Qinfen LU, Xiaoyan HUANG, Yunyue YE，Youtong FANG

Zhejiang University

Experiment and analysis of high power line-start PM motor

***Abstract**. This paper investigates the performance of a high power line-start permanent-magnet motor (LSPM) by experiment, which is developed for industrial fans, pumps and compressors to reduce the energy consumption. The no-load back-EMF is measured and compared with predicted result of FEM. In order to assess the line starting ability, the rotor-locked test is carried out and then the starting torque ratio is deduced which is lower than that of induction motor of the same power. By adjusting the load, the efficiency and power factor during all operation condition are obtained. It is found this proposed LSPM has not only higher power factor and efficiency, but also high overload ability. After its starting ability of reduced voltage is analyzed, several useful methods are pointed out for designing high power LSPM which should start with limited current.*

***Streszczenie.** Zbadano właściwości silnika wysokiej mocy LSPM w zastosowaniu przemysłowym do pomp, wentylatorów i kompresorów pod kątem redukcji zużycia energii. Zbadano silnik przy zablokowanym wirniku i na tej podstawie przewidywano moment startowy. Przy zmianie obciążenia określono współczynnik mocy i sprawność. (**Eksperyment i analiza silnika dużej mocy o rozruchu bezpośrednim typu LSPM**)*

Keywords: High power, line-start, Permanent-magnet motor, experiment, start ability, reduced voltage
Słowa kluczowe: silnik z magnesami trwałymi, silnik LSPM.

Introduction

The high power motors are widely used to drive fans, pumps and compressors in industry, so their efficiency is improved as possible for saving the energy. Compared with induction motor, line-start permanent-magnet motor (LSPM) has higher efficiency and power factor. Moreover, it can direct replace the existing induction motor without adding any equipment. Therefore, it is an attractive choice [1-3].

From topology, the stator of LSPM is the same as that of a normal induction motor, and permanent magnets are inserted in the squirrel cage rotor. In ideal condition, its starting torque is produced by electromagnetic induction phenomenon at the rotor conductor bars, and the synchronously operating torque is generated by permanent magnets. In fact, the inserted permanent magnet not only decides LSPM's performance at synchronous speed, but also worsens its starting ability because it produces braking torque and affects the magnetic field circuit. Since the start ability of LSPM depends on both squirrel cage rotor bars and the inserted permanent magnets including their shape, material, size and position [4-6], the suitable configuration of rotors are continually proposed to improve the performance [7].

Normally, the low power LSPM is designed to line start which can makes the starting torque maximize. But it should be indicated high power LSPM (>100kW) is often not allowed to line start in normal industrial application. Although there are many papers on the research on the low power LSPM [1-9], the high power LSPM still need be developed in theory and application due to rigorous starting condition [10-12].

In this paper, the performance of a 4-pole 250kW LSPM which keeps the configuration of induction motor as much as possible is measured including no-load test, rotor-locked test and load test. By analysis these test data, it is found that this LSPM has not only high efficiency at synchronous speed, 1500r/min, but also a sufficient line starting ability with voltage, 380V. Since this LSPM is often asked to start at low voltage in industry, the starting ability of low voltage is analyzed. The results show this design method of only inserting permanent magnets to rotor is not suitable to high power LSPM with requirement of reduced voltage starting. At last, several useful designing methods are introduced to improve starting ability.

Motor configuration

As many low power LSPMs, this 250kW LSPM also keeps the configuration of induction motor as much as possible. Table I lists the main specifications.

Table 1. Specifications of proposed LSPM

Items	Quantity
Rated power (kW)	250
Rated speed (rpm)	1500
Rated voltage (V)	380
Rated current(A)	410
Rated efficiency	0.97
Rated power factor	0.96
Winding connection	Δ
Number of pole pairs	2
Stator outer diameter(mm)	590
Stator inner diameter(mm)	400
Number of turns of stator slot	10
Number of stator slots	72
Air gap length(mm)	1.6
Number of rotor slots	62
Rotor outer diameter(mm)	396.8
Rotor inner diameter(mm)	130
The material of rotor bar	Aluminium
Coercive force of magnet (kA/m)	987
Remanence of NdFeB magnets (T)	1.3

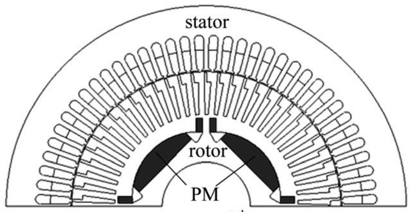


Fig.1. Cross section of half of proposed LSPM.

