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BSI Standards Publication

Rotating electrical machines —

Part 32: Measurement of stator end-winding vibration at form-wound windings

National foreword

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Rotating electrical machines –
Part 32: Measurement of stator end-winding vibration at form-wound windings

INTERNATIONAL
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COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ROTATING ELECTRICAL MACHINES –

Part 32: Measurement of stator end-winding vibration at form-wound windings

FOREWORD

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Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60034-32, which is a Technical Specification, has been prepared by IEC technical committee 2: Rotating machinery.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
2/1810/DTS	2/1849/RVC

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

NOTE A table of cross-references of all IEC TC 2 publications can be found on the IEC TC 2 dashboard on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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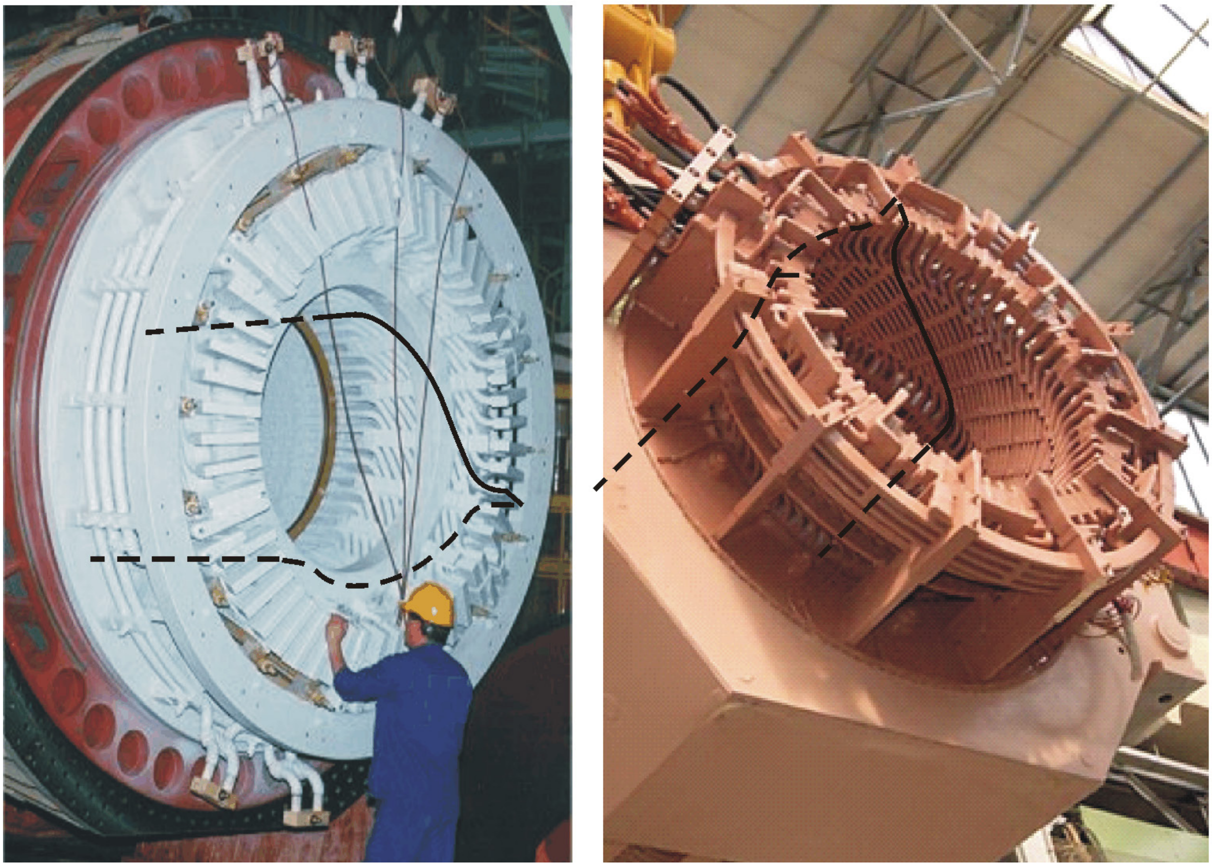
INTRODUCTION

Large alternating current (AC) machines are equipped with multiphase stator windings. The information in this document is based on a dual-layer design. Such windings are connected to a multiphase voltage system (multiphase current system), which establishes a rotating magnetic field in the air gap between the rotor surface and stator bore. The voltage and current can vary during operation in order to adapt to varying mechanical load. Electrical machines are normally designed for motor or generator operating mode. The majority of AC machines are equipped with symmetrical three-phase windings, consisting of three, electrically isolated, spatially distributed winding parts that are intended for common operation.

Large AC rotating electrical machines are typically equipped with form-wound windings consisting of form wound coils (as defined in IEC 60034-15:2009, 2.3), single winding coils (single winding bars) which are given their shape before being assembled into the machine.

The winding overhang, or end-winding, is the portion of the stator winding that extends beyond the end of the magnetic core and is, in most cases, formed as a circular cone, see some examples in Figure 1 below.



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NOTE Individual coil end marked with black line.

Figure 1 – Stator end-winding of a turbogenerator (left) and a large motor (right) at connection end with parallel rings

The majority of large AC machines with form-wound stator windings are equipped with a stator end-winding support structure. Among other functions it is expected to withstand the high electromagnetic force loading when the machine is exposed to an electrical fault in the electrical supply system. This includes a fault in the supply lines of an electrical grid or in an electronic supply device. In many cases the stator end-winding support structure is not only designed to increase the structural strength, but also provide appropriate structural stiffness and inertia to systematically influence structural dynamics and thus the vibration level during operation.

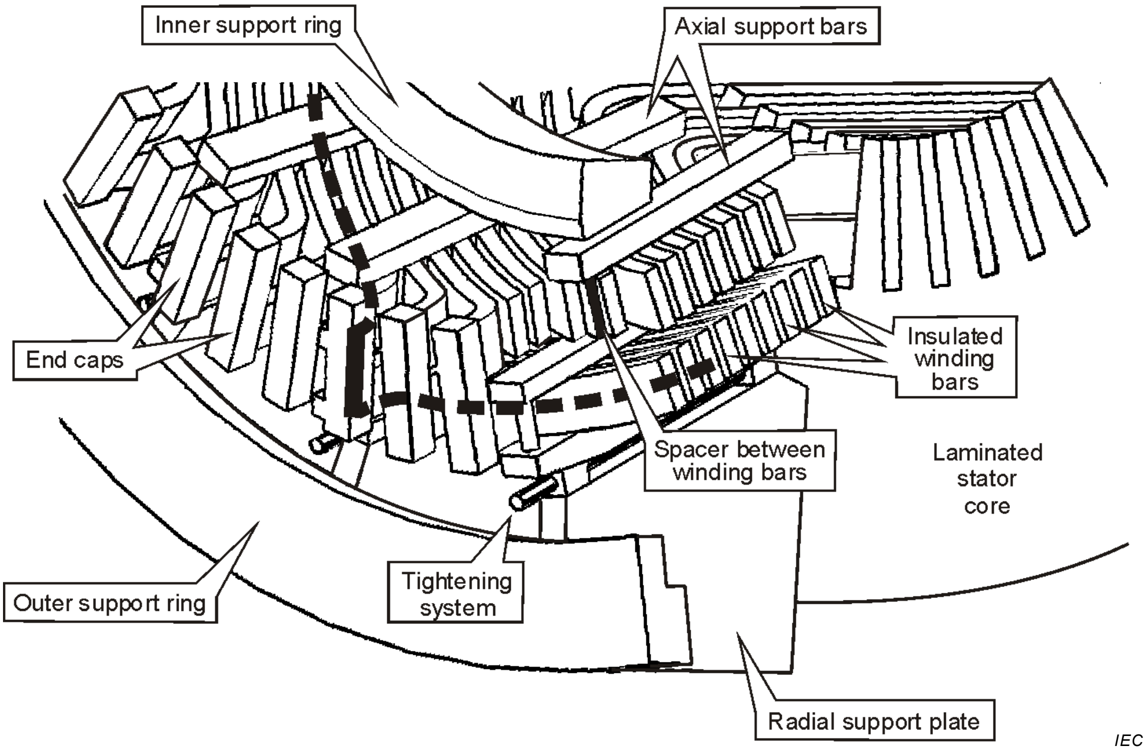


Figure 2 – Example for an end-winding structure of an indirect cooled machine

Typical support elements are plates and rings, which support the end-winding cone as a whole. Moreover, the distance between coils (or bars) of the end-winding are defined by spacing elements and their positions are fixed by fastening components. The typical materials used for support elements, spacers and fasteners are composites containing glass fibre materials as well as resin impregnated felts, cords and bandings (see Figure 2). Also, high electrical fields surrounding metal parts could produce electrical discharges compromising long term electrical strength.

Until now there existed no general Technical Specification to get reliable and comparable results for the identification of natural frequencies during stand-still and for vibration behaviour of stator end-windings during operation.

The experimental modal analysis of stator end-windings is a well-established tool which has also been used for the verification of natural frequencies and mode shapes of large electrical machines worldwide. The goal is to avoid operation of the machine with increased end-winding vibration levels under the influence of natural frequencies. Measurement of transfer functions and identification of structural dynamic properties (e.g. natural frequencies, mode shapes and other modal parameters) with an impact test is a common testing procedure. It is applied to new machines by the manufacturer and also used as a maintenance tool by the user or contractor during a major overhaul of large rotating machines.

Operational measurement of vibrational behaviour of stator end-windings can be performed by the installation of special vibration transducers at selected end-winding locations for periodic measurements or permanent on-line monitoring.

Although measurements of natural frequencies and vibration levels of stator end-windings are well established techniques, the interpretation of results is still a matter of further improvement and development. Therefore this first edition is a Technical Specification and not an International Standard.

ROTATING ELECTRICAL MACHINES –

Part 32: Measurement of stator end-winding vibration at form-wound windings

1 Scope

This part of IEC 60034 is intended to provide consistent guidelines for measuring and reporting end-winding vibration behaviour during operation and at standstill. It

- defines terms for measuring, analysis and evaluation of stator end-winding vibration and related structural dynamics,
- gives guidelines for measuring dynamic / structural characteristics offline and stator end-winding vibrations online,
- describes instrumentation and installation practices for end-winding vibration measurement equipment,
- establishes general principles for documentation of test results,
- describes the theoretical background of stator end-winding vibrations.

This part of IEC 60034 is applicable to:

- three-phase synchronous generators, having rated outputs of 150 MVA and above driven by steam turbines or combustion turbines;
- three-phase synchronous direct online (DOL) motors, having rated output of 30 MW and above.

This document is limited to the description of measurement procedures for 2-pole and 4-pole machines. For smaller ratings of machines than defined in this document, agreement can be made between the vendor and the purchaser for the selection of measurements in this document to be applied.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60034-1, *Rotating electrical machines – Part 1: Rating and performance*

IEC 60034-15, *Rotating electrical machines – Part 15: Impulse voltage withstand levels of form-wound stator coils for rotating a.c. machines*

IEC 60079 (all parts), *Explosive atmospheres*

ISO 7626-5:1994, *Vibration and shock – Experimental determination of mechanical mobility – Part 5: Measurements using impact excitation with an exciter which is not attached to the structure*

ISO 18431-1, *Mechanical vibration and shock – Signal processing – Part 1: General introduction*

ISO 18431-2, *Mechanical vibration and shock – Signal processing – Part 2: Time domain windows for Fourier Transform analysis*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1

turbine driven generator

three-phase synchronous generator with cylindrical rotor with 2 or 4 poles driven by a steam turbine or combustion turbine

Note 1 to entry: In this document, the term turbogenerator will be used.

3.1.2

partial discharge

electrical discharge that only partially bridges the insulation between conductors

Note 1 to entry: A transient gaseous ionization occurs in an insulation system when the electric stress exceeds a critical value, and this ionization produces partial discharges.

Note 2 to entry: See IEC TS 60034-27.

3.1.3

stator end-winding

portion of the stator winding that extends beyond the end of the core and is formed as a circular cone

3.1.4

stator end-winding support structure

components like rings, plates, spacers and fasteners as well as components for tightening, blocking and roving which are supporting and fixing the stator end-winding

3.1.5

stator end-winding structure

assembly of both the stator end-winding and the stator end-winding support structure

3.1.6

stator bar

single electrical slot conductor as part of the stator winding

3.1.7

parallel rings

electrical components connecting the stator winding to the main leads

Note 1 to entry: Parallel rings are also called connection rings, phase rings or circuits rings.

3.1.8

displacement amplitude

amplitude of displacement vector

Note 1 to entry: See ISO 2041.

3.1.9
phase angle
angle of a complex response which characterizes a shift in time at a given frequency

Note 1 to entry: See ISO 2041.

3.1.10
measurement position
measurement location and direction

3.1.11
1x-vibration
vibration with rotational frequency

3.1.12
2x-vibration
vibration with twice rotational frequency

3.1.13
1f-vibration
vibration with once line frequency

3.1.14
2f-vibration
vibration with twice line frequency

3.1.15
mode shapes
shapes of a natural mode of vibration of a mechanical system, usually normalized to a specified deflection magnitude

Note 1 to entry: See ISO 2041.

3.1.16
local modes
vibration involving part of a stator end-winding structure with typically small spatial expansion relative to the circumference of the stator end-winding

3.1.17
global modes
vibration involving a large part of the stator end-winding structure, i.e. the winding bars outside the stator core and the support components

Note 1 to entry: See 8.1.3.

3.1.18
4-node mode
global vibration mode, which exhibits 4 nodes over the circumference of the stator end winding

Note 1 to entry: See 8.1.3.

3.1.19
8-node mode
global vibration mode, which exhibits 8 nodes over the circumference of the stator end winding

Note 1 to entry: See 8.1.3.

3.1.20
modal force
generalized force which is equal to the dot (scalar) product of the mode shape and the physical force vector (that is, the projection of the force distribution on the mode shape)

Note 1 to entry: Individual modes are excited by the modal force.

3.1.21
impact test
test to obtain the vibration response characteristics of a structure with a calibrated impact force

3.1.22
modal test
test to obtain modal parameters of a structure, including natural frequencies, mode shapes, modal damping

3.1.23
transient load condition
operational parameter outside of steady state operation regime

3.1.24
single bar end connection
electrical connection between bars in a stator

3.1.25
coherence
degree of linear relationship between the response and the force for each sampled frequency

Note 1 to entry: The value of the coherence function is always between 1 and 0.

3.1.26
operating deflection shape
ODS
vibration pattern of measured points on a structure under given operating conditions

3.2 Abbreviated terms

Abbreviated term	Definition
ADC	analog digital converter
DOL	direct on line
DPA	driving point analysis
DP-FRF	driving point frequency response function
EMA	experimental modal analysis
FFT	Fast-Fourier transformation
FRF	frequency response function (see ISO 7626-1 and ISO 2041)
IEPE	internal electronic piezoelectric

Abbreviated term	Definition
MDOF	multi-degree of freedom (see ISO 2041)
MIMO	multi input multi output analysis
OEM	original equipment manufacturer
PD	partial discharge
SDOF	single degree of freedom (see ISO 2041)

4 Causes and effects of stator end-winding vibrations

The physical background of stator end-winding vibration is described in Annex A.

The predominant cause for stator end-winding vibration is the force-distribution due to the electromagnetic field in the active part and the machine's end-winding region. These forces depend on operational parameters (active power, reactive power) and are generally unavoidable. They are dominated by twice the fundamental frequency of phase currents, i.e. 100 Hz if operating at 50 Hz grid and 120 Hz if operating at 60 Hz grid.

Global and local aspects of stator end-winding vibrations are generally distinguished: a global vibration involves a large part of stator end-winding structure, i.e. the winding bars outside the stator core and the support components. Local vibration involves only a part of the stator end-winding structure with typically small spatial extension relative to the circumference of the stator end-winding. Local vibration modes can always be excited during operation. On the other hand, global vibration modes are not always excited, even if their natural frequency matches the frequency of electromagnetic force-excitation. A global vibration mode can generally lead to significant operational vibration levels, if the mode-shape of a 2-pole machine exhibits 4 nodes or if the mode-shape of a 4-pole machine exhibits 8 nodes. In some cases, even for 4 poles, the 4-node mode can induce a significant operational vibration level (e.g. in case of fractional slot winding). Another force that may lead to end-winding vibration is due to rotor vibration at one times the rotational speed (1x). The rotor vibration through the bearings may couple to the stator frame and core, and then to the end-winding.

Although the vibration excitation is due to a rotating electromagnetic field inside the machine, the vibration amplitude is generally not constant along the circumference of the stator end-winding. A sufficient number of equidistantly distributed sensors is required to estimate the maximum of global vibration.

Stator end-winding vibration levels may change over time due to operational parameter changes, such as active power, reactive power, voltage, operational temperature. Operation parameters of the electric machine should be recorded in parallel with vibration data and be available for analysis. Apart from this, long-term changes of the stator end-winding vibration level at comparable operational parameters could indicate a change in structural dynamics, which typically results in gradually decreasing natural frequencies of the relevant vibration modes. The detection of such long-term changes is the main purpose of the vibration trending. Sudden changes of the monitored vibration amplitudes after electrical faults could also be an indicator for a changed stator end-winding structure and can be irreversible.

Specific frequency or vibration limits are not part of this document. It should be pointed out that changes in the monitored vibration are likely to be of greater significance than the actual magnitude of such values (for more detailed information, see 7.2). For the time being, if acceptance or operational monitoring vibration criteria are required they should be based on experience with a particular class and type of machine – if such experience exists – and agreed on a case by case basis between the customer and manufacturer.

NOTE This is because the vibration is very much dependent on the specific design features of a particular electrical machine, for example stator end-winding designs differ a lot between air cooled, hydrogen cooled and water cooled generators and between different manufacturers. For HV motors the variation of the end winding design depends on the specific application. Therefore it is not possible to apply a universal set of limits which can be applied to even nominally similar types of machines from different manufacturers. Furthermore, currently there is only a small amount of data available and this is insufficient to define internationally accepted vibration criteria for acceptance or operational monitoring.

5 Measurement of stator end-winding structural dynamics at standstill

5.1 General

Clause 5 defines the conditions and procedures to measure frequency response function (FRF) and to derive the natural frequencies, mode shapes and modal damping ratios of stator end-windings.

The common excitation method for stator end-windings is by impacting with a hand held impact hammer. Excitation with a shaker (e.g. electro-dynamic) allows applying other excitation signals, like harmonic, swept sine or the use of broadband signals. The advantages of using an impact hammer are the ease of setup, portability and cost. The advantages of using a shaker are repeatability, wider frequency range and speed of data acquisition for many locations as well as the possibility to use it for multi input multi output analysis (MIMO) and a controlled application of excitation force-levels.

Impact hammer excitation is primarily used for end-winding structure modal analysis. Therefore the following sub chapters refer only to this excitation method.

There are two purposes of impact testing:

- Determination of global modes to assess whether a specific mode may be excitable during operation (experimental modal analysis, EMA).
- Determination of local dynamic flexibility (driving point analysis, DPA).

5.2 Experimental modal analysis

5.2.1 General

The experimental modal analysis (EMA) is a well-established method to identify natural frequencies, mode shapes and modal damping ratios of any structure.

For stator end-windings, EMA is used to identify the natural frequencies and mode shapes of those modes which are excitable during operation of the electrical machines.

These identified modes are referred to as the so-called global mode shapes, describing the ring-like behaviour of the stator end-winding.

The most relevant mode shapes are the 4-node modes for 2-pole machines and the 8-node modes for 4-pole machines. However there are also other mode shapes that may be excitable as well, but they would not contribute as much to the vibration level compared to the above mentioned modes which are contributing most to the vibration response.

EMA consists of 2 steps:

a) measurement of a set of frequency response functions (FRF), which requires measurement of the excitation force and responses due to this excitation force;
b) identification of natural frequencies, mode shapes and modal damping ratios from the measured FRFs.

NOTE ISO 7626 (all parts) describe good practices for the measurement of FRFs. ISO 7626-5 relates to measurements using impact excitation with an exciter which is not attached to the structure. It specifies procedures for measuring frequency-response functions of structures excited by means of a translational impulsive force. The signal analysis methods covered are all based on the discrete Fourier transform.

The end-winding is excited with a calibrated excitation device at one point in the radial direction. The response is measured at the point of excitation and at other response points in three directions. To limit the number of measurement channels the accelerometer can be moved to the other points (roving accelerometer method). Each response location should be measured with a minimum of three force excitations. The average of these values represents the measurement of a column in the FRF matrix. In general, this procedure should be repeated for a minimum of two different circumferential excitation points.

To allow for identification of mode shapes, it is recommended to locate the impact points and the measurements in accordance with 5.2.3.4 and Table 1.

The following subclauses describe in detail the various aspects to identify the natural frequencies and mode shapes of those modes which are excitable during operation of the electrical machine.

5.2.2 Measurement equipment

5.2.2.1 General

ISO 7626-1 defines basic terms and specifies calibration tests, environmental tests, and physical measurements to determine the suitability of motion transducers and load cells necessary for the measurement of the frequency response functions.

