Journal of
Energy
Technology

JET Volume 14 (2021) p.p. 35-45
Issue 3, November 2021
Type of article 1.01
www.fe.um.si/en/jet.html

COMPARATIVE ANALYSIS OF SYNCHRONOUS MOTORS

PRIMERJALNA ANALIZA SINHRONSKIH MOTORJEV

Vasilija Sarac[ℜ], Goce Stefanov[1], Dragan Minovski[1]

Keywords: FEM models, synchronous motors, steady-state characteristics, transient characteristics

Abstract

This paper compares the parameters, steady-state and transient characteristics of two different types of synchronous motors (SM) – a motor with surface mounted magnets on the rotor, and a motor with embedded magnets and squirrel cage winding, widely known as a line-start synchronous motor. The comparison is based on results obtained from analytical, numerical and transient models of both motors for the same output power of the motors. The models for obtaining transient characteristics allow comparison of acceleration of both motors taking into consideration that the line-start SM is a self-starting motor while the SM with surface magnets is always started with the aid of a PWM inverter. The results obtained from the analytical, numerical and transient models of the motors should assist in choosing the most cost-effective solution in terms of the type of the motor for the appropriate application.

Povzetek

V članku je predstavljena primerjava parametrov, ustaljene in tranzientne karakteristike dveh različnih tipov sinhronih motorjev (SM) – motorja s površinsko nameščenimi trajnimi magneti ter motorja z vgrajenimi trajnimi magneti in kratkostično kletko. Primerjava temelji na pridobljenih rezultatih iz analitičnega, numeričnega in tranzientnega modela obeh motorjev pri enaki izhodni moči motorjev. Modeli za določitev tranzientnih karakteristik omogočajo primerjavo hitrosti obeh motorjev upoštevajoč, da je SM s trajnimi magneti in kratkostično kletko samozagonski motor, medtem ko se

---

[ℜ] Corresponding author: Prof. Vasilija Sarac, University Goce Delcev, Faculty of Electrical Engineering, Krste Misirkov 10-A, 2000 Stip, North Macedonia, Tel: +389 32 550 650, E-mail address: vasilija.sarac@ugd.edu.mk

[1] University Goce Delcev, Faculty of Electrical Engineering, Krste Misirkov 10-A, 2000 Stip, North Macedonia

SM s površinsko nameščenimi trajnimi magneti vedno zažene s pomočjo PWM pretvornika. Rezultati prej omenjenih modelov motorjev naj bi bili v pomoč pri izbiri stroškovno najugodnejše rešitve s stališča tipa motorja za določeno aplikacijo.

