Transient acoustic simulations of electrical drive-trains

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Introduction

During the first half of the 20th century, Jordan introduced the idea that the interaction of electromagnetic force density waves with the mechanical and acoustic characteristics of the machine is the key to understanding and solving the problem of audible noise of electric machinery. In [4], Jordan uses the rotating field theory and derives formulae for the occurring ordinal numbers of the rotating field waves, calculates the eigenfrequencies and forced vibration of stators, treated as thin rings and even approximates the radiated acoustic power level of induction machines. So far only grid connected motors are analysed. The numerical simulation of electromagnetic force excitations and of forced vibration as the outcome of structural simulation together presents a so called coupled problem. For speed variable drives, the coupling of the electromagnetic problem and a circuit simulator is for example studied in [5]. The proposed models are capable for the simulation of single operating points. Therefore the emphasis in this publication is on transient modeling of the electromagnetically excited forces. This paper proposes a methodology for the acoustic simulations of electrical drives including a permanent magnet excited synchronous motor applying two fundamental steps: drive simulation with force excitation and a transfer functions to assess the structural behavior and the radiation characteristics of the machine in a single procedure. Scope of the proposed approach is the acoustic simulation of electrical drives taking into account all relevant speeds and loads. The electrical drive model includes the power electronics, a digital control and the electrical machine. It is based on an enhanced dq-model [1]. The electromagnetic model allows for the speed and load dependent simulation of the exciting electromagnetic forces. The forces acting on the stator of the electrical machine are simulated in time domain and are decomposed by a spatial Fourier transform. The electromagnetic excitation can be simulated for arbitrary load spectrums. In combination with so called *FEM2measurement* transfer functions, which are based on an OTPA, the operational vibrations can be analyzed. All relevant steps for the simulation are discussed and applied to a specific permanent magnet synchronous drive. Fig. 1 shows the general concept of the proposed simulation model.

Transient drive model

The proposed electric drive model includes the power electronics, a digital control and the electrical machine. It is based on an enhanced dq-model [1]. It allows for the speed and load dependent simulation of the exciting electromagnetic forces. The forces acting on the stator of the electrical machine are simulated in time domain and are decomposed by a spatial Fourier transform. The electromagnetic excitation can be simulated for arbitrary load spectra. As an example a linear run-up from $n = 0 - 3000 \text{ min}^{-1}$ and a load step at constant speed ($n = 1000 \text{ min}^{-1}$) are presented. Based on the enhanced dq-model a transient model for the simulation of the electromagnetic forces acting on the stator in dependence of i_d, i_q and the rotor position is developed. This model enables the required steps for true speed and load variable simulations. Results of the electromagnetic simulation are shown in Fig. 8 - 5. The time response of the machine currents during run-up and a load-step are presented in Fig. 2(a) and 4(a) respectively. The displayed frequency amplitude and harmonic content are simulated based on the proposed model. As an example the electromagnetic forces for the discussed run-up and load-step are shown in Fig. 2(b) and 4(b). The excited motor orders and the PWM can be evaluated based on the proposed model. In order to evaluate the acoustic radiation, the excited forces are decomposed by a spatial Fourier transform. The force-waves with the ordinal number $r = 0, 8, 16, 24$ are relevant for the studied motor. As an example the force excitations of the ordinal number $r = 0, 8$ are shown in Fig. 3 for the run-up and in Fig. 5 for the load-step.

