Axial and Centrifugal Compressors Application Guide

Bently Nevada Asset Condition Monitoring*

Contents

application guide

1 Disclaimer

This application guide is intended to provide guidance only. The procedures provided will not apply to all situations, and may vary based on different circumstances such as government or industry regulations, customer-specific requirements, and public safety laws and regulations.

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2 Purpose

The purpose of this document is to establish guidelines for the selection and installation of GE's Bently Nevada transducers and protection and monitoring systems on axial and centrifugal compressors with fluid film bearings – classified as critical machines. These recommendations apply to both new machines and existing machine installations targeted for retrofit.

3 Scope

The American Petroleum Institute (API) 617 style compressors are typically found in refinery and petrochemical applications.

GE strongly recommends the continuous collection, trending and analysis of the radial vibration, axial position, and temperature data using a machinery management system such as System 1* software. Use of these tools will enhance the ability to diagnose problems and analyze the performance of the compressors.

Compressor asset management best practices indicate the use of the following items:

- Proper transducer suite
- Corresponding 3500 machine protection system
- System 1 asset monitoring platform
- Thermodynamic performance
- Automated machinery diagnostic functionality (RulePaks)

The table to the right provides a more detailed view of the specific components.

	Compressor type		
Best Practice Components	**Centrifugal**	**Axial**	**Integrally Geared**
TRANSDUCERS	·	·	·
Radial Vibration (X/Y)	●	●	●
Axial Position (Thrust)	●	●	●
Casing Accelerometers (Gearbox)	·	·	●
Keyphasor* and Speed	●	●	●
Temperature	●	●	●
PROCESS INPUTS (DCS)	·	·	·
Pressures	●	●	●
Flows	●	●	●
Temperatures	●	●	●
Speed	●	●	●
Machine State (SU/SD, Steady State)	●	●	●
MACHINERY PROTECTION SYSTEM (MPS)	·	·	·
3500 Local Display	●	●	●
3500 Rack	●	●	●
3500 Power Supplies	●	●	●
3500 TDI Module	●	●	●
3500 Monitoring Modules	●	●	●
3500 Relay Modules	●	●	●
MACHINERY CONDITION MANAGEMENT SYSTEM (MCMS)	·	·	·
System 1 Core	●	●	●
System 1 RulePaks - Integrally Geared Compressors	·	·	●
System 1 RulePaks - Centrifugal Compressors	●	·	·
System 1 RulePaks - Axial Compressors	·	●	·
Bently Performance (Thermodynamics)	●	●	●
SmartSignal Integration	●	●	●
Machine State	●	●	●

4 References

1. API Standard 670 Fifth Edition, November 2014
2. API Standard 617 Eight Edition, Axial and Centrifugal Compressors and Expander-compressors for Petroleum, Chemical and Gas Industry Services, September 2014
3. API Standard 613 Fifth Edition, Special Purpose Gear Units for Petroleum, Chemical and Gas Industry Services

5 Protection/Management

Protection Solution - The recommended protection system for axial and centrifugal compressors follows the API 670 Standard for Machinery Protection Systems.

Management Solution - The recommended management solution for centrifugal compressors includes the protection solution with the addition of System 1* trending and analysis software. The table above shows recommended protection transducers on a centrifugal compressor. Each item is discussed in detail in the Transducer Selection section of the document.

Note: *It is recommended that the management solution include the pre-packaged diagnostics and performance applications (if applicable) to manage issues before the protection system must act (i.e. the Integral Gear Compressor application package).*

Additional Measurements - Many measurements, such as thermography and oil analysis, can be made on API 617 compressors. In many cases, new or emerging technology enables the online implementation of these parameters. As the robustness and value proposition of these technologies prove out, these measurements may be included in future Bently Nevada Best Practices from GE. Separate application notes provide transducer, monitor, and installation recommendations for these measurements. For a copy of these application notes, please contact your local account manager.

Instrument Diagnostics:

Extensive self-testing is performed continuously on each of GE's Bently Nevada 3500 or 3701 instrumentation packages. Self-test failures are displayed to the end user in several ways, including: the green OK LED being extinguished, the instrument rack OK relay (normally energized) changing state, a note in the operator display (if supplied), and a note in the monitor events list. It is extremely important that end users are aware of and take advantage of these self-test indicators so that instrumentation problems can be addressed before there is a false or missed alarm event.

6 Types of Centrifugal Compressors

6.1 Process Centrifugal Compressors

Horizontally Split – Horizontally split compressors are used primarily for low and medium pressure applications in ethylene and fertilizer plants refineries, liquid natural gas (LNG) for refrigeration, air compression, and so on.

Barrel – Vertically-split barrel compressors are used primarily for high-pressure applications such as ammonia, urea and methanol synthesis, refinery recycle, natural gas compression and injection, and hazardous gases.

Integrated Compressor Line – Integrated compressor line (ICL) is designed to achieve balance between productivity and the environment, power demands and space limitations, performance goal and maintenance requirements, reliability, and availability.

Overhung Single Stage – Overhung compressors are mainly used as boosters in petrochemical applications or for recycle in polypropylene and polyethylene plants. The single-stage overhung configuration is simple and easy to maintain. Almost all gases can be handled by this type of compressor with appropriate construction materials and seal systems.

Pipeline – These compressors are specifically designed for pipeline compression stations. They are used for low and medium pressure ratio pipeline service and in recycle applications such as those performed in methanol plants, etc.

6.2 Package Centrifugal Compressors (integrally geared compressors)

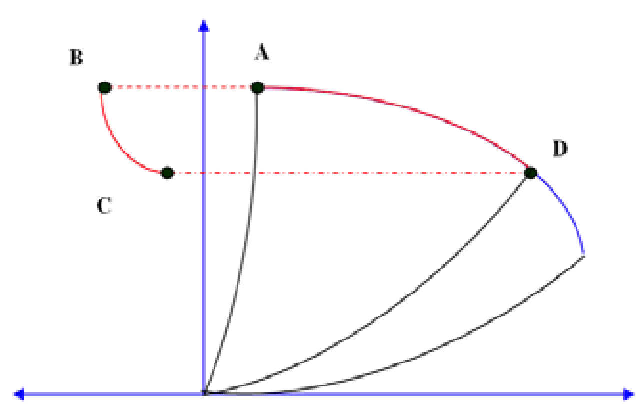
These machines are produced as a package with the entire machine mounted on a common foundation. The machines are integrally geared, and used in several refineries, petro chemical plants and applications, either for low pressure/high-flow, or low-flow/high pressure conditions. This type of compressor has from one to four high speed pinions and the bull gear can be driven directly by an electric motor or by a turbine (gas or steam). One or two impellers, open or closed, tri- or bi-dimensional type can be mounted on each pinion-shaft. Optimal impeller speed and the ability to inter-cool compression stages supports very high efficiency. A large variety of gases can be handled by this compressor line with appropriate construction materials, seal and control systems. Sometimes these machines are referred to as four-posters (for four stages) or simply as air machines, because the most common service is general plant compressed air supply.

