Maciej GWOŹDZIEWICZ, Jan ZAWILAK

Politechnika Wrocławska, Instytut Maszyn, Napędów i Pomiarów Elektrycznych

Influence of the rotor construction on the single-phase line start permanent magnet synchronous motor performances

Streszczenie. *W artykule przedstawiono konstrukcję jednofazowego silnika synchronicznego z magnesami trwałymi. Na podstawie jednofazowego silnika indukcyjnego masowej produkcji został zbudowany model polowo-obwodowy jednofazowego silnika synchronicznego z magnesami trwałymi w programie Maxwell wersja 14. Wzięto pod uwagę różnorodne konstrukcje wirnika. Zbadano wpływ konstrukcji wirnika na właściwości silnika. Zbadano właściwości rozruchowe silnika. (**Wpływ konstrukcji wirnika na właściwości jednofazowego silnika synchronicznego z magnesami trwałymi o rozruchu bezpośrednim**).*

Abstract. *The paper deals with construction of single-phase line start permanent magnet synchronous motor. Circuit-field single-phase line start permanent magnet synchronous motor model based on the mass production single-phase induction motor was applied in Maxwell ver. 14 program. Various rotor constructions were taken into account. Influence of the rotor construction on the motor properties was examined. Starting motor properties were investigated.*

Słowa kluczowe: silnik jednofazowy, silnik synchroniczny, magnesy trwałe, rozruch bezpośredni.
Keywords: single-phase motor, synchronous motor, permanent magnets, line start.

Introduction

Single-phase induction motors are widely used in domestic appliances and light-duty industrial applications where three-phase supply is not readily available. Rated power of this electric motor type is limited by rated current of the single-phase 230 V socket which is almost always equal to 16 A. It follows that single-phase motor rated power does not exceed 3 kW.

In induction motors torque is developed due to slip between stator rotating magnetic field and rotor bars. It causes rotor copper loss due to flowing current through the rotor bars. Moreover, magnetizing current is needed to produce magnetic flux. It causes additional stator copper loss due to flowing current through the stator winding.
In synchronous motors magnetic flux is produced by the excitation: electromagnets or permanent magnets. It follows that the whole or most of the magnetic flux can be produced inside the machine and no or relatively small value of the reactive power [and simultaneously of the magnetizing current] is drawn by the working motor. However, typical synchronous motor has electromagnetic excitation which needs high maintenance and additional DC supply. In case of permanent magnet excitation of a synchronous motor there is no rotor copper loss due to no slip and no DC current flowing through the excitation winding. The main drawback of synchronous motors is bad starting properties.

Stators of induction motors and synchronous motors are practically the same so the simplest way to obtain both high power factor and high efficiency [advantages of a synchronous motor] and inherent self-starting property, simplicity and ruggedness [advantages of an induction motor] of an AC motor is installation of permanent magnets inside the induction motor rotor saving its squirrel-cage [1, 2]. This type of motor is called Line Start Permanent Magnet Synchronous Motor.

In case of three-phase motors this operation is relatively easy because of circle rotating magnetic field. In case of single-phase motors the air gap magnetic field would be an ellipse field (because of the asymmetry of stator configuration) and can be decomposed into a positive-sequence rotating field and a negative-sequence one [3]. The negative-sequence magnetic field produces a braking torque in the motor, which makes efficiency and output torque low, and makes the mechanism character being soft [4]. This phenomenon causes a big problem during motor starting and synchronization but it can be solved by additional start-capacitor in the auxiliary winding. Start-capacitor connected in parallel with run-capacitor improves starting properties but simultaneously makes worse running properties so after starting it must be switched-off by centrifugal switch or time switch [3, 4].

FEM models

Two dimensional field-circuit models of the single-phase line start permanent magnet synchronous motor were applied in Maxwell ver. 14 program. The models are based on the mass production single-phase induction motor Seh 80-4B type with P_n=750 W, U_n=230 V, f_n=50 Hz, n_n=1370 rpm. Neodymium magnet N45H type with B_r=1.34 T and H_{cb}=995 kA/m was chosen for the excitation of the synchronous motor. Single-phase induction motor was changed into single-phase line start permanent magnet synchronous motor by replacement standard squirrel-cage rotor with squirrel-cage permanent magnet rotor. In the first model (with 22 rotor bars like in case of the original induction motor) rotor slots were kept without changes. End ring width was reduced because permanent magnets were installed in the end ring area. The end sheets of the rotor core do not contain the permanent magnet slots to avoid flowing hot aluminum into them during casting of the rotor squirrel-cage. The rotor squirrel-cage is cast in the same way both for single-phase induction motor and for single-phase line start permanent magnet synchronous motor but in case of SPLSPMSM the end rings and the end rotor sheets are machined after casting to open slots for installation of permanent magnets.

