Frequency-domain analysis of electrical machine dimensions and material property uncertainties by finite-element

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This paper presents a method to reduce the uncertainties on a machine geometrical dimensions and material properties with electrical tests and simulated FE experiences. When performing mechanical measurements on an existing generator, we propose to reduce the possible uncertainties (air gap, slot dimensions, magnetic properties…) by performing the StandStill Frequency Response (SSFR) tests. Using the experimental signature, we complete the identification of main machine parameters with FEM simulations of the SSFR response. The SSFR test was chosen for its fast resolution in 2D magneto harmonic and detailed signature over a wide frequency range. This method is applied on a laboratory 5.4 kVA turbo generator. We test the influence of three parameters and present how the d and q operational inductances are influenced by these parameters. For the case at hand, the improvement of both responses is impressive.

***Index Terms*—AC Machines, Finite element analysis, Frequency response, Uncertainty, Parameter estimation**

I. INTRODUCTION

THE Finite-Element Analysis (FEA) of an existing electrical machine requires a precise knowledge of its geometry and material properties. When performing analyses on existing machines, the drawings and material properties are usually not available. The direct measurements of the mechanical dimensions are often hard to complete with high level of confidence on the measurements. This leads to uncertainties that may have large effects on the machine behavior. The FE method is very sensitive and allows the study of small imperfections [1]. To reduce these uncertainties, it is possible to proceed to additional electrical tests.

The StandStill Frequency Response (SSFR) test is a standard test used for the identification of simplified model parameters [2]. The SSFR is gaining interest in the industry since it is safe, easy to implement and can be carried during down-time [3]. It provides a continuous phase and amplitude response over a wide frequency range. The identified transfer functions using this method are well suited to create high order model. Application of the FE model to the frequency-domain is particularly efficient to speed up the simulations [4].

In this paper, we illustrate the combined use of SSFR tests with FE analysis in the frequency domain to reduce the uncertainties on a laboratory 5.4kVA turbo generator. This generator has three stator phases and four rotor poles with 24 copper damper bars (Fig.1). The damper bars can be unbolted from each short-circuit ring, thus the effect of contact resistance is not negligible. The stator slot tooth openings are very narrow (mean value measured 0.6 mm), and the mechanical air-gap is small (mean value measured 0.34 mm). These gaps are not uniform because of irregularities in the cutting and the assembly of laminations. As we will demonstrate, uncertainties on these parameters have a large effect on the electrical behavior. Magnetic properties of the laminations are also unknown.

We initially modeled the generator's cross section in a 2D FE software based on mechanical drawings and some measured dimensions. Initially, the simulated SSFR results deviated from measurements. We then carried sensibility studies on the most uncertain parameters in order to find the most appropriate set of values.

This paper briefly reviews the SSFR method. We then present a parameter sensibility study on the damper bars contact resistance, the magnetic permeability and the stator slot tooth opening. We present the effect of these parameters on the d-axis operational inductance response over a wide frequency range. Each parameter has a stronger influence over a specific frequency range. Finally, having adjusted the value of the air gap thickness, the best parameter values are compared with the experimental frequency response.

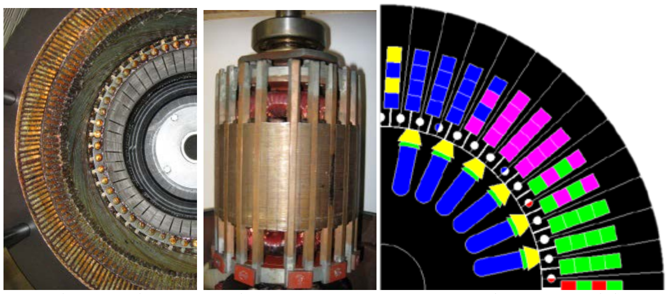

Fig. 1. Laboratory turbo generator (stator, rotor, and 2D FE model)

II. STANDSTILL FREQUENCY RESPONSE

In accordance with the SSFR procedure [2], the rotor is aligned along the direct or quadrature axis and two stator phases are fed in series, with a sinusoidal voltage. The frequency sweep range varies from 0.01Hz to 1 kHz. During the experimental test, the current level is kept low in order to avoid magnetic saturation. The current harmonics are negligible. In this work, we used three transfer functions: the direct-axis $L_d(s)$ and quadrature-axis $L_q(s)$ operational inductances and the armature to field transfer function G(s). For these transfer functions, the field winding is shorted.

Classical assumptions of time-harmonic magnetodynamic resolution are appropriate to solve the SSFR by FE method [5] : standstill rotor, time sinusoidal variation of quantities, quasi-steady-state regime, and linear magnetic permeability. It takes roughly 6 minutes to simulate the SSFR of this machine.

The resolution is very fast because the potential vector is solved in complex (frequency domain). The experimental tests take 3 hours to perform due to the low frequency points.

III. PARAMETER SENSIBILITY STUDY

The parameter sensibility study was carried on the d-axis operational inductance $L_d(s)$. It is noted that each parameter affects only a certain frequency range. Such observation could not be made using time-based analysis.

