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METHOD FOR CALCULATION OF NO-LOAD BACK EMF OF HIGH VOLTAGE LINE-START PERMANENT MAGNET SYNCHRONOUS MOTOR

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When the finite element method is used to calculate the no-load back EMF of the high voltage line-start permanent magnet synchronous motor (HV-LS-PMSM), choosing the actual length and effective length of the stator core will cause different calculation results. In order to accurately calculate the no-load back EMF of HV-LS-PMSM with ventilation ducts, the 1000 kW, 10 kV HV-LS-PMSM is taken as an example to establish the finite element model of the prototype, and the correctness of the model is verified by analytical calculation. Firstly, based on the actual length of the stator core, the finite element models of 2D and 3D without ventilation ducts are established. The difference between the two models is compared in calculation of no-load back-EMF, and the difference between them is obtained. Secondly, based on the effective length of the stator core, a 2D finite element model is developed to compare the difference between the actual length of the stator core and its effective length in calculation of the no-load back EMF. Finally, the 3D finite element model with ventilation ducts is proposed, and the influence of ventilation ducts on the no-load back-EMF is analyzed. In this paper, the method for calculation of the no-load back-EMF is presented by 2D finite element model, which simplifies the calculation process and improves the efficiency of motor design. References 14, figures 6, tables 2.

Key words**:** line start; permanent magnet; synchronous motor; finite element method; no-load back EMF; actual length and effective length of the stator core; marginal effect.

1. Introduction. Due to the advantages of high efficiency, high power density and high power factor of HV-LS-PMSM, it is widely used in industrial field instead of the induction motor [1-3, 10], and it doesn't need an extra device at start-up [5-6, 8]. The no-load back-EMF is one of the important parameters in the design of HV-LS-PMSM, and it requires accurate calculation. Because of the particularity of the structure of HV-LS-PMSM, the 3D finite element model is usually used to calculate no-load back-EMF [4, 12]. However, the 3D finite element calculation takes a long time and consumes more computer resources, which seriously affects the process of motor design. In this paper, the 2D finite element model is used to calculate the no-load back-EMF of HV-LS-PMSM.

In recent years, many specialists have done some research on simplified 3D model calculation. In work [9], an end-effect equivalent 2D model to analyze back-EMF of high speed permanent magnet synchronous motor (PMSM) in order to consider a leakage flux in the end region of stator and air-gap is proposed and the method is verified by results of 3D finite-element calculations and experiment. Paper [7] presents the axial flux permanent magnet machines (AFPMMs) and analytical model for them to predict the no-load air-gap flux density distribution, flux-linkage, back-EMF, and cogging torque. The results are verified by 3D finite-element simulations. In article [13], the complex 3-D model was simplified into 2-D analytic model, and an analytical formula for the winding factor that adapting different coreless stator winding is proposed. The analytical solution for no-load back EMF is calculated by using this method. In [11], the method combining particle swarm optimization algorithm and response surface methodology is proposed to optimize a transverse flux permanent magnet machine (TFPMM). The optimization aims to maximize the no-load back EMF to get higher torque density in the same space of the motor. However, many researchers did not consider the simplified calculation of no-load back-EMF of HV-LS-PMSM.

Based on the above problems, the 1000kW, 10kV HV-LS-PMSM is taken as an example to developed the 2D and 3D finite element models. The correctness of the model is verified. Firstly, based on the actual length of the stator core, the difference between 2D and 3D models in calculation of no-load back electromotive force is compared. Secondly, based on the effective length of the stator core, the 2D model is established. The difference between the effective length of the stator core and the actual length of the stator core in calculation of the no-load back EMF is compared. Finally, based on the analysis of the marginal effect of the HV-LS-PMSM, the rationality of using the actual length of the stator core is revealed in the 2D model, and the 3D finite element model with ventilation ducts is established to verify the correctness of the above analysis.

