi}{6\mu_0(K_W N_c)}\left(B_r h_m - B_d(g + h_m)\right) \quad (1)$$

where: K_w is the winding coefficient, N_c-conductors per slot, B_r is the residual flux density in Tesla, g is the air gap length in meters and h_m is the magnet thickness in meters.

This maximum permitted steady-state current must be greater than the rated one to prevent the demagnetization.

Once the input parameters for the design of the IM have been set, a computer program is run for analytical calculation of steady-state characteristics. Obtained output results of the derived computer model of IM are compared with experimental data. Table 4 presents this comparison.

Table 4. Comparison of IM analytical model and experiment

Parameter	Experiment	Analyt. model
phase current (A)	5	5.1
no-load phase current (A)	2.4	2.89
no-load input power (W)	170	135
locked-rotor phase current (A)	21	22.1
locked rotor torque ratio	2.2	2.4
nominal output power (kW)	2.2	2.19
nominal power factor	0.81	0.8
rated speed (rpm)	1410	1356
rated torque (Nm)	14.9	15.4

The similarity of the results in Table 4 verifies the design of the IM as accurate enough for further modifications and analysis.

Once, the analytical model of the IM is verified, it provides a good starting point for the modification of the IM into PMSM by replacing the cage rotor winding with surface mounted permanent magnets. For both developed analytical models of the motors, steady-state characteristics are calculated. The newly developed PMSM is aimed for constant power application, similarly like the original IM. Output characteristics of both motors are analysed and compared taking into consideration that newly derived PMSM should satisfy torque and power requirements of the IM but in the same time should have improved efficiency factor in comparison to the IM. Further improvement of derived model of PMSM is achieved by modelling the rotor pole of the synchronous machine, i.e. varying the pole coverage with magnets and shaping the magnets. Therefore, the new improved model synchronous permanent magnet motor is obtained with respect to the cogging torque of the synchronous machines. From all analytical models, numerical models of the motors are derived based on FEM. In order, FEM models to be able to solve the set of Maxwell equations and to determine the potentional magnetic vector A and magnetic flux density B, the whole object cross-section must be divided into numerous elements (triangles) that create the mesh of finite elements. After the mesh is created, a set of Maxwell equations is solved for time-harmonic case i.e. operating frequency of 50 Hz.

For all models, characteristics of materials are input (B-H curve of the laminations, properties of SmCo magnets and properties the copper conductor of distributed stator winding). As an output results from FEM models flux density in the motor models is obtained and transient characteristics of motor torque as well. Obtained results of torque from numerical models are compared with the analytical results. Similarity of the results of torque of both models analytical and numerical confirms the accuracy of the models and proposed methodologies.

3. Results

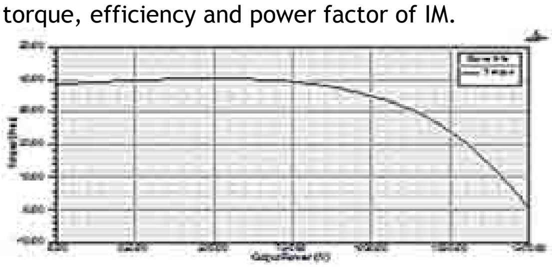
Rotor of the IM motor is modified by replacing the rotor cage with permanent magnets resulting in analytical model of PMSM.

Table 5 presents results obtained from this model.

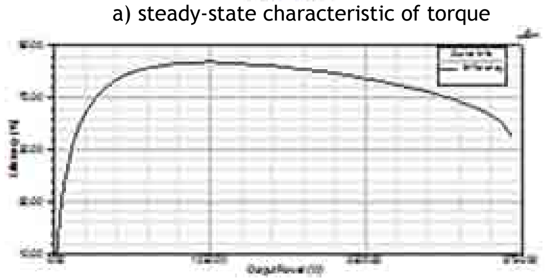
Table 5. PMSM analytical model-rated operation

Parameter	Value
phase current (A)	5,05
nominal power (kW)	2,2
rated speed (rpm)	1500
rated torque (Nm)	14
efficiency factor (%)	93.07
Air gap flux density (T)	0.5
Total net weight (kg)	12.8