The lamination stack gave an uneven surface that made the gap for the stator slot opening hard to measure. It could range from 0.55 to 0.8 mm. Fig. 2 shows that varying the stator tooth opening has mainly an effect on the high frequency behavior. Induced currents in the short-circuited rotor are increasing with frequency and generate more stator leakage flux. The best-fit value compared to test data (not shown on Fig. 2) is 0.78 mm. It takes roughly 6 minutes to simulate one curve.

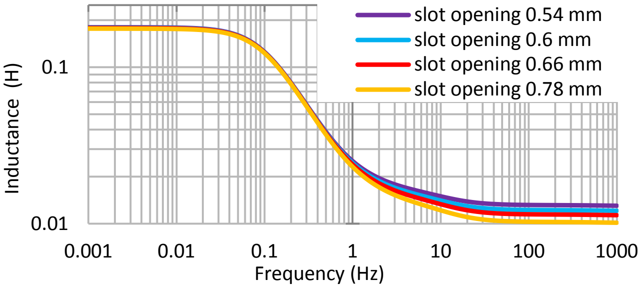

Fig. 2. Effect of slot opening on d-axis operational inductance magnitude

The low frequency inductance is influenced by the relative permeability of the magnetic material (Fig. 3). The air gap also has a strong influence on this frequency range (not presented).

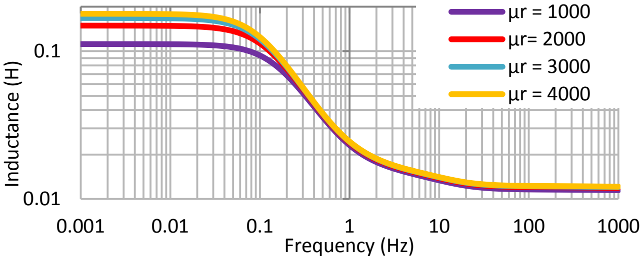

Fig. 3. Effect of permeability on d-axis operational inductance magnitude

We considered an equivalent resistivity for the damper bars to account for the contact resistance to the end ring. Modifying this parameter has an effect on middle range frequencies between 0.1 to 10 Hz (Fig. 4). We conclude that the skin effect does not influence the magnitude of d-axis operational inductance [6].

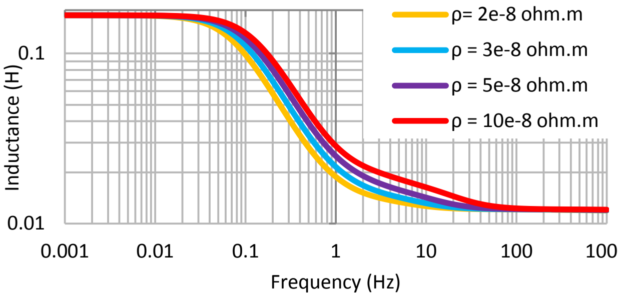

Fig. 4. d-axis operational inductance magnitude depending on resistivity

IV. VALIDATION OF THE PARAMETERS BEST VALUE

We apply an iterative method to identify the best value of the machine uncertain parameters. The initial guess and best values obtained from the sensibility study are given in table 1.

TABLE I

INITIAL AND FINAL MACHINE PARAMETERS VALUE

Parameter	Initial Guess	Best value
Air gap	0.34 mm	0.30 mm
Slot opening width	0.60 mm	0.78 mm
Relative permeability	3000	4000
Damper bars resistivity	15.6 nΩ.m	100 nΩ.m

Fig. 5 and Fig. 6 show that the FE model frequency response over the entire range is significantly closer to the measured data than the initial guess. The improvement is even more evident on the q-axis operational inductance (Fig. 6). These parameters have a considerable effect on the transient behavior such as the sudden short-circuit. It will be discussed in the final paper.

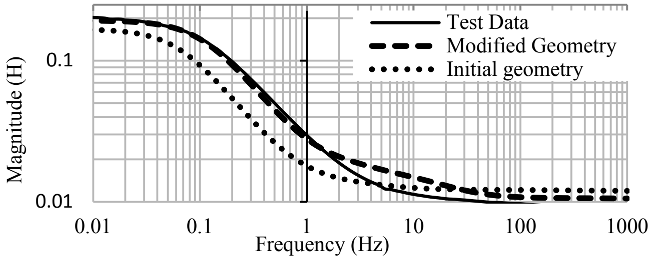

Fig. 5. Comparison of d-axis operational inductance magnitude for initial and modified geometry to test data

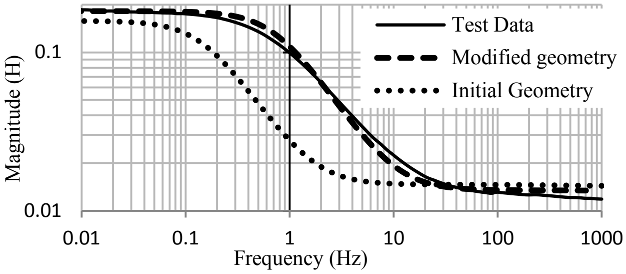

Fig. 6. Comparison of q-axis operational inductance magnitude for initial and modified geometry to test data

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