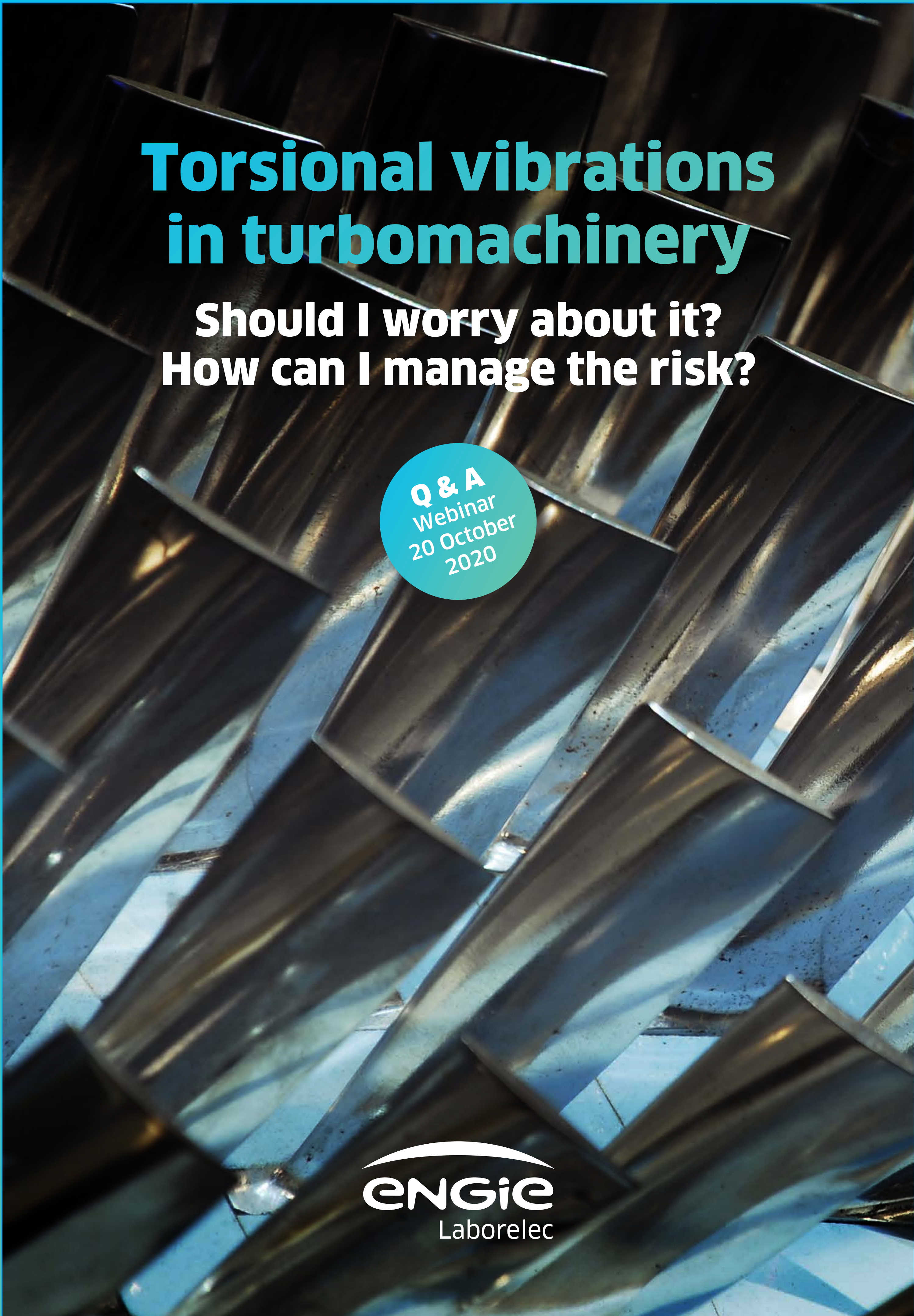
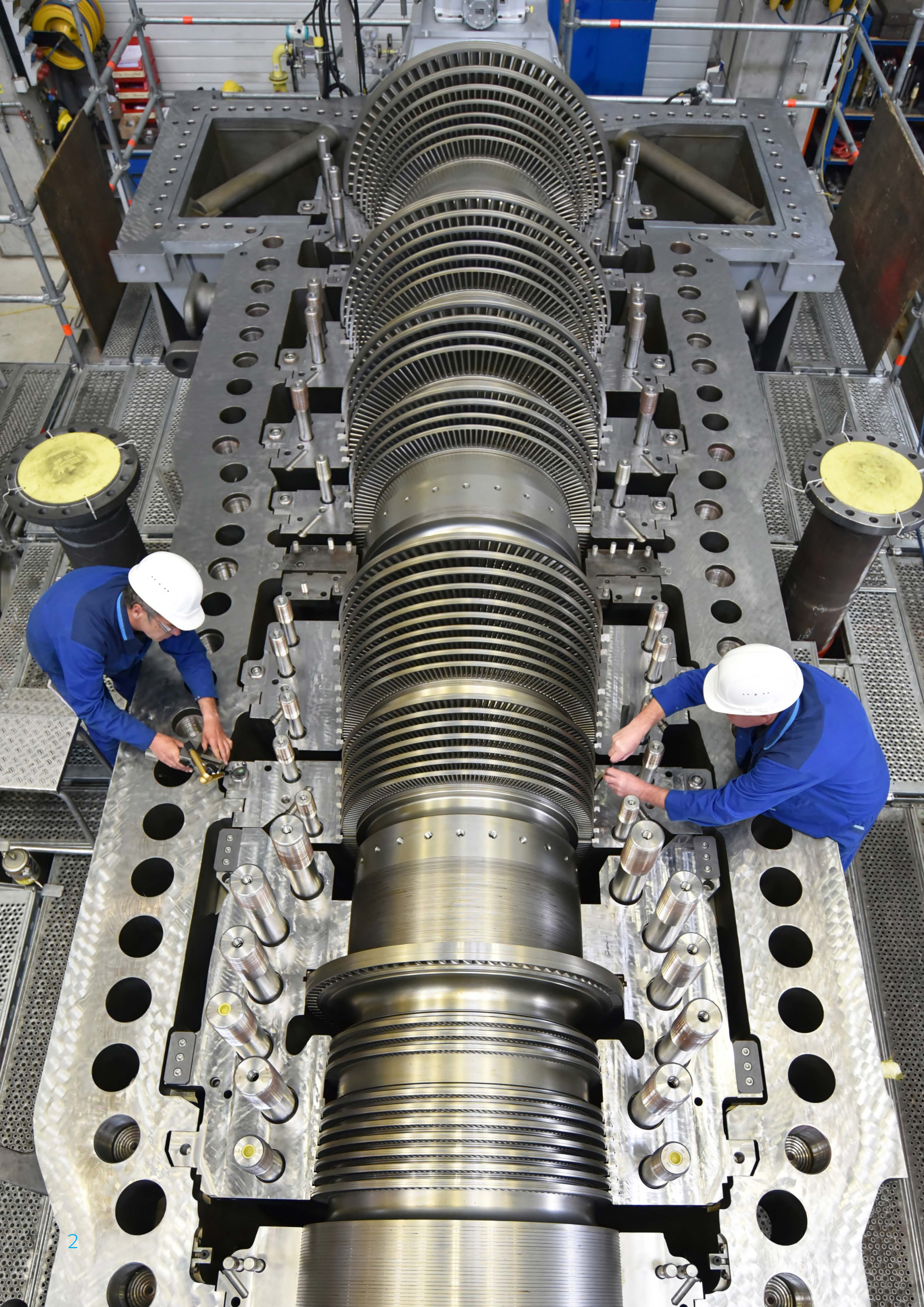