7 Examples of Centrifugal Compressor Malfunctions

7.1 Compressor Surge

Surge is the point at a given operating speed when the compressor cannot increase gas pressure to overcome the system resistance or backpressure. This causes a rapid, cyclic flow reversal. As a result, thrust reversal causing high axial vibration, temperature increase because of recompression of the same portion of gas are common symptoms and some radial vibration also can occur. In centrifugal compressors these occurrences can damage the interstage/eye labyrinth seals, impellers, couplings, and the compressor driver. Most compressors are designed to withstand occasional surging. However, if the machine is allowed to surge repeatedly over a long period of time, or if it is poorly designed, prolonged periods of surging can result in a catastrophic failure.

The incipient surge (i.e. before flow reversal develops) can be detected in the radial vibration signal as subsynchronous vibration at a frequency of approximately 0.10X to 0.20X (10 to 20 percent of the rotor speed). Fully developed surge is self-excited vibration characterized by flow reversal and causes low frequency, high amplitude axial vibration, typically in the 0.3 Hz to 3 Hz frequency range. Some radial vibration at the same frequency can also be observed due to coupling of axial and radial vibration, but the levels may be insufficient to cause alarm.



The above figure can be used to illustrate the surge cycle as follows:

- The compressor reaches surge point A and loses its ability to make pressure.

- Suddenly pressure at the discharge drops, causing pressure at the discharge line to be higher than compressor discharge pressure. The compressor surges, the flow reverses, and the compressor operating point goes to point B (negative flow).
- The result of the flow reversal is that the pressure at the discharge goes down, so now there is less negative flow. The operating point goes to point C.
- The system pressure is going down, and the compressor is again able to overcome pressure in thedischarge line. Thus, the compressor "jumps" back to the performance curve and goes to point D.
- Forward flow is re-established. The compressor starts to build pressure and follows the pressure-flow characteristic curve, toward surge. Point A is reached. The surge cycle is complete.

Note: *Surge is a coupling effect between the compressor and the network (for example: resistor, capacitor). The working point is the intersection between the compressor performance curve and the network. Physically, the pressure ratio fixed by the upstream and downstream pressures of the network will determine the flow.*

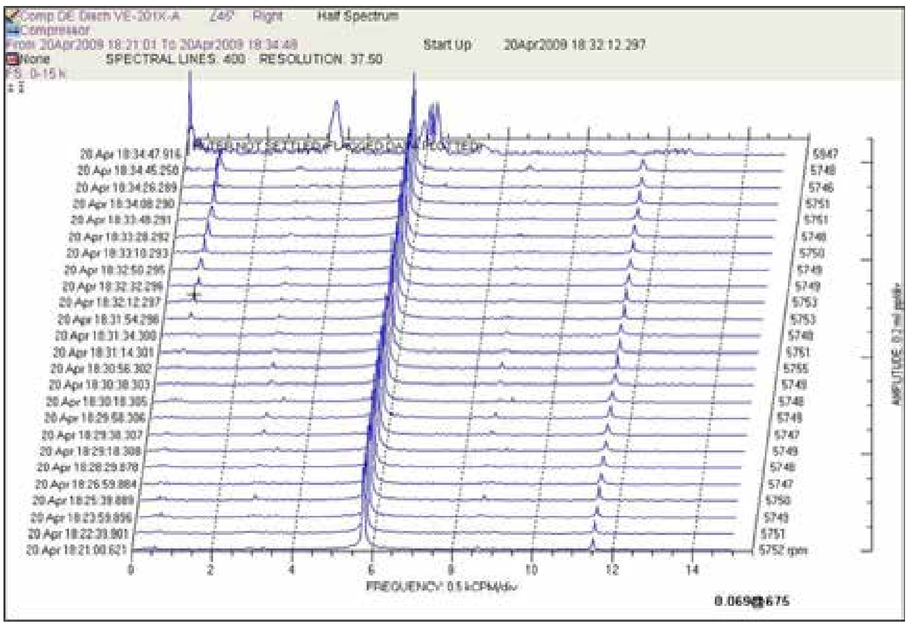


Figure: Surge event on shaft relative vibration, half spectrum waterfall.

Compressor surge is typically controlled by detecting when the compressor is nearing the surge line on the compressor characteristic curve and modifying the compressor operation to avoid entering into a surge cycle. In air compressors, surge control can be accomplished by opening a discharge end bypass valve and venting air to the atmosphere. This increases the flow, with an accompanying loss of pressure, and avoids the potentially harmful surge cycle. However, continuous operation in this manner is costly and inefficient and the root cause of the reduced flow needs to be identified to allow corrective action to be taken to re-establish the compressor on an optimal operating point.

Process compressors use a recycle valve to allow some of the high pressure compressed product to be reintroduced into the low pressure compressor inlet (after appropriate cooling if necessary), thus maintaining flow below the surge line with some loss in process efficiency. Again, the root cause of the reduced flow needs to be determined and the compressor brought back to its design point as soon as practical.

An anti-surge device is a common part of most centrifugal compressors control systems. However, the operation of most systems depends on the experimentally identified stable operation limit on compressor characteristic. When the compressor characteristics change in time (due to some wear or failure) the anit-surge system may not react properly on real surge conditions. The OptiComp* compressor control suite is GE's latest comprehensive software package for controlling centrifugal and axial compressors. It improves upon the standard industry anti-surge control and protection algorithms and effectively and safely matches compressor performance to process demand within the operational constraints of the compressor, its driver, and the process. In addition, OptiComp uses a specially developed algorithm for detection of real surge events based on thrust position measurements from the 3500 monitoring system. The presence of surge condition is detected before single full cycle of reversal occurs.