1 INTRODUCTION

Finding an adequate type of motor for certain applications is not an easy task for electrical engineers. There are varieties of induction motors, which nowadays are often used in various drive applications. The development of power electronics has made this choice even harder. Until recently, the three-phase asynchronous motor has dominated in the industries' drive system due to its robustness, low price and low maintenance costs. The power electronics facilitates its operation in variable speed drives, as the speed of this type of motor (asynchronous motor) can be easily regulated by frequency inverters. However, the low efficiency and the low power factor remain one of the major drawbacks of this type of induction motor. In contrast, synchronous motors have a high efficiency and power factor, which make them a main competitor of asynchronous motors. However, the choice of the most cost-effective solution in terms of motor type in a specific application is not so simple. Synchronous motors can be divided into two major groups – motors without cage winding on the rotor, and with various geometries of the magnets mounted on the rotor surface or embedded inside the rotor. This type of synchronous motor cannot be started without the aid of voltage inverters, i.e. they are not self-starting motors or they cannot be started directly from the mains power supply. Therefore, the cost of the motor rises as the cost of the inverter must be added to the cost of the motor. The second group of synchronous motors is the line-start synchronous motor with a design very similar to that of the asynchronous squirrel cage motor. The only difference in construction from the asynchronous squirrel cage motor is the magnets embedded inside the rotor. The squirrel cage winding assists in motor starting while the magnets pull the motor into synchronism. In an era where energy efficiency is of paramount importance, it is understandable why there has been increased interest in synchronous motors in the scientific community. The control theory, including sensorless speed control based on different original control techniques for improving the speed regulation of synchronous motors with surface or embedded magnets, is analysed in [1]-[3]. Another field of research is the losses of synchronous motors [4]. The early detection of motor faults by monitoring the stator currents or derating the motor due to a broken bar fault was studied in [5]-[6]. An in-depth analysis of motor losses can be found in [5]. Not just faults are those that limit the motor operation and life expectancy. Noise and vibration often accompany operation of the motor. The choice of the most adequate combination of the number of slots and number of poles can reduce noise and vibration, and make operation of the motor smoother [7]. Synchronous motors have wide application in the automotive industry, e.g. in high-speed applications. A detailed study of the transient characteristics of an induction motor with copper and aluminium bars in high-speed applications can be found in [8]. Another aspect of usage of synchronous motors in high-speed applications is the mechanical design of the rotor in terms of the reduction of mechanical stress. An in-depth study of the mechanical construction of the rotor with surface and embedded magnets in terms of the mechanical stress can be found in [9]. Another issue that arises in terms of the operation of synchronous motors is the harmonics that are often present when a synchronous motor is operated by an inverter [10]. The literature review undertaken for this research showed that very few papers address the comparison between synchronous motors with surface mounted magnets (SMSPM) and line-start synchronous motors (LSSPMM). This comparison is interesting from a design point of view as well as from the point of view of the operating characteristics of the motors. Three different methodologies were used for developing the motor models and obtaining the operating characteristics – a computer model for analytical calculation of parameters and steady state characteristics, a numerical model for magnetic flux density distribution, and a dynamic model for obtaining the transient characteristics. Both motors were constructed for the same power output and with minimum material consumption (copper and permanent magnets), which allowed maximum efficiency and power factor to be obtained. The results obtained from all three methods were compared and adequate conclusions were derived. The comparison shown should assist in finding an adequate motor for certain applications by taking into consideration all the advantages and drawbacks of the analysed motors.

2 METHODOLOGY AND RESULTS

2. 1 Computer models for analytical calculation of parameter and steady-state characteristics

Ansys software was used in modelling the computer models of both synchronous motors, which allows calculation of motor parameters and operating characteristics. Both types of synchronous motors were derived from the asynchronous motor type 2AZ155-4 or the new model of motor-5AZ100LA-4, produced by the Croatian company Rade Končar [11]. Both synchronous motors were modelledwith one constraint: the output power should remain unchanged, i.e. 2.2kW, the same as the asynchronous motor. In order for the computer models to reach a solution and provide accurate results, the exact geometry of the motors must be defined as well as all the materials used in construction of the motor. A cross-section of both motors is presented in Fig.1. The output results from the computer models are the motor parameters at rated load, no load and locked rotor, as illustrated in Table 1. The comparison of these two types of synchronous motors is justified by the fact that in spite of their quite different rotor configuration, both motors do not exhibit any Joule’s losses in the rotor.