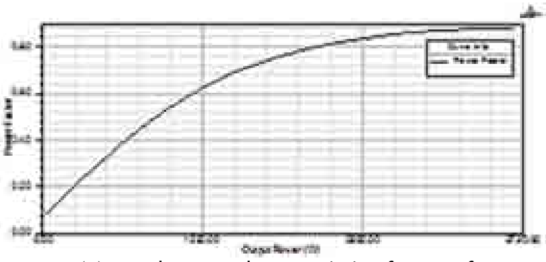
Figure 2 presents the steady-state characteristics of torque, efficiency and power factor of IM.



a) steady-state characteristic of torque



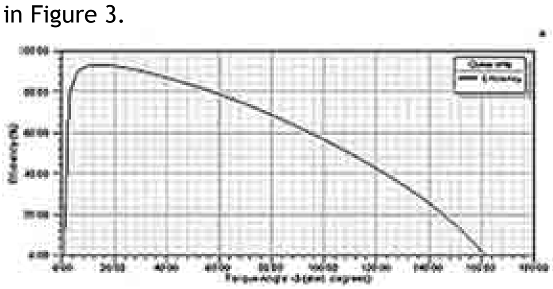
(b) steady-state characteristic of efficiency



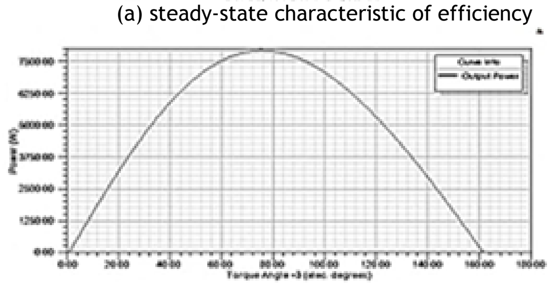
(c) steady-state characteristic of power factor

Figure 2. Steady-state characteristics of IM

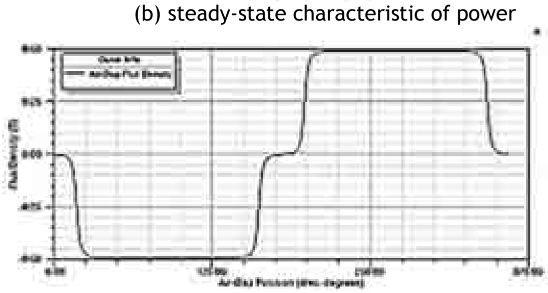
The results obtained for the PMSM they are presented in Figure 3.



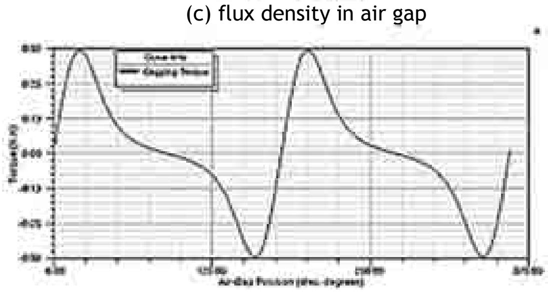
(a) steady-state characteristic of efficiency



(b) steady-state characteristic of power



(c) flux density in air gap



(d) cogging torque of SPMM

Figure 3. Steady-state characteristics of PMSM

From Figure 3d, presence of the significant cogging torque in the operation of PMSM can be observed. Reduction of the cogging torque is an important issue in operation of the synchronous motors if smooth operation is required with fast dynamic responses. Several different measures for reducing the cogging torque are observed in the literature [19-22].

They can be divided into two major groups: reduction of cogging torque by the control circuit of the motor [23], or modifications in the motor construction.

Measures taken to minimize the torque ripple by motor design include elimination of slots, skewed slots, special shape slots and stator laminations, selection of the number of stator slots with respect to the number of poles, decentred magnets, skewed magnets, shifted magnet segments, selection of magnet width, direction-dependant magnetization of permanent magnets or creating the magnet circuit asymmetry [24].

Each of the mentioned approaches has its own limitations. For example, skewing stator slot one-slot pitch can eliminate all cogging torque. Nevertheless, this approach will be difficult to implement in practice with standard winding machines. Another possibility is to skew the magnets. However, skewed magnets are difficult to position and align properly [13].

In this paper, shaping of the magnets is proposed as a solution for reducing the cogging torque. Simultaneously, the pole embrace (the ratio of the pole arc to pole pitch) is increased from 0.8 to 0.85 (Figure 4).