5.2.2.2 Vibration transducers

The sensors used are typically piezoelectric accelerometers.

Both basic types, charge mode accelerometers as well as internally amplified accelerometers or IEPE (internal electronic piezoelectric) can be used.

The sensors shall provide an adequate output signal to provide good coherence of the measurements. Sensor response shall be high enough to not create digitizing errors at the lowest signal levels. Single-axis or tri-axial acceleration pickups with sensitivity between 1 V/g (or in $V/(m/s^2)$) and 100 mV/g (or in $V/(m/s^2)$) are generally used. The response shall also not be beyond the linear range of the vibration transducer. This range is affected by the mounting method.

Vibration transducer fixation is typically done using wax or putty. An adhesive non-conductive wax or putty that will conform to the end-winding surface and hold the vibration transducers in place is an excellent material. The putty should be easily removed with little residue left on the stator end-winding.

5.2.2.3 Impact hammer

The measurement of frequency response functions with hammer impact is described in ISO 7626-5. For the calibration of the hammer, see ISO 7626-5:1994, 7.2.

The hammer mass and tip is chosen such that the frequency range of interest in the force spectrum does not decay by more than 10 dB to 20 dB and above that frequency range excessive energy is not applied. The frequency range of interest is typically from 10 Hz to 200 Hz but may also go up to 500 Hz. In general a soft tip is useable for a frequency range up to 200 Hz, a medium tip up to 500 Hz and a hard tip for a range above 500 Hz. When using an impact hammer for excitation, a weight of 500 g to 2 kg is recommended. An appropriate tip is recommended so that the coherence is better than 0,80 in the vicinity of natural frequencies within the frequency range of interest.

If it is chosen to impact the stator core, lower levels of coherence may occur if the transferred excitation into the end windings is low. Alternatively a heavier hammer (more than 5 kg) is recommended to be used at these locations.

Possible causes of low coherence for an impact measurement include:

a) noise in the force signal;
b) noise in the response signal;
c) variation in the location or direction of the impacts during averaging;
d) certain types of nonlinearity.

WARNING – Certain types of error are not indicated by the coherence function.

This is the case if the impact force is repeatable, resulting in deterministic errors, including:

e) leakage due to truncation of the response (inadequate frequency resolution);
f) structural nonlinearities;
g) signal clipping.

If low coherence is due to noise at the response signal (background vibrations), accurate unbiased measurement can still be made by a sufficiently high number of averages.

(See also ISO 7626-5:1994, Clause 9: Tests for validity of the measurements.)

5.2.2.4 Dynamic signal analyser

It is recommended to use a multichannel frequency analyser for measuring and storing the signals for evaluation by means of a Fast-Fourier transformation (FFT). The minimum practical number of channels is 4 (1 hammer and 1 tri-axial transducer), but more channels may be used to speed up the measurement process. At least 16 bit multi range or 24 bit analog to digital converters may be used, settable to 0 Hz to 500 Hz frequency range with a resolution less than 1 Hz and anti-aliasing filters. The signal analyser should provide adequate window functions. It should be possible to calculate the frequency response functions and coherence function. Averaging in the frequency domain should be possible.

5.2.3 Measurement procedure

5.2.3.1 General

In the following subclauses, also refer to ISO 7626-5:1994, Annex A.

5.2.3.2 Required tests

The preferred method of acquiring the FRF functions is using a roving transducer measurement where the impact location remains fixed. This is due to the fact that, for a given impact location a number of pre-tests is to be made, since the energy transfer to the structure does not depend only on the conditions of the hammer, but also on the local stiffness at the impact location. In the following a set of frequency response functions is defined as all FRFs measured for one impact location.

The roving hammer method, using a tri-axial measurement sensor, can be used if the impact can be applied in all three measurement directions.

Precondition

– The individual parts of the measurement chain shall be calibrated. ISO 7626-5:1994, 7.2 can be used as reference.

Pre-tests

– Define impact location. Radial impact direction is normally chosen.
– Define gain of amplifier.

- Check force spectrum for flatness.
- Define overload limits.
- Define double-hit settings, if available.
- Define pre trigger.
- Define force window if necessary, as per ISO 18431-2.
- Define cut off frequency of anti-aliasing filter, as per ISO 18431-1.
- Check time signal and apply exponential window if necessary.
- Check influence of number of impacts per averaging calculation on coherence and fix the number for the duration of the test (minimum of 3).

Check impact point and structural behaviour

- Choose impact points with respect to excitation of 4-node modes (2-pole machines) or 8-node modes (4-pole machines).
- Measure linearity, see Figure B.2.
- Measure reciprocity, i.e. if the impact point and the measurement point are exchanged, the same transfer function should be measured, see Figure B.3.

Conduct measurement of one set of frequency response functions

- Check coherence for each measurement position.
- Adjust the ADC (analog digital converter) voltage range as required to keep the signal in the medium range of the voltage range or higher to get the best coherence.
- Check for double hit and over-excitation/clipping.
- Impact with a similar force level as tested during the linearity check.
- Always include driving point FRF in measurement even when not in measuring plane.

Repeat the first FRF measurement and compare repeatability. It is recommended to repeat the pre-tests and then conduct the measurement of the new set of FRFs.

5.2.3.3 Machine and ambient conditions

The modal tests should be conducted in the absence of any other work that would induce vibrations in the stator from other sources. Examples for such other sources are hammering, the use of impact wrenches, rolling of the stator, and all welding activities. Armature and core support systems should be in the “as operated” state to provide correct spring/dampening conditions.

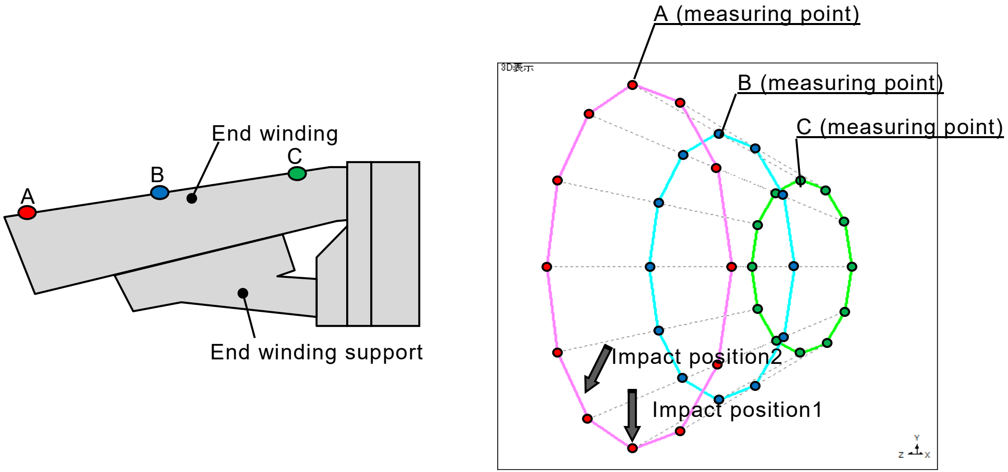
It may be impossible to eliminate vibrations from a shaft train running adjacent to the machine being tested in a power plant. This may affect the data by inducing peaks in the frequency spectrum due to vibration from other sources. These peaks can usually be identified by their being much sharper than sought natural frequency peaks and poor coherence at these frequencies. These peaks should be omitted from the curve fits manually in post processing. Line frequency noise may also be present due to poorly grounded equipment. Best efforts should be made to eliminate noise. Cables should be temporarily attached or supported by convenient winding components while data is being taken. Supporting cables by hand induces vibration into the sensor which will affect the quality of the measurements so this should be avoided. For units in service with significant signs of wear, the above mentioned coherence requirements may not be achievable. Best efforts should be made and the condition of the machine should be mentioned in the report.

The winding temperature influences the mechanical properties of the stator end-windings. Therefore, the winding temperature needs to be documented. It is recommended to perform the measurement with winding temperature changes of less than 10 K over the course of the measurement.

5.2.3.4 Recommended number, position and direction of measurements

The most suitable locations of measurement may vary with the specific design. Number and locations of the measuring points are decided with expected or predicted mode shapes. If measuring points are increased, more detailed mode shapes are obtained.

The measurement locations are typically arranged in 'measurement planes', since the winding bars and the supporting components are conically or cylindrically shaped respectively arranged. Figure 3 below illustrates a typical measurement setup with three measurement planes at three axial positions of the conical stator end winding. The vibrational pattern of these three rings is representative for the vibration shape of the stator end winding cone. The measurement plane at the stator bar ends (A) is regarded as essential and represents a minimum measurement setup. For clear identification of modes, it is necessary to use at least two different impact positions on the circumference (see Figure 3).



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NOTE Different numbers of measuring points in different measurement planes can be used.

Figure 3 – Measurement structure with point numbering and indication of excitation

Additional measurement planes at the support structure could be advisable for detailed studies, see the examples in Figure A.1.

In order to sample the vibration shape of a continuous ring, a minimum number of measurement positions is required. According to the Nyquist-Shannon theorem it can be stated: If N is the highest number of nodes of all expected mode shapes in the evaluated frequency range, the required number of equally distributed measurement positions is N+1, see Table 1. Two-pole turbogenerators do often not exhibit higher modes than 8-node in the frequency range up to 200 Hz. Thus a minimum of 9 measurement locations can be recommended for such machines and especially acceptable when measured at solid support rings. If the measurement plane is located not on a continuous ring but on individual components (e.g. bar ends) it may be necessary to have a higher number than N+1.

Independent from the number of winding bars, every 3-phase machine with 2 poles exhibits 6 winding zones that are identically shaped and supported. An arrangement with 6 sensors in the centre of every winding zone (as recommended in A.3.4 for vibration monitoring) is not sufficient for sampling vibration mode shapes with node numbers higher than 4. Typical measurement setups have 2 or 3 measurement positions distributed on the length of a winding zone resulting in a total number of 12 or 18 measurement positions at the bar ends.

Table 1 – Node number of highest mode shape in relevant frequency range and minimum number of measurement locations

Highest expectable order of mode-shape N	Minimum number of locations at a continuous ring (= N + 1)	Recommended number at winding bars of a 2-pole machine
6-node	7	12 or 18
8-node	9	12 or 18
10-node	11	12 or 18
12-node	13	18

The acceleration sensors need to be mounted on solid parts of the winding (such as bar surface) measuring at least in the radial direction, but typically the measurement is done with tri-axial transducers. If the rotor is removed, measurement planes on the inside of the end-winding structure may be used. At both ends of the stator the same rings should be used, if possible. The ideal approach is to utilize a sufficient number of sensors for simultaneous measurement. However, it is acceptable to perform sequential measurement of the sensor locations if not enough sensors or measurement channels are available for simultaneous measurement. In that case, the positions of the sensors are moved from one place to the next while the location and direction of excitation remains the same.

5.2.4 Evaluation of measured frequency response functions, identification of modes

As a result of the FFT analysis the output is a frequency-dependent transfer function of the acceleration over the impulse force signal. With the help of mathematical algorithms the modal parameters (natural frequency, mode shape and damping) are estimated from the FRFs.

For lightly coupled modes SDOF techniques should be used and for heavily coupled modes MDOF techniques should be used.

An overlay plot of all FRFs or a mode indication function will give a first indication of which frequency ranges the modes should be estimated.

5.2.5 Elements of test report

The test report should include the following information:

Structure measurement planes point numbering and impact locations, see an example in Figure 3.

Report for example the top coil slot number of each measurement. The slot numbers can be taken out of the winding diagram of each individual unit. The documentation of measurement positions shall be sufficient to assign the transfer functions to excitation and measurement positions. If raw data is provided, an assignment of measurement channels and measurement positions shall be provided. It is helpful to take a photograph or drawing where the sensor/impact locations are clearly marked.

Documentation of pretests:

- Force-time signal and spectrum.
- A typical FRF and coherence example.
- Linearity, at least for one impact position (see Figure B.2).
- Reciprocity, at least for one impact position (see Figure B.3).
- Filter settings.

Overlay plot of FRFs and/or mode indicator function (see Key in Figure B.4):

- Classification of mode shapes to the natural frequency peaks, or
- Table with natural frequencies, verbal assignments of mode shapes.
- Always include driving point FRF in measurement even when not in measuring plane.

Mode estimation algorithm, software name and version used.

Mode shapes with frequencies and damping:

- Figures (containing deformed and not deformed structures), or
- Animations.

It is recommended to plot the perspective view to better distinguish between different mode shapes.

Global modes of the stator end-windings shall be presented in a graph indicating the type of natural mode along with the specific natural frequency. Figure B.5 shows different natural modes.

The accelerance (=acceleration/force), the mobility (=velocity/force) and the dynamic compliance (=displacement/force) will produce vastly different graphs. For global modes, dynamic compliance should be used due to advantages at lower frequencies (see Key in Figure B.4). Accelerance can also be used in addition for global modes at higher frequencies.

5.2.6 Interpretation of results

The results of the experimental modal analysis are not easy to interpret in regard to the resulting operational vibration level, which is the most relevant quantity for assessment. Experimental modal analysis is often used for root cause analysis after increased stator end-winding vibration are observed. It is generally recommended to combine various measurement actions for the interpretation of results. Refer to 7.3 for further guidelines.

The vibration characteristics that can be derived from experimental modal analysis are described in A.1.3. From the experimental modal analysis the following results are of main interest:

- the measured dynamic compliance close to 1x and 2f (most relevant), accelerance may be used in cases where historical data was taken in accelerance, the same units should be used as in the historic documents;
- the natural frequencies of
  - 2-node vibration modes close to rotational frequency (1x),
  - 4-node modes (2-pole machines) / 8-node modes (4-pole machines) close to twice line frequency (2f),
  - local vibrations modes close to twice line frequency (2f).

The filtered 2f-component of the operational vibration is typically predominant. It is therefore advisable to firstly assess the dynamic compliance close to 2f and as well the natural frequency distance to 2f of the nearest 4-node mode for 2-pole machines (8-node mode for 4-pole machines). This gives an indication of whether the measured dynamic compliance at 2f is caused by an excitable vibration mode.

NOTE The measured dynamic compliance depends on the impact location, impact direction and measurement locations. The operational forces depend on the stator and rotor currents, winding layout and geometrical dimensions. Thus, the ratio of measured dynamic compliance and operational vibration level varies with the machine’s design and rating.

In a simplified way, the dynamic compliance can be understood as the product of the static structural compliance and the dynamic amplification factor. Subclause A.2.1 explains the possible causes for increased vibration level. The presence of a natural frequency at or close to 2f is not necessarily cause for increased vibration even though the related vibration mode is excited (i.e. a 4-node or 8-node mode). A low static structural compliance, a low modal force, or considerable modal damping may lead to vibration levels that are not increased despite the presence of a global or local resonance close to 2f. On the other hand, the absence of an excited vibration mode at or close to 2f does not necessarily lead to low vibration levels. A high static structural compliance and a non-resonant situation can result in increased vibration levels.

Often specifications request a certain frequency range around 2f to be free of natural frequencies of excitable modes. This is a conservative approach. Instead one should consider that the dynamic compliance close to 2f may be more relevant than the existence of a peak in the measured FRFs. If the natural frequency is close to 2f, and a low vibration level is confirmed in a factory type test or in field operation for a machine, the winding may still yield long life. In this case, type test data including factory test data or the vibration data during machine operation should be presented.

Impact tests are usually performed at ambient condition and the resulting frequency response functions are different from those present at operational temperature. This has to be considered when evaluating results from experimental modal analysis. Refer to 7.2 where the influence of operational parameters is explained in more detail.

It is recommended to involve the respective original equipment manufacturer (OEM) or winding manufacturer for the interpretation of results from experimental modal analysis, if necessary, because the experience on the specific design and manufacturing can considerably help in interpretation. Aspects of machine’s condition and its history should always be considered, refer to 7.4 for further details.

5.3 Driving point analysis

5.3.1 General

Local vibration modes could always be excited during operation and result in increased vibration levels, when the natural frequency is close to twice line frequency or the compliance (displacement/force) is relatively high at twice line frequency. Similarly increased vibration may also occur when there is a natural frequency close to the rotational speed (1x).

This local behaviour of components may not be possible to identify from EMA because the response points may not be part of the selected measurement scheme of the EMA. Thus it is recommended to check the components which might show local behaviour, for example stator bar ends, phase bar connectors, parallel rings and main leads including bushings.

The local vibration behaviour is tested by measuring driving point frequency response functions (DP-FRF), which are obtained by impacting at one point/direction and measuring the response at the same point/direction. Ideally all bar ends are measured in all three directions. If it is decided to perform the test only on a limited number of points, it is recommended to test the same positions and directions as in earlier tests and those positions which show wear or looseness visually.

DP-FRFs showing high peaks at frequencies which do not coincide with the natural frequencies of identified global modes from the EMA indicate positions with local vibration behaviour. Their peaks can be assumed to be due to local modes. For the peaks close to twice line frequency the level of dynamic compliance is to be documented clearly as frequency and peak value. In addition high compliances at or close to twice line frequency shall be documented even when not showing a distinct peak. The preferred unit of the compliance of DP-FRF is micrometer per kN = 10^{-9} m/N.

The measured positions (location/direction) need to be clearly documented.

The following subclauses describe in detail the various aspects to identify the positions of the stator end-winding with high compliance at or close to twice line frequency by measuring DP-FRF.

5.3.2 Measurement equipment

Complete 5.2.2 above is also applicable for DPA.

5.3.3 Measurement procedure

5.3.3.1 Required tests

Precondition

The individual parts of the measurement chain shall be calibrated. ISO 7626-5:1994, 7.2 can be used as reference. If the DPA is done in conjunction with the EMA the calibration of the measurement chain is already done.

Pre-tests

Similar checks should be done as described in 5.2.3.2. If the DPA is done in conjunction with the EMA the dynamic behaviour of the structure is sufficiently known and the pre-tests do not need to be repeated.

Conduction of measurement:

Similar checks should be done as described in 5.2.3.2.

5.3.3.2 Machine and ambient conditions

See 5.2.3.3.

5.3.3.3 Recommended number, positions, and direction of measurements

The number of measuring points depends on the target of the measurement. The positions should be impacted in the directions necessary to determine the local flexibility of the component.

Ideally all bar ends shall be tested in all three directions. If it is decided to perform the test only on a limited sample it is recommended to test the same positions as in earlier tests and those positions which show wear or looseness visually. The sample positions need to be documented clearly for future reference.

5.3.4 Evaluation of measured FRFs, identification of modes

The DPA tests are typically done at room temperature. In operation the end-winding is operating at a much higher temperature. At high temperature the stiffness of the winding will decrease. This will cause the natural frequencies to decrease. The decrease in Hz is dependent on the end-winding temperature, but may decrease by as much as 10 Hz to 20 Hz.

All measured driving point frequency response functions (FRFs) are to be checked for peaks, which do not coincide with formerly identified global modes. These peaks can be assumed to be due to local modes. For these peaks near the excitation frequency the level of dynamic compliance is to be documented clearly (frequency and peak value).

For bar ends, the levels of compliance for those peaks, which can be assigned to natural frequencies of global modes, may also help to determine the relevance of such global modes.

Very low compliance levels (compared to dominant peaks) indicate that this global mode would not lead to an increased vibration level during operation.

5.3.5 Elements of test report

The measuring position needs to be clearly reported, for example by front view and circumferential positions, pictures or sketches. The documentation of measurement positions should be sufficient to assign the transfer functions to excitation and measurement positions. If raw data is provided, an assignment of measurement channels and measurement positions shall be provided.

Visualization of frequency response functions should be done over the entire measuring range. Amplitude, phase and coherence signals of the FRF shall be presented in separate overlaid graphs, see example in Figure B.7.

For components of the same type (e.g. bar end connections) it is convenient to plot the frequency response spectra on the same plot for easy identification of comparable structural dynamics.

5.3.6 Interpretation of results

Results of the driving point analysis are not easy to interpret in regard to the resulting operational vibration level, which is the most relevant quantity for assessment. DPA is used on a new winding, if necessary to determine a reference, as a periodic maintenance test to establish if structural changes have occurred and/or as a diagnostic test after end-winding vibration indications are observed. Driving point analyses are often used for root cause analysis after indications for increased stator end-winding vibration are observed. It is generally recommended to combine various measurement actions for the interpretation of results. Please refer to Table 2 for further guidelines.

The measured frequency response functions represent the local dynamic flexibility of a certain stator end-winding component. The dynamic compliance close to 2f is most relevant. The results should also be checked with each other.

NOTE The measured local dynamic flexibility depends on the impact and response location and direction. The operational forces depend on the stator and rotor currents, winding layout and geometrical dimensions. Thus, the ratio of measured local dynamic flexibility and operational vibration level varies with the machine's design and rating.