Fig.2. Rotor photo of proposed LSPM.

Fig.1 shows the cross sections and Fig.2 shows photo of its rotor. Its stator is almost same to that of induction motor with same power. The only difference is that the stator slots are skewed by one rotor slot pitch in order to reduce the cogging torque. To rotor, squirrel cage and axis are same and the interior permanent magnets are inserted in rotor yoke without any vents. In addition, its air gap is larger than that of induction motor. There are three pieces of permanent magnets of one pole, one is large and radial magnetized, and other two are small and circumferential magnetized. Two air holes between permanent magnets have functions of the flux barrier and vents.

Motor experiments

The test platform is shown in Fig.3 including test LSPM, transducer, DC motor, temperature tester, resistance tester and digital testing system. The test LSPM is connected with a DC motor by a torque-speed transducer. The DC motor acts as motor to drive the LSPM at no-load, while acts as generator at load. By this test platform, the steady performance and transient starting performance can be obtained by adjusting operation condition.

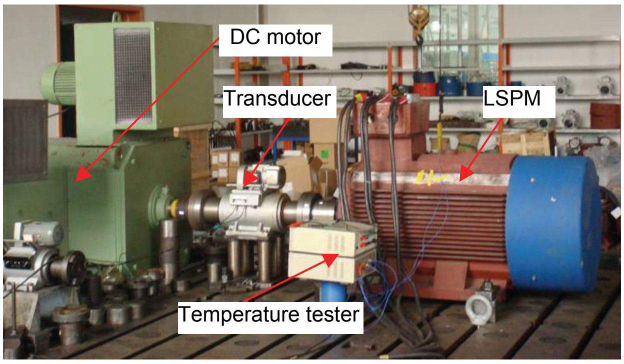


Fig.3. The test platform of LSPM.

A. No-load back-EMF

When DC motor drives the LSPM to rated speed, 1500r/min, the no-load back-EMF is measured. Fig.4 shows its fundamental wave component of measurement and predicted results by FEM. As it can be seen, the measurement is equal to rated line voltage, 380V, and is a little bigger than that of FEM, 365V. The error is mainly caused by two reasons, one is performance of permanent magnet is better than calculation value and the other is actual air-gap length exists certain error. That is to say, the prototype is a little overexcitation. Although it improves the stability performance and pull-in torque, it also worsens the start ability. If the line voltage improves to 400V, the start ability becomes better in line start condition.

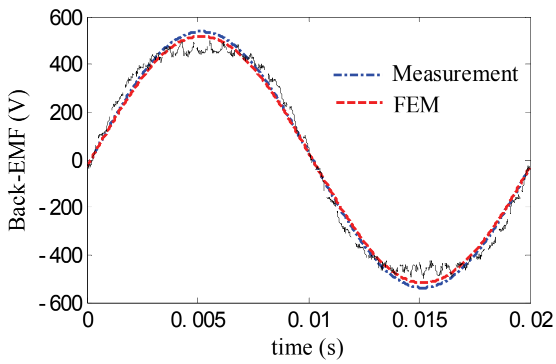
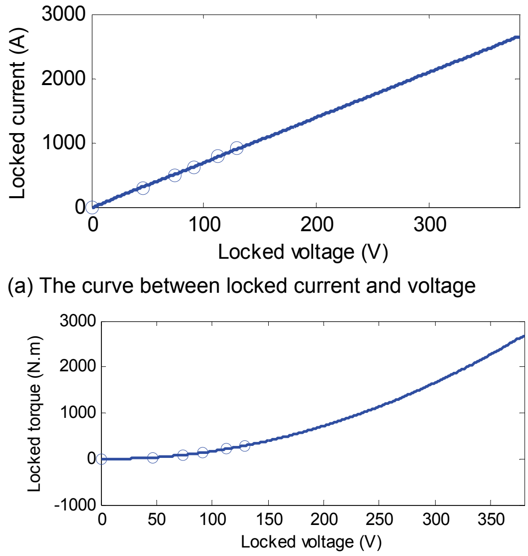


Fig.4. Fundamental component of Back-EMF.

