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Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 10:
Diagnostic techniques for electrical generators with fluid-film bearings

Surveillance et diagnostic d'état des machines — Surveillance des vibrations —

Partie 10: Techniques de diagnostic pour les générateurs électriques de puissance à paliers à film fluide

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Foreword

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This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

A list of all parts in the ISO 13373 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides guidelines for the procedures to be considered when carrying out vibration diagnostics of electrical generators with fluid-film bearings. It is intended to be used by vibration practitioners, engineers and technicians and it provides them with useful diagnostic tools which include the use of flowcharts and fault tables.

ISO 20816-2 sets out the criteria for monitoring the vibration of gas turbines, steam turbines and generators in excess of 40 MW and establishes provisions for evaluating the severity of the in-situ, broad-band vibration.

ISO 13373-1 presents the basic procedures for analysing narrow-band vibration signals. It includes the types of transducers to be used, their ranges, their recommended mounting locations on various types of machines, on-line and periodic vibration monitoring systems and potential machinery problems.

ISO 13373-2 includes descriptions of the signal conditioning equipment that is required, the time and frequency domain techniques that can be used and the waveforms and signatures that represent the most common machinery operating phenomena or faults encountered when performing vibration signature analysis.

ISO 13373-3 describes some procedures to determine the causes of vibration problems common to all types of rotating machines. It includes descriptions of systematic approaches that can be used to characterize vibration effects, the diagnostic tools available, which tools are needed for particular applications and recommendations on how the tools can be used for different machine types and components. ISO 13373-3 does not preclude the use of other diagnostic techniques.

Note that ISO 17359 indicates that diagnostics can be

a) started after detection of an anomaly during machine monitoring, or

b) carried out in parallel with machine monitoring.

This document considers only where diagnostics are performed after an anomaly has been detected and focusses mainly on the use of flowcharts, process tables, fault and symptom tables as diagnostic tools, since it is felt that these are the tools that are most appropriate for use in the field.

The flowchart and diagnostic process table methodology presents a structured procedure for use by a person in the field to diagnose a fault and find its cause. This step-by-step procedure guides the practitioner to be able to diagnose the machine anomaly in order to establish the probable root cause of this anomaly.

The fault tables present a list of the most common faults found in machinery, as well as their manifestations in the machine and vibration data. The symptom tables contain the main distinguishing vibration features of the main faults. When used with the flowcharts, the tables assist with the identification of machinery faults.

When approaching a machinery problem that manifests itself as a high or erratic vibration signal, the diagnosis of the problem should be done in a systematic manner. This document and ISO 13373-3 achieve that by providing guidance regarding the selection of the measuring and analysis tools, their use and the step-by-step procedures that can be used to diagnose the problem.

Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 10: Diagnostic techniques for electrical generators with fluid-film bearings

1 Scope

This document gives guidelines and requirements for the procedures to be followed when carrying out vibration diagnostics of 2- and 4-pole electrical generators of cylindrical pole design with fluid-film bearings.

This document does not apply to salient pole generators.

This document establishes a practical step-by-step vibration-based approach to fault diagnosis.

The requirements of this document should be considered together with those in ISO 13373-4.

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.

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 13372, *Condition monitoring and diagnostics of machines — Vocabulary*

ISO 13373-1, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 1: General procedures*

ISO 13373-2, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 2: Processing, analysis and presentation of vibration data*

ISO 13373-3:2015, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 3: Guidelines for vibration diagnosis*

ISO 21940-2, *Mechanical vibration — Rotor balancing — Part 2: Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041, ISO 13372 and ISO 21940-2 apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

4 Measurements

4.1 Vibration measurements

Vibration measurements may be obtained using two main categories of transducers:

a) non-contacting (e.g. inductive, capacitive and eddy current probes used on rotating shafts);

b) seismic (e.g. accelerometers or velocity transducers used on non-rotating parts, such as the bearing housing).

International Standards have been written to help in assessing the vibration severity for both types of measurements (e.g. ISO 20816 (all parts) and ISO 10816 (all parts)).

It is important to recognize that the appropriate transducer, signal conditioning, measurement and analysis system shall be used for the diagnosis of faults related to electrical generators with fluid-film bearings. Before any measurements are taken, it is good practice to consider whether the grounding (earthing) and electrical fields of the machine will have any effect on them.

Descriptions of the transducers, measurement systems and analysis techniques are given in ISO 13373-1 and ISO 13373-2, which shall be used as appropriate.

Other diagnostic technologies are available for taking measurements on generators that can be considered in specific cases (e.g. model based voltage and current systems, strain gauges and optical sensors).

Many electrical generators are equipped with stator end-winding and core vibration monitoring systems. For guidelines regarding generators with end-winding vibration measurement systems see IEC/TS 60034-32. Evaluation of the measurement results is very design specific and outside of the scope of this document.

It is recommended to adhere to the manufacturer's and service provider's guidelines regarding end-winding and core vibration evaluation for specific machine designs and/or similarly designed units.

4.2 Machine operational parameter measurement

Data from operational parameters (e.g. rotational speed, load, mounting configuration [with solid or flexible support arrangement] and temperature) that can have an influence on the machine vibration and characteristics are important to acquire in order to arrive at an appropriate fault diagnosis. For a given machine, operational parameters can be associated with a range of steady state and transient operating conditions.

5 Initial analysis

The analysis shall be performed using the guidelines given in ISO 13373-3:2015, Annex A.

This analysis shall identify and include any safety concerns, such as the presence of high vibration and its vibration severity, past vibration history, effect of operating parameters on machine vibration, the consequences of not taking corrective action and the need for machine shutdown.

The analysis shall also include items such as the machine mounting configuration, machine position relative to other rotating machines, building structure in which the machine is installed and the environment in which the machine operates (see ISO 13373-3:2015, Annex B to Annex D for a description of common faults resulting from machine installation and bearing defects).

