# CASE STUDY OF OPERATIONAL MODAL ANALYSIS (OMA) OF A LARGE HYDROELECTRIC GENERATOR

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## ABSTRACT

In the context of a study of existing generators' power increase, full instrumentation was installed on several high-power hydro-generators (> 60 MW). Some vibration measurement and analysis bases on FFT analysis were presented last year at CMVA annual symposium [1]. These results also included the measurements of the Operating Deflection Shape (ODS) to illustrate the dynamic motion of the stator during operation of the hydro-generator unit. This presentation will focus on the Operational Modal Analysis (OMA) of a high-power hydroelectric generator using a vector autoregressive ARMA model, employed in a short time manner in order to identify and survey the monitoring of excitation frequencies and modal parameters. A mode classification technique is developed for the discrimination of the most excited electromagnetic harmonics from natural frequencies and spurious modes. This discrimination allows for the monitoring of close modes, the frequency response function spectrum and of the operating deformation shapes due to electromagnetic excitations. The conclusion of these temporal analyses will be compared with standard FFT spectrum analysis.

Key words: Operational Modal Analysis, Vibration, Hydro-Generator, Power Increase

## 1. INTRODUCTION

This case study is part of a project on the power increasing on large hydroelectric generators (> 60 MW) [1, 2, 3]. Evaluating the response of the stator to the electromagnetic loading is an arduous task since the power generator is a complex multi-physics system which requires interaction and exchange within mechanics, electromagnetisms, thermo and fluid dynamics. Since analyzing the vibration signal permits the modal identification and the comparison to the anticipated frequencies of mechanical and electromagnetic loads, operational modal analysis has been conducted. This paper presents vibration monitoring of the generator using standard FFT analysis, Operating Deflection Shape (ODS) [1, 5] and Operational Modal Analysis (OMA) [4].

## 2. TEST DESCRIPTION

A newly refurbished high power generator was selected for the test. General specifications of the generator are given in Table 1. Figure 1 shows a picture of the generator stator during refurbishing. The vibration instrumentation on the stator is installed at the back of the magnetic core when the hydroelectric group is stationed in order to be compliant with the applicable safety

rules. Because of the large dimension of the stator which has a circular form, 16 accelerometers have been distributed on a section of stator core in order to capture mode shapes in both radial and axial directions (Figure 2). Due to the limits of the data acquisition system, three series of measurements have been conducted by using each time a common sensor at a reference location and measurements have been realized at 46 locations (3×15+1). The global mode shapes were therefore extrapolated from the symmetry of the stator (Figure 3).

**Table 1: Generator characteristics**

| Characteristics | Parameters |
|---|---|
| Total power (winter/summer) | 150,6/112,6 MVA |
| Power factor | 0.9 |
| Rated power (winter/summer) | 135,5/110,3 MW |
| Rotation speed | 120 rpm, 2,0 Hz |
| Poles number on rotor | 60 |
| Notches number on stator | 504 |
| Outer diameter of rotor | 10.59 m |
| Inner diameter of stator | 10.62 m |
| Air gap | 15.9 mm |
| Rotor height | 1.7 m |

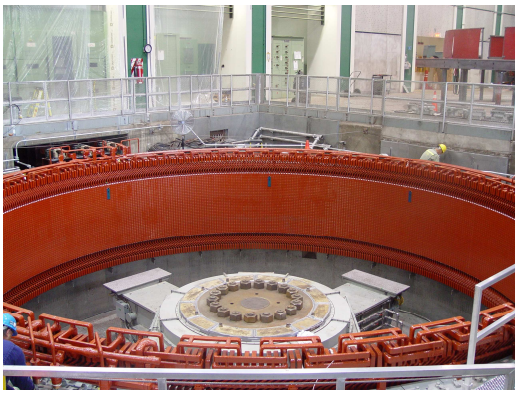

**Figure 1: Stator during refurbishing.**

**Figure 2: Accelerometers on stator.**

In order to evaluate the dynamics parameters of the machine, measurements were conducted when the generator was operated in three working conditions. Tests were performed at three powers of the generator: 71% of the summer rated power (110MW), 100% and 123% in steady regimes. The electromagnetic excitation and structural modes were identified.