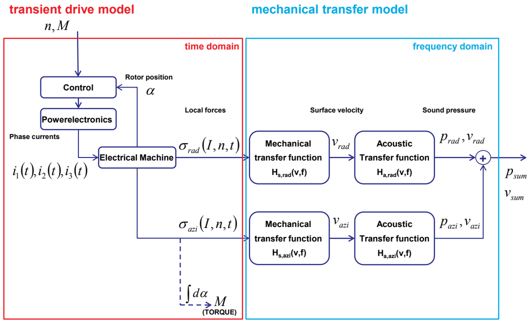
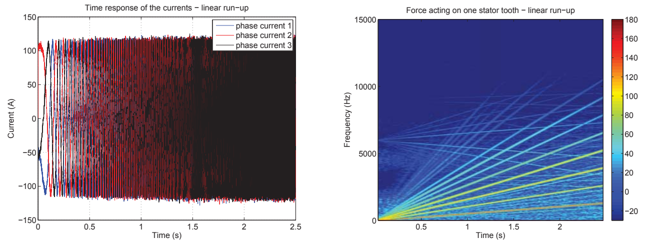


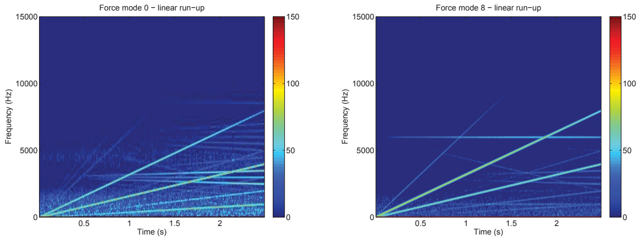
Figure 1: General concept of the proposed simulation modelGeneral concept of the proposed simulation model.



(a) Time response of the current during run-up.

(b) Spectrogram of the radial forces acting on one stator tooth.

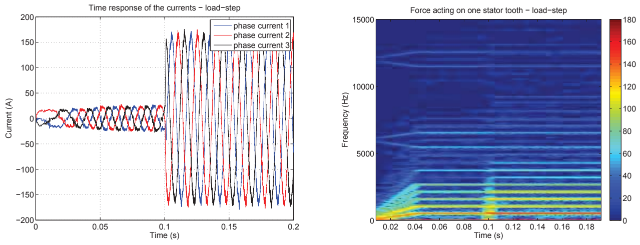
Figure 2: Time response of the current three phase currents and spectrogram of the electromagnetic force acting on stator tooth during run-up.



(a) Spectrogram of the radial forces of the circumferential mode $r = 0$.

(b) Spectrogram of the radial forces of the circumferential mode $r = 8$.

Figure 3: Spectrogram of the Fourier decomposition of electromagnetic forces acting on the stator during run-up.



(a) Time response of the current during load-step.

(b) Spectrogram of the radial forces acting on one stator tooth.

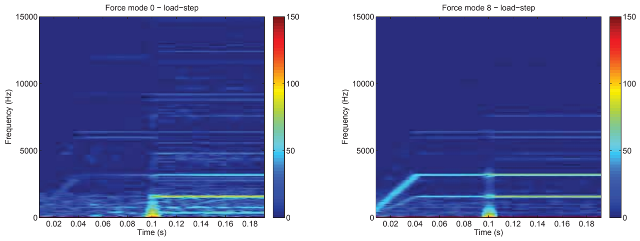
Figure 4: Time response of the current three phase currents and spectrogram of the electromagnetic force acting on stator tooth during load-step.

Mechanical transfer model

Theoretical background

In [2], Roivainen analyses the vibro-acoustic behavior of direct-torque-controlled (DTC) induction machines. A structural dynamic analysis based on simulated unit-forces-responses is performed. In [3] an application of the unit-forces-response is discussed based on measurements. The mechanical transfer function discussed is based on the so called *FEM2measurement* transfer functions. The idea of the *FEM2measurement* is based on [2], [3] and the OTPA approach. In comparison to the OTPA, the exciting forces are simulated instead of measured. To determine the frequency dependent transfer function of a system, the excitation with a well defined excitation signal, covering the frequency range of interest, is essential. In the case of an electrical machine, the forces under operation cannot be measured easily. Therefore simulated force excitations are assumed to determine the transfer functions. The general approach is shown in Fig. 6(a). When illustrating the surface velocity, during a run-up by means of a spectrogram, various lines indicating significant excitation can typically be observed. Each line corresponds to exactly one order but can be the result of force waves acting with different structural modes. If one mode predominates, the transfer function is determined by performing an order cut, i.e., extracting the amplitudes on the line, and dividing the resulting frequency dependent signal by the corresponding simulated force density. If more than one mode is significant, the procedure is slightly different. The problem can be formulated as

