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ROTOR STRUCTURE WITH DOUBLE CAGE FOR IMPROVED SYNCHRONOUS CAPABILITY OF LINE-START PERMANENT MAGNET SYNCHRONOUS MOTORS

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Line start permanent magnet synchronous motors (LSPMSMs) have a problem of synchronization. In this paper the rotor of LSPMSM with double cage is proposed to improve synchronous capability of the motor. Key factors concerning the starting performance and synchronous capability of LSPMSM are given, and the conflict relationship between starting performance and synchronous capability is analyzed. The performances of starting and synchronization of the motors with singe cage rotor and double cage rotor are compared and analyzed based on the conflict. The results obtained for the motor with double cage rotor can improve the synchronous capability within the wide range. The principal results of the paper provide the reliable theoretical propositions for improving LSPMSM performance.
References 15, figures 11, tables 3.
Key words**:** LSPMSM, finite-element method, double cage rotor, starting performance, synchronous capability.

1. Introduction. The permanent magnet synchronous motors have the higher efficiency and power factor as compared to induction motors [1–4]. The permanent magnet synchronous motors replaced induction motors in many fields connected with energy saving and development of rare earth materials. However, permanent magnet motors can not start without other devices. Line-start permanent magnet synchronous motors (LSPMSMs) combine the advantages of induction motors and permanent magnet motors, they can start without other devices, and also have the high efficiency and power factor. LSPMSMs are applied widely in oil industry and pump field [5–7].

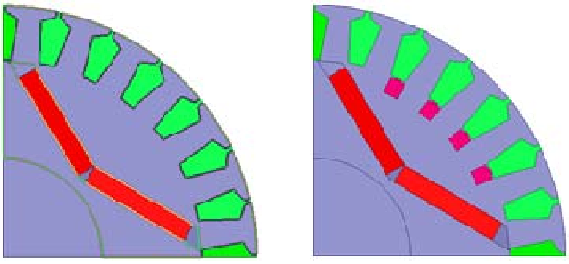
In the starting process of LSPMSM, many torques such as asynchronous torque, generation braking torque, reluctance torque and pulsating torque are of importance. These torques also vary with slip variation [8–9]. The combined effect of the torques makes the starting process more complex and hard to study, so the study of starting process of LSPMSMs is difficult. LSPMSMs also have a special process in the starting, when the speed becomes gradually close to the synchronous speed, the motor begin to pull in synchronization. According to current research, some key factors affected the starting performance have different influences on the synchronous capability. So when the high start ability is ensured, the synchronous capability is easy to neglect.

Double cage structure is often used in induction motors, but the application of double cage in LSPMSM is rare. Many experts carried out the study of the starting performance and synchronous capability. For example, Miller in [9] analyzed the starting process of LSPMSM and revealed the influence of the torques on the starting process, the variations of the torques with the slip are also studied. The process of LSPMSM pull in synchronization is also explained in [9]. Cheng Ming in [10] put forward a method to calculate the synchronous capability accurately and verify the accuracy of the method, and then the influences of some key factors on the synchronous capability are calculated by this method [10]. Esmaeil Sarani ([11]) proposed the new configuration for LSPMSM with low consumption of permanent (PM) magnet material providing improved performance. This configuration can decrease the PM volume and improve the performances [11]. Ding analyzed and compared three different rotor structures of LSPMSM, investigated the effects of some geometrical and physical parameters on performances; as found, the interior PM motor has better performance than the other motors [12]. But the study of double cage structure is usually concentrated on induction motors, and the results do not apply well to LSPMSM [13–14]. Ugale in [15] proposed two novel LSPMSM rotors after the electromagnetic analysis and the test as compared to the usual rotor structures, got the result that one of the rotor structure with double cage and surface magnet can improve the starting performance and synchronous capability, and the another rotor can improve the steady state performance, at the same time the rotor structure that improve the starting performance is not analyzed in detail [15].

In this paper, based on the finite-element method, the models of motors with single and double cage are established, and the starting performance and synchronous capability are analyzed. Then the difference of the starting and synchronous capability between these two rotor structures are obtained, the electric and magnetic fields are compared, the reason of this difference is analyzed. The results revealed are of great significance for the improvement of synchronous capability.