In another models the rotor with 22 bars is changed for rotors with 18 and 26 bars. The volume of the aluminum and sum of the rotor teeth width are kept without changes. Permanent magnets width, thickness and length are kept without changes also, only their arrangement is changed to keep safe distance from the rotor bars for mechanical reasons.

Influence of the rotor slots opening is investigated. Two cases are determined: no slots opening and 1 mm slots opening.

Field parts of the motor model are shown in Fig. 1 and circuit part of the motor models is shown in Fig. 2.

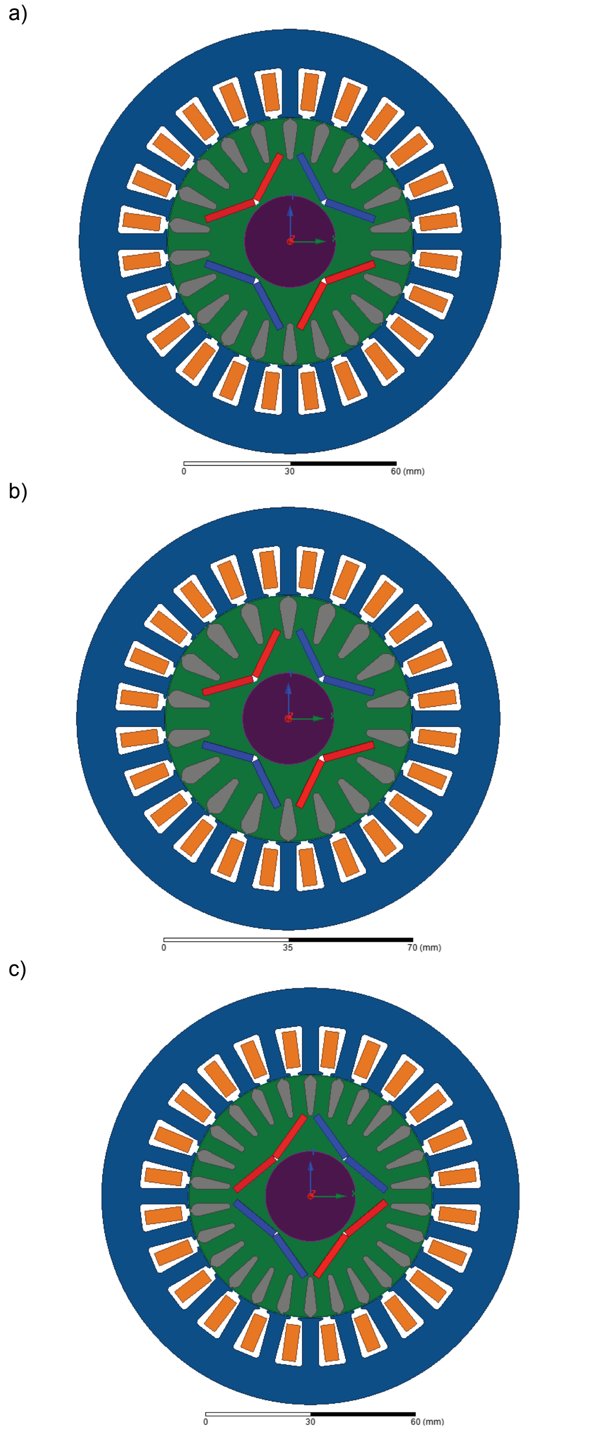

Fig.1. Field parts of the motor models: a) 22 rotor slots, b) 18 rotor slots, c) 26 rotor slots

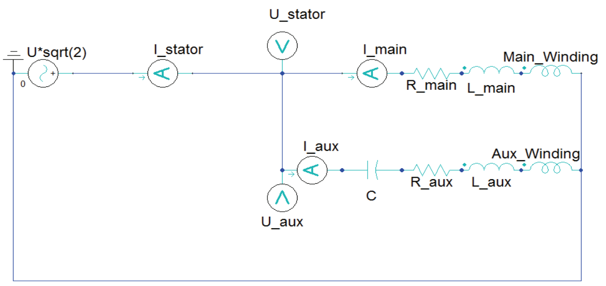

Fig.2. Circuit part of the motor models

Optimal solution

LSPMSM can be recommended for drives with constant load torque and low starting torque such as pump or fan [4]. The motor to drive a pump or a fan is chosen according to the formula (1):

$$P_{motor} = k \cdot \frac{Q \cdot \Delta p}{\eta} \tag{1}$$

where: P_{motor} - motor power,k - reserve coefficient (k=1.1–1.15), Q - flow rate, Δp- static pressure, η- fan/pump efficiency.

