TORSIONAL VIBRATION SYMPOSIUM

HIGH VIBRATION OF INTEGRALLY GEARED COMPRESSOR DUE TO VARIABLE FREQUENCY DRIVE

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Abstract

High vibration levels were occurring on the integrally geared compressor causing the unit to trip. The compressor manufacturer verified the vibration readings, replaced the bearings, and found evidence of backlashing on the gear teeth. There is a variable frequency drive (VFD) that is primarily utilized for electrical soft-starting but remains engaged at full operating speed of the induction motor (3583 RPM, 60 Hz).

A strain gage telemetry system was installed on the motor shaft and used to measure alternating torque of more than ±120% of the full load torque (FLT), which is an abnormal condition for centrifugal machinery. The predominant frequency of the torque fluctuation was the first torsional natural frequency (TNF) of the system. The excitation source was the VFD when operating at any speed above the TNF even though there was sufficient separation margin (SM) from torsional resonance.

The medium voltage drive was found to be in Volts/Hz (scalar) mode, which is typical for equipment not requiring precise speed or torque control. Correlation was made between the torque fluctuation and sidebands in the electrical current at the motor junction box, also indicating the VFD was the source of the excitation. Several attempts were made to tune the VFD parameters with no significant improvement.

The VFD was changed from scalar mode to sensorless vector mode, which is better able to control the torque and magnetizing portions of the current. The motor had to be decoupled from the compressor and operated solo so that the drive parameters could be tuned. Upon restart of the compressor unit, the alternating torque was dramatically reduced to an acceptable level. If this torsional vibration problem had not been detected and corrected, the high alternating torque levels could have damaged the motor shaft, coupling components, and gearing in the compressor.

INTRODUCTION

Torsional vibration is sometimes referred to as “silent” because it occurs in the shaft axis of rotation that accelerometers mounted on bearing housings and shaft proximity probes may not detect. Indications of severe torsional vibration and reversing torque include coupling chatter and warping of the disc packs, referred to as “pop canning.” It is possible this could be observed with a strobe light shining on the coupling disc packs with the guard removed. Otherwise, torsional problems are often not detected until after a catastrophic failure occurs.

The exception is with geared systems such as this where significant torque variation will affect the tangential and separating forces at the teeth, which then causes lateral vibration of the pinion shafts. A liquified natural gas (LNG) plant was experiencing vibration issues on one of two integrally geared centrifugal compressor units. Fortunately, the affected unit experienced only slight gear wear before adjustments were made to the VFD to correct the problem.

Both units at the plant are similar and consist of three stages of compression for nitrogen service. The first and second stages are on the low-speed (LS) pinion shaft and the third stage is on the high-speed (HS) pinion shaft. The pinion shafts are driven by a bull gear. A two-pole induction motor (rated 4690 HP at 3583 RPM) drives the compressor through a long disc coupling. The motor is rated for full load current of 534 amps at 4160 volts. Unit 2 is shown in Figure 1.

Figure 1 – VFD Motor, Coupling, and Compressor for Unit 2

The operating speed of the motor is controlled by a medium voltage, variable frequency drive (VFD). The main difference between these two units is the make and model of VFD. Unit 1 also has a bypass contactor where the VFD only starts up the motor to reduce SAG voltages on utility lines, and then switches to the bypass contactor to run the motor full time. Unit 2 (experiencing the high compressor vibration) did not have this switching capability and remained on VFD control when operating at full speed.

VFD CONTROLS

In North America, the line frequency from the electrical power grid is 60 Hz. The VFD first rectifies the supplied AC power to the DC bus. The VFD then inverts from DC back to AC power at the required electrical frequency to drive the motor at the desired speed. This is a medium-voltage VFD using pulse width modulation (PWM). Modern PWM drives typically produce smooth waveforms with minimal torque ripple.

The VFD was initially operating in Volts/Hz mode, also referred to as scalar mode. This is the most basic form of speed control where the VFD simply outputs a voltage proportional to electrical frequency. No active feedback is provided for motor speed (open loop).

If the load torque changes, the induction motor will slip, and the operating speed will vary slightly since the VFD output frequency remains constant. For the 2-pole motor in this paper, the fundamental (1×) electrical frequency will be slightly less than 1× the mechanical frequency (running speed), depending on the load and slip of the induction motor.

Current will be drawn based on the required load (torque). Any variation in torque due to torsional vibration will appear as a load change. Figure 2 is from the VFD manual and shows the feedback loops based on the current measurements. Slip frequency compensation was disabled, but the frequency and voltage stabilization control loops were still active. These loops appear to be PI controls (proportional gain and integration time constant). Any ripples in the current due to torsional vibration could affect the operation of the VFD, causing feedback similar to a microphone held too close to a speaker.

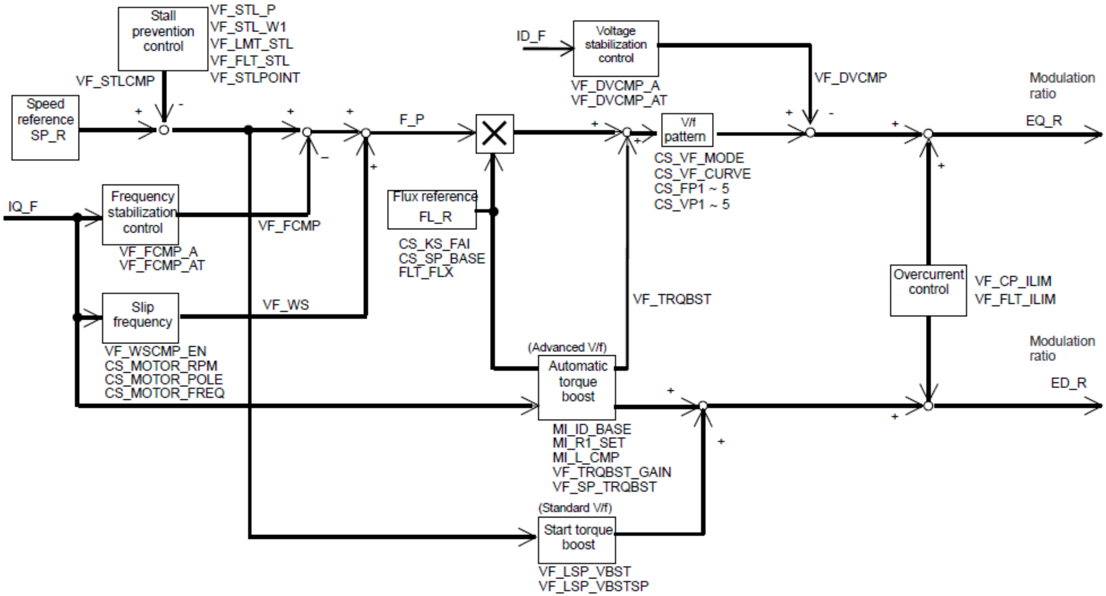

Figure 2 – Volts/Hertz Control Block Diagram [1]

From the second author's previous experience, this model VFD can be very sensitive to certain parameters. Four parameters were adjusted for torque compensation. The "DV" parameters affect the field current or magnetizing current of the motor. The "F" parameters affect the frequency stabilization or the torque current of the motor.

