

The effect analysis of single-double layers concentrated winding on squirrel cage induction motor

Jianjun Fang, Yufa Xu^a, Yudong Luo and Yaxin Chen

School of Electrical, Shanghai DianJi University, Shanghai, China

Abstract. As the key component of the electromagnetic energy conversion in the motor, the type of winding has an important influence on the high order harmonics and losses. In order to study single-double layers concentrated winding for high order harmonics and losses reduction, taking a 2.2kW squirrel cage induction motor as an example, the analysis model was established based on the time stepping finite element method (T-S FEM), and the variation of air gap flux density of single-double layers concentrated winding and double-layer lap winding was compared, pointed out that single-double layers concentrated winding can effectively reduce the high harmonics. Further, on the premise of original starting performance, the variation of stator copper loss, iron loss and rotor copper loss was computed and compared, and the efficiency of motor improved about 3.1%.

Keywords: stator windings; harmonics analysis; induction motors; iron; copper.

1 Introduction

As the key component of the electromagnetic energy conversion in the motor, the stator winding will produce a series of high order harmonics in addition to the fundamental wave. High order harmonics will increase the stray loss, reduce efficiency and produce additional torque, seriously affect the operation performances [1]. Therefore, in addition to ensure that the basic performances of the motor to meet the requirements, it is important to takes some measures to suppress high order harmonics. The squirrel cage induction motor usually adopts three-phase symmetrical short-pitch and distributive winding to suppress high order harmonics [2-3], for example double-layer lap winding and single-double layers concentrated winding. Theoretically, the low harmonic winding can completely eliminate the high order harmonics in the motor, but due to the limit of the number of conductors in the practical application, there are still high order harmonics in the motor. Therefore, it is of great significance to analyze the influence of the winding on the high order harmonic and the loss.

At present, many scholars have analyzed the influence of single-double layers concentrated winding on higher order harmonic by calculating the parameters of winding coefficient, harmonic magnetic potential and turns ratio[4-6]. However, there is a big error in analytical calculation, which cannot provide strong support for the further accurate analysis of the loss.

In this paper, taking a 2.2kW squirrel cage induction motor as an example, the analysis model was established based on the time stepping finite element method (T-S FEM), the change of air gap flux density of the motor under different winding types is compared and analyzed, and the effect of iron

^a Corresponding author: xuyf@sdju.edu.cn

loss, copper loss and copper loss of rotor is analyzed. The research results of this paper can provide important theoretical support for the further improvement of the efficiency of squirrel cage induction motor through the low harmonic winding.

2 T-S FEM model and loss calculation method

2.1 T-S FEM model with field-circuit-motion coupled

Considering skewed slot, the formula of T-S FEM model with field-circuit-motion coupled shown as the following[7]:

$$KX + DX' = F \quad (1)$$

Where K and D is coefficient matrix, X and X' is state variable, F is excitation source that is composed with supply voltage.

2.2 Loss calculation method based on T-S FEM

The calculation of core loss uses the three type constant coefficient model based on hysteresis loss, eddy current loss and abnormal loss which is proposed by the scholar Bertotti, the formula shown as the following [8]:

$$P_{Fe} = k_h f B_m^2 + k_e (f B_m)^2 + k_a (f B_m)^{1.5} \quad (2)$$

Where P_{Fe} is density of iron loss; k_h , k_e and k_a is the coefficient of hysteresis loss, eddy current loss and abnormal loss; B_m is magnetic flux density amplitude; f is frequency.

The calculation of stator copper loss comes from the fundamental and harmonic currents, the formula shown as the following [9]:

$$P_{SCL} = \frac{1}{T} \sum_v \int_0^T R_s (i_{vA}^2 + i_{vB}^2 + i_{vC}^2) dt \quad (3)$$

Where P_{SCL} is stator copper loss; R_s is stator Winding Resistances; i_{vA}^2 , i_{vB}^2 and i_{vC}^2 is current of each frequency of stator winding, among $v=2k+1(k=0,1,2,3,...)$ is harmonic frequency of stator winding.