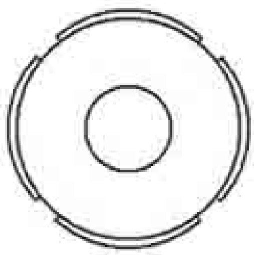


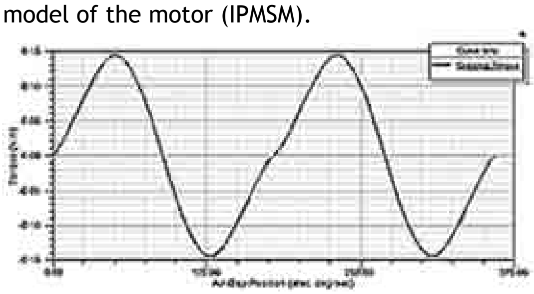
Figure 4. Rotor configuration of IPMSM

This leads to the new improved model of the synchronous motor-IPMSM. Table 6 presents the results from the calculation of the IPMSM model.

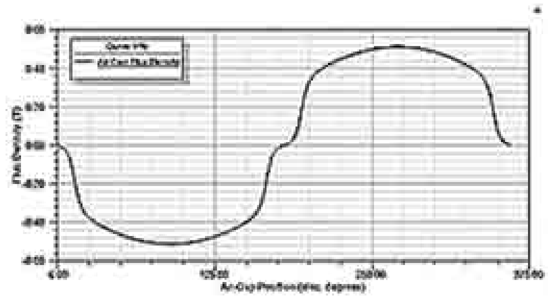
Table 6. Parameters of IPMSM

Parameter	Value
phase current (A)	5,23
nominal power (kW)	2,2
rated speed (rpm)	1500
rated torque (Nm)	14
efficiency factor (%)	92.56
air gap flux density (T)	0.5

Figure 5 presents the cogging torque and air gap flux density as the most interesting characteristics for this model of the motor (IPMSM).



(a) cogging torque



(b) air-gap flux density

Figure 5. Steady-state characteristics of IPMSM

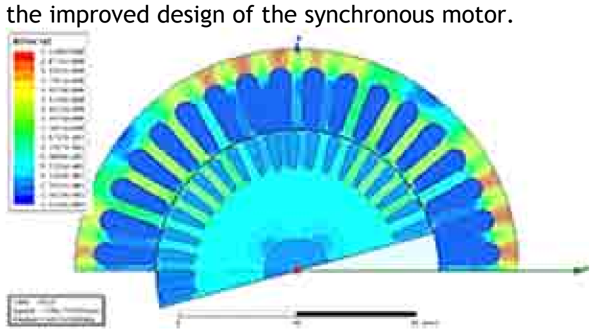
Influence of the magnet shape on the shape of air gap flux density can be observed from Figure 5b. Now the air gap flux density tends to have more sinusoidal distribution as a result of the magnet shaping.

Motor analysis is extended by creating numerical motor models based on FEM. FEM is a reliable numerical tool for calculating variety of parameters and characteristics in the electric machines [25-30]. It is especially useful in obtaining the magnetic flux density in the cross-section of the motors as this parameter is difficult to be measured or anticipated by any other methods.

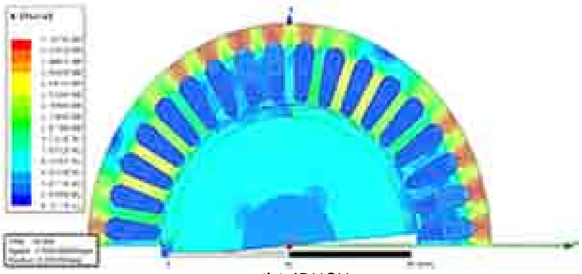
Transient electromagnetic field simulation allows analysis of dynamic systems with nonlinear materials and permanent magnets under the variety of conditions, employing sinusoidal waveforms and any other pulsed wave excitations. The process requires sequential calculation, over many time steps, of saturation, eddy currents, slotting effect and rotor movement in time and space [31].

On the other hand, points of the magnetic core close to the saturation can be detected. This so called “week pats” of the motor construction can be improved by redesigning the motor in terms of the geometry of the stator and rotor yoke or slots. Also, redesigning of stator winding or height of the magnets can be considered in case of the core saturation in motor models. Therefore, the FEM models of the motors are created based on previous analytical models. Furthermore, based on the FEM models, transient characteristics of torque and induced voltage are analysed. Back EMF at synchronous motor is another aspect that must be considered in the design of this type of the motor.

