WORLD-CLASS OUTSTANDING INTERNATIONAL

PROGRAM | EXHIBITION | NETWORKING

ELECTROMECHANICAL OPTIMIZATION AGAINST TORSIONAL VIBRATIONS IN O&G ELECTRIFIED TRAINS

MICHELE GUIDI [GE O&G]

ALESSANDRO PESCIONI [GE O&G]

42nd Turbomachinery
29th Pump SYMPOSIA

GE Oil & Gas

TEXAS A&M ENGINEERING
TEES
TURBOMACHINERY LABORATORY

GEORGE R. BROWN CONVENTION CENTER
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Topics

INTRODUCTION - Mechanical vibrations in electrified trains

CASE STUDY 1 - Minimization of Gearbox vibration on Motocompression Train

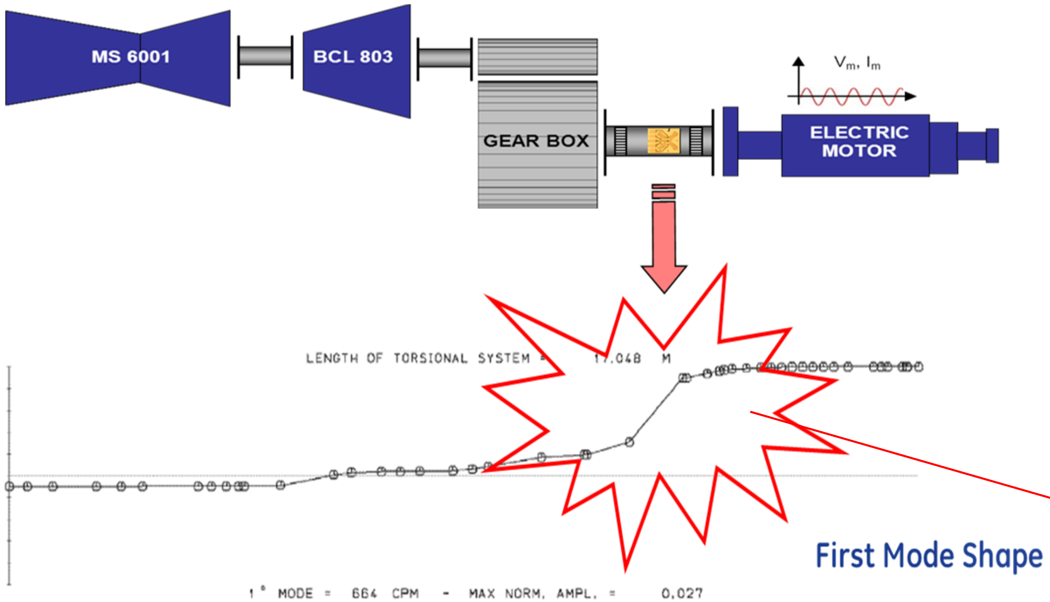
CASE STUDY 2 - Optimization of Torsional Vibration on LNG Train

CONCLUSIONS

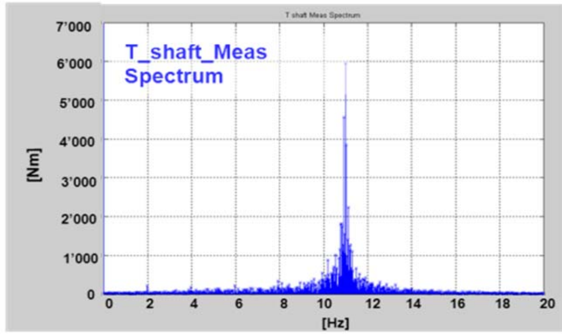
Introduction – Mechanical Vibrations in electrified trains

Torsional Vibrations

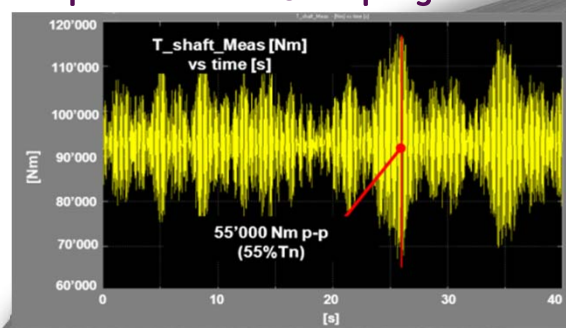
- Relative twist along the shaft line sections.
- Trains have high dynamic response at their Torsional Natural Frequencies → low mechanical damping.
- Not detectable without dedicated equipment (e.g. strain gauge, toothed wheels).
- Torsional vibration seen as lateral vibration on gearbox.
- Most severe potential risk is the failure of couplings → plants shutdown



Example with 1st TNF @ 11Hz:



Torque oscillation @ coupling:



Introduction – Mechanical Vibrations in electrified trains

Potential Causes

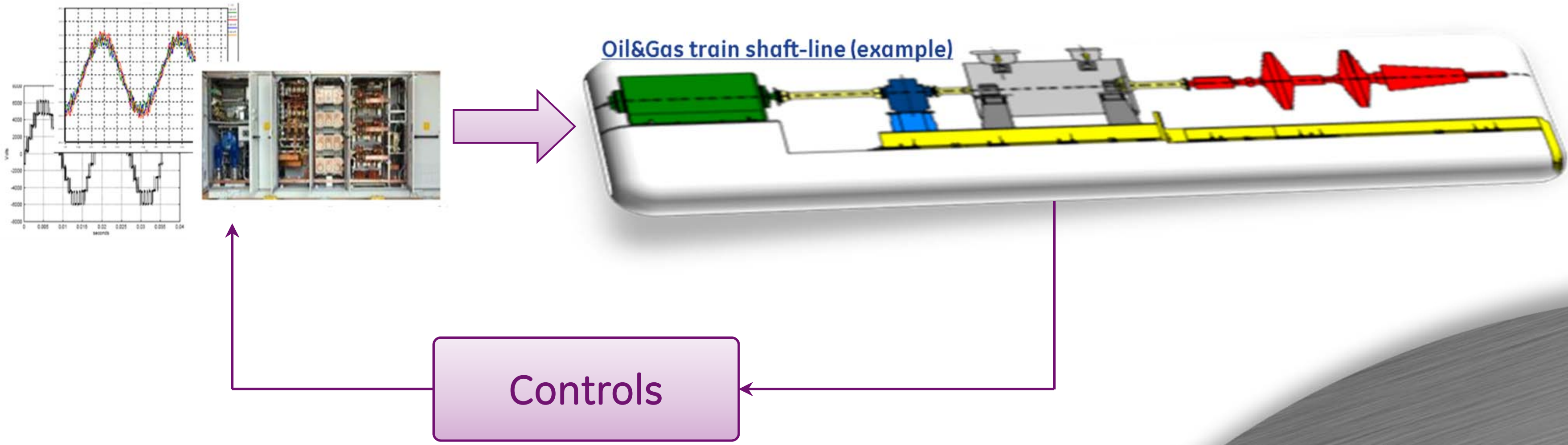
1. Mechanical marginal stability: Low mechanical damping and torsional-to-lateral vibration transfer (flexo-torsional phenomena).