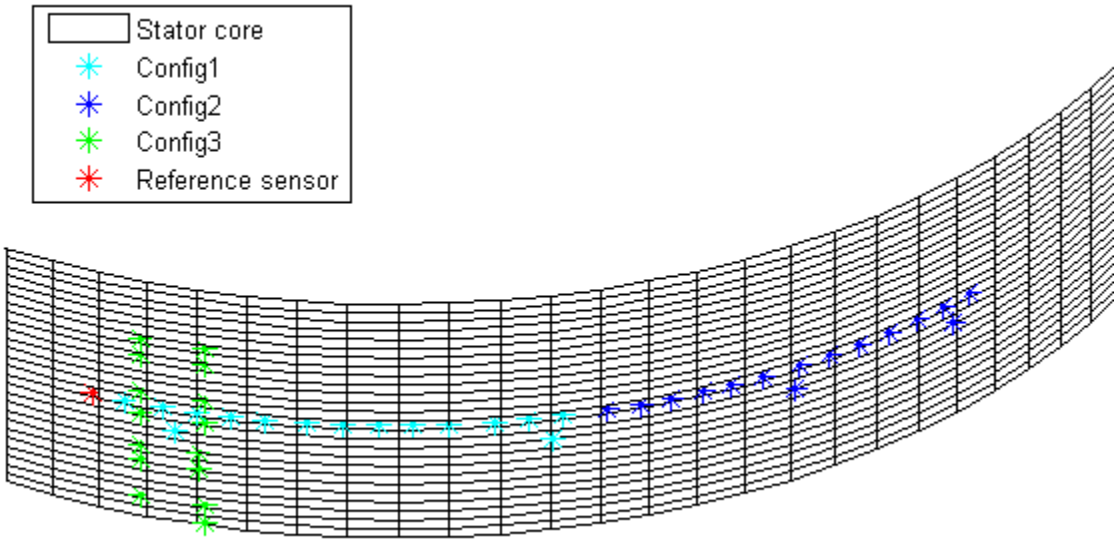


**Figure 3: Sensor configuration of the stator**

## 3. RESULTS AND ANALYSIS

This section will present the results an analysis from the different vibration analysis tree methods available:

- Standard FFT analysis [1, 2, 3]
- Operating Deflection Shape (ODS) [1, 5]
- Operational Modal Analysis (OMA) [4]

The technical and theoretical aspects of these measurements and analysis methods are well described in the literature and the above references, so we will emphasize the measurement results and their analysis.

### 3.1 Standard FFT analysis

In previous work, a methodology for the analysis of the standard FFT vibration analysis was developed. It allowed us to:

- Determine the stator displacement in regards to acceptance vibration limits.
- Find the vibration peaks for a specific sensor and a specific operating condition.
- Find the common excitation frequencies between the peaks for different sensors and for the same operating condition.
- Follow the evolution of one or more excitation peaks for a specific sensor and a different operating condition.

The application of the analysis methodology allowed us to determine that the stator vibration at 120 Hz was much lower than the 15 μm limit on the stator core. In fact, the calculated displacement from the acceleration measurement showed a maximum of 2.8 μm at the measurement points for operating power of 123% of the nominal. This situation shows that the power increase is not limited by the 120 Hz vibration.

The following table (Table 2) presents typical results of the average vibration level for the first configuration of accelerometers at the operating condition of 100% of the nominal power. These peaks in $m/s^2$ are presented for the stator and the stator frame (carcasse).

**Table 2: Vibration peaks stator 100% (110 MW)**

| Amplitudes de vibration ($m/s^2$) pour le stator et la carcasse en fonction de chaque condition d'opération (classé par amplitude décroissante au stator) | | |
|---|---|---|
| **Fréquence Hz** | **Moyenne stator** | **Moyenne carcasse** |
| 960 | 0.526 | 0.095 |
| 120 | 0.268 | 0.142 |
| 1080 | 0.173 | 0.127 |
| 1920 | 0.088 | 0.071 |
| 480 | 0.075 | 0.054 |
| 600 | 0.070 | 0.038 |
| 360 | 0.070 | 0.046 |
| 60 | 0.049 | 0.088 |
| 240 | 0.048 | 0.066 |
| 1200 | 0.047 | 0.035 |
| 1320 | 0.040 | 0.024 |
| 840 | 0.039 | 0.061 |
| 1440 | 0.035 | 0.043 |
| 1800 | 0.031 | 0.009 |
| 1020 | 0.022 | 0.021 |
| 1560 | 0.022 | 0.046 |
| 934 | 0.020 | 0.012 |
| 720 | 0.016 | 0.010 |
| 1084 | 0.015 | 0.019 |
| 1680 | 0.014 | 0.006 |
| 1040 | 0.013 | 0.006 |
| 2040 | 0.011 | 0.012 |
| 1140 | 0.009 | 0.009 |