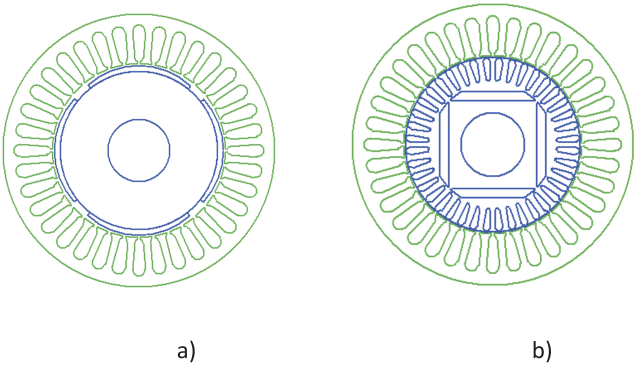
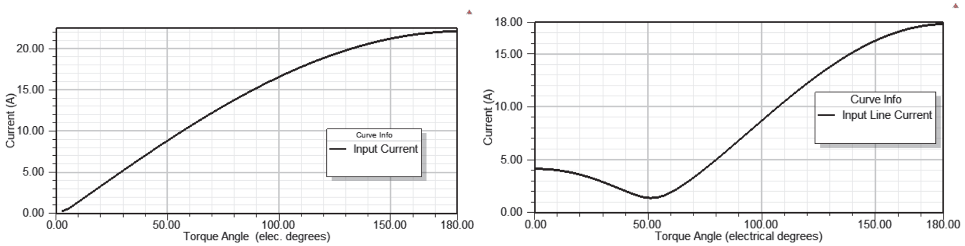

a) b)

Figure 1: *Cross-section of the analysed motors*

Table 1: *Parameters and operating characteristics of analytical model*

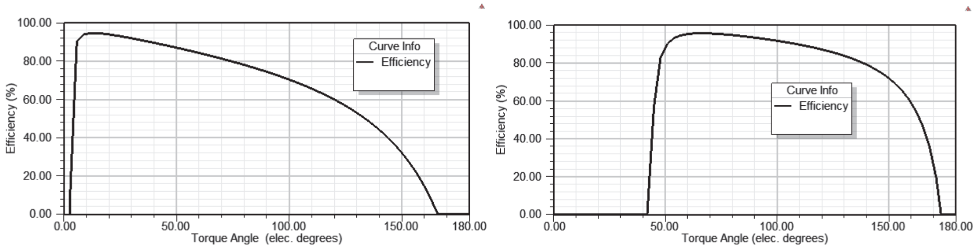
Parameters	SMSPM	LSSPMM
Stator phase resistance R_1 (Ω)	2.95	1.8
Number of conductors per slot	125	97
Wire diameter (mm):	0.8	0.9
Stator slot fill factor (%):	70	69.9
Stator copper weight (kg):	3.91	3.83
Permanent magnet weight (kg):	0.61	0.5
Armature core steel weight (kg)	4.4	4.4
Rotor core steel weight (kg):	3.7	2.7
Rotor winding weight (kg)	/	0.61
Total net weight (kg):	12.6	12.1
Maximum output power (W)	6,113	5,764
Rated load operation		
Armature current (A)	3.56	3.52
Input power (W)	2,349	2,303
Output power (W)	2,200	2,199
Frictional & windage loss (W):	22	22
Iron-core loss (W):	14.2	13.9
Armature copper loss (W)	112.2	68
Total loss (W):	148.4	104
Efficiency (%)	93.7	95.5
Rated speed (rpm)	1,500	1,500
Rated torque (Nm)	14	14
Power factor (/)	0.996	0.992
Torque angle (°)	18.5	69.3
Locked rotor operation		
Start Torque (Nm)	**/**	62
No-load operation		
No-Load Line Current (A)	0.27	1.76
No-Load Input Power (W)	36.9	53

The SMSPM does not have any rotor winding so no losses are associated with it. At LSSPMM there is no current induced in the rotor winding when motor operates at a synchronous speed and no losses are associated with this winding. The predefined motor parameter is the output power which should remain unchanged. Both motors are derived from the three-phase asynchronous squirrel cage motor by redesigning the rotor. The same materials are used in both the motor configurations as in the original asynchronous motor. The same type of magnets are used in both motors. In order to achieve similar operating characteristics, the stator winding of the SMSPM has to be modified, i.e. the number of conductors per slot is increased. The programme automatically reduces the wire diameter in order to maintain the same slot fill factor, i.e. to maintain the same output power of the motor while not exceeding the limited slot fill factor of 75%. The increased number of conductors per slot increases the winding resistance and consequently the armature copper losses are higher in the SMSPM compared to the LSSPMM. Since all the other losses are almost the same, this increase of copper losses reduces the efficiency of the LSSPMM compared to the SMSPM. Both motors have almost the same power factor. The net weight and consumption of material are somewhat higher in the SMSPM. In terms of the maximum output power, both motors have satisfactorily high values, i.e. the overloading capability of both motors is almost the same and is sufficiently high, i.e. the ratio of breakdown torque to rated torque is 2.8 in the SMSPM and 2.62 in the LSSPMM. The motor current and efficiency for the various torque angles are presented in Fig. 2 and 3 respectively. The results in both the aforementioned figures should verify the data in Table 1 and illustrate the operation of both types of motors. The adequate values of the torque and efficiency can be read for the appropriate torque angle which defines the rated operation of the motor.