Table 1

Parameters	Values
Output power	1000kW
Power frequency	50Hz
Rated voltage	10kV
Inner diameter of stator	600 mm
Outer diameter of the stator	880 mm
Inner diameter of rotor	360 mm
Outer diameter of the rotor	595.8 mm
Air gap	2.53 mm
total length of the stator core	710mm
actual length of the stator core	610 mm
effective length of the stator core	643 mm

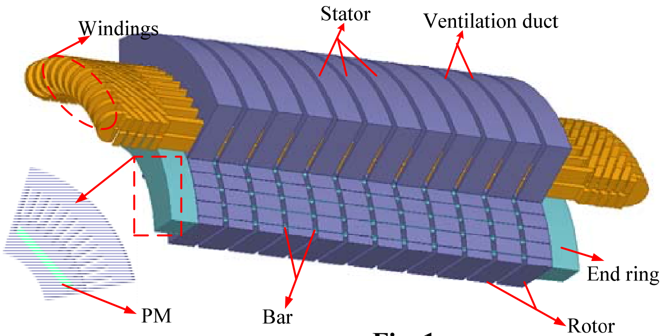

Fig. 1

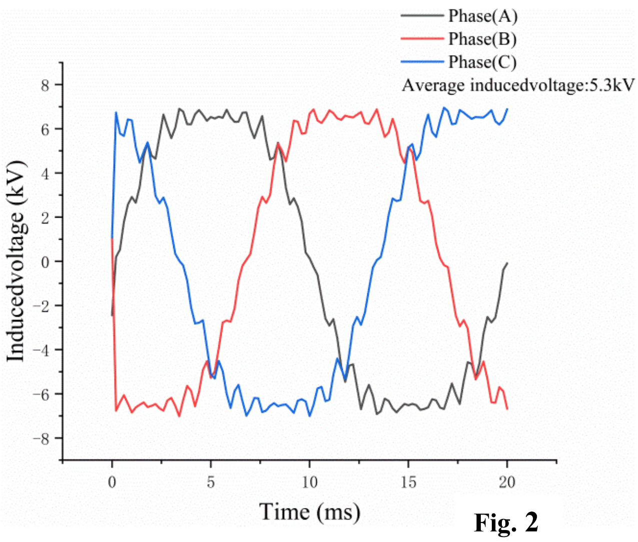

Fig. 2

2. Parameters and model of HV-LS-PMSM. 2.1 Parameters and model. The object studied of this paper is 1000kW, 10kV HV-LS-PMSM. The simplified calculation of no-load back-EMF of HV-LS-PMSM with ventilation ducts is analyzed. Based on the design structure of the HV-LS-PMSM, the 3D model of the prototype is established, as shown in Fig.1. The basic parameters are given in Table 1. The Ansoft is a business software, which is widely used in the mechanical, electromagnetic, thermodynamics and other fields because of its high calculation accuracy. In this paper, the finite element transient magnetic field based on Ansoft Maxwell program is used for analysis.

2.2 Analytical calculation. Based on the actual parameters of the HV-LS-PMSM and the magnetic circuit calculation of the HV-LS-PMSM, the no-load back EMF of the prototype is determined. The formula for the no-load back EMF is as follows

$$E_0 = 4.44 f K_{dp} N \Phi_{\delta 0} K_{\Phi}, \qquad (1)$$

where E_0 is the no-load back EMF, f is the frequency, K_{dq} is the winding factor, N is the number of turns, $\Phi_{\delta 0}$ is the no-load main magnetic flux, K_{Φ} is the air gap flux waveform coefficient.

According to the following equation (2), it can be calculated the effective length of the stator core of HV-LS-PMSM with ventilation ducts:

$$\begin{cases} l_{ef} = l_t - N_v b_v' \\ b_v' = \dfrac{b_v^2}{b_v + 5\delta / 2} \end{cases}. \qquad (2)$$

Here N_v is the number of ventilation ducts, b_v' is the length due to a radial ventilation ditch along the axial direction of the stator core, l_t is the total length of the stator core, δ is the air gap length, l_{ef} is the effective length of the stator core, b_v is the width of the ventilation ducts.