VF_DVCMP_A - Field Current Stability Anti-Overshoot Gain. Sets anti-overshoot gain for voltage stabilization compensation.

VF_DVCMP_AT - Field Current Stability Anti-Overshoot Response Gain. Sets anti-overshoot time constant for voltage stabilization compensation.

VF_FCMP_A - Frequency stabilization compensation anti-overshoot gain. Sets anti-overshoot gain for frequency stabilization compensation for Torque Current Stability.

VF_FCMP_AT - Frequency stabilization compensation anti-overshoot time constant. Sets anti-overshoot time constant for frequency stabilization compensation for Torque Current Stability.

Another VFD control method is sensorless vector control (SVC), which is designed to provide more precise speed or torque regulation. SVC is used for applications requiring higher dynamic performance, such as paper rolling and cranes, but is not typically required for centrifugal fans and compressors. However, if the VFD is not configured properly, using the SVC mode could actually cause increased excitation. Examples of other torsional vibration problems involving VFDs, including low voltage drives, are given in technical papers [2-6].

TORSIONAL VIBRATION ANALYSIS

A torsional vibration analysis (TVA) was conducted by the compressor manufacturer in the design stage. It was reported that the motor had an inertia of 918 lb-ft^2 and the coupling had a torsional stiffness of 14.9x10^6 in-lb/rad. The equivalent torsional stiffness between the motor and compressor, including the shaft extensions, is 7.10x10^6 in-lb/rad and the equivalent inertia of the bull gear, pinion shafts, and compressor impellers is 777 lb-ft^2, referred to the motor speed.

Using this simplified two-inertia model, the first TNF would be estimated to be 33.8 Hz, which is 56% of the full speed. Although, the TVA did not include forced response calculations with possible excitation from the VFD motor, gearing, and compressor impellers, there should have been more than enough separation margin.

For the forced response calculations, the VFD manufacturer would need to provide the expected level of torque ripple produced. However, a typical TVA would not normally be able to predict a stability issue with the VFD control.

ALTERNATING TORQUE GUIDELINE

Centrifugal machinery should not experience high amplitude alternating torque when operating under normal conditions. A typical value of alternating torque in rotating equipment that is operating smoothly would be 10% or less of FLT. Based on the nameplate for this motor, the FLT is 82,500 in-lb. Therefore, the guideline for normal alternating torque would be 8,250 in-lb 0-p or less in the motor shaft.

Generally, the alternating torque amplitude should not exceed 25% for a geared system. Severe alternating torque that causes fully reversing torque is considered excessive. In this case there was a high potential for damage to the keyed motor shaft, disc pack coupling, and/or gears if allowed to continue.

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INSTRUMENTATION FOR FIELD TESTS

Field tests were performed to determine the cause(s) of the vibration. A battery-powered strain gage telemetry system was installed on the motor shaft extension to measure transmitted and alternating torque as shown in Figure 3.

Figure 3 – Strain Gage Telemetry System on Motor Shaft

Other sensors included:

- Current probes in the motor junction box
- Triaxial accelerometers on the motor bearing housings, compressor case and base support
- An optical tach near the coupling to measure motor speed
- Connected to existing proximity probes

During the tests, the VFD manufacturer's representative attempted to reduce the excitation from the VFD by adjusting (tuning) many of the control parameters. While adjusting the VFD, it is important to have instant feedback of motor torque levels as measured by the strain telemetry system to determine whether there was an improvement, deterioration, or no effect at all.

RESULTS OF FIELD TESTS

Field tests included the initial run with the VFD in V/Hz mode (as found), additional runs with the VFD in V/Hz, but while changing various drive parameters, and the final run with the VFD in sensorless vector mode. The test results are as follows.

Initial Tests with VFD in V/Hz Mode

Unit 2 was running at constant speed and load during this test. The VFD frequency was 60 Hz, and the motor speed was approximately 3594 RPM. Ideally, the torque should have minimal fluctuation, 10% or less is typical for centrifugal machinery. However, this system was experiencing extremely high torque fluctuation of more than 100%, resulting in fully reversing torque 34 times per second. The source was believed to be the VFD exciting the first TNF of the system.

Figure 4 shows the waterfall plot of the measured alternating torque during startup. The first TNF was 34 Hz, which agreed with the predicted value. The second TNF was found at 247 Hz. Note that even when the electrical drive frequency was well above 34 Hz, the first TNF was still being excited, which is indicative of unstable VFD operation.