| Fréquences (Hz) des pics sur le stator et la carcasse (par amplitude décroissante) | |
|---|---|
| **Moyenne stator** | **Moyenne carcasse** |
| 960 | 120 |
| 120 | 1080 |
| 1080 | 960 |
| 1920 | 60 |
| 480 | 1920 |
| 600 | 240 |
| 360 | 840 |
| 60 | 480 |
| 240 | 1560 |
| 1200 | 360 |
| 1320 | 1440 |
| 840 | 600 |
| 1440 | 1200 |
| 1800 | 1320 |
| 1020 | 1020 |
| 1560 | 1084 |
| 934 | 2040 |
| 720 | 934 |
| 1084 | 720 |
| 1680 | 1140 |
| 1040 | 1800 |
| 2040 | 1680 |
| 1140 | 1040 |

### 3.2 Operating Deflection Shape (ODS)

The ODS use several accelerometer measurements on the stator magnetic core and one reference accelerometer for relative amplitude and phase. This method allows an animated display of the

machine or structure's operating deflection shapes that are often very helpful. In most cases, structural responses at or near a resonant (modal) frequency are "dominated" by the mode, and the ODS closely approximates the mode shape [6]. The ODS can also allow visualization of the forced response of the structure. The modal superposition theorem shows the response *Y* versus the modal parameters as in equation (1):

$$Y(\omega) = F(\omega) \sum_{i=1}^{n} \frac{\phi^T \phi}{(\omega_i^2 - \omega^2) + (2\xi_i \omega_i \omega) j} \qquad (1)$$

where:

*Y* is the displacement vector of the structure;
*F* is the force vector applied on the structure;
$\phi_i$ and $\omega_i$ are respectively the vectors of the modal deformation of $i^{th}$ mode and the $i^{th}$ natural frequency of the structure;
T denotes the transposed vector;
$\xi_i$ is the damping of the $i^{th}$ mode;
and finally ω is the frequency of the applied force.

Typical results from the frequency identification methodology show the difference in the stator vibration signature for a 122.6 MVA generator as in Figure 4. As showed in Table 2 and Figure 4, the vibration content of the stator consists principally of harmonics of the even multiple of the electric fundamental frequency (120 Hz, 240 Hz, …) but we also see the presence of additional frequencies that may be associated with mode shapes.

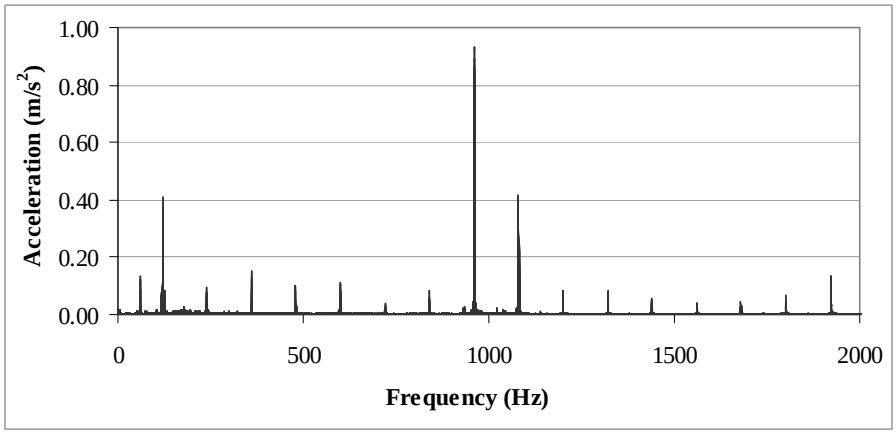


**Figure 4: Radial acceleration on stator at rated output conditions (122.6 MVA)**

The stator ODS allows the identification of some excitation such as this 960 Hz deflection (Figure 5) that is moving clockwise and matching a dominant calculated electromagnetic excitation from the simulations (Figure 6). In this case, the mode shape has 24 nodes and is corresponding with the excitation of mode 24 of the electromagnetic simulation. This allows us to consider that this mechanical mode has a frequency close to the 960 Hz electromagnetic excitation. The ODS analysis and mode identification as to be extended to all other frequencies

of interest, such as 1080 Hz, also recorded during on site measurements. This allowed confirming the electromagnetic model of the generator.

