

Influence of Rotor Slot Wedges on Stator Currents and Stator Vibration Spectrum of Induction Machines: a Transient Finite Element Analysis.

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Abstract—The stator currents and stator vibration spectrum of a 45 kW 4-pole induction machine is computed using a transient 2D finite element analysis. The analysis is performed for two different rotor geometries: with open and with closed rotor slots. Open rotor slots increase the harmonic content of the airgap field, and also the harmonic content of the stator currents. Open rotor slots thus increase the stator vibration level for frequencies higher than 1 kHz.

Keywords—Rotating machine transient analysis, wedges.

I. INTRODUCTION

Closed rotor slots are usually applied for machines up to 250 kW. Larger machines have deep slender rotor bars, so that the permeance at the top of the rotor bar (i.e. the bridge permeance) is not that important. Closed rotor slots hold the rotor conductors in place and allow for easier diecasting and rotor surface machining. Closed rotor slots are also expected to partially eliminate the rotor slot harmonics, leading to less noise and less iron losses in the stator teeth tips [1,2]. However, since the rotor slot wedges (or bridges) saturate during rated operation, the question remains whether the presence of slot wedges will indeed significantly diminish noise and iron loss. This question is answered here using a transient finite element analysis of a 45 kW induction machine.

II. TIME-HARMONIC VERSUS TRANSIENT ANALYSIS

Time-harmonic finite element analysis of rotating electric machines can only capture phenomena at one particular frequency. The slip transformation enables us to find the fundamental electromechanical parameters of the machine. However, for this technique, the magnetic field is still solved for a rotor mesh that is stationary with respect to the stator mesh. Time-harmonic analysis can only correctly incorporate motion effects when the moving parts have a uniform geometry in the direction of motion, e.g. a rail or a slotless

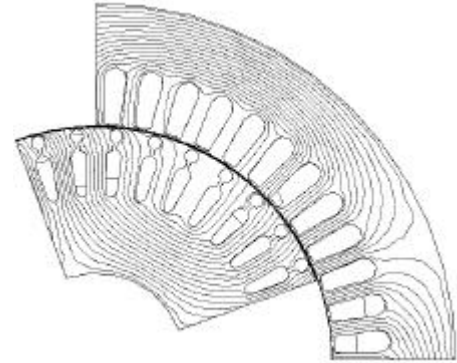


Fig.1 Magnetic field inside the induction machine for rotor position $\theta=20^\circ$.

rotor made of a single material. As a result, for an induction machine, the time-harmonic analysis with slip transformation cannot capture those field harmonics due to the motional eddy currents in the rotor [3]. Time-harmonic finite element analysis of rotating electric machines cannot therefore accurately represent the effects of geometrical rotor details, such as open or closed rotor slots, and can neither give any information about the current spectrum.

The transient analysis however provides the entire harmonic content of the stator current, within the limits of the transient model, e.g. mesh size and time step Δt . Here, assuming a sinusoidal voltage supply, the *transient* analysis is applied to two models of the induction machine with different rotor geometry: with open and with closed rotor slots. This comparison allows us to estimate the influence of rotor slot wedges on the stator current harmonic content and stator vibration spectrum. During steady-state operation, all electromagnetic and mechanical phenomena occur at various fixed frequencies. It is therefore possible to perform a frequency domain analysis based upon a set of samples taken from the time domain and computed using a transient finite element analysis.

III. CALCULATION OF THE STATOR VIBRATION SPECTRUM

For every time step of the transient analysis, the instantaneous magnetic field is used to post-process the reluctance forces acting on the stator teeth. Fig.1 shows the flux pattern for one pole of the 4-pole induction machine for a certain rotor position. Fig.2 shows the corresponding reluctance forces acting on the entire stator. The magnetic

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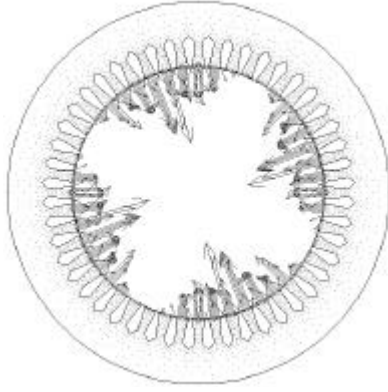


Fig.2 Force distribution acting on the stator teeth for rotor position $\theta=20^\circ$ calculated using (1).