Torsional vibrations in turbomachinery

Should I worry about it?
How can I manage the risk?

Q & A
Webinar
20 October
2020

ENGIE
Laborelec



Frequently asked questions about torsional vibrations in turbomachinery

Does the effect of DC conversion stations on torsional vibration vary depending on whether you're exporting power from your grid or importing it?

There are different situations where a converter station may cause torsional vibrations at a nearby power plant. For the Line Commutator Converter (LCC) type, interaction is only considered to be possible at the rectifier side, so when exporting power from the AC grid to the DC line. Other issues have recently been reported in China, where a large number of converter stations are being installed. There, issues are also reported on the inverter side (importing power to AC grid) after numerous commutation failures.

What is the relation between electrical sub-synchronous frequency (sub-harmonics) and mechanical torsional frequency of the shaft?

The torsional frequency fm seen on the shaft is equal to the grid frequency f0 minus the electrical frequency fe. So fm=f0- fe. As the shaft is running at a certain speed, the electrical frequency becomes modulated on top of this rotational speed. So, a 40Hz component on the grid will be seen as 10Hz mechanically. A torsional frequency fm will induce electrical components at fe=f0 +/- fm, so both sub-and supersynchronous components.

Concerning electrical frequency and mechanical torsional frequency, can one measurement determine the other?

Yes, but reconverting the electrical components into torsional vibration amplitudes is far less straightforward.

What is a safe permissible torsional vibration level for GT & Generator?

The underlying damage mechanism for torsional vibrations is fatigue. For every torsional vibration mode, the most stressed location on the shaft can be different and hence the allowable torsional vibration level at the GT/Generator can be different too. It also depends on the local geometry, local stress concentration effects, material, and mean stress, for example. You also need to consider the measurement position. So, there is no generally applicable rule.

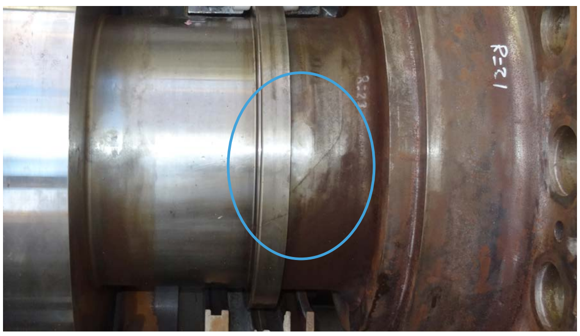
Is the second mode of 95Hz typical for the given example of a turbo machine, and is it different for each shaft line? What is the determining factor for this 95Hz frequency?

