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COMPARATIVE ANALYSIS OF SYNCHRONOUS MOTORS

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Abstract: Paper compares the parameters, steady state and transient characteristics of two different types of synchronous motors (SM)-the motor with surface mounted magnets and the motor with the embedded magnets and squirrel cage winding, widely known as line-start synchronous motor. The comparison is based on results obtained from analytical, numerical and transient models of the 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 line-start SM is the self-starting motor while SM with surface magnets is always started with the PWM inverter. Obtained results from the analytical, numerical and transient models of the motors should assist in choosing the most cost effective motor for the appropriate application.

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

INTRODUCTION

Finding the adequate type of the motor for the certain application is not an easy task for the 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 due to its robustness, low price and low maintenance costs. The power electronics facilities its operation in variable speed drives, as the speed of this type of the motor can be easily regulated by frequency inverters. However, the low efficiency and power factor remain as one of the major drawbacks of this type of the induction motor. On the contrast, the synchronous motors have high efficiency and power factor, which make them a main competitor of the asynchronous motors. Yet, the choice of the most cost effective solution regarding motor type in a specific application is not so simple. The synchronous motors can be divided into two major groups. The motors without the 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 the synchronous motors 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 main power supply. So the cost of the motor rises as the cost of the inverter must be added to the cost of the motor. On the other hand, in the second group of the synchronous motors is the line start synchronous motor with the design very similar to the asynchronous squirrel cage motor. The only difference in the 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 the synchronism. In the era where energy efficiency is the main paramount, it is understandable why the interest for the synchronous motors has raised in the scientific community. The control theory including sensorless speed control based on different original control techniques for improving the speed regulation of the synchronous motors with surface or embedded magnets is analysed in [1]-[3]. Another field of research is the losses of the synchronous motor [4]. The early detection of motor faults by monitoring the stator currents or derating the motor due to the broken bar fault has been studied in [5]-[6]. A very detailed analysis of motor losses can be found in [5]. Not just faults are those that limit the motor operation and the life expectance. Noise and vibrations often accompany the motor operation. The choice of the most adequate combination of number of the slots and number of the poles can reduce the noise, vibration, and improve the smooth operation of the motor [7]. The synchronous motors have wide application in automotive industry i.e. in the high-speed applications. A detailed study of transient characteristics of induction motor with copper and aluminium bars in high-speed applications can be found in [8]. Another aspect of usage of synchronous motors in the high-speed applications is the mechanical design of the rotor in terms of reduction the mechanical stress. A very detailed 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 rises at the operation of the synchronous motors is the harmonics which are often present when synchronous motor is operated by the inverter [10]. The review of the literature showed that very few papers address the comparison between synchronous motor with surface mounted magnets (SMSPM) and line start synchronous motor (LSSPMM). This comparison is interesting from the construction point of view also 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. The computer models for analytical calculation of parameters and steady state characteristics, the numerical models for magnetic flux density distribution and the dynamic models for obtaining the transient characteristics are developed. Both motors were constructed for the same power output and with minimum material consumption (copper and permanent magnets) which allows obtaining maximum efficiency and power factor. The obtained results from all three methods are compared and adequate conclusions are derived. The presented comparison should assist in finding the adequate motor for the certain

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application by taking into consideration all the advantages and drawbacks of the analysed motors.

METHODOLOGY AND RESULTS

Computer model for analytical calculation of parameters and steady-state characteristics

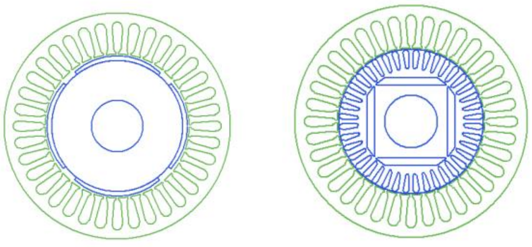
Ansys software was used in modelling the computer models of the both synchronous motors that allow calculation of motor parameters and operating characteristics. The both types of synchronous motors were derived from the asynchronous motor type 2AZ155-4 or the new model of the motor-5AZ100LA-4, product of company Rade Končar from Croatia [11]. The both synchronous motors were derived with one constrain: the output power should remain un-changed i.e. 2.2 kW like at the asynchronous motor. In order computer models to reach the solution and give as an output accurate results, the motors exact geometry must be defined as well as all the materials used in the motor construction. The cross section of both motors is presented in Fig.1. Output results, from the computer models are the motor parameters at rated load, no load and at locked rotor. They are presented in Table 1.