The total length of the stator core of the prototype is 710 mm. The number of ventilation ducts is 11, and the width of the ventilation ducts is 10 mm. The air gap length is 2.53 mm. According to equation (2), the effective length of the stator core of HV-LS-PMSM with ventilation ducts is 643 mm.

In this paper, the analytical calculation is used to calculate the no-load back EMF to verify the correctness of the model. After proper correction, the simple engineering calculation equation is obtained and used in product design. The equation has high calculation accuracy and greatly facilitates engineering calculation. The no-load back EMF of the prototype is 5.5 kV by analytical calculation. In addition, due to the special structure of HV-LS-PMSM, the 3D finite element is usually used to calculate the no-load back EMF [4, 12]. The 3D finite element model with ventilation ditch is developed to solve the no-load back EMF, as shown in Fig. 2.

The comparison of other performances of the motor under rated load is given results shown in Table 2. This table presented results of 2D and 3D calculations under rated power.

Table 2

Parameters	Model 2D	Model 3D	Difference
Current	62	67	8%
Torque	9556	9451	1.1%
No-load back EMF	5.4	5.3	2%
Efficiency	97%	95.5%	1.5%
Power factor	0.989	0.99	0.1%

As seen from Table 2 the current, torque, power factor, no-load back EMF and efficiency of the HV-LS-PMSM with ventilation ditch have a little difference. The 2D model replaces the 3D model to calculate the no-load back EMF, and gives good effects.

The correctness of the 3D model of the prototype is verified in this work.

3. The no-load back EMF by 3D and 2D finite element model. The no-load back EMF is an important parameter in motor design, and it precise calculation directly determines the performance of the motor. The finite element method is widely used in motor design because of its accurate calculation [14]. When the finite element model of the HV-LS-PMSM is established for motor design, the 2D and the 3D finite element models will produce different results in the calculation of the no-load back-EMF. In order to analyze the difference between the two models in calculation the no-load back EMF of the HV-LS-PMSM, the 2D and 3D finite element models are established by taking the actual length of the stator core as an example. The no-load back EMFs of the 2D and 3D finite element models are given in Fig. 3.

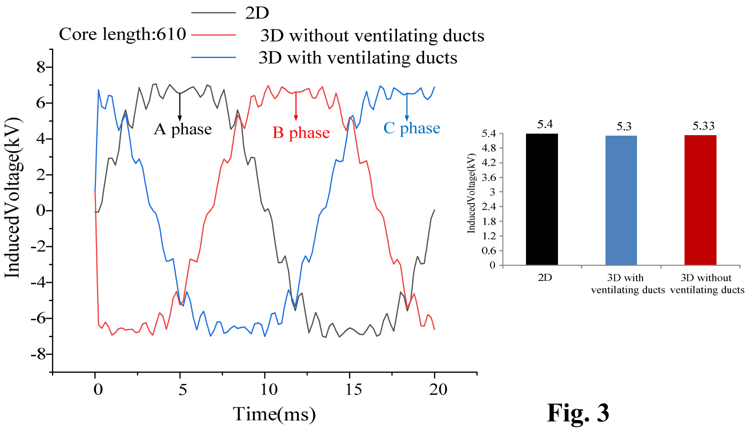

Fig. 3

It can be seen from Fig. 3 the difference between the 2D and 3D finite element models in calculation of the no-load back EMF is small at calculation of the actual length of the stator core. In addition, in the 3D model, the difference between 3D finite element model taking onto account ventilation ducts and the 3D model without ventilation ducts in calculation of no-load back EMF is also small. The no-load back EMFs of the 2D and 3D (with ventilation ducts) finite element models are 5.4 kV and 5.3 kV, respectively, and the difference between them is only 1.8%. The no-load back EMFs determined by 3D models without and with ventilation ducts are 5.33kV and 5.3kV, respectively, and the difference between them is only 0.6%.