2. Direct torsional excitation from VFD: Air gap torque harmonic components (voltage/current distortion caused through the converter supply).

3. System closed-loop behavior: interaction between electrical and mechanical systems through the controls settings.

Electric Variable Speed Drive

Oil & Gas train shaft line:



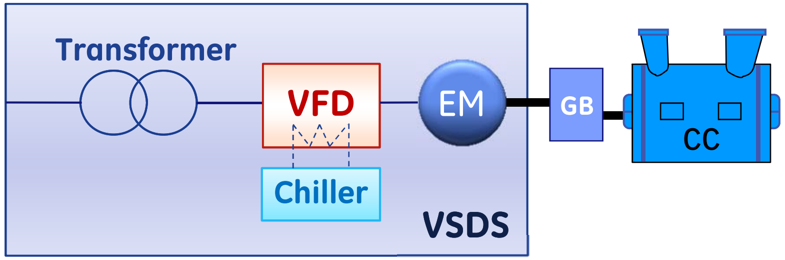
Mechanical vibrations are "system's" phenomena → the entire shaft line need to be analyzed as a whole system with a closed-loop integrated approach.

CASE STUDY 1

Minimization of Gearbox vibration on a Motor Compression Train

Compression Train Composition

- Step-Up Transformer + VSI Frequency Converter
- 10 MW Induction Electric Motor
- Gearbox
- Centrifugal Compressor



Problem during the internal string test (no-load):

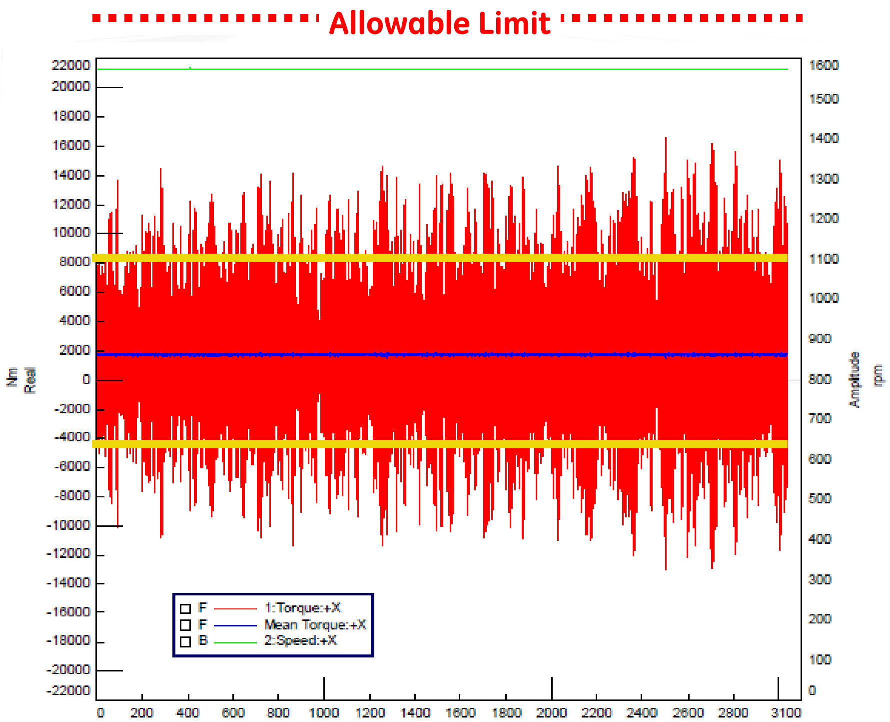
- High lateral vibrations, over acceptance limits, on Gearbox High Speed Shaft side.

	Vibration limit			
	Recommended by manufacturer		GEO&G acceptance criteria	Specific job acceptance criteria
	Alarm	Trip		
Wheel	92 µm	137 µm	35 µm	25 µm
Pinion	59 µm	88 µm	35 µm	25 µm

- Vibrations characterized by low-frequency and low amplitude broadband, sub-synchronous vibrations that fluctuate randomly.
- 17 Hz lateral vibration component related with the train 1st TNF (Torsional Natural Frequency)
- Torsional oscillating torque (@ motor coupling) well below acceptance limits (~30 kNm)

Torque Response vs. Time

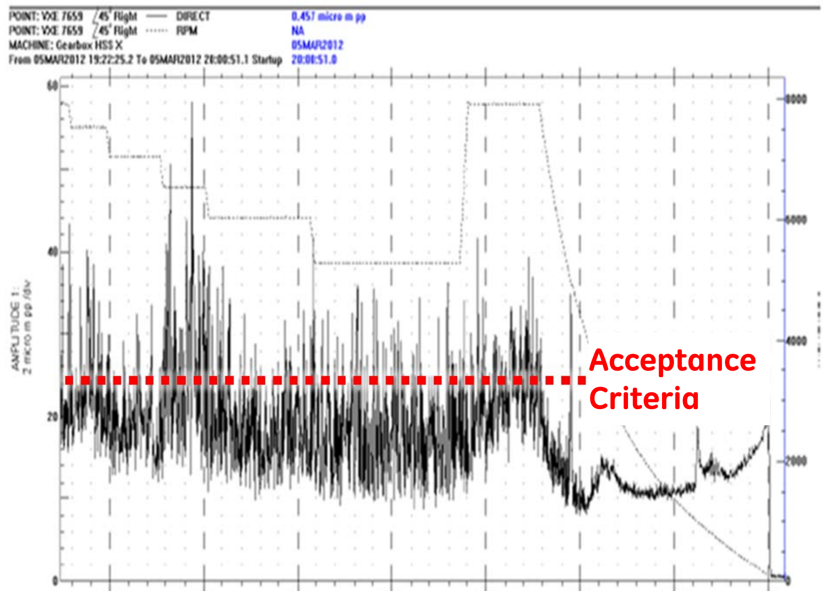
Motor–Gearbox load coupling (LSS)



Alternating Torque ≈ 12kNm << coupling capability (≈ 30kNm)

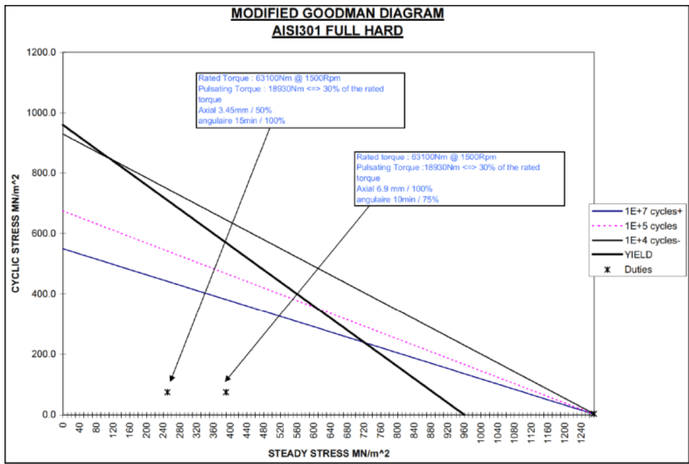
Lateral Vibrations vs. Time

Gearbox HSS bearing



Peak Amplitude 40 - 60µm-pp >> acceptance criteria (25 µm-pp)