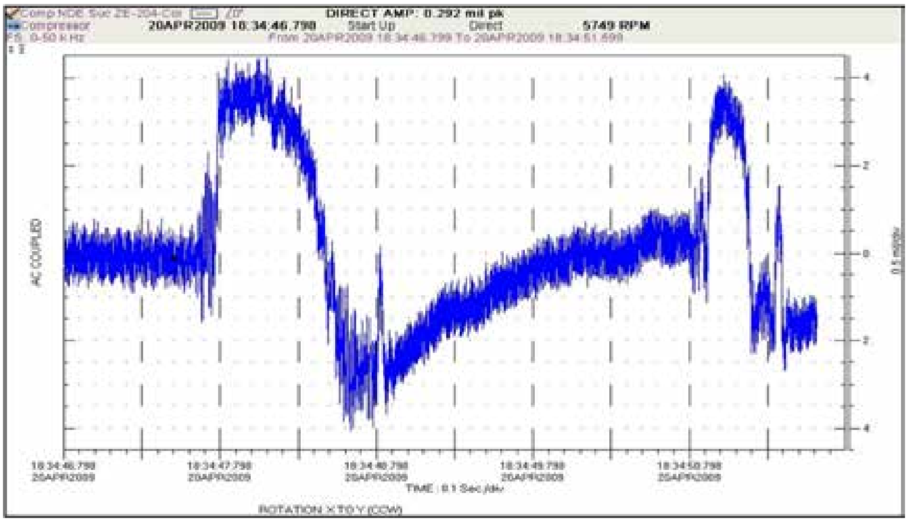


Figure: Surge event (detected and controlled before full cycle occurs) from thrust position movement.

7.2 Compressor Stall

Stall is a local disruption of flow within the compressor that continues to provide compressed flow but with reduced effectiveness. The boundary layer of the flow moving along a diffusing passage, such as impeller and diffuser, may be retarded enough by the static pressure gradient to bring it to rest and to reverse it, causing the flow to separate from the wall. Stall can create a single rotating cell or multiple rotating cells in one or several stages.

The aerodynamic instability due to impeller stall typically causes forward subsynchronous rotor vibration at a frequency of "less than 1X", typically 0.6X to 0.8X (60 to 80 percent of the rotor speed). Diffuser stall is often accompanied by forward subsynchronous rotor vibration at a low frequency of around 0.2X to 0.4X (20 to 40 percent of the rotor speed). And the disturbances in the area between stationary and rotating channels (for instance, due to axial misalignment) can produce a forward subsynchronous component from the 0.4X to 0.6X range. Flow reversals do not occur, and axial vibration at the above frequency or significant movement is not detected. The energy level of stall phenomena is not significant and it is not proven that stall condition can cause any damage to machine elements; however the occurrence of stall can be considered an operational problem because increased vibration may reach trip limits. Additionally, if the process is within limits that in the past were not causing stall, then there is likely some change in the geometry of channels (such as flow obstruction, blade damage, or fouling), indicating that stall can be a consequence and symptom of another problem.

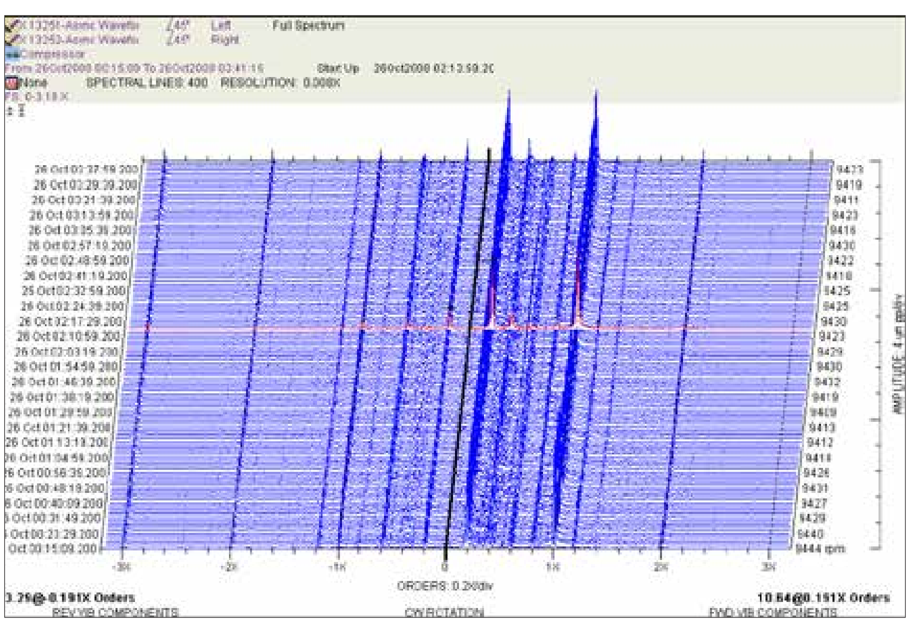


Figure: Subsynchronous component at approximately 0.2X and accompanied orbit/timebase plot, caused by stall in the stationary channels.

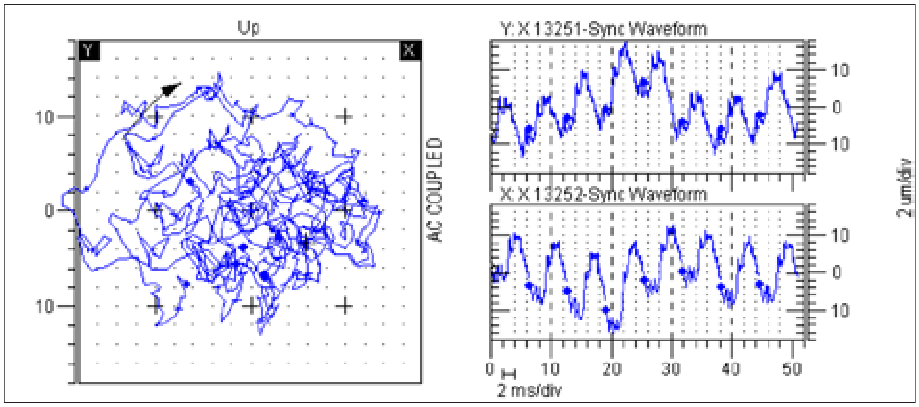


Figure: Full size sample orbit for stationary channel (diffuser) stall.

7.3 Unbalance

Mass unbalance occurs when at given section of the rotor, the geometric center and the mass center of a rotor do not coincide. While there is always some remaining unbalance in the real rotors, the problem starts if there is an excessive one – because the unbalanced centrifugal forces are forcing excessive 1X rotor response. The result is elevated 1X vibration that is forward in precession and with a circular or, more typically, elliptical orbit shape. Centrifugal force is not changing if the speed is constant; this means that the elliptical orbit shape is changing because of the supporting stiffness (bearing, bearing supports) that is typically anisotropic (different in different radial directions). It is worth noting that the 1X vibration response depends proportionally on the magnitude of unbalance force but inversely proportionally on synchronous dynamic stiffness, so not every situation in which 1X vectors are increased is related to increase in unbalance force. Consider for instance the situation in which the bearing clearance is increased causing lower bearing stiffness. Or consider that the stiffness is reduced because the bearing was unloaded as result of misalignment. The shaft relative vibration will increase then, for the unchanged level of unbalance force.