Figure 6 presents the magnetic flux density distribution in both motor models asynchronous and in the improved design of the synchronous motor.



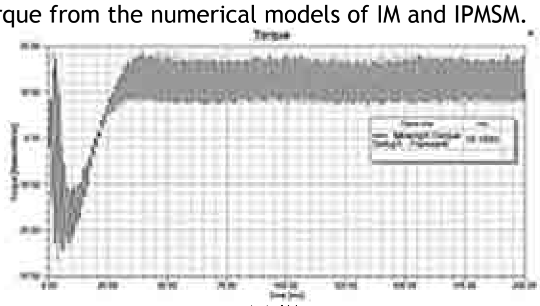
(a) IM



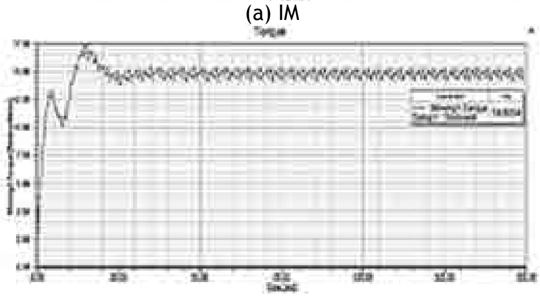
(b) IPMSM

Figure 6. Magnetic flux density at motor cross-section

Figure 7 presents the transient characteristics of torque from the numerical models of IM and IPMSM.



(a) IM



(b) IPMSM

Figure 7. Transient characteristic of torque

Another important point in the calculation of the synchronous motor is the value of the induced back EMF. In general, it should not exceed the rms value of 220 V.

Figure 8 presents the induced voltage in IPMSM, obtained from the numerical model.

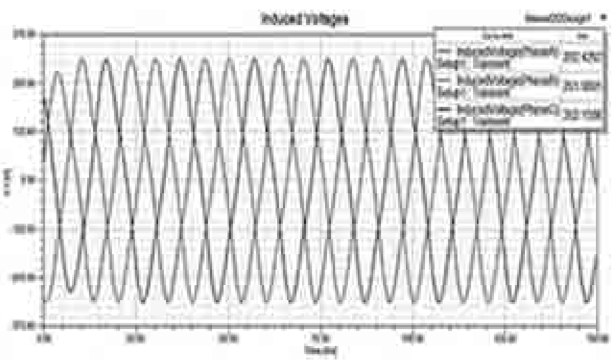


Figure 8. Transient characteristic of back EMF at IPSM

4. Discussion

The starting point in the research is the three-phase squirrel cage induction motor. The goal is to modify the induction motor into synchronous motor with surface mounted magnets on the rotor and to compare the performance characteristics of both motors expecting that the synchronous motor should have bigger efficiency than the asynchronous. As the synchronous motor is aimed to be a replacement of the asynchronous motor, its performance characteristics should be as close as possible to those of the asynchronous motor. Therefore, mathematical model of the asynchronous motor suitable for computer aided design of the machine and obtaining the motor parameters and performance characteristics is derived.

From Table 4 (*supra*), it can be observed that derived model is accurate enough as performance characteristics of this model are very close to the experimental ones.

This verifies the design procedure and accuracy of the obtained model of the asynchronous motor. Accurate enough model of the asynchronous motor is a good starting point for its modification into synchronous motor. After calculating the rotor geometry, the model of the synchronous motor applicable for computer-aided design is obtained. The accuracy of the model of the synchronous motor is validated by comparing its output characteristics with those obtained by the asynchronous motor. This comparison is presented in Table 7.

Table 7. Comparison of IM and PMSM-rated operation

Parameter	Value	
	PMSM	IM
phase current (A)	5,05	5.2
nominal power (kW)	2,2	2.19
rated torque (Nm)	14	15.4
efficiency factor (%)	93.07	79.6
air gap flux density (T)	0.5	0.56

It can be reported, from presented comparison in Table 7, that main criteria in the design of the synchronous motor, the constant power operation, is satisfied. Both motors have output power of 2.2 kW. Output torque is slightly decreased at PMSM for rated operation, which is comprehensible because synchronous motor rotates with synchronous speed, bigger than the rated speed of the induction machine, and consequently for the same power rating the output torque decreases.