forces (both Lorentz forces and reluctance forces) are obtained using [4]

$$\mathbf{F}_{\text{mag}} = -\frac{\partial W}{\partial \mathbf{a}} = -\int_0^A \mathbf{A}^T \frac{\partial \mathbf{M}(\mathbf{A}, \mathbf{a})}{\partial \mathbf{a}} d\mathbf{A} \quad (1)$$

where W represents the magnetic energy and \mathbf{a} represents the displacement or deformation. $\mathbf{M}\mathbf{A}=\mathbf{T}$ represents the magnetic finite element system: \mathbf{M} is magnetic stiffness matrix, \mathbf{A} is the vector of nodal values of magnetic vector potential and \mathbf{T} is the source term representing the current excitation. The mechanical finite element equation of motion of the stator structure is

$$\mathbf{M}_m \ddot{\mathbf{a}} + \mathbf{C}_m \dot{\mathbf{a}} + \mathbf{K}\mathbf{a} = \mathbf{f}(t) \quad (2)$$

where \mathbf{M}_m is the mass matrix, \mathbf{C}_m the damping matrix and \mathbf{K} the mechanical stiffness matrix. The reluctance force patterns are correlated to the stator mode shapes, giving the mode participation factors. Using the stator mode shapes, the equation of motion (2) is decoupled into a set of modal equations of motions that are then solved separately in the frequency domain. Superposing the modal response spectra

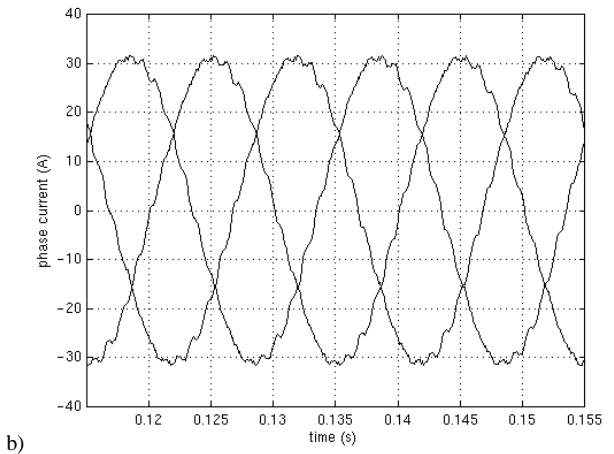
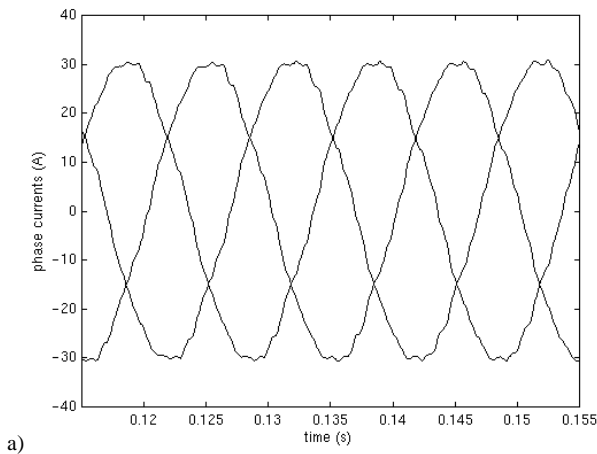


Fig.3 Three-phase stator currents for the induction machine with closed rotor slots (a) and open rotor slots (b).

then yields the total vibration spectrum of the stator. Details of transforming mode shapes and the reluctance forces acting on the stator teeth into the stator vibration spectrum are given in [4,5].

IV. EXAMPLE: 45 KW INDUCTION MACHINE

As a starting solution for the transient analysis, a time-harmonic solution for rotor position $\theta = 0^\circ$ is used. The time step of the transient analysis is $\Delta t = 0.113$ ms which is the time needed for the rotor to turn $\Delta\theta = 1^\circ$. Once the machine is in steady state, $T \setminus \Delta t \approx 355$ time steps are used to cover a time span of $T=0.04$ s. Each time step yields the instantaneous stator currents and flux pattern, which is converted into a reluctance force pattern using (1). In order to speed up the transient analysis, a quality mesh is constructed with as few elements as possible. The magnetic finite element mesh contains 8272 elements and one time step takes approximately 10 seconds of CPU time on a HP-B1000 workstation. The entire transient analysis thus takes approximately one hour.

The stator winding scheme of the induction machine can be interpreted as the parallel connection of two smaller machines with rated current $I = 23.5$ A for Y-connection, corresponding to a current amplitude of 33.2 A. Fig.3 shows the computed stator currents obtained for the rotor with closed slots (a) and open slots (b). For open rotor slots, there is more harmonic content in the stator current. Fig.4 shows the stator vibration spectra obtained for the rotor with closed slots (dashed line) and open slots (solid line). The difference between the two spectra is small below 1000 Hz, but substantial for higher frequencies.