a) SMSPM b) LSSPMM

***Figure 2:** Line current*

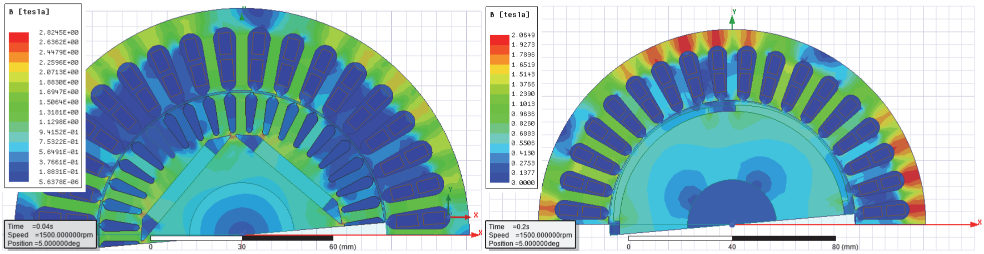


a) SMSPM b) LSSPMM

***Figure 3:** Efficiency factor*

2. 2 FEM Model for numerical calculation of flux density

The FEM models of the electrical machines have become part of the standardised procedure for the design of motors. There are several rreasons for this: availability of various commercial or non-commercial programmes for creating FEM models of the machines, the importance of detection of areas of the cross-section of the motor with the high flux density, and detecting the need of machine redesigning if there are large areas of the machine cross-section with the high flux density. For both the analysed motors, FEM models were created for calculating the flux density distribution inside the motors. The results obtained are shown in Fig. 4.



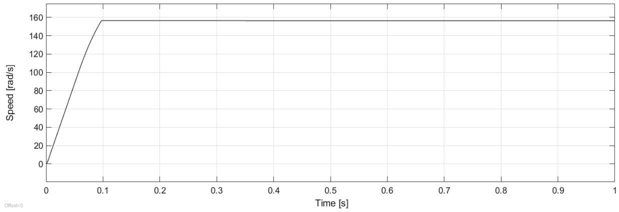
a) LSSPMM b) SMSPM

Figure 4: *Flux density distribution*

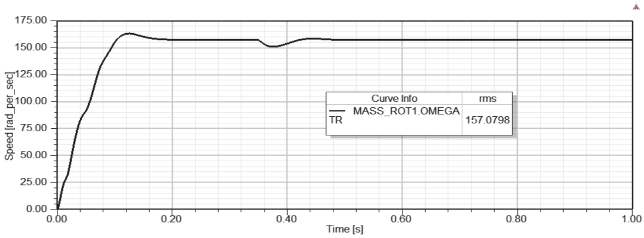
As can be seen from the results illustrated in Fig.4, the critical parts in the motor construction in the case of the LSSPMM are the edges of the flux barriers near to the rotor slots. One solution could be to alter the design of the rotor slots in order to provide a thicker magnetic core in this part of the motor. For both motors, the high flux density in stator yoke can be decreased by increasing the motor outer diameter. This could form part of an additional analysis as both the motors were derived from a three-phase asynchronous squirrel cage motor without changing the outer dimension of the motor or the original geometry and material of the stator laminations.