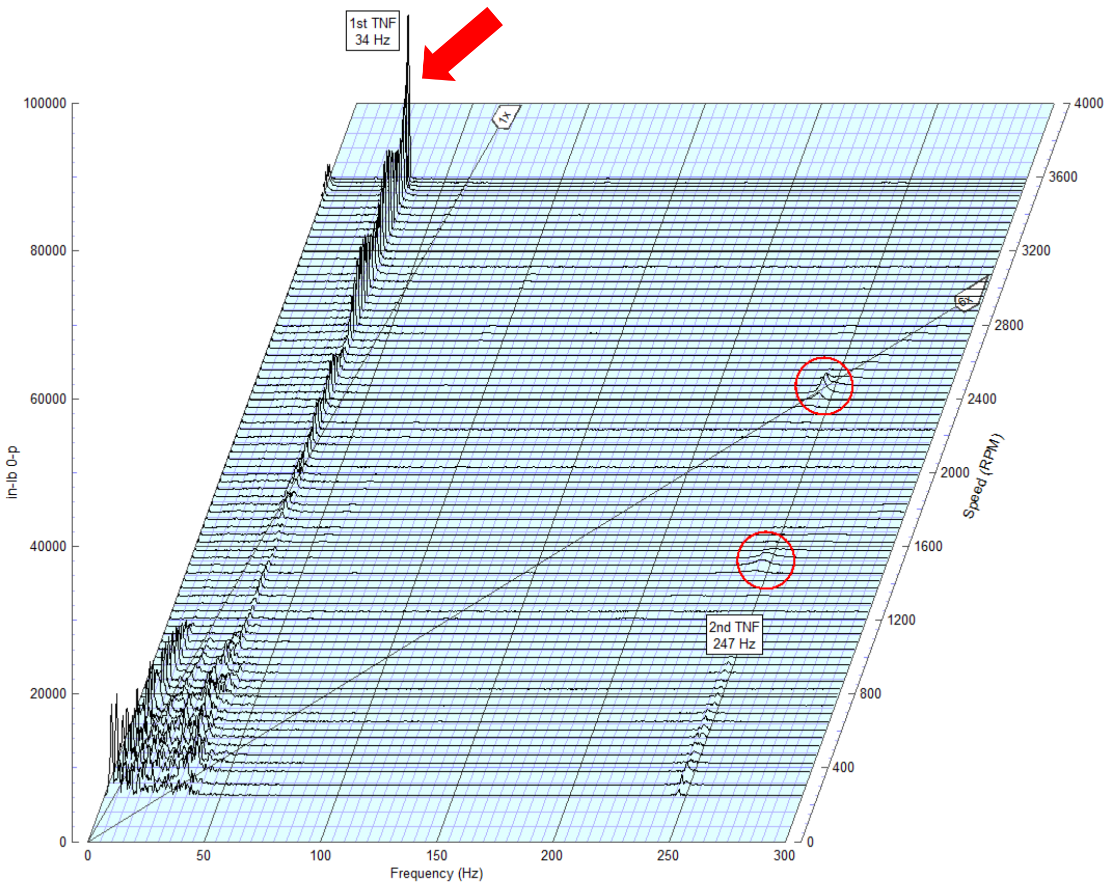

Figure 4 – Waterfall Plot of Alternating Torque During Startup

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Measured torque in the motor shaft was trended over time. There was full reversing torque during loaded operation. Normally the maximum and minimum torque lines should be near the transmitted torque. Alternating torque with an amplitude of 10% or less is considered typical for centrifugal machinery operating off resonance. However, this unit was experiencing alternating torque of more than 100% of FLT, which is abnormal and potentially damaging.

Figure 5 shows the trend plot of torque while the frequency stability setting was adjusted (VF_DVCMP_A to 1000). Note that the alternating torque increased dramatically indicating the sensitivity of this system to the drive parameters previously discussed.

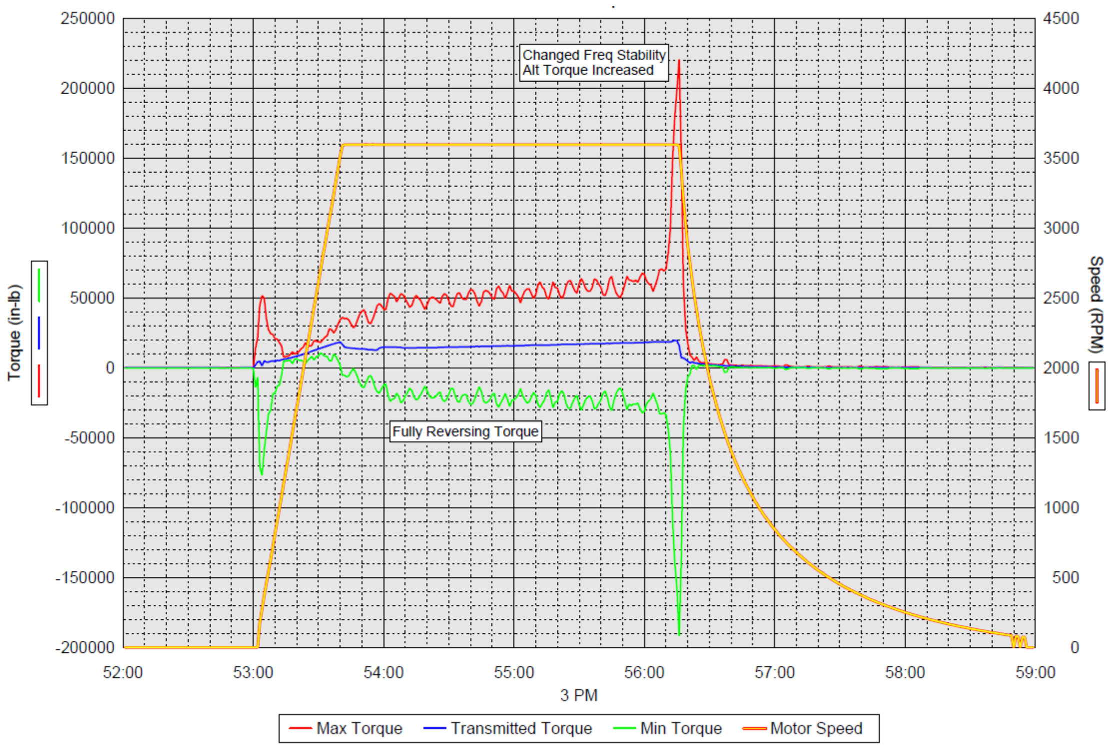

Figure 5 – Trend Plot of Measured Torque in Motor Shaft

Figure 6 shows frequency spectra plots captured while operating at full speed. The alternating torque is well above FLT and occurred at 34 Hz (the first TNF). The motor current is 60 Hz but has notable sidebands at +/- the first TNF. This also indicates instability in the electrical system.

Figure 7 shows a comparison of before (black trace) and after (red trace) the VFD parameter VF_DVCMP_A was changed to 1000. This dramatically increased the amplitude of alternating torque occurring at 34 Hz as well as the sidebands in the motor current. Note that the motor was operating near 3597 RPM and the VFD was at 60 Hz electrical frequency so there is a wide separation margin from the TNF at 34 Hz (not operating near a torsional resonance).