Therefore, before claiming an unbalance problem, it may be beneficial to measure the absolute casing vibration (because the compressors are typically not equipped with this type of measurement the portable data collector with temporary installed velocity transducers can be used) to confirm the elevated level of the forces transmitted to the bearing. Another important aspect is to recognize that rotors for critical, high-speed machinery are typically well balanced in the whole range of speed, before installation. So even if unbalance is confirmed on an operating compressor, the historical data should be analyzed to help understand when the unbalance first appeared, whether it is changing in time, what the potential source could be, and so on. Coupling damage, a missing coupling bolt, or a cracked impeller blade are examples of an unbalance source that would not be appropriate to treat by balancing. In addition, not every 1X forcing change is caused by mass unbalance. For instance, rotor bow due to a rub generated hot spot or due to transverse crack development can also look like simple unbalance until historical data is properly analyzed. Finally, the compressor rotors do not always have field accessible balancing planes so field balancing is often limited to weight placement on coupling flanges.

Field balancing is a valid tool in the diagnostic toolbox – provided that the balancing decision is made based on firm evidence of the problem. Direct and 1X filtered orbits, transient and steady-state vector changes for the 1X component (Bode and polar plots, trends, both for shaft relative and casing absolute vibration), and shaft centerline position changes should always be analyzed before making a decision to perform balancing.

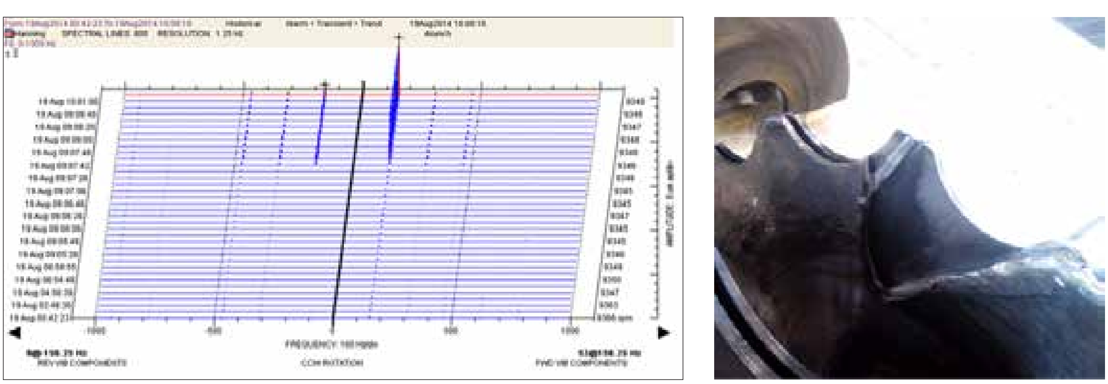


Figure: The full spectrum waterfall shows step change in the forward precession 1X vibration of the compressor stage. This type of step-like "change of mass distribution" was not a candidate for a balancing attempt. The fatigue crack on the impeller disc was diagnosed as the result of sonic excitation of the disc mode (sound wave resonance) due to recent modernization of the stage.

7.4 Electrostatic Discharge

For an example of another 1X vibration problem that is not unbalance related, see the vibration trend below.

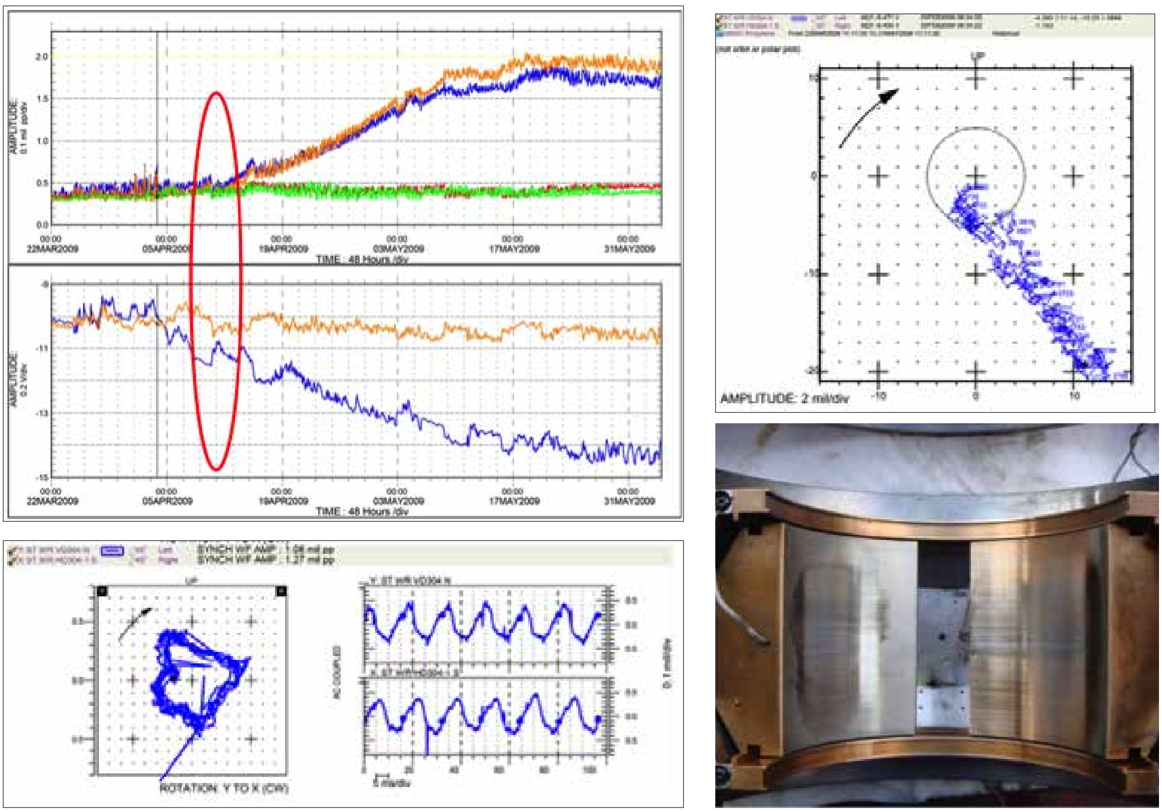


Figure: The electrostatic discharge case shows both data and inspection results.