As for rotor copper loss, due to the skin effect caused by the high frequency harmonic current, the current in the rotor guide strip is concentrated in the surface layer. Therefore, the formula shown as the following [10]:

$$P_{RCL} = \sum_{\Delta} \sum_v \frac{1}{\delta} L_{ef} S_{\Delta} J_{\Delta v}^2 \quad (4)$$

Where P_{RCL} is rotor copper loss; σ is rotor conductivity; L_{ef} is effective length of rotor bar; S_{Δ} is unit area of rotor bar; $J_{\Delta v}$ is effective value of fundamental and harmonic current density of rotor bar, among $v=2k+1(k=1,2,3,...)$ is harmonic frequency.

2.3 The main parameters of the prototype are analyzed

In this paper, taking a 2.2kW squirrel cage induction motor as an example, pole number is 4 poles, stator slot type is pear shaped slot, slot number is 36 slots, rotor slot type is a closed slot, slot number is 28 slot, winding type were used double-layer lap winding and single-double layers concentrated winding.

3 Effect of single-double layers concentrated winding on high order harmonic

3.1 Winding connection type

The winding connection types of single-double layers concentrated winding and double-layer lap winding are shown in figure 1 and figure 2. The connection rule of single-double layers concentrated winding is that in the same period, the upper and the lower layers of the same groove are combined into a single layer coil, while the different phases of the same slot are kept in a double layer wiring, single turns number is 46, double turns number is 42, average pitch is 7, the winding resistance is 2.93 ohm. The connection rule of double-layer lap winding is every poles three upper side of the coil with the same side equal to three coil winding pitch three lower layer coil edges are connected into a pitch equal, after a poles winding coil stack pressure on top of poles windings, winding turns number is 42, average pitch is 8, the winding resistance is 3.17 ohm.

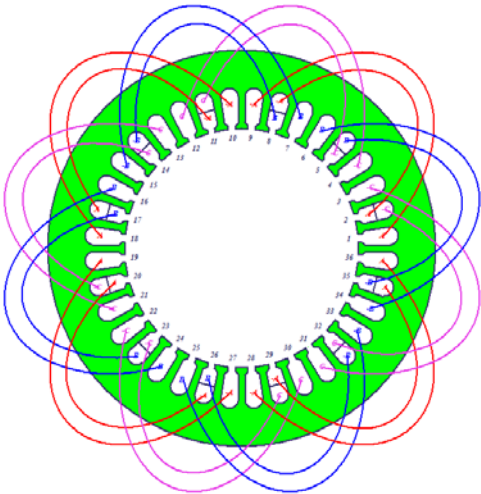


Figure 1. Single-double layers concentrated winding

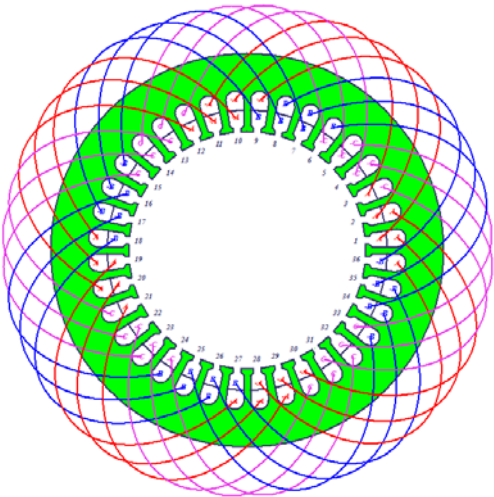


Figure 2. Double-layer lap winding

Compared with the double-layer lap winding, average pitch of single-double layers concentrated winding is smaller that the wire can be saved effectively, the slot of single layer can remove interlayer insulation and increase turns number, which can increase the slot fullness. But, winding assembly process of single-double layers concentrated winding is more difficult, it has higher requirements on the technological level.

