New method for experimental modal analysis of hydrogenerator's stator core using the excitation from the Poles

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Abstract: The study of stator core vibrations generated by electromagnetic forces in electrical machines is of great practical and theoretical interest. An important part of the problem is the correct determination of mode shapes and eigen frequencies of the mechanical system. This work brings to discussion a new experimental modal analysis (EMA) method developed for synchronous machines in which the traditional instrumented hammer impulse is substituted by a magnetic pulse generated by currents applied in two poles. Experimental results obtained in a real 190 MVA hydrogenerator are shown.

1 Introduction

A suitable evaluation of stator core vibrations brings benefits for reliable design of new machines and also for proposing solutions on existing machines with stator core vibration issues. One approach that can be adopted for this evaluation is based on decomposition of the electromagnetic forces and core response into the mechanical system mode shapes [1–3]. The electromagnetic data are applied as input in harmonic analysis of a 3D stator mechanical model; however, the accuracy of the results may not be enough in some cases since the effective material properties of the stacked core laminations and influence of complex parts such as stator frame and foundation are hard to be predicted.

For performing a precise analysis, it is mandatory to calibrate the mechanical model in terms of eigenmodes and frequencies to properly take into account the stator core material properties and the influence of the stator frame (including foundation support). Several experimental techniques are available and potentially capable to contribute with the experimental identification of the modal parameters of a stator. A very well-known experimental modal analysis (EMA) method is based on the structure's excitation through an impulsive loading (i.e. using an instrumented hammer) that allows a calculation of a frequency response function (FRF), providing them the actual structure's mode shapes and eigen frequencies [4, 5].

Due to a lack of physical access to the impact application points given by constructive characteristics of a stator core, the magnitude of the generated impulse may be insufficient to produce measurable structural response, especially at very large hydrogenerators. In this context, the authors present an alternative EMA method developed for synchronous machines in which the traditional instrumented hammer impulse is substituted by a magnetic pulse generated by currents applied in two poles as shown in Fig. 1.

One advantage of the proposed method is that the impulsive force can be adapted during the tests by changing the magnitude of the excitation current applied to the pole winding. Another consequent advantage relies on the fact that the mechanical impulse generated by the hammer excites many modes that are not relevant for the stator vibration phenomenon. The excitation generated by the poles provides a radial force distribution which is similar to the one corresponding to a typical operational condition.

This method was successfully applied in a real 190 MVA (~11 m diameter, 72 salient poles) hydrogenerator. The main findings during the method development, experimental setup, and tests results are presented on this work as well as the results from a conventional EMA with instrumented hammer and final calibration of a numerical calculation model.

2 Fundamentals of EMA

Conventionally, the EMA is categorised by the excitation source used during the tests. The most common are the shaker excitation and hammer excitation. Due to the size and configuration of the structure of a generator stator core, normally the tests using hammer excitation are applied.

In this kind of test, the structure is excited in different locations by an instrumented hammer while the vibration response is measured in a few fixed accelerometers. These accelerometers normally stay in the same position during the test for as much as the structure is excited in different points, one by one. For each excitation, it is possible to determine a transfer function, or frequency response function (FRF), based on the evaluation in...
First, a conventional approach was applied in order to determine models, which states that the transfer function is equal when you generated by currents applied in 2 of machine poles.

The EMA analysis uses the reciprocity property of modal models, which states that the transfer function is equal when you apply the excitation in the point A and evaluate the response in the point B or vice-versa (excitation in B and evaluation in A). So for N points of excitation and M points of evaluation, the FRFs can be considered as a M × N matrix \([4]\). The evaluation of all the obtained FRFs gives the structure’s natural mode shapes and frequencies.

In order to achieve the best results in the FRFs, the duration of the impact should be the minimum value as possible. For an ideal impact (when the time duration tends to zero), the FFT of the response signal will be proportional to the FRF itself.