Table I

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)	6113	5764
Rated load operation		
Armature current (A)	3.56	3.52
Input power (W)	2349	2303
Output power (W)	2200	2199
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)	1500	1500
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

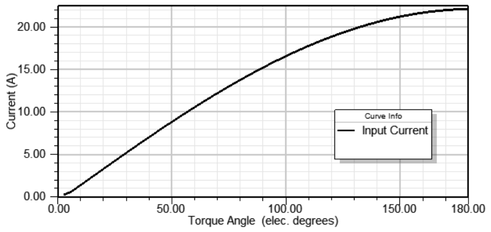
The comparison of these two types of synchronous motors is justified by the fact that in spite their quite different rotor configuration, both motors do not have Joule losses in the rotor. The SMSPM does not have any rotor winding so there are no losses associate with it. At LSSPMM there is no current induced in the rotor winding when motor operates with the synchronous speed and again there is no losses associate with it. 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 the both motor configurations as there are in the original asynchronous motor. The same type of magnets is used in the both motors. In order to achieve the similar operating characteristics, for the SMSPM, the stator winding has to be modified i.e. the number of conductors per slot are increased. The program 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 and in the same time not to exceed 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 at SMSPM in comparison to LSSPMM. As all the other losses are almost the same this increase of copper losses reduces the efficiency of LSSPMM in comparison to SMSPM. The both motors have almost the same power factor. The net weight and the consumption of material are somewhat higher at SMSPM. As for the maximum output power both motor have satisfactory high values i.e. the overloading capability of both motor is almost the same and sufficiently high i.e. the ratio of breakdown torque to rated torque is 2.8 at SMSPM and 2.62 at LSSPMM.



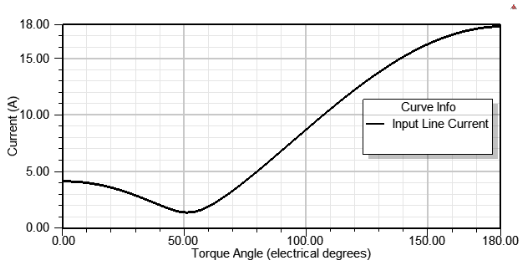
(a) SMSPM (b) LSSPMM

Fig.1 - *Cross- section of the analysed motors.*

The motor current and efficiency for the various torque angles are presented in Fig. 2 and 3 respectively. Presented results in the mentioned Figures should verify the data in Table 1 and illustrate the operation of the both types of the 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.

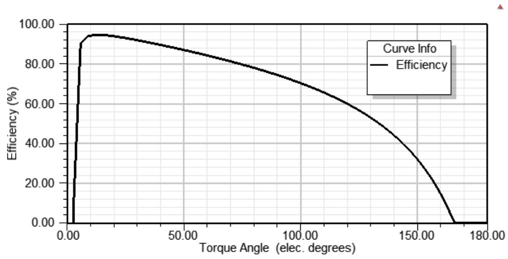


(a) SMSPM

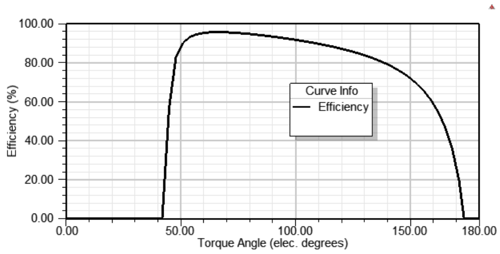


(b) LSSPMM

Fig.2 - *Input current*.



(a) SMSPM

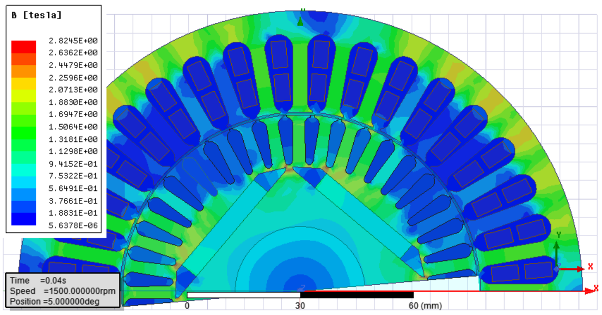


(b) LSSPMM

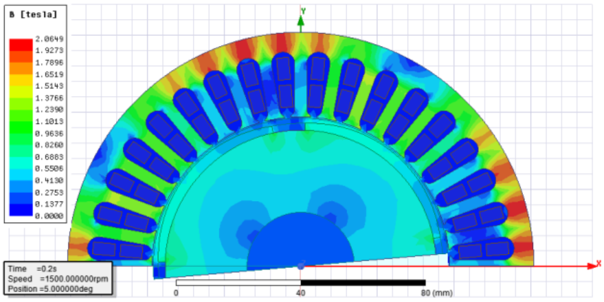
Fig.3 - *Efficiency factor*.

FEM model for numerical calculation of flux density

The FEM models of the electrical machines have become a part of the standardized procedure for design of the motors. Reasons are several: availability of various commercial or non-commercial programs 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, discovering the need of machine redesigning if there are large areas of the machine cross-section with the high flux density. For the both analysed motors, FEM models were created for calculating flux density distribution inside the motors. Obtained results are presented in Fig. 4.