The analysis shows the difference between 2D finite element model and 3D finite element model in accuracy of calculation of the no-load back EMF. The following analysis shows the difference in solution time between them. The number of mesh elements in the model directly determines the solution time. Fig. 4 shows the mesh for the 2D and 3D finite element models.

As seen from Fig. 4, in terms of solution time, the 3D finite element model is much larger than the 2D finite element model. The number of the 3D finite elements is equal to 265000, and the number of the 2D finite elements is only 4564, which is 58 times different. As to calculation accuracy of no-load back EMF, the difference between 2D model and 3D model is only 1.8%.

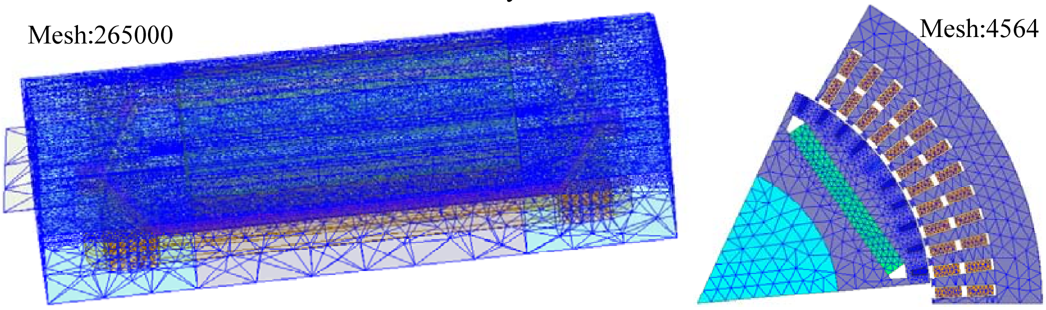

Fig. 4

In the design of motor, the 2D finite element model can be used to calculate the no-load back-EMF of HV-LS-PMSM, which can avoid the long calculation time of the 3D finite element model and improve the efficiency of HV-LS-PMSM design.

4. Analysis of no-load back EMF calculated by 2D finite element model. The 3D finite element model requires large computer resources. At the same time, as for calculation of no-load back EMF, the difference between 2D and 3D model is very small. Therefore, this chapter proposes the method for accurate calculation of no-load back EMF of the motor by 2D finite element model. That can improve the efficiency of HV-LS-PMSM design.

The actual length of the stator core and the effective length of the stator core are used to build the motor models, and the difference between them in calculation of no-load back EMF is compared. Because the 3D model can consider the primitive structure of the HV-LS-PMSM, the calculated results are relatively accurate, and it is used as a reference to measure the accuracy of the calculation of the 2D finite element model.

In fig. 5 610 mm corresponds to the actual length of stator core, 643 mm is the effective length of stator core. As seen from Fig. 5 the calculation of the no-load back EMF of the HV-LS-PMSM using the actual length of the stator core is the closest to the calculation of the 3D finite element model with ventilation, (difference between them is 1.8%). The no-load back EMF calculated by 2D model and using the effective length of the stator core is equal to 5.7 kV. Comparison with the no-load back EMF calculated by 3D finite element model with ventilation ducts gives the difference of 7.5%. Therefore, the actual length of the stator core is used in the 2D finite element model to calculate the no-load back EMF of the HV-LS-PMSM.