### 3 Details of tested machine

Experimental tests were taken on a real hydrogenerator with characteristics summarised in Table 1 below.

| Table 1 Hydrogenerator main characteristics |
|---------------------------------------------|
| rated output                                | 190 MVA |
| rated voltage                               | 13.8 kV |
| rated frequency                             | 60 Hz   |
| power factor                                | 0.9     |
| number of salient poles                     | 72      |
| stator core outer diameter                  | 11 m    |
| stator core length                          | 2.27 m  |
| core yoke radial height                     | 141.5 mm|
| rated excitation current                    | 2005 A  |

### 4 Conventional hammer excitation EMA results

First, a conventional approach was applied in order to determine the natural frequencies and modal shapes of the stator core using a hammer excitation EMA test. Due to constructive characteristics of the stator core and its dimensions, they were select 200 bumping points divided into five different axial levels. It was used an instrumented hammer of 2 kg and eight accelerometers of 100 mV/g, and each point was measured three times.

However during the post-processing, it was found that the energy transferred to the structure with the bump was not enough to excite the modes of interest. Some examples of typical found responses are shown in Figs. 2–4.

Fig. 2 shows that the excitation was fast enough to theoretically excite modes until 400–500 Hz; however, Fig. 4 showed no abrupt transitions on the phases indicating that no natural frequency was found. In Fig. 3, it was shown the FFT results for several bumps in the same accelerometer and in all analysis it was not found clear vibration peaks. It was then concluded that the conventional hammer-based EMA test was not able to define the natural frequencies or mode shapes of the structure.

### 5 New proposed EMA

After the unsuccessful of the hammer-based campaign, a new test was proposed. The main idea of the method is to substitute the traditional instrumented hammer impulse by a magnetic pulse generated by currents applied in 2 of machine poles.

The current flowing through the pole field windings will generate magnetic field distribution \(B_i(t, r)\) along the angular position \(\theta\) in the machine air gap proportionally to the current magnitude at each time instant \(t\). In fact, the field will also be influenced by induced currents on the pole damper windings, stator winding parallel circuits, and Foucault currents on iron parts; however, these effects can be assumed in first approximation to be also proportional to the pole field winding current itself, resulting that field distribution remains practically proportional to this same current.

Assuming as approximation that the field has only radial component in the air gap and that the ferromagnetic materials have infinite permeability, a magnetic radial pressure distribution \(\rho(\theta, t)\) acting on the core face will be generated as consequence and can be derived from the Maxwell stress tensor \([6]\) as:

\[
\rho(\theta, t) = \frac{B_i(\theta, t)}{2\mu_0} \tag{1}
\]

The mechanical impulse magnitude can then be assumed to be proportional to the square of the field current impulse. Therefore, the measurement of this current during the test can play the role of the acceleration signal obtained from the conventional instrumented hammer, which will be necessary to recover the structure’s FRF.

Since the magnetic field distribution can be assumed to be uniform along the axial direction, so the magnetic pressure distribution also is. This characteristic brings the desirable consequence that only ‘axially symmetrical’ mode shapes are excited (those that are in fact excited by the electromagnetic forces during the machine normal operation) and then the identification of relevant mode shapes becomes much easier. The difficulty of identifying relevant mode shapes among all the excited modes by a conventional hammer have already been reported in literature \([7]\).

The idea of exciting only two poles is to have existing forces as concentrated as possible (as it happens with a hammer), so that the greater number of circumferential mode shapes can be excited. Similarly, it is also necessary to guarantee that the current impulse duration is short enough to excite a wide range of natural frequencies, which is a big challenge faced to the set-up equipment limitations.

Finally, the various necessary impulses at different locations (as described in item 2) can be obtained by changing the angular position of the two excited poles and repeating the current impulses. This can be achieved by manually rotating the complete rotor, for instance.
5.2 Test set-up and procedure

It is proposed a test with a fully standstill machine as detailed below. The treated case refers to a machine with field current supplied through slip ring and brushes.