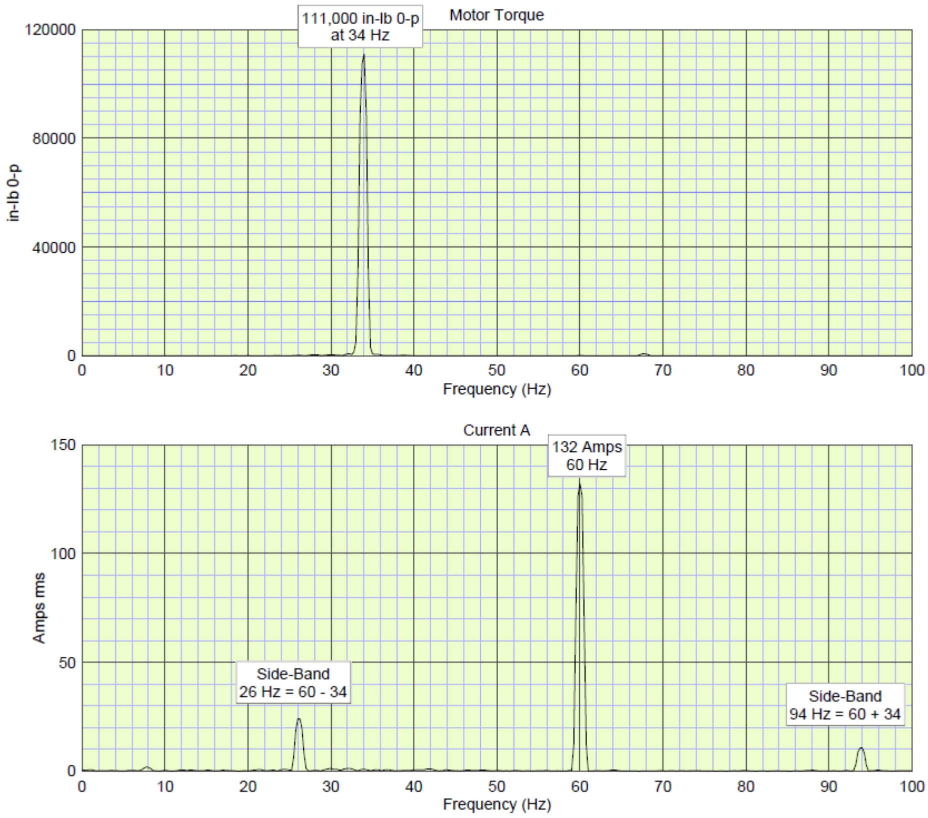

Figure 6 – Frequency Spectra Plots of Torque and Motor Current

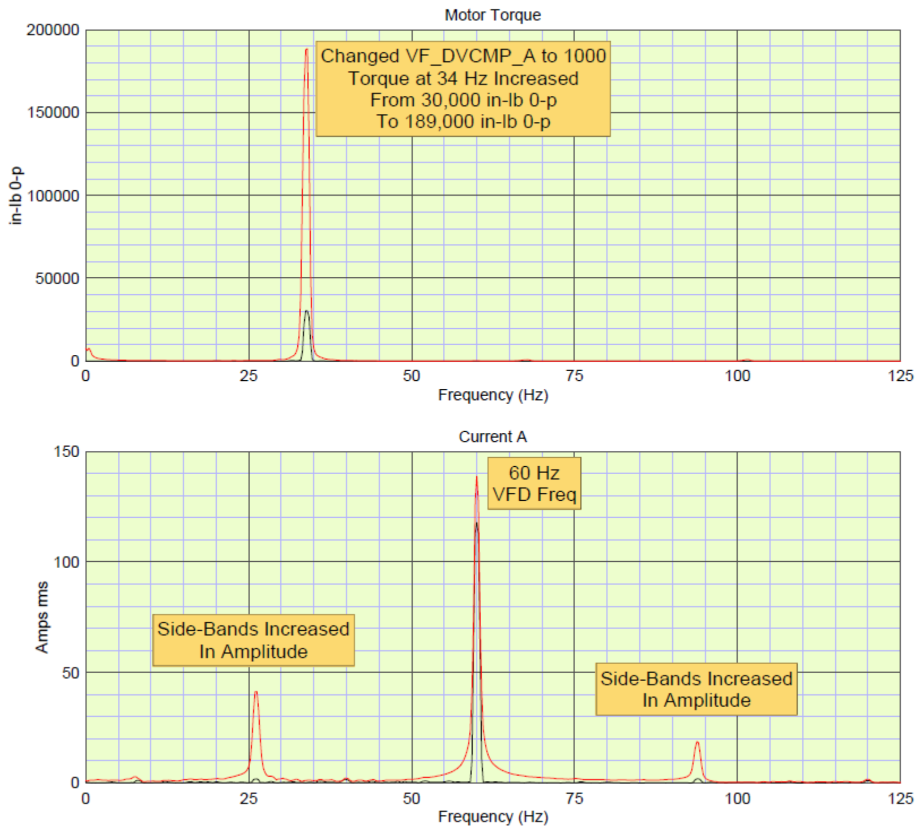

Figure 7 – Effect of Changing VFD Parameter

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Since the alternating torque briefly reached 188,000 in-lb 0-p or 230% of FLT, this would increase the variation of separation and tangential forces on the gearing inside the compressor case. These forces due to high alternating torque translate into increased vibration on the compressor case as noted at 34 Hz in Figure 8.

