Tomasz ZAWILAK

Wrocław University of Technology, Institute of Electrical Machines, Drives and Measurements

Utilizing the deep bar effect in direct on line start of permanent magnet machines

Abstract. *This work presents the results of simulations of the influence of the deep bar effect on the starting properties of a double-cage synchronous permanent magnet motor. Using a field/circuit model, the relation between torque and current in the asynchronous state was determined for different properties of cage materials. The braking torque of the magnets was calculated and the total asynchronous torque was determined in relation to the rotational speed of the motor. It was shown that the double-cage solution enables obtaining of a starting torque greater than the nominal torque in the full range of speeds.*

Streszczenie*. W pracy przedstawiono symulacyjne wyniki badań wpływu efektu wypierania prądu na właściwości rozruchowe dwuklatkowego silnika synchronicznego wzbudzanego magnesami trwałymi. Wykorzystując model polowo-obwodowy wyznaczono zależność momentu oraz prądu w stanie asynchronicznym dla różnych właściwości materiałów klatek. Obliczono charakterystykę momentu hamującego od magnesów oraz określono całkowity moment asynchroniczny w funkcji prędkości obrotowej silnika. Wykazano, że rozwiązanie z dwoma klatkami rozruchowymi pozwala na uzyskanie momentu rozruchowego większego od momentu znamionowego w pełnym przedziale prędkości.(****Wykorzystanie efektu wypierania prądu w rozruchu bezpośrednim maszyn wzbudzanych magnesami trwałymi****).*

Keywords: synchronous motor, permanent magnet, direct on line start, deep bar effect.
Słowa kluczowe: silnik synchroniczny, magnesy trwałe, rozruch bezpośredni, efekt wypierania prądu.

Introduction

The trend to constantly increase the energy efficiency of electrical machines results in the appearance of increasingly strict norms with regards to the minimum efficiency of new machines. Future requirements (IE4) might be difficult to meet for traditional induction-based machines [1, 2, 3]. An alternative is a Line Start Permanent Magnet Synchronous Motor (LSPMSM). The widespread use of this design was, until now, limited by its main flaw – much worse starting properties in comparison to induction-based machines [4]. During the start, permanent magnets produce braking torque which decreases the resultant breakaway torque, particularly in the lower range of rotational speeds. Additionally, the start process must complete with successful synchronization, which is difficult when the drive's moment of inertia is large (e.g. in fans) [5, 6].

For these two reasons, the torque produced by the starting cage should be high in the lower range of rotational speeds to compensate for the braking torque of the magnets, and high at speeds near to the synchronization speed, which allows for obtaining high values of pull-in torque.

In induction motors, increasing torque in the lower rotational speed range is done by using solutions based on the deep bar effect.

The purpose of this work is to examine the usefulness of the deep bar effect for improving the start properties of LSPMSM motors.

Model description

The LSPMSM motor has been designed based on a 2Sg315M8Bz induction motor (Celma, Cantoni Motors Group). The properties of the original motor and the modified permanent magnet motor are shown in Table 1.

The original induction motor uses a double aluminum-cast cage. The LSPMSM motor designed here is using two starting cages: the top one made of circular bars and the lower one made of rectangular bars.

The motor model was created using Maxwell 2D software (v.14). In the simulations, the "transient" solution type was used, which allowed modeling of the machine working under a forced voltage source while also taking movement into account, and which provided the most accurate representation of the phenomena described here. The model geometry is shown in Figure 1.

Table 1. Nominal properties of the original 2Sg315M8Bz motor and the designed LSPMSM motor.

