Research on the Radial Electromagnetic force of an Inverter-Fed Induction Machine on Different Load conditions Using FEM

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***Abstract*—The radial magnetic forces contribute to a great extent to the generation of vibrations and noise in an induction machine. Different load conditions would affect the radial magnetic forces in an inverter-fed induction machine, further the vibrations and noise. Traditionally, experiment of magnetic noise can be taken to analyze the effect on different load conditions. In this paper, we conducted a 2-D field-circuit coupling analysis by time-stepping finite element method (FEM) to get the radial magnetic forces. Moreover, experiment of different load conditions have been done to verify the correctness of the method.**

***Index Terms*—Finite element methods, magnetic forces, rotating machines, pulse width modulation inverters**

I. Introduction

In China, the motor noise measurement is generally performed under no-load steady-state [1], while the motor in the actual operation is always on load, which reflects the level of the motor's noise more accurately. Therefore, many international motor companies have set the motor load noise as a performance of the motor [2].

The asynchronous motor's noise can be divided into mechanical noise, aerodynamic noise and electromagnetic noise. Due to the motor's speed change is very small between no-load and load operation, only small changes happened in the value of motor mechanical noise and aerodynamic noise, but it would generate strong harmonic magnetic field as the load increases, which causes changes in the electromagnetic noise. Therefore, the asynchronous motor's load noise is mainly electromagnetic noise. Especially in inverter fed motor, higher time harmonics in the stator winding currents will cause large vibration. Radial electromagnetic force generated in the stator core is the main source of electromagnetic noise and vibration, so this paper mainly focuses on the effect to the radial electromagnetic force of an inverter-fed induction machine on different load condition.

In previous studies, it is often done by experimental methods to estimate the influence of the loads [3-6]. This way is direct and easily to get an accurate conclusion. But its drawback is that the design cycle is longer, larger costs and resources are required. With the development of computer-aided techniques, the motor R&D manufacturing already change gradually from traditional cycle design mode of "preliminary design-trial-improved trial-improved design-cycle- design stereotypes" to virtual design. It is not only improved the overall performance of the motor, and also shorten the development cycle and saving the cost.

In this paper, we conducted a 2-D field-circuit coupling analysis by time-stepping finite element method (FEM) to get the radial magnetic forces. Analysis of the impact of the load on the radial force, and the correctness of the method is verified by experiment.

II. Formulation

In the 2-D electromagnetic analysis, the governing equation of a moving conductor can be expressed using ***A**, φ-**A*** method. In the moving conductor eddy current area can be described by the magnetic vector potential ***A*** and scalar potential φ:

$$\nabla\times\left(\upsilon\nabla\times\boldsymbol{A}\right)+\sigma\nabla\varphi+\sigma\frac{\partial\boldsymbol{A}}{\partial t}-\sigma\boldsymbol{v}\times\nabla\times\boldsymbol{A}=0 \tag{1}$$

Non-eddy current area is described by the vector magnetic potential ***A*** as

$$\nabla\times\left(\upsilon\nabla\times\boldsymbol{A}\right)=\boldsymbol{J_S} \tag{2}$$

Where ***A*** is the magnetic vector potential; υ is the reluctivity; ν for the conductor velocity; σ is the conductivity; $\boldsymbol{J_s}$ is the source current density.

Regional boundary is described as

$$A=0 \tag{3}$$

If we let R and L_{σ}, the analytically computed resistance of stator winding per phase and inductance of the end-windings, respectively, the following equation is obtained on the stator winding.

$$V_s=I_sR+L_\sigma\frac{dI_s}{dt}+\frac{d\phi}{dt} \tag{4}$$

The current density of the k-th rotor bar is

$$J_r=-\sigma\frac{\partial A}{\partial t}+\sigma\frac{u_k}{L_{ef}} \tag{5}$$

The time derivation can be discretized as follows by equation (6) and (7). Here we assumed that the acceleration of the rotor is constant in each step of time.

$$\Omega^{(n)}=\Omega^{(n-1)}+\frac{T_{em}^{(n)}-T_L}{J_m}\Delta t \tag{6}$$

$$\Delta\theta^{(n)}=\Omega^{(n)}\Delta t+\frac{1}{2}\frac{T_{em}^{(n)}-T_L}{J_m}\Delta t^2 \tag{7}$$

Since the magnetic permeability of the ferromagnetic core is much higher than that of the air gap, the magnetic flux lines are practically perpendicular to the stator and rotor cores. Thus, the tangential component $b_r(\alpha,t)$ of the magnetic flux density is much smaller than the normal component $b(\alpha,t)$. Then, according to the Maxwell stress tensor, the radial magnetic force per unit area or magnetic pressure waveform at any point of the air gap is

$$p_r(a,t) = \frac{1}{2\mu_0}[b^2(a,t) - b_t^2(a,t)] \approx \frac{1}{2\mu_0} b^2(a,t) \quad (8)$$

III. Numerical Model of Induction Machine

A test induction machine is designed for validating the electromagnetic force acting on the end winding. In order to get larger forces, the number of pole pairs is less. Table I is the main parameters of the machine.