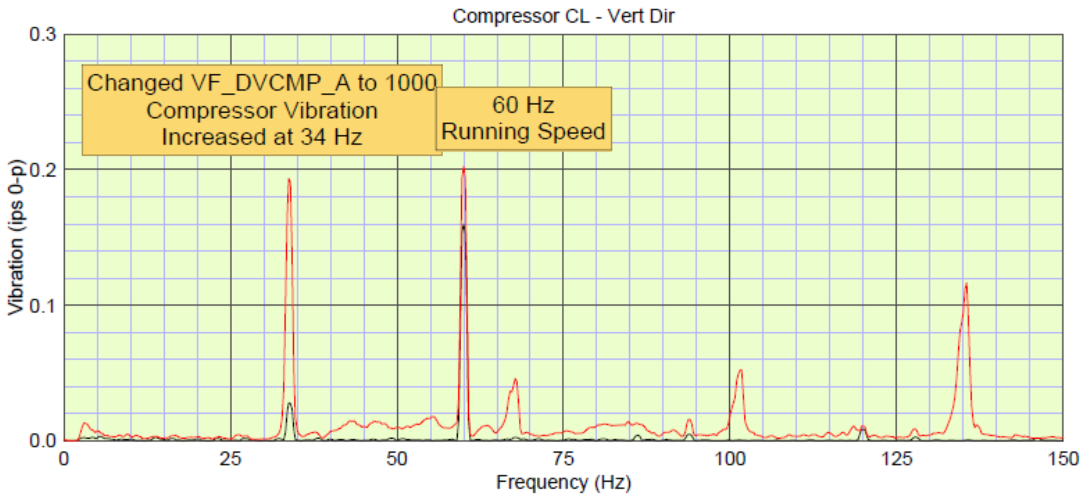

Figure 8 – Frequency Spectra Plot of Compressor Vibration

These test results demonstrate how the compressor train is affected by changes to the VFD parameters. No other speed or load changes occurred during the two-minute test. The VFD parameter is associated with “stabilization control” of the drive, which leads to the conclusion that the VFD was the likely source of the excitation and resulting high torsional and lateral vibration experienced on the unit.

Additional Tests with VFD in V/Hz Mode

Small changes were made to the various VFD parameters, but did not significantly improve the high alternating torque measured in the motor shaft. While the transmitted torque was 34,100 in-lb or 41% load, the alternating torque ranged from maximum of 140,000 in-lb to a minimum of -69,000 in-lb. The negative value indicates fully reversing torque, which could be damaging to the shafts, coupling, and gear components over time.

The alternating torque was 140,000 – (-69,000) = 209,000 in-lb p-p or an amplitude of 104,500 in-lb 0-p. This amplitude is 127% of FLT, and greatly exceeds the 10% guideline for centrifugal machinery. It is important to note that the alternating torque is occurring at 34 Hz, the first TNF of the system, even though the VFD motor was operating at full speed (60 Hz). High amplitude torsional vibration occurring at this subsynchronous frequency (below running speed) without an apparent forcing function is indicative of drive instability as opposed to a typical torsional resonance where a forced response from a defined VFD torque harmonic would excite the TNF.

The motor shaft vibration increased with the alternating torque. For example, one of the proximity probes on the drive end (DE) reached nearly 6 mils p-p, which is considered high. Lateral vibration levels were measured using magnetically mounted accelerometers on the compressor case and motor bearing housings. The overall levels on the motor bearing housings were more than 0.3 ips 0-p, which is considered high. Overall vibration levels on the case of the compressor, foot and on the skid were severe, more than 0.6 – 1.6 ips 0-p. The fully reversing torque was likely causing backlash of the gears and high vibration on the compressor case.

Adjustment of the VFD parameter, VF_FCMP_AT, had a noticeable effect on the measured alternating torque and current. The torque fluctuation briefly reduced in amplitude while the VF_FCMP_AT parameter was adjusted to values of 150, 220, and 300 as shown in Figure 9. Once this parameter was adjusted below 150, higher alternating torque and current returned. Even though the measured alternating torque was reduced with the adjustment of the FCMP_AT parameter, it was never reduced to an acceptable level.

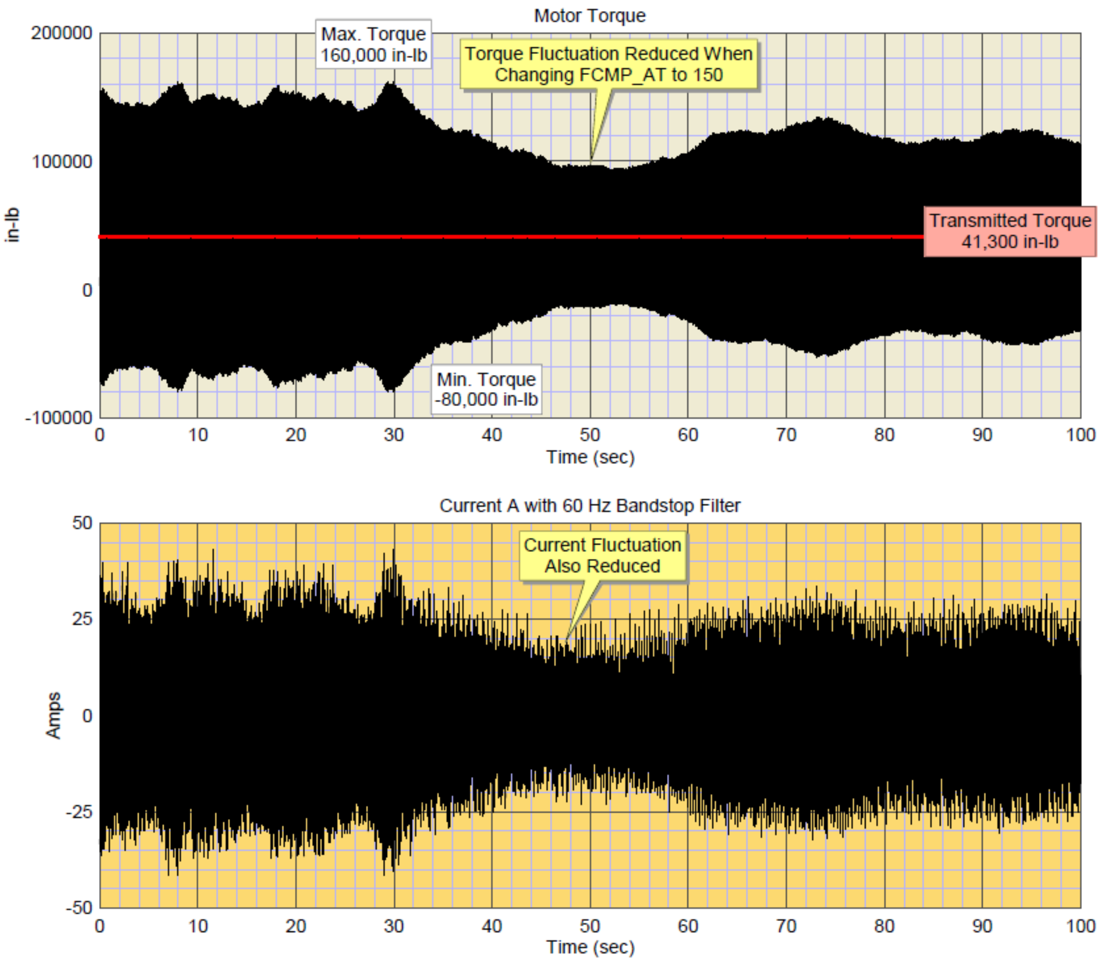

Figure 9 – Time Wave Forms of Torque and Motor Current

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Figure 10 shows a correlation between the ±34 Hz sidebands (26 and 94 Hz) above and below the 60 Hz motor current and the alternating torque measured in the motor shaft. This is also indicative of an instability of the VFD/mechanical system. Note that 60 Hz electrical frequency was filtered out for plotting clarity.