Parameter	Induction motor	LSPMSM
P_n [kW]	110	110
n_n [rpm]	737	750
M_n [kW]	1,425	1,400
U_n [kW]	500	500
I_n [kW]	181	134.5
$\cos\varphi_n$ [-]	0.75	0.98
η [%]	93.5	96.4
I_r/ I_n	4.2	7.6
M_r/ M_n	1.7	2.86

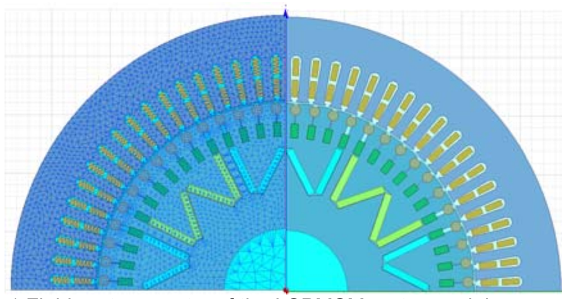

Fig. 1 Field part geometry of the LSPMSM motor model

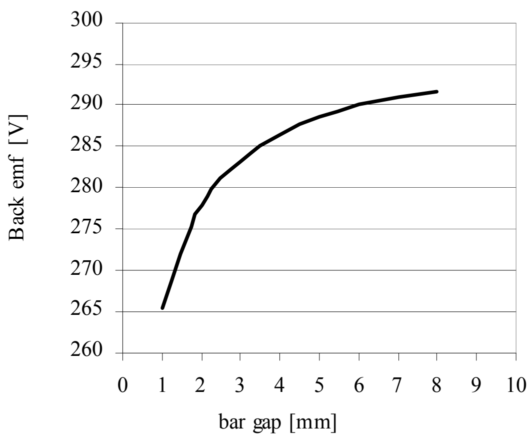

Fig. 2 The effective value of induced voltage depending on the cage bar gap width at the ends of the poles.

Research results

A. Influence of the cage bar gap on the permanent magnet back EMF value

Due to the flux leakage phenomenon, it is not recommended to use the same gap between cages in all of the slots. The influence of the gap width between bars at the ends of the magnet poles on the voltage induced in a currentless state was examined. The relation of the effective value of the back EMF harmonic and the gap width is shown in Figure 2.

The diagram shows that the leakage flux going between the cage bars changes from about 10% with a 1mm gap (the same value as used for the other slots) to about 1% with an 8mm gap. A solution with a 4mm gap was selected for further examination.

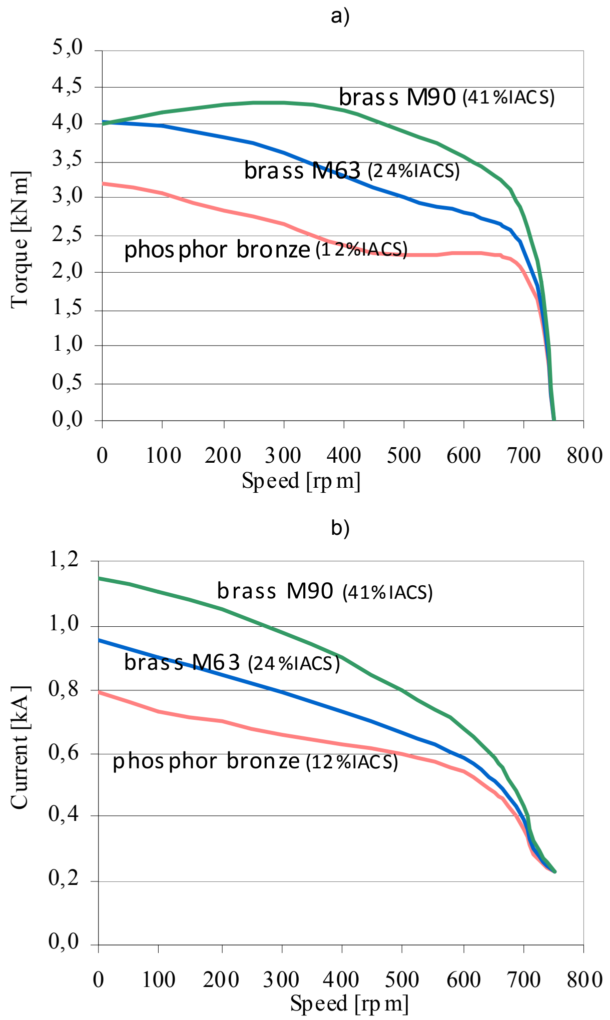

Fig. 3 Asynchronous torque vs. speed (a) and current vs. speed (b) for various starting cage materials.