$$\begin{pmatrix} v_{o1}(\omega)\\ v_{o2}(\omega)\\ \vdots\\ v_{ok}(\omega)\end{pmatrix} = \begin{pmatrix} \sigma_{o_1,r=-n} & \cdots & \sigma_{o_1,r=0} & \cdots & \sigma_{o_1,r=n}\\ \sigma_{o_2,r=-n} & \cdots & \sigma_{o_2,r=0} & \cdots & \sigma_{o_2,r=n}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ \sigma_{o_k,r=-n} & \cdots & \sigma_{o_k,r=0} & \cdots & \sigma_{o_k,r=n}\end{pmatrix} \cdot \begin{pmatrix} H_{r=-n}(\omega)\\ \vdots\\ H_{r=0}(\omega)\\ \vdots\\ H_{r=n}(\omega)\end{pmatrix} \qquad (1)$$



(a) Spectrogram of the radial forces of the circumferential mode $r = 0$.

(b) Spectrogram of the radial forces of the circumferential mode$r = 8$.

Figure 5: Spectrogram of the Fourier decomposition of electromagnetic forces acting on the stator during run-up.

where $v_{oi}(\omega)$ denotes the measured velocity of order o_i, e.g., extracted from a spectrogram, σ describes the amplitude of the force density wave with order o and mode r and $H(\omega)$ represents the unknown transfer function. In this case equation (1) can be solved for the transfer function $H(\omega)$ as

$$\boldsymbol{H}_r(\omega) = \boldsymbol{\sigma}^+ \cdot \boldsymbol{v}_o(\omega) \qquad (2)$$

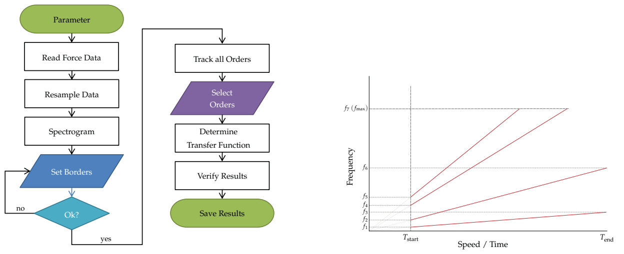
where $\boldsymbol{\sigma}^+$ is the pseudo inverse the of matrix $\boldsymbol{\sigma}$.

It is evident, that the number of tracked orders has to be at least equal to the number of different modes excited, otherwise the equation system is under-determined and cannot be solved. In other words, the rank of the simulated force matrix $\boldsymbol{\sigma}$ has to equal the number of occurring modes.

Fig. 6(b) shows a typical spectrogram to visualize the frequency ranges of the different orders. As can be seen, each order covers its unique frequency range. If there is only one mode significantly participating in the excitation of this order, the transfer function for this mode can be determined for the entire frequency range covered by the order. If, however, two or more modes are significant, more orders have to be combined in order to calculated the transfer functions. In this case, only the overlapping frequency range of the participating orders can be evaluated. The proposed approach thus divides the entire frequency spectrum into sub domains. As indicated in Fig. 6(b), the starting and ending point of each order indicate the beginning of a new frequency sub domain. The frequency range $f_1 - f_2$ is, e.g., only covered by the first order, whereas the range $f_2 - f_3$ is covered by both, the first and the second order and so on.