6 Specific analysis of electrical generators with fluid-film bearings

The specific analysis shall be performed using Annex A, which presents the most prevalent generator defects that cause excessive vibration. Annex A also includes the identification of generator vibration resulting from hydrodynamic bearing problems. However, the root cause of and remedial actions that can be taken to resolve such problems are addressed separately in ISO 13373-3:2015, Annex C.

The fault table to be used for the diagnosis of electrical generators is given by Table A.1, the symptom table is given in Table A.2, while the methodology of vibration diagnosis is presented in Annex B. Examples of the use of the fault table, symptom table and methodology of vibration diagnosis of electrical generators are given in Annex C.

Due to their method of rotor construction, 2-pole and, to a lesser extent, 4-pole electrical generators produce a 2× excitation force and a corresponding 2× vibration. This is an inherent characteristic of generator rotor design and some level of 2× vibration is normal and expected. Also, 2× line frequency (100 Hz or 120 Hz) excitation from the rotating electromagnetic field in the stator is present during operation and can excite structural resonances (e.g. in the machine pedestal and/or frame).

For a 2-pole generator synchronized to the grid, 2× line frequency corresponds to 2× frequency of rotation and is therefore hard to separate for diagnostic purposes.

One of the most common causes of high vibration in a generator is a transient rotor bend due to shorted turns. The shorted turns develop over time due to normal insulation degradation and can be diagnosed by specialized testing, which is described, for example in Reference [1], pp. 875 to 902. The same reference also provides details for performing thermal sensitivity testing and analysis (Reference [1], pp. 907 to 912) and heat-run testing (Reference [1], pp. 913 to 914) which is also useful for detecting issues with cooling gas flow.

7 Considerations when recommending actions

Several factors influence any remedial or corrective actions that can be taken, such as:

a) their safety;

b) commercial considerations;

c) incorrect machine design;

d) machine assembly issues.

Clearly, the appropriate action(s) for a particular diagnosis depend(s) on individual circumstances and it is beyond the scope of this document to make specific recommendations. Nevertheless, it is important to consider possible actions resulting from the diagnosis and the implications of those actions.

Recommended actions depend on the degree of confidence in the fault diagnosis (e.g. if the same diagnosis has been made correctly before for this machine), the fault type and severity as well as on safety and commercial considerations. It is neither possible nor the aim of this document to recommend action(s) to be taken to cover all circumstances.

Annex A
(normative)

Systematic approach to the vibration analysis of electrical generators with fluid-film bearings — Fault tables

A systematic approach to the vibration analysis of electrical generators is shown by the fault table in Table A.1 and the symptom table in Table A.2. The information included in Table A.1 is not intended to be exhaustive but includes the most prevalent faults associated with these types of electrical generators.

For example, some of the faults that occur with this type of generator are shown in Annex C.

Table A.1 — Fault table for the vibration analysis of electrical generators with fluid-film bearings

Fault	Conditions under which the vibration change occurs	Initial rate of change of vibration amplitude	Major frequency component of changed vibration amplitude	Subsequent behaviour of vibration with time	Effect on resonance speed	Behaviour on barring	Repeatability	Comments
Shorted turns (transient rotor bend)	During loading and/or reactive power change	Follows excitation current and/or reactive power.	1×	Amplitude can increase as the fault progresses.	No change in vibration level on run-up. Possible significant increase in vibration level on coast-down.	Change in shaft runout possible but dissipates over time.	Typically repeats for the same operating conditions.	Presence of shorted turns can be detected by electrical tests.
Slip layer malfunction (transient rotor bend)	During loading and/or reactive power change	Follows excitation current and/or reactive power.	1×	Amplitude can increase as the fault progresses.	No change in vibration level on run-up. Possible significant increase in vibration level on coast-down.	Change in shaft runout possible but dissipates over time.	Typically repeats for the same operating conditions.	Cannot be detected by electrical tests.
Obstruction to coil(s) expansion (transient rotor bend)	During initial loading	Rapid after certain excitation current is reached.	1×	Continues to increase with current.	No change in vibration level on run-up. Possible significant increase in vibration level on coast-down.	Change in shaft runout possible but dissipates over time.	Typically repeats for the same operating conditions.	Typically caused by broken blocking or improper coil(s) positioning. Cannot be detected by electrical tests.
Bearing elevation (height) change	Following operational transient	Slow, unless oil whirl is predominant.	Predominantly 1×. Less than 1× can be exhibited (see oil whirl).	Under steady conditions a new steady level will be reached.	Can reduce on the affected rotor.	Not affected	Trends, but not necessarily amplitudes. Will tend to repeat following similar transients.	Reversal of transient will not immediately reverse the vibration change. Correlates with bearing oil wedge pressures and metal temperatures.
Shaft unbalance resulting from rotating component material loss	Usually steady state but can be transient.	Step change or series of changes	1×	Steady following step change	Vibration level significantly changed	Rubbing can be heard in extreme cases.	None	Often subsequent damage to stator windings leads to tripping the unit.
Shaft unbalance	Steady state	Immediately evident	1×, phase consistent with mode shape	Steady	None	Not affected	Repeatable	None
Oil whirl (or whip)	During speed change or bearing unloading	Very rapid	Predominantly just less than 1/2× or at rotor critical speed frequency	Erratic at higher level than normal	None	Not present	Will repeat under identical operating conditions.	See [2] pp. 258 to 260
Rubbing	Speed or load change (see bearing elevation change)	Rapid	1×, multiples sub-synchronous and super-synchronous, depending on severity and design	Cyclic amplitude with phase rotation or variation. Can also be random in timing and behaviour.	Response level can be significantly changed.	Rubbing can be heard in extreme cases.	Not necessarily repeatable each time the transient is undergone.	Typically occurs after overhauls. Rubbing at hydrogen seal rings can be affected by changes in seal oil pressure or temperature (see Figure B.2).
Frame or pedestal resonance	Steady state	Can be immediately evident or develop over time due to looseness.	1×, 2× radial and/or axial	Depending on the cause, it can be steady or increase.	None	None	Repeatable	Can cause a drop in support stiffness lowering rotor's critical speed. More pronounced on seismic vibration.