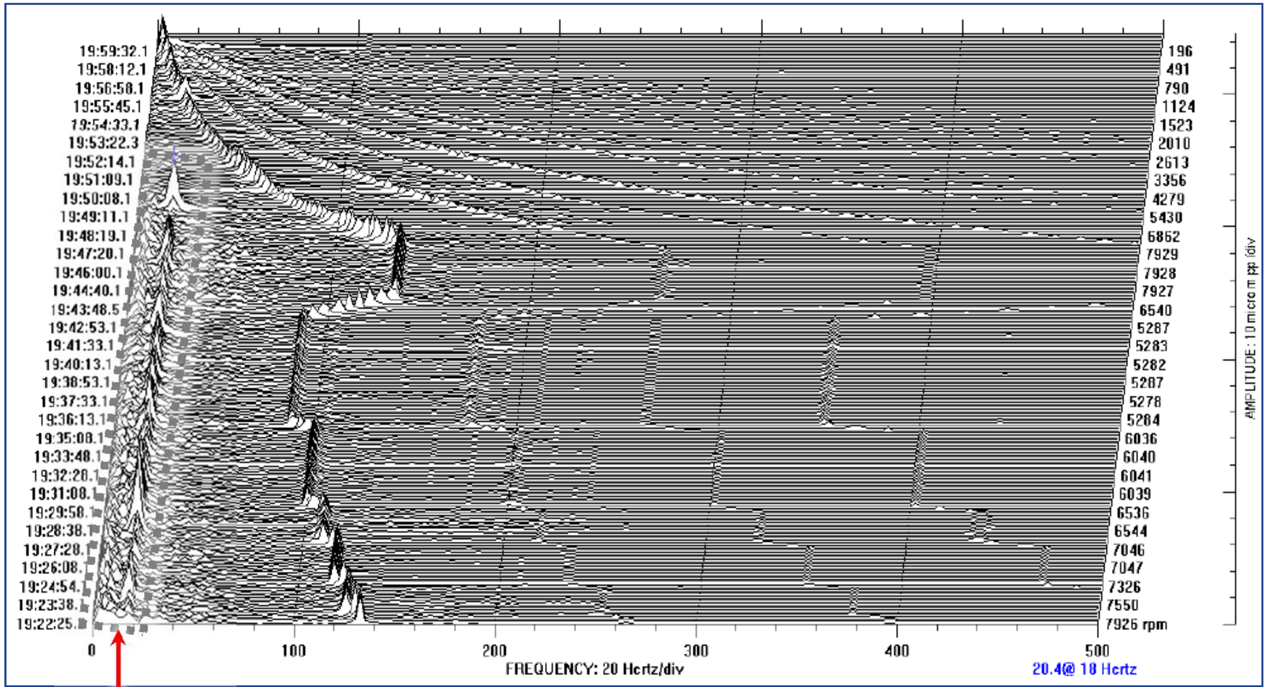
Coupling life verified with Goodman diagram



Due to the **low mechanical stability** shaft torsional oscillation have **transferred through the gearbox** on lateral vibrations

Waterfall diagram (Frequency components vs. Time)

Lateral Vibration on Gearbox HSS bearing



Vibration component @ 1st TNF

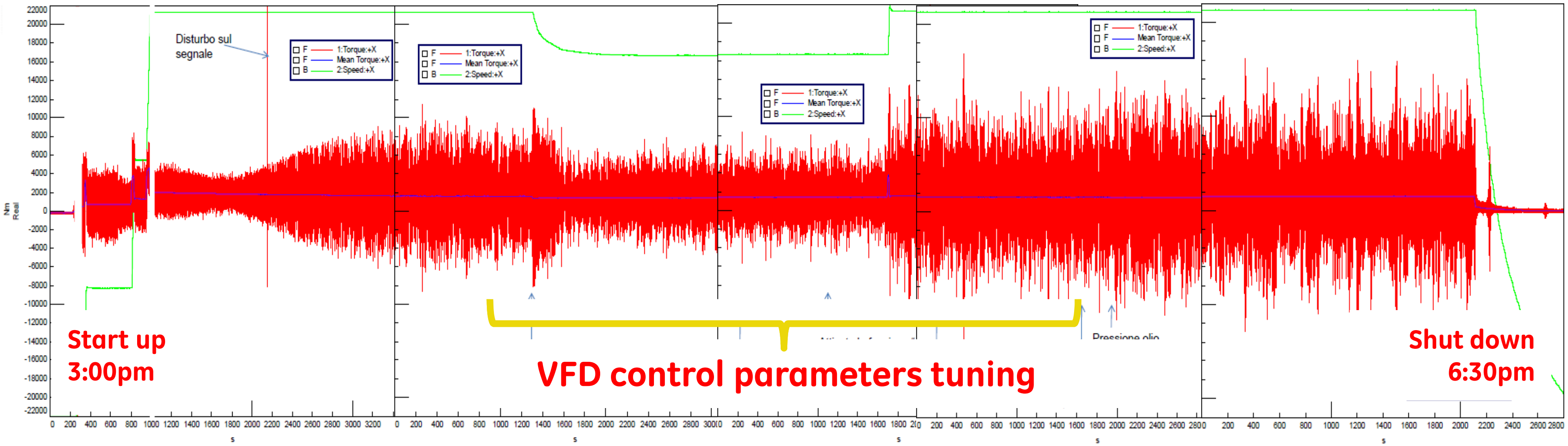
Low mechanical stability and **flexo-torsional phenomena** lead to a **lateral vibration** on the gearbox high speed shaft, above acceptance limits.

Mitigation steps:

- **Phase 1:** VFD control settings optimization through parameters tuning
- **Phase 2:** Mechanical modification on gearbox bearing to improve mechanical damping

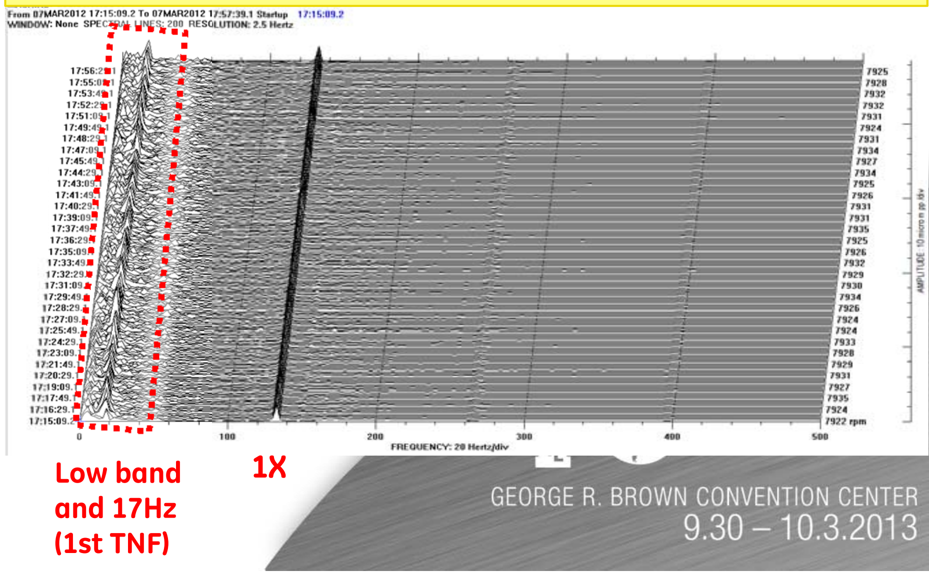
Mitigation Steps - Phase 1: VFD control settings parameters tuning