2. Parameters and model of LSPMSM. In this paper, the LSPMSM with double cage is proposed by the single cage rotor prototype. Double cage rotor structure is usually used in induction motors to solve the problem of poor starting performance, to improve both the motor starting performance and steady state performance. In induction motors, the design can be characterized by the relatively large outer-bar resistance and inner-bar leakage inductance, the rotor current is mostly concentrated in the outer cage during the startup transient at high slip due to the heavy skin effect. And the inner cage effect in the steady state can improve efficiency of induction motors due to lower resistance.

But the structure with double cage in LSPMSMs has different effect, though the outer cage is also mostly effect in startup transient, the effect of inner cage is different. When the motors are operated at steady state in rated speed, the effect of the cage could be disregarded. But it can also improve synchronous capability due to its low resistance in the inner cage. The LSPMSM with double cage rotor that proposed in this paper, and the difference between the structures of single cage rotor and double cage rotor is confirm.



a ***b***

Fig. 1

The single cage rotor is shown in Fig. 1, *a*. The LSPMSM with double cage rotor is given in Fig. 1, *b*.

The starting cage slots are distributed around the rotor periphery, and the outer cage of double cage rotor is same to that of prototype rotor. The stators of both types are identical. As compared to the prototype rotor, only inner cage is set up additionally at the inner place of the corresponding outer cage except for the three outer cage bars near the magnet bridge. There are interruptions in the inner cage pattern due to the magnets extending nearly to the outer cage. This position of inner cage is designed for enough space to improve the mechanical strength of the rotor and place for permanent magnet. Both the two types have aluminum outer cage, but the inner cage of the double cage rotor is made of copper having lower resistance. The equivalent circuit of the prototype and the motor with double cage rotor are shown in Fig. 2.

Taking this 2.2 kW LSPMSM as an example, the parameters of the LSPMSM are given in table 1. Using these parameters, the 2D finite-element model is developed (see Fig. 3). The finite-element software Ansoft Maxwell is used to calculate the performance of the LSPMSM.

3. Experimental testing and data comparison. In order to verify the correctness of the finite-element model, the LSMPMSM prototype is tested. The test system consists of a Magtrol's dynamometer machine, HIOKI PW6001 power analyzer, industrial condensing unit, DSP (digital signal processor) data acquisition system, permanent magnet motor and other equipment. The motor under test is connected to the dynamometer, the industrial condensing unit keeps the temperature within the soft range, the load torque could be adjusted with DSP controller. Stable state data could be tested and recorded by the power analyzer, the starting process and the operated performance could be presented in the system displayer. The motor is

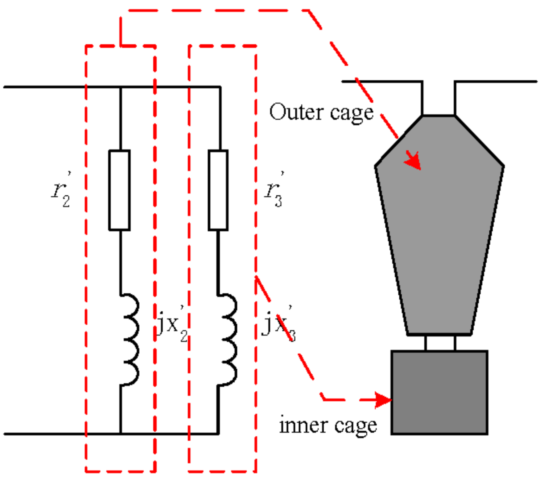
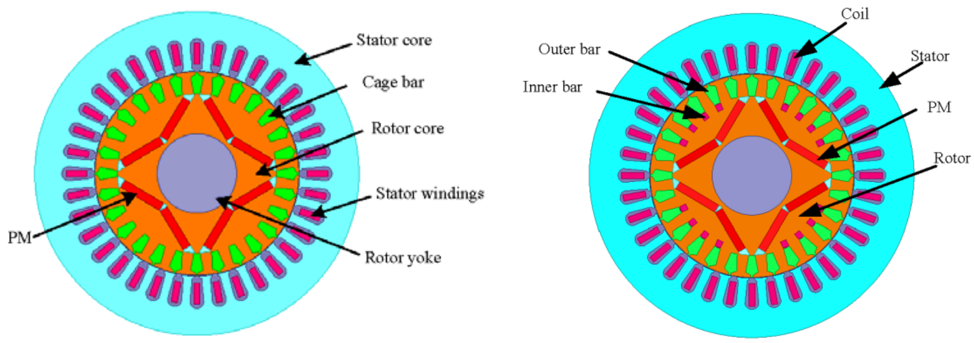