Every dynamic structure is characterized by its natural frequencies, which in turn are determined by the inertia and stiffness properties of the shaft line. For the gas turbine unit in the example, the three lowest natural frequencies are 18Hz, 95Hz and 130Hz. They will be different for other gas turbine units, but qualitatively it will be comparable.

Typically, there is one subsynchronous natural frequency, around 15-25Hz, at which the gas turbine twists out-of-phase with the generator. Higher modes involve twisting of the main rotors (gas turbine against compressor, internal twist at generator) and are therefore higher. For ST units or single shaft units, it is more complex and multiple subsynchronous natural frequencies are seen.

Severe compressor rotor cracking caused by torsional vibration resulting in losses of several millions of Euros.

This huge crack in a compressor rotor shaft was recently discovered at a power plant. The location and orientation of the crack suggests that it was caused by torsional vibrations. For the power plant, this came as a complete surprise. They were under the impression that their shaft line was running smoothly, while in fact excessive torsional vibrations had been present for almost 10 years, but went undetected because they occurred only in very specific conditions. Because the cracking lay undiscovered for so long, fatigue damage accumulated and finally led to enormous financial losses.



You speak about CCGT turbines. Are these phenomena applicable to hydraulic turbine shafts?

Torsional interaction can occur in every unit, so steam turbine units too, for instance. For hydro turbines, the risk of grid interaction is typically low because the generator has a very large inertia compared to the turbine. It therefore acts as a filter, effectively blocking oscillating energy from the grid. The water from the turbine also provides more damping to the torsional vibrations compared to GT and ST units where the overall damping is very low (only material damping and small damping due to steam at larger LP blades).

Less stable grid: what would be the shortest (or longest) phenomenon that could trigger a harmful torsional vibration? Can normal changes in wind speed or direction, or variations in sun cause damage?

Normal changes in wind or solar production have a negligible effect on torsional vibrations. This holds for transient events in general except, for example, in the case of short circuits at the generator clamps of the power plant. As long as the transient events involve power changes of less than 50% of the nominal power of the power plant, they are not considered lifetime consuming.

Renewables, however, render the grid less stable as grid inertia reduces. A stronger rate of change of frequency is therefore already considered (for Europe, see available ENTSO-e guidance documents). A less stable grid can also cause more contingencies (e.g. loss of a transmission line), impacting the potential interaction of the power plant with the grid. Other changes include more and larger power electronics on the grid which can also increase the risk of interaction.

Does the added mass/inertia/damping at turbine impeller vanes influence torsional vibrations?

For a turbine impeller, the inertia of the water must be taken into account as it lowers the torsional natural frequency of the system. Typically, the water is added as a lumped mass. Hydro-acoustic effects are typically not considered for the overall torsional vibration behaviour of the shaft line. They do need to be considered when the dynamics of the impeller itself are analysed. The water also introduces some damping in the system which reduces the torsional vibration amplitudes.

In 2006, a major grid incident occurred across Europe with under- and over-frequency of +/- 1.5 Hz. Was there any known damage caused by this incident?

We still have the grid frequency measurements for Belgium from that time. A change in the grid frequency is not necessarily an issue for the shaft line as long as this change is limited to avoid excitation of torsional natural frequencies nearby 1x and 2x grid frequency. The incident could have been more significant in terms of changes in grid configuration and grid strength which in turn increases the risk of torsional interaction.
We are not aware of any damage from this incident but, since it concerns fatigue damage, it cannot be excluded that rotor lifetime was consumed at some power plants.

What exactly is the principle behind the measurement Laborelec makes at the end of the generator shaft? Is it mechanical, or electrical?

We have implemented an optical encoder at the shaft end of our nuclear units. The advantage is that you have a perfectly uniform toothed wheel (for fewer harmonics) and also a 1 per revolution signal which facilitates post-processing.

Our insurer allows for measuring just one of a series of similar shaft lines. Would a different location be a contra-indication for this approach?

That depends on what you are aiming for. If the goal is to confirm 1x and 2x grid frequency exclusion zones for the torsional natural frequencies of the shaft line, then this seems justified. If potential interaction with the grid is under study, additional analysis would be required.

Are torsional vibrations specific to particular types of gas or steam turbines?

When issues are caused by grid interaction, this is not fleet specific. The interaction can happen for every type of machine. Identical machines are not necessarily subject to the same interaction since the local grid configuration plays a role here.

If the underlying cause is internal to the power plant, for instance due to voltage or speed control instabilities, this can be a fleet issue and therefore fleet/machine specific.

This is exemplified by two recent examples in the MHPS fleet after which a technical bulletin was distributed to the entire MHPS fleet.

How would you compare the magnitude of torsional vibrations induced by a generator trip with a load, versus all other causes (such as grid variations)?