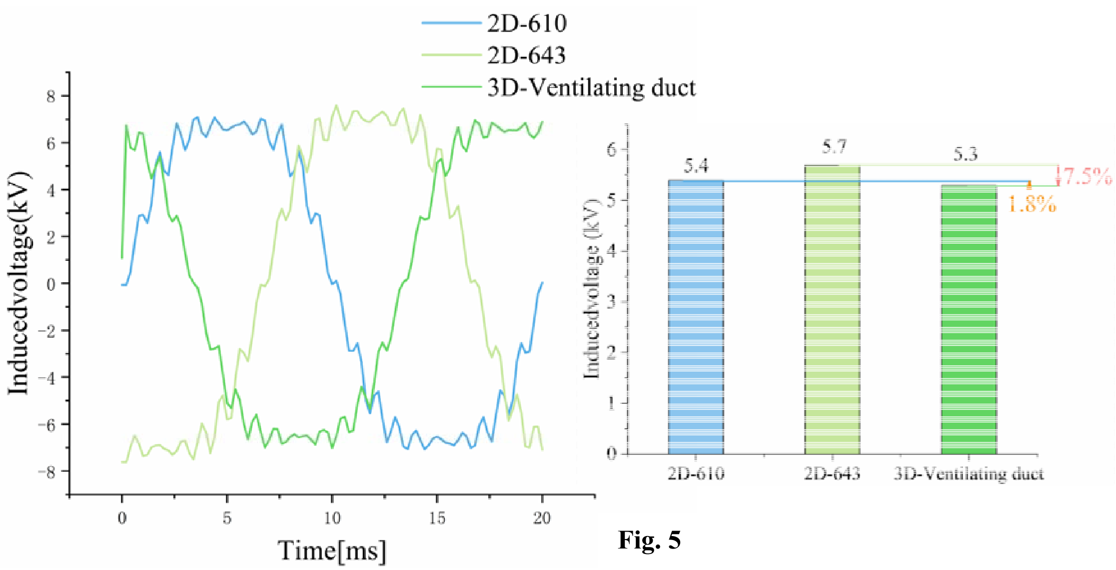

Fig. 5

In order to verify the correctness of the above analysis, the magnetic field of the motor is analyzed in the next section.

5. Analysis of HV-LS-PMSM marginal effect. The length of armature is the basic design parameter of the motor. The armature length is related to the axial distribution state of the air gap of the motor. The magnetic flux density in air-gap is considered to study the influence of radial ventilation ducts. As shown the results of calculations by the 3D finite element model, the marginal effect has a little effect on the calculated accuracy of the no-load back EMF (Fig. 6).

It can be seen from Fig. 6 that there is a marginal effect at the edge of the ventilation ducts, but the marginal effect is relatively weak.

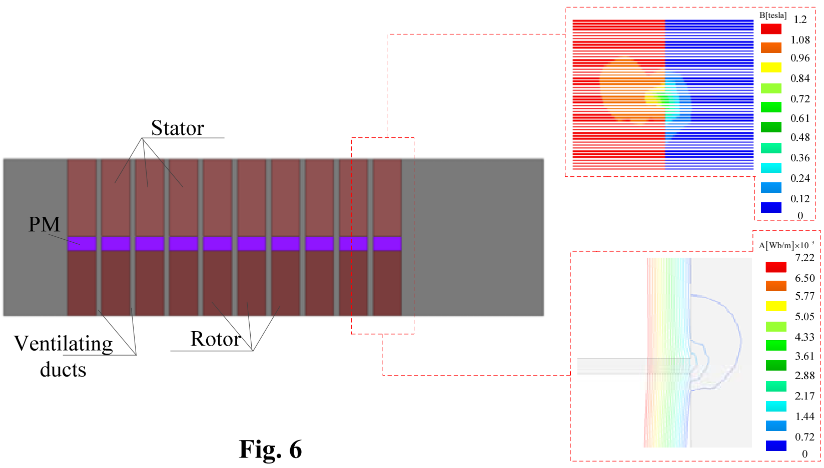

Fig. 6

6. Conclusions. In this paper, the 10kV, 1000kW HV-LS-PMSM is taken as an example. The 2D model for calculation of no-load back-EMF of HV-LS-PMSM with ventilation ducts is proposed. The following results are obtained:

1. On the base of calculation of the actual length of stator core, the difference in calculation of no-load back EMF between the 2D and 3D models with ventilation ducts is small, this difference is

only 1.8%. On the base of calculation of the effective length of the stator core, the difference in calculation of no-load back EMF between these models with ventilation ducts is 7.5%. Therefore, the actual length of the stator core is used in the 2D finite element model to calculate the no-load back EMF of HV-LS-PMSM. In addition, the values of no-load back EMF calculated by 3D models without ventilation ducts and with ventilation ducts are 5.33 kV and 5.3 kV, respectively, the difference between them is only 0.6%.