Fig. 2

Table 1

Parameters	Values
Rated power (kW)	2.2
Rated speed (r/min)	1500
Rated load (N · m)	14
Pole number	4
Frequency (Hz)	50
Rated voltage (V)	380
Stator outer diameter (mm)	155
Stator inner diameter (mm)	98



a *b*

Fig. 3

a **Fig. 4** *b*

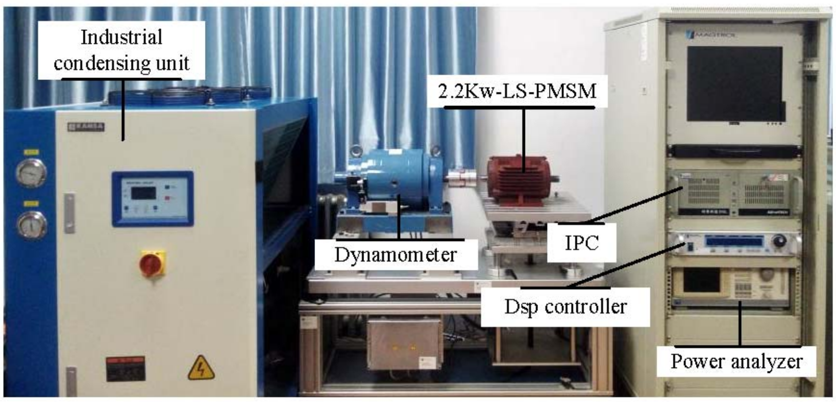


Fig. 5

supplied using directly the laboratory three-phase 50 Hz 380 V source. The correctness of the calculated result is verified. The prototype structure and experimental platform are shown in Figs. 4 and 5, respectively.

The test data of the prototypes and the calculated results obtained by 2D finite-element model are shown in table 2. As seen, there is little difference between the experimental and calculated values for the prototype under different loads. The errors are up to 5%. The experimental data are in good agreement with the calculated data.

Table 2

Performances	Test data	Calculated results	Errors
Current /A	3.89	3.78	2.8%
EMF/V	200	204	2%
Power factor	0.96	0.98	2.1%

4. Influence of key factors on starting performance and synchronous capability. The starting performance requires higher start torque with lower start current. The synchronous capability is estimated by the combination of load torque and inertia. The larger the combination of load torque and load torque, the better the synchronous capability. The mechanical motion equation in the pull-in synchronous process of LS-PMSM is expressed as

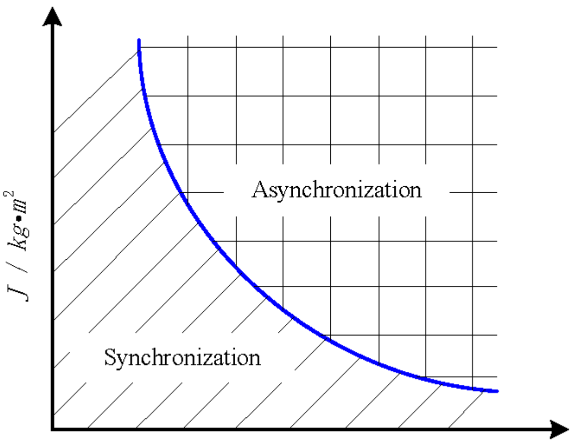


Fig. 6

$$T_{em} - T_L = J\frac{d\Omega}{dt} = -\frac{1}{p}J\omega_s s\frac{ds}{d\theta}, \quad (1)$$

where ω_c is the synchronous angular velocity, J is the rotational inertia, T_{em} is the electrical magnet torque, T_L is the load torque, s is the slip between synchronous speed and the rotor speed.

The synchronous capability is usually presented as the synchronization critical curve, as shown in Fig. 6. When the point of the combination of inertia and load torque fall in the region under the critical curve, motor could pull in synchronization, when the point fall in the region upon the critical curve, motor is operated asynchronously.

Some sensitive factors have different influence on the starting performance and synchronous capability. It is hard to get better starting performance and great synchronous capability at the same time.