Peaks in the driving point frequency response functions (DP FRFs) indicate natural frequencies of local vibration modes, if no corresponding natural frequencies of global modes are identified. In this context it is important, that all global modes are identified by means of experimental modal analysis (see 5.2). Small differences between natural frequencies of EMA and peaks in the DPA in the range of 0,5 Hz to 1,5 Hz can be due to different impact locations, directions and force levels and do not usually indicate the presence of an additional local vibration mode at this frequency. The end winding structure is in good condition if the deviation between frequencies is low when measuring individual comparable end bar connections. Phase bars show different behaviour from other bars due to differing design. Higher variation in measured frequencies between connections of individual comparable bar fixation is an indication of local structural disturbances. Disturbances of local structure can be verified by additional information from local visual inspections (e.g. poorly impregnated bandings, dusting). Comparisons to the references of the winding when new are also useful.

Impact tests are usually performed at ambient condition and the resulting frequency response functions are different from those at operational temperature. This has to be considered when evaluating results from driving point analysis. Refer to 7.2, where the influence of operational parameters is explained in more detail.

It is recommended to involve the respective OEM for the interpretation of results from experimental modal analysis if necessary, because the experience on the specific design and manufacturing can considerably help to assess. Aspects of machine's condition and its history should always be considered, refer to 7.4 for further details.

6 Measurement of end-winding vibration during operation

6.1 General

During operation the stator end-winding is subject to vibration due to mechanical and electrical forces. The level of stator end-winding vibration may change due to change of the excitation forces, which depend on various operational parameters of the electrical machine and may also change due to change of the structural dynamic behaviour. The primary frequency component of the end-winding vibration is usually twice line frequency (2f). Thus the total displacement and at a minimum the 2f displacement amplitude and phase angles should be measured. Similarly the 1x displacement amplitude and phase angles should be measured.

The measurement of stator end-winding vibration is intended to identify the change of vibration levels over time due to change of the structural behaviour. Thus it is required to record the relevant operational parameters in parallel with the vibrations to enable the identification of a change in vibration levels over time under comparable operational parameters (see 6.2.4). The following operational parameters need to be recorded in parallel as a minimum: electrical frequency (Hz), stator voltage (kV), active power (MW), reactive power (Mvar), stator currents (kA) and a representative temperature (°C) of the stator winding and representative temperatures (°C) for the stator end-winding. Note that cooling gas pressure can influence the end-winding temperatures and thus should be recorded.

For correlation with global modes this document recommends for two pole machines to use 6 vibration sensors equally distributed on the circumference in the centre of the phase group (12 sensors for 4-pole machines) each at both stator end-windings (see A.1.3). For correlation with local modes this document recommends installing sensors where the compliance (or accelerance) magnitudes are the largest close to 2f as recorded in the DPA (5.3). The sensors are usually positioned at the bar ends of stator end-windings and are directed in radial and tangential direction (or perpendicular to the end-winding cone). Armature architecture and geometry contribute to response maxima and minima at certain circumferential positions. An example is the non-symmetry of the connection end of the armature and the attachment of leads to the frame. It could also be useful to have the vibration level of the magnetic core. Normally one core vibration sensor is used, but in special cases more sensors can be installed along stator core.

Two main types of accelerometers are used: fiber optic or piezoelectric accelerometers.

The vibration signals may be measured periodically with data acquisition systems connected from time to time for certain periods or may be continuously monitored. Depending on the specific machine and operating regime, the OEM and the end user together may define certain indicating levels for specific actions to be taken (see also A.2.2).

The following subclauses describe in detail the various aspects when stator end-winding vibrations shall be measured during operation.

6.2 Measurement equipment

6.2.1 General

ISO 13373-1 discusses general procedures of vibration condition monitoring. ISO 16063-1 specifies a method, procedures and the specifications for apparatus to be used for testing the magnetic field sensitivity of vibration and shock transducers. Details and important points specific to the application of monitoring stator end-winding vibration are given below.

6.2.2 Vibration transducers

6.2.2.1 General

Accelerometer is the common term for online vibration transducers used for monitoring of stator end-windings. The accelerometer used shall be designed to operate satisfactorily in the environment for which it is to be used, for example with respect to temperature, humidity, magnetic fields, electric fields. The accelerometer shall be correctly mounted to ensure that its presence does not affect the response characteristics of the stator end-winding. Accelerometers are available to measure 1, 2 or 3 axes in one device. As a minimum a single axis sensor mounted in the radial direction is needed to measure vibration in said direction. Dual- and triple-axis sensors are available which may be helpful to observe local vibrations (see 6.3.1.3).

The characteristics of the measurement system should be known with regard to the effects of the environment, including:

a) temperature variations;
b) magnetic fields;
c) airborne and structure-borne noise;
d) power source variations;
e) cable impedance;
f) transducer cable length;
g) transducer orientation;
h) stiffness of the transducer attachment.

The accelerometers shall be correctly mounted to ensure that the mounting arrangement does not degrade the accuracy of the measurement.

According to the technical background as described in Annex A, the typical requirements for an accelerometer to be used to monitor stator end-winding vibration are:

– Withstand magnetic fields up to 1,3 T RMS at 50 Hz/60 Hz without change of its original sensitivity by more than 5 %.
– Electric fields up to 5 kV/mm without change of its original sensitivity by more than 5 %.
– Cross-sensitivity between different measuring axes shall be less than 5 %.
– Minimum frequency range: 20 Hz to 350 Hz (–3 dB). For generators which have been in service and show looseness, a higher frequency range up to 1 000 Hz may be advisable.
– Dynamic range: 0 g to 40 g.
– Linearity: ±5 % from 0,1 g to 40 g.
– Resonance frequency: above 1,5 times upper limit of frequency range, to avoid harmonics of the forcing frequency.
– Temperature range –20 °C to +130 °C, for a thermal class 155 insulation system.
– Temperature sensitivity less than 5 % in whole temperature range.
– Survive a 100 g shock.
– The cable to the accelerometer shall not produce any signal if the cable itself is vibrating.

Sensors should be type tested at a minimum to the above performance requirements.

The sensor manufacturer should provide test data to demonstrate that the sensor performance does not change over an expected life of more than 10 years.

There are two main types of accelerometers which have been used historically.

6.2.2.2 Fiber optic accelerometers

Fiber optic accelerometers do not contain conductive parts and thus are not sensitive to the electric and magnetic fields present in the high voltage stator end-winding area.

6.2.2.3 Piezoelectric accelerometers

Piezoelectric sensors may be used for end-winding vibration monitoring, however careful selection is required as some contain ferromagnetic material. In close proximity to the high currents in the stator end-winding, ferrous materials will heat up due to losses induced by magnetic fields. Non-ferrous types are available with low magnetic sensitivity. Installation of piezoelectric accelerometers needs special attention on installation because metallic cables could transfer high voltage out of the electrical machine and therefore lead to a health and safety issue (see 6.3.2).

6.2.3 Electro-optical converters for fiber optic systems

If fiber optic accelerometers are being used to monitor stator end-winding vibration, the signal from the optical accelerometer will require conditioning to be processed and converted to a numeric value. It needs to be ensured that the electro-optical converters are not affected by the magnetic fields. A convenient solution for this conversion is at the stator frame penetration. An alternative solution is to carry the fiber optic signal away from the generator to perform the conversion and avoid any electromagnetic interference.

If the optical converters are inside the machine or within the feedthroughs, separate maintenance of the components may be difficult. The optical converters inside the feedthroughs have the advantage of less optical attenuation, which may be important for some types of sensors. On the other hand, to avoid problems with chemical attack due to the internal atmosphere (humidity, H2), optical converters may be completely outside of the stator. With an optical converter outside of the stator, it is possible to do maintenance on the converter during operation.

6.2.4 Penetrations for hydrogen-cooled machines

For hydrogen-cooled generators the frame feedthroughs need to be in accordance with IEC 60079 (all parts) on explosive atmospheres.

For new machines it is the responsibility of the manufacturer to declare the hazardous zone, for machines in operation the operator is responsible to declare it. Care should also be taken as ATEX certified components may not comply with the other requirements for gas leakage.

For hydrogen-cooled generators, a penetration and feedthrough cable is required to pass the signal through the generator casing. To avoid hydrogen leaks, this assembly should be pressure tested.

A gas leakage test according to EN 1779 test method B3 or B4 at an absolute pressure of 8 bar as a qualification test of the feedthrough would give a reliable measure of the efficacy of the seal. This can be performed on most designs of feedthrough assembly prior to installation in the machine.

6.2.5 Data acquisition

Instrumentation is required to collect the vibration data from the accelerometers and provide a tool to trend the end-winding vibration conditions. Typical requirements for instrumentation data acquisition are:

a) The cut-off frequency of the low pass filter shall be set to lower than the upper frequency limit of the vibration sensor.

b) The sampling rate in samples per second shall be an integer power of 2 and at least 2,56 times the upper frequency limit of the sensor in hertz (i.e. 1 024 samples per second for a sensor with frequency range 20 Hz to 350 Hz).

c) The sampling time shall be one second yielding a frequency spectrum resolution of 1,0 Hz/line.

This can be performed periodically or continuously. Winding vibration signals can either be incorporated into the plant SCADA system or be monitored remotely or periodically using a stand-alone system.

Periodic measurements will provide an overview of the condition of the end-winding structure and will need to be appropriately scheduled in order to maximize the information gained with a small amount of data.

Continuously collecting on-line data with a monitoring system enables capturing sustained increases more effectively than periodic measurements and also identifies when sudden increases in vibration data occur (e.g. after a high current transient). As well, continuous monitoring is much more effective in correlating high vibration levels with changes in operational parameters to help determine the optimal conditions by minimizing operation at higher end-winding vibration. For an effective system raw waveforms should be stored on a daily basis. Once a reference at the range of operational parameters has been established data can be stored only if there is a significant change in vibration amplitudes.

For both periodic measurements and continuous monitoring of end-winding vibration it is necessary that the relevant operational parameters influencing the end-winding vibration are recorded in parallel with the stator end-winding vibration signals.

The following summarizes the relevant operational parameters to be recorded for different machine types in parallel with the end winding vibration signals:

- Active power and reactive power (for generators only) or alternatively stator current, stator voltage, and power factor.
- Line frequency (over- or under-frequency operation).
- Winding and warm gas temperature.
- Application dependent external vibration factors.

When operational parameters are not recorded, conclusions about changes of structural dynamics are not possible. See 7.2.

In order to remove the offset DC voltage or low frequency component, the high pass filter should strongly suppress signals below 10 Hz.

6.3 Sensor installation

6.3.1 Sensor locations

6.3.1.1 General

Where the sensors are placed will depend on the purpose of the on-line data acquisition: measuring of global vibration levels or local vibration in specific components.

6.3.1.2 Global vibrations

Typically the vibration amplitudes are greatest in the radial direction, which should be monitored as a minimum.

NOTE “Radial” is notional, since there is usually a small twist in the coils in the end-winding which means that it is possible that the accelerometer axis is not truly radial.

An effort should be made to distribute the accelerometers sufficiently to maximize coverage for monitoring of end-winding vibration.

In order to get a good estimate of the global vibration level, it is shown in A.3.4 that for a two pole machine 6 sensors equally distributed on the circumference (12 for 4-pole machine) are adequate. On the winding connection end, the sensors shall be positioned in the centre of the phase group. In order to enable operating deflection shape analysis, more sensors may be needed within the same plane.

Additionally, one accelerometer may be installed on the stator core back iron to provide a reference for the influence of core vibration on end-winding vibration.

6.3.1.3 Local vibrations

For detection of local deflections, accelerometers can be mounted on individual bars or coils, leads from coils to circuit ring busses, support rings or circuit ring busses. It may be worthwhile to install a reference sensor to distinguish between global vibration and locally measured vibration, if not available otherwise. In general, the sensors can be located based on the results of DPA testing (5.3) and/or past experience of high vibration locations from similar machines. The response of the end-winding structure indicated by offline impact testing and a modal analysis (5.2) may suggest where the accelerometers are to be located. The sensors should be installed where the local dynamic flexibility is the highest. Where possible, the machine manufacturer or experienced service providers could be consulted for the optimum number of sensors installed and their locations.

6.3.2 Good installation practices

The installation of the sensors needs to ensure a proper mechanical coupling of the sensor to the structure in the frequency range of interest. The sensors should be secured in place with a ‘hard setting’ structural adhesive such as a 2-component electrical grade epoxy resin, secondary mechanical support such as resin impregnated taping or clamping should also be applied. Any epoxy shall be chemically compatible with the stator coil insulation system and end-winding support structure components. The accelerometer shall sit flat on the mounting surface and mounted such that there is no relative movement between the accelerometer and the component being monitored. Epoxy soaked felt will provide full contact between the mounting area and the accelerometer, and to ensure that the accelerometer will sit flat. The accelerometer shall be fixed securely to the component; if the felt is not fully saturated (soft) or not secured firmly in place it may dampen the signal giving an inaccurate indication of the stator end-winding vibration. If a piezoelectric sensor is used, an insulating material of sufficient thickness between the stator bar/coil or jumper and the sensor will be required, to ensure the sensor does not initiate elevated partial discharge (PD) and electrical tracking.

Cables are required to transmit the signals generated by stator end-winding vibration from the accelerometer to measurement instruments outside the machine.

Fiber optic cables are immune to high electric and magnetic fields. The fiber optic cables should not be bent sharply or kinked. Refer to the manufacturer’s instructions for limitations on routing. A glass fiber cable will minimize the effect on stator reliability or the measured vibration, but standard procedures shall still be observed when running the cables. It is not a good practice to secure the cable across multiple live components around the end-winding. Bridging between adjacent phases should be avoided. The cables should not be installed tautly as there will be some movement in the end-winding during operation. However cables should be well secured to minimize movement and whip due to high velocity gas flow to prevent eventual breakage. Cables should be routed along the stator frame or on the series caps instead of across the windings and circuit ring busses.

Where piezoelectric sensors are used, the metallic cables need to be secured to bars/coils, jumpers and circuit ring busses to prevent any impact on long term reliability due to induced PD. Cables from piezoelectric accelerometers should be sufficiently insulated and protected from high voltage and routed along bars/connections of similar potential and beyond the high voltage stress grading region of the stator end-winding. The preferred means is to route along a path that only utilizes elements operating at the lowest voltages, and beyond the high voltage stress grading region of the stator end-winding.

The qualification and testing of the insulation of piezo-sensors including their coaxial cables in the overhang is part of the qualification and testing of the whole winding insulation: similar to other sensors like temperature ones. Therefore, the high voltage testing according to IEC 60034-1 and IEC 60034-15 shall be done as a minimum requirement, with the sensors and their coaxial cables grounded.

If these tests are passed and additional information is needed, PD-measurements can be done according to IEC TS 60034-27. Here it is advised to use the rated phase-phase-voltage as in case of one ground fault in another phase, the phase-ground-voltage may become as high as the phase-phase-one for a limited period of time. It is not recommended here, to define any quantified acceptance criteria for this test in terms of pC or nC since this is not done in IEC TS 60034-27 either. However, a “dark house PD-testing” or a PD-test with a UV-camera could be done here in parallel, in order to optimize the arrangement to achieve the lowest or no PD-activity.

As a special additional test, this could also be done with the winding and frame grounded and the sensor at high voltage potential, knowing that this is not reflecting the same field distribution as in service and more effort is needed than necessary for the operation, to isolate the sensor and especially the cables against ground.

If the sensors are expected to serve on a long term basis, for example a whole expected life time, passing the routine test voltage according to IEC 60034-1 would not be sufficient. It is advisable that sensors are qualified according to IEC 60034-18-31, IEC 60034-18-32, IEC TS 60034-18-33, or IEC 60034-18-34 to be fit for purpose under electrical, thermal, mechanical and ambient stresses. Depending on the environmental conditions with respect to humidity or foreign substances on the surface of the overhang, additional requirements may apply.

Sufficient cable support is needed to reduce induced noise and the likelihood of damage during machine operation and care is needed to reduce the likelihood of damage during maintenance activities.

It is recommended that the measurement system i.e. the accelerometer, wiring (including frame penetration) and signal conditioning should be assessed to ensure extraneous noise is suppressed and signal quality is maintained.

If in doubt, contact the OEM, the sensor manufacturer or independent and experienced service providers for installation advice.

6.4 Most relevant dynamic characteristics to be retrieved

As a minimum the instrumentation should produce the waveform of the acceleration signal. A phase reference signal (see A.3.2) should be retrieved together with a time stamp for later correlation.

Typically the following processed data is used for monitoring:

- total displacement versus time;
- displacement (amplitude and phase) at rotational speed frequency (1x) versus time;
- displacement (amplitude and phase) at twice line frequency (2f) versus time.

Additional data may be stored depending on specific monitoring requests or needs.

ISO 13373-2 discusses "Processing, analysis and presentation of vibration data". Examples of many of these plots are given in Annex A. The data should be made available in electronic format.

6.5 Identification of operational deflection shapes

Operational deflection shape measurement is used to find the deformation of stator end-windings at specific frequencies, typically rotational frequency (50 Hz/60 Hz for 2-pole machines) and twice line frequency (100 Hz/120 Hz). The measurement of the ODS requires the accelerometers to be located in positions as described in 6.3.1.1. It is measured under steady-state operation of the machine where one accelerometer is used as the reference and the remaining accelerometers around the end-winding are measured relative to that reference. Typically, the reference accelerometer is selected at the location with the highest vibration magnitude. The differences in magnitude and phase between the reference and the remaining accelerometers determine how the end-windings are vibrating relative to one another and can be used as a way to identify particular parts of the end-winding that have excessive deflection. Operational deflection shapes can be plotted in terms of the deflection vector (or component), excitation frequency/frequencies. Significant changes over time at comparable operation conditions can be attributed to structural degradation of the end-winding support system.

Similar to modal analysis, operational deflection shape test assumes linearity. If the measurements are collected sequentially they also assume time invariance meaning that the steady-state conditions do not change for all measurement pairs (reference and one remaining accelerometer in sequence). For this reason it is preferred that all data is collected in parallel (all accelerometers at the same time) for improved analysis. Finally, typical Fast Fourier transformation (FFT) assumptions also apply for this analysis.

In contrast to modal analysis, operational deflection shapes are only valid for the forcing frequencies that are present (i.e. rotational speed and twice line frequency). For a complete dynamic description of the end-winding, modal testing is required to determine mode shapes, frequencies, and damping ratios that are not necessarily excited during normal machine operation. Operational deflection shapes can be more difficult to understand than mode shapes, but they are advantageous from a diagnostics point of view. The operational deflection shapes are influenced by the forces during machine operation at load and temperature.

6.6 Elements of test report

The test report shall contain the items as given below as well as in Clause 7.

Sensor installation details:

- Power plant, customer.
- Type of sensors, serial number, frequency bandwidth, etc.
- Name of test engineer.
- Installation location, measurement direction, etc.

Summary table:

- Operational parameters (active power, reactive power, stator current, winding temperature, etc.).
- Overall vibration levels (acceleration, velocity, displacement) given as rms, 0-pk or pk-pk values.
- Specific frequency displacement levels (50 Hz/60 Hz, 100 Hz/120 Hz, etc.).
- Change in trend (slow increase, step change, no change, etc.).

Diagnosis and recommendations:

- Measurement results (spectral shape, trend data, etc.).
- Comparison with earlier measurements if available.
- Observations made during the measurement.
- Correlation with offline DPA results if available.

Sample data:

- Acceleration waveforms.
- Displacement spectra.
- Trend data (vibration with operational parameters).
- Statistical data (maximum, minimum, average, etc.).

6.7 Interpretation of results

The main results of the online-monitoring of stator end-winding vibrations are:

- the global vibration level of the stator end-winding, as it can be measured with radial directed sensors in the centre of the winding zones (as proposed in B.3.4),
- the local vibration level of an individual stator end-winding component relative to a reference position, see Clause A.2.

It is recommended to correlate vibration levels and operating parameters. The vibration levels can be used for comparison with measured vibration levels of similar machines at comparable operational parameters. Refer to 7.2 for the specification of comparability. General vibration limits are not possible to specify for the reasons given in Clause A.2. Apart from a trend of overall vibration magnitudes, there is the possibility to trend the amplitude and phase angle of the (usual predominant) 2f vibration component. A gradually increasing lagging phase shift of the 2f-vibration (that is measured with an identical sensor type at identical sensor position) could indicate a natural frequency passing-through the excitation frequency, see details in A.3.2. Such trending of phase angles is possible for global vibrations (see Figure A.8) as well as local vibrations (see Figure A.9).

When discussing a gradually increasing vibration level, it might be advisable to also refer to impact test data (see Clause 5). The dynamic compliances (as they are measured for EMA or DPA) could give valuable hints about possible future development of vibration levels. In this context, the influence of operational temperature on natural frequencies has to be considered. Refer to 7.2 for further details.

A further possibility for the interpretation of measurement results in regard to structural changes is given with the harmonic content of measured operational vibrations. Mechanical looseness could generate beside the 1x and 2f content also additional frequencies at multiples of 1x and 2f (harmonics), which are generally caused by non-linear structural behaviour. It is important to identify the state of higher harmonics with reference measurements at a new machine (or at the beginning of online-monitoring), as some technologies for fastening and spacing of stator bars exhibit a typical nonlinear structural behaviour, which is certainly not of concern. It shall be considered, that the amplitude-ratios of higher harmonics to the 2f-content is generally different for measured displacements, velocities and accelerations.