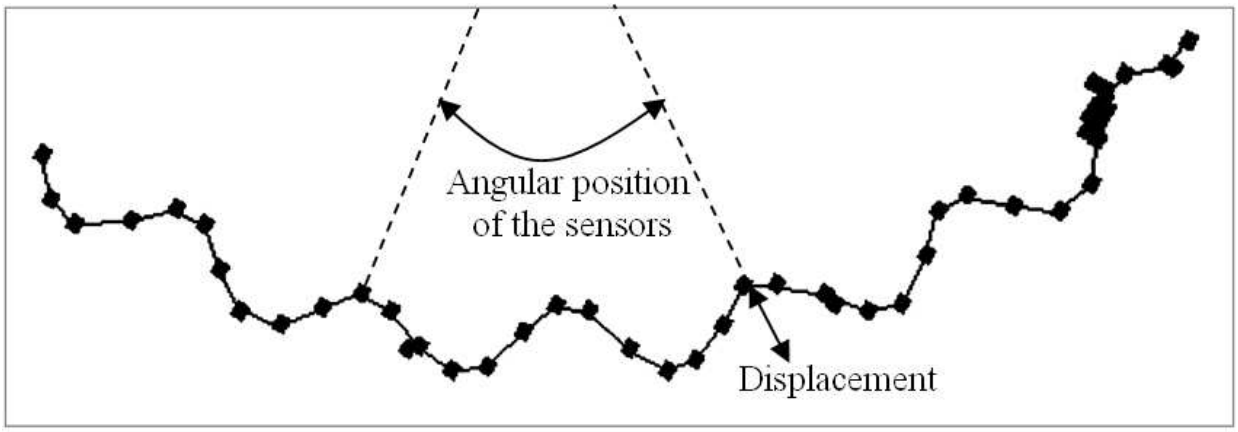


**Figure 5: ODS of the stator from a typical generator at 960 Hz, n=24, measured on 90° of the outer radius of the lamination (radial displacement not to scale)**

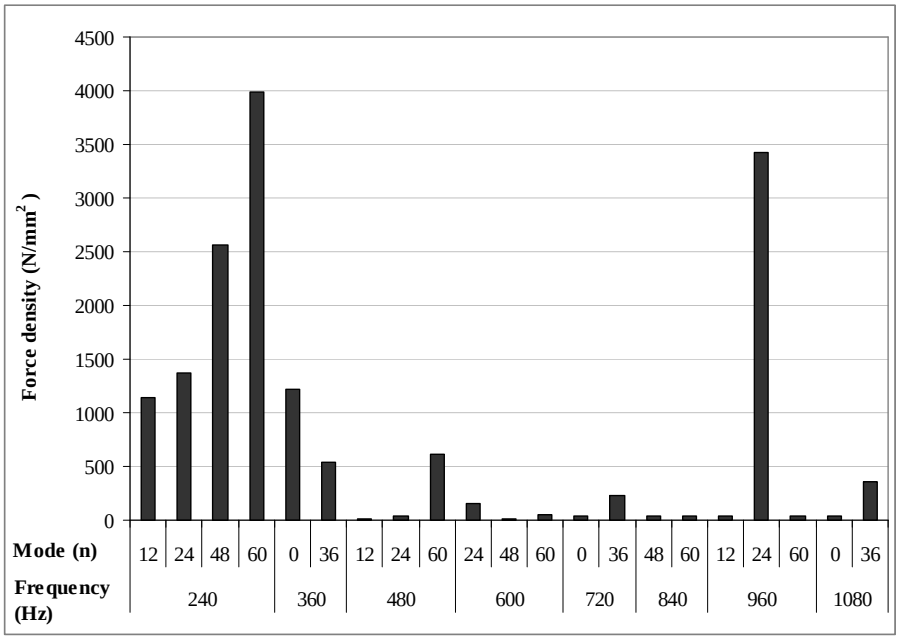


**Figure 6: Force density of electromagnetic excitation versus frequencies and mode number (excluding the 120 Hz for graph scaling purpose)**