Table A.1 *(continued)*

Fault	Conditions under which the vibration change occurs	Initial rate of change of vibration amplitude	Major frequency component of changed vibration amplitude	Subsequent behaviour of vibration with time	Effect on resonance speed	Behaviour on barring	Repeatability	Comments
Looseness in stator to foundation attachment	Steady state	Slow initially	1× predominantly. Possibly with low amplitude harmonics, 2× line frequency.	Increases as condition worsens.	None	None	Trends	More pronounced on seismic vibration (see [2] pp. 279 to 280 for an example)
Slip in couplings or shrunk-on parts	After torsional event (e.g. short circuit)	Step change	1×	Steady	None	None	Repeatable	Similar behaviour to mass unbalance
Rotor crack (transverse crack)	Run-up or coast-down. Can be at steady load conditions.	Slow initially. Because of normal presence of 2×, the presence of cracks can be undetected until very large ones have formed.	1× and higher harmonics. 2× can be only evaluated on comparative basis. 1× and 2× phase can undergo significant change.	Amplitudes can reduce initially, but will exponentially grow over time.	Excessive vibration on coast-down or run-up. This is when a crack is typically suspected. Can be evident on coast-down through sub-multiples of critical speeds leading to acceleration of damage.	Not affected unless the condition is severe.	Does not respond to balance as predicted.	Steady state vibration changes can be insignificant. Observe trends of harmonic vibration components. Hydrogen leakage increase is another diagnostic tool.

Table A.2 — Observable symptoms of typical faults

Fault type	Elevated vibration signals				Time				Critical speed changed	Barring			Varies with load	Repeatable	Comments
	< 1×	1×	2×	> 2×	Transient	Sudden appearance	Gradual increase	Steady state		Audible rubbing	Increased slow roll	Barring not possible			
Shaft unbalance (generic)		•				•	•	•						•	Immediately evident
Shaft unbalance (loss of material)		•			○	•	○	•	•	○					Most effect at bearings of affected rotor
Bearing elevation change	○	•			○	○	•	•	○					○	Occurs following transient.
Shorted turns (transient rotor bend)		•					•	•					•	•	
Slip layer malfunction (transient rotor bend)		•					•	•					•	•	
Obstruction to coil(s) expansion (transient rotor bend)		•					•	•					•	•	
Hard rubbing (transient rotor bend)		•	○	○	•				○						During speed or load change
Oil whirl (or whip)	•				○	○								○	Whip locks rotor to first critical speed.
Rotor crack		•	○			•	•	•	○						Critical speed can reduce and show two peaks.
Looseness in bearing or pedestal	•	•	•	○			•	•	○						

This table is not exhaustive but contains the most prevalent faults associated with steam and gas turbines with fluid-film bearings.

• Indicates symptom likely to be seen if fault occurs.

○ Indicates symptom can or cannot be seen.

Annex B
(informative)

Methodology for diagnosing vibration problems in electrical generators with fluid-film bearings

In this annex, only the most common faults found in electrical generators with fluid-film bearings are included in the diagnostic flowcharts in Tables A.1 and A.2.

The analysis and diagnosis of faults found in electrical generators is an elaborate process and, in many cases, requires the creation of a rotordynamic model to investigate the faults found and to predict their cause. The creation of a rotordynamic model requires special expertise, but the flowcharts shown in Figure B.1 to Figure B.3 do not elaborate on the steps needed in carrying out the more involved rotordynamic analysis.

Firstly, the analysis described in ISO 13373-3:2015, Annex A should be carried out and once the main fault has been established, it should be evaluated (see Figure B.1).

There are two options for establishing the cause of the vibration,

a) if the vibration is mainly 1× and an operating parameter dependency is observed, then the flowchart in Figure B.2 should be used, and

b) if a) is not the case, then Figure B.3 provides guidance for establishing generator steady state operation.