2. 3 Dynamic models and transient characteristics

The analysis of the motors' dynamics covers the transient characteristics of the speed, torque or current during acceleration of the motors up to steady-state operation. Although starting of these two types of synchronous motors is different, i.e. the LSSPMM is started directly from the mains while the SMSPM only required an inverter to start, an analysis of their transient characteristics is necessary in order to obtain data relating to their starting time, synchronisation and possibility to drive various loads. The dynamic model of the LSSPMM is simulated in Ansys while that of the SMSPM is simulated in Simulink. Both the motors were loaded with a step load of 14Nm, 0.35 seconds after the motor was started. The obtained transient characteristics of speed, torque and current are presented in Figs. 5, 6 and 7.



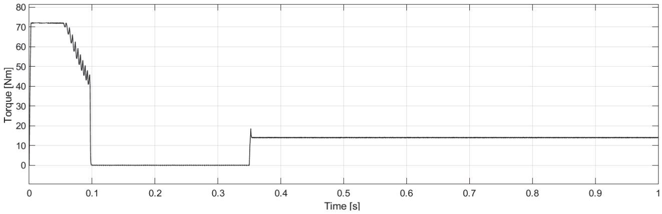
a) SMSPM



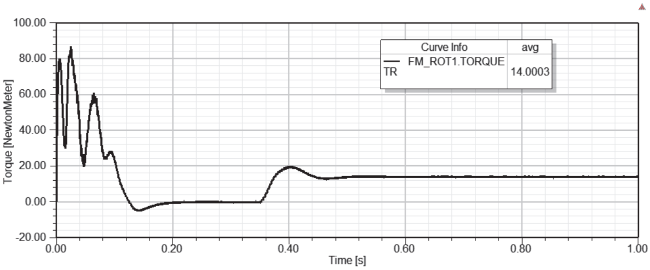
b) LSSPMM

Figure 5: *Transient characteristics of speed*

As can be seen from the illustrated transient characteristics of speed, the acceleration time of both motors is nearly the same and they achieved a synchronous speed of 1,500rpm or 157.07 rad/s. Both motors maintained the synchronous speed after they were loaded with the load torque.



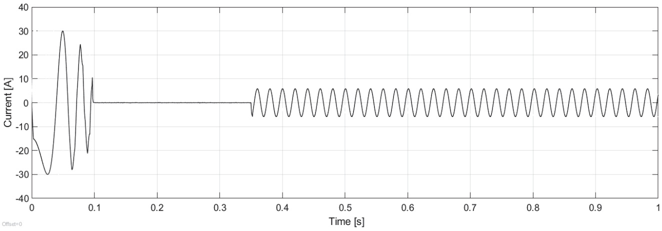
a) SMSPM



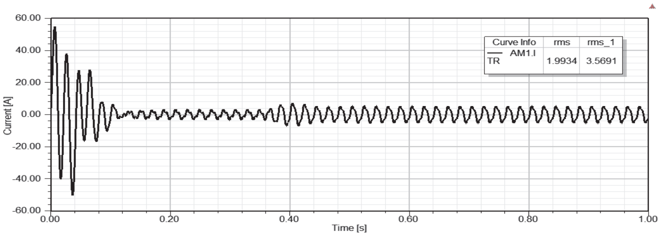
b) LSSPMM

Figure 6: *Transient characteristics of torque*

In both motors, the output torque after the acceleration has finished, reaches the no-load torque. After the step load of 14Nm is coupled to the motor shaft, the output torque reaches 14Nm.



a) SMSPM



b) LSSPMM

Figure 7: *Transient characteristics of current*

From the transient characteristic of current of the SMSPM, after acceleration, the current reaches almost zero value which correlates with the data in Table 1 for the no-load current of 0.27A. After the step load of 14Nm is coupled to the motor shaft, the current increases to the rated current 4A (rms) and correlates with the analytical result of 3.5A. A similar observation can be derived for the current of the LSSPMM.