Sudden changes of global vibration levels are typically caused by fault cases. Other influencing factors shall also be considered. Refer to 7.4 for further details.

7 Repeated measurements for detection of structural changes

7.1 General

Clause 7 describes repeated measurements for the detection of structural changes, which is the most typical target of measurement campaigns. Impact tests (see Clause 5) as well as online-monitoring (see Clause 6) are discussed with regard to comparability of measurement results. The operational parameters and their influence on measurement results are discussed, as they typically complicate the assessment of results. Moreover, hints are given for the choice of the appropriate measurement actions with a link to the cause effect chain.

Aspects due to incorrect measurement method are not addressed. Refer to Clauses 5 and 6 to get detailed information on the measurement procedures.

7.2 Reference measurements, operational parameters and their comparability

Reference measurements can be obtained to get a reference for future comparison of measurement results. Such reference measurements will support a later detection of potential structural changes and can be obtained as a baseline for online-monitoring (see Clause 6) as well as impact testing (see Clause 5). Whereas online monitoring can provide continuously measurement data for such comparison purposes, the impact testing has the disadvantage of long time intervals in between without information (i.e. the time distance between regular maintenance activities, which requires opening of the machine). Reference online-measurements are ideally conducted during the commissioning (or initial operation phase). But they can also be conducted at the beginning of the measurement campaign (e.g. just after the installation of an online-monitoring system or a repair of the stator end-winding structure), which is practised in most cases. Reference impact tests are ideally conducted on a new or refurbished machine.

Repeated measurements for comparison purposes can be performed during the entire lifetime of the machine. It is advantageous to do more frequent repeat measurements at the beginning of the life.

Measurement data obtained by online-monitoring or impact tests shall be comparable. In this context, online vibration measurement results are comparable if the following tolerances are kept in steady state condition:

- Active power in [MW], reactive power [MVAr]: sqrt[(delta P)^2 + (delta Q)^2] / S less than 5 %
- Line frequency: ±0,2 Hz.
- Characteristic stator winding temperature: ±5 °C.

NOTE Steady state conditions can be achieved by holding electrical operational parameters constant. It can be assumed that all relevant operational parameters (including temperature) have reached the steady state condition, when the measured vibrations reach a stationary level.

Without repeated operation of the machine at certain pre-selected operational conditions (within tolerances as given above), it is hard to differentiate influences from operational parameters and structural changes. Such comparable operational parameters are ideally specified when conducting the reference measurements. But they can also be retrospectively defined, if the machine was driven with a characteristic operating regime and such repeated operation points can be found. If certain operational parameters are selected for reference measurements or any other vibration analysis, the operational parameters should be selected with regard to:

- the typical operating regime of the unit being monitored,
- the specified range of active and reactive power (power chart), and
- potentially the characteristic stator temperatures.

For reasons explained in A.1.4, the dependency of the excitation level on active and reactive power varies with the machine’s design. For turbogenerators, the rated load or the most frequent operation point can be recommended as a preferred load point for reference-measurements. For motors it should be defined from the driven load process where the motor is highest loaded.

The selection of operational parameters based on a measurable characteristic stator temperature might also be advisable. As described in A.1.4, the modal stiffness may change depending on the temperature of the stator end-winding structure. Thus, global or local resonance amplification may occur at part load condition (in a certain range of stator current or apparent power, respectively). Changing the operating regime could therefore cause different vibration levels than experienced before. A re-definition of reference-operating for future trending is in such cases advisable.

The most interesting values for comparison of online monitoring data is typically

- the global vibration level (i.e. the maximum of vibration levels as measured at all sensors, see 6.3.1.2 and A.3.4),
- the local vibration level relative to a reference position (see 6.3.1.3 and Clause A.4).

For comparison of online vibration data, it is important to define a reference vibration level (100 %) of the global vibration for each of the operating conditions used for the reference measurements at steady state condition (see requirements given in 7.2). The maximum level of the available sensors defines the global vibration level (see A.3.4).

In case of additional sensors placed at locations of special interest, this sensor may need its own reference vibration level (100 %).

An increase or decrease in operational vibration levels (at comparable operating conditions) less than 25 % may not be significant. An example of variation in vibration levels at steady state condition is shown in Figure B.11 (see key in the figure).

Repeated measurements at standstill (impact tests) can be performed in addition to vibration monitoring or solely. The online-measurements often give only an indication of a potential resonance situation. In such a case, scheduling measurements at standstill are advisable to confirm the suspected resonance.

If impact tests are repeated for comparison purposes, the following requirements shall be fulfilled:

- the impact force level is similar and the impact positions are identical,
- only identical measurement positions are considered for comparison,
- the same or higher frequency resolution is obtained with the repeated measurement,
- the temperatures during testing are similar (±10 °C).

The most interesting characteristics for comparison are typically

- the measured dynamic compliance close to 2f (most relevant),
- the natural frequencies of
  - 2-node vibration modes close to rotational frequency (1x),
  - 4-node modes (2-pole machines)/8-node modes (4-pole machines) close to twice line frequency (2f),
  - local vibrations modes close to 2f.

It is generally recommended to use the same units and scaling of diagrams for repeat measurements at the same machine. The preferred units are: FRFs in [μm/kN], operational vibration levels as peak to peak displacement amplitudes in [μm], phase angle in [°], frequencies in [Hz], temperatures in [°C].

Impact tests are usually performed at ambient condition and the resulting frequency response functions are different from those which would be present at operational temperature. This is due to a changed modal stiffness, see A.1.4. The related natural frequency decrease of global modes may be 1 Hz to 20 Hz or more, depending on the cooling technology as well as stator end-winding design and manufacturing technology. The expected frequency drop is typically in the range of a few hertz for direct water cooling and a stiff stator end-winding support. Indirectly cooled machines exhibit higher frequency drops, especially if the support structure is so flexible that a decrease of winding-insulation stiffness with temperature increase can significantly influence the modal stiffness.

When measurement results from impact tests have to be correlated to measured operational vibration levels the impact of operational temperature on modal stiffness shall be considered. This means that the measured dynamic compliance has to be evaluated for frequencies above 2f with a frequency distance equal to the specific frequency shift due to temperature increase.

7.3 Choice of measurement actions

Typically, stator end-winding vibrations are predominantly excited by the electromagnetic field inside the machine. The level of excitation forces depends on the size and rating of the machine as well as the actual operational parameters. Generally, these excitation forces cannot be avoided. The stator end-winding structure (with consideration of its design, manufacturing technology and ageing status) determines the static flexibility and the dynamic amplification, both of which could significantly influence the resulting vibration level. The dynamic properties of the stator end winding structure (natural frequencies, mode shapes and dynamic compliance, as they are measured by means of impact tests at standstill of the machine) provide the key-information for understanding the root-cause of increased vibration levels. On the other hand, dynamic properties are difficult to interpret in regard to the resulting operational vibration level, which is the only relevant quantity for assessment. The monitoring of vibration during operation provides reliable reference values for specific operational parameters (active and reactive power as well as characteristic temperature). The maximum of possible vibration levels can only be determined in an extensive measurement campaign with consideration to a wide variation of active and reactive power.

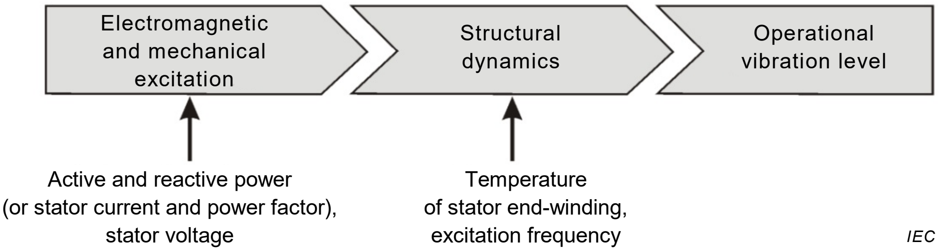


Figure 4 – Simplified cause effect chain of stator end-winding vibration and influencing operational parameters

A combination of measurement actions may help to provide sufficient information for interpretation. Figure 4 illustrates a simplified cause effect chain and related influencing operational parameters, which should always be considered whenever vibrations are discussed. Table 2 lists possible measurement actions for providing adequate information about various parts of this cause-effect chain.

Table 2 – Possible measurement actions to gain insight into various aspects of the cause-effect chain.

	Consideration of different electromagnetic and mechanical excitation	Detection of changes of structural dynamics	Nature of measured vibrations (global/local)
Measurements at standstill (Impact tests according to Clause 5)		– Reference and repeat measurements: • Identification of natural frequencies (EMA, DPA) • Identification of mode shapes (EMA) • Determination of structural response level (EMA) • Determination of local dynamic flexibility (DPA)	– EMA to investigate global vibration phenomena – DPA to investigate local vibration phenomena
Measurements during operation (Online-monitoring according to Clause 6)	– Monitoring at various comparable load conditions (see 7.2) – Recording electrical operational parameters during trending, active and reactive power (see A.1.4)	– Long-term trending of overall vibration level at comparable operational parameters, most favourable with respect to reference-measurements – Recording of a characteristic temperature – Recording of filtered 2f vibration amplitude and phase angle	– Measurements of global vibration level by means of a suitable number of sensors (see 6.3.1.2) – Measurements of local vibration level (see 6.3.1.3) – Measurement of the local vibration relative to a reference position (see B.4)

7.4 Aspects of machine’s condition and its history

Gradually developing changes of the vibration level or natural frequencies over time (as they are measured at comparable operational parameters) indicate a structural change, which may have been caused by long term operational effects. Abrupt changes can occur in global vibration levels with respect to natural frequencies of global modes. Other influencing events like electrical faults, repair activities or changed operating regime should be considered as potential causes and should be examined (refer to Clause B.2 for further details). The complete machine’s history is an inevitable base for any vibration diagnostics. A resurvey of visual inspection reports could also contribute to any related root cause analysis.

Annex A
(informative)

Background causes and effects of stator end-winding vibrations

A.1 Stator end-winding dynamics

A.1.1 Vibration modes and operating deflection shape

The operational vibration of the stator end-winding can be mathematically described with the method of modal analysis. According to this method, the vector of operational deflections at different locations due to a single-frequency force excitation acting simultaneously at several locations can be expressed with:

$$\{X\}=\sum_{r=0}^{N}\underbrace{\underbrace{\{\phi\}_r^T\cdot\{F\}}_{Modal\ \ Force}\cdot\frac{1}{k_r}\cdot\{\phi\}_r}_{Modal\ \ Static\ Deflection}\cdot\underbrace{\frac{1}{\left(1-\frac{\omega^2}{\omega_r^{\,2}}\right)+\left(i\cdot\eta_r\right)}}_{Modal\ \ Dynamic\ Amplification}$$

in which:

$\{\,\}$	is generally representing a vector of time-independent complex amplitudes, which can be physically interpreted as a spatial distribution,
$\{X\}$	is the operating deflection shape (ODS) (or forced vibration mode),
$\sum_{r=0}^{N}$	is the sum over N relevant modes, with the mode number $r=0,1\,..\,N$,
$\{\phi\}_r{}^T\cdot\{F\}$	is the modal force, in which
$\{\ldots\}^T$	is the transposition of a column vector to a row vector,
$\{\phi\}_r$	is the r-th mode shape (or eigenvector),
$\{F\}$	is the vector of time-independent complex force amplitudes,
$\omega=2\pi\cdot f$	is the angular frequency of the force excitation, in which
f	is the excitation frequency.
$\omega_r=2\pi\cdot f_r=\sqrt{\frac{k_r}{m_r}}$	is the angular natural frequency of the r-th mode, in which
f_r	is the natural frequency of the r-th mode,
k_r	is the modal stiffness of r-th mode,
m_r	is the modal mass of r-th mode,
η_r	is the structural damping loss factor of r-th mode.

The operational vibration magnitude of the stator end-winding results from a superposition of responses due to the various modes. These modes behave like single degree of freedom systems with independent ‘modal stiffness’, ‘modal damping’ and ‘modal mass’ parameters.

Subclause 5.2 describes the experimental modal analysis as a testing and analysing method to determine these modal parameters.

NOTE The formula above is valid for operational vibrations (which are due to operational forces) as well as for structural responses due to test-excitations (as performed during measurements at standstill of the machine).

A.1.2 Excitation of stator end-winding vibrations

Stator end-winding vibrations are predominantly excited by electromagnetic forces. They are due to the interaction of a magnetic field and an electrical current, each alternating with the line frequency (‘1f’). The resulting local forces are acting with a non-oscillating term and a superimposed second term, which is alternating with double line frequency (‘2f’). Thus the frequency spectrum of vibration is dominated by twice the fundamental frequency of phase currents:

– $2f$ = 100 Hz, if operating the electrical machine at 50 Hz grid,

– $2f$ = 120 Hz, if operating the electrical machine at 60 Hz grid.

Apart from the electromagnetic field, there are additional sources for stator end-winding vibrations. The stator end-windings participate with the vibration of the whole machine set, shaft train and its support system (e.g. foundation). Other possible sources for such interaction with stator end-winding vibration can be:

– rotor unbalance,

– weight induced shaft vibration of horizontal 2-pole rotors,

– alternating air-gap torque,

– other mechanical vibration sources in the neighborhood of the electrical machine.

Some of these sources have a frequency other than the electromagnetic 2f-excitation. Rotor unbalance, with the frequency of the rotor rotational speed, is an example and may cause other spatial deflection shapes.

A.1.3 Relevant vibration characteristics of stator end-windings

The following characteristics are most relevant for the assessment of stator end-winding vibrations:

a) The operational vibration deflection $\{X\}$.

b) The natural frequency f_r of a vibration mode (respectively its ratio to the excitation frequency f), which determines the modal dynamic amplification,

c) The mode shape $\{\phi\}_r$, which describes the vibration deformation of a mode when being excited and determines the modal force.

The operational vibration deflection $\{X\}$ is the most decisive parameter, as it indicates whether a permanent stator end-winding vibration of a certain level can impact structural integrity or not. The measurement of operational vibrations (see Clause 6) has therefore the highest significance for assessment. Even a permanent presence of a resonance situation does not endanger structural integrity, if the operational vibration is on an acceptable level.

Further information can be obtained with impact tests, i.e.:

– Modal parameters, in particular natural frequency, mode shape and modal damping as results from experimental modal analysis (see 5.2).

– Structural response level, i.e. the level of the frequency response functions (see 5.3).

– Local dynamic flexibility as a result from driving point analysis (see 5.3).

Such impact tests at stator end-windings are performed either

- to gain additional information on structure dynamics as a complement to available measurement data on operational vibrations, or
- to assess structure dynamics in regard to operational vibration, if no operational vibration measurements are available for extrapolation.

Stator end-winding vibrations are typically discussed with regard to their spatial expansion. Two different types of vibration modes should be distinguished as they behave differently during machine operation and require different measurement methods:

- A global vibration mode involves a large part of stator end-winding structure, i.e. the winding bars outside the stator core and the support components. Winding connections are typically also involved.
- A local vibration mode involves only a part of the stator end-winding structure with typically small spatial expansion relative to the circumference of the stator end-winding. Parts of individual winding bars or individual winding connections are typically in focus when discussing local vibrations.

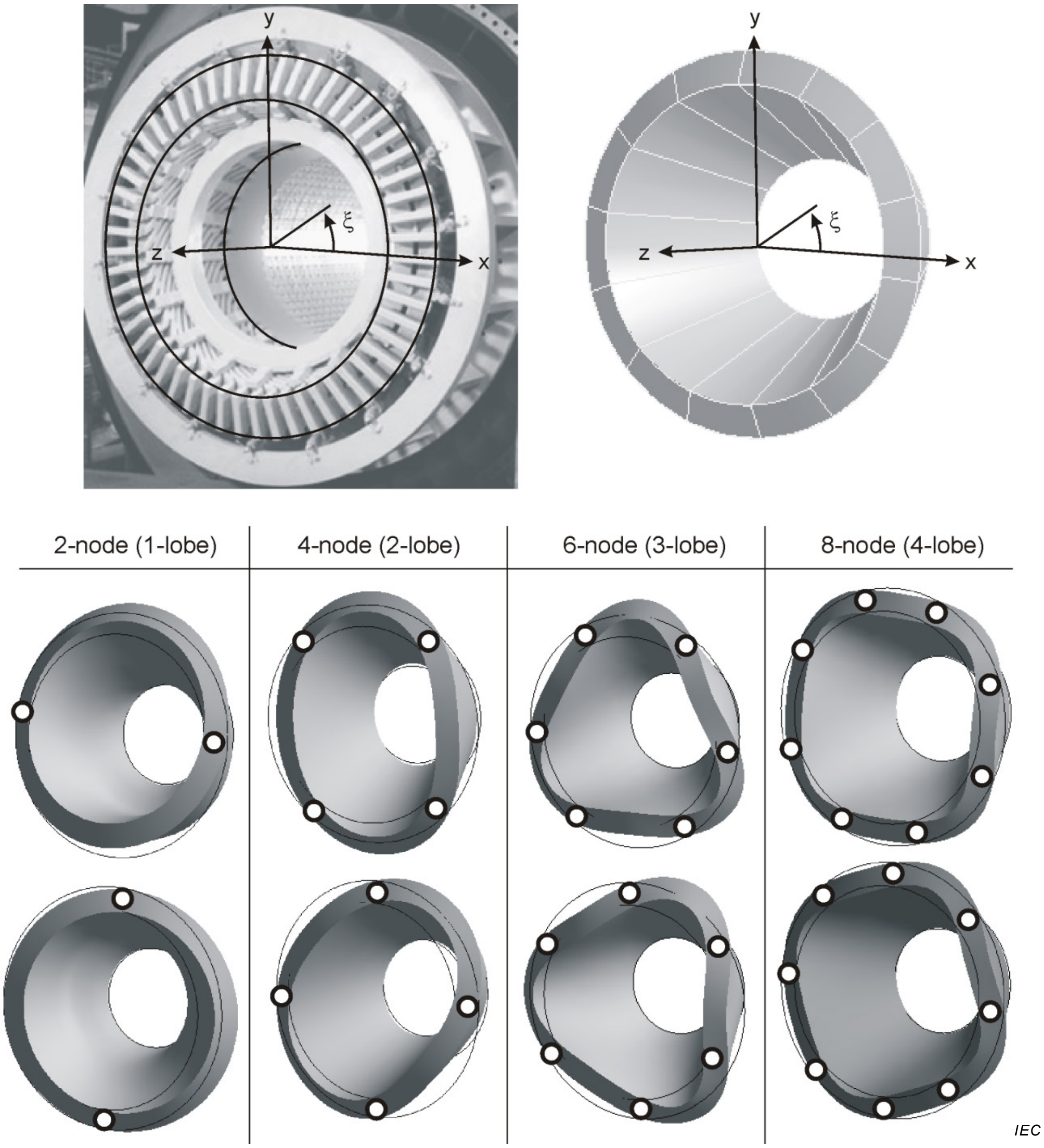
In accordance with the general formula in A.1.1, only those modes with a significant modal force contribute to the operational vibration level, that is, those that are associated with a mode shape being correlated with the spatial distribution of the electromagnetic forces. This has to be considered when assessing global vibration modes, because they are not necessarily resulting in an increase of vibration amplitude which is the dynamic amplification when exciting with a frequency equal to the related natural frequency. As a direct consequence of the general winding layout of multi-phase machines, the magnetic field and the electrical currents are distributed with a periodicity of $1p$ over the circumference, where p is the number of pole pairs. It is equal to 1 for two-pole machines and equal to 2 for four-pole machines. The interaction of field-distribution and current-distribution leads to a predominant electromagnetic force which is a component of the total force distribution $\{F\}$ with:

- a periodicity of 2 over the circumference for two-pole machines (p = 1),
- a periodicity of 4 over the circumference for four-pole machines (p = 2).

This general statement applies to the fundamental wave of all multi-phase machines, independent from their design and technology. Further periodicities of force can be present, but these are generally exciting on a significantly lower level. Therefore the main interest is on those global modes, which have the same periodicity as the force excitation and can lead to a modal force $\{\phi\}_r^T \cdot \{F\} \neq 0$. They are the so-called:

- ‘4-node’ modes, having a periodicity of 2 (relevant for 2-pole machines), and
- ‘8-node’ modes, having a periodicity of 4 (relevant for 4-pole machines)

Figure A.1 illustrates typical global mode shapes as they occur at stator end-windings of multi-phase machines.



NOTE The global vibration modes are illustrated as they typically occur with stator end-winding structures of large multi-phase machines (at the top: stator end-winding (left) and cone-idealization (right); at the bottom: global mode shapes with marked node-positions)

Figure A.1 – Illustration of global vibration modes

There are generally two different mode shapes with the same number of nodes, but different node-positions. The related natural frequencies are nearly the same for isotropic stator end-winding structures. Different natural frequencies are expected for those stator end-windings that are featured with winding connections which generally results in an asymmetric topology.