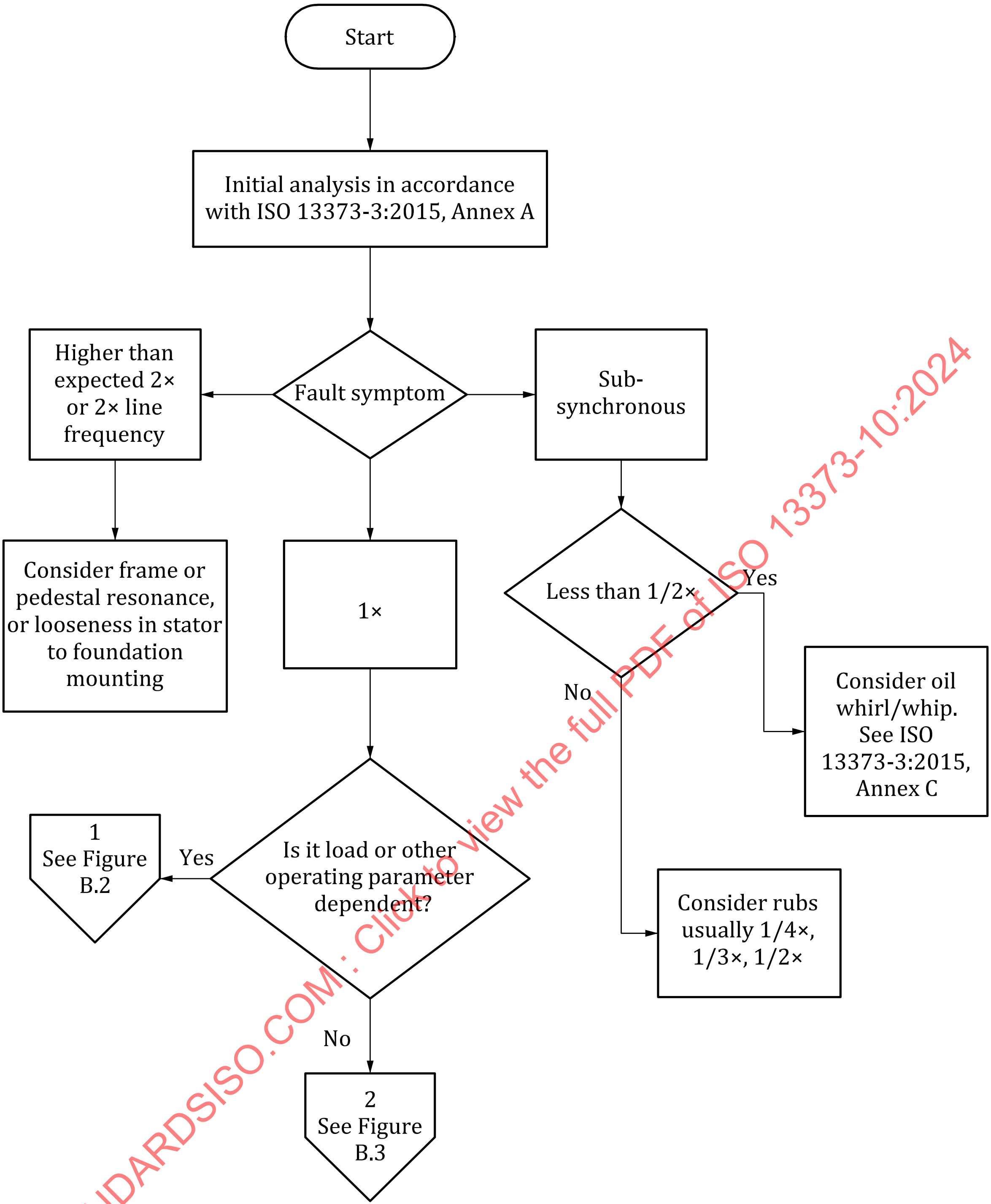


Figure B.1 — Diagnostic flowchart

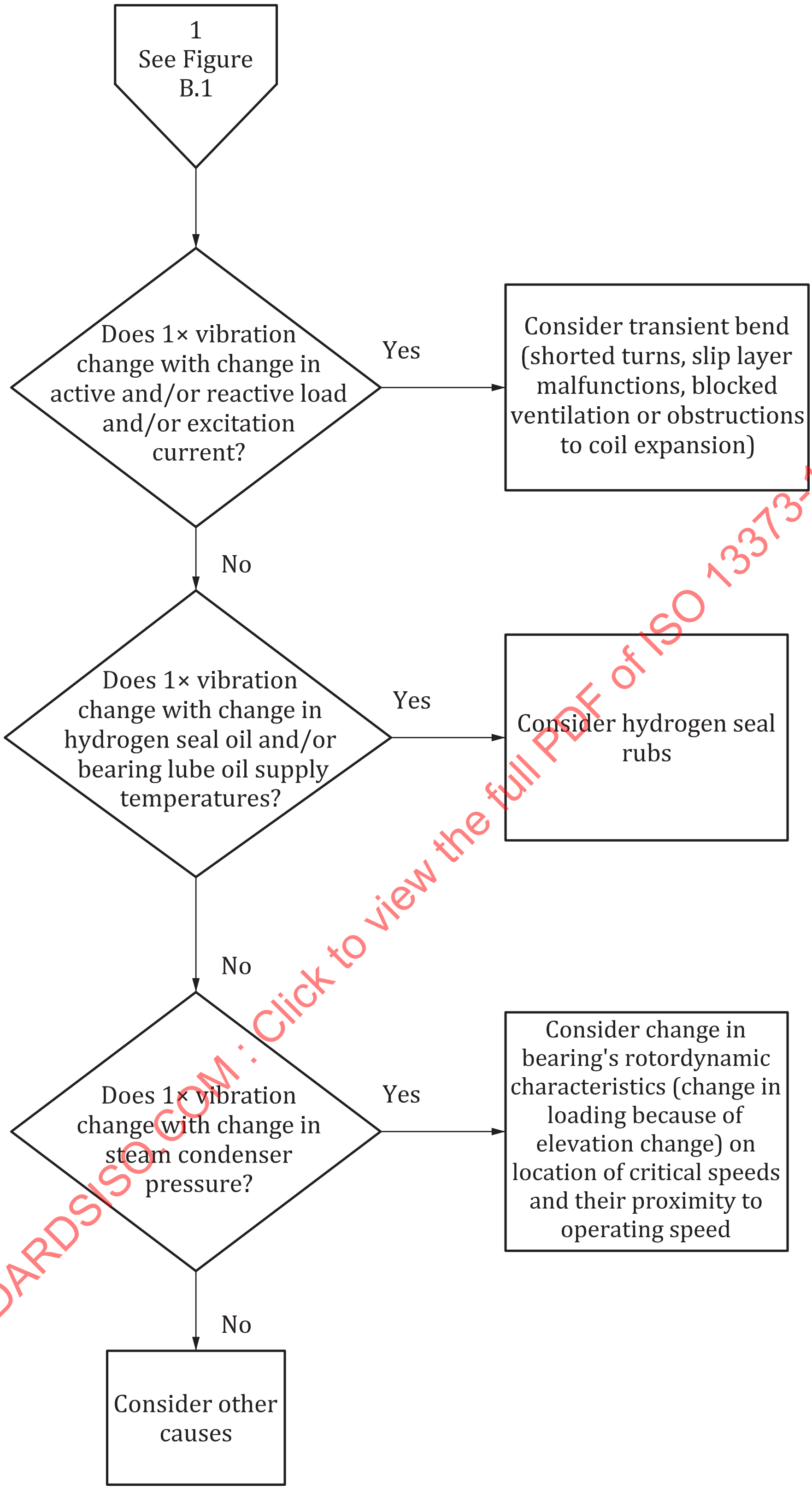


Figure B.2 — Diagnostic flowchart for electrical generators with steady state 1× vibration