A trip of the unit at nominal load will cause a torsional oscillation of the lowest torsional natural frequencies with an amplitude initially equal to the static angle at nominal load. In terms of fatigue lifetime consumption, a trip event is considered to have very limited impact. Grid interaction can induce much higher torques (e.g. 5x static torque) which can also last longer.

Is there any instrumentation on the market which can be fitted to the couplings?

Not to my knowledge. Sometimes the outer diameter of a coupling is machined (see right side of picture on slide 3 of the webinar) to allow torsional vibration measurement with a speed pick-up.

What continuous condition monitoring actions can monitor torsional vibrations?

In torsional vibration condition monitoring, the main interest lies in the lifetime consumption of the unit. If events are detected that consume significant shaft line lifetime, the power plant would be alerted. After detection, more detailed analysis can be initiated to understand the underlying cause and measures to avoid the problem in the future.

To enable monitoring, a torsional vibration model needs to be built based on the available technical drawings. Simplified torsional vibration models (required at the design stage) are typically provided by the OEM. From a practical point of view, it needs to be verified whether the existing speed sensors can be used. In rare cases where this is not possible, additional sensors need to be installed.

To identify the torsional frequencies and produce the models, is measurement data from one rotor sufficient (using speed probes or external measurements) or do you need to measure all the connected rotors separately?

The torsional vibration model, along with the mode shapes, are typically available from the OEM. Based on this information, the sensor location can be assessed. Measurement at one location on the shaft line is normally sufficient, at least for the subsynchronous modes. It depends on the measurement location and the mode shapes of the different torsional natural frequencies. If the sensor is located in a node of a mode, a single location is not enough. Typically, 2-3 sensors are sufficient to capture all the natural frequencies.

How do you monitor torsional frequency on pumps and compressors?

The measurement principles are the same. As explained in the webinar, there are many different technologies available for measurement.

Can you say a bit more about how you managed to protect the unit from future torsional vibrations in the previous example?

The root cause analysis has unfortunately not yet been finalized and so a final solution has also not been implemented.

Would we be able to identify external interactions, such as load rejection or any grid transient, using phase difference between the turbine shaft and the generator shaft? Which area would most likely be affected from the perspective of visual inspections during outage?

Typically, the most important torsional vibration modes are the subsynchronous ones. With one single measurement on the shaft and the underlying model, we can determine the stress levels at every point of the shaft. Based on the mode shapes, we can already identify (without measurement) the positions on the shaft where damage is most likely to occur, which can serve as inspection guidelines. Typically, this is on the intermediate shaft between the main rotors at the fillet transition of a coupling for instance.

What would you recommend as a good inspection regime for torsional vibration impact on rotors, or for transients?

This is difficult to answer as this would require dedicated monitoring, such as with a torsional vibration monitoring system. When such a system is available, the fatigue lifetime consumption can be tracked over time and serve as an input for inspections.

Can the torsional vibration impact be mitigated at the mechanical design stage of the shaft?

Possible means of mitigation:

- eallocating the natural frequency if it is close to 2x grid frequency;
- reducing the local stress concentration effect (larger fillet radius for instance);
- if an intermediate shaft is present, ensure that this is the weakest link, so that if torsional vibrations damage the machine, you won't have to replace a rotor, which would be more costly;
- a torsional vibration damper.

In the examples, how would the retaining rings be affected?

Retaining rings are typically shrink-fitted onto the generator rotor. If torsional vibrations are present, the generator will oscillate back and forth. This means that the retaining ring needs to follow this oscillation as well. The inertia of the retaining ring will induce a force onto the shrink-fit surface and cause a phenomenon called fretting fatigue. This can initiate micro-cracks on the surface which can further propagate.

The energy transition in South Africa is a topical issue, and the 2019 integrated resource plan estimates that wind and solar will represent 23% and 11%, respectively, of electricity generation by 2030. With that in mind how can an existing wind farm adequately prepare itself against the risk of the uptake of renewables?

Torsional interaction has also been observed in wind farms on occasion. In some incidents, the damage was incurred within one second of interaction with a series capacitor bank. There is increasing research ongoing in order to improve understanding of this and risk management.
Clearly, monitoring seems to be the first step in gathering experience. In some cases, the electrical parameters are already being measured and could therefore be used as monitoring input.

Is the rupture more likely at high or low pressure?

Failure occurs at the weakest link in terms of fatigue lifetime and depends on the frequency at which the unit is excited. In general, these are locations where the diameter is least. For high- and low-pressure steam turbines, there is no general rule. For the lowest vibration mode of a steam turbine unit, the highest stress typically occurs between the generator and the LP turbine.

Is it normal to have a problem every five years due to vibrations?

Vibration issues occur quite frequently, as is clear from experience all over the world. This could be due to design issues or changes in operational conditions (e.g. grid configuration). There is no real time-based relationship.

Does a normal FFT from a high quality timewave captured with an optical probe and zebra tape show the torsional vibration frequency?

Normally, the output is a digital signal (e.g. TTL) which needs to be processed by TIM (Time Interval Measurement). An FFT will generate a lot of harmonics. The torsional frequencies will appear as sideband modulations of the main speed harmonic component. The amplitude, however, won't make much sense.