B. Starting torque

Due to the line-start current is much bigger than that of power limitation, it can't be direct measured. Therefore, this paper adopted rotor-locked test to measure starting torques at serial low voltages. Based on these data, the short-circuit impedance is calculated, and then the line-start current and torque are calculated. Fig.5 shows the measurements. The line-start current is 2650A and the line-start torque is 2683.1N.m. Compared with rated value, the starting current ratio is 6.46 and the starting torque ratio is 1.69. They are lower than that of induction motor due to reducing magnetic field circuit. Apparently, it can start smoothly at full line voltage with pump load.



(a) The curve between locked current and voltage

(b) The curve between locked torque and voltage

Fig.5. The rotor-locked measurements of LSPM.

C. Load Performance

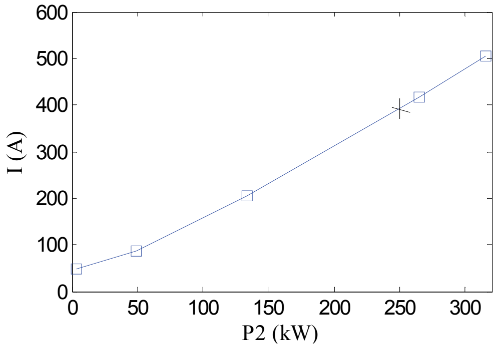
Due to the limited of power supply, this LSPM can't realize line-start function in this platform. In this experiment, the DC motor is adopted to help the start of this LSPM. There are three steps in this experiment. First, this LSPM without power supply is driven close to synchronous speed. Secondly, this LSPM is connected with power supply when the back-EMF and line voltage have same phase angle measured by rotating-lamp method. Finally, this LSPM can be measured at different load by adjusting excitation current of DC motor. At line voltage 380V, the measured rating power factor and efficiency are 0.964, 0.966 respectively, which accord with the design requirement.

Since the back-EMF is equal 380V, the line voltage class can be increased to 400V in order to improving the start ability. The steady performance of different load is shown in fig.6. At rating output power, the power factor and efficiency are 0.932, 0.969 respectively. At output power, 315kW, the power factor and efficiency are 0.93, 0.968 respectively. As it can be seen, the efficiency keeps almost constant and power factor is lowered along with voltage improving, which is still higher than that of induction motor. Provided that line start is allowed, the voltage class of this LSPM prefers 400V to 380V.

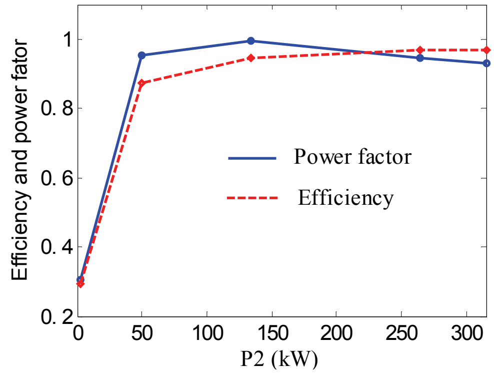
D. Temperature

Compared with induction motor, the LSPM have lower steady-state current and high efficiency, therefore, the temperature is certainly lower than that of induction motor without changing the stator. When this LSPM operates in steady temperature condition, the measured temperature rise of winding is only 43.7K. In addition, the measured temperatures of stator iron, bearing and shell are 55.7℃, 47.7℃ and 37.7℃. Apparently, the steady temperature is much lower than that of insulation class. Therefore, the output power can be improved to 315kW without any problem.

By experimental investigation, this LSPM meets the design requirement including high steady performance at rating power and sufficient line-start ability. Moreover, it can improve its power class to 315kW due to low temperature rise.