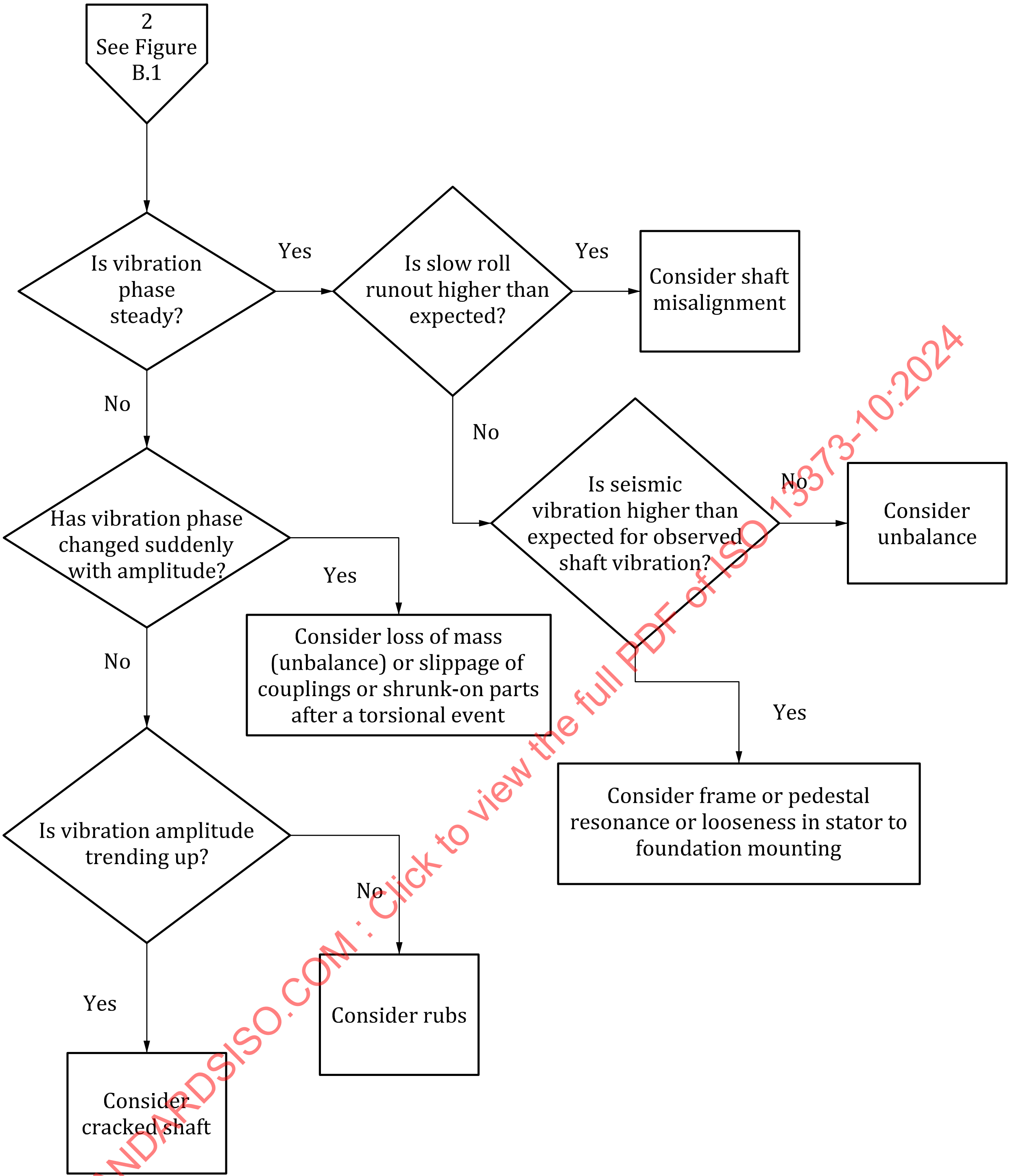


Figure B.3 — Diagnostic flowchart for electrical generators with steady state 1× vibration

Annex C
(informative)

Examples of faults occurring in electrical generators with fluid-film bearings

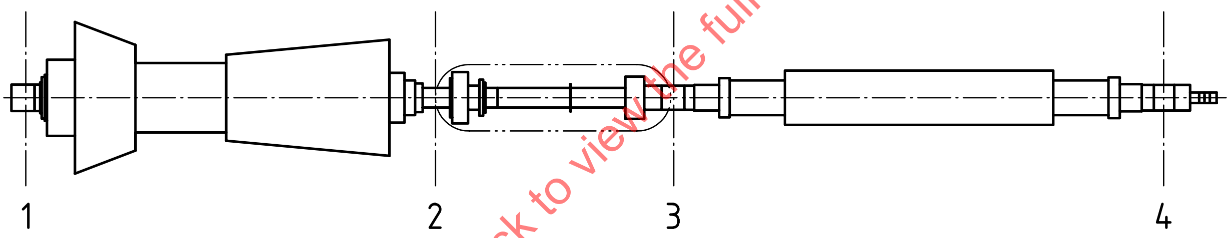
C.1 Shaft misalignment

A 300 MW gas turbine generator set (see Figure C.1) has experienced a gradual increase in overall vibration, primarily on the generator turbine end at bearing 3. Vibration analysis indicated that the increase is mostly due to 1× vibration component and the phase remained steady. The vibration was also not affected by a change in operating parameters.

Following the flowcharts shown in Figures B.1 and B.3, misalignment and unbalance can be considered the main causes for the increased vibration and the slow roll runout readings were very low and did not help to clearly distinguish between the two.

The unit had a history of foundation settling leading to a change in alignment and vibration increase – it was realigned twice during the first two years of service.

A decision was made to check/correct the shaft alignment and to re-balance the generator if necessary.