• Accelerometers are installed in the outer core diameter at different axial positions.
• Field winding and damper winding electrical connections between the two poles to be used and the others must be opened as shown in Fig. 1. The two poles used are those connected directly to the slip ring terminals. Finally, the other two field terminals of the used poles are connected through a cable so that they stay in series.
• The circuit terminals that will feed the two poles are connected directly to the slip ring, while all the brushes are disconnected.
• The circuit responsible for generating the current pulse is detailed represented in Fig. 5. It consists basically of: a rectifying diodes bridge; a DC circuit breaker with controlled command coil; a limiting series resistor; a discharge resistor with free wheel diode; and measurement signals of pole current and voltage.
• All the measurement signals are registered together within an acquisition system.

During the time that the circuit breaker is closed, the complete circuit can be resumed to a series RL circuit with poles equivalent inductance (including damper winding effect etc.) fed by a DC-voltage supply. The current will increase proportionally to \( \frac{1-e^{-t/\tau}}{R_1} \), where the time constant \( \tau \) depends of the relation \( L/R_2 \). The resistance \( R_2 \) is chosen to guarantee that current decay will be sufficiently fast.

With that, the control of peak impulse current and impulse duration can be achieved by varying the time delay command to open the circuit breaker and also by varying the series connected resistance, what can be done during the tests until a suitable adjustment is figured out.

During the time that the circuit breaker is opened, the current closes through the free wheel diode and the circuit can be resumed to a parallel RL circuit with poles equivalent inductance. The current will decrease proportionally to \( e^{-t/\tau'} \) where the time constant \( \tau' \) depends of the relation \( L/R_2 \). The resistance \( R_2 \) is chosen to guarantee that current decay will be sufficiently fast.

It is worth to highlight that, in fact, the real circuit can be described by a more complex transfer function with several time constants; however, the simplification to an equivalent time constant is enough for understanding of the application discussed here.

After circuit resistances and circuit breaker time delay command are adjusted, a current impulse command is given with the machine at standstill and the acceleration and field current measurement signals are registered together. This procedure is repeated for different rotor positions.

Fig. 6 illustrates the real set-up used for the 190 MVA machine.

5.3 Experimental results and numerical model calibration

For the real example case of a 190 MVA machine presented here, a total of 25 impulses were given at different rotor angular positions. The graphs in Figs. 7–10 show the result for one single impulse in time and frequency domains as example.

The current impulse reached a maximum peak of \( \sim 1150 \text{ A} \) during the tests, what corresponds to 57% of the machine-rated excitation current.

The FRF is obtained dividing the accelerometers frequency domain spectrum by the current square spectrum. Based on the FRF results from all the 25 impulses, the mode shapes and frequencies shown in Table 2 were obtained. Due to limitation of

Fig. 5 Current impulse generating circuit

Fig. 6 Real set-up example

Fig. 7 Time signals (accelerometer on the left and current square on the right)

Fig. 8 Accelerometer signal in frequency domain

Fig. 9 Current square signal in frequency domain

Fig. 10 Obtained mode shapes examples (mode of order 2 on the left and order 3 on the right)
the circuit breaker time response to actuate, the duration of the impulse could not be shorter than \(\sim 0.1\) s, so the modes with higher eigen frequencies than those in Table 2 were not sufficiently excited.

With these results, it was possible to calibrate a 3D numerical model of the stator. The agreement between measurements and calibrated model is represented in Figs. 11 and 12.

6 Conclusion

An alternative new method for EMA in synchronous machines stator core was proposed and validated on a real 190 MVA hydrogenerator. The main advantages are the possible adjustment of impulsive force magnitude and duration during the tests (by changing the magnitude and duration of the excitation current applied to the pole winding) and the excitation of only relevant mode shapes due to the uniformity of the distributed load generated by the poles along the axial direction.

Future work could consist of the optimisation of test set-up and theoretical detailing of test dimensioning.

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8 References

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Table 2 Obtained modes and eigen frequencies

| Mode order (n° of node pairs) | Eigen frequency, Hz |
|-----------------------------|---------------------|
| 2                           | 22                  |
| 3                           | 28                  |
| 4                           | 36                  |
| 5                           | 42                  |
| 6                           | 53                  |

Fig. 11 Stator numerical model illustration

Fig. 12 Comparison between measurements and calibrated model