3.2 The change of high order harmonics

In the process of solving the electromagnetic field of the motor, the following assumptions are made:

- 1) The magnetic field along the axial direction of the motor is well-distributed;
- 2) The skin effect of stator core and winding is ignored;
- 3) The influence of the external magnetic field of the motor is ignored, stator outer diameter circle is zero vector magnetic potential line.

Taking the whole motor as the solution area, the physical model of the motor is set up as shown in figure 3. The air gap flux density of the two types winding is obtained by the simulation of the model, and the air gap flux density of different harmonic orders is obtained by Fourier decomposition, as shown in figure 4.

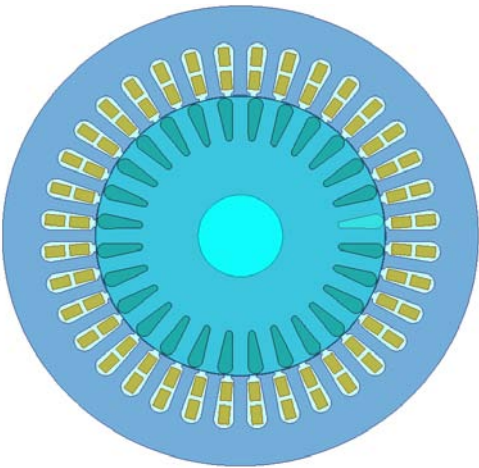


Figure 3. Model of motor

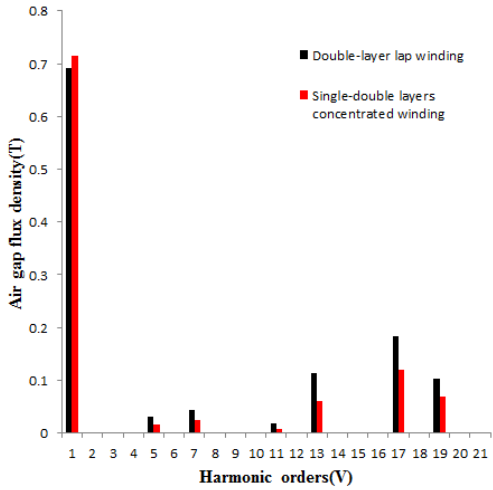


Figure 4. The change of high order harmonics

Compared with the double-layer lap winding, when the motor adopts single-double layers concentrated winding, 5th harmonics is decreased about 49.6% and 7th harmonics is decreased about 42.4%. In addition, it is obvious that 13th, 17th and 19th harmonic can be reduced in different degrees. Therefore, single-double layers concentrated winding can effectively suppress high order harmonics, that will optimize the performance of the motor.

4 Effect of single-double layers concentrated winding on loss

4.1 The change of loss in the motor

The loss of motor is closely related to size of magnetic flux density. When the motor adopts single-double layers concentrated winding, the size of magnetic flux density is changed, and the loss of motor will be changed. The change of stator copper loss, core loss and rotor copper loss is compared result in Table 1.

Table 1. The change of stator copper loss, core loss and rotor copper loss

	Stator copper loss	Core loss	Rotor copper loss
Winding1	40.4W	60.4W	2.7W
Winding2	31.1W	59.8W	2.6W

Remark: winding 1 is double-layer lap winding, winding 2 is single-double layers concentrated winding.

In Table 1, stator copper loss decreased about 23%, core loss decreased about 1.0% and rotor copper loss decreased about 3.7%. Here, the friction loss of motor is 21W and it is not changed, the efficiency of motor will improve about 3.1%.

4.2 The reasons of loss change

Through the above analysis, it is known that stator copper loss, core loss and rotor copper loss have been reduced. The common reason is that the high order harmonics have been weakened. The change of stator copper loss is the most, a vital reason is the wire has been saved. Therefore, the motor adopts single-double layers concentrated winding can effectively improve the efficiency.

5 Experimental verification

According to two kinds of winding connection mode, the experiment results are verified by two kinds of prototype machine. Because the rotor copper loss cannot be directly measured in the test process, so the rotor copper loss and iron loss are measured together. Calculated and measured no-load loss data are shown in Table 2.