Key

1 bearing 1
2 bearing 2
3 bearing 3
4 bearing 4

Figure C.1 — Gas turbine generator configuration

During a planned outage, the machine alignment was checked and found to be out of tolerance. The alignment was corrected and all generator vibration was then lower than before the outage.

Table C.1 shows the vibration readings on bearing 3 taken before and after the re-alignment.

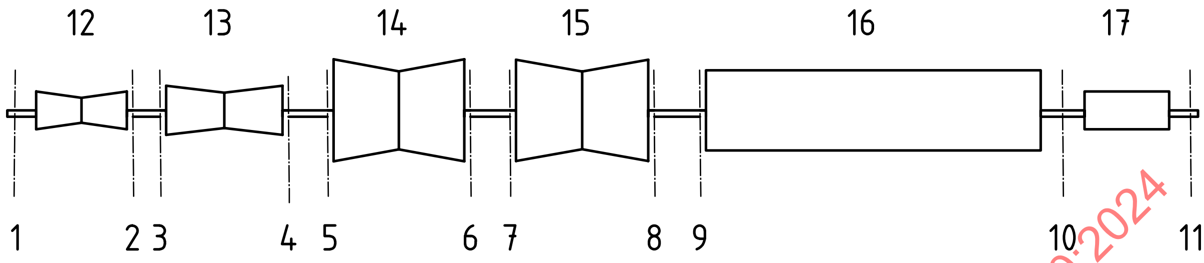
Table C.1 — Bearing 3 vibration before and after re-alignment at a generator output of 300 MW

Broadband vibration measurement	Before outage	After outage
Bearing pedestal absolute vertical velocity, rms	4,3 mm/s	1,4 mm/s
Bearing pedestal absolute horizontal velocity, rms	3,9 mm/s	2,2 mm/s
Shaft relative, peak-to-peak	57 µm	40 µm

C.2 Hydrogen seal rub

A 760 MW steam turbine generator (see Figure C.2) experienced unusual vibration at the steam turbine heat soak speed (~2 050 r/min) during startup after a major outage.

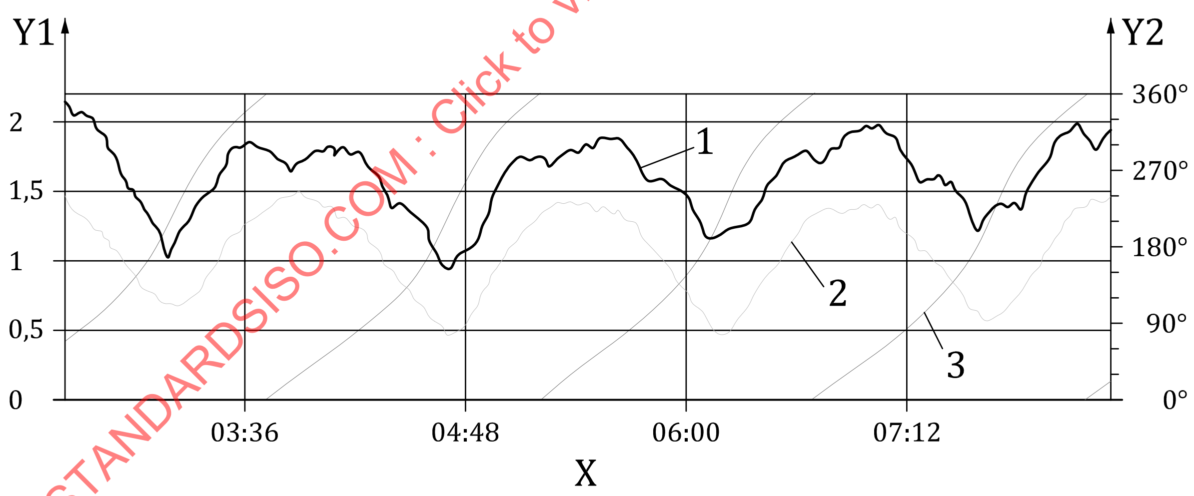
During this hold time, bearings 9 and 10 were showing cyclic variations in the 1× vibration amplitude and phase angle. These conditions were most evident on bearing 10 (see Figure C.3).



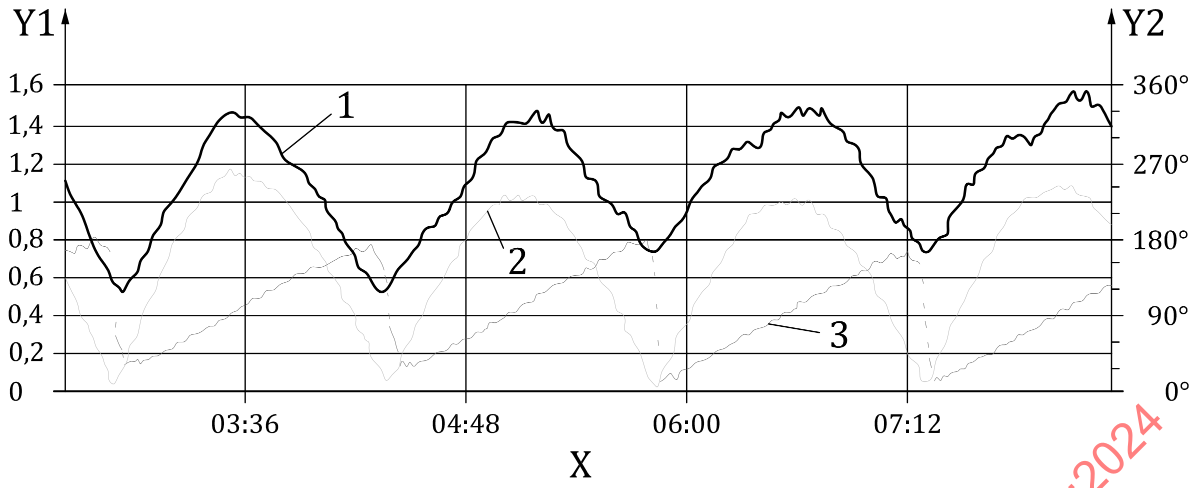
Key

1 bearing 1
2 bearing 2
3 bearing 3
4 bearing 4
5 bearing 5
6 bearing 6
7 bearing 7
8 bearing 8
9 bearing 9
10 bearing 10
11 bearing 11
12 high pressure turbine
13 intermediate pressure turbine
14 low pressure turbine 1
15 low pressure turbine 2
16 generator
17 collector