2. As to calculation accuracy of the no-load back EMF, the difference between 2D and 3D models is only 1.8%. However, the solution time by 2D model is 58 times faster than that by 3D model. The 2D finite element model can be effectively used to calculate the no-load back-EMF of motor, to avoid the problem of long calculation time of the 3D finite element model and improve the efficiency of motor design.

3. The marginal effect at the edge of the ventilation ducts takes place, but the marginal effect is relatively weak. When the 2D finite element model is used to calculate the no-load back EMF, the marginal effect has a little effect on the calculated accuracy of the no-load back EMF.

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МЕТОД РАСЧЕТА ПРОТИВО-ЭДС ХОЛОСТОГО ХОДА ВЫСОКОВОЛЬТНОГО СИНХРОННОГО ДВИГАТЕЛЯ С ПОСТОЯННЫМИ МАГНИТАМИ ПРЯМОГО ПУСКА

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При применении метода конечных элементов для расчета противо-ЭДС холостого хода высоковольтного синхронного двигателя с постоянными магнитами прямого пуска (HV-LS-PMSM) выбор фактической и эффективной длины сердечника статора приводит к различным результатам расчета. Приведен пример точного определения обратной ЭДС холостого хода двигателя с вентиляционными каналами. В качестве прототипа для реализации конечно-элементной модели выбран двигатель мощностью 1000 кВт, 10 кВ. Корректность модели подтверждена аналитическим путем. Сначала на основе фактической длины сердечника статора рассматриваются 2D и 3D конечно-элементные модели без вентиляционных каналов. Различие между этими моделями определяется путем вычисления противо-ЭДС холостого хода. Затем эффективная длина сердечника статора 2D модели определяется по разнице расчетных значений ЭДС холостого хода для моделей фактической длины. Наконец рассматривается 3D конечно-элементная модель с вентиляционными каналами, анализируется влияние вентиляционных каналов на противо-ЭДС холостого хода. Таким образом, в статье представляется метод расчета противо-ЭДС холостого хода для конечно-элементной 2D модели, что упрощает расчетный процесс и повышает эффективность проектирования двигателя. Библ. 14, рис. 6, табл. 2.

МЕТОД РОЗРАХУНКУ ПРОТИ-ЕРС ХОЛОСТОГО ХОДУ ВИСОКОВОЛЬТНОГО СИНХРОННОГО ДВИГУНА З ПОСТІЙНИМИ МАГНІТАМИ ПРЯМОГО ПУСКУ

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При застосуванні методу скінченних елементів для розрахунку проти-ЕРС холостого ходу високовольтного синхронного двигуна з постійними магнітами прямого пуску (HV-LS-PMSM) вибір фактичної і ефективної довжини сердечника статора призводить до різних результатів розрахунку. Наведено приклад точного визначення зворотної ЕРС холостого ходу двигуна з вентиляційними каналами. Як прототип для реалізації кінцево-елементної моделі обраний двигун потужністю 1000 кВт, 10 кВ. Коректність моделі підтверджена аналітичним шляхом. Перш за все на основі фактичної довжини сердечника статора розглядаються 2D і 3D кінцево-елементні моделі без вентиляційних каналів. Різниця між цими моделями визначається шляхом обчислення проти-ЕРС холостого ходу. Потім ефективна довжина сердечника статора 2D моделі визначається по різниці розрахункових значень ЕРС холостого ходу для моделей фактичної довжини. Нарешті розглядається 3D кінцево-елементна модель з вентиляційними каналами, аналізується вплив вентиляційних каналів на проти-ЕРС холостого ходу. Таким чином, у статті представлено метод розрахунку проти-ЕРС холостого ходу для кінцево-елементної 2D моделі, що спрощує розрахунковий процес і підвищує ефективність проектування двигуна. Бібл. 14, рис. 6, табл. 2.

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