The asynchronous torque is expressed by

$$T_{asyn} = \frac{mpU^2 R_2^{'2}/s}{2\pi f\left[(R_1 + c_1 R_2^{'2}/s)^2 + (X_1 + c_1 X_2^{'})^2\right]}, \quad (2)$$

where c_1 is the coefficient caused by adopting the Γ approximate equivalent circuit, R_1 and X_1 are the stator resistance and leakage reactance, respectively, R'_2 and X'_2 are the conversion values of the rotor resistance and leakage reactance.

4.1. Influence of rotor resistance on the starting and synchronous capability. Since only asynchronous torque that generated at the cage is affected at the start moment, the start torque and the rotor resistance are expressed by equation (3)

$$T_{start} = \frac{mpU^2 R_2^{'2}}{2\pi f\left[(R_1 + c_1 R_2^{'2})^2 + (X_1 + c_1 X_2^{'})^2\right]}. \quad (3)$$

Based on this equation, only considering the effects of $R_2^{'}$, the equation that calculating the derivative of T_{start} is given as

$$\frac{dT_{start}}{dR_2^{'}} = \frac{mpU^2\left[(X_1 + c_1 X_2^{'})^2 + R_2^{'} - c_1^2 R_2^{'2}\right]}{2\pi f\left[(R_1 + c_1 R_2^{'})^2 + (X_1 + c_1 X_2^{'})^2\right]^2}. \quad (4)$$

The value of $R_2^{'}$ corresponding to maximum starting torque is equal to

$$R_2^{'} = \frac{1}{c_1}\sqrt{R_1^2 + (X_1 + c_1 X'_2)^2}. \quad (5)$$

When $R_2^{'}$ less than $\frac{1}{c_1}\sqrt{R_1^2 + (X_1 + c_1 X'_2)^2}$, the starting torque increases with increasing $R_2^{'}$. The cage bar of LSPMSM is usually made with aluminum or copper, the resistance is larger than $\frac{1}{c_1}\sqrt{R_1^2 + (X_1 + c_1 X'_2)^2}$. In other words, the increase of resistance gives higher starting performance.

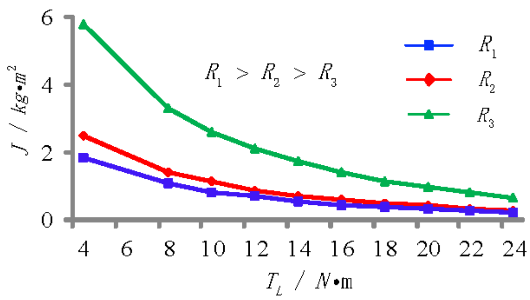


Fig. 7

Using presented method the critical curves are different for different three rotor resistance (Fig. 7). It can be seen that the curve of rotation inertia versus load torque is higher when the rotor resistance is lower. It means that the better synchronous capability will be get at lower rotor resistance. The high resistance leads to higher starting torque with lower synchronous capability when the rotor resistance is lower than $\frac{1}{c_1}\sqrt{R_1^2+(X_1+c_1X'_2)^2}$. And the lower rotor resistance promotes the better synchronous capability but the starting torque will have a negative influence. This conflict is important for designing of LSPMSM.

4.2. Influence of rotor reactance on the starting and synchronous capability. When the key factor comes to rotor reactance, the relevance of starting torque and rotor reactance is expressed as equation (6)

$$\frac{dT_c}{dX_2'} = -\frac{mpc_1U^2R_2'^2(X_1+c_1X_2')}{s\pi f[(R_1+c_1R_2'^2/s)^2+(X_1+c_1X_2')^2]^2}. \qquad (6)$$

It can be seen that the derivative of rotor reactance is lower than zero constantly. So the start torque decreases with rotor increasing reactance. The better starting performance required lower rotor reactance.