Are there any examples of ENGIE Laborelec's torsional vibration system installed here in the UAE?

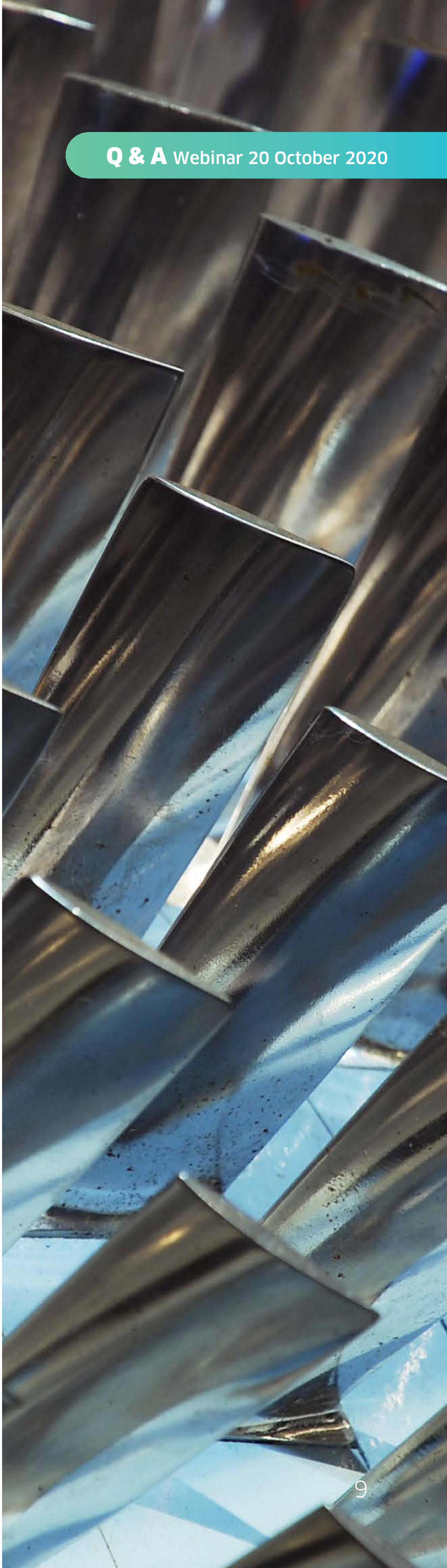
No. We have TORSO on 25 units in Peru and Chile and six units in Europe. There are many different temporary campaigns ongoing.

We experienced defects from variable frequency drivers (VFD). Can we set some variables to avoid these defects?

The first thing is to conduct a root cause analysis to confirm that the VFD is causing the defects. This requires at least analysis of the failures found including metallurgical analysis and a design review. A detailed measurement campaign (radial/torsional vibrations, electrical measurements) can further help to identify the issue (potential resonance?).

The VFD is known to be a source of torsional vibrations (6x, 12x, 18x operating speed, and greater), but other components on the train can also serve as a source (e.g. pump impeller).

If the VFD is causing the issue, harmonic content could be reduced by changing the type of VFD (e.g. Pulse Width Modulation instead of Current Source Inverter). If a resonance condition is identified, then the options are to avoid the speed range at which resonance occurs or to apply a structural modification in order to reallocate the natural frequency outside of the operating range.



Does variation in grid frequency cause the torsional vibrations? What are the typical values for the tolerable range of grid frequency? Are generator/turbine trips kept/based on these considerations?

Allowable grid frequency variation depends on the grid standards. In Europe, the current ROCOF (Rate of Change of Frequency) is rather low and in practice it has never exceeded 1Hz/s. With the increasing amount of renewables, this is expected to increase and ROCOF values up to 2Hz/s should be anticipated. The impact on the machine of an increased ROCOF is on different levels. In a direct sense, the change in frequency will cause an inertial torque on the machine, the size of which depends on the actual frequency gradient and the inertia of the shaft line. Another impact is related with the control logics (speed, voltage) at the power plant level. These should be able to recover from such grid frequency changes without rendering the system unstable.

The change in grid frequency itself has a limited effect, unless for instance if torsional natural frequencies are moved closer (too close) to 1x and 2x grid frequency. In Europe the grid frequency is limited to 49.8Hz and 50.2Hz.

Any known failure examples for hydropower units?

Not to my knowledge. For hydro turbines, the risk for grid interaction is typically low because the generator has a very large inertia compared to the turbine. It therefore acts as a filter, effectively blocking oscillating energy from the grid. The water from the turbine also provides more damping to the torsional vibrations compared to GT and ST units where the overall damping is very low (only material damping and small damping due to steam at larger LP blades).

The TSO usually provides the harmonics background at the connexion point. Could this information be used to assess potential transfer to turbines?

The harmonics play a role in the power quality and are therefore an indication of perturbations on the grid. For instance, they can be used as an indication for what interaction with an AC arc furnace plant involves. If a large amount of harmonic energy content is present, the impact on the conventional power plant might be significant. However, interaction occurs typically at subsynchronous frequencies which is not reflected by the harmonics. The useful info they can provide is therefore limited.