(a) LSSPMM



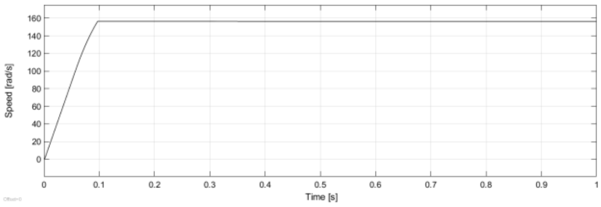
(b) SMSPM

Fig.4 - *Output power and air gap power*.

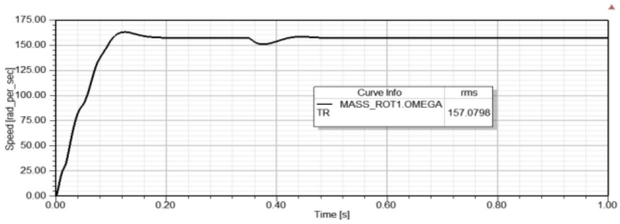
From the presented results in Fig.4 the critical parts in the motor construction in case of LSSPMM are the edges of flux barriers near to the rotor slots. One solution can be altering the design of the rotor slots in order to provide thicker magnetic core in this part of the motor. For the both motors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

Dynamic models and transient characteristics

The analysis of the motor's dynamics covers the transient characteristics of the speed, torque or current during the motor acceleration up to the steady-state operation. Although starting of these two types of the synchronous motors is different namely the LSSPMM is started directly from the mains while SMSPM is started only by the aid of the inverter, the analysis of their transient characteristics is necessary in order to obtain data regarding their starting time, synchronization and possibility to drive various loads. The dynamic model of LSSPMM is simulated in Ansys while of SMSPM is simulated in Simulink. The both motors were loaded with the step load of 14 Nm, 0.35 seconds after motor starting. The obtained transient characteristics of speed, torque and current are presented in Fig. 5, 6 and 7.



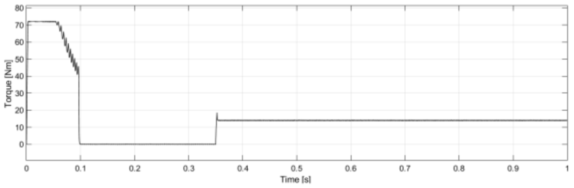
(a) SMSPM



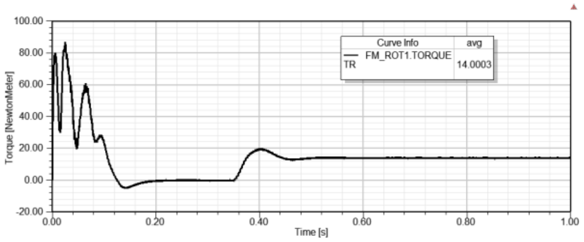
(b) LSSPMM

Fig.5 - *Transient characteristic of speed*.

From the presented transient characteristic of speed both motors accelerate for nearly the same time and achieve the synchronous speed of 1500 rpm or 157.07 rad/s. Both motors maintain the synchronous speed after they were loaded.



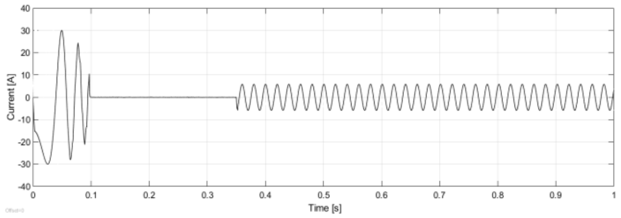
(a) SMSPM



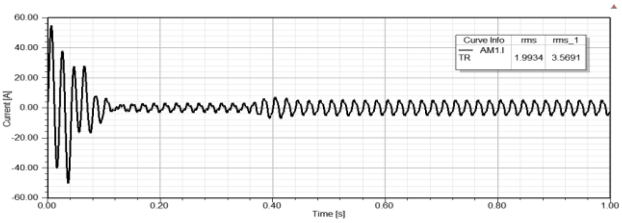
(b) LSSPMM

Fig.6 - *Transient characteristic of torque*.

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



(a) SMSPM



(b) LSSPMM

Fig.7 - *Transient characteristic of current*.

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

CONCLUSION

The LSSPMM and SMSPM are compared and analysed in this paper. Regarding efficiency and material consumption the LSSPMM has an advantage over SMSPM. On the other hand, the SMSPM has bigger overloading capability. The SMSPM has simple construction but there is always a danger of demagnetization of the magnets due to the surface placement on the rotor. As the magnets are glued to the rotor often there is a need of bandage to protect them from hazard at high speeds. LSSPMM has more complicated design of the rotor but here there is no demagnetization of the magnets as they are embedded inside the rotor and there is no need for bandage. Regarding simplicity for operation the LSSPMM has the advantage of self-starting without the need of inverter in contrast to the SMPSM. Yet, in high speed applications and electrical mobility synchronous motors with surface magnets are often present 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 which type of the two analyzed motors is better. Each motor should be evaluated in terms of its specific application.

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