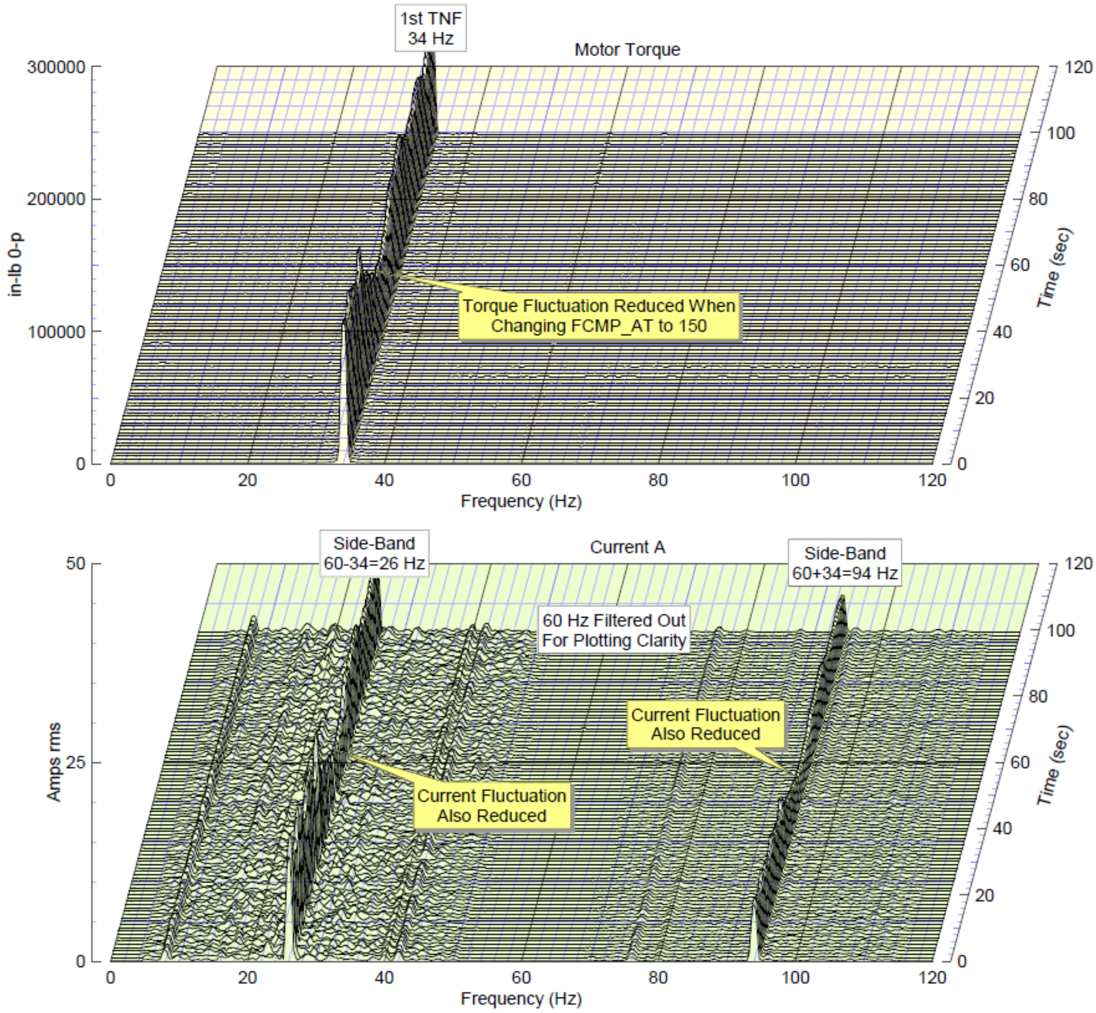

Figure 10 – Correlation of Torque Fluctuation and Current Sidebands

Final Tests with VFD in Sensorless Vector Mode

Measurements were repeated with V/Hz mode to demonstrate the ongoing problem to the VFD representative. Some additional adjustments were tried, but he felt the problem would be better solved by switching the VFD to sensorless vector mode. The next day, the VFD was switched to sensorless vector mode and tuned with the motor running solo (coupling disconnected).

Figures 11 and 12 provide a before and after comparison of the alternating torque in V/Hz mode and sensorless vector mode, respectively. As represented by the green and red curves in Figure 12, torque fluctuations were drastically reduced to only 5% or less in sensorless vector mode and are considered acceptable.