The electromagnetic forces are exciting the various modes of the stator end-winding structure in the radial, tangential and axial directions. The resulting operational deflection shape (ODS) has also radial, tangential and axial components, which are caused by the shapes of the excited modes. The vibration level is typically highest at the bar ends and mainly in the radial direction. Therefore, the 'global vibration level' is usually determined by the measurement of the radial deflection at the stator bar ends, see A.3.1.

Local vibration modes are always excited during operation because their spatial extension is small compared to the electromagnetic force distribution. The modal force $\{\phi\}_r^T \cdot \{F\}$ is generally not negligible. Their level of vibration has to be determined by operational vibration measurements and not extrapolated from impact test results.

A.1.4 Influence of operational parameter

Stator end-windings are predominantly excited by the electromagnetic forces $\{F\}$. Thus the vibration level strongly depends on electrical operational parameters.

New types of large turbine driven generators are normally run during type tests in the factory, see IEC 60034-4:2008, 6.4 (no-load saturation test) and 6.5 (sustained three phase short circuit test). During the short circuit test the stator end-winding vibration is mainly caused by the electromagnetic forces acting on the stator end-winding and depends on the stator current. During the no-load test the stator end-winding vibration is mainly caused by the stator core deflection and depends on the stator voltage.

For electrical machines operating on grid (with power loading), both excitation sources occur simultaneously and the vibration response is a superposition of both. The load influences both excitation components differently. The electromagnetic forces are dependent on the stator and rotor currents (or roughly from the square of stator current or apparent power) act directly. The excitation by stator core deflection mainly depends on the stator voltage and reactive power. Therefore, it is strongly recommended to record

– either the stator current, the stator voltage, the power factor,
– or the active and reactive power as the most relevant electrical operational parameters.

Further electrical parameters like stator voltage and line-frequency could also influence the vibration level. Recording stator voltage and line-frequency in addition is also advisable.

Changes of the operational load lead to a transient change of the vibration level. This shall be considered when evaluating vibration data.

Local stator end-winding vibrations are excited by the vibrations of the global structure and the locally acting electromagnetic forces, as well. Therefore, the local vibration level relative to a reference position (see Clause B.4) generally shows another dependency from the electrical operational parameters than global vibrations. Locally applied sensors are required to measure the dependency of local vibration level from active and reactive power, see 6.3.1.3.

The modal stiffness k_r can also depend on the winding temperature, which is changing with the apparent power of the electrical machine. The additional recording of a characteristic temperature could also be advisable.

A.2 Increased stator end-winding vibrations

A.2.1 General aspects of increased vibration

During normal operation, electromagnetic forces are always exciting vibrations of the machine’s structure. The cause for vibrations is inherently associated with the rotating magnetic field inside the AC-machine and goes along with its function, namely the conversion of electrical power to mechanical power (motor operation) or vice versa (generator operation). Electromagnetically induced vibrations of the stator end-winding structure are generally not avoidable.

The manufacturer of electrical machines designs and dimensions the stator end-winding structure in such a way, that the resulting operational vibration does not impair the mechanical and electrical integrity of the machine. There is a significant spread of the acceptable operational vibration levels because the mechanical integrity is dependent on:

- the overall stator end-winding design and any specific design features, which have been introduced to enable the machine to withstand abnormal dynamic forces,
- the dimensioning,
- manufacturing technology,
- maintenance, and
- age of the machine.

Therefore, it is not possible to give more precise guidelines for acceptable operational vibration.

When interpreting modal analysis results, a resonance condition does not necessarily lead to high operational vibration:

$$\{X\} = \sum_{r=0}^{N} \underbrace{\underbrace{\{\phi\}_r^T \cdot \{F\}}_{Modal\ \ Force} \cdot \frac{1}{k_r} \cdot \{\phi\}_r}_{Modal\ \ Static\ Deflection} \cdot \underbrace{\frac{1}{\left(1-\dfrac{\omega^2}{\omega_r^{\,2}}\right)+\left(i\cdot\eta_r\right)}}_{Modal\ \ Dynamic\ Amplification}$$

- If the amplitude of F is small compared to the static stiffness k, the resulting vibrations can also be small.
- If the force distribution F does not match the mode shape φ, the modal force is very small (e.g. 6-node modes excited by the fundamental wave).
- Even if the frequency ratio ω / ω_r is equal to 1, the resulting modal dynamic amplification can be small if the modal damping η_r is high.

Even if $\omega = \omega_r$ and the mode shape is a 4-node mode, the structural response level (e.g. the measured dynamic compliance at natural frequency) still needs to be judged because a high stiffness k_r and/or a high damping η_r can result in a low vibration level. Generally this check can be done by the measurement of operational vibrations.

A.2.2 Increase of stator end-winding vibrations levels over time and potential remedial actions

Mechanical structures can respond with increased vibration level due to changes of

a) excitation force $\{F\}$;

b) excitation frequency f;

c) modal stiffness k_r;

d) natural frequencies f_r and mode shapes $\{\phi\}_r$ of the structure;

e) damping η_r.

See formula in A.1.1.

Stator end-winding vibration levels may change over time due to a changed operational parameter, such as double line frequency (influence of b), active power (influence on a), reactive power (on a), operational temperature (on c, d and e), harmonic content of phase currents (a, b), or due to a changed structure dynamics for example dynamic stiffness (c) or damping (e).

The excitation by electromagnetic forces is dependent on the operational parameters and not avoidable when the machine is operated.

The structural dynamics of the stator end-winding is typically changing because of a decreasing structural stiffness (c) going along with gradually decreasing natural frequencies (d) of the relevant vibration modes. Such effects may lead to vibration levels above the level where damage of the end-winding may occur, which may lead to further degradation of the stator end-winding structure and further loss of structural stiffness.

In such cases it is recommended to operate the machine in such a way (e.g. change active power, reactive power) that the operating vibration levels are reduced until remedial action is conducted. Modifications of the stator end-winding support structure can help to change the natural frequency of the predominantly excited mode. Such detuning measures target the increase of natural frequency clearly above the excitation frequency (high tuning) or the reduction of natural frequency clearly below the excitation frequency (low tuning). Subsequent vibration monitoring can be used to confirm the reduced vibration level.

The decrease of structural stiffness is typically going along with abrasion at the surface of the winding insulation or with a loosening of spacers and fasteners. Some machine manufacturers have implemented retightening systems to simply remove loosening by applying clamping force. Resin injection and refastening are other typical maintenance activities to sustain the structural stiffness. Abrasion at the surface of the winding can damage the electrical potential grading system and can cause additional electrical degradation. It is strongly recommended to involve technical experts to distinguish the signs of mechanical abrasion and electrical degradation.

Operational vibrations are not the only cause for gradually decreasing natural frequencies. The decrease of structural stiffness can be initiated by abnormal operational parameters like electrical faults. Also power cycling can cause cyclic thermal elongation/contraction and/or thermal stress in the stator end-winding structure, if the stator end-winding support structure is not designed to allow for thermal flexibility. Such thermal stress might lead to an initial loosening that can develop further due to vibrations.

The measurement of stator end-winding vibration at standstill (Clause 5) is used to periodically check the change of structural dynamics when planned outages give the opportunity for opening the machine.

The measurement of stator end-winding vibrations during operation (Clause 6) enables the detection of long-term changes of stator end-winding vibrations which are due to a gradual decrease of structural stiffness.

A.2.3 Transient conditions as cause for structural changes

Electrical faults like sudden short circuits to ground or phase-to-phase shorts at or near the machine terminals cause high transient currents in the stator windings which could influence the structural behaviour of stator end-windings. It can be outlined as follows.

- The maximum amplitude of transient fault currents can exceed the rated current at steady state operation by a factor of ten or more. As forces during faults grow roughly with the power of two of the current, the increase of transient mechanical forces may reach more than hundred times the forces at rated condition.
- Although the transient forces are of short duration, the high level causes the stator end-winding structure to have a large deflection, which could endanger its mechanical integrity.
- The highest transient forces occur where coils or bars of different phases are located side-by-side (phase splits and parallel rings). Depending on the current direction in both coils/bars the spacing and fastening elements are exposed to high contracting and expanding forces, which could locally crack the fixation structure.

– Stressing the local support components such as spacing, clamping and fastening elements with high transient forces could create loosening of several areas of the stator end-winding support structure. The structural stiffness of stator end-windings changes.

– The change in structural stiffness could result in higher global and local vibration levels during the normal operation conditions.

– When monitoring the vibration level an impact of high transient forces could be indicated by a sudden change in trend amplitudes at comparable load conditions.

NOTE Measurements of stator end-winding vibrations typically focus on normal (steady state) operation. Manufacturers of large generators perform type tests, in which transient vibration deflections are also monitored and documented. Permanent or frequently repeated vibration measurements during plant operation are not usually configured for recording the vibrations during fast transients. The required resolution of vibration deflection over time results in a huge amount of data which can usually not be managed for long term monitoring. Usual trending of vibration levels facilitates only the detection of a changed vibration level during normal operation which might be caused by a transient condition in between.

A.2.4 Special aspects of main insulation

The condition of main insulation is generally a crucial factor for the life cycle of high-voltage stator end-windings, which might be affected by increased stator end-winding vibrations or vice versa might cause increased stator end-winding vibrations.

The main insulation also provides structural stiffness and facilitates the mechanical contact between the electrical conductor and the stator end-winding support system. Whereas the main insulation has only a minor effect on natural frequencies by changes of its stiffness, the contact function of the insulation appears to be the predominant effect.

A.3 Operational deflection shape of global stator end-winding vibrations

A.3.1 General

The number and positioning of sensors for measurement of global vibration level is given in 6.3.1.2 for two pole machines (6 equidistantly positioned sensors) and for four pole machines (12 equidistantly positioned sensors). The following gives the reasoning for this.

A.3.2 Force distributions relevant for global vibrational behaviour

In most cases it is appropriate and sufficient to discuss operational stator end-winding vibrations only in regard to the fundamental wave of electromagnetic excitation forces (i.e an elliptical distribution in case of 2-pole machines), see A.1.3. The angular velocity of the rotating magnetic field inside the multiphase-machine, which is operating with a symmetrical current system, is equal to:

$$\omega_F = \frac{2\pi \cdot f}{p},$$

in which f is the line frequency and p is the number of pole pairs.

NOTE Negative sequence voltage components in electrical grids can cause related negative sequence currents. Such unsymmetrical operation leads to an additional rotating field in reverse rotation direction.

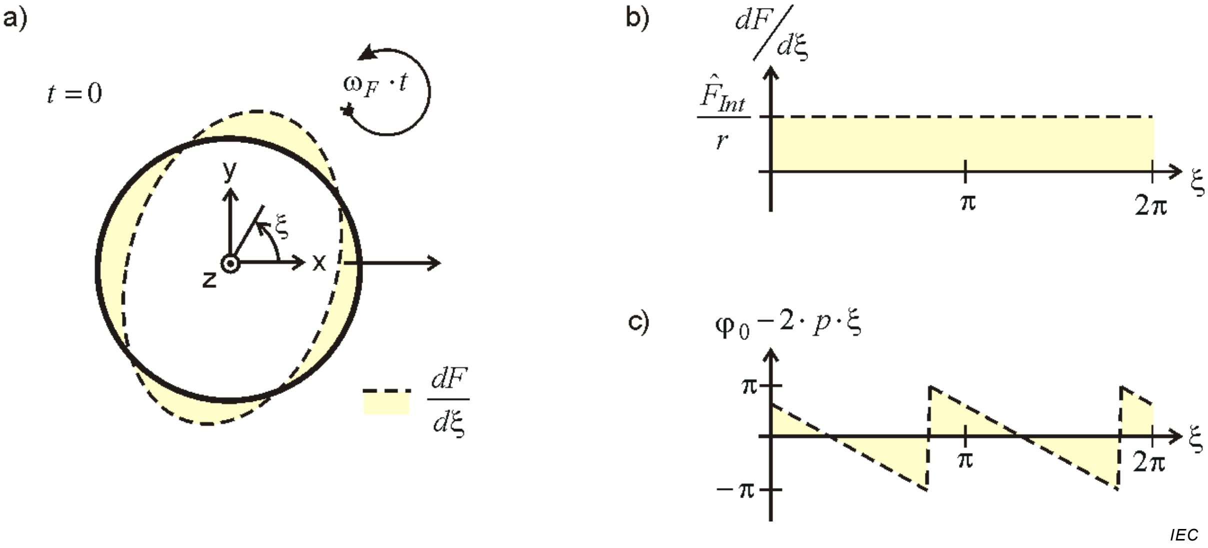
Using the coordinate system as given in Figure A.1, the fundamental wave of force-density $dF/d\xi$ (i.e. the portion of force dF acting on a circumferential sector $d\xi$ of the stator end-winding) can be described with the general analytical expression:

$$\frac{dF}{r \cdot d\xi} = \frac{\hat{F}_{Int}}{r} \cdot \cos\left(4\pi \cdot f \cdot t - 2p \cdot \xi + \varphi_0\right),$$

where

$\hat{F}_{Int}$	is the amplitude of a radial, tangential or axial force component integrated of half of wavelength (i.e. 1/(4 $\cdot\, p$) of circumference of the end-winding structure) in [N],
r	is the mean radius of the end-winding structure in [m], for which the force $\hat{F}_{Int}$ is determined,
t	is the time in [s],
ξ	is the circumferential coordinate (azimuth) in [rad],
$r \cdot \xi$	is the circumferential length in [m],
φ_0	is the initial phase in [rad] ($t = 0$, $\xi = 0$).

This simple analytical description of the electromagnetic forces is sufficient to work out the typical vibration deflection of stator end-windings while in operation. Figure A.2 below illustrates this relation for a two-pole machine.



Key

a) Instantaneous distribution of force, which is acting in radial, tangential or axial direction at t = 0.

b) Amplitude of force density as a function of azimuth ξ.

c) Phase of forces as a function of azimuth ξ.

Figure A.2 – Example of rotational force distribution for p = 1

A.3.3 Idealized global vibration behaviour while in operation

A rotating wave of vibration deflection with constant amplitude follows the force excitation wave with a certain time-delay. If the stator end-winding structure were to be perfectly isotropic, the rotating wave of vibration deflection would have constant amplitude $\hat{U}$, which can be measured with a sensor at any circumferential position of the end-winding:

$$u = \hat{U} \cdot \cos\left(4\pi \cdot f \cdot t - 2p \cdot \xi - \varphi_{Dyn} + \varphi_0\right),$$

where

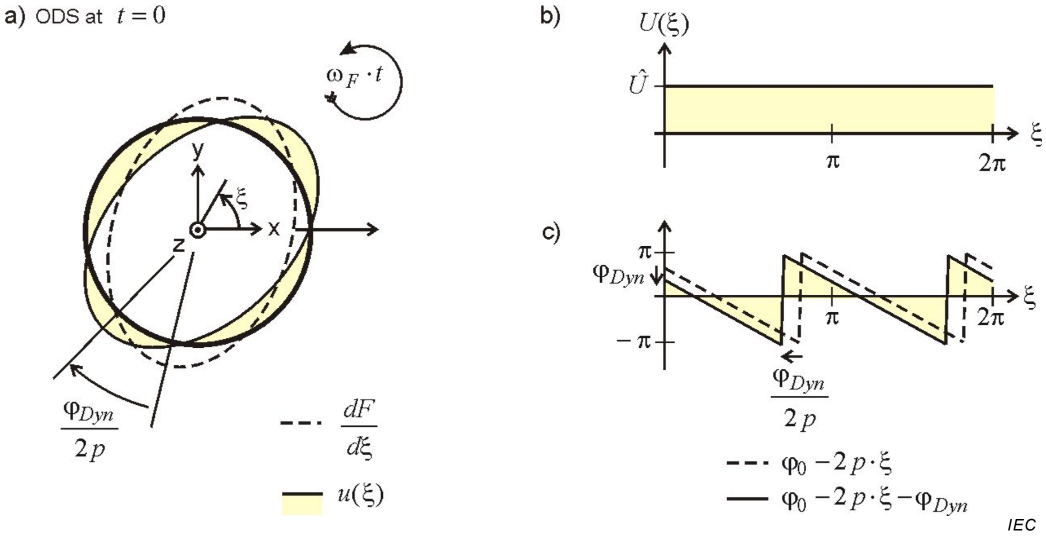
u	is the instantaneous values of global vibration,
$\hat{U}$	is the amplitude of global vibration deflection,

φ_0 is the initial phase (as defined by the electromagnetic forces, see A.3.1),

φ_{Dyn} is the phase shift between force- and deflection-wave due to global structural dynamics of the stator end-winding.

Figure A.3 illustrates this idealized global vibration behaviour of stator end-winding, where the dashed curves represent the electromagnetic force and the solid curves represent the operating deflection.

In this idealized situation, one sensor at an arbitrary position would be sufficient to detect the global vibration level.



Key

a) Instantaneous spatial distribution of forces and vibration deflection at $t = 0$.

b) Vibration amplitude as a function of location ξ.

c) Vibration phase as a function of location ξ.

Figure A.3 – Example of rotating operational vibration deflection wave for p = 1

The behaviour of high tuned stator end-winding structures is dominated by their structural stiffness and show a shape in phase to the force. This means a negligible lagging phase shift φ_{Dyn} of the vibration deflection wave relative to the fundamental wave of force distribution. If the structure is excited at or close to its natural frequency by an appropriate modal force, the vibration deflection is lagging by $\varphi_{Dyn} \approx 90°$. Low tuned stator end-winding structures show a lagging of nearly $\varphi_{Dyn} \approx 180°$, which means a vibration deflection in counter phase to the forces.

In practice, the phase of operational vibration is not measured in relationship to the electromagnetic force. The measurement device typically evaluates the phase by comparing the phase of measured vibration with that of a reference signal, which can be derived from

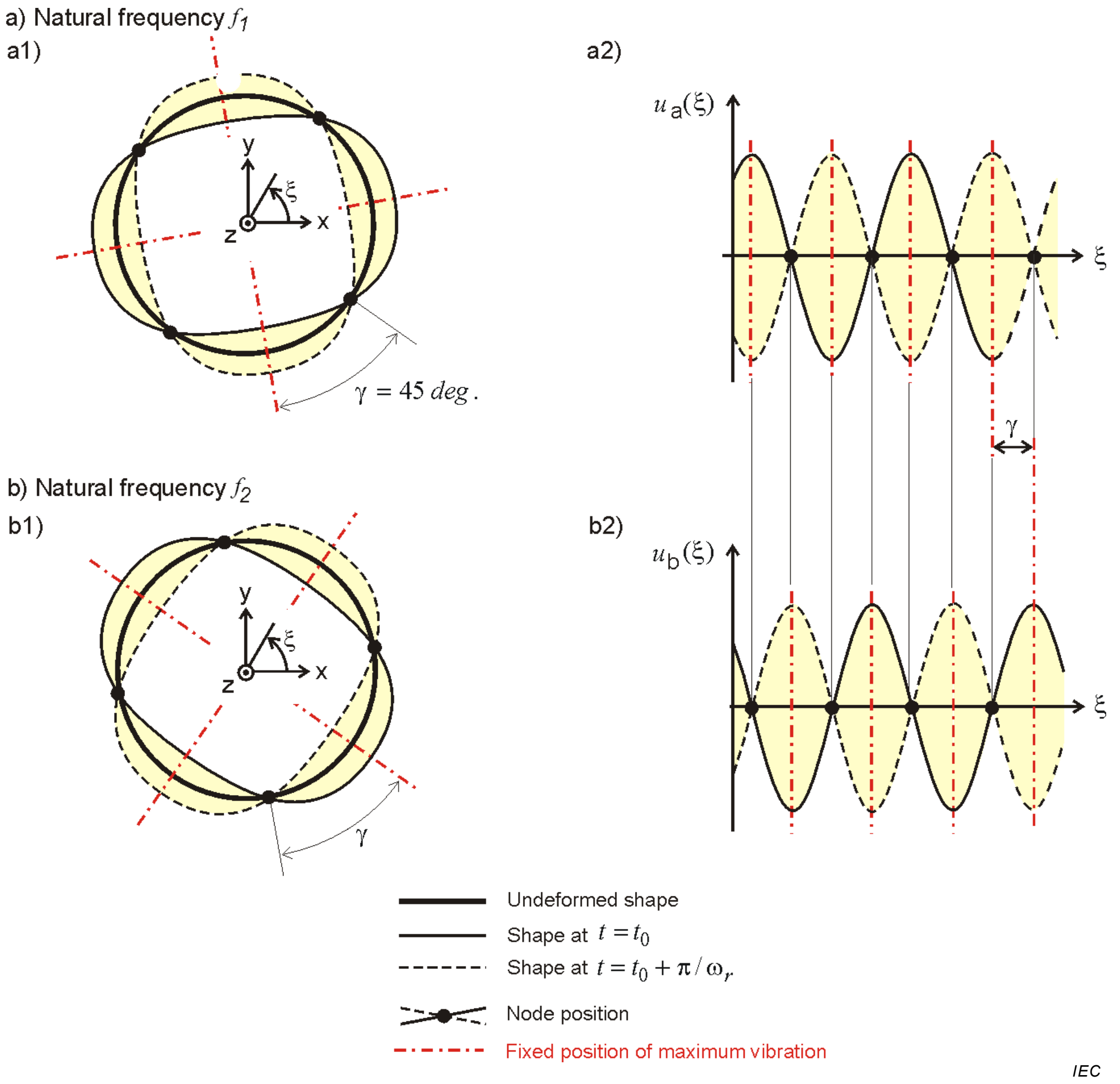
- a phase reference rotating with the rotor (shaft synchronization signal),
- a vibration probe mounted somewhere on the machines stator structure,
- one of the machines stator voltages,
- one of the machines stator currents.