On the other hand, efficiency is significantly increased which is important for energy saving. Increased efficiency in synchronous machine is mainly due to the absence of squirrel cage winding on the rotor side and reduced losses originating from the rotor winding. Similarity of the obtained results in Table 7 validates the design of the synchronous motor as a reliable replacement of the asynchronous motor in industrial processes where efficiency of the motor plays an important role. Synchronous motor is also well known for the existence of the cogging torque during motor operation, which deteriorates its performance.

Therefore, the characteristic of the cogging torque, presented in Figure 3 (*supra*), is analysed and further measures for reducing the cogging torque are considered. After several iterations and variations of different parameters of the synchronous motor, it is proposed the pole embrace to be increased from 0.8 to 0.85 and magnets to be shaped as it is presented in Figure 4 (*supra*).

Results obtained from this improved model of synchronous motor are presented in Table 6 (*supra*). Further, they are compared with the starting model of the synchronous motor. This comparison is presented in Table 8.

Table 8. Comparison of PMSM and IPMSM-rated operation

Parameter	Value	
	IPMSM	PMSM
phase current (A)	5,23	5,05
nominal power (kW)	2,2	2,2
rated torque (Nm)	14	14
efficiency factor (%)	92.56	93.07
air gap flux density (T)	0.5	0.5
cogging torque (Nm)	0.15	0.38
permanent magnet weight (kg)	0,6074	0,651

From characteristics of the cogging torque of the starting and the improved synchronous motor (Figures 3d and 5a) it is evident that cogging torque is reduced from 0.38 Nm to 0.15 Nm. At the same time, the efficiency factor at the improved synchronous model is slightly reduced (Table. 8). All other operating characteristics remain almost the same, except from the significant improvement in the reduction of the cogging torque. The permanent magnet material consumption is reduced due to the magnet shaping. Downside of the IPMSM is that the price of the synchronous motor increases. Shaping the magnets adds additional costs to the motor production that are increasing overall production costs of the motor.

Finally, at IPMSM is observed more sinusoidal distribution of the flux density in the air gap compared to PMSM (Figures 3c and 5b). The sinusoidal distribution of the magnetic flux density is desirable when there is a requirement to minimize noise, torque ripple, and maximize efficiency [32]. The presence of a sinusoidal variation of the flux density across the pole face prevents sharp changes in force production and avoids oscillatory torques.

Created FEM models of the motors extend the analysis of asynchronous and improved synchronous motor. Analytical models of the both motors (IM and IPMSM) are validated by FEM and their design is checked with respect to the flux distribution in the cross section of the motor. Presented results in Figure 6 show the satisfactory distribution of the magnetic flux density in motor cross-section, although some points of the stator yoke have increased flux density near to the point of the material saturation. In addition, there is an increase of the flux density in synchronous motor compared to the asynchronous. The approach in the design of the synchronous motor was the stator lamination to remain unchanged, only the rotor was replaced inside the existing stator. One measure that can be applied to reduce the magnetic flux density, without changing the stator lamination, is to increase the thickness of the magnets. It is expected, stator current to decrease and consequently the flux density in the stator yoke [33]. The presented design in this paper is with minimal weight of the magnets. Increasing the magnet thickness will increase the production costs due to the cost of magnets.

Transient characteristics of torque are obtained from the numerical models of the motors Their rms values are compared with the results from the analytical models and they show satisfactory agreement. This comparison is presented in Table 9.

Table 9. Comparison of torque-FEM and analytical models

	Torque [Nm]	
Type of the motor	FEM model	Analytical model
asynchronous	16.1	15.4
synchronous	14.6	14

Induced back EMF in the synchronous motor should not exceed 220 V in order to avoid over-voltages in motor windings. The presented design (Figure 8), satisfy this requirement.

