Analysis of Structure-Dynamic Behaviour of an Induction Machine with Balancing Kerfs

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***Abstract*— Any rotating mechanical part, for example rotors of electrical machines, with an asymmetric mass distribution in relation to the rotating axis generates un-balances. These un-balances result in centrifugal forces proportional to the square of the speed. The forces can charge the bearings with a not admissible mechanical load. Therefore, the rotors of electrical machines usually are balanced before mounting. Depending on the principle, balancing can affect the electromagnetic behaviour of an electrical machine in such an unfavourable manner that the machines operational behaviour is unacceptable. Here, an induction machine with squirrel-cage rotor with balancing kerfs in the rotor is regarded. The effect of balancing to the electromagnetic and structure-dynamic behaviour is studied.**

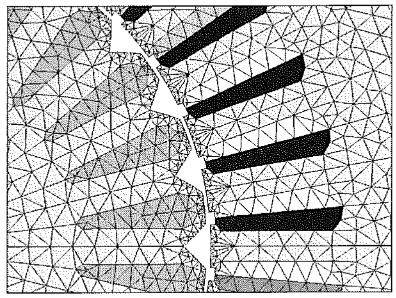


Fig. 2. FE-Model of IM with Worst-Case Balancing Kerfs.

I. INTRODUCTION

Balancing rotating machine parts, for example rotors of electrical machines, can be performed by various principles [1]. Depending on the mechanical part, its size and the space either mass is added on the opposite side of the rotor's unbalance (i.e. balancing of wheel rims on cars) or mass is removed at its location (often used for rotors of electrical machines). Here, an induction machine with squirrel-cage rotor (IM) is analysed which is balanced by removing mass. As Fig. 1 depicts, the mass is milled out of the iron of the rotor lamination on both ends of the rotor. In the series machine four neighbouring rotor teeth are affected on each side different from the prototype shown.

II. ELECTROMAGNETIC SIMULATION

In order to estimate the worst case the maximal balancing kerfs are considered for the electromagnetic, 2-dimensional Finite-Element (FE-)model (Fig. 2). As reference a model without kerfs is applied. Both models are simulated with a transient solver [2]. For each of the $N = 2056$ time steps simulated the flux-density distribution is provided. From this the torque and the surface-force density on the stator teeth are derived [3],[4],[5].

The analysis of the air-gap flux-density shows that the "balanced" model generates extra pole-pair numbers. The 4-pole IM now has odd numbers showing the dynamic eccentric impact of the balancing kerfs to the machine's behaviour. For the analysis of the torque the results of the two models are combined, since the balancing kerfs only affect a short axial portion of the rotor (about 17 % of the armature length). Therefore, the torque is averaged. 83 % are taken from the reference model and each 8.5 % of a model with kerfs depending on their location on the circumference. This results in a rather small impact to the torque behaviour decreasing the average torque by about 1.4 %. However, balancing results for the example machine in high net forces of about $F = 23\,\mathrm{N}$ acting onto the bearings. Due to symmetry the net forces of the reference model can be neglected.

As the analysis of the surface-force density on the stator teeth shows the balancing kerfs have some local effect to the force excitation of the IM. Fig. 3 depicts the surface-force density-excitation for the same stator teeth and the same time step for both models. It can be seen that the kerfs generate some extra force peaks and raise the amplitude of already existing. Since the kerfs rotate with the rotor these results in a modulation of the surface-force density-spectrum [3],[4].

III. STRUCTURE-DYNAMIC SIMULATION

In the next step the mechanical, structure-dynamic behaviour of the IM is studied to estimate the impact of the balancing kerfs. Therefore, a mechanical model is applied [6] which

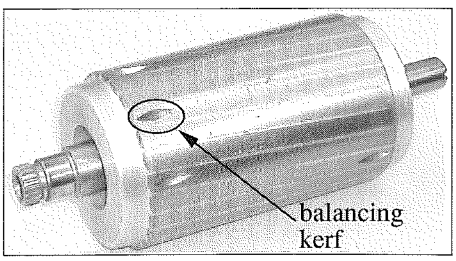
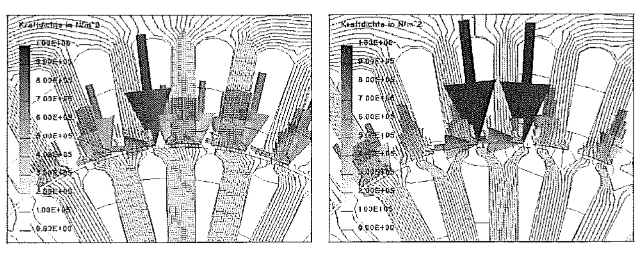


Fig. 1. Rotor of IM with Balancing Kerfs.



(a) Forces without Kerfs. (b) Forces with Kerfs.

Fig. 3. Surface-Force Density for Both Models at same Time Step.