Even though the method of critical curve (Fig. 6) is widely accepted to present the synchronous capability, the method is limited to be used widely because of complex calculation. The slope of torque versus torque curve which determines the critical speed when motor beginning pull in synchronization is also important for synchronous capability. The higher critical slope means the higher speed of the motor when beginning to pull in synchronization. The rotor has more possibility to operate at synchronous speed, and the motor has higher synchronous capability. The slop of this curve could be expressed as

$$\frac{dT_c}{ds} = \frac{mpU^2R_2'^2\left\{c_1^2R_2'^2 - s^2[R_1^2+(X_1+c_1X_2')^2]\right\}}{2\pi fs^4[(R_1+c_1R_2'/s)^2+(X_1+c_1X_2')^2]^2}. \qquad (7)$$

This slop has an influence on the rotor reactance. The derivative of the torque versus slip curve slope is expressed by equation (8)

$$\frac{d(dT_c/ds)}{dX_2'} = -\frac{mpU^2R_2'}{2\pi fs^4}\left\{\frac{2c_1s^2(X_1+c_1X_2')}{[(R_1+c_1R_2'/s)^2+(X_1+c_1X_2')^2]^2} + \frac{4c_1(X_1+c_1X_2')\left\{c_1^2R_2'^2 - s^2[R_1^2+(X_1+c_1X_2')^2]\right\}}{[(R_1+c_1R_2'/s)^2+(X_1+c_1X_2')^2]^3}\right\}. \qquad (8)$$

As seen from this equation, the value of the derivative is lower than zero, so the torque is improved when the rotor reactance decreases. It means that the better synchronous capability is got with low rotor resistance. Influences of rotor reactance on starting performance and synchronous capability are analogous. Then the lower rotor reactance has a positive impact on both the starting performance and synchronous capability.

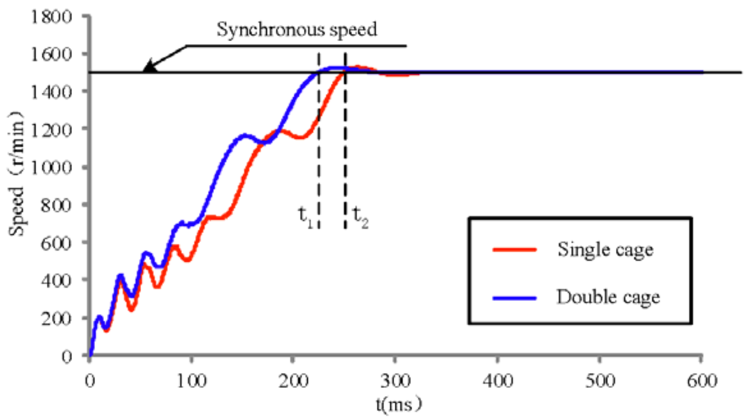


Fig. 8

5. Double cage rotor. The inner cage is made of copper with low resistance and low reactance to improve motors' synchronous capability, and the outer cage is still aluminum to provide low starting torque.

When the motor is running at rated load, the complex magnetic field is generated by permanent magnet and armature. This section mainly analyzes the air-gap magnetic field at the rated load operation.

When the LSPMSM has single cage and double cage rotor at 14 N·m load torque and 0.05 kg·m^2 rotational inertia. The start performances are calculated by finite-element method. Such starting pro-

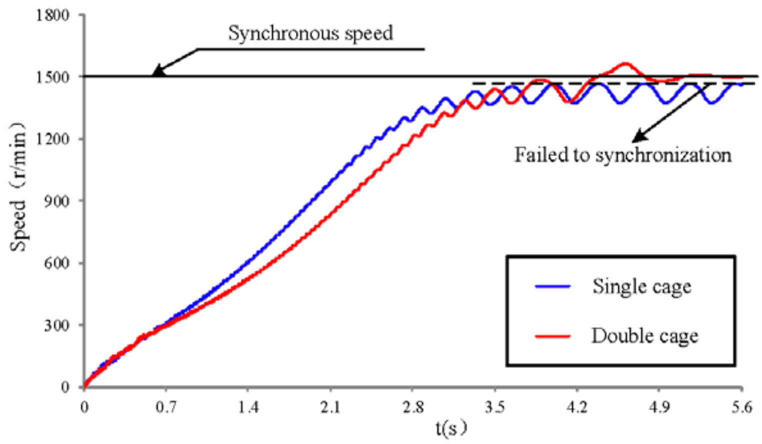


Fig. 9

cesses are show in Fig. 8. As seen, the motor with single cage starts more quickly and comes to synchronous speed earlier. But the results also vary with the increase of rotational inertia. The starting processes of prototype and double cage motor at 14 N·m load torque and inertia of 0.7 kg·m^2 is presented in Fig. 9.