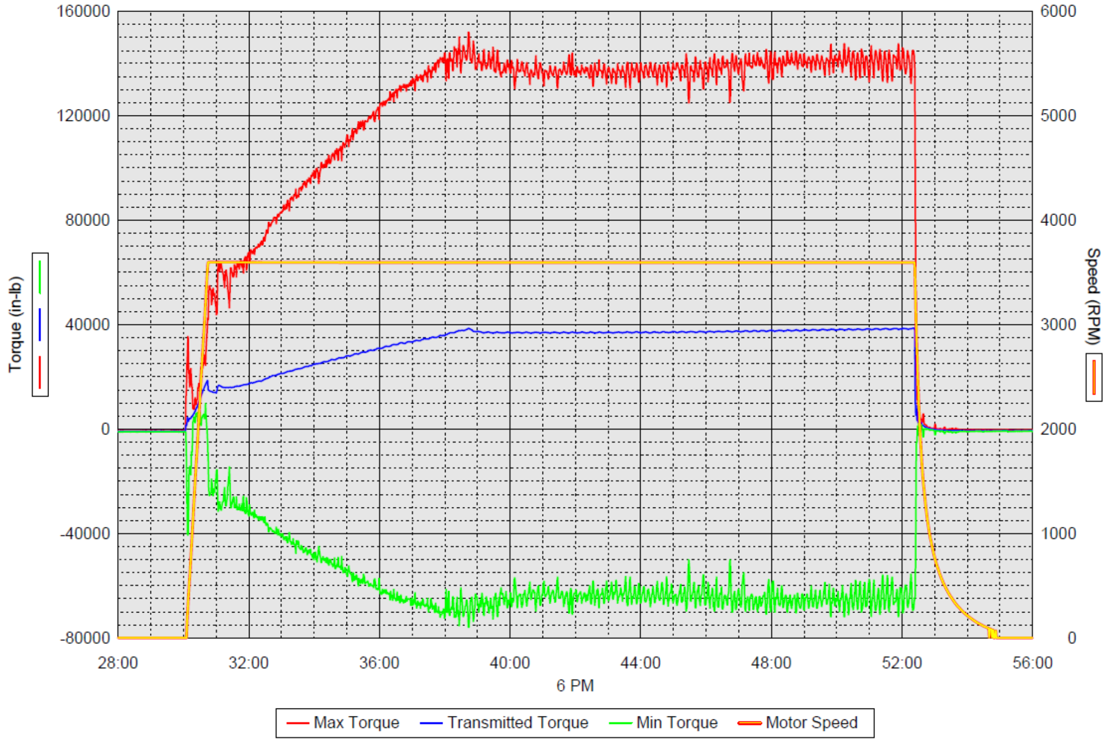

Figure 11 – Trend Plot of Motor Torque with VFD in V/Hz Mode

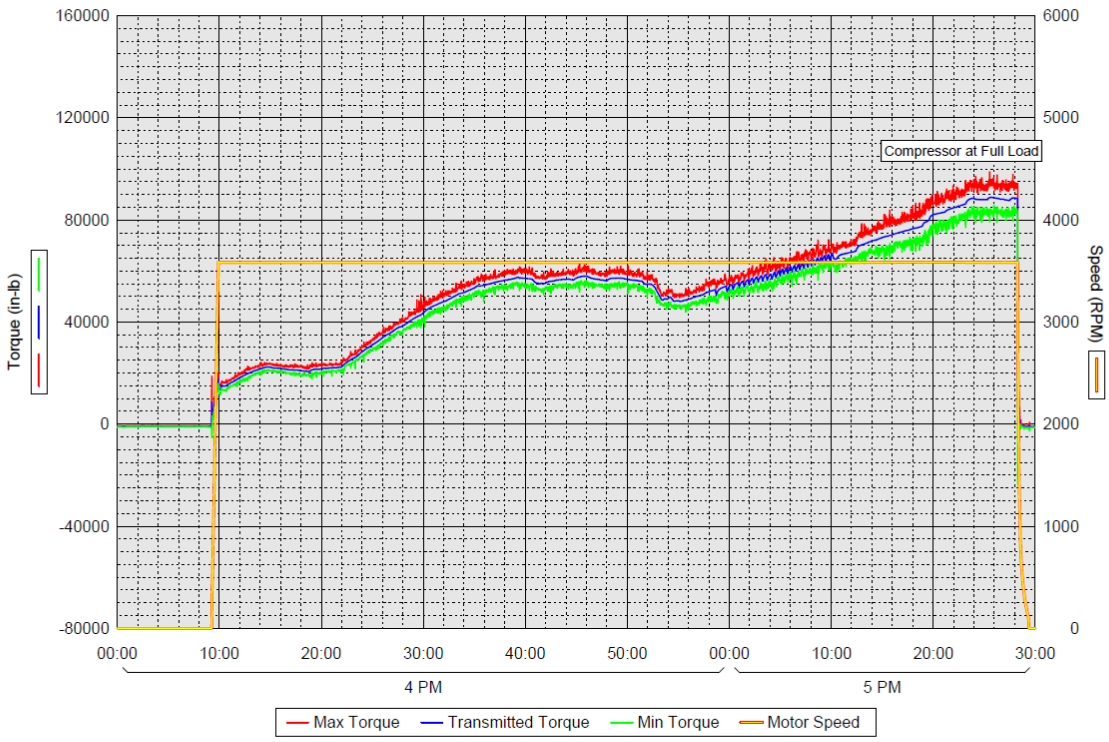

Figure 12 – Trend Plot of Motor Torque with VFD in Sensorless Vector Mode

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Figure 13 shows that the torque fluctuation at the first TNF of 34 Hz was significantly reduced with the VFD operating in sensorless vector mode.