The gradual increase of vibration was compared with the position in the bearing and the apparent increase in bearing clearance found. The increase in vibration is 1X related, however the unbalance force is constant and the synchronous dynamic stiffness is reduced. The chaotic spikes observed on orbit/timebase plots allowed a conclusion of the electro static discharge (ESD) problem. Replacement of grounding brushes stopped the change in vibration; however the bearing had to be replaced at the closest opportunity. Bearing inspection confirmed ESD damage. It took only six weeks to wear the bearing pad more than 20 mils (0.5 mm) deep.

7.5 Misalignment

Machine alignment can be defined as proper positioning of bearing supports (external alignment such as between machines in the train) measured at the coupling; and alignment between rotating and stationary parts (internal alignment measured as available clearance around a rotating part at a given location). Misalignment can be defined as excessive error in alignment, whether external or internal, that results in excessive radial preloads (for example, static radial forces acting on rotor and bearings).

The effects of misalignment (and generally any other excessive preload) can include overloading of the bearing causing premature damage or unloading of the bearing that may lead to instability; and cyclic stress on rotating elements leading to fatigue. For most compressors, the damage is typically fastest at the coupling elements, designed as a weak link, but a crack in the shaft is also a possible result. Extreme change in the position can lead to contact between the rotor and a stationary part (or rub).

With deformation of the casing, the clearance position is changed or the shape of clearance can be deformed, and flow asymmetry can generate high fluidic preloads. Therefore, thermal changes in bearing position, limitations in thermal expansion, piping stress, and soft foot issues fall into the same category of problems because their effect is the generation of preload forces. And, even if machine alignment was ideal there could be many reasons it changed during the period of operation or due to changes related to a specific condition.

The detection of excessive preloads is important, and can be ensured by combining information from several sources. Any change in radial loads acting on the rotor will cause a change in bearing reaction that will result in a change to the position of the shaft in the bearing. Therefore, a shaft centerline position plot is extensively used for evaluation of alignment/radial preload changes.

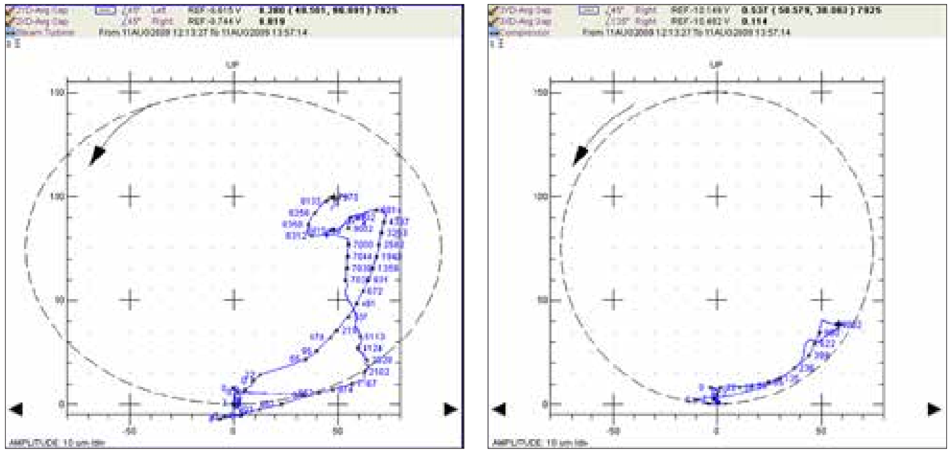


Figure: Shaft centerline position plots suggesting misalignment between bearing 2 (turbine) and bearing 3 (compressor).

A change in preload will also change the support stiffness in particular radial directions (for example, a change anisotropy of stiffness) and as a consequence in flatness or in orientation of 1X filtered orbit. Flatness of orbit can be tracked in full spectrum plots (for instance, trended in full spectrum waterfall). The change in 1X vectors (amplitude and phase) can be observed in trends or in an acceptance region plot (a variation of polar plot for tracking steady state data). While a flat 1X orbit can be considered a symptom of misalignment, care should be taken because the orbit could also be flat for other reasons, such as an operation close to resonance speed. Proper diagnosis must consider several types of data to confirm the problem.

Because excessive preload, which moves the rotor closer to clearance boundary, causes higher dynamic stiffness, shaft relative vibration amplitudes can go down. Conversely, a higher load on the bearing causes an increase in absolute vibration. When this occurs, other symptoms of excessive preload can be observed such as abnormal casing absolute to the shaft relative vibration ratio.

Additionally, a higher load on the bearing results in a change of bearing metal temperature and bearing oil temperature. Because the former is a localized measurement, if the bearing is preloaded at a position distant from where the temperature sensor is normally installed, the readings can be lower than normal values. This indicates that any change from normal bearing temperatures, up or down, should be investigated.

Finally, for some types of couplings (for instance, gear coupling and grid coupling), the misalignment can produce 2X and other harmonics of 1X. This can be explained by vibration coupling elements (for instance, teeth) with two stress cycles for shaft revolution. In such situations, the amplitude of the 2X component rises with the power transmitted, but because the load of the compressor is often controlled by rotating speed change the relationship between speed and amplitude is often observed. As a result of this 2X component, some typical orbit shapes like "banana" or "figure eight" are often quoted as misalignment symptoms. However, they are present only for specific types of couplings and a similar pattern can be obtained due to nonlinearity in stiffness (rub, looseness, nonlinear behavior of oil film), therefore they should not be used as a primary indicator of an alignment problem.

7.6 Rubs

Rub occurs when a rotating part is in contact with a stationary part that is not designed for such contact. The only parts designed for contact are bearings and some seals. In the fluid bearing, the contact should be maintained through a film of oil. In the types of seals that allow some contact by design – either constantly during operation (oil seals) or occasionally (carbon seals, brush seals, and honeycomb seals), the latter category will show symptoms of rub contact as a part of normal behavior.

Because there are many possible rub scenarios, it is often called a multi-face phenomenon. Rub varies depending on contact forces, friction coefficients, material hardness, and so on.

A short list of rub symptoms includes:

- Changes in 1X vibration amplitude and phase due to a change of orbit shape and size.
- Changes in 1X due to a contact spot temperature increase and generated bow.
  - A spiral vector change on a polar plot, or limited cycle can be observed due to contact spot migration (known as Newkirk type rub).
  - A similar (or identical) pattern can be the result of Morton effect, but this phenomenon is without surface contact. Morton effect is caused when oil in the fluid bearing sharing generates slight difference of temperature on both sides of the journal that results in a configuration with a significantly overhung mass. The generated bow increases the effect of the unbalance of the overhung part and 1X vibration in the bearing increases the temperature differential on two sides of the journal.
  - Subtle differences in some situations make it possible to differentiate between the Newkirk and Morton effect, but such details are beyond scope of this overview.