TABLE I. Main Specifications Of Test Machine

Parameter	Value	Parameter	Value
Rated power (KW)	220	Number of pole pairs	1
Rated frequency (Hz)	50	Number of stator slots	48
Full length of stator core (mm)	215	Number of rotor slots	40
Outer diameter of stator core(mm)	620	Number of turns in series in stator coil	8
Inner diameter of stator core(mm)	350	Number of parallel branches of stator winding	2
Full length of rotor core (mm)	215	Coil span of stator coil (stator slot pitches)	17
Inner diameter of rotor core (mm)	120	Number of phases	3

This paper established a 2-D field-circuit coupling analysis by time-stepping FEM, as shown in Fig.1. As the complex of the stator end-winding, it is equivalent by the circuit parameters. The radial electromagnetic forces are analyzed in the case of no-load, 25% of the rated load, 50% of the rated load and 75% of the rated load and rated load.

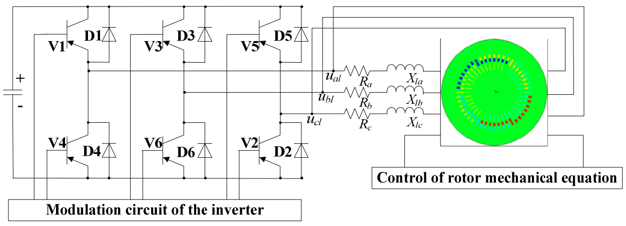

Fig.1. 2-D field-circuit coupled model with the inverter-fed induction machine

Fig.2 shows the experimental induction machine, these cases also been done in tests.

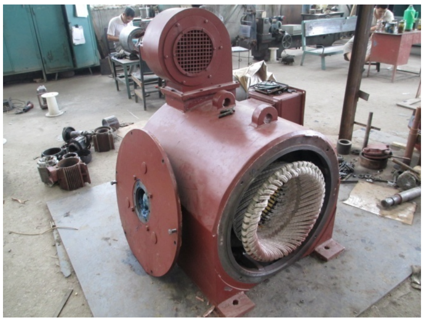

Fig.2. Test machine

IV. Results

Due to the content limit, this abstract only presented the air gap's electromagnetic radial force at 2.2s in no-load case.

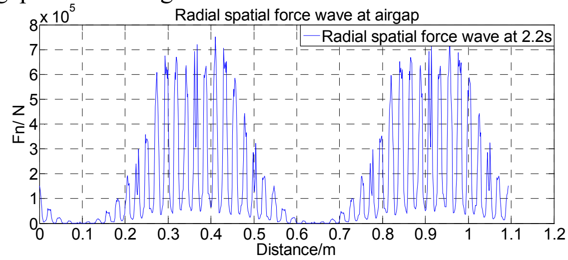

Fig.3. Radial spatial force wave at 2.2s

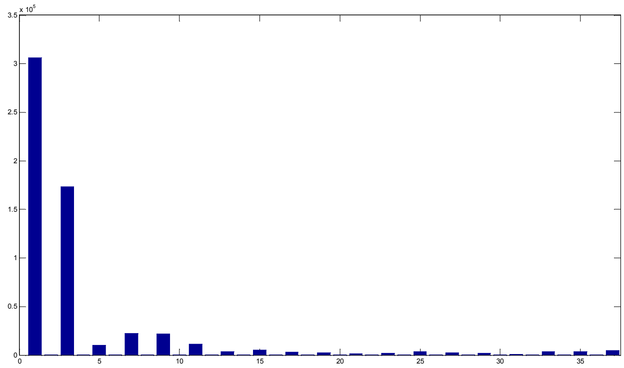

Fig.4 Amplitude of harmonic components

Decompose the radial spatial force wave with FFT. As can be seen in Figure 4, fundamental order's wave has larger amplitude, followed by 3 order's wave, while others are very small. Therefore we need to focus on these two kinds of order's waves.

V. Conclusions

This paper presents on an inverter-fed induction machine. The study offers guidance to the study of the effect of the loads on radial magnetic forces by FEM. Due to the content limit, the detail comparison and analysis will be given in full paper.

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