In our power plant there is a GE torsional protection system based on the speed signal of ST. Is that speed signal enough to protect the machine?

For protection, more than one sensor should be used for redundancy. Whether or not one axial location on the shaft line (with two sensors) is enough depends on the mode shapes. If that sensor is able to see the different mode shapes, then this can be sufficient.

How much has the interaction of negative sequence current components in torsional vibrations been considered? It is known that during line-to-line short circuits, high magnitudes of this current occur and during unbalanced loads. Is this component of the stream considered within TORSO?

Negative sequence currents introduce excitation at 2x grid frequency. At the design stage, exclusion zones are imposed for natural frequencies near 1x and 2x grid frequency. Some guidelines are given in the ISO 22266-1 standard. At 100Hz, the theoretical model is more prone to errors, such that these exclusion zones are not met. Different LP blade failures have been reported in the past. When measuring on-site, the exclusion zones are verified (with TORSO for instance) and mitigation actions can be taken (see for instance the first example in the webinar) if needed.

Is there a technology to disconnect the grid breaker to isolate the source of torsional vibration excitation?

Yes, there are several so-called torsional vibration protection systems on the market, typically offered by OEMs. Laborelec has developed its own protection system, which is currently installed on more than 30 units. The main functioning is based on the underlying fatigue damage consumption as described in the webinar (slide 30). When significant fatigue damage is being consumed, the protection system will trigger a relay which will automatically trip the unit and disconnect it from the grid.

For GT unit maintenance, what could be the recommended "standard" inspection to be carried out using PT (penetrant testing) on the shaft, bearing in mind that they are units that have daily starts?

Based on the model and technical drawings, the most critical locations can be identified for inspection. This will be on sections where the diameter is smallest and where the stress concentration is highest, e.g. at a fillet radius of a coupling for instance.

How can you identify a compressor crack in a vibration analysis?

A crack is not always visible in the radial vibrations. Typically, it is only identified when they have reached a considerable size compared to the rotor diameter, such that the local unbalance and/or stiffness change. It can then be seen in the 1x and/or 2x components of the radial vibrations, either during the transient at the critical speed or at nominal speed.

The increase in vibration amplitudes can be over the course of less than a day or over several months. This depends on the crack location, geometry, length or other factors. There is no real generic rule.

What is the amplitude of frequency (+/- 50 Hz) on the grid to avoid torsional vibration?

Variation of grid frequency in itself does not cause torsional vibrations, unless natural torsional frequencies are moved closer (too close) to 1x and 2x grid frequency or where control interaction occurs after these grid frequency changes.

Can the rotating stall of a compressor cause torsional vibrations?

A phenomenon has been reported where the rotating stall can couple with the torsional mode of the blade dynamics. To further couple with the torsional vibrations of the entire shaft line, the zero nodal diameter of that blade row would need to be excited and the torsional natural frequency should lie at the same frequency. I would not exclude it a priori, but the chances are slight.

How do steam flow variations influence torsional vibrations?

Steam flow provides some excitation of the shaft line, but this is rather random, and the resulting torsional vibration response is limited.

Can the phenomena originate from the power train control system, such as GT gas valve speed or main steam turbine valve speed?

Yes, in addition to excitation due to grid interaction, excitation is also possible due to internal control instability. Examples are voltage control instabilities due to interaction with the Power System Stabilizer (PSS). Speed control instability has also been reported due to a malfunctioning gas fuel valve. Any control action which can interfere at higher frequencies can introduce torsional vibration issues. In most cases, a torsional filter can be used to resolve the instability issue.

We have suffered some cases where gas compression failures have caused broken engine crankshafts. Do you have any experience of compression equipment you can share?

Not directly. In Belgium we have encountered a failed crankshaft on a diesel engine where propagation was due to torsional vibrations initiated by excessive bending forces. It would be interesting to know whether a root cause analysis has been performed on your cases.

How many locations do you need to measure?

In most cases, one axial location on the shaft line is sufficient. Sometimes a second temporary sensor is added in order to have some validation of the underlying model.

Does the position of your sensor influence the quality of your calculations?

If the sensor is too close to a nodal point of the mode shape, the uncertainty can become too great, and significant errors could be introduced in the correlation between measured torsional vibration amplitude and stress level elsewhere.

Can a torsional vibration expert detect torsional vibrations using conventional vibration monitoring systems (with sensors installed on the bearings measuring radial and axial vibration and a tacho), such as System I?

Except for shaft lines with a gearbox, there is no strong coupling between the radial vibrations and the torsional vibrations. The radial vibrations cannot therefore typically be used to assess torsional vibrations.

The tacho typically aims at providing an average speed signal in which the higher torsional frequency content is not present. The tacho might be used (depending on what type of signal comes out), but dedicated hardware/software is needed to convert this to torsional vibrations.

Is torsional vibration cumulative? To assess the risk, is it necessary to quantify the cumulative damage and remaining life?

The underlying damage mechanism is fatigue. Fatigue damage accumulates over time and so, to assess the risk of continued operation, the remaining lifetime needs to be determined. We have applied this in the past to assess the risk of continued operation of parallel units after the failure of one or more units of the same power plant.