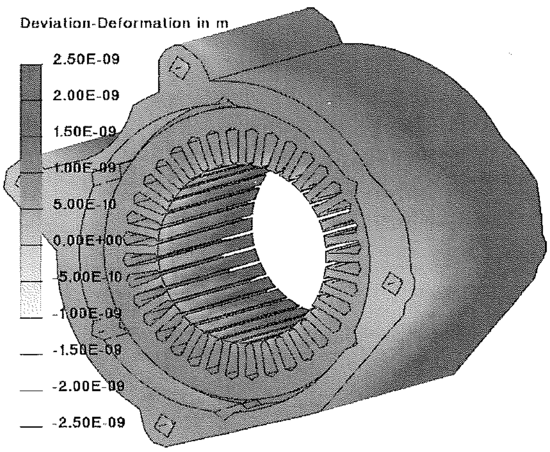


Fig. 4. Example: Deviation of the Deformation.

consists of all mechanical parts of the IM such as stator, rotor, shaft, housing, bearings, and housing caps. The IM is mounted on the front plate. Hence, the rear part of the machine can oscillate freely.

For the analysis of the vibrations of the IM the surface-force density derived from the electromagnetic model is transformed to the frequency domain and than for each regarded frequency to the mechanical model. Significant frequencies are the slot harmonics of stator and rotor. The rotor-slot harmonic is modulated with the double stator frequency. Finally, the rotor speed has to be considered due to the dynamic-eccentric effect of the balancing kerfs. The studied frequencies are: $f = 20$, 98, 422, 520, 618, 720, 942, 1040, and 1138 Hz. For these frequencies the force excitations of four different electromagnetic models are taken into account: reference model, model with kerfs only on front end of rotor, model with kerfs on rear end, and model with kerfs on both ends.

A. Deviation of the Deformation

In a first step the deviation of the deformation is analysed. Fig. 4 depicts exemplarily the difference of the deformation for $f = 1040\,\text{Hz}$ of housing and stator. Here, balancing kerfs on both ends of the rotor are compared to the reference model. Similar to a dynamic eccentric rotor the balancing kerfs result in higher deformation of the complete structure. Especially the rear (free) end of the IM oscillates stronger (dark regions in figure). Independent of which balanced model is regarded this effect is stated more or less.

B. Body-Sound Index

The second analysis scheme is the level of the Body-Sound Index L_{BSI}. The L_{BSI} is an integral value of the deformation of an entire body for instance the housing of the IM. For the nodes of all elements p of the body the normal component of the velocity of deformation $\vec{v}_p$ is summed up. The sum is related to the reference values $S_0 = 1\,\text{m}^2$ and $h_{U_0}^2 = 25 \cdot 10^{-16}\text{m}^2/(\text{s}^2)$ and the level is calculated:

$$L_S(f) = 10 \log \left(\frac{\sum_{p=1}^{N_{el}} \int_{S_p} |\vec{v}_p \cdot \vec{n}^p|^2 dS}{S_0 \cdot h_{U_0}^2} \right). \quad (1)$$

$\vec{n}^p$ is the normal vector of the element p, f is the frequency and N_{el} the number of elements. Therefore, the L_{BSI} allows for the evaluation and analysis of a body's entire deformation.

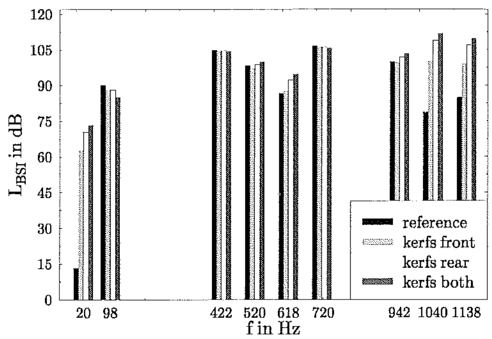


Fig. 5. Body-Sound Index of the IM's Housing.

The body sound of the housing can be transmitted to other parts of the mechanical construction i.e. the mounting. Therefore, the L_{BSI} of the housing is studied. Fig. 5 collects the results of the four models. Except for $f = 98$, 422, and 720 Hz the balancing kerfs rise the level of the body sound of the housing. Especially the higher orders at $f = 1040$ and 1138 Hz increase by up to 35 dB. For rotor speed at $f = 20$ Hz the level is increased up to 60 dB. But being very low for the reference model this order keeps smallest in the spectrum also for the balanced models.

C. Body-Sound Level

Finally, the Body-Sound level L_{BS} allows for local analysis of the vibration. The analysis of the L_{BS} shows a similar result. The levels for higher orders and for rotor speed increase strongly.

IV. CONCLUSION

As a result of the studies presented in this paper the analysed IM is no longer balanced. The resulting un-balanced fugal forces are smaller than the net forces produced by balancing. Without balancing the IM radiates less body-sound to the mechanical system and the IM is hardly excited at rotor speed. For this frequency the balancing kerfs result in strongly increasing body sound. At frequencies above $f = 1000$ Hz the body sound rises significantly as well. Further results will be discussed in the full paper.

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