The type of reference signal shall be the same, when phase changes are compared for different load conditions. Most common is the use of phase reference rotating with the rotor (shaft synchronization signal).

A.3.4 General vibration behaviour of stator end-windings

The operational vibration often differs from the idealized vibration behaviour as described above in A.3.2. This can be due to additional excitations (as described in A.1.2) or due to non-isotropic dynamic behaviour of the stator end-winding structure. In the following, only the effects of anisotropy are discussed.

As already illustrated in Figure A.1, the excitable 4-node respectively 8-node modes have mode shapes with different node positions and in the case of an anisotropic behaviour they also have different natural frequencies. The node positions of the mode shapes are fixed in space independent from the excitation. Figure A.4 below illustrates this phenomenon.



Key

a1, a2) Shape of mode 1 having the natural frequency f_1.

b1, b2) Shape of mode 2 having the natural frequency f_2.

Figure A.4 – Illustration of two vibration modes with different orientation in space (example for p = 1)

Such kind of anisotropic vibration behaviour can be caused by:

– the presence of winding connections, and/or,
– an anisotropic support system.

The angular distance between both mode shapes is generally given by:

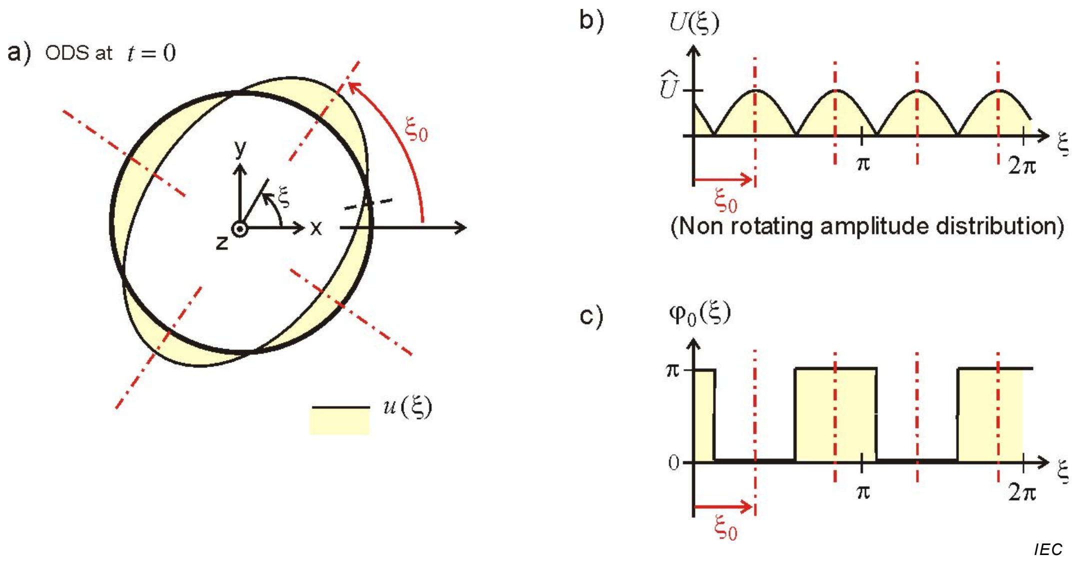
$$\gamma = \frac{\pi}{4 \cdot p}$$

This means an angular distance of:

– 45° for two-pole machines ($p = 1$), and
– 22,5° for four pole machines ($p = 2$).

It is important for the conduction of experimental modal analysis that the impact is chosen such that a node is not impacted. Vibration modes, which are relevant for operational vibration levels, might remain undiscovered. In order to ensure a reliable result from experimental modal analysis, at least two impact positions should be performed with an angular distance of approximately 45° for 2-pole machines and 22,5° for 4-pole machines.

Strongly pronounced anisotropy of the stator end-winding structure can result in considerable differences of the natural frequencies. Therefore, in operation only the mode which has its natural frequency closer to the excitation frequency $2f$ can be excited. This results in a variance of operational vibration amplitude and phase over the circumference as shown in Figure A.5. The red chain dotted lines mark the fixed orientation of the vibration maximum. Only sensors that are positioned at the positions of the chain dotted lines can measure the true amplitude.



Key

a) Instantaneous spatial distribution at t = 0.
b) Amplitude as a function of location ξ.
c) Phase as a function of location ξ.

Figure A.5 – on-rotational operational vibration deflection wave (example for p = 1)

An analytical expression for the operational vibration deflection can be stated for such special situations:

$$u = U(\xi) \cdot \cos(4\pi \cdot f \cdot t + \varphi_0),$$

where ξ_0 identifies the azimuth of the vibration maximum and

$$U(\xi) = \hat{U} \cdot \cos(2 \cdot p \cdot (\xi - \xi_0))$$

is the measurable vibration amplitude in dependency of the azimuth ξ. The maximum measurable amplitude $\hat{U}$ is here the level of global stator end-winding vibration.

Figure A.6 shows an example of amplitude and phase distribution for a more general situation, when a rotating vibration deflection wave (Figure A.3) superimposes a non-rotating vibration deflection wave (Figure A.5). The vibration amplitude $U(\xi)$ can be measured when positioning a sensor at the location ξ.

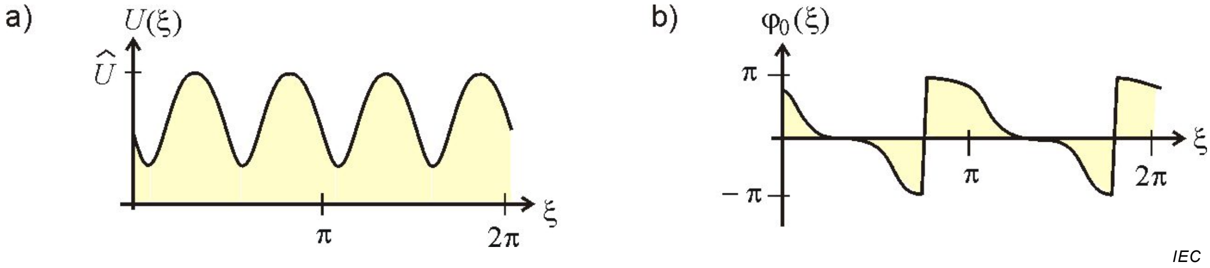


Figure A.6 – Amplitude and phase distribution for a general case.

EXAMPLE Vibration superimposed by 30 % of a rotating vibration deflection wave (Figure A.3) plus 70 % by a non-rotating vibration deflection wave (Figure A.5).

(a) Amplitude of sensor signal, measurable with a sensor at location ξ

(b) Phase angle of sensor signal, measurable with a sensor at location ξ

The negative sequence current component, which occurs when operating the electrical machines with unsymmetrical voltage, causes a vibration wave with inverse rotating direction. The shape of the total operational vibration cannot be distinguished from the situation described above. Significant unsymmetrical operation conditions shall therefore be reported when documenting measured operational vibration.

A.3.5 Positioning of sensors for the measurement of global vibration level

The sensors for the measurement of operational vibration level are often positioned at the bar ends of stator end-windings and are usually directed radially. This is because the excitable modes of stator end-windings typically have their highest structural response at the bar ends in the radial direction. The operational vibration, as described in A.3.3 for a general case, requires using multiple sensors distributed over the circumference of the stator end-winding in order to catch the maximum vibration level $\hat{U}$.

The winding arrangement of 3-phase machines with two poles has 6 equally shaped winding zones over the circumference. It is recommended to mount the sensors (approximately) in the centre of winding zones, which is between two winding connections, if present. Figure A.7 below illustrates this situation.

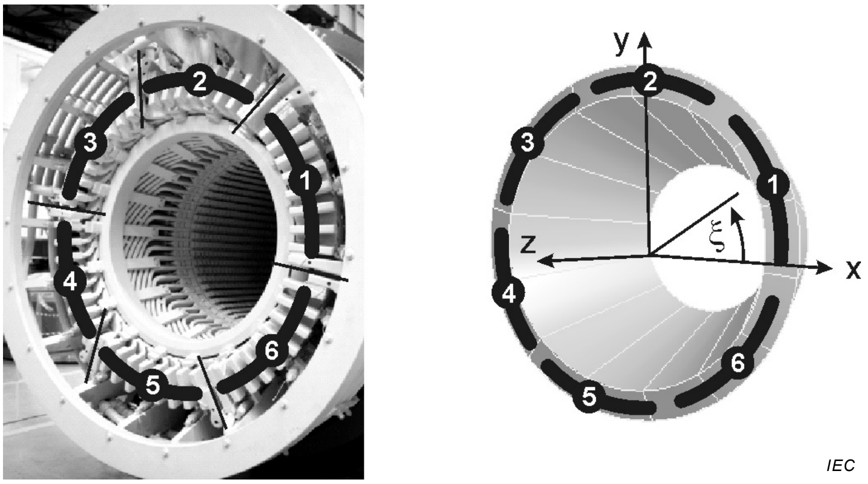
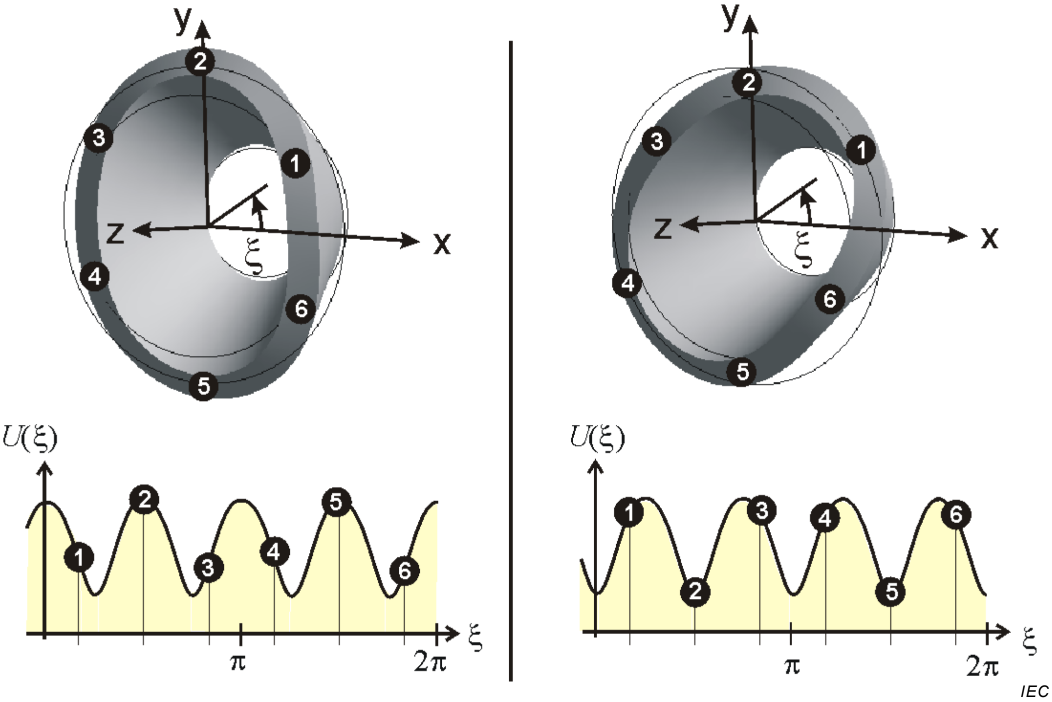


Figure A.7 – Sensors for the measurement of global vibration level centred in the winding zones

It can be shown that using this configuration at minimum one of the sensors is positioned at close to one of the vibration maxima. Figure A.8 demonstrates this by two exemplarily chosen fixed orientations of 4-node modes, as they are excitable for 2-pole machines.



Key

At the top: two 4-node mode shapes with arbitrarily chosen fixed orientation

At the bottom: resulting distribution according to the example in Figure A.6

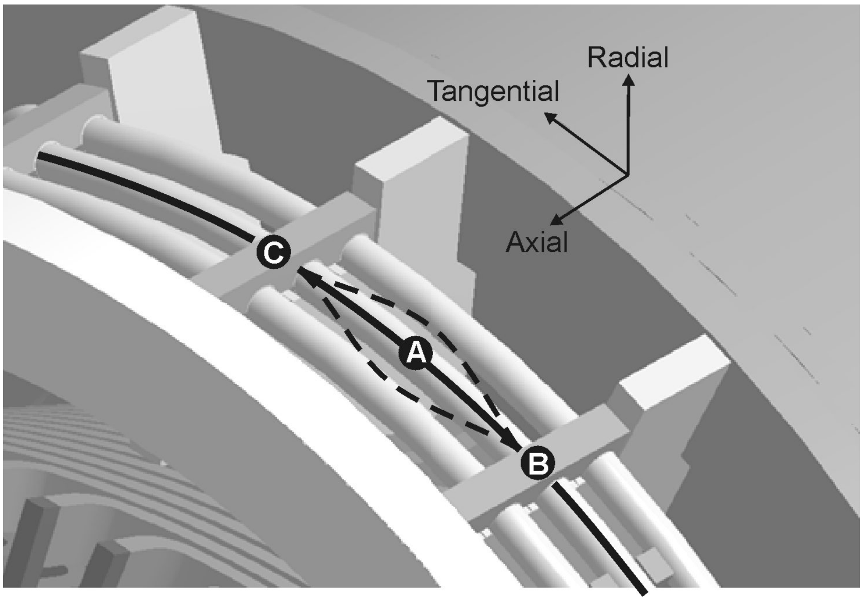
Figure A.8 – Measurement of global vibration level with 6 equidistantly distributed sensors in the centre of winding zones

NOTE The exact maximum can also be derived through a spatial Fourier analysis.

For four poles machines, in analogy with 12 winding zones, 12 sensors would be required. It is however conceivable to reduce the number of sensors to 6 and distribute these 6 sensors only over half of the circumference.

A.4 Operational deflection shape of local stator end-winding vibrations

Vibrations of individual components attached to the general global end-winding structure will be discussed in the following as local stator end-winding vibrations. Such components might be winding connections, specific winding parts, parts of support etc. These components can have a vibration level different to the global one. If this local vibration level has to be investigated, it is recommended to perform such measurement only in addition to global vibration measurements (see A.3.4). In order to distinguish between a forced kinematic coupling with global vibration behaviour and real local resonance, it might also be advisable to measure the locations where the vibrating component is attached to the global structure, see as an example points B and C versus A in Figure A.9.



NOTE Sensor positions C and B are chosen to provide the global end-winding vibration level and A to measure the local vibration level of the winding connection. The dashed lines illustrate the shape of the vibration.

Figure A.9 – Example – Sensor positions for the measurement of local vibration level of the winding connection relative to global vibration level

The measurement position for the measurement of local vibration can be chosen:

- according to an assumed vibration shape of the local mode,
- based on the results of experimental modal analysis (see 5.2),
- based on the measured local dynamic flexibility at several positions (see 5.3).

Since it might be difficult to predict the direction of maximum vibration, it is recommended to measure the vibration in three directions.

Annex B
(informative)

Data visualization

B.1 General

Annex B describes the options and gives examples for data visualization (see Figures B.1 to B.16).

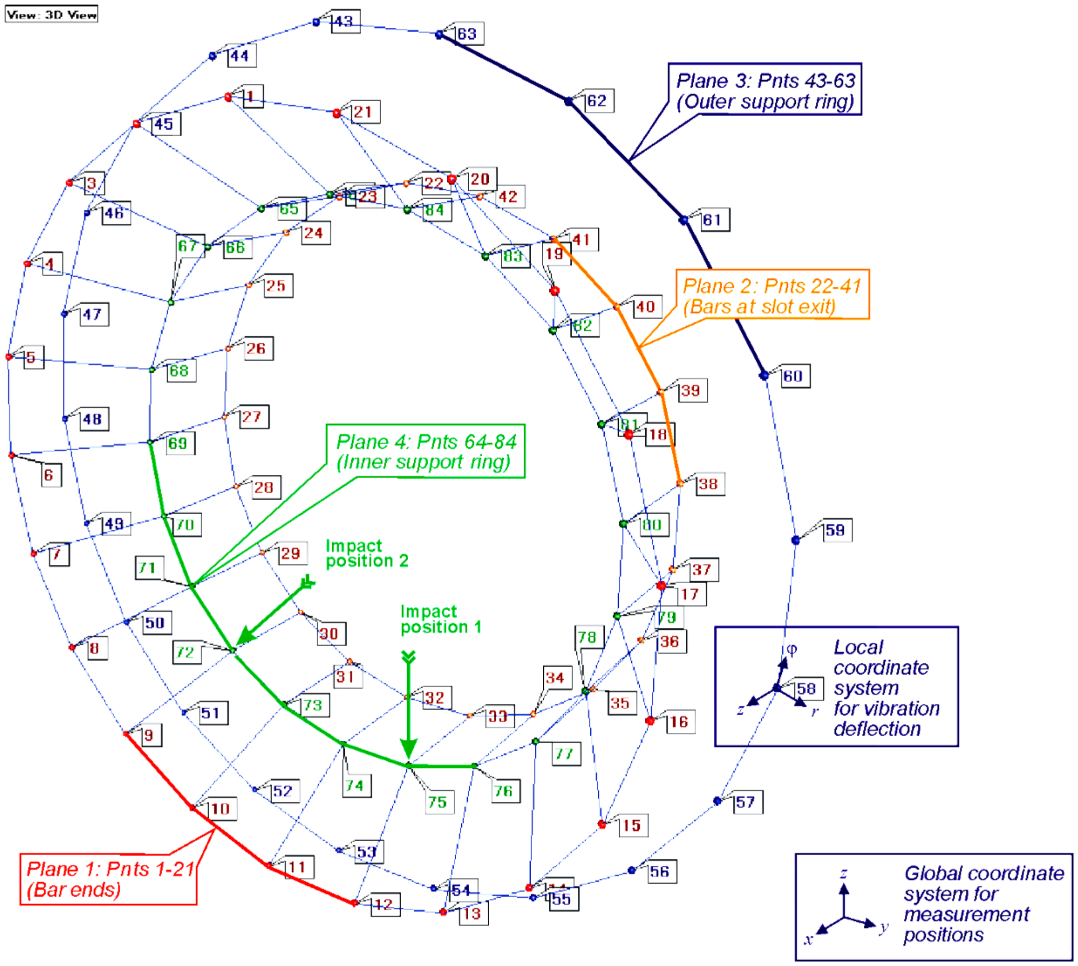


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Figure B.1 – Measurement structure with point numbering and indication of excitation

B.2 Standstill measurements

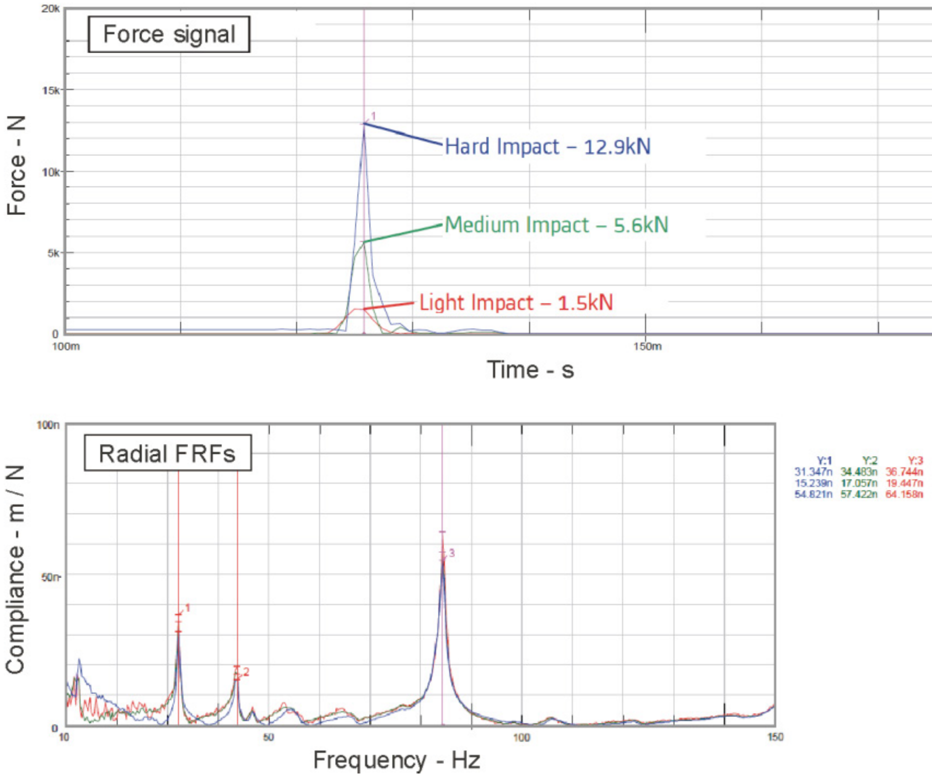

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Figure B.2 – Example for linearity test – Force signal and variance of related FRFs