Fig. 9 shows that the starting times for two type motors are longer with inertia of 0.7 kg·m^2, even though the motor with single cage starts faster and reaches the speed closed to synchronous speed earlier, but it is failed to pull in synchronization. Conversely, the motor with double cage rotor has a slower start process but it is pulled in synchronization successfully at this combination of load torque and rotational inertia.

Table 3

Performance	Single cage	Double cage
Start current (A)	57.4	58.2
Start torque (N · m)	57.9	54.7
Critical inertia with rated load (kg)	0.55	0.75

Table 3 gives the starting performances and synchronous capability of the motors with single cage and double cage rotors, respectively. It can be seen that the motor with single cage rotor has higher start torque and lower start current as compared with the motor having double cage. It means that its starting performance is better than the motor with double cage, but this difference is not obvious. When it comes to the synchronous capability, the motor with single cage rotor could be pulled in synchronous speed with the maximum inertia 0.55 at rated load torque 14 N·m, but the motor with double cage motor is pulled in synchronous speed with the maximum inertia 0.75 – by 36.4% greater as compared to the motor with single cage rotor.

To reveal the reason of the starting performance difference between the motor with single and double cage rotor, Fig. 10 gives the current density of motors with the two rotor structures. It can be seen that the value of current density both of the two motors increases from inside to outside on circumferential direction. The current is most concentrated at the end of the cage bar. This means that the skin effect is obvious and the effective area of rotor bar decreases, so the effective resistance increases actually. The start torque and the rotor resistance are expressed by equation (2).

When the material of the cage is aluminum, the increment caused by the skin effect increases the start torque. In the double cage rotor, the current is mostly concentrated in the inner cage made of copper, but it also can be seen that the skin effect is also obvious in the outer cage, and the current density is close to that of single cage rotor. This means that even though the resistance of the double cage rotor is smaller than that of single cage rotor because the low resistance inner cage is connected to the outer cage, but the skin effect makes the difference not obvious at the same dimensions and shape of the cage bar. So the starting performance of double cage rotor is worse than that of single cage rotor, but the value of this difference is small.

Fig. 11 gives the current density of the cage when the motor speed is close to synchronous speed. As seen, the cage bar without inner cage in double cage rotor has the same current density as compared to single cage rotor. It has little current density in the whole cage bar. In other words, there is almost no current in the bar at this moment.

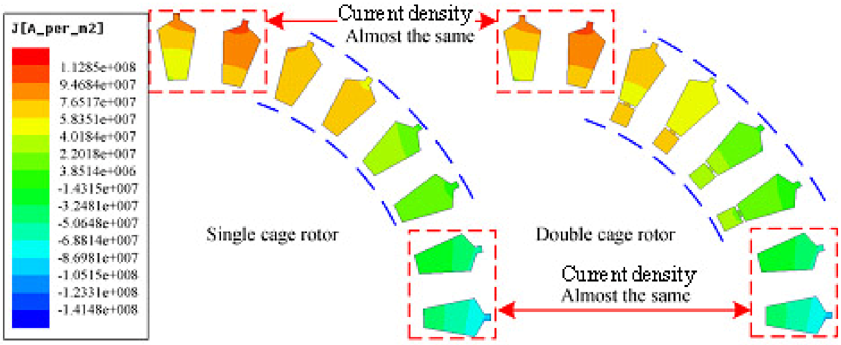


Fig. 10

But in double cage rotor, even though the outer cage of the double cage rotor is same in size and shape, but the current density in the outer cage of the double cage rotor is higher than that of single cage rotor. It means that the connection of inner cage could provide more torque in pull-in process and improve the synchronous capability. For double cage bar, the connection of inner cage and outer cage makes rotor resis-

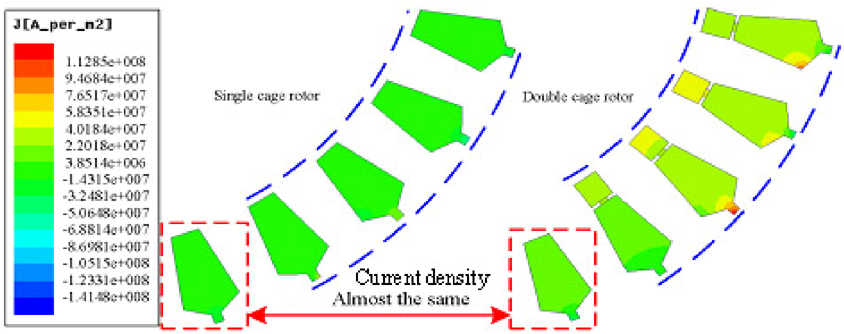


Fig. 11

tance lower, and at the speed close to synchronous speed, the effect of skin effect is too weak and could be neglected. So the low resistance gives the high current density and better synchronous capability.