### 3.3 Operational Modal Analysis

The vibration response data were recorded in steady state working conditions. Spectral analysis and operating deflection shapes (ODS) methods were first conducted. Operational Modal Analysis (OMA) was used in the time domain using the application of the multivariate autoregressive model. This ARMA autoregressive model represents a relationship between the output dynamic responses to the unknown excitation via the handling of modal parameters and the modal residue. This method is described in several references [4, 7]. The method was programmed (called GENERATORMODAL) in an adapted software for large hydroelectric generator. The advantage of the method is that excitation frequencies, resonance frequencies and structural damping can be obtained along with mode shapes using only the vibration response of the structure. This is an advantage of the method in comparison to frequency domain modal analysis methods because the excitation force of a large structure like a hydroelectric generator stator is not an easy parameter to measure.

The generator was first operated at its nominate power (100% capacity at 110MW). Figure 7 displays the stationary vibration response data of all accelerometers within one second.

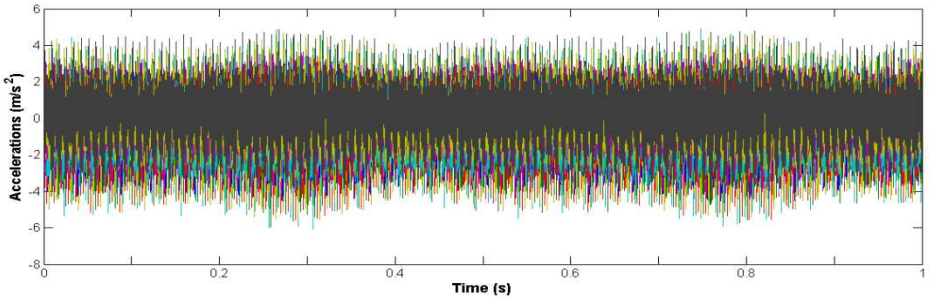


**Figure 7: Stationary data at 110 MW.**

By applying the model updating up to order 30, one can observe the evolution on the frequency stability diagram (Figure 8) where all frequencies start to be stable from order 7, computed from a Noise-rate Order Factor (NOF) [7].

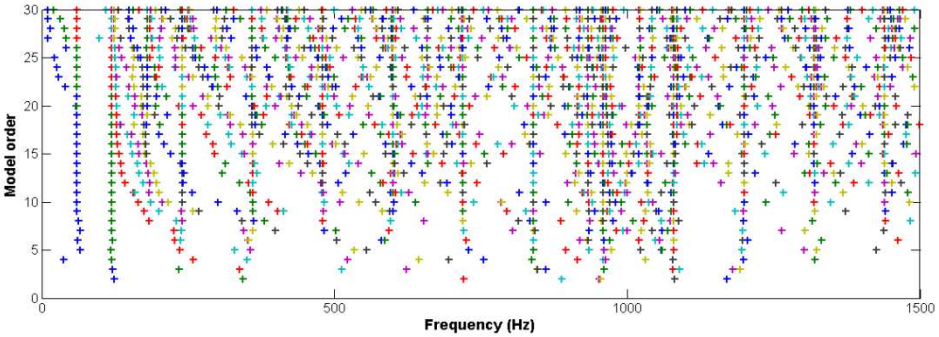


**Figure 8: Frequency stability of stator at 110MW.**

Figure 9 represents the classification of modes by the DMSN and corresponding damping rates. It is seen that there are about 25 frequencies hidden inside the data included electromagnetic harmonics and natural frequencies.

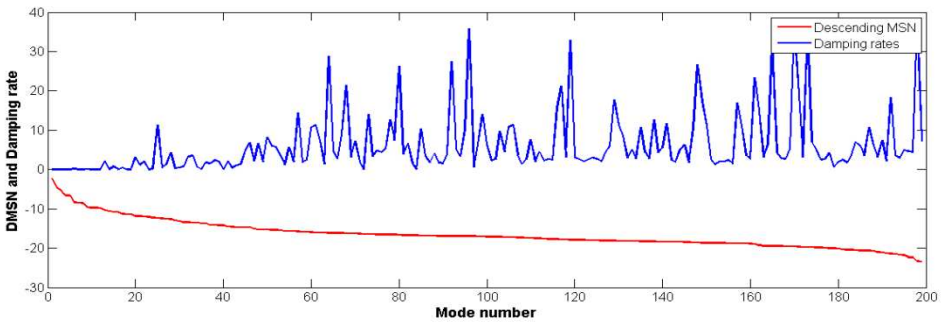


**Figure 9: Determination of number of frequencies.**

Those peaks can be seen on the display of the spectrum on Figure 10.