On the basis of the equation (1) the motor to drive a fan or a pump is chosen with reserve of the power. It follows that in nominal conditions the motor works in the range of the load power (0.86–0.91) P_n.

According to the above-cited facts in [6] the authors introduce basic strategy for the design of the auxiliary winding (number of the auxiliary winding turns and capacitance of the run-capacitor) to obtain the maximum of the motor efficiency in the range of the load power (0,86–0,91) P_n.

The single-phase induction motor rated power P_n=750 W. SPIM is changed into SPLSPMSM by replacement standard squirrel-cage rotor with squirrel-cage permanent magnet rotor. SPLSPMSM has higher rated power [4, 5]. Electric motors are classified by their rated power with proper values. Next step in this classification for the motor with P_n=750 W is the motor with P_n=1100 W. For the investigated SPLSPMSM model the rated power was determined as the next step in the motor rated power classification so $P_{SPLSPMSMn}$=1100 W.

Investigations in [6] show that change of the auxiliary winding parameters (number of the turns and capacitance of the run-capacitor) has influence on the motor efficiency curve what is presented in Fig. 3.

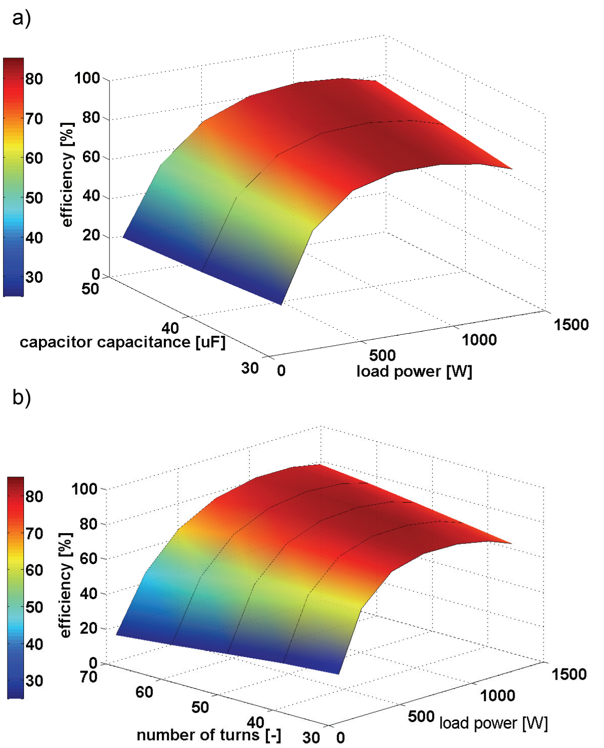

Fig.3. Influence of changes of: a) the auxiliary winding turns for C_{RUN}=40 μF, b) the run capacitor capacitance for N_{AUX}=50 turns, on the motor efficiency

According to [6] the optimal solution (in regard to the established criterion) is obtained for $N_{AUXturns}$=50 turns and C_{run}=40 μF and this solution would be compare with the base SPIM for which $N_{AUXturns}$=94 turns and C_{run}=20 μF.

Running properties

Comparison of the SPIM and SPLSPMSM load characteristics is presented in Fig. 4. The obtained results of the SPIM and SPLSPMSM rated performance are shown in Tab. 1.