5. Conclusions

In recent years, synchronous motors with surface permanent magnets are replacing the asynchronous motors especially in applications where wide range of speeds is required. Paper presents the analytical design and steady state characteristics of the synchronous motor with the surface mounted magnets derived from the asynchronous motor with a simple replacement of the rotor. Both motors are designed for constant power application and by comparing their characteristics, it is found that output power in both motors remains the same 2.2 kW, while torque of the synchronous motor is slightly reduced from 15 Nm at asynchronous to 14 Nm at synchronous motor. In the same time efficiency factor of the synchronous motor is increased, from 79.6 % at the asynchronous motor to 93.07 % at synchronous. Cogging torque of the synchronous motor is analysed, and its value is reduced by shaping the magnets and adjusting the rotor surface coverage with magnets or pole embrace from 0.80 to 0.85. In the new improved model of synchronous motor, the cogging torque is reduced from 0.38 to 0.15 Nm. All other operating characteristics remain almost the same in the improved model compared with the starting model of the same type of the motor. Both models of the asynchronous and the improved synchronous motor are analysed with Finite Elements and in some points of the stator yoke, increased flux density at the synchronous motor is observed with respect to the asynchronous motor. This aspect of the design of the synchronous motor can be further improved by increasing the magnet thickness and decreasing the stator winding current. Stator geometry will remain unchanged while smaller stator winding current should decrease the flux density in stator yoke. Transient characteristics of torque are obtained from the numerical models. The rms value of the torque from transient characteristics is in a good agreement with obtained torque from the analytical models. This confirms the accuracy of the analytical and the numerical model of the synchronous motor. Power converter is connected to the synchronous motor allowing motor starting and operation with high speeds in field-weakening region. However, this operation in the field-wakening region is not problem-free. The relatively high value of the no-load current at high speeds is often present due to the relatively small inductance of the synchronous motors with surface magnets. Therefore, the further research of the authors will be focused on the operation of the motor with the converter and on the motor parameters that influence the operation with the converter. Possible further modification of the design of the synchronous motor for on-line starting without converter should be considered as well.

6. Bibliographic references

[1] ARORA A.S., SINHG G. "Review of design and performance of permanent magnet synchronous motor" in *Proc. of 6th IRES International conference on engineering and science*; 2015, 16th August; Melburn, Australia, pp. 107-115.

[2] LATEB R., TAKORABET N., MEIBODY-TABAR F., MIRAZIN A., ENON J., SARRIBOUETTE A., " Performance comparison of induction motors and surface mounted PM motor for POD marine propulsion", in *Proc. Industry application Conference*, 2005, vol.2, pp. 1342-1349.

[3] MELFI M.J., ROGERS S.D., EVON S.M MARTIN B., "Permanent magnet motors for energy savings in industrial applications", in *Proc. Petroleum and Chemical Industry Conference*, 2006, pp. 1-8.

[4] HASELMAN D., *Brushless permanent magnet motor design*. Ohio, 2nd edition, Magna Physics Publishing, 2006, pp 117-120.

[5] SMITH J.S, WATSTON A.P, "Design, manufacture and testing of a high speed 10 MW permanent magnet motor and discussion of potentional applications", in *Proc. of thirty-fifth turbomachinery symposium*, 2006, pp. 19-24.

[6] POPA D-C., VARATICEANU B., FODOREN D., MINCIUNESCU P., MARTIS C., "High speed motor used in electric vehicle", in *Electrotechnika, Electronica, Automatica (EEA)*, 2016 vol. 64, (no.3), pp. 1-11, ISSN 1582-5175.

[7] ZHANG Z., ZHOU L, " Design and rotor geometry analysis of permanent magnet-assisted synchronous reluctance machine using ferrite magnet", in *Journal of Electrical Engineering* [online], 2015 , vol.66, (no.6), pp. 311-316, [viewed 15 July 2016], available from: DOI: 10.2478/jee-2015-0051.

[8] PELLEGRINO G., VAGATI A., GUGLIELMI P., BOAZZO B., "Performance Comparison between surface mounted and interior PM motor drives for electric vehicle application", 2012, in *IEEE Transactions on industrial electronics* [online], vol.59 (no. 2) pp. 803-811, [viewed 15 July 2016], available from: DOi: 10.1109/TIE.2011.2151825.

[9] CHRIS MI C. "Analytical design of permanent magnet traction-drive motors", 2006, *IEEE Transaction on Magnetics* [online], vol.42, (no.7), pp. 1861-1866, [viewed 15 July 2016] available from: DOI: 10.1109 /TMAG.2006.874511.

[10] PROCA B.A, KEYHANI A., EL-ANTABLY A., LU W., DAI M., "Analytical model for permanent magnet motors with surface mounted magnets", in *IEEE Transactions on Energy Conversion* [online], 2003, vol. 18, (no.3), pp. 386-391, [viewed 15 May 2016], available from: DOI: 10.1109/TEC.2003.815829.