3 CONCLUSION

This paper describes an anaylsis of an LSSPMM and SMSPM. In terms of efficiency and material consumption, the LSSPMM has an advantage over the SMSPM, while the SMSPM has a greater overloading capability. Construction of the SMSPM is simple, however there is an ever-present danger of demagnetisation of the magnets due to the surface placement on the rotor. As the magnets are glued to the rotor, there is often a need to ‘bandage’ them to protect them from hazard at high speeds. The design of the rotor of the LSSPMM is more complicated, but the risk of demagnetisation of the magnets is lower as they are embedded inside the rotor and there is no need to ‘bandage’ them. In terms of simplicity of operation, the advantage of the LSSPMM is that it is self-starting and does not require an inverter in contrast to the SMPSM. However, in high-speed applications and electrical mobility, synchronous motors with surface magnets are often present and due to their isotropic rotor, the d- and q-axis inductances are identical and the saliency ratio ($\xi = Lq/Ld$) is 1. Therefore, no reluctance torque occurs. There is no straightforward answer as to which type of the two analysed motors is better. Each motor should be evaluated in terms of its specific application.

References

[1] **M. Štulrajter, V. Hrabovcová. M Franko**: *Permanent magnet synchronous motor control strategies*, Journal of Electrical Engineering, Vol.58, Iss.2, p.p. 79-84, 2007

[2] **E. Ojionuka, I. Chinaeke-Ogbuka, C. Ogbuka, C. Nwosu**: *Simplified sensorless speed control of permanent magnet synchronous motor using model reference adaptive system*, Journal of Electrical Engineering, Vol.70, Iss.6, p.p.473-479, 2019

[3] **G. Park, G. Kim, B-G. Gu:** *Sensorless PMSM inductance estimation based on the data drive approach,* Electronics, Iss.10, pp.1-19, 2021

[4] **P. Hudák, V. Hrabovcová, P. Rafajdus, J. Mihok:** *Core loss analysis of the reluctance synchronous motor with barrier rotors,* Journal of Electrical Engineering, Vol.55, Iss.9, pp.273-276, 2004

[5] ***J. Faiz, A. M. Takbash:*** *Derating of three-phase squirrel cage induction motor under broken bar fault,* Facta Universitatis, Series Automatic Control and Robotics, Vol.12, Iss.3, pp.147-156, 2013

[6] **P. Pietrzak, M. Wolkiewicz:** *Comparison of selected methods for the stator winding condition Monitoring of a PMSM using the stator phase currents*, Energies, Vol.14, 2021, pp.1-23.

[7] **M. Mendizabal, A. McCloskey, J. Poza, S. Zarate, J. Iriondo, L. Irazu**: *Optimum Slot and Pole Design for Vibration Reduction in Permanent Magnet Synchronous Motors*, Applied Sciences, Vol.11, 2021, pp.1-17.

[8] **D-C. Popa, B. Văraticeănu, D. Fodorean, P. Minciunescu, C. Martis:** *High speed induction motor used in electrical vehicles*, Electrotehnică, Electronică Electrotehnică, (EEA), Vol.64, Iss.3, pp.5-11, 2016

[9] **B.D. Văraticeănu, P. Minciunescu, D. Fodorean:** *Mechanical design and analysis of a permanent magnet rotor used in high-speed synchronous motor*, Electrotehnică, Electronică, Automatică, Vol.62, Iss.1, pp.9-17, 2014

[10] **R. Anand, B. Gayathridev, B.K. Keshavan:** *Vertical Transportation: Effects of Harmonics of Drives by PM Machines*, Power Electronics and Drives, Vol.3(38), No.1, 2018, pp.47-53.

[11] **Končar-Mes**. Available: https://koncar-mes.hr/wp-content/uploads/2020/08/Electric-motors.pdf (29.10.2021)