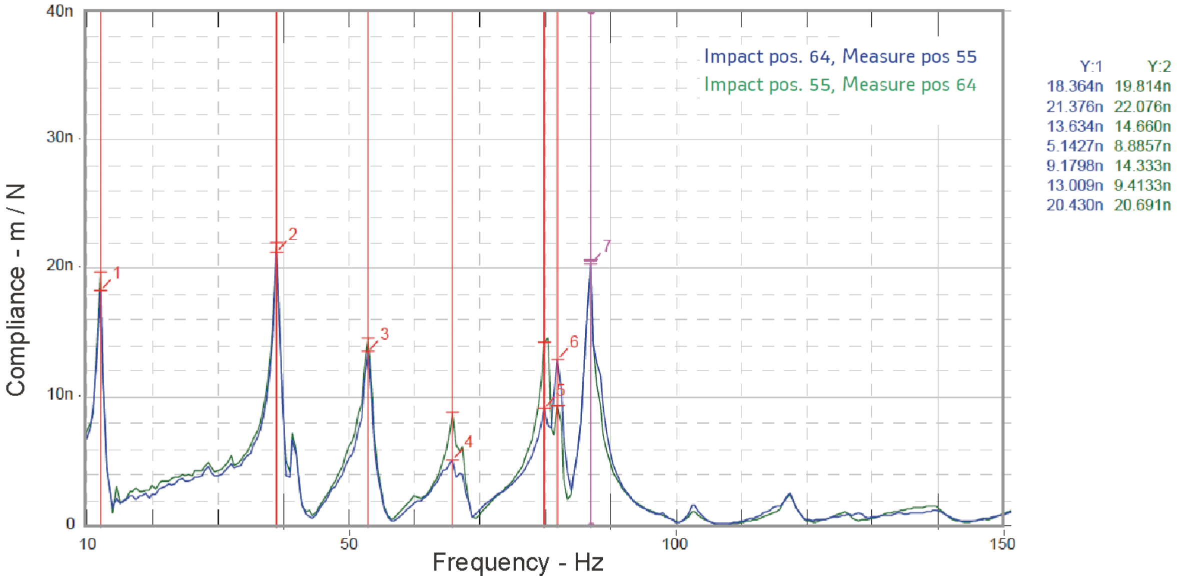

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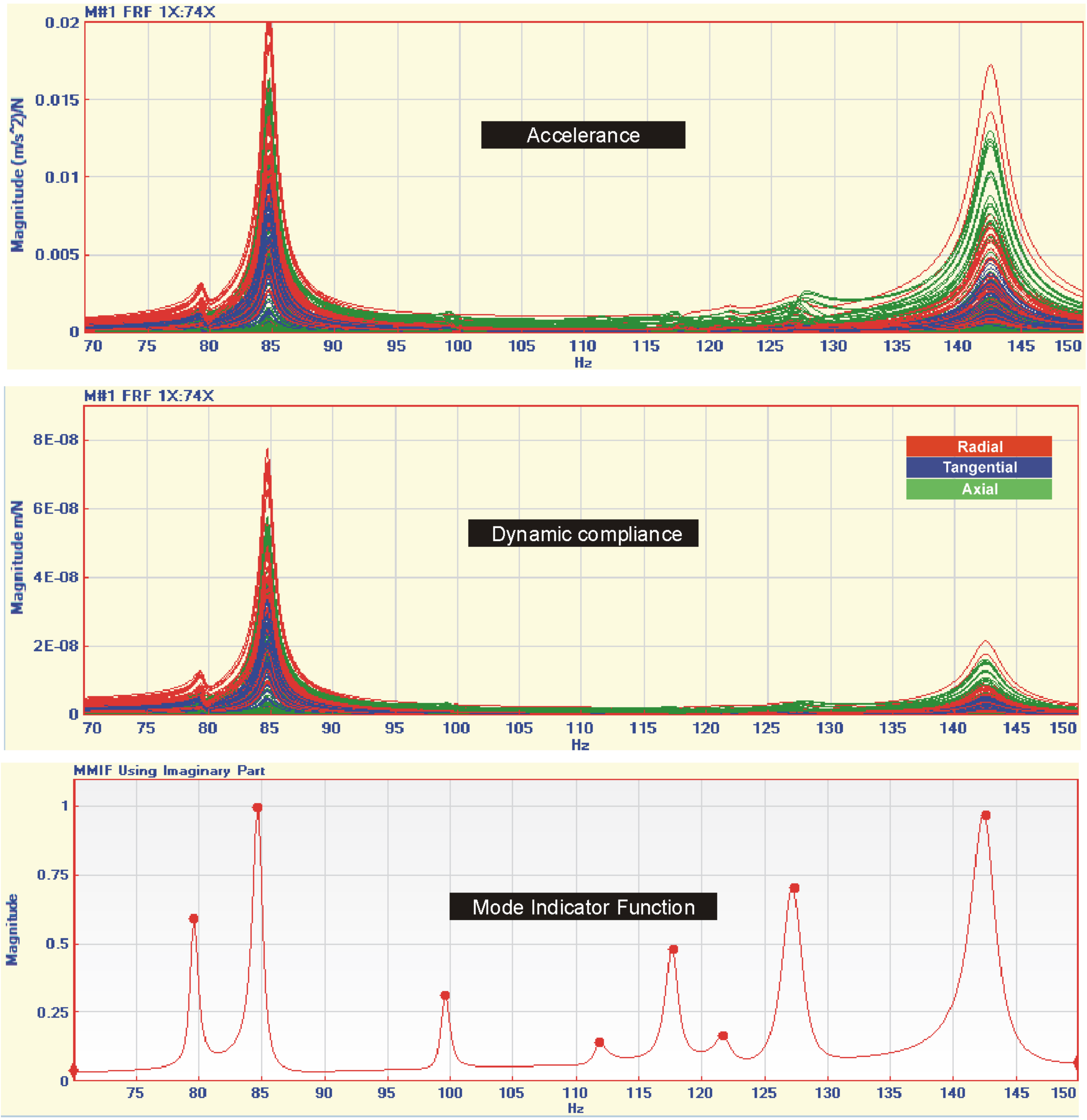
Figure B.3 – Example for reciprocity test – FRFs in comparison



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Key

At the top: Plot of the accelerance (= vibration acceleration/force)

In the middle: Plot of the dynamic compliance (= vibration displacement/force)

At the bottom: Mode indicator function

Figure B.4 – Example – Two overlay-plots of the same transfer functions but different dimensions

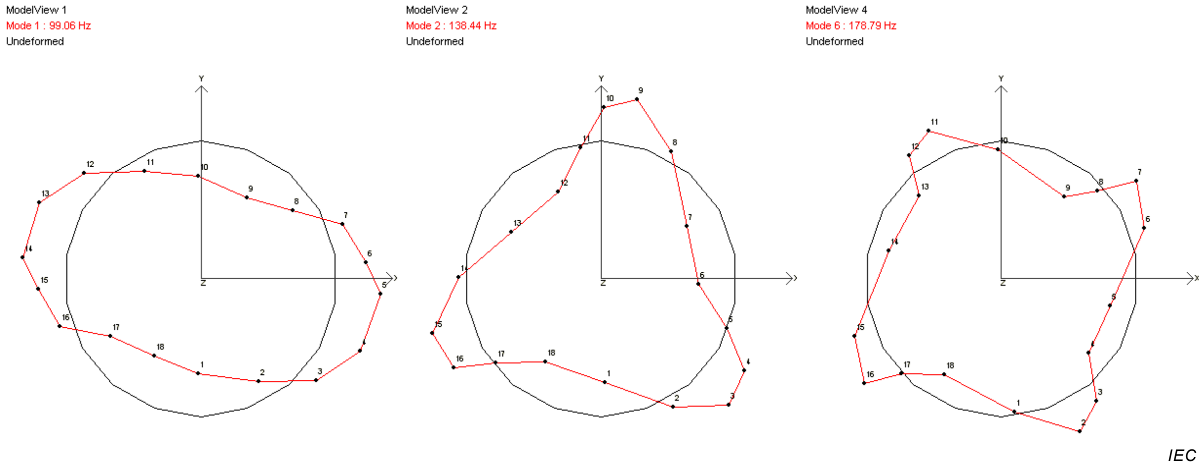

Figure B.5 – Shapes of the 4, 6 and 8-node modes with natural frequencies, measurement in one plane

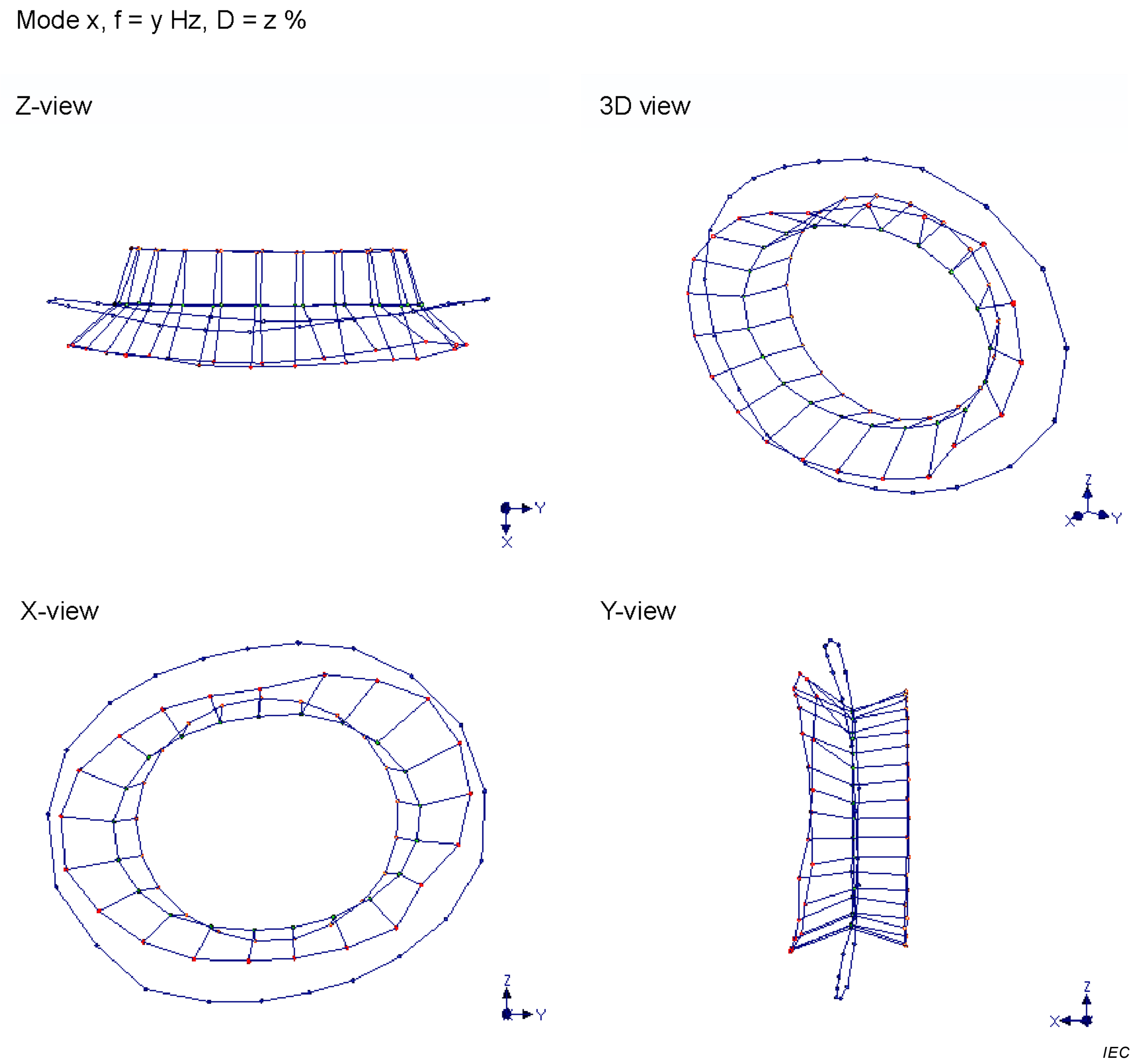

Figure B.6 – Mode shape of a typical 4-node mode with different viewing directions (stator end-winding and outer support ring)

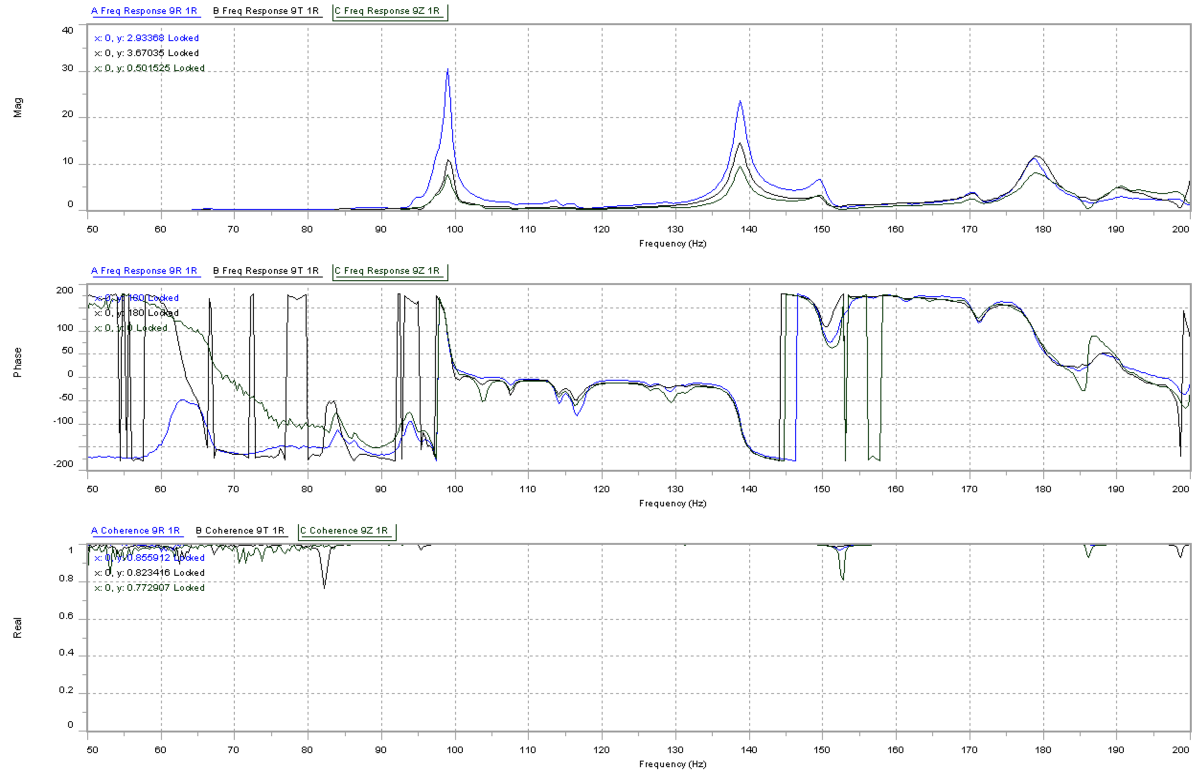

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Figure B.7 – Example – Amplitude and phase of dynamic compliance and coherence

B.3 Measurements during operation

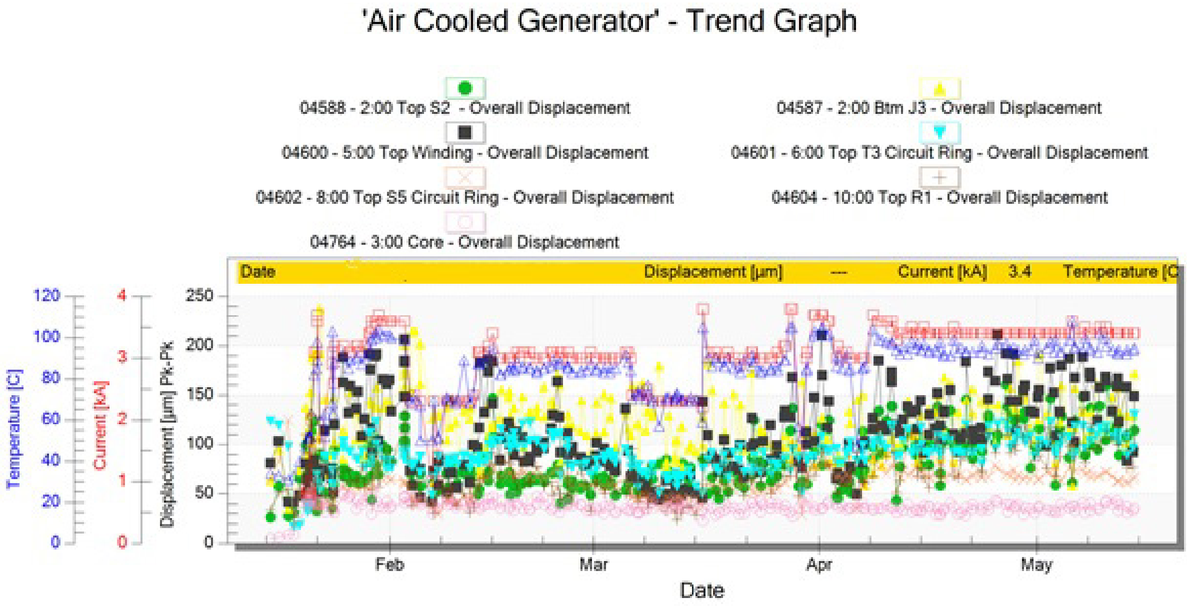

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Figure B.8 – 2-pole, 60 Hz generator – Trend in displacement over time for 10 stator end-winding accelerometers, as well as one accelerometer mounted on the stator core

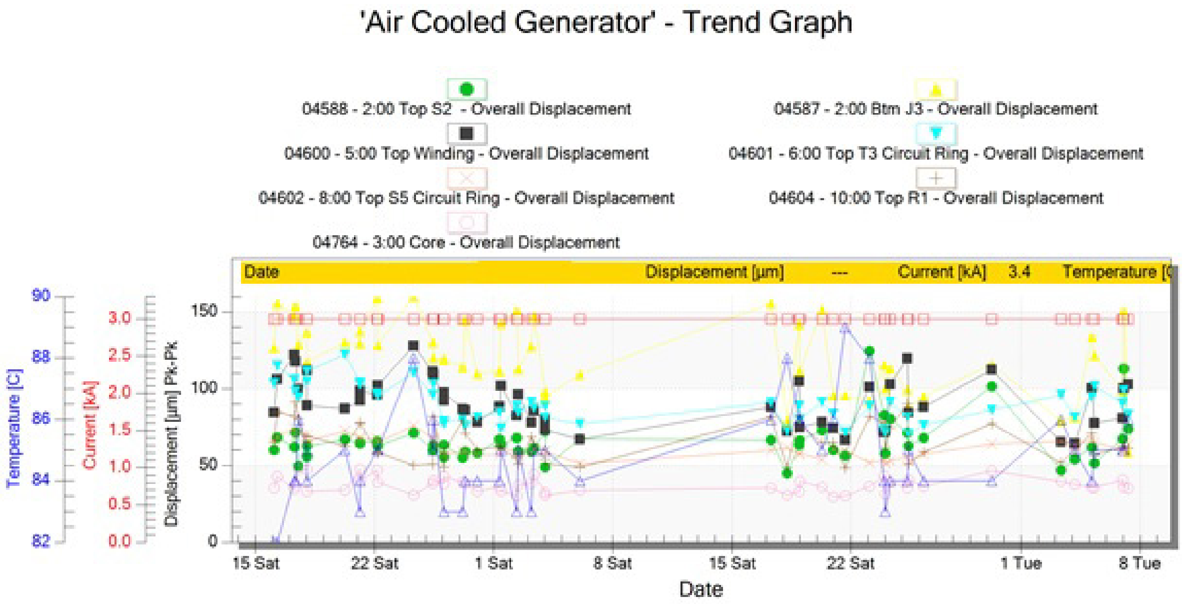

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Figure B.9 – 2-pole, 60 Hz generator – End-winding vibration, winding temperature trends over time, constant stator current

