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Starting process of medium power line start permanent magnet synchronous motor

Abstract. *The paper deals with analysis of line start permanent magnet synchronous motor start and synchronization process. Four-pole 160 kW low-voltage LSPMSM was investigated. FEM method was applied.*

Streszczenie *Artykuł zawiera wyniki badań procesu rozruchu i synchronizacji silnika synchronicznego średniej mocy wzbudzanego magnesami trwałymi o rozruchu bezpośrednim. Badania wykonano wykorzystując model polowo-obwodowy.*
*(**Analiza właściwości rozruchowych silnika synchronicznego z magnesami trwałymi o rozruchu bezpośrednim średniej mocy**)*

Keywords: synchronous motor, permanent magnet, medium power motor, synchronization
Słowa kluczowe: silnik synchroniczny, magnesy trwałe, silnik średniej mocy, synchronizacja

Introduction

Line start permanent magnet synchronous motors, hereinafter LSPMSM, contain rotor winding to obtain asynchronous torque during starting. Hence LSPMSM are as reliable, robust, low-maintenance as induction motors. Their main drawback are starting properties which are noticeable worse in comparison with induction motors starting properties [7]. It is caused by braking torque due to permanent magnets inside the motor rotor. The biggest influence of the braking torque on the LSPMSM resultant torque occurs in low range of the motor speed.

Except load torque, moment of inertia also limits the LSPMSM starting capability. For high value of the load inertia, like fans, LSPMSM can start-up but simultaneously be not able to run in synchronism and stall below synchronous speed [4]. LSPMSM with double squirrel cage rotor construction can withstand this phenomenon and make the motor able to synchronize successfully. Rotor bars must be made with proper dimensions and materials then.

Motor model description

Two dimensional four-pole medium power LSPMSM was built in Maxwell software. Rated motor parameters are: power P_n=160 kW, voltage U_n=400 V, frequency f_n=50 Hz, mechanical size H=315 mm. Permanent magnets type N42SH were chosen for excitation. Magnets dimensions were calculated to obtain motor power factor $cos\varphi$=1 for rated load. This feature and high efficiency are main advantages of LSPMSM. The motor pull-out torque ratio T_{max}/T_n=1,7. The rotor contains two squirrel cages. Top cage is made from round bronze bars. Four bronze types were taken into account: B4 (γ=11,8 MS/m), B6 (γ=9,0 MS/m), B8 (γ=7,5 MS/m) and B12 (γ=6,2 MS/m). Bottom cage is made from copper M1E type (γ=57 MS/m). Common rings are mode also from copper M1E type. Motor stator and rotor sheets are presented in Fig. 1. Motor running properties are shown in Table 1.

Table 1. Running properties of the 160 kW 2p=4 LSPMSM model

p_{load}	efficiency	power factor
--	%	--
0,50	96,8	1,00
0,75	97,3	1,00
1,00	97,4	1,00

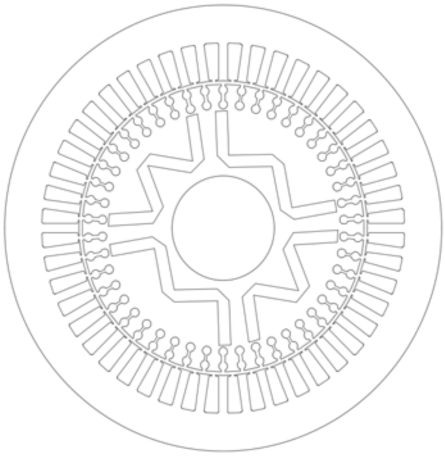

Fig.1. Cross-section of the 160 kW *2p*=4 LSPMSM model

Starting properties – start-up

Influence of the motor starting torque t_r on the maximum load torque t_{start} was investigated. Maximum load torque t_{start} enables the motor to start-up and obtain subsynchronous speed despite braking torque due to permanent magnets. Starting torque was determined for rated voltage and slip s=1. Different values of the motor starting torque were achieved due to various top rotor squirrel cage material: bronzes B4, B6, B8 and B12 type. Load torque was assumed as constant torque. Voltage drops during motor start-up Δu were taken into consideration. Investigation results are shown in Fig. 2. Examples of successful and unsuccessful motor start-ups are presented in Fig. 3. LSPMSM braking torque t_{brake} due to permanent magnets are shown in Fig. 4.