From these results it can be concluded that the presence of rotor slot wedges indeed decreases the harmonic content of the stator current and the stator vibration spectrum. Fig.5a shows the rotor slot geometry for closed and open rotor slot. Fig.5b shows a typical flux pattern in the vicinity of the rotor bridge. Investigating the flux density in the vicinity of the rotor slots, it is seen that on the left side of the slot bridge the

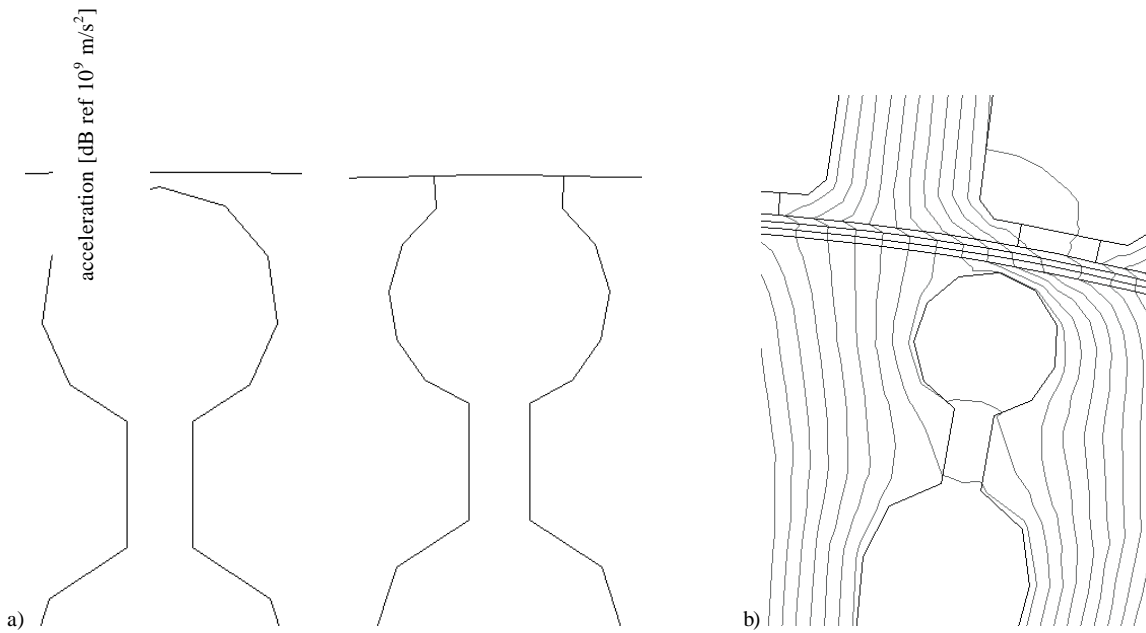


Fig. 5 a) Geometry of closed and open rotor slots, b) typical flux line pattern in rotor wedge vicinity.

flux density is relatively low (< 1 T), while the right side is in deep saturation (> 2.5 T). One side of the rotor bridge does saturate, but the other side does not. As a net effect, the closed slot rotor geometry yields *less* spatial rotor harmonics, leading to a lower level of stator vibration.

V. ROTOR HARMONICS

Rotor harmonics produce fields in the airgap at frequencies [1,6]

$$f_m^{rsh} = f_s \left(m \frac{N_r}{p} (1-s) \pm 1 \right), \quad (3)$$

where m is an integer, $N_r=36$ the number of rotor slots, $p=2$ the number of pole pairs, $s=0.01467$ the slip and $f_s=50$ Hz the supply frequency. For $m=1$, field harmonics at 837 Hz and 937 Hz are found. The corresponding force components are found at the double frequencies 1674 Hz and 1874 Hz as well as at the cross-term frequency 1774 Hz. The corresponding vibration components at 1674 Hz and 1774 Hz are clearly visible in Fig.4 (dashed line). These rotor harmonics are not captured by a time-harmonic analysis.

VI. CONCLUSION

When rotor wedges are present, one side of the rotor wedge does saturate, but the other side does not. As a result, the closed slot rotor geometry still gives less spatial rotor harmonics and less stator current harmonics. This leads to a lower level of stator vibration for frequencies above 1 kHz for the 45 kW induction machine. A transient finite element analysis is necessary to analyze this phenomenon because

time-harmonic models do not have the capacity to capture the full harmonic content of the magnetic field.

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