Deformation Analysis of Induction Machines by means of Analytical and Numerical Methods

Christoph Schlensok, Dirk van Riesen, Michael van der Giet, Kay Hameyer
Institute of Electrical Machines, RWTH Aachen University
Schinkelstraße 4, D-52062 Aachen, Germany
Christoph.Schlensok@iem.rwth-aachen.de

***Abstract*— The estimation and calculation of the acoustic sound of electric machinery is of high interest. Various approaches have been presented relying either on analytical or on numerical models. In general, the analytical models are based on the electromagnetic-field theory and the results are compared to measurements. Numerical models allow for the separation of different exciting forces stemming from various effects. In the studied case of an induction motor (IM) with squirrel-cage rotor three effects are taken into account in the analytical model: the fundamental field, saturation, and eccentricity. Nevertheless, the numerical results have to be verified. Hence, they are compared to the physically based analytical results. The radiated noise depends directly on the surface's deformation of the machine. Therefore, the analysis is focused on the structure-dynamic vibrations. The combined analysis presented here, allows for the reduction of vibrations and noise optimizing the coupling of stator and housing. Its housing is mounted with six spiral-steel springs to the stator. With the presented method the impact of different numbers of pins is analyzed.**

I. Introduction

THERE have been several contribution to both, the analytical [1]-[3] and numerical [4], [5] approach of estimating the radiated noise of electrical machinery. A comparison as well as a combination of both methods allows for more reliable predictions and faster improvements of the machine's structure. In this paper an Induction Machine (IM) with squirrel-cage rotor is studied by means of analytical and numerical methods. At first, the applied models are introduced. In general, the structure of an IM is not purely cylindrical as the analytical models of [1]-[3] assume. Therefore, an add-on of the analytical model is presented. For comparison reasons different numerical Finite-Element (FE) models are introduced and results are analyzed.

II. Analytical Model

The analytical model [1] is based on the analysis of the force-wave behavior resulting from the normal component of the air-gap flux-density B_n depending on space x and time t:

$$F_r(x,t) = \frac{B_n^2(x,t)}{2\mu_0} \tag{1}$$

with μ_0 being the magnetic field constant. $B_n^2(x,t)$ results from the fundamental and harmonic field of the stator interacting with the induced fundamental and harmonic field of the rotor. Three major effects are considered in the analytical model: The fundamental air-gap field, the saturation

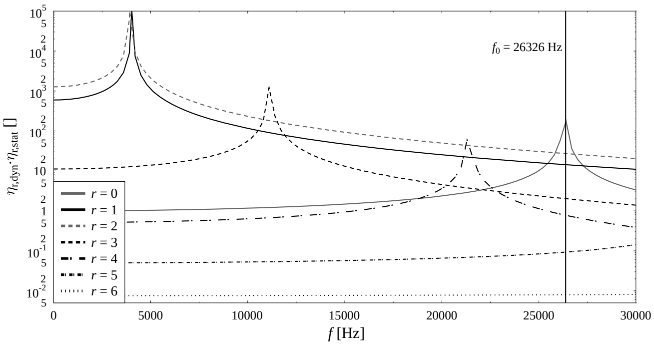

Fig. 1. Resulting factor $\eta_{stat} \cdot \eta_{dyn}(r)$.

of the lamination and static and dynamic eccentricity. Each harmonic, i.e. each exciting force-wave frequency, results in oscillating space modes along the circumference of the stator at the air gap. The mode numbers r depend on the origin of the interacting field components of stator and rotor.

Depending on the mode the structure of the IM shows different behavior and resonances. The analytical model of [1] distinguishes into static and dynamic deformation Y resulting in factors for both effects:

$$Y_r = \eta_{r,stat} \cdot \eta_{r,dynamic} \cdot Y_{0,stat}\,, \tag{2}$$

where $Y_{0,stat}$ is the static deformation of $r = 0$. Fig. 1 shows the resulting behavior of the factor $\eta_{stat} \cdot \eta_{dyn}(r)$. Each mode number r shows a resonance. Due to the small size of the regarded IM the resonance frequencies are high. For $r \geq 4$ they are beyond the human ear's hearing ability. Next to this the modes $r \geq 3$ produce small amplification factors throughout the spectrum. For the analysis of the studied machine, the spectrum is reduced to $f_{max} = 1200\,\text{Hz}$. Here, the entire range of frequencies shows nearly constant amplifications for all modes. Therefore, the analysis of the deformation is reduced to small mode numbers $r \leq 10$. In case there are even two modes at the same frequency, the amplification factor decides, which of whom is important and which is negligible.