Table 2. The change of stator copper loss, core loss and rotor copper loss

	Winding 1		Winding 2	
	Computed	Measured	Computed	Measured
Stator copper loss	40.4W	41.8W	31.1W	33.7W
Core loss and rotor copper loss	63.1W	65.4W	62.4W	64.1W
Total	103.5W	107.2W	93.5W	97.8W

The two-dimensional electromagnetic field calculation cannot consider transverse current over the bars of squirrel cage rotor and other factors, so the loss computed value is slightly lower than the

experimental value. In Table 2, measured total loss of winding 2 is smaller than winding 1, this is consistent with theoretical analysis.

6 Conclusion

For studying effect of the single-double layers concentrated winding the high order harmonics and the loss of stator copper loss, core loss and rotor copper loss, taking a 2.2kW squirrel cage induction motor as an example, the change of high order harmonics and loss are analyzed through the method of T-S FEM, the conclusions of this paper are as follows:

- 1) When the motor adopts single-double layers concentrated winding, high order harmonics can be suppressed effectively, reducing the harm caused by high order harmonics;
- 2) The electromagnetic loss is effectively reduced because of the suppression of high order harmonics and the decrease of copper content, motor efficiency is improved;
- 3) The effect analysis of single-double layers concentrated winding on the high order harmonics and loss are analyzed through T-S FEM, which is able to accurately consider the variation of high order harmonic and loss, and provide technical support for further improving the efficiency of motor.

Acknowledgment

This paper is supported by the Natural Science Foundation of Shanghai (No. 11ZR1413900), Shanghai Educational Committee Leading Academic Discipline Project (No. J51901), Shanghai Educational Committee key scientific research project (No. 09ZZ211), Shanghai Economic and Information Technology Committee (No. 13X1-37), Science and Technology Commission of Min Hang Municipality (No.2013MH180), the Key Discipline Project of Shanghai Dian-ji University(No. 09XKJ01). Especially, we are highly grateful to the referees and Editor-in-Chief, for their valuable comments.

References

1. Chapman S J. Electric Machinery Fundamentals [M].New York: McGraw-Hill Science Engineering Math, 193-196 (2011).
2. Huazhang Ding. Principle and calculation about low harmonic winding [J]. Electric Machines&Control Application, **25** (5): 4-9 (1998).
3. Qingpu Zhao. Study on low harmonic windings [J]. Electric Machines&Control Application, **25** (6) : 2-7 (1990).
4. Yunsong Chen, Aimin Wei, Xiaoxing Wang. Effect analysis of three-phase practical single-double layer unequal turn number sine winding application [J]. Electric Machines&Control Application, **36** (10) : 34-36,54 (2009).
5. Yan Chen, Guorong Zhou. Discussion on how to reduce the harmonic magnetic potential of three phases A. C. motor [J]. Explosion-Proof Electric Machine, **42** (1): 5-6, 25 (2007).
6. Dexin Ma. Effects of copper and energy-saving in designing single-double layer windings for small-sized induction motor [J]. Explosion- Proof Electric Machine, **42** (6): 8-11 (2007).
7. Haisen Zhao, Xiaofang Liu, Jia Hu, et al. The influence of wye and delta connection on induction motor losses taking slot opening and skew effect into account[C]/IEEE International Electric Machines and Drives Conference. Miami: 213-218 (2009).
8. Haisen Zhao, Xiaofang Liu, Yaqiu Yang, et al. Stator Slot Optimal Design of Premium Motors Based on Time-stepping Finite Element Method [J]. Proceedings of the CSEE, **31** (33): 115-122 (2011).
9. Haisen Zhao, Xiaofang Liu, Yingli Luo, et al. Losses characteristics of cage induction motors under voltage deviation conditions[J].Electric Machines and Control,**14** (5) : 13-19 (2010).

10. Xinzhen Wu, Xiangheng Wang. Calculation of skin effect for double-cage rotor bar of the induction machine [J]. Proceeding of the CSEE, **23** (3): 116-120 (2003).