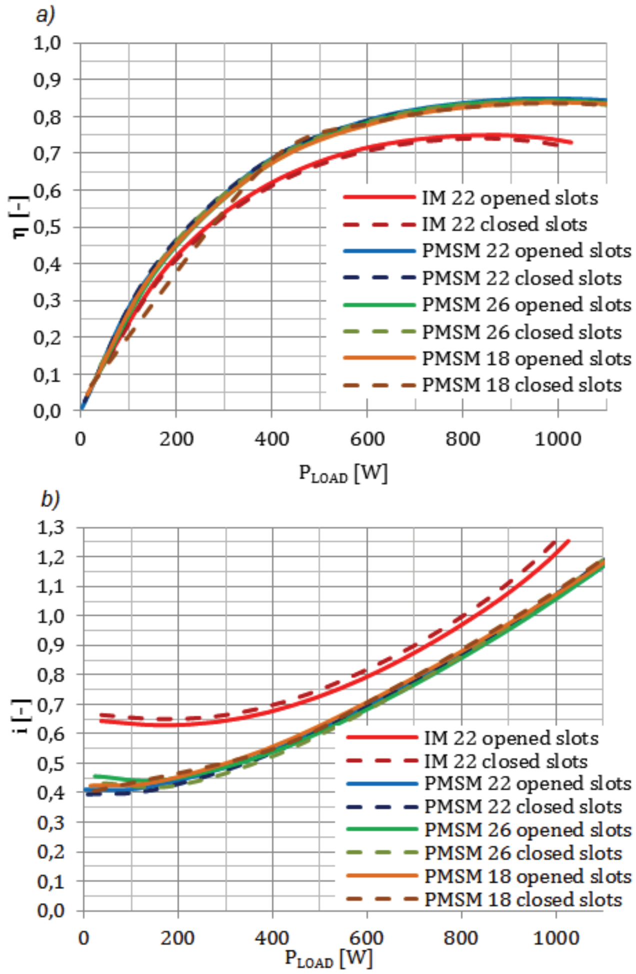

Fig.4. SPIM and SPLSPMSM: a) efficiency, b) current in load domain

Table 1. IM and PMSM rated performance

motor	P	η	cosφ
	W	%	-
IM 22 opened slots	750	74.3	0.97 lagging
IM 22 closed slots		73.5	0,96 lagging
PMSM 22 opened slots	1100	84.5	0,97 leading
PMSM 22 closed slots		83.9	0,98 leading
PMSM 26 opened slots		83.7	0,98 leading
PMSM 26 closed slots		83.2	0,98 leading
PMSM 18 opened slots		83.5	0,98 leading
PMSM 18 closed slots		83.2	0,98 leading

SPLSPMSM efficiency is much higher than SPIM efficiency because SPLSPMSM rotor copper loss is much lower than SPIM rotor copper loss what is presented in Fig. 5.

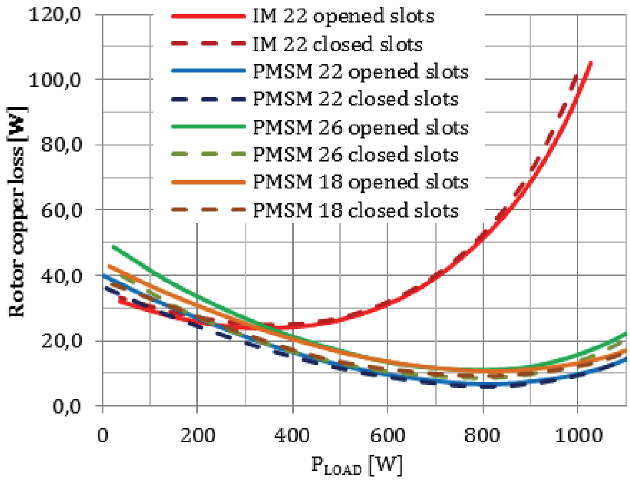

Fig.5. SPIM and SPLSPMSM rotor copper loss in load domain

Single-phase motors with opened rotor slots in comparison with single-phase motors with closed rotor slots obtain higher efficiency. Single-phase induction motor draws reactive power and single-phase line start permanent magnet synchronous motor produces reactive power. Rotor slots opening has influence on the rotor leakage flux what affects the reactive power absorption (in case of SPIM) or reactive power production (in case of SPLSPMSM)

SPLSPMSM starting properties

LSPMSM are recommended for pumps or fans because of good running properties and poor starting properties [5]. Typical pump or fan load characteristic is shown in Fig. 6.

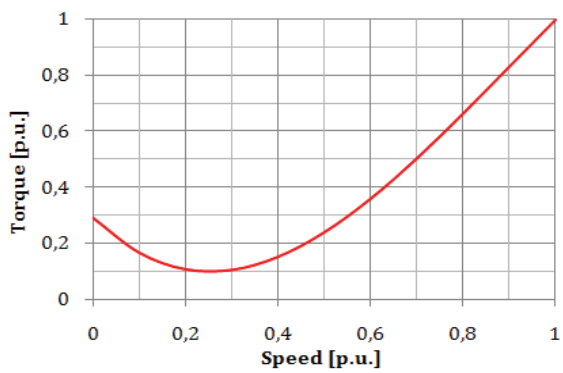

Fig.6. Typical pump/fan load characteristic

To investigate starting properties of the SPLSPMSM (with 22 opened rotor slots) pump/fan load characteristic was assumed. The rated load torque was equal to the SPLSPMSM rated torque and moment of inertia of the whole drive system was assumed to be five times greater that the SPLSPMSM moment of inertia according to the formula (2):

$$J = 5 \cdot J_{motor} = 0.01 kgm^2 \quad (2)$$

where: J – the whole drive system moment of inetria, J_{motor} - motor moment of inetria.