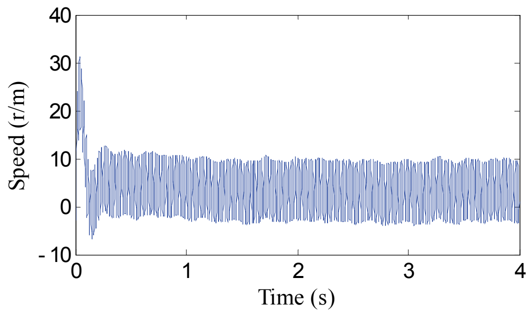


(a) Stator current

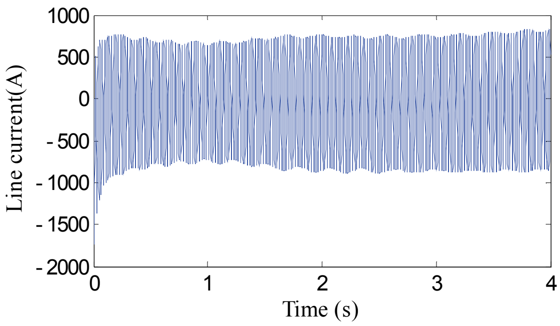


(b) Power factor and efficiency

Fig.6. Measured results of LSPM at voltage, 400V.



(a) Speed



(b) Current

Fig.7. The transient starting speed and current of LSPM at no load with current limitation, 1000A.

By transient model of FEM, the starting ability of different voltage is investigated. The results are shown in Fig.7 and Fig.8. Apparently, Fig.7 shows this LSPM can't start at no load with current limitation, 1000A. In order to start this LSPM at no load, the minimum voltage is 257V. The corresponding starting current is approximate 1792A and starting torque is about 1227N.m. The braking torque is so big that the start process becomes difficult. On this point, the permanent magnet is overused in order to guarantee high rated power factor. Therefore, the design value of rating power factor should be lowered for improving the start ability of reduced voltage.

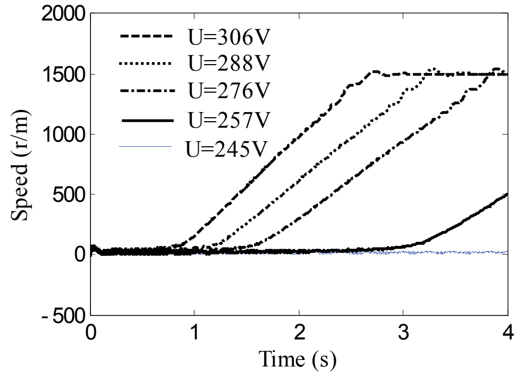


Fig. 8. Transient starting speed of different voltage.

Method of improving starting ability

When the LSPM starts, the starting torque includes asynchronous driving torque produced by rotor bars and synchronous braking torque produced by permanent magnets. The former one is mainly decided by voltage and rotor resistance, while the latter one depends on slip, back-EMF, stator resistance and synchronous reactance. At line start, the former one arrives to maximum value so it is much bigger than the latter one. It can start without question with pump load, only the starting time is longer than that of induction motor. Moreover, the speed of LSPM increases not so smoothly as that of induction motor, especially at lower speed.

To low power LSPM, the starting is no problem since the line-start is allowed. Except this, its power factor and efficiency can be improved much since that of corresponding induction motor are not so high. That is to say, this design of low power LSPM is relatively easy. Sometimes, the amending method is only inserting the permanent magnet to available rotor.

Unlike low power LSPM, the high power LSPM is often asked to start of reduced voltage due to the limitation of power system. Its starting ability worsens rapidly because the former one decreases along with the square of voltage and the latter one almost keeps constant. Therefore, the improving starting ability of reduced voltage should be carried out on two hands. One is improving asynchronous driving torque as possible, and the other is decreasing the synchronous braking torque properly. Of course, the design should make sure the steady performance of LSPM is better than that of induction motor at first. Since the high power of induction motor has high power factor and efficiency, the rated power factor of LSPM can't be asked improving so much as that of low power LSPM. To the high power LSPM of reduced voltage starting, the amending method of only inserting permanent magnets to rotor as that lower power LSPM can't be adopted any more in order to improving the starting ability and high rated performance. In general, the main amending methods are follows:

(1) The rated power factor of designed LSPM should adopt suitable value. Then the volume of permanent magnets can be controlled to let LSPM operate in underexcitation condition.

(2) Both rotor and stator of iron core are optimized in order to enlarge the rotor room as possible.