[11] CEROVSKY Z., LEV M. "Permanent magnet synchronous machine parameters identification for load characteristics calculation", *Automatika* [online], 2015, vol. 56, (no. 2), pp. 217-225, [viewed 3 August 2016], available from: DOI: 10.7305/automatika.2015.07.813.

[12] MUSAK M, STULRAJTER M., "Novel Methods for Parameters Investigations on PM Synchronous Motors", in *Acta Technica Corviniesis*, 2013, vol.6 , (no. 1), pp. 51-56, ISSN 2067-3809.

[13] FEI W., LUK P. C. K, " A new technique of cogging torque suppression in direct-drive permanent magnet brushless machine" [online], in *IEEE Transactions on Industry Application*, 2010, Vol.46, (no.4), pp. 1332-1340, [viewed 10 August 2016], available from: DOI: 10.1109/TIA.2010.2049551.

[14] ANSYS Inc, *User's Guide -Maxwell 2D*, REV 5.0 2010.

[15] AKAR M, EKER M, "Demagnetization fault diagnosis in permanent magnet synchronous motors", in *Przezglad Electrotechniczny*, 2013, vol. 89, (no. 2a), pp. 229-233, ISSN 0033-2097.

[16] SHENBOO Y., RENYUAN T., "Electromagnetic and mechanical characterization of noise and vibration in permanent magnet synchronous machine", in *IEEE Transactions on Magnetics* [online], 2006, vol. 42 (no. 4), pp. 1335-1338, [viewed 10 September 2016], available from: DOI 10.1109/TMAG.2006.871637.

[17] HUR J., "Characteristics analysis of interior permanent-magnet synchronous motor in electrohydraulic power steering system", in *IEEE Transactions on Industrial Electronics* [online], 2008, vol. 55, (no. 6), pp. 2316-2323, .[viewed 10 September 2016] available from: DOI 10.1109/TIE.2008.918402.

[18] DUAN Y., *Method for design and optimization of surface mount permanent magnet machines and induction machines*, Dissertation, Georgia Institute of Technology [online], 2010, [viewed February 2017], available from: https://smartech.gatech.edu/bitstream/handle/1853/37280/duan_yao_201012_phd.pdf

[19] DOISEK L., PILLAY. P., "Cogging torque reduction in permanent magnet *machines", in* IEEE Transaction on Industry Applications [online], 2007, vol. 43, (no.6), pp. 1565-1571, [viewed 10 October 2016], available from: DOI: 10.1109/TMAG.2007.908160.

[20] YOKO Y., HIGUCHI T., "Stator design of alternate slot winding for reducing torque pulsation with magnet designs in surface-mounted permanent magnet motors", in *IEEE Transactions on Magnetics*, 2015, vol. 51 (no. 6), article sequence number 8202911, [online], [viewed 11 November 2016] available from: DOI: 10.1109/TMAG.2015.2394771.

[21] GASPARIN L., FISER R., "Sensitivity of cogging torque to permanent magnet imperfections in mass-produced PM synchronous motors", in *Przezglad Electrotechniczny*, 2013, vol 89, (no 2b), pp. 80-83, ISSN 0033-2097.

[22] LEVIN N., ORLOVA S., PUGACHOV V., OSE-ZALA B., JAKOBSONS E., " Methods to reduce the cogging Torque in permanent magnet synchronous machines" [online], in *Elektronika ir Elektrothenika*, 2013, vol. 19 (no. 1), pp. 23-26, [viewed 15 November 2016], available from: DOI: http://dx.doi.org/10.5755/jo1.eee.19.1.3248.

[23] BRANDSTETTER P., KRECER T., "Speed and current control of permanent magnet synchronous motor drive using IMC controllers", in *Advances in Electrical and Computer Engineering* [online], 2012, vol. 12 (no. 4), pp. 3-10 [viewed 10 October 2016], available from: DOI: 10.4316/AECE.2012.04001.

[24] GIERAS F. J, *Permanent Magnet Motor Technology*, 2nd ed., New York, Marcel Deker Inc, 2002, pp. 258-261.