Torque response vs. Time on Motor-Gearbox load coupling:

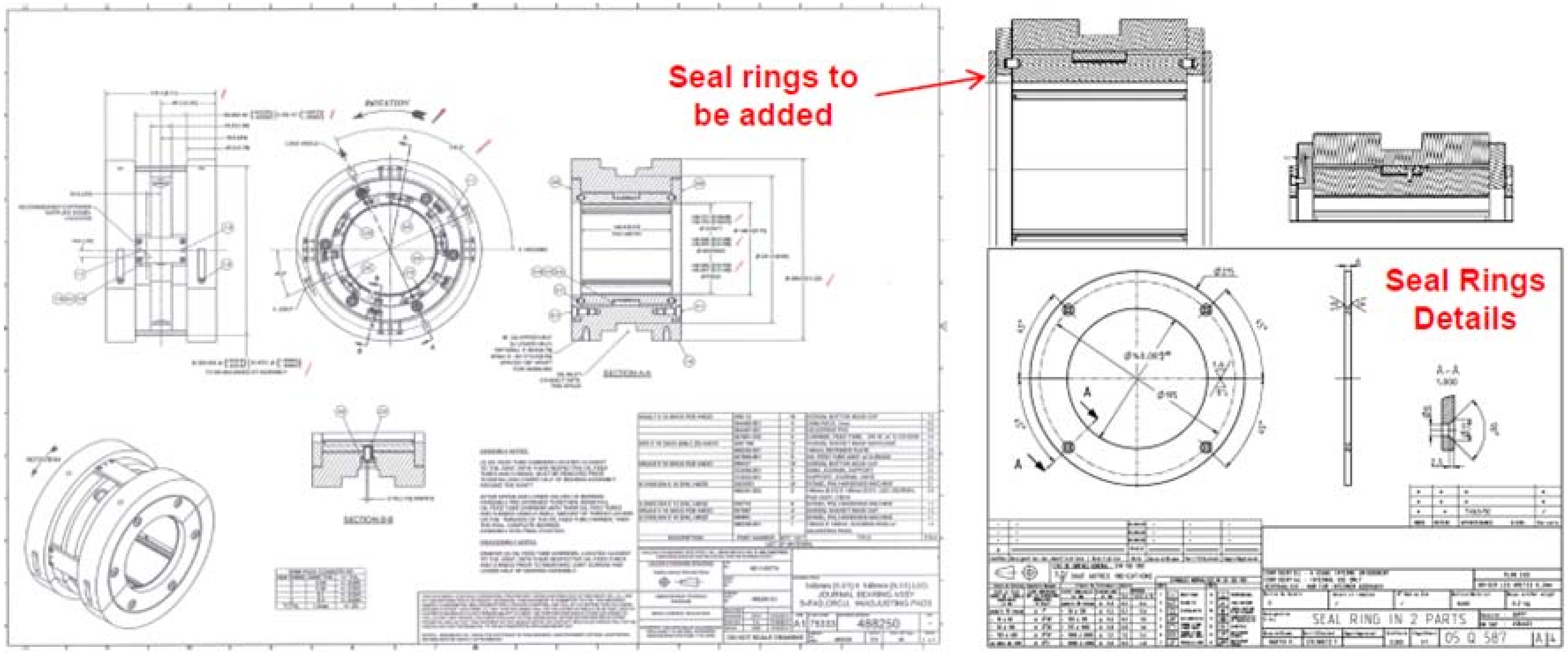


- Changed VFD speed controller parameters (Kp and Ti) to simulate an "open loop" control (slow control).
- Temporary reduction of alternating torque due to the speed reduction (effect of the reduced torque reference)
- Enabled dedicated software filter, tuned on the 1ST TNF (@17Hz).
- No significant modification on the oscillating torque @ coupling.
- Lateral Vibration and low frequency components still present.

Waterfall - Lateral Vibrations (on GB HSS) After VFD tuning



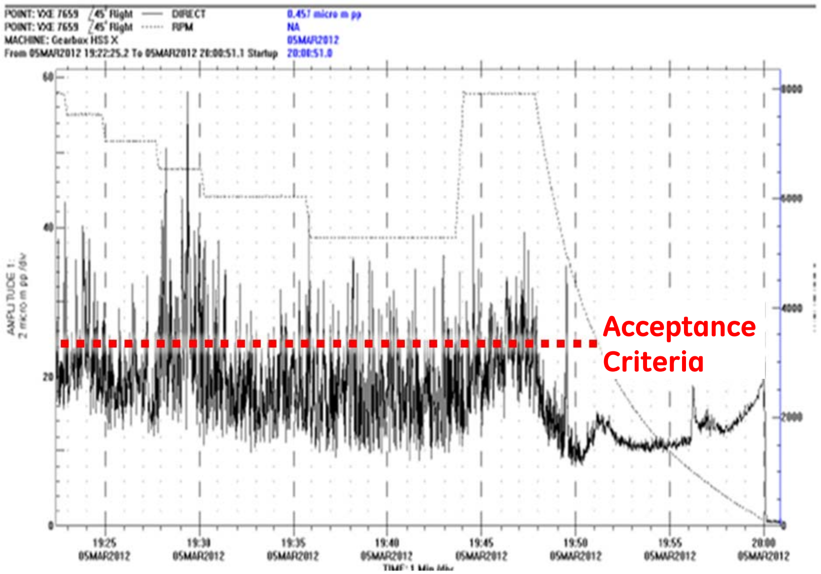
Mitigation Steps - Phase 2: Mechanical modifications to increase stability