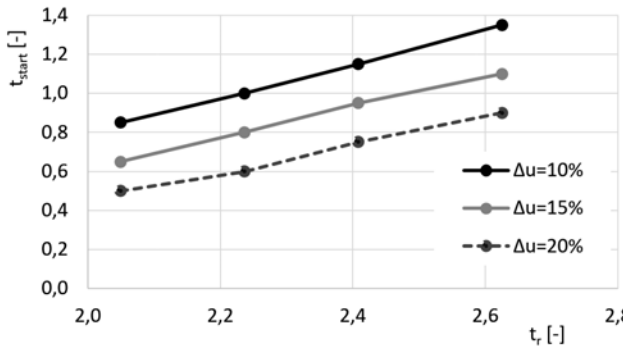

Fig.2. Influence of the LSPMSM starting torque t_r and voltage drop during motor start-up Δu on the maximum load torque t_{start}

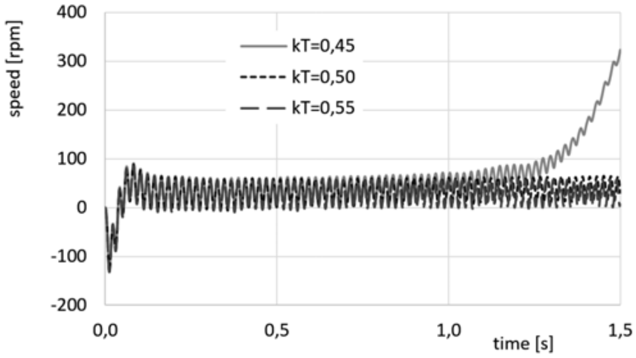

Fig.3. LSPMSM speed curves during start-up, voltage drop during motor start-up Δu=20%, upper rotor squirrel cage material bronze B12, constant load torque, load torque value ratio $kT=T_{load}/T_n$=var

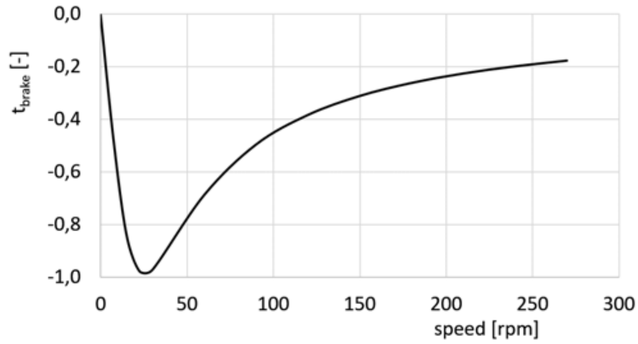

Fig.4. LSPMSM braking torque t_{brake} due to permanent magnets

The obtained results are analogues to the literature [4], 6]. Maximum load torque t_{start}, which enables LSPMSM to start-up and obtain subsynchronous speed, is given by the formula

$$t_{start} = t_r \cdot (1 - \Delta u)^2 - t_{brake} \tag{1}$$

where: t_{start} – maximum load torque, t_r – LSPMSM starting torque, Δu – voltage drop during motor start-up, t_{brake} – LSPMSM braking torque due to permanent magnets.

According to the formula (1) LSPMSM braking torque t_{brake} constrains the motor starting capability and is independent from voltage drop during motor starting. This phenomena is the biggest drawback of LSPMSM. Braking torque shown in Fig. 4 is zero for speed n=0, peaks for speed a little bit higher than 0 and becomes negligible for higher speed range.

Starting properties – synchronization

Influence of the voltage drop during motor start-up Δu, moment of inertia Jk (relative to the motor rotor moment of inertia) and rated pull-in torque $t_{pull-in\_n}$ on the LSPMSM synchronization were investigated. Rated pull-in torque $t_{pull-in\_n}$ was determined as asynchronous motor torque for slip s=5%. Moreover, definition of maximum pull-in torque $t_{pull-in\_max}$ was introduced as torque which enables the motor to run in synchronism successfully for given voltage drop during motor start-up Δu and drive system moment of inertia kJ. Load torque was assumed as fan torque because typical applications of LSPMSM are pumps and fans with square torque characteristic. Results of investigation are presented in Fig. 5–8.