- Changes in direct orbit shape due to any of the following:
  - Heavy rub can reduce vibration in some directions and result in a characteristic D-shape orbit.
  - Light rub tends to re-bounce the shaft and increase vibration in the direction of contact. If the friction forces are high enough, the normally forward motion of the orbit reverses for part of the cycle, resulting in external loop on the orbit. It is also possible for 1X to become reversed for some speed range, typically in the resonance regions.
- Changes in transient 1X response characteristics due to increased stiffness at the rub location, cause the resonance frequency to be shifted up.
- Harmonics of 1X due to the truncation of the normal sine wave.
- Exact fractional components generation (such as ½ X, 1/3 X, and so on) and their harmonics are generated due to re-excitation of rotor resonance at specified speed ranges. When rotor speed is slightly above n-times resonance speed the 1/n X component can be generated.
- A similar effect and very similar orbits will be generated due to looseness in the support when 1/n X components can be generated when operating slightly below n-times resonance speed. This is called Mathieu type rub (or looseness) condition and the effect is due to periodic change in system stiffness during the vibration cycle. Since rub is increasing stiffness, and looseness is reducing this for part of the cycle, the resonance condition for the average value of stiffness will be above n-time resonance speed for rub and below n-times resonance speed for looseness. Taking into account the typical ratio of operating speeds to resonance speeds, the most typical situation is excitation of exactly ½ X. This is an exactly fractional component contrary to instability situations that were characterized by some subsynchronous but not exactly fractional components. It can be easily observed on orbit/timebase plots, where Keyphasor dots are locked at the same location on orbit for particular revolutions of the shaft (compare with plots for stall or fluid instability, earlier in the document).

Whether identification of rub symptoms is normally relatively easy because of multiple but characteristic patterns, the localization of the rub requires combining vibration and position data with information about machine design, especially the position of seals, clearance data, and so on.

Because rub is a secondary phenomenon, the primary cause must be identified before the problem can be solved. The rub can be due, and only due, to:

- Anything that causes excessive relative vibration levels, such as unbalance, fluid induced instability, or oversized bearing clearance.
- Anything that causes extreme shaft position – excessive preload, internal or external misalignment, casing deformation, limitation in thermal expansion, piping stress, and so on.
- Anything that causes limited clearance such as thermal expansion, assembly, manufacturing or design errors, or deposit formation.
- Any combination of the above that leads to rotor to stationary part contact.

After detecting the rub symptoms, the vibration, position, and process data are analyzed to identify the conditions leading to rub and to track the primary source of it.

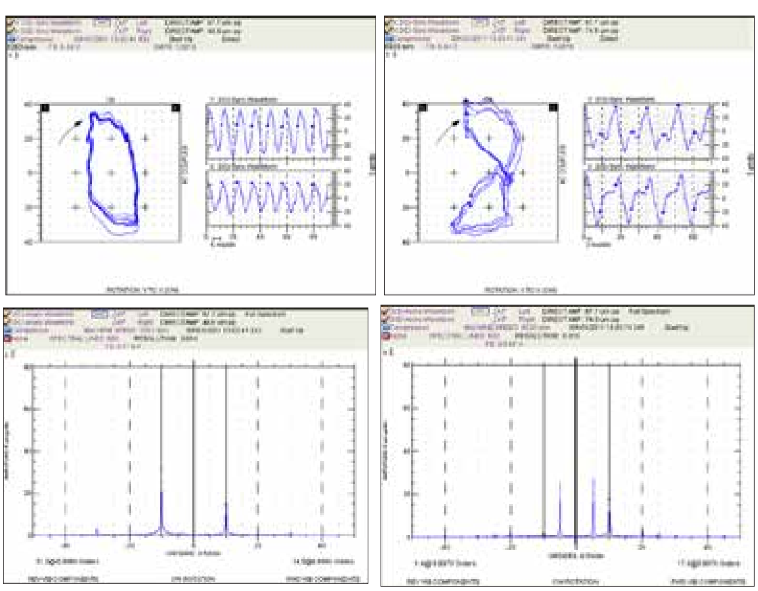


Figure: Sample orbit/timebase plots for rub condition. The orbit on the left shows 1X and higher frequency components, the 1X precession is reversed. In the orbit on the right (the same case, another measurement speed) there is exact ½ X present. The full spectrum for the same condition is shown below the orbits.

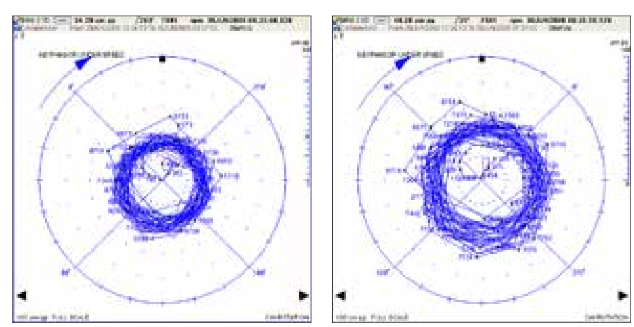


Figure: Rotating 1X vector on polar plot due to Newkirk type rub in the carbon seal. Note that the similar picture can be due to the Morton effect.

7.7 Malfunction Review Summary

From the brief review above, some conclusions can be drawn. Because the detection of machine problems requires proper data, the first, necessary condition is the installation of the proper suite of transducers at the right machine locations and in the correct manner. Next, the signals can be connected to the monitoring and protection system. Some information about this process is provided in sections 8 and 9 of this document. The conversion of data into actionable information is a complex task that requires proper diagnostic software as well as knowledge and skills (refer to the overview of System 1 software in section 11 for more information). To facilitate data interpretation, real-time, continuous, automated diagnostic capabilities are offered by RulePaks, which use a rule processing engine to evaluate collected vibration, position, and process data to detect typical rotating machinery malfunctions.

About GE's Bently Nevada Marchinery Diagnostic Service

For more in-depth analysis, both in-situ and remote diagnostics are offered by GE's Bently Nevada Machinery Diagnostic Service (MDS), with more than 130 diagnostic engineers available worldwide. The same diagnostic methodology used by MDS is offered as diagnostic training courses available to customers:

Machinery Diagnostics – This course covers the solid basics of data interpretation by teaching causes, effects, and indicators of typical machine malfunctions for fluid film bearing supported rotating machinery.