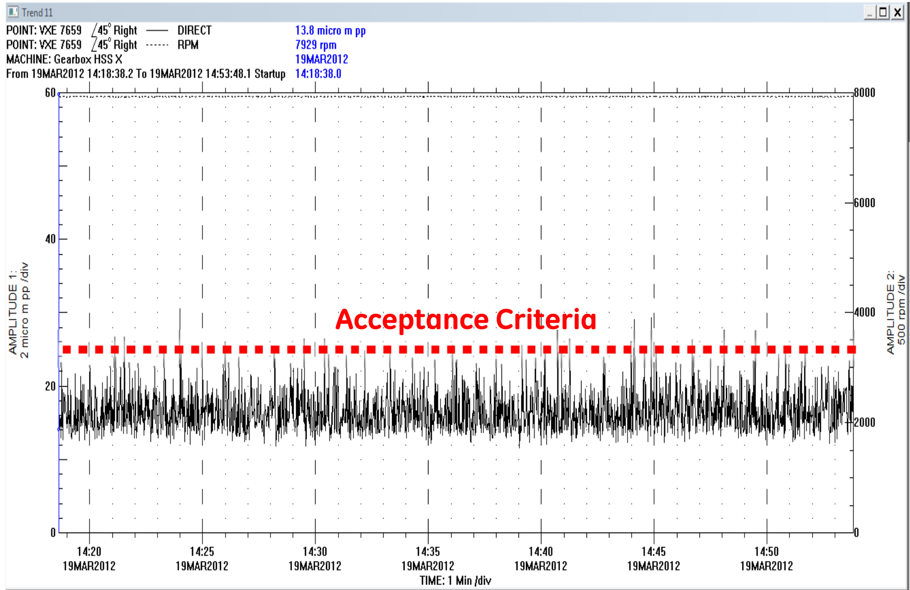
- Improved bearing cavity flooding mounting seals rings on the gearbox HSS bearing.
- Increased bearing oil flow changing supply orifices (oil flow mesh reduced in order to maintain total oil flow).
- Increased mechanical damping (specifically in low-load / no-load conditions).
- Enhanced overall mechanical stability.

Mitigation Steps - Phase 2: Mechanical modifications to increase stability

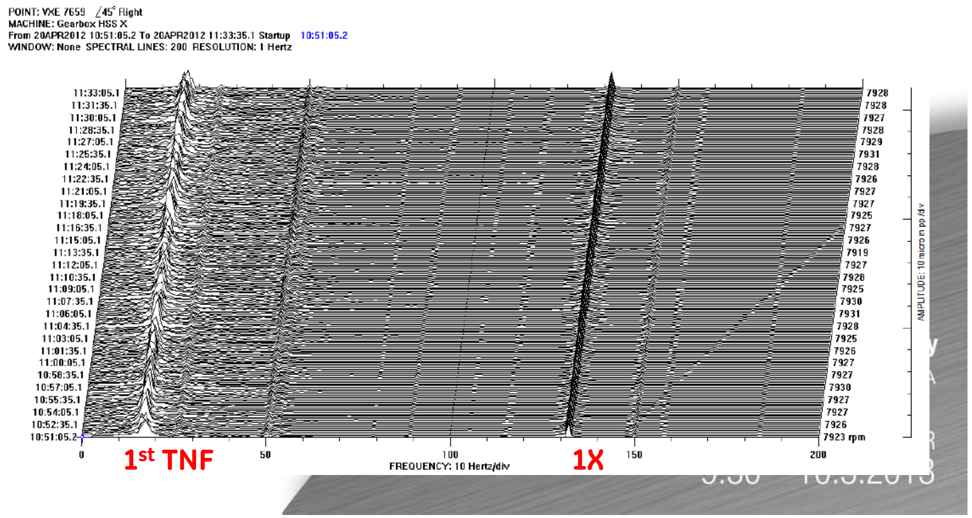
Lateral Vibrations (on GB HSS)
Before mechanical modification…



Lateral Vibrations (on GB HSS)
…after mechanical modification

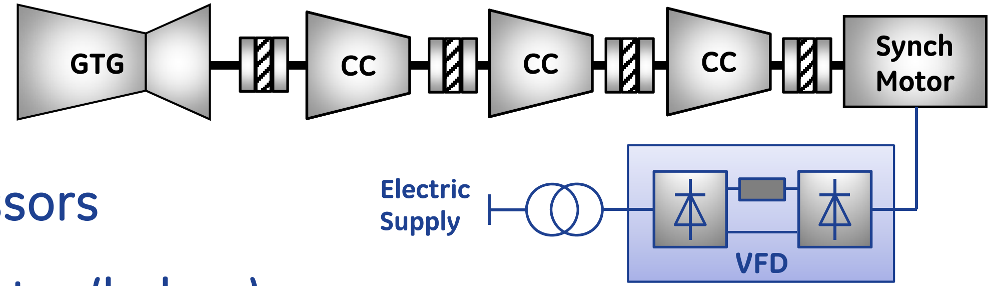


- ✓ Enhanced overall mechanical stability.
- ✓ Gearbox Lateral vibration within the test acceptance criteria.
- – Mechanical modifications → impact on project schedule.



CASE STUDY 2
Optimization of Torsional Vibrations on LNG Train

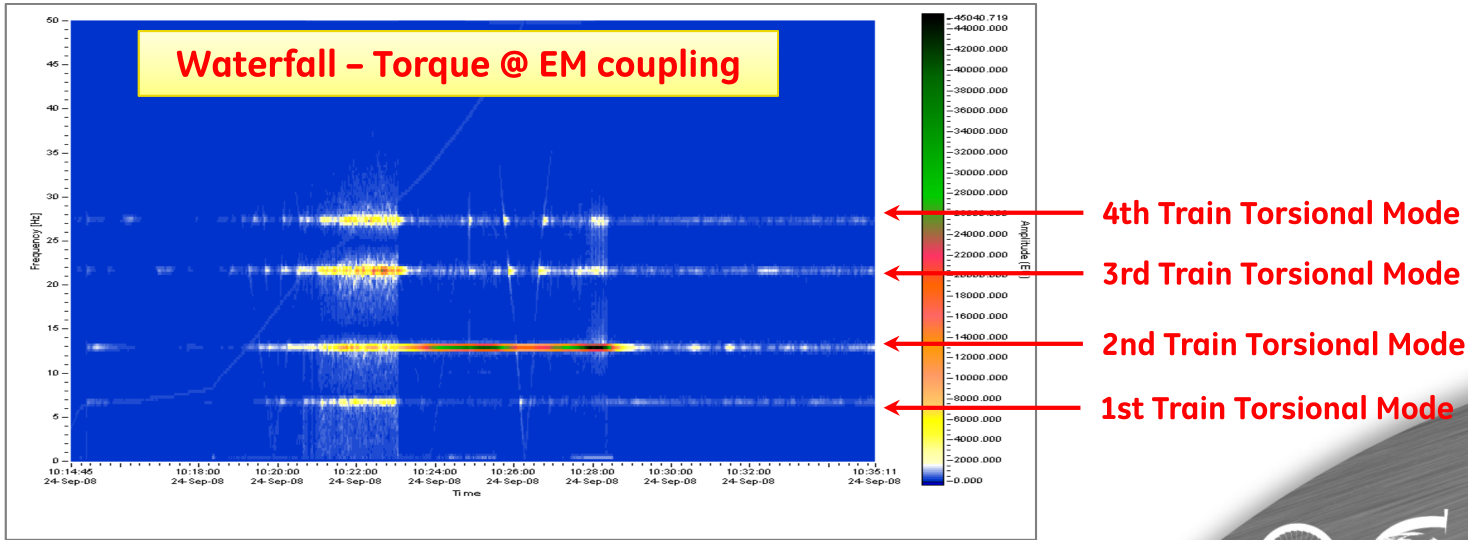
LNG Train Composition



- Gas Turbine (main driver)
- Quantity 3 Centrifugal Compressors
- 18 MW Synchronous Electric Motor (helper)
- Step-Up Transformer (incl. Harmonic Filters) + LCI frequency converter

Problem experienced during internal full-load full-speed string test:

- **High torsional vibrations** due to instability of the complete system (GT + CCs + VFD controls).