According to the results presented in Fig. 5 and 6 maximum LSPMSM pull-in torque can be described by the equation

$$t_{\mathrm{pull-in\_max}} \sim C \cdot t_{pull-in\_n} - 0{,}25 \cdot \log_2 \frac{J_{drive}}{J_{rotor}} \tag{2}$$

where: $t_{pull-in\_max}$ – maximum pull-in torque, C – constant, $t_{pull-in\_n}$ – rated pull-in torque, J_{drive} – drive system moment of inertia, J_{rotor} – rotor moment of inertia.

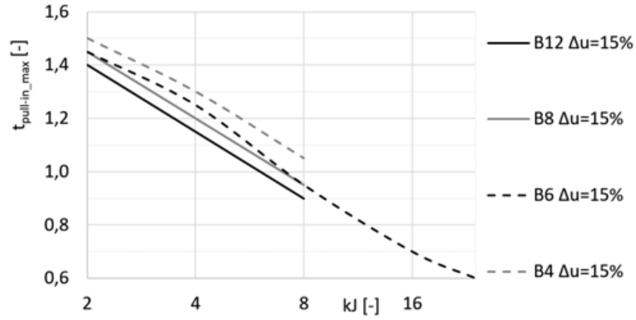

Fig.5. Influence of the drive system moment of inertia kJ on the LSPMSM maximum pull-in torque $t_{pull-in\_max}$, top squirrel cage material bronze type: B12 γ=6,2 MS/m, B8 γ=7,5 MS/m, B6 γ=9,0 MS/m, voltage drop during motor start-up Δu=15%

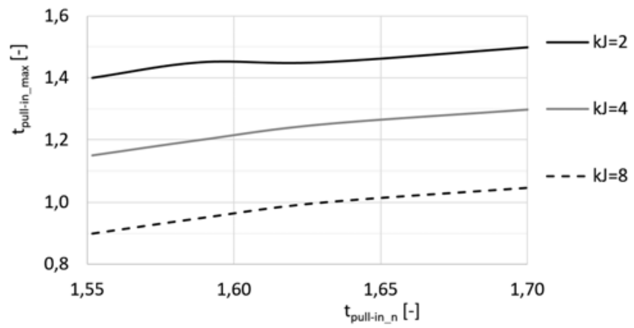

Fig.6. Influence of LSPMSM rated pull-in torque $t_{pull-in\_n}$ on the maximum pull-in torque $t_{pull-in\_max}$, the drive system moment of inertia kJ=var, voltage drop during motor start-up Δu=15%

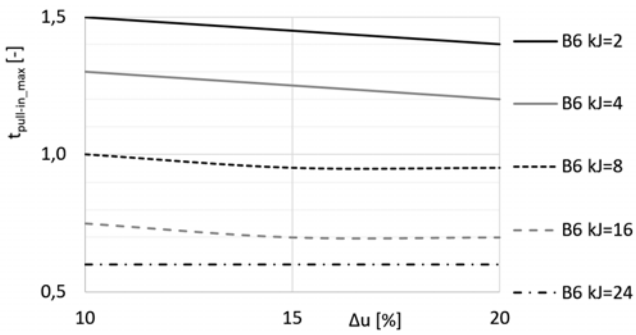

Fig.7. Influence of voltage drop during motor start-up Δu on the LSPMSM maximum pull-in torque $t_{pull-in\_max}$, drive system moment of inertia kJ=var, top squirrel-cage material bronze B6 type

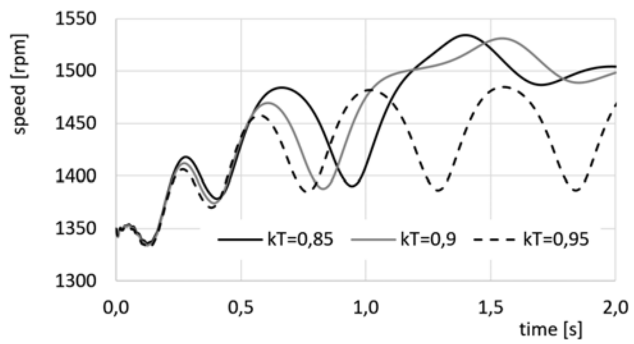

Fig.8. Example of successful and unsuccessful synchronization of four pole LSPMSM, rated load torque ratio kT=var, fan characteristic of the load torque, voltage drop during motor start-up Δu=20%, top squirrel cage material bronze B8 type