At start moment, though the copper rotor cage has lower resistance, and the connection of inner cage and outer cage makes the effective resistance more lower, but the current is concentrated at the end of the rotor cage bar, and the skin effect due to the high slip leads to not very large difference of effective resistance of single cage and double cage rotor, so the influence on the starting performance is not obvious. When the motor speed is close to the synchronous, the slip is close to zero. There is almost no skin effect, so the copper inner cage and its lower resistance play a main role in synchronous process. It could provide more torque at the moment of pull-in synchronization.

6. Conclusions.

In this paper, the 2.2 kW LSPMSM is considered as an example. The finite-element method is used to analyze and calculate the starting performance and synchronous capability. The following conclusions are obtained:

The double cage structure rotor is mainly used to improve the synchronous capability. In general conditions, the high value of rotor resistance has a positive effect on the starting performance of LSPMSM, but better synchronous capability requires lower rotor resistance. When it comes to rotor reactance, both the starting and synchronous capability could be improved by lower rotor reactance. Taking into consideration these influences of the rotor resistance and reactance on starting and synchronous capability, the LSPMSM with double cage rotor that proposed in this paper can solve the conflict with a little decrement of starting performance and great improvement in synchronous capability. The decrement of starting performance is only by 5.5% worse than singe cage rotor, but the increment of synchronous capability could be 36.4%. The double cage rotor promotes the synchronous capability of LSPMSM.

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СТРУКТУРА РОТОРА С ДВОЙНОЙ КЛЕТКОЙ ДЛЯ УЛУЧШЕННОЙ СИНХРОНИЗАЦИИ СИНХРОННЫХ ДВИГАТЕЛЕЙ С ПОСТОЯННЫМИ МАГНИТАМИ

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Процесс синхронизации синхронных двигателей с постоянными магнитами для запуска линии является проблемным, требующим изучения и совершенствования. В статье с целью улучшения синхронизации предлагается ротор двигателей выполнять с двойной клеткой. Приведены ключевые факторы, относящиеся к пусковым характеристикам и синхронной способности синхронных двигателей. Изучены взаимные связи между характеристиками пуска и синхронной способностью. На основании этого сравниваются и анализируются характеристики двигателей с одноклеточным ротором и двухклеточным ротором. Двигатели, имеющие ротор с двумя клетками, обладают улучшенной синхронной способностью в широком диапазоне характеристик. Разработаны теоретические подходы для повышения эффективности функционирования синхронных двигателей с постоянными магнитами. Библ. 15, рис. 11, табл. 3.

Ключевые слова: синхронные двигатели с постоянными магнитами для запуска линии, метод конечных элементов, ротор с двойной клеткой, пусковая характеристика, синхронная способность.

СТРУКТУРА РОТОРА З ПОДВІЙНОЮ КЛІТКОЮ ДЛЯ ПОКРАЩЕННЯ СИНХРОНІЗАЦІЇ СИНХРОННИХ ДВИГУНІВ З ПОСТІЙНИМИ МАГНІТАМИ

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Процес синхронізації синхронних двигунів з постійними магнітами за для запускання лінії є проблемним, що вимагає вивчення та удосконалення. З метою покращення синхронізації пропонується ротор двигунів виконувати з подвійною кліткою. Наведено ключові фактори щодо пускових характеристик і синхронної спроможності синхронних двигунів. Вивчено взаємні зв'язки між характеристиками пуску та синхронною спроможністю. Базуючися на цьому, порівнюються та аналізуються характеристики двигунів з одноклітковим та двоклітковим ротором. Двигуни, що мають ротор із двома клітками, мають покращену синхронну спроможність у широкому діапазоні характеристик. Розроблено теоретичні підходи для підвищення ефективності функціонування синхронних двигунів з постійними магнітами. Бібл. 15, рис. 11, табл. 3.

Ключові слова: синхронні двигуни з постійними магнітами для запускання лінії, метод кінцевих елементів, ротор із подвійною кліткою, пускова характеристика, синхронна здатність.

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