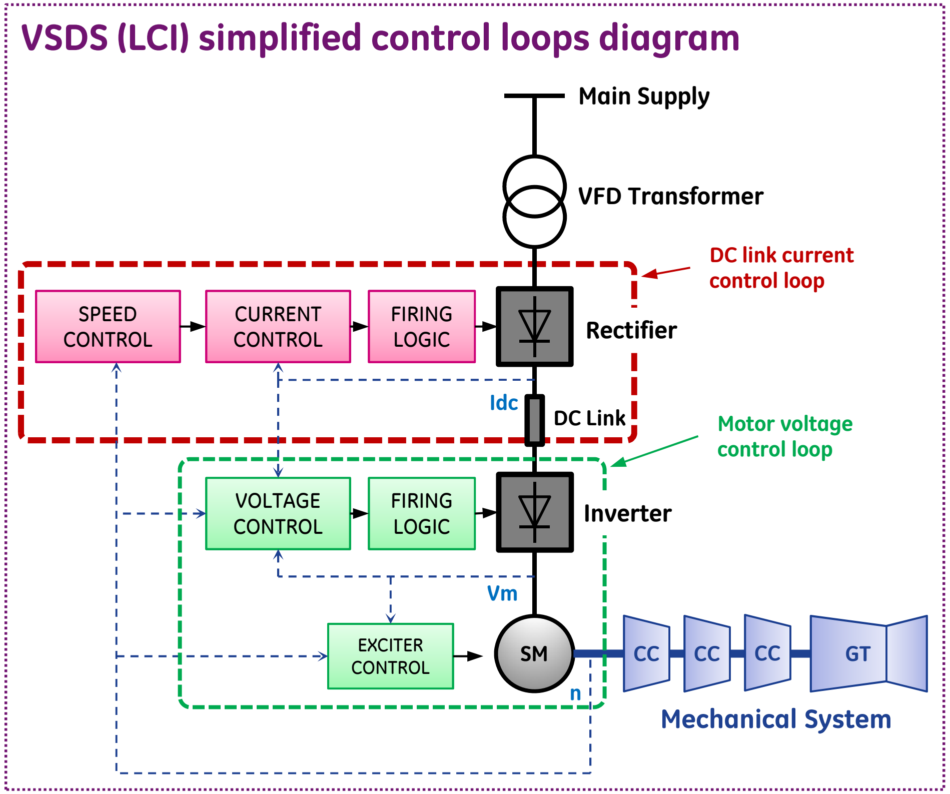
- Train dynamic response at the torsional natural frequencies due the **electro-mechanical interaction** between mechanical system and VFD control system.

Mitigation steps:

- Specific test plan including **VFD control parameters tuning** has been executed during string test.
- Optimization of train torsional behavior achieved by acting on the **gain of the VFD current regulator** in order to improve the closed loop dynamics of the system.

VFD tuning action for electro-mechanical closed-loop optimization:

VSDS control reacts to train's torsional oscillations (mech. system) as **variation of actual speed**.

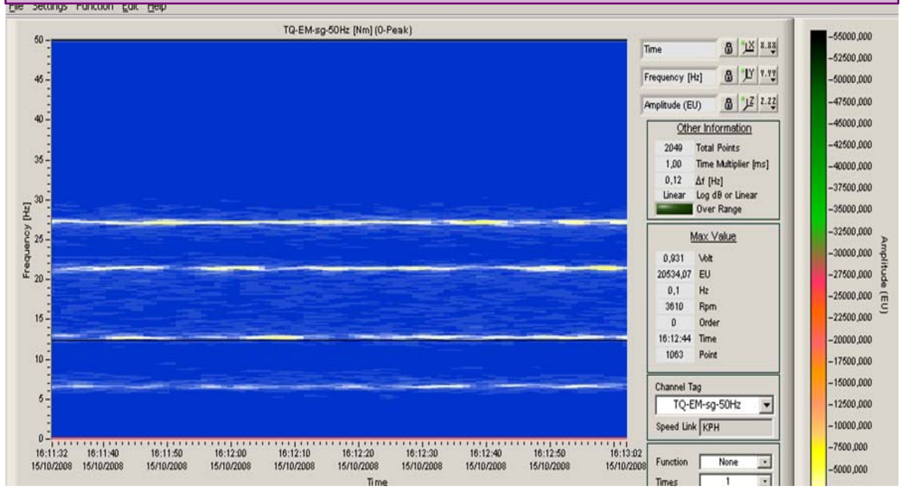


- Two main control loops: **DC link current control** and **motor voltage control**.
- Typical strategy for baseline settings is to make VFD control slow (use the natural damping of the mechanical system).
- **DC link current control** is the «ideal» candidate to counteract electro-mechanical instability, since the DC link **is the closest source of stored energy to the mechanical system.**

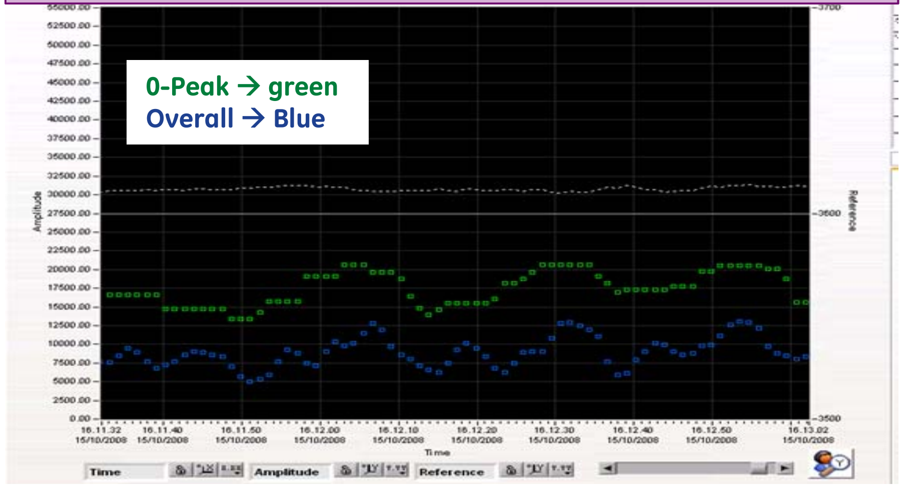
Increasing the Gain of the DC link control loop significantly contributed to compensate the exchange of energy associated to the torsional oscillation of the shaft line, and **enhanced the system overall damping.**

Test Results after VFD parameters tuning:

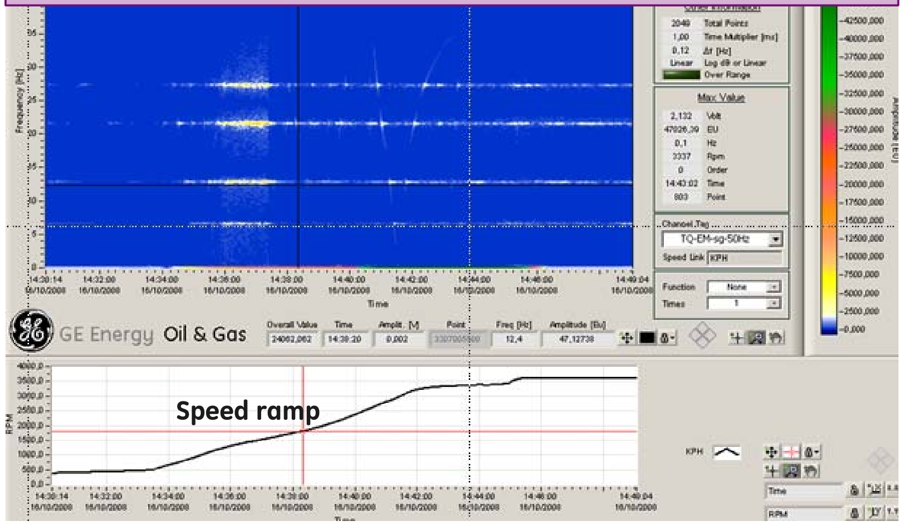
Alternating Torque (0-pk) @ EM coupling



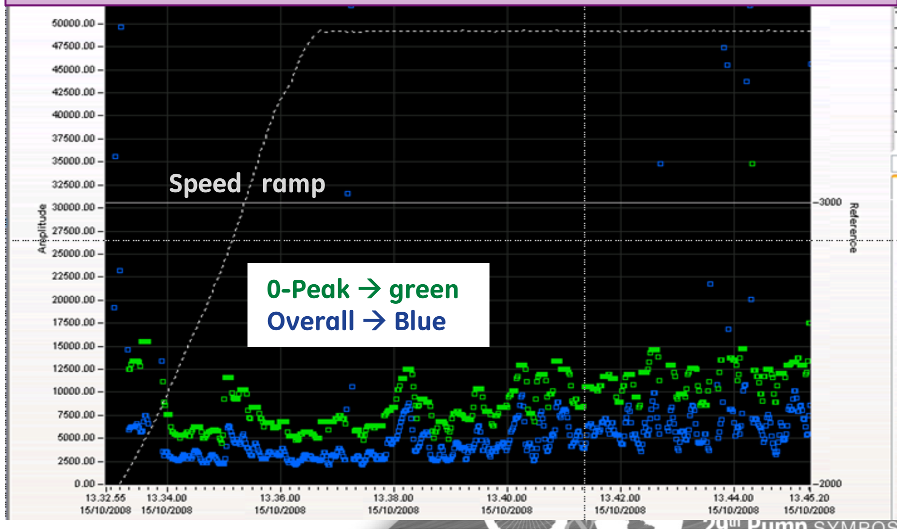
Trend of Alternating Torque @ EM Coupling



Alternating Torque @ EM coupling during train start-up



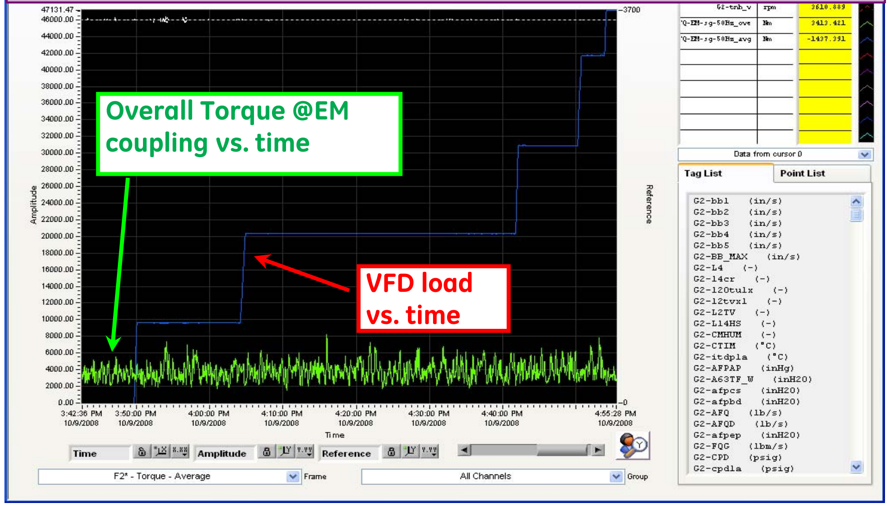
Trend of Alternating Torque @ EM Coupling during train start-up



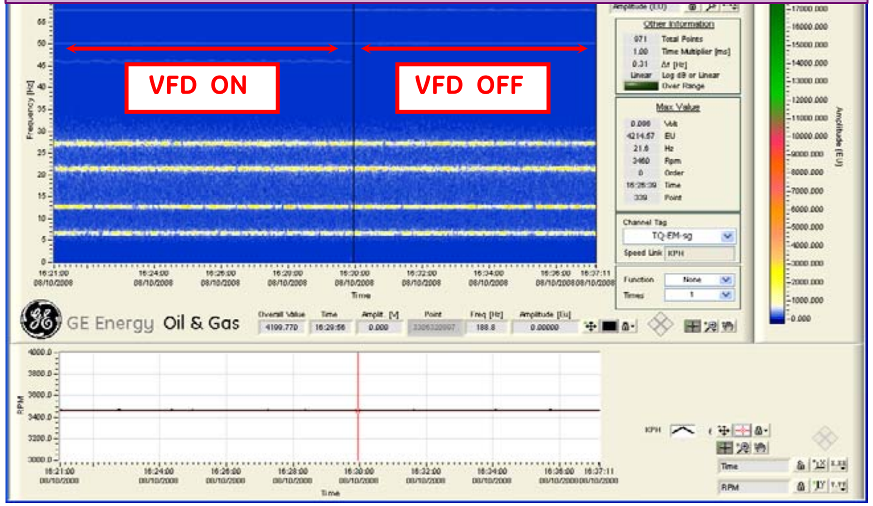
✓ The alternating torques measured @ EM coupling after parameter optimization resulted well below allowable values in both steady state and start-up conditions.