[25] SERGEANT P., CREVECOEUR G., DUPRE L., VAN den BOSSCHE A., "Characterization and optimization of a permanent magnet synchronous machines", in *The International Journal for Computation and Mathematics in Electrical Electronic Engineering-COMPEL* [online], 2009, vol. 28 (no.2), pp. 272-285, [viewed 15 October 2016], available from: DOI: 10.1108/03321640910929218.

[26] GULEC M., YOLACAN E., DEMIR Y., OCAK O., AYDIN M., "Modelling based on 3D Finite Element Analysis and experimental Study of a 24-slot, 8-pole axial flux permanent-magnet synchronous motor for no cogging torque and sinusoidal back-EMF", 2016, in *Turkish Journal of Electrical Engineering & computer Sciences-TUBITAK* [online], 2016, vol.24, (no.1) , pp. 262-275, [viewed 15.10.2016], available from: DOI:103906/elk-1308-150 .

[27] TUDORACHE T., MELCESCU L., "FEM optimal design of energy efficient induction machines", in *Advances in Electrical and Computer Engineering* [online], 2009, vol. 9, (no. 2), pp. 58-64, [viewed 15 October 2016], available from: DOI: 10.4316/AECE.2009.02009.

[28] SAAVEDRA H., RIBA J.-R., ROMERAL L., "Detection on inter-turn faults in five-phase permanent magnet synchronous motor", in *Advances in Electrical and Computer engineering* [online], 2014, vol.14 (no.4), pp. 49-54, [viewed 15 October 2016], available from: DOI: 10.4316/AECE.2014.04008.

[29] SEKERAK P., HRABOVCOVA V., PYRHONEN J., KALAMEN L., RAFAJDUS P., ONUFER M., "Ferrites and different winding types in permanent magnet synchronous motor", in *Journal of Electrical Engineering* [online], 2012, vol.63, (no. 3), pp. 162-170, [viewed 20 Oct. 2016], available from: https://doi.org/10.2478/v10187-012-0024-8.

[30] MELCESCU L.M., DEMETER E., COSTEA-MARCU I., CRAIU O., COVRIG M., "3D Numerical model of permanent magnet synchronous motor for metropolitan electric transport system", in *Electrotehnica, Electronica, Automatica (EEA)*, 2010, vol.58, (no.3), pp. 50-58, ISSN 1582-5175.

[31] Ansys INC, *ANSYS Maxwell and SGI® UVTM 3000 Maximizes Electromagnetic Computation Throughput*, available from: https://www.sgi.com/pdfs/sgi_wp_uv3000_ansys_maxwell.pdf.

[32] RASMUSSEN F. K., DAVIES J. H., MILLER T.J.E., McGILP I. M., OLARU M., "Analytical and numerical computation of air-gap magnetic fields in brushless motors with surface permanent magnets", in *IEEE Transactions on Industry Applications* [online], 2000, vol. 36 (no. 6), pp. 1547-1554, [viewed 27 Oct. 2016], available from: DOI: 10.1109/28.887205.

[33] WEIWEI G., XIAOYONG Z., QUAN L., DU Y., " Design and optimization of permanent magnet brushless machines for electric vehicle applications", in *Energies* [online], 2015, vol. 8, (no. 12), pp. 13996-14008, [viewed 27 Oct. 2016], available from: 10.3390/en81212410.

Funding Sources and/or Acknowledgments

This work was financially supported by the University "Goce Delcev" of the Republic of Macedonia, under the Scientific Project "Functional Spaces, Topological and Statistical Aspects and their Application in Electrical Engineering"; No 2302-37 /6/2016.

Authors' Biography

Vasilija SARAC was born in Skopje (Macedonia), on July 24, 1972.
She graduated at the Faculty of Electrical Engineering in Skopje (Macedonia), in 1995.
In 1999, she received M.Sc. in Electrical Engineering from the same institution.
She received PhD degree in electrical engineering from the Faculty of Electrical Engineering (Macedonia), in 2005. Currently she is employed as associate professor at the University Goce Delcev, in Stip (Macedonia). Her research interests concern: electric machines and power electronics.
e-mail address: vasilija.sarac@ugd.edu.mk

Dejan ILIEV was born in Prilep (Macedonia) on October 29, 1986. He graduated at Technical University Sofia –major field of study electronic and automation. He is a employed as chief engineer for instrumentation and measurement at Feni Industry. His research interest is automations systems and electrical drives.
e-mail address: dejan.i@feni.mk