(3) Rotor slots are shortened and shaped for large starting ability. The starting torque ratio prefers to three times more.

(4) Due to line start capability of the high power LSPM is limited by large staring current, so high voltage is better choice to obtain good performance.

Conclusions

This paper investigates the performance of a high power LSPM which keeps the configuration as much as that of induction motor. Its no-load back-EMF, starting torque and steady-state performances at different loads are measured by a test platform. Compared with design requirement, this LSPM not only has higher efficiency and power factor, moreover keeps sufficient line-start ability at pump load. But it can't start considering current limitation, 1000A. As a result, the amending method of only inserting permanent magnets into the rotor isn't suitable to high power LSPM with reduced voltage starting. Finally, corresponding useful methods are introduced. In the future, the new LSPM with starting ability of reduced voltage will be developed.

The authors acknowledge the financial support of the National Natural Science Foundation of China (NSFC 51077115) and and Zhejiang Provincial Natural Science Foundation of China (R1110033).

REFERENCES

[1] R.Y. Tang, Modern Permanent Magnet machines- theory and design, Beijing: *Machine Industry press*, 1997(In Chinese).
[2] K. Kurihara and M. A. Rahman, "High-efficiency line-start interior permanent-magnet synchronous motors," *IEEE Trans. Ind. Appl*.,vol.40, no.3, pp.789-796, 2004.
[3] G.H. Kang, J. Hur, H. Nam, J.P. Hong and G.T. Kim, "Analysis of irreversible magnet demagnetization in line-start motors based on the finite-element method," *IEEE Trans. Magn*.,vol.39, no.3, pp.1488-1491, 2003.
[4] C.K. Lee, B.I. Kwon, B.T. Kim, K.I. Woo and M.G. Han, "Analysis of magnetization of magnet in the rotor of line start permanent magnet motor," *IEEE Trans. Magn*.,vol.39, no.3, pp.1499-1502, 2003
[5] F. Libert, J. Soulard, and J. Engstrom, "Design of a 4-pole line start permanent magnet synchronous motor," *In Proc. ICEM 2002*, Brugge, Belgium, Aug. 25–28, 2002
[6] D. Rodger, H.C. Lai, R.J. Hill-cottingham, P.C. Coles and F. Robinson, "A new high efficiency line start motor with high starting torque, *In Proc. IET 2006*, Mar.,2006, pp.551-555
[7] W. Fei, P. C. K. Luk, J. Ma, J. X. Shen and G. Yang, "A High-performance line-Start permanent magnet synchronous motor amended from a small industrial three-phase induction motor", *IEEE Trans. Magn*.,vol.45, no.10, pp.4724-4727, 2009.
[8] A.M. Knight and C. Mcclay, "The design of high-efficiency line-start motors," *IEEE Trans. Ind. Appl*., vol.36, no.6, pp.1555-1562, 2004.
[9] D. Stoia, M. Antonozie, D. Ilea and M. Cernat, "Design of line-start PM motors with high power factor," *In Proc. Powereng* 2007, Portugal, Apr. 2007, pp.342-346.
[10] M. A. Rahman and A. M. Osheiba, "Performance of a large line-start permanent magnet synchronous motor," *IEEE Trans. Energy Convers*., vol. 5, Mar. 1990,pp. 211–217.
[11] Q. Zhao, X. Wang, S. Yu, D. Zhang, Z. An and R. Tang, "Study and design for large line-start permanent magnet synchronous motor," *In Proc. ICEMS 2003*, vol.1, Beijing, 2003, pp.132-133.
[12] Qinfen Lu and Yunyue Ye, "Design and analysis of high power line-start Permanent-Magnet motor", *IEEE Trans. Magn.*,vol.44, no.11, pp.4417-4420, 2008.
[13] C. K. Lee and B.I. Kwon, "Design of post-assembly magnetization system of line start permanent-magnet motors using FEM," *IEEE Trans. Magn.*,vol.41, no.5, 2005, pp.1928-1928

Authors
Associate professor Qinfen Lu works in college of Electrical Engineering, Zhejiang Unversity, P.R.China, 310027 Dr. Xiaoyan Huang works in college of Electrical Engineering, Zhejiang Unversity, P.R.China, 310027, Email:eezxh@zju.edu.cn.