According to the results presented in Fig. 7 there is no influence of the voltage drop during motor start-up *Δu* on LSPMSM maximum pull-in torque $t_{pull\text{-}in\_max}$ for high value of drive system moment of inertia *kJ*. This phenomenon will be analysed during next LSPMSM synchronization properties investigation. If LSPMSM during synchronization exceeds synchronous speed the motor run almost always in synchronism. When LSPMSM is not able to run in synchronism its speed is below synchronous speed

Double cage LSPMSM asynchronous torque forming

Starting current i_r is one of the many required parameters which designed motor must fulfilled. This current determines the motor starting capability. Based on the presented in article LSPMSM investigation significant conclusions can be drawn. LSPMSM starting torque t_r must exceed sum of braking torque due to permanent magnets and load torque. LSPMSM rated pull-in torque $t_{pull\text{-}in\_n}$ must enable the motor to run in synchronism successfully.

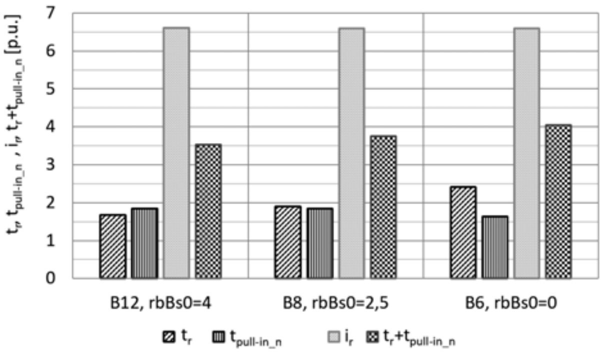

Fig.9. Influence of the top squirrel cage material (bronze type: B12 γ=6,2 MS/m, B8 γ=7,5 MS/m, B6 γ=9,0 MS/m) and bottom slots openings width *rbBs0* on the LSPMSM starting torque t_r, rated pull-in torque $t_{pull\text{-}in\_n}$ and sum of both torques, starting current i_r=const

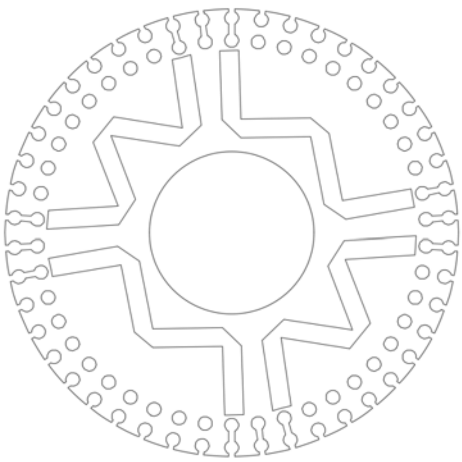

Fig.10. Cross section of double cage four pole LSPMSM without bottom slots openings

To increase double cage motor starting torque with saving motor starting current i_r resistance of top squirrel cage must be lower and simultaneously bottom squirrel cage leakage reactance greater. It can be done by increasing conductivity of the top squirrel cage material and constricting bottom slots openings. Motor rated pull-in torque decreases then and its synchronization capability.

To increase double cage motor rated pull-in torque with saving motor starting current i_r resistance of top squirrel cage must be greater and simultaneously bottom squirrel cage leakage reactance lower. It can be done by decreasing conductivity of the top squirrel cage material and widening bottom slots openings. Motor starting torque decreases then and its start-up capability [8].

Results of double cage LSPMSM asynchronous torque forming for constant value of the motor starting current i_r are shown in Fig. 9.

During consideration of the sum of starting t_r and rated pull-in $t_{pull\text{-}in\_n}$ torques of LSPMSM noteworthy fact was noticed: the maximum sum of both torque occurs for closed bottom rotor slots. Construction of double cage LSPMSM without bottom slots openings is good solution for drives with low value of the moment of inertia such as pumps [1], 2, 3, 5]. Example of this construction is presented in Fig. 10. Noteworthy is fact that in this double cage LSPMSM construction bottom rotor slots openings between magnetic poles are not removed to limit permanent magnet leakage flux.

Conclusions

The most significant LSPMSM starting parameters are starting torque t_r and rated pull-in torque $t_{pull\text{-}in\_n}$. The first parameter determines motor start-up capability. The second one determines synchronization capability. Braking torque t_{brake} due to permanent magnets limits motor start-up capability and is negligible during motor synchronization process.

Proper designing of LSPMSM rotor winding enables to obtain sufficient motor starting properties and acceptable starting current.

Similar LSPMSM to the presented in article construction work in Polish copper mine. They are utilized intensively and have very good running properties.

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