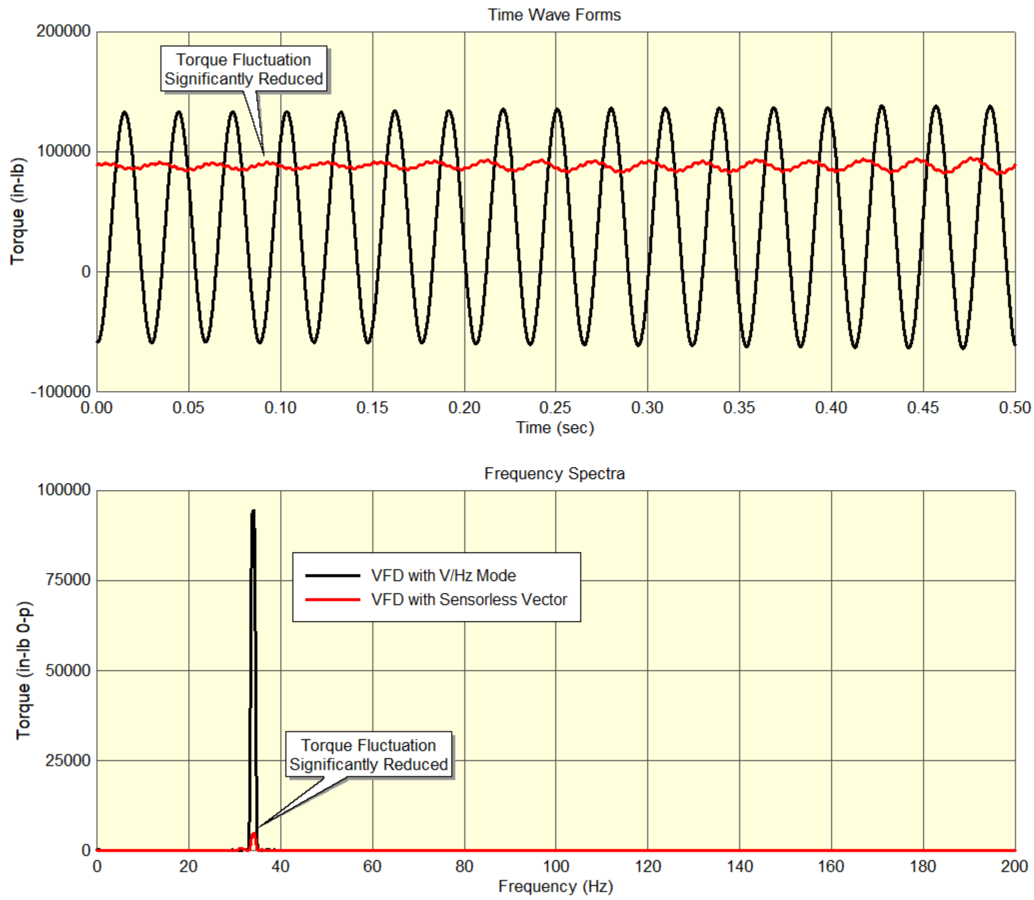

Figure 13 – Torque with V/Hz vs Sensorless Vector

Figure 14 shows that the current sidebands at 26 and 94 Hz have been eliminated with the VFD in sensorless vector mode. With the reduction of subsynchronous torsional vibration and sidebands in the motor current, the system appears to now be operating in a stable manner.

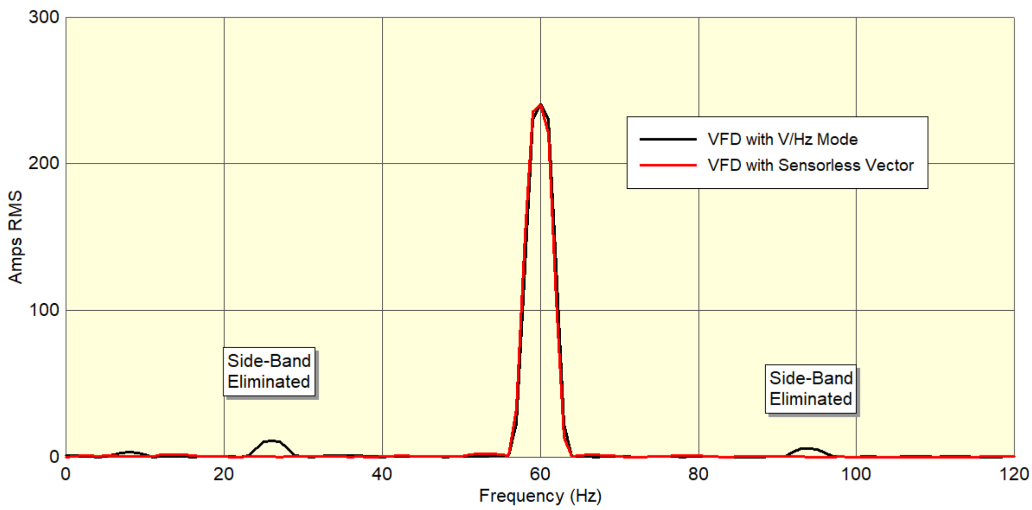

Figure 14 – Current with V/Hz vs Sensorless Vector

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CONCLUSIONS

- Sufficient separation margins from dangerous torsional resonances are required to prevent failures. However, for this system the first TNF continued to be excited, even when operating well above the torsional resonance. This behavior and the sidebands observed in the motor current are indications of unstable VFD control, and/or issues with the PWM inverter.

- The first TNF of the system was measured at 34 Hz, which compared well to the predicted value. Although the first TNF had a sufficient separation margin from the operating frequency of 60 Hz, it was continually excited by unstable control from the VFD. The second TNF was measured to be 247 Hz, well above the operating speed, and did not pose a problem.

- The torsional damping of the mechanical system is very low. Therefore, the first TNF can be sensitive to even low excitation levels from the VFD. This compressor system with the bull gear has a significant inertia, which can make it more susceptible to unstable control.

- The source of torsional excitation was determined to be the VFD reacting to the first TNF at the operating speed, not just at resonance. This was confirmed by the sidebands in the motor current that had spacing equal to the first TNF. In addition, the vibration at the first TNF disappeared immediately after the VFD was de-energized and the motor coasted down without power.

- With the VFD in V/Hz mode, the alternating torque was excessive. Continued operation at these torque levels could damage the shafts and coupling. Cracks typically start forming at high stress risers such as base of the keyways. Coupling disc packs can also be damaged from “pop canning.”

- The sidebands in the motor current occur at +/- the first TNF showing the connection between the electrical system and the mechanical system. Current has a magnetizing component and a torque producing component. The current and torque are related. For example, a 5× and 7× current ripple from the drive will combine to produce a 6× torque ripple in the motor.

- Four different parameters were adjusted while the VFD was in V/Hz mode. Although some improvement was noted, it was not enough to reduce the torsional vibration amplitude to an acceptable level.

- By changing the VFD to sensorless vector mode, the magnetizing current appeared to be better controlled, and the alternating torque was significantly reduced to an acceptable level. This disrupted the “virtual feedback loop” where the V/Hz mode was reacting to the first TNF. With the elimination of these sidebands and the subsynchronous torsional vibration, this confirms that the VFD/mechanical instability in V/Hz mode was the root cause of the excessive torsional vibration in the system.

- The compressor vibration was reduced due to lower alternating torque at the gear meshes. The compressor representative verified that the lateral vibration levels are now acceptable.

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RECOMMENDATIONS

For this system:

- The coupling as well as the shafts at the keyways should be inspected for possible damage. The compressor representative already inspected the gear teeth and found minimal wear.
- The VFD should be left in sensorless vector mode for Unit 2. Eventually the transfer equipment will be installed to allow for across-the-line operation (similar to Unit 1).
- Verify that current limits, etc. are programmed into the VFD for motor protection.

In general:

- A complete TVA should be performed in the design stage that includes forced response calculations.
- The VFD manufacturer should provide the expected torque ripple.
- The VFD should be properly tuned for the type of system and service. High precision speed control is not required for centrifugal compressors, pumps and fans.
- A vibration test including torsional measurements should be performed during commissioning of the equipment to identify any potential problems and to establish a baseline.

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