Figure C.2 — Steam turbine-generator configuration



a) Shaft relative vibration in direction of *y*-axis



b) Shaft relative vibration in direction of *x*-axis

Key

X time in h

Y1 magnitude of shaft relative vibration in µin

Y2 phase in °

1 overall vibration level

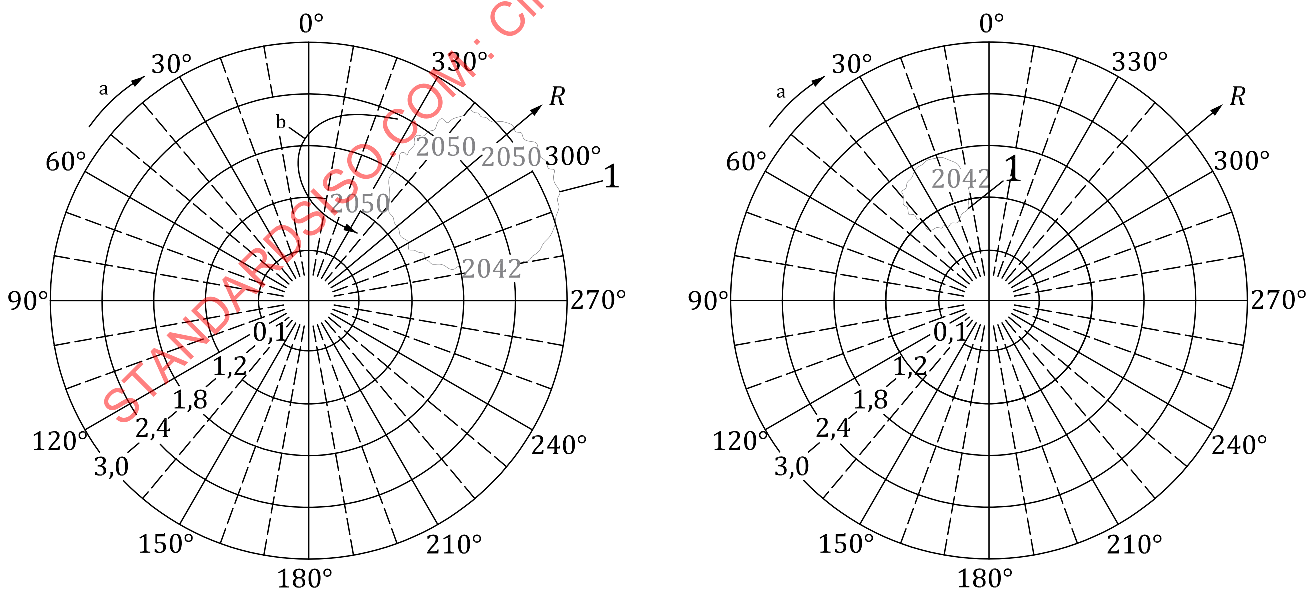
2 1× vibration level

3 phase

Figure C.3 — Bearing 10 shaft relative vibration trend

The polar plots shown in Figure C.4 and Figure C.5 show the generator bearing vibration phase shift for bearings 9 and 10.

Note how bearing 10 is the more severely affected, shifting almost 360° against shaft rotation.



a) Shaft relative vibration in direction of *y*-axis **b) Shaft relative vibration in direction of *x*-axis**

Key

R magnitude of shaft relative vibration in µin

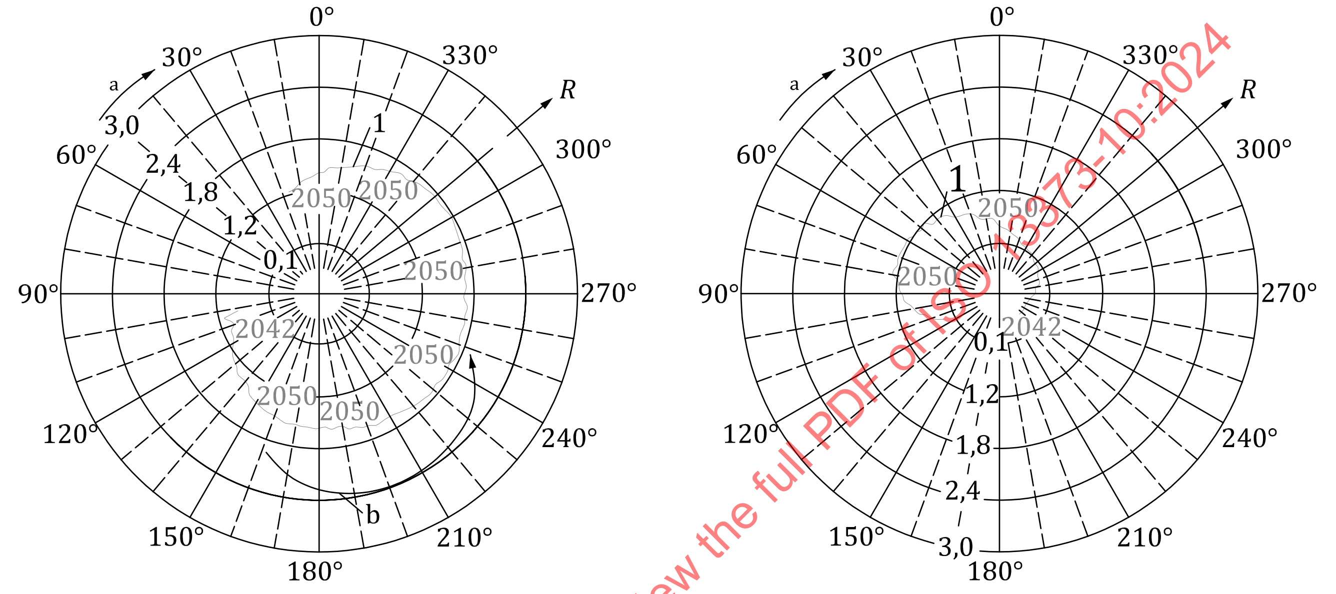
1 1× vibration level

a Direction of shaft rotation.

b Direction of change of shaft relative vibration.