For the SPLSPMSM two start-capacitors was applied: 100 μF and 150 μF. The results of starting simulation are presented in Fig. 7.

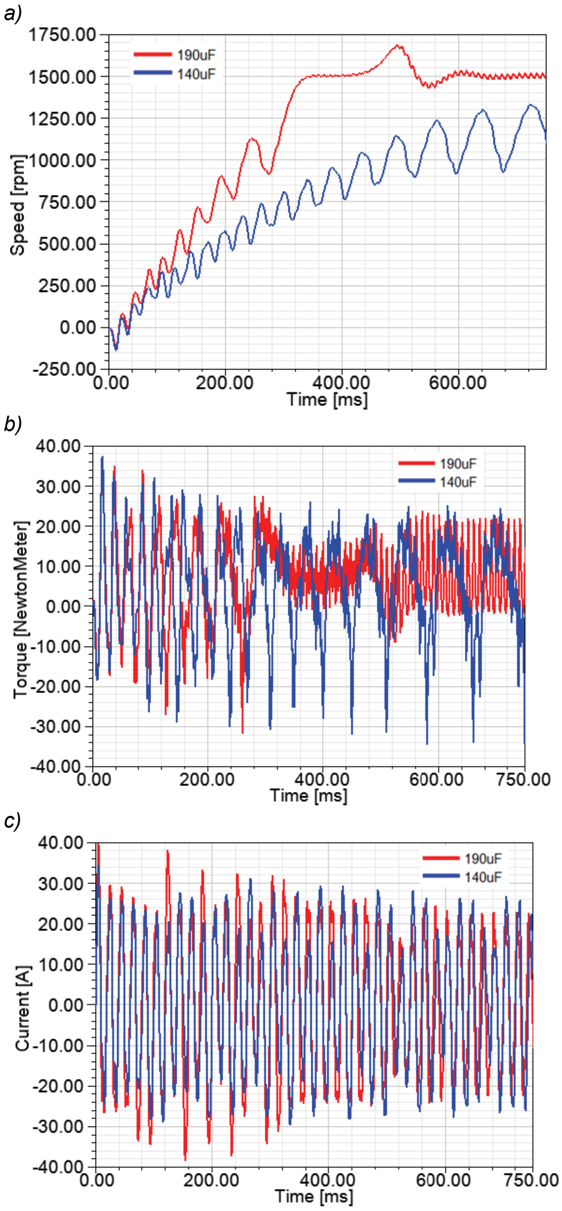

Fig.6. LSPMSM starting: a) speeds, b) torques, c) currents

According to the obtained starting simulation results it follows that increase of capacitance of the start-capacitor improves starting properties of SPLSPMSM and makes better ability to synchronisation. Moreover, increase of capacitance of the start-capacitor causes a little increase of the starting current.

Conclusions

Rotor slot opening in line start permanent magnet synchronous motor has significant influence on the motor efficiency. LSPMSM with opened rotor slots obtain higher efficiency. Moreover, rotor slot opening cause limitation of the rotor leakage flux so LSPMSM with opened rotor slots utilize permanent magnets better what is very important in case of the relatively high price of neodymium magnets.

The optimal number of the rotor bars in LSPMSM with 24 stator slots is 22 due to the lowest rotor copper loss and the highest motor efficiency.

Starting properties of LSPMSM can be improved by the start capacitor with higher capacitance.

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Authors*: M.Sc. Maciej Gwozdziewicz, Ph.D. student, Wroclaw University of Technology Institute of Electrical Machines, Drives and Measurements, 50-372 Wroclaw, ul. Smoluchowskiego 19, maciej.gwozdziewicz@pwr.wroc.pl, Prof. Jan Zawilak, Wroclaw University of Technology Institute of Electrical Machines, Drives and Measurements, 50-372 Wroclaw, ul. Smoluchowskiego 19, jan.zawilak@pwr.wroc.pl.*