Do cracks in the shaft due to torsional vibrations start on the outside or the inside of the shaft?

They start from the outside because that is where stress levels are highest (linear increase with diameter). Initiation is typically at stress concentrations (e.g. fillet).

Is there a difference between torsional vibration damage on generators and on electromotors?

On large synchronous generators, damage observed at the generator due to torsional vibrations is at the retaining rings, which fail due to fretting fatigue. For electromotors, it's a completely different story – the entire drive train needs to be considered. Damage is more likely to occur in the intermediate parts (e.g. at couplings).

How accurate is using a magnetic pick-up compared to an encoder used continuously?

The encoder also provides a pulse train. The difference with a magnetic pick-up is that the tooth profile is more uniform compared to a machined toothed wheel. The number of teeth is also typically higher than for a toothed wheel but, as we are interested in frequencies below 200Hz, this does not have an impact on accuracy.

TORSO, ENGIE Laborelec’s torsional vibration monitoring and protection system

Keep a watchful eye for harmful torsional vibration in shaft lines

Among the potential harmful conditions for turbo-groups, torsional vibration is one that is generally overlooked. Because it can lead extremely quickly to dramatic failures, effective protection systems must be able to react within seconds.

TORSO, Laborelec’s torsional vibration monitoring system for turbo-groups, tackles this issue effectively and brings peace of mind back to your condition monitoring strategy.

What is torsional vibration?

Torsional vibration is angular vibration of an object—commonly a shaft along its axis of rotation. It is superposed to the static torsion and occurs at the frequency of the torsional excitation. It may coincide with the shaft's natural frequencies. Torsional vibration is often a concern in power transmission systems using rotating shafts or couplings where it can cause failures if not controlled.

An understated but real enemy

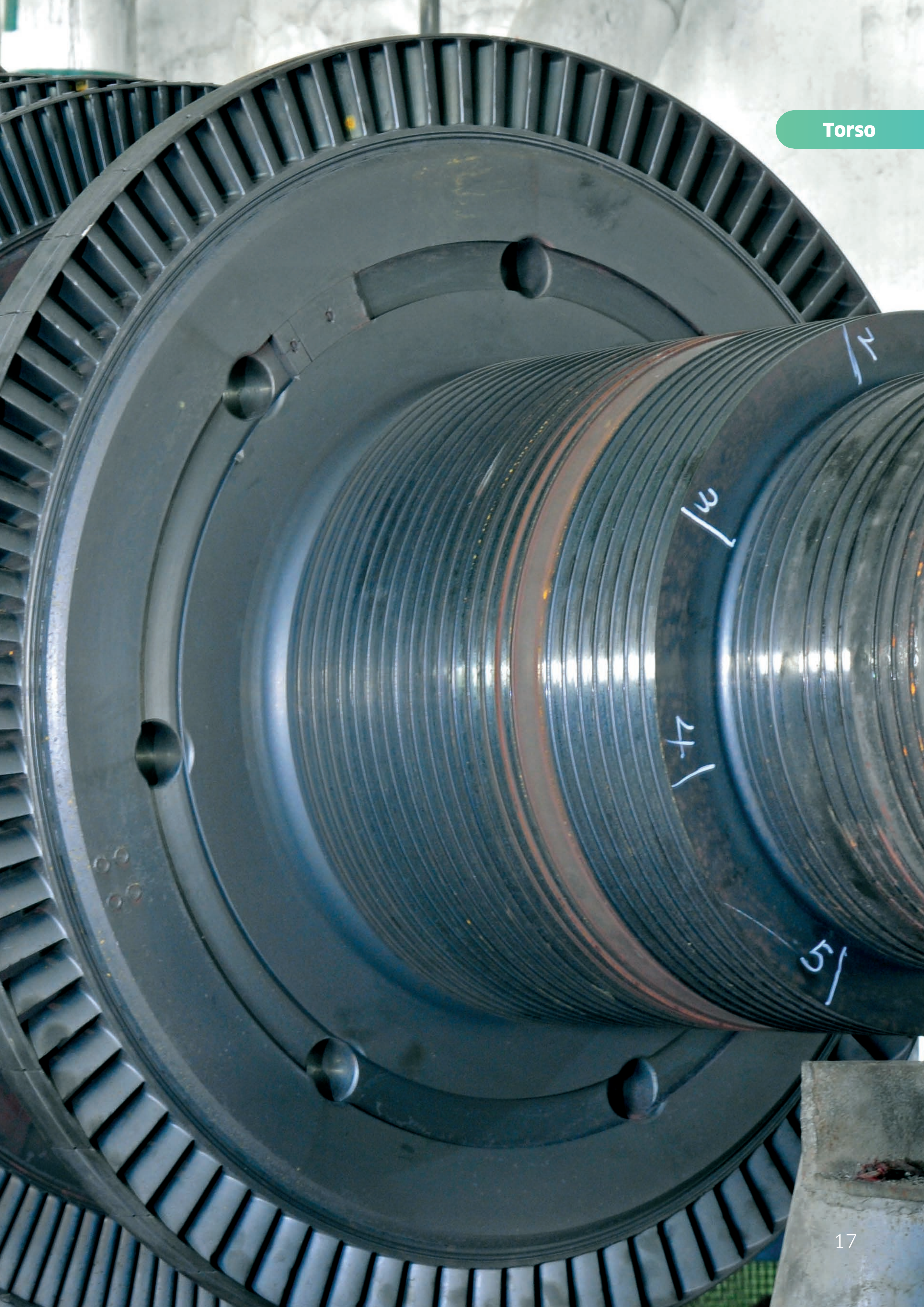
Although the risk of damage due to torsional vibration is generally well assessed at the design stage of a power generation system, later adjustments to the shaft line, or modifications to the external power system, can create the perfect conditions for certain phenomena to develop. These conditions include sub-synchronous resonance or interactions with high voltage DC stations which, in turn, lead to excessive levels of torsional vibration. In most operational environments, this specific type of vibration is not tracked, even though it can abruptly lead to heavy damage such as shaft cracking, blade loss or gearbox failure.