B. Cage asynchronous torque

The resultant asynchronous torque during the motor start is a sum of two components: the cage torque and the braking torque of the magnets. The transient and amplitude of the braking torque cannot be changed substantially, as they result from parameters specified at the machine design stage in order to obtain specific working properties. It follows that the starting properties are best adjusted by modeling the starting cage asynchronous torque. In welded double-cage motors, the desired properties can be obtained by choosing appropriate materials for the cage. The influence of the material of the top cage on the transient of asynchronous torque was examined. Calculations were made with the assumption that the top cage bars are made of M90 brass (41% IACS), M63 brass (24% IACS) or phosphor bronze (12% IACS). In all cases, the material of the bottom cage was copper.

For the previously described model, calculations were performed to establish the starting cage asynchronous torque. For this purpose it was assumed that air is where the permanent magnets would be located and the rotational speed of the rotor was being changed parametrically. The graph of average torque as a function of rotational speed for various top cage materials is shown in Figure 3a. The transient of effective current value for the state discussed here is shown in Figure 3b. It was found that, for the model discussed here, the best properties are obtained when the top cage is made of M63 brass and the bottom one of copper.

C. Resultant starting torque

The cage asynchronous torque was added to the calculated braking torque from the permanent magnets in order to obtain the resultant torque. The transient of the torque as a function of rotational speed is shown in Figure 4. It is noteworthy that the value of torque is greater than the nominal torque in a full range of speeds, which makes it possible to start the motor under a full load on the motor shaft.

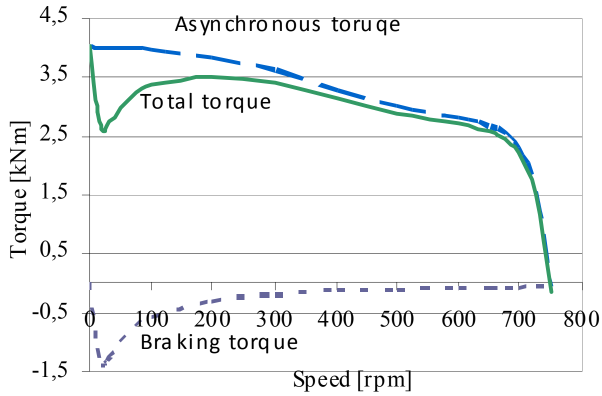

Fig. 4 Total asynchronous torque and its components for the researched LSPMSM motor.

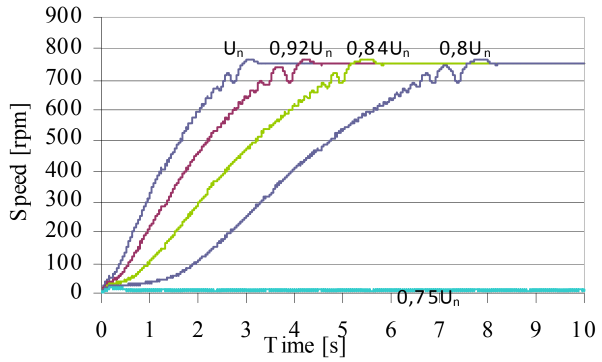

Fig. 5 Transient of rotational speed during motor start for different voltage drops in the supply network.

D. Power supply network influence on the motor starting properties

Due to worse starting properties, LSPMSM motors are much more vulnerable to voltage drops in the supply network than induction motors. The problem is present particularly in high power machines where the ratio of the network's short circuit power to motor power is usually lower. For this reason, the influence of network parameters on the starting properties of the LSPMSM motor discussed here was examined. For this purpose, the motor start with a serially connected inductance, representing the impedance of the network, was simulated. The inductance value was parametrically changed so as to obtain voltage on the motor terminals in its initial starting stage, ranging from $0.75U_n$ to U_n. The transient of rotational speed resulting from the simulation is shown in Figure 5.