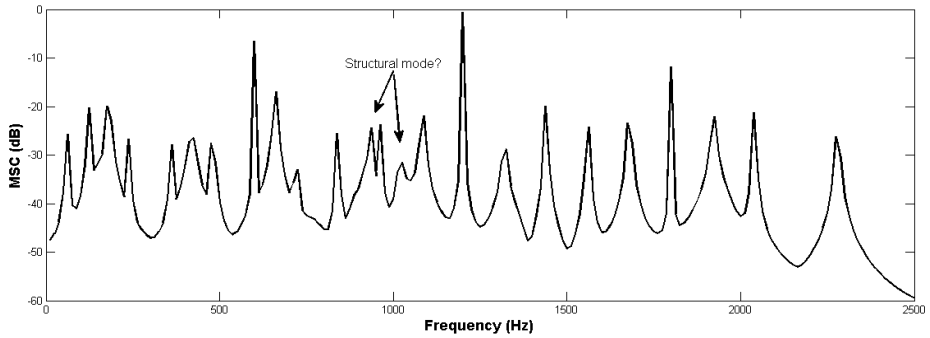


**Figure 10: Stator spectrum at 110MW.**

Table 3 presents the identified frequencies and damping ratios classified in the descending DMSN index. The harmonic frequencies are corresponding to zero-closed damping rates. According to the electromagnetic analysis, the sources of those harmonics, which are even multiples of the electric fundamental frequency of 60 Hz, are related to the electromagnetic excitations.

In order to evaluate the effect of power of the generators, the machine has also been run at 78 MW (71% of the nominate power) and at 134 MW (123% of the nominate power), and the modal identification has been performed on all these operation conditions. It is also found that the electromagnetic harmonics are present at multiples of 60 Hz. The dominant harmonic frequencies, with the highest power amplitudes and which are multiple of 60Hz, are found at 960 Hz, 1080 Hz, 840 Hz, 1920 Hz and 120 Hz.

After eliminating spurious frequencies, three structural modes have been identified in the measured range as summarized in Table 4. It is revealed that the second and third modes are

found close to the harmonic excitations of 960 Hz and 1080 Hz, which explains why these excitations are dominant on the frequency map.

**Table 3: Identification of frequencies at 110MW operation condition**

| DMSN index | Frequency (Hz) | Damping rate (%) | Possible source |
|---|---|---|---|
| 1 | 960 (16 x 60) | 0.0 | Electromagnetic excitation |
| 2 | 1080 (18 x 60) | 0.0 | Electromagnetic excitation |
| 3 | 840 (14 x 60) | 0.0 | Electromagnetic excitation |
| 4 | 1920 (32 x 60) | 0.0 | Electromagnetic excitation |
| 5 | 120 (2 x 60) | 0.0 | Electromagnetic excitation |
| 6 | 60 | 0.2 | Electromagnetic excitation |
| 7 | 720 (12 x 60) | 0.0 | Electromagnetic excitation |
| 8 | 600 (10 x 60) | 0.0 | Electromagnetic excitation |
| 9 | 360 (6 x 60) | 0.0 | Electromagnetic excitation |
| 10 | 1800 (30 x 60) | 0.0 | Electromagnetic excitation |
| 11 | 1200 (20 x 60) | 0.0 | Electromagnetic excitation |
| 12 | 480 (8 x 60) | 0.0 | Electromagnetic excitation |
| 13 | 942.5 | 2.1 | Spurious frequency |
| 14 | 1320 (22 x 60) | 0.0 | Electromagnetic excitation |
| 15 | *1042.2* | 0.8 | *Structural frequency* |
| 16 | 240 (4 x 60) | 0.0 | Electromagnetic excitation |
| 17 | *963.4* | 0.5 | *Structural frequency* |
| 18 | 1440 (24 x 60) | 0.0 | Electromagnetic excitation |
| 19 | 2040 (34 x 60) | 0.0 | Electromagnetic excitation |
| 20 | 956.4 | 3.1 | Spurious frequency |
| 21 | 955.7 | 1.2 | Spurious frequency |
| 22 | 968.1 | 2.1 | Spurious frequency |
| 23 | 1560 (26 x 60) | 0.0 | Electromagnetic excitation |
| 24 | *933.5* | 0.2 | *Structural frequency* |
| 25 | 149 | 11.2 | Spurious frequency |