TORSO keeps the installation safe

Using specific sensors, easily mountable on toothed wheels or on shaft ends, TORSO protects the shaft line from the effects of harmful torsional vibration. It rapidly detects when this reaches pre-defined thresholds, and trips the unit before severe damage can occur.

Mounting of a sensor at the turbine - generator coupling

Typically, between 1 and 3 well-positioned sensors are sufficient for the system to offer full protection. Our experts can advise on the most appropriate sensor locations, since these are machine-specific. In addition, existing speed sensors can be used in most cases.



Benefits

- **EASY TO INSTALL.** Adjustable and easy to install on the most commonly-encountered types of machines.
- **OPTIMISED ALARM STRATEGY.** Unique, intelligent strategy for triggering alarms and tripping.
- **MONITOR & DIAGNOSE.** Historical data available for further analysis and troubleshooting.
- **NOT A BLACK BOX.** Open system allowing power plant staff to visualise and work with data.
- **VERSATILE.** Available for both permanent and temporary monitoring.

How it works

Initial modelling of the shaft line

- A specific rotor mode shape analysis makes it possible to select the best locations for the sensors in accordance with the expected mode shapes.
- The results of this initial modelling is validated at a later stage with on-site measurements, to ensure the best protection level is achieved.

Installation and validation

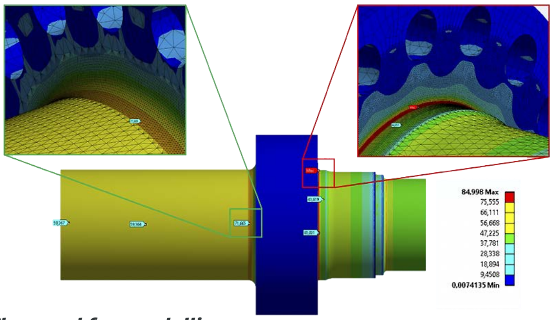
- Sensors are installed at different locations along the rotor to build in redundancy and provide better signal processing functionality for the system.
- Alarm or trip signals can be wired either to the control system or to one of the generator relays. Frequency and amplitude signals of monitored frequency bands can be wired to the DCS or SCADA system.

Monitoring

- Frequency and peak amplitude of critical resonance frequency bands are continuously monitored by the system.
- The common alarm/trip strategy comprises a watchdog alarm, an event detection level alarm and a trip level alarm.

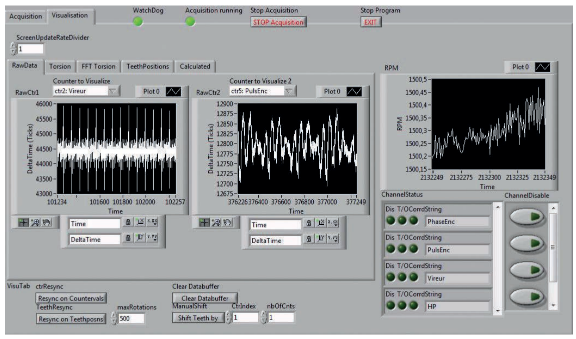
Diagnosis of specific issues

- Through its customisable interface, measurement data are presented for analysis, diagnosis and identification of remedial action by power plant staff or Laborelec experts.



The need for modelling

Each specific machine is different and vibrates in a slightly dissimilar way. Critical locations where material damage is most likely to occur are precisely calculated due to TORSO's underlying theoretical shaft line modelling.



Finding the right alarm thresholds

Alarm thresholds set too high will lead to undetected excessive torsional vibration and severe damage. However, excessively low thresholds can generate a large number of unwanted alarms. The model behind TORSO makes it possible to calculate precise thresholds, and determine a safe middle course.


Five reasons for you to choose
ENGIE Laborelec
Wide-ranging technical expertise in electricity generation, grids, and end-use
Customers enjoy enhanced profitability and sustainability of energy processes and assets
Unique combination of contract research and operational assistance
Independent advice based on certified laboratory and field analysis worldwide
More than 50 years of experience
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