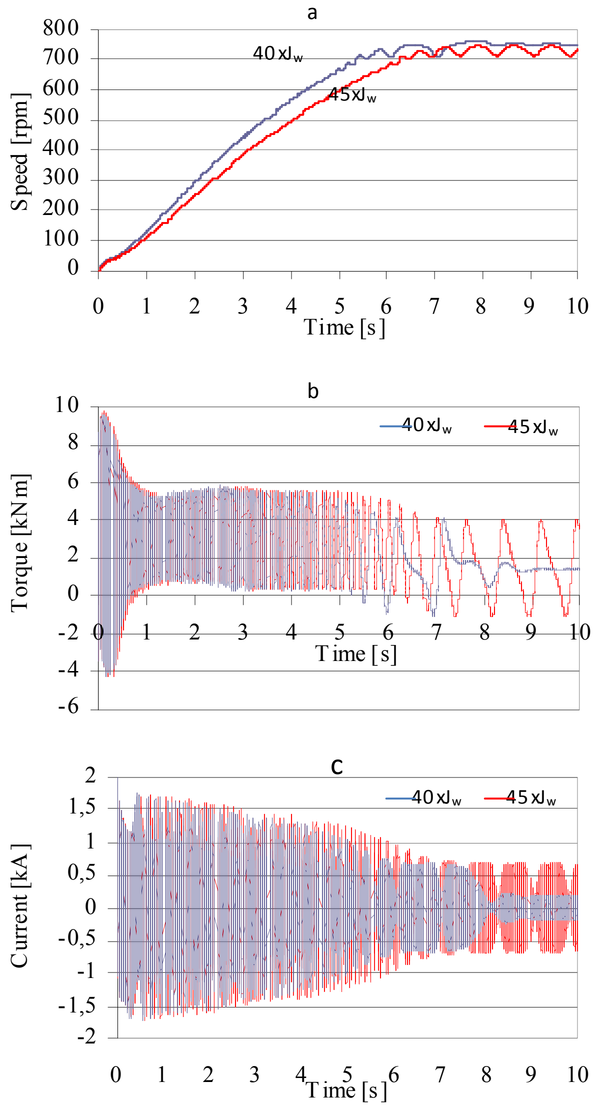

Fig. 6 Transients of rotational speed (a), electromagnetic torque (b) and phase current (c) during the start of the motor with different values of the drivetrain moment of inertia.

From the simulations conducted, it appears that the motor examined here can start under a full load with a voltage drop reaching 20%, which is a borderline value for industrial networks.

E. Influence of the drive moment of inertia on the synchronization properties of the motor

During start with a nominal load on the motor shaft, the synchronization properties of the motor depend most of all on the total moment of inertia of the drivetrain. For this reason, the maximum moment of inertia at which the motor reaches synchronous speed was determined through simulation. Figure 5 shows the results of start simulations for two different moments of inertia values. Based on the results, one can conclude that the borderline moment of inertia value is about 40 times the moment of inertia of the motor's rotor.

Conclusions

Utilizing the deep bar effect in line start of permanent magnet synchronous machines allows for a marked improvement in their starting properties. Through the right choice of appropriate materials for the starting cages, it is possible to model the asynchronous torque to compensate for the braking torque from the permanent magnets, thus obtaining a minimal torque higher than the nominal torque. The double-cage design proposed here shows significantly better start and synchronization properties than single-cage designs. The calculations performed indicate that it is possible to start a LSPMSM motor during voltage drops of up to 20%, and with external moment of inertia reaching as much as 40 times the rotor's moment of inertia.

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***Author**: dr inż. Tomasz Zawilak, Wrocław University of Technology, Institute of Electrical Machines, Drives and Measurements, Smoluchowskiego 19, 50-372 Wrocław, E-mail: tomasz.zawilak@pwr.wroc.pl*