Machinery Fundamentals/Applied Diagnostics – This intermediate-level course provides additional information about design machinery (for instance, compressors, electric motors, and steam and gas turbines). Learning occurs primarily through the completion of workshop tasks in which students perform diagnostic analysis based on data from real-world cases.

Advanced Machinery Dynamics – The highest level course provides a deep dive into the details of machine design and their influence on machine dynamics. It connects calculation (rotor, bearing system modelling), measurement (radial and torsional vibration of rotating machinery, structural analysis) and machine design expertise (rotors, couplings, bearings and seals) approaches to solve some of the most demanding diagnostic cases.

Refer to **http://ge-energy.turnstilesystems.com/MachineryDiagnosticians.aspx** for more information about MDS courses.

8 Transducers

8.1 Transducer/Location Selection

Sensors are installed in or on the machine to make appropriate measurements such as vibration, position, speed, and pressure. API 670 standard, Machinery Protection Systems, should be followed for selection of transducers. The transducer types and methodologies described here apply to axial, centrifugal and integrally-geared compressors.

Typically, each radial bearing requires a pair of X-Y proximity probes to monitor shaft vibration and shaft centerline position. Each thrust bearing requires two proximity probes to monitor the axial position. A Keyphasor* probe is required to obtain a phase reference (and can provide speed measurement although a multi-tooth wheel may be required for higher resolution speed measurements) from each shaft. Accelerometers are required on integrally-geared compressors to measure gear-related vibrations.

8.2 Proximity Probes

A 3300 XL 8 mm proximity transducer system is typically used, consisting of three components: a 3300 XL 8 mm probe with 3/8-24 UNF threaded body, a 3300 XL extension cable (when required), and a 3300 XL Proximitor* sensor. These components comprise a tuned system, and must be selected to achieve a combined standard electrical length for proper operation. Often a 5-meter system with a 5-meter Proximitor sensor is used. A 9-meter system with a 9-meter Proximitor sensor can be used if longer physical length is needed between probe and Proximitor. When possible, the consistent use of one electrical length is desired for simplicity and standardization.

The 3300 XL 8 mm proximity transducer system provides up to 80 mils (2 mm) of linear range with an output of 200 mV/mil (7.87 V/mm) when observing AISI standard type 4140 steel. This addresses the majority of compressor monitoring applications for radial vibration, axial (thrust) position, speed, and Keyphasor measurements. Shaft materials other than AISI 4140 steel require a modification to the Proximitor sensor to preserve the standard 200 mV/mil (7.87 V/mm) scale factor. The system should be provided with hazardous area and country certifications appropriate to the installation. The gap between the probe and the shaft should be adjusted to approximately mid-range (approximately -10 volts) for optimal use of the full linear range when monitoring radial vibration. Axial position monitoring requires a precise setup for the expected motion of the thrust bearing.

Intrinsic safety barriers or galvanic isolators are required for sensors located in some areas classified as hazardous. These should be supplied in accordance with the user's general instrumentation standard and selected to ensure compatibility with the transducer system and associated monitor modules. Refer to the monitoring system's field wiring diagrams and instructions for details.

For all proximity probes, an "external" probe mounting arrangement is often preferred, as it allows adjustment or removal of the probe without disassembly of the machine. This method uses a part number 31000 or 32000 Proximity Probe Housing Assembly and a reverse-mount style probe. The Probe Housing Assembly should be mounted to a structural component of the machine that firmly positions the probe to accurately represent the movement of the shaft relative to the corresponding bearing. If this mounting location is a distance from the shaft surface of 15 inches or more, a bracing support at the tip of probe sleeve must be installed so that it the probe tip does not vibrate laterally relative to the observed surface of the shaft. Lateral vibration could fatigue the probe sleeve and possibly introduce measurement errors. Also, this method of installation often introduces thermal error in shaft centerline position measurements because of movement of the fixture in relation to the bearing. By fixing the probe to the bearing as close to the probe tip as possible, the quality of the data used for diagnostic purposes can be improved.

A variant of the external arrangement is the PROXPAC XL* proximity transducer assembly. This modular proximity transducer system is a 31000 housing that contains a special 3300 XL Proximitor sensor and uses a 1-meter reverse-mount proximity probe (no extension cable is needed between the probe and Proximitor sensor).

When the external mounting arrangement is dimensionally unworkable, or a stable external mounting location cannot be found, an "internal" mounting arrangement can be used. This arrangement positions the probes inside the machine case or underneath the bearing cover using standard or custom mounting brackets. The cables are routed through the cover or case using cable seals. When this arrangement is used, it is recommended that a second set of X-Y radial proximity probes, and a spare axial (thrust) probe and Keyphasor probe be installed, preferably in the locations described in API Standard 670 guidelines. The extension cables for these spare probes should be routed to where the Proximitor sensors for the primary probes are located, for connection to a Proximitor sensor should they be needed.

Note: *All brackets should be designed to minimize the possibility of thermal deformation causing error in shaft centerline position readings.*

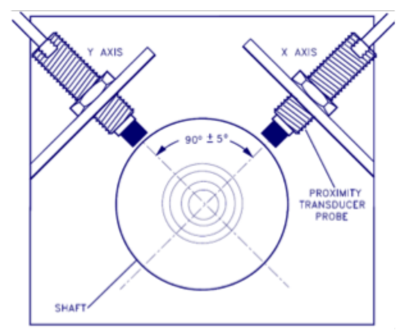
The shaft surface observed by the probe should be smooth and free of plating, scratches, residual magnetism, and shoulders or edges. Radial probes should observe a probe target area on a circular shaft that is concentric to the bearing journal. Axial probes should observe a flat surface. The probe's eddy current field should not interact with metal surfaces alongside the probe tip or the field from adjacent proximity probes. When mounting space is tight or the observable shaft surface area is small (such as in integrally-geared air compressors), consider using the 3300 5 mm or 3300 XL NSv* (narrow side view) proximity transducer systems, which have a ¼-28 UNF threaded body.

Note: *Refer to API 687 for additional information about measurement path preparation and verification.*

A transducer system verification check should be performed before and after installation to ensure system integrity. The Bently Nevada TK-3 instrument enables the installer to perform a calibration check and exercise (loop test) the transducer and monitor system prior to installing the transducer in the machine. Recalibration based upon the TK-3 calibration graph is not recommended. This is because all probes, cables and Proximitor sensors are factory calibrated using precision instrumentation and field recalibration may have an adverse effect on the interchangeability of components if it becomes necessary to replace a part.