Application

As an example an automotive traction drive is studied. Fig. 7(a) shows the measured surface velocity during run-up at one arbitrary point on the surface of the housing. The electromagnetic forces acting on the stator for this exact test are calculated based on the previous described numeric simulation model. Applying (2) with the measured surface velocity and simulated forces

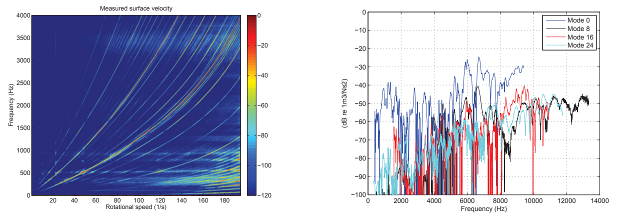


(a) General approach for the determination of the *FEM2measurement* transfer function.

(b) Frequency range of the determined *FEM2measurement* transfer functions.

Figure 6: Approach for the determination and frequency range of the *FEM2measurement* transfer function.

the transfer functions $H_r(\omega)$ are determined. The *FEM2measurement* transfer functions for the circumferential modes $r = 0, 8, 16, 24$ are shown in Fig. 7(b).



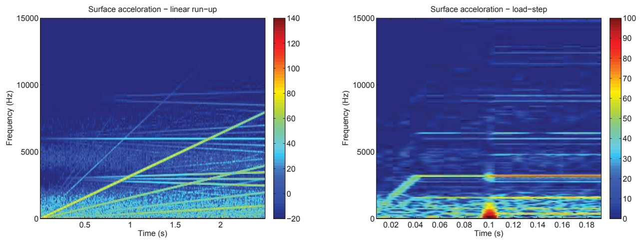
(a) Measured surface velocity during run-up.

(b) Estimated transfer functions.

Figure 7: Measured surface velocity during run-up and estimated transfer functions.

Results

As results of the combined transient drive and mechanical transfer model the simulated surface velocities for the described run-up and load-step are presented below. The influence of the current harmonics due to the control and PWM can be evaluated by the proposed model. Fig. 8(a) and Fig. 8(b) show the simulated spectrum of the surface velocity at one arbitrary chosen point on the surface of the housing during run-up and load-step respectively. The PWM frequency is chosen to be $f_{PWM} = 3k\text{Hz}$. The order cuts reveal the influence of the electromagnetic forces, the digital control and the power electronics. Furthermore, the eigenfrequencies of the mechanical structure can be seen.



(a) Simulated spectrogram of the surface velocity purely based on the proposed simulation model during run-up.

(b) Simulated spectrogram of the surface velocity purely based on the proposed simulation model during load-step.

Figure 8: Simulated spectrogram of the surface velocity purely based on the proposed simulation model.

In order to validate the proposed model, the simulated and measured sound power level of a run-up from standstill to $n = 3000\text{min}^{-1}$ is studied. Fig. 9 shows the comparison between measurements and simulation.

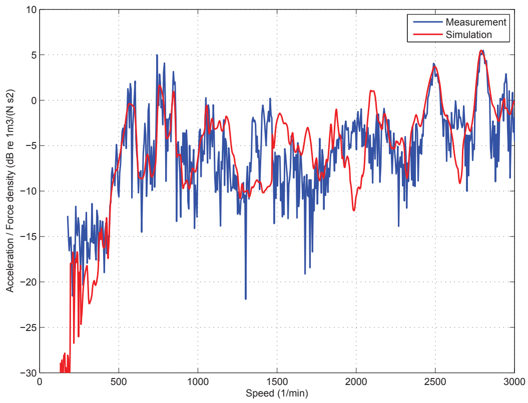


Figure 9: Simulated and measured sound reassure level during run-up.

Conclusions

A fully transient model for the simulation of the local forces acting on a stator of an electrical machine is presented. The transient model takes into account the discrete control, PWM, the exact geometry of the machine and the non-linear soft magnetic properties. In combination with so called *FEM2measurement* transfer functions the operational vibrations for transient duties can be analyzed. When simulating the mechanical transfer functions, this model can be applied for the acoustic optimization of electrical drives in the design stage. It was found that the harmonic content of the stator currents due to saturation and the feeding may have significant influence on the electromagnetically excited forces.

References

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