**Table 4: Identification of modal parameters at three operation conditions**

| Frequency (Hz) | | | Damping rate (%) | | |
|---|---|---|---|---|---|
| 78 MW | 110 MW | 134 MW | 78 MW | 110 MW | 134 MW |
| 934.1 | 933.5 | 933.7 | 0.3 | 0.2 | 0.2 |
| 973.7 | 963.4 | 976.6 | 1.3 | 0.6 | 0.7 |
| 1043.1 | 1042.2 | 1041.4 | 1.1 | 0.8 | 0.6 |

With the availability of modal mode shapes, Figure 11 displays the mode shapes of the three identified structural modes on the measured area of the stator core from radial angle $6.6^{o}$ to $70.5^{o}$ and on 1.4 m height. The number $n$ and $m$ represent the estimated number of waves on circular and vertical directions respectively, which are considered as mode orders. It is seen that those mode shapes represent the complexity of the modal deformation with respect to the natural frequencies.

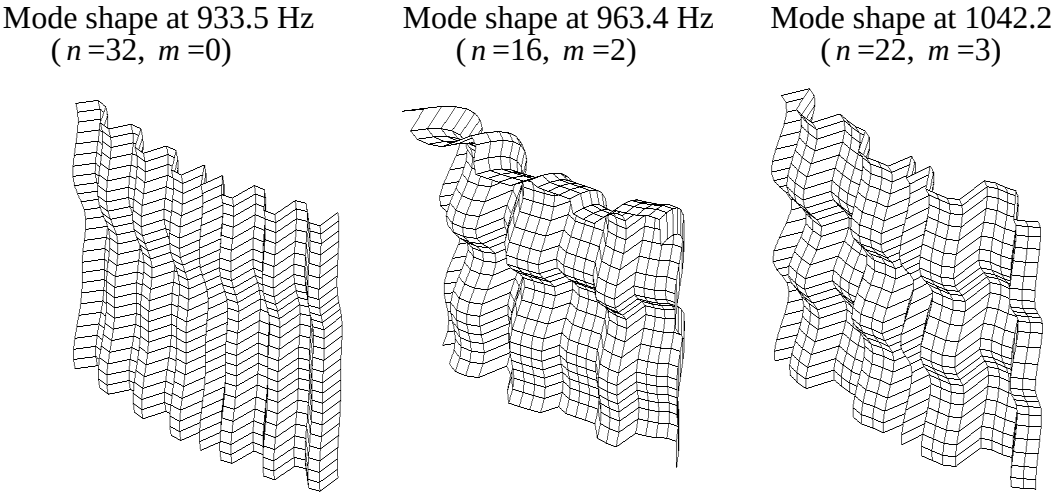


**Figure 11: Identified mode shapes of stator.**

The OMA analysis allowed identifying the structural mode shape (frequencies, damping and shape) around the major excitation on 960 Hz and 1080 Hz. This is very helpful in establishing the mechanical model of the generator. The concordance with the FFT and ODS results are good. The OMA was not able to confirm the ODS results about the 960 Hz deflection (Figure 5) that is moving clockwise showing that the two methods are complementary.

## 4. CONCLUSION

The vibration analysis of a large generator was performed using different analysis methodologies including classical FFT and ODS. These analyses permitted to identify the stator displacement compliance and the correspondence with the 24 node mode shape of electromagnetic simulation. Operational modal analysis (OMA) has been conducted on large scale structures such as hydro-electrical generators. When the excitation is unknown, the vector-autoregressive model allows for fitting the data in order to identify the modal parameters among a large number of harmonics. It is found that this method can identify and distinguish accurately the electromagnetic harmonics and structural modes from the spurious modes, even when a structural mode lies closely to a harmonic frequency. The method can also evaluate the dominance of each individual frequency on the vibration map and evaluate them without the availability of an analytical model. All the methodologies used were in good accordance and complementary. Future research on non-stationary vibration responses in the transient regime is in progress.

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