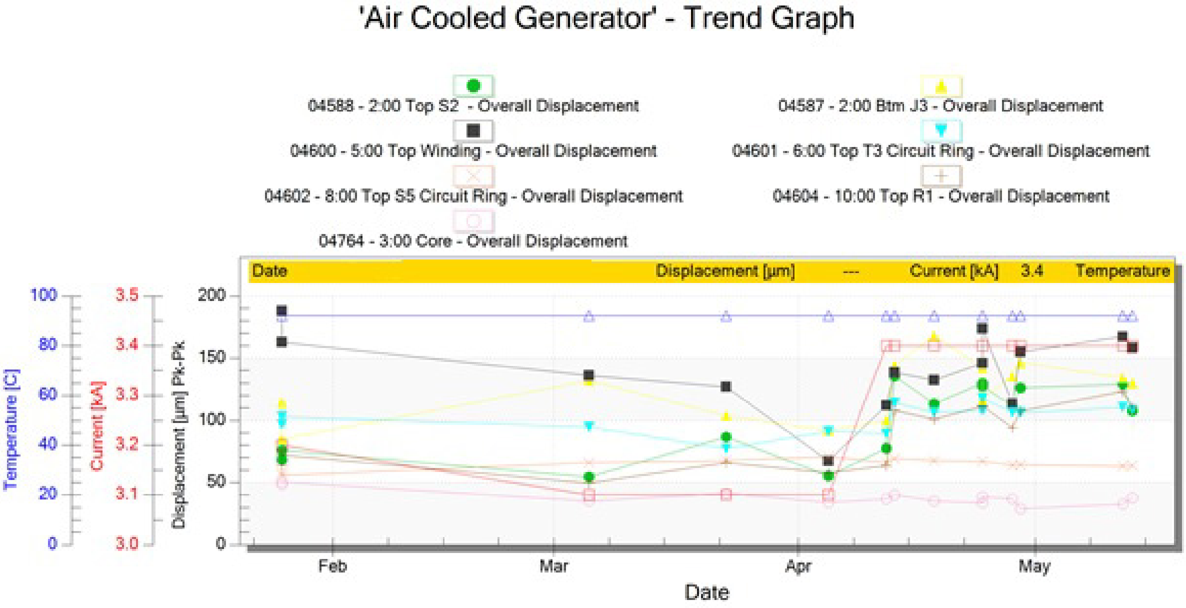

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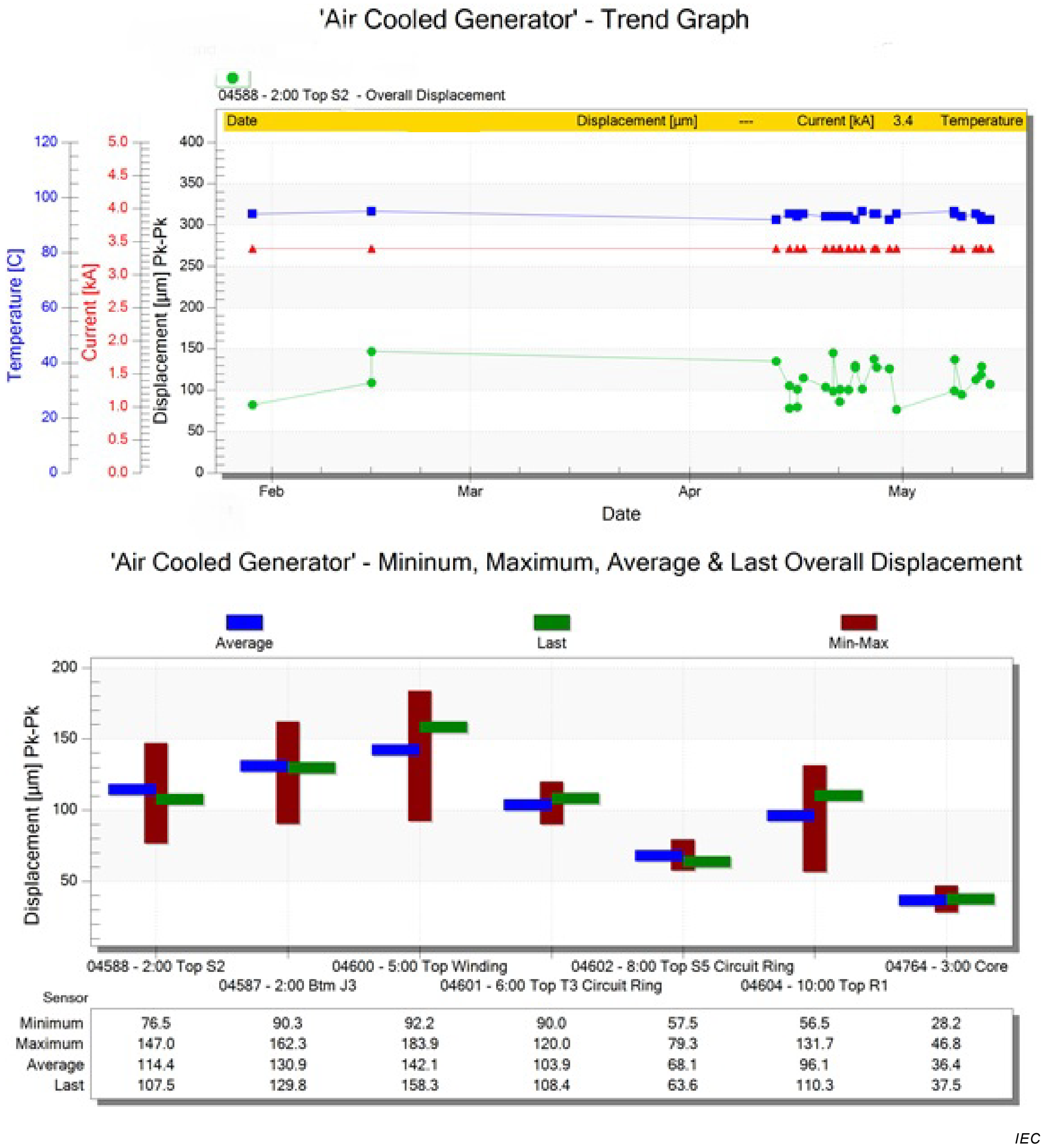
Figure B.10 – 2-pole, 60 Hz generator – End-winding vibration, stator current trends over time, constant winding temperature



'Air Cooled Generator' - Trend Graph

'Air Cooled Generator' - Mininum, Maximum, Average & Last Overall Displacement

Sensor	04588 - 2:00 Top S2	04587 - 2:00 Btm J3	04600 - 5:00 Top Winding	04601 - 6:00 Top T3 Circuit Ring	04602 - 8:00 Top S5 Circuit Ring	04604 - 10:00 Top R1	04764 - 3:00 Core
Minimum	76.5	90.3	92.2	90.0	57.5	56.5	28.2
Maximum	147.0	162.3	183.9	120.0	79.3	131.7	46.8
Average	114.4	130.9	142.1	103.9	68.1	96.1	36.4
Last	107.5	129.8	158.3	108.4	63.6	110.3	37.5

Key

Stator current: 3,4 kA to 3,6 kA

Winding temperature: 92 °C to 96 °C

Active power: 80 MW to 82 MW

Reactive power: –5 Mvar to 5 Mvar

Figure B.11 – 2-pole, 60 Hz generator – Example of variation in vibration levels at comparable operating conditions

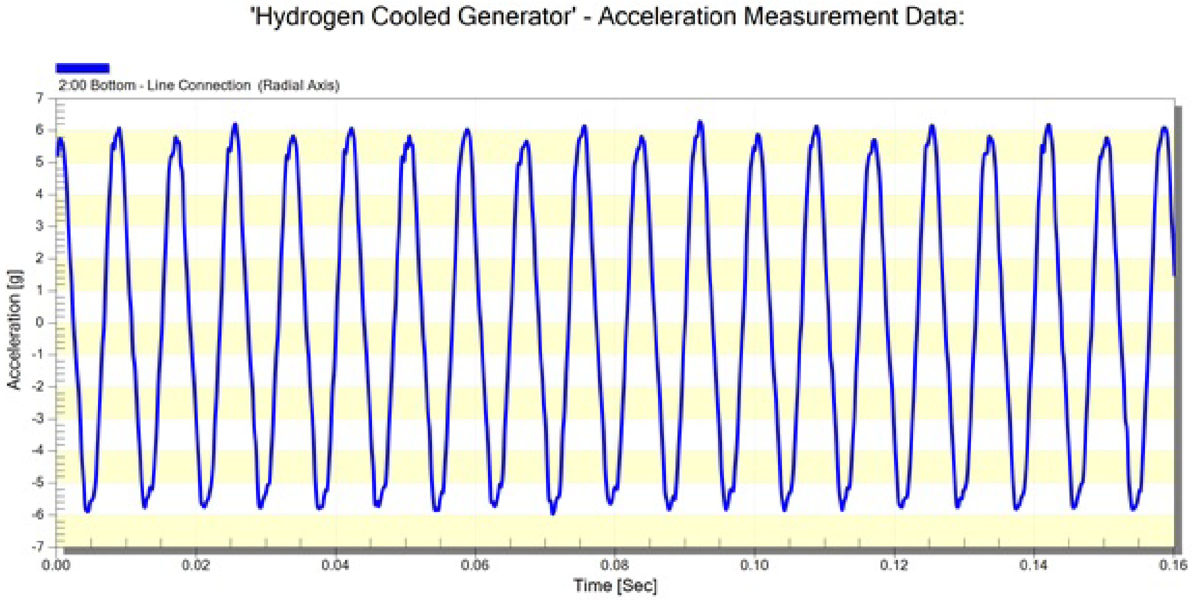


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Figure B.12 – 2-pole, 60 Hz generator – Raw vibration signal, acceleration waveform

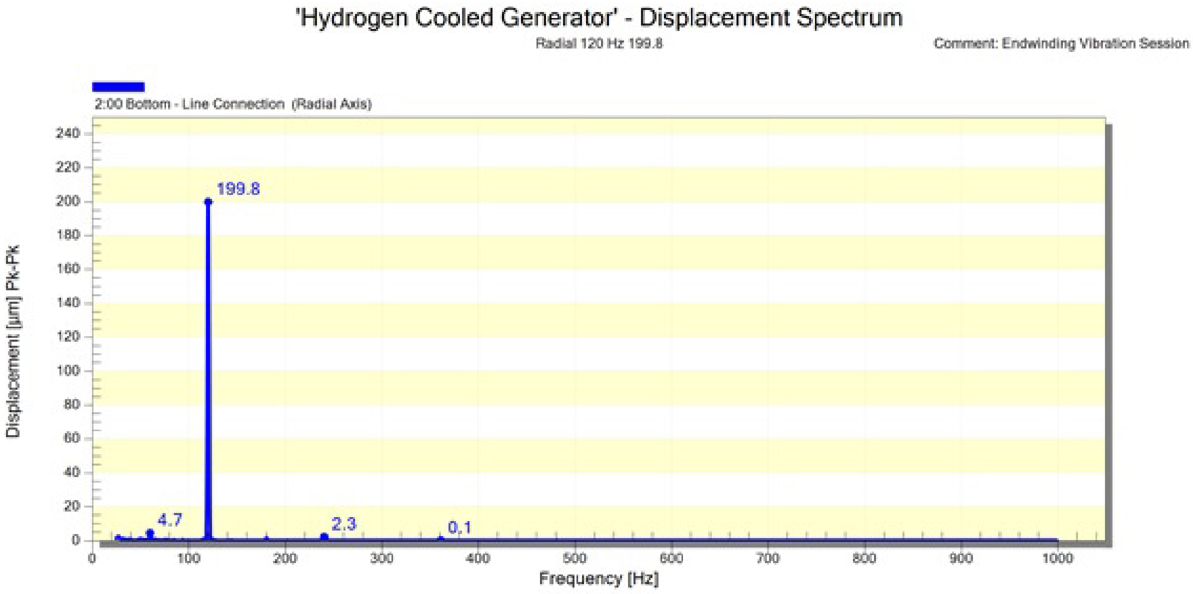

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Figure B.13 – 2-pole, 60 Hz generator – FFT and double integrated vibration signal, displacement spectrum

On generator stator end-windings the main frequency component will be 2f. Higher frequencies such as harmonics of the rotation speed can appear due to various factors (looseness, etc.). Historically, displacement has been the main measure of vibration used to assess the condition of stator end-windings. Displacement is a measure of the distance moved from the initial position and emphasizes low frequencies. Because the fundamental frequencies of the forces acting on a stator end-winding are low frequencies, typically 50 Hz or 60 Hz (operating frequency for 2-pole machines) and 100 Hz or 120 Hz (due to electromagnetic forces), this is generally acceptable.

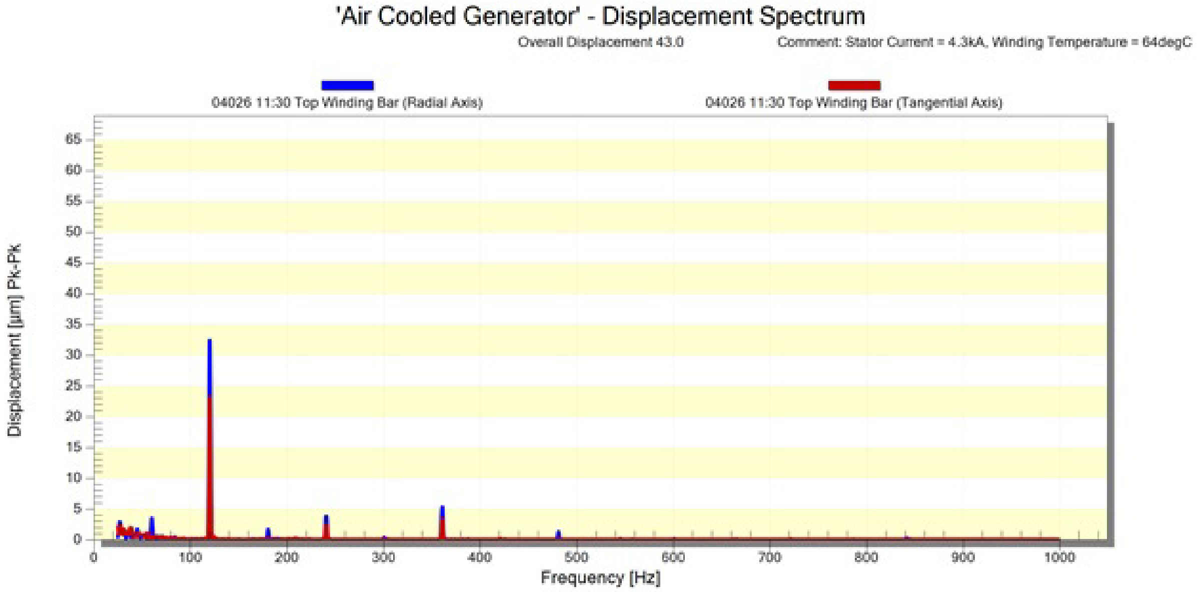

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Figure B.14 – 2-pole, 60 Hz generator – Displacement spectrum

Velocity is a measure of the rate of change in displacement or the speed (and direction) of vibration and provides a smoothing effect over a wide range of frequencies. As structures loosen and/or rub, the response becomes non-linear and results in harmonics of the fundamental frequencies to many multiples (10 or more). The smoothing effect of velocity will provide equal weighting to the fundamental frequencies (at 50 Hz and 100 Hz) and the corresponding harmonics that may develop from looseness and/or rubbing in the structure across a wide frequency range. This characteristic of velocity should be considered when assessing the condition of the stator end-winding.

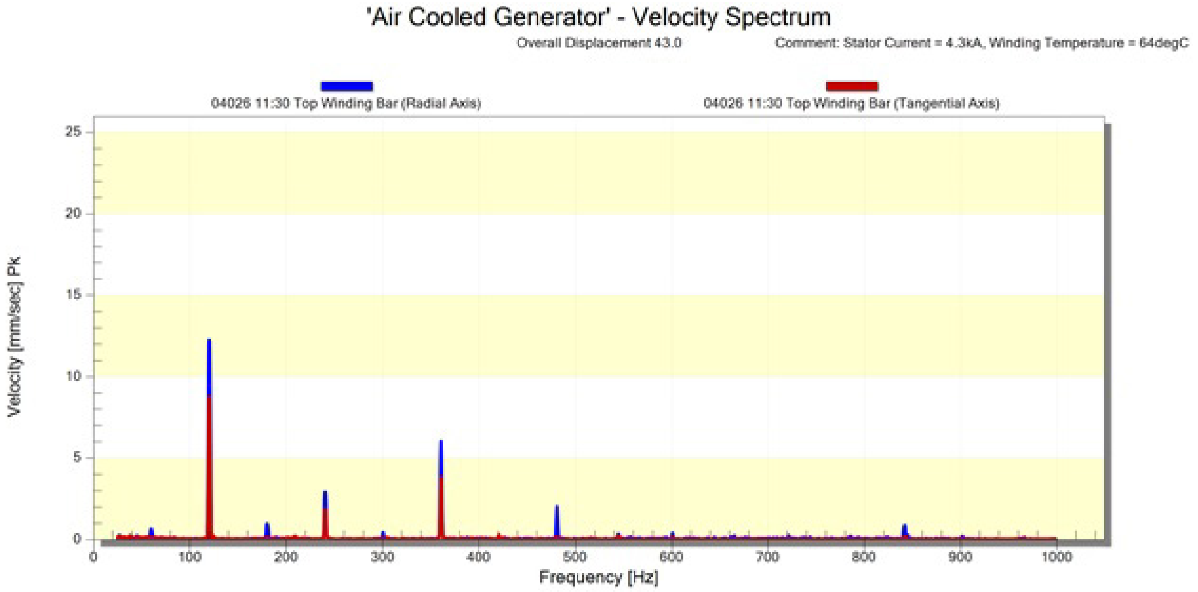

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Figure B.15 – 2-pole, 60 Hz generator – Velocity spectrum

Acceleration is a measure of the rate of change in velocity. It is the raw signal from an accelerometer. With this in mind, acceleration should not be ignored, especially at higher frequency harmonics. These may be excited by natural frequencies resulting in a resonant response that may not be present when considering displacement. If we have considerable strain at a higher frequency, over the same time there will be more cycles and thus a shorter time to failure at the same level of displacement. The same displacement at 10 times the frequency results in 100 times the acceleration.

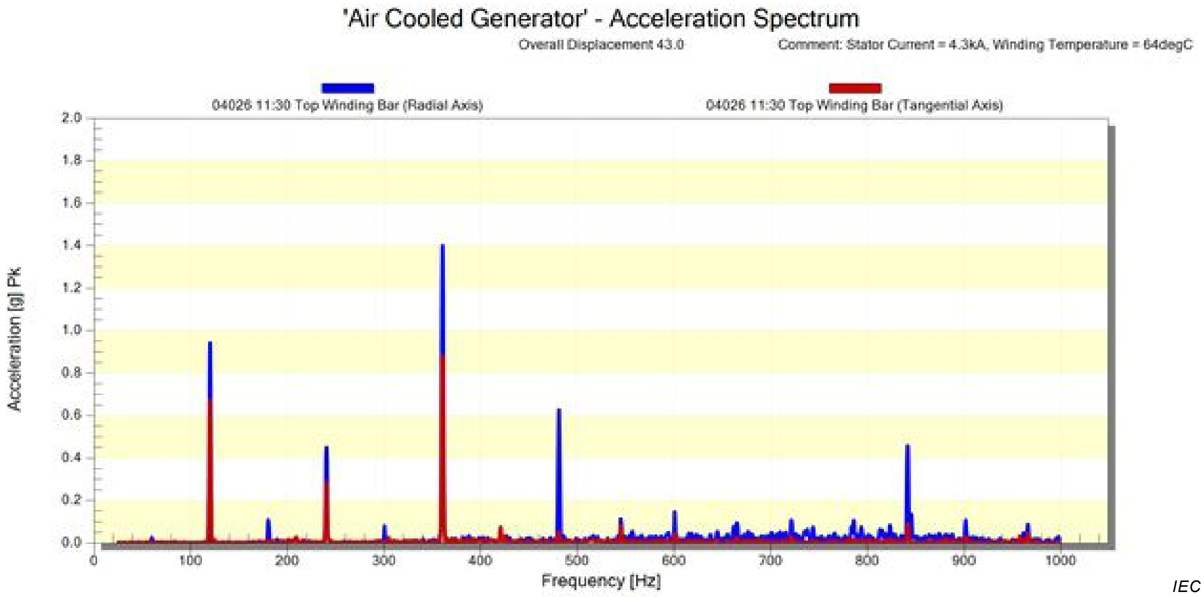

Figure B.16 – 2-pole, 60 Hz generator – Acceleration spectrum

As discussed, all three measures of vibration (displacement, velocity, and acceleration) have their place when assessing the condition of a stator end-winding and should be available from the vibration monitoring system.

Multi-axis vibration transducers can be utilized to obtain additional information on how the component being monitored is vibrating. Trace plane curves of the vibration can be produced because the sensors are mutually perpendicular. The resulting Lissajous figure provides a more accurate representation of the overall vibration than when measuring in a single axis. Two single axis sensors mounted mutually perpendicular can also achieve this result as long as the signals are captured at the same time.

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