III. Numerical Model

The Finite-Element model (FE) of the studied IM includes all mechanical parts of the machine as Fig. 2 shows. This complicated structure of the IM does not correspond exactly to the cylindrical analytical model. The simple model consists

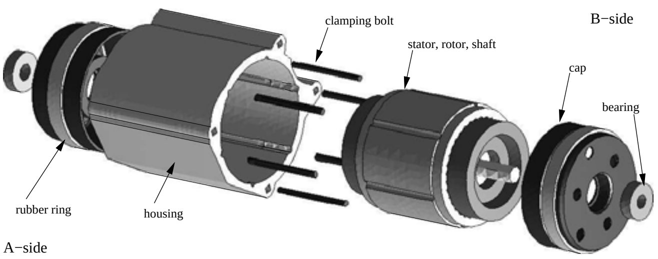

Fig. 2. Mechanical FE-model (exploded view).

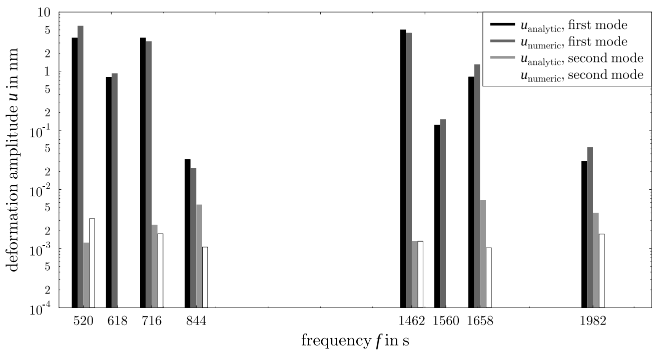

Fig. 3. Comparison of deformation amplitudes for models without housing.

of the stator with winding. The numerical model provides the deformation for all nodes of the Finite-Element FE-model. The solver takes Hooke's law into consideration [6]:

$$\sigma = H \cdot \epsilon\,, \tag{3}$$

where H is Hooke's matrix, ϵ the strain, and σ the tension.

IV. Results

At first the results of the analytical and numerical models without housing are compared. The deformation is analyzed by separating the modes r. By this, the impact of the mode number can be studied as well. Resuming the deformation values for some selected frequencies, Fig. 3 shows, that in the case of two significant modes of the exciting surface-force density the lower mode number has a significantly higher impact in any case. At $f = 844\,\text{Hz}$ for example, the mode numbers $r = 4$ and 8 occur, the latter having the higher force magnitude. Nevertheless, $r = 4$ reaches the higher deformation amplitude by a factor of 5.8. In general, if two modes appear the higher can be neglected. The only exception is the case of $r = 0$, which might produce lower deformation than $r = 1$ and 2. Next to this, Fig. 3 also states the very good accordance of the analytical and numerical models. Since the analytical model has been verified by measurements many times before [1] the numerical model is stated to be reliable.

Finally, the deformation is calculated for the machine model with the entire structure (Fig. 2) by exciting the housing with sampled forces at the locations of the steel springs. In doing so, the impact of different stator-to-housing couplings is analyzed. Three models are studied: A model each with 3 and 6 spiral-steel springs and one with a shrinked stator which is equivalent

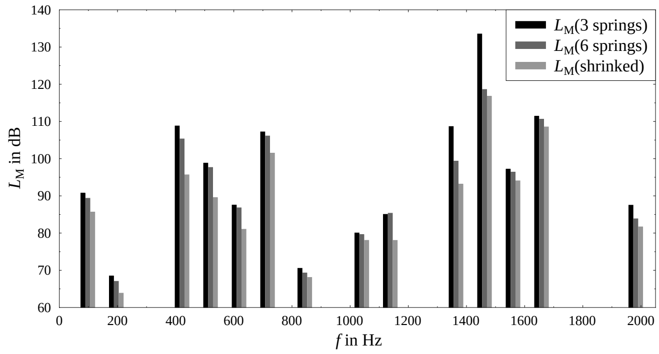

Fig. 4. Comparison of different stator-to-housing couplings.

to an infinite number of springs. From the comparison of the analytical and numerical models with 6 springs two effects can be stated: The first is, that the housing increasing the stiffness of the machine as an additional mass, i.e. the height of the cylinder ring increases, reduces the maximal deformation values. On the other hand, the aliasing effect results in smaller and additional mode numbers producing higher deformation. Both effects are detected. For example $f = 844\,\text{Hz}$ shows higher deformation values for the model with housing and six springs. This is due to the fact that the original mode number $r = 8$ is transmitted to $r = 1$ and 2. for $f = 520\,\text{Hz}$ the maximal deformation reached at mode $r = 2$ is reduced by more than $50\,\%$.

Fig. 4 shows the comparison of the three different stator-to-housing couplings applying the body-sound index L_M. It can be stated that for all analyzed frequencies the shrinked model results in lowest deformation and vibration. Therefore, this variant will produce the lowest noise radiation. The variant with 3 springs is worst and should be avoided.

V. Conclusion

The presented paper resumes the analytical theory of [1] and verifies the introduced numerical structure-dynamic model. The analysis of the deformational modes shows, that small mode numbers have the strongest impact by far. The coupling of housing and stator should either apply shrinking or and adequate number of spiral-steel springs. Further results will be discussed in the full paper in more detail.

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