NOTE This measurement was made between 06:03 and 07:20 at 2 050 r/min.

Figure C.4 — Bearing 9 polar plots



a) Shaft relative vibration in direction of *y*-axis **b) Shaft relative vibration in direction of *x*-axis**

Key

R magnitude of shaft relative vibration in µin

1 1× vibration level

a Direction of shaft rotation.

b Direction of change of shaft relative vibration.

NOTE This measurement was made between 06:03 h and 07:20 h at 2 050 r/min.

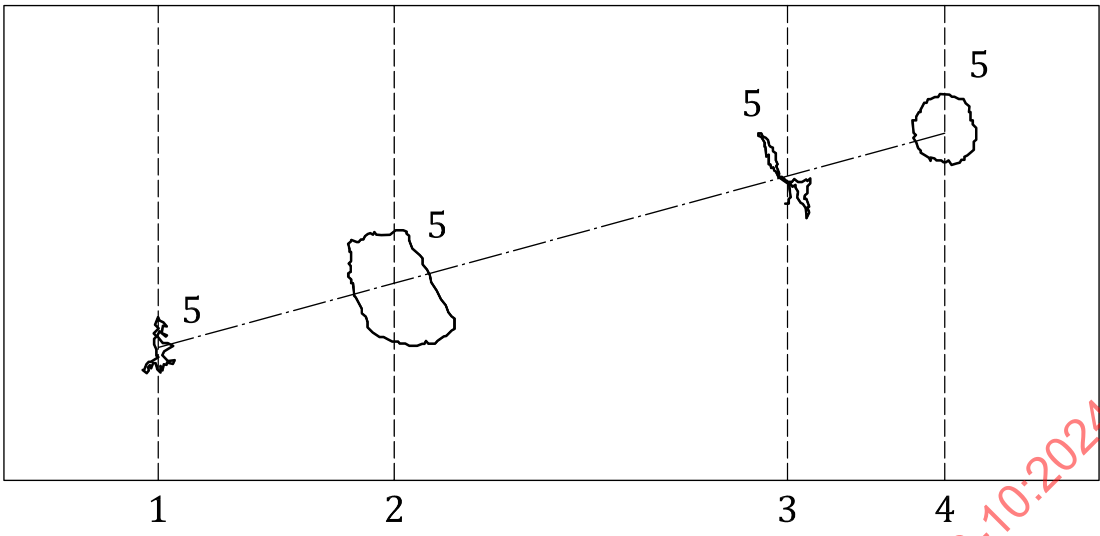
Figure C.5 — Bearing 10 polar plots

In reading the flowcharts (see Figure B.1 to Figure B.3) and the fault table (see Table A.1), rubbing can be considered the cause of the observed behaviour.

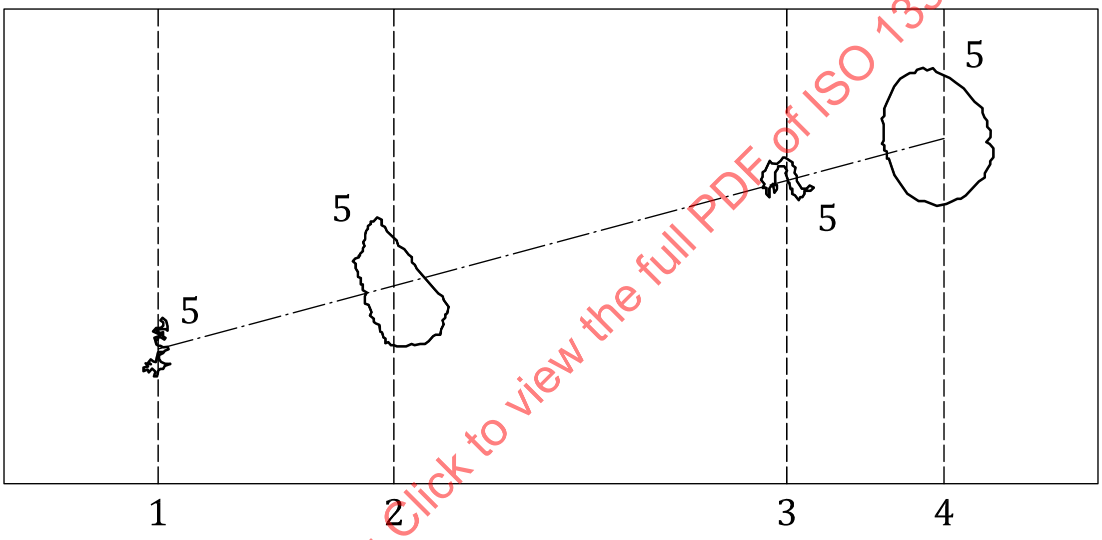
The shaft orbits measured at the generator and exciter bearings indicated a rub at the exciter end of the generator [see Figure C.6 a)]. Note the oscillating distortion of the generator end orbits measured at various times during the soak speed period [see Figure C.6 b) and Figure C.6 c)].

For hydrogen cooled generators, the hydrogen seals are the most likely source of rubbing because of the tight clearances.

Adjusting the hydrogen seal oil pressure and temperature settings cleared the rub condition.



a) At 02:49 h



b) At 03:16 h