Sensitivity vs. VFD load change and Speed variation:

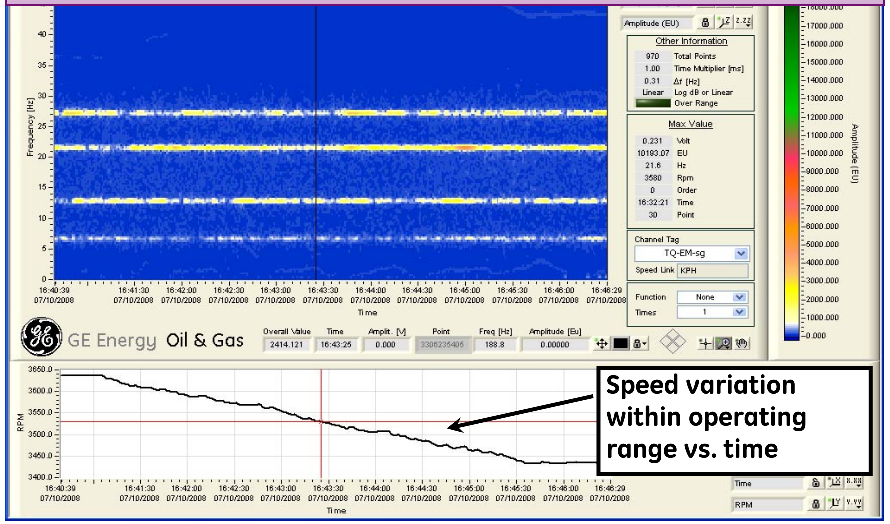
Alternating Torque measured @ EM coupling during VFD load step variations



Shaft Torque measured @ EM coupling Comparison: VFD ON vs. VFD OFF



Alternating Torque measured @ EM coupling during Speed variation



Sensitivity analysis tests versus VFD load and speed variation have been performed to prove the strength of the final setting achieved on the control parameters and avoid any related issue at site:

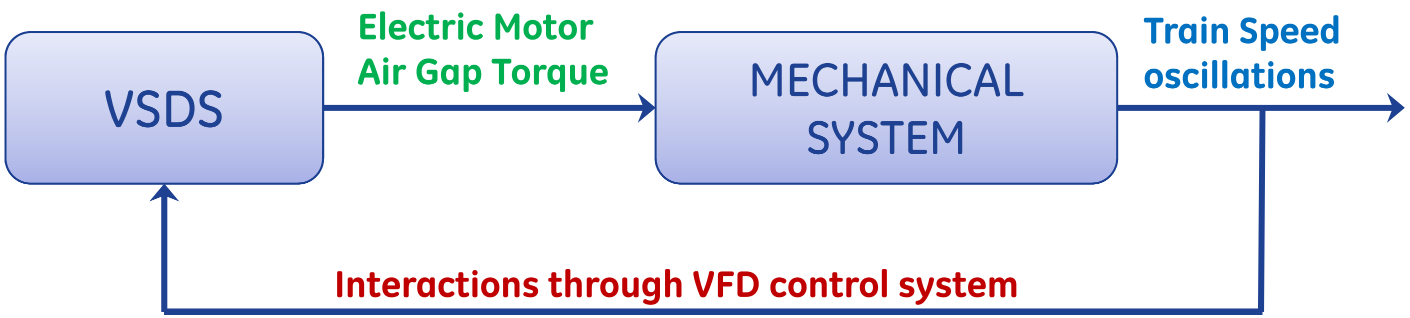
- ✓ Torsional behavior stable vs. VFD load variation.
- ✓ Torsional behaviour stable vs. speed variation within the train operating speed range.

CONCLUSIONS

Observations on electro-mechanical system closed loop behavior:

- Train torsional response is strictly **related** and **influenced by VFD** (LCI and PWM).

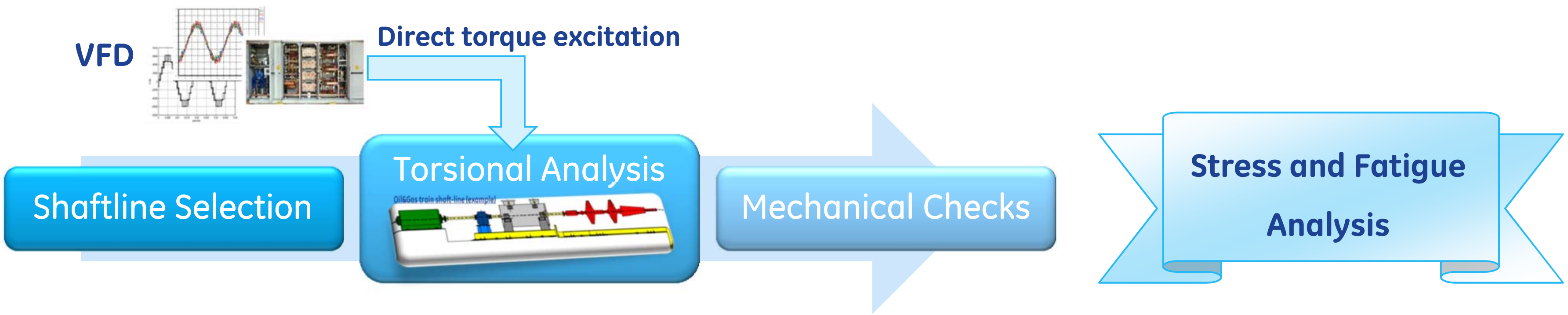
- Closed loop electro-mechanical interactions are due to the **low system stability** at torsional natural frequency, and occur when the train torsional oscillations introduce, **through the electric motor and the VSDS control system**, additional harmonics in the converter current and voltage:



- The system overall damping (mechanical + electrical) may lead to an amplification or an attenuation of torsional response on the train shaft.

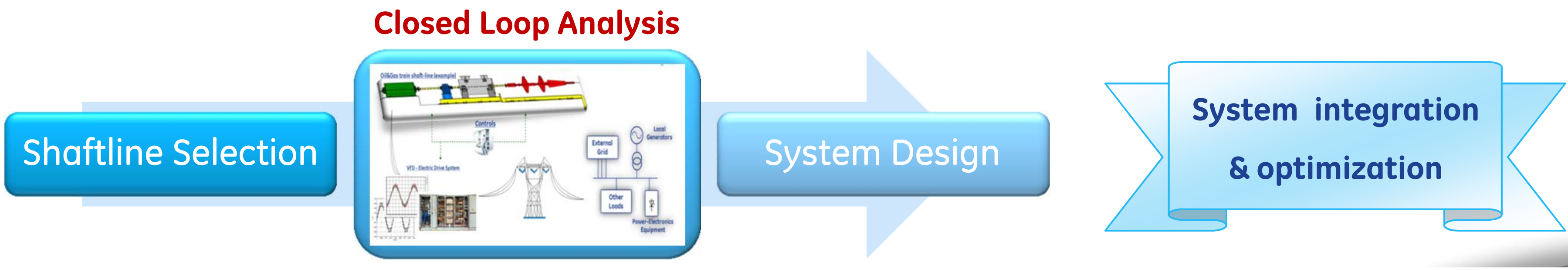
- Possible actions to mitigate low stability conditions are:
  - ✓ Proper VFD control design (need detailed analysis) and tuning (dedicated testing activities);
  - ✓ Supplemental damping controls (additional software/hardware);
  - ✓ Mechanical modifications (potential impacts on project);

From a sequencial «open-loop» approach…



- Not suitable for complex electromechanical interactions.
- Cannot adequately estimate the closed-loop behaviour of the entire system.

… to an integrated system «closed-loop» approach:



- **Reproduction of system electromechanical effects through integrated electrical and mechanical modeling allow "closed loop" analysis and proper VFD optimization.**
- **Can be used to perform control system sensitivity analysis and optimization during design phase (reduce design margins).**

Design @ system level

Thanks for your attention

QUESTIONS

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