8.3 Shaft Radial Vibration

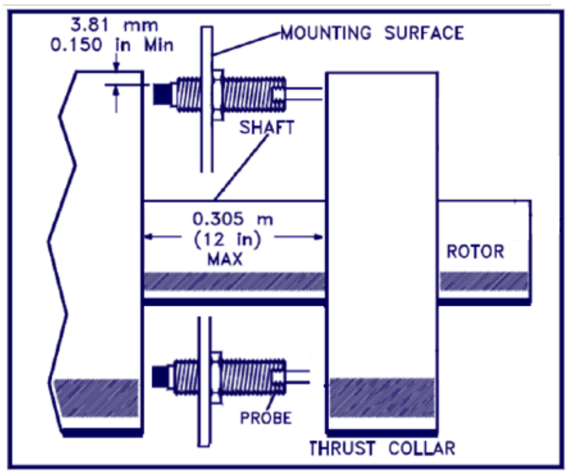
GE's recommendation for radial vibration measurements is two (2) vibration transducers mounted coplanar and 90 degrees apart (X and Y) within 3-inches (75 mm) of the bearing. This X-Y configuration provides a complete picture of the shaft centerline vibration and radial position within the bearing clearance. The probes are mounted perpendicular (within ±5°) to the shaft centerline with an angular separation of 90°±5°. Typical probe orientation is 45° left and 45° right, referenced to vertical (up) and viewed from driver to driven end of the machine train. Where practical, a consistent probe orientation should be used for all radial bearings on a machine case or train to simplify diagnostics and balancing.



On integral geared compressors used for air compression service, a single probe per bearing is acceptable when space constraints prevent two probes in the X-Y configuration.

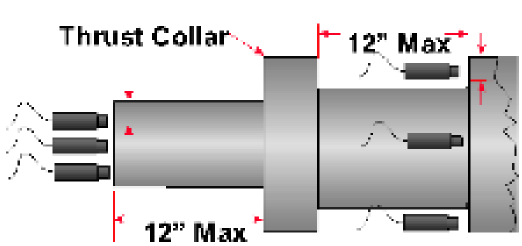
8.4 Axial (thrust) Position

Thrust bearing failure is considered a catastrophic failure and typically leads to an immediate catastrophic failure of the machine. Two (2) thrust probes should be used for redundancy to ensure reliable machine protection. When the internal mounting arrangement is used, a third (spare) probe and extension cable is recommended. For installations requiring SIL 3 compliance, a third probe is installed to provide a 2 out of 3 voting scenario. Position measurements utilize the DC component of the transducer signal. Mount the probes at the thrust bearing end of the machine and within 12 inches (300 mm) of the thrust bearing to minimize the effects of shaft growth due to thermal expansion. For example, 12 inches (300 mm) of 4140 steel with a temperature change of 100°F (38°C) will grow 0.008 inches (0.2 mm). Therefore, the measurement could show 8 mils of apparent thrust motion that is due only to thermal growth if all else remains fixed. This must be considered when establishing thrust alert and danger setpoints.



The preferred mounting arrangement for the thrust probes is directly through the thrust bearing, but the machine design does not always permit this. Thrust probe installation may also be engineered to observe the end of the shaft within 12 inches (300 mm) of the thrust bearing, or another collar on the shaft within a similar proximity to the thrust bearing. If all probes cannot observe the same plane, one of the two probes can be mounted to observe the end of the shaft, and the other to observe the thrust collar.

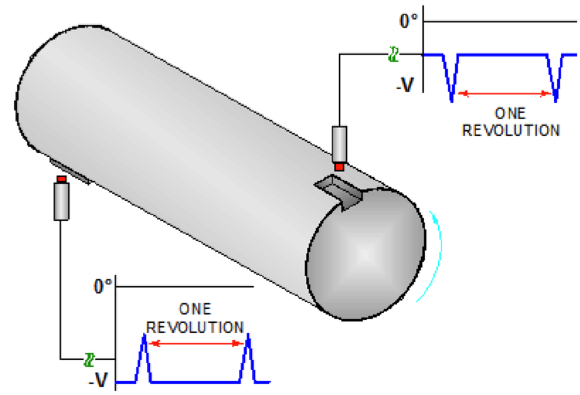
Due to the compact design of some integrally geared compressors, manufacturers may elect to provide a single axial proximity displacement transducer on the blind end of each pinion shaft instead of the bullgear. This is acceptable per API STD 672, section 7.10.8. (This is an exception to the best practice of using dual axial positon transducers and is driven by the space available for the sensor installation). Specialty sensor designs such as "button probes" may be employed for this purpose when the geometry of the machine prohibits conventional sensors.



8.5 Keyphasor Sensor

The Keyphasor probe provides a once-per-turn phase reference voltage pulse that is combined with vibration measurements to derive synchronous (1X, 2X, nX, etc.) amplitude and phase angle of vibration values. It is necessary for diagnostics and balancing, and is required by the System 1 condition monitoring platform for synchronous sampling.

A Keyphasor transducer should observe each output shaft of the driver or (if present) gearbox. A spare Keyphasor transducer is recommended and is especially important when the probes are mounted internal to the machine. If possible, Keyphasor transducer(s) should observe each pinion shaft of an integrally-geared compressor. Ideally, Keyphasor transducer(s) should also observe the input shaft of the compressor to provide a dedicated and consistent phase angle reference for the compressor despite replacement or rework of the driver or gearbox. Keyphasor probe and notch/projection locations and orientations should be documented for future reference.



Keyphasor probes should be mounted radially; axial Keyphasor probes observing the end of a shaft should be avoided, but may be the only option on integrally-geared compressor pinion shafts. The notch or projection observed by the Keyphasor transducer should be intentionally designed into the shaft, should avoid high torque areas and utilize radiuses to minimize stress concentrations, and should be located and/or dimensioned such that axial shaft movement due to thermal growth or rotor float does not affect the Keyphasor measurement.

The minimum width and length of the notch should be one and one-half times the diameter of the probe tip, and the minimum depth should be 0.06 inch (1.5 mm). Except for small edge radiuses, the notch or projection should present a well-defined step that results in a Proximitor output voltage change of no less than 7 volts.

Note: *It is a recommended practice, where possible, to input the Keyphaser signal(s) into one channel(s) of a 3500/42 monitor to allow capture of the Keyphasor signal waveform(s).*

8.6 Accelerometers (seismic transducers)

An accelerometer mounted to the gearbox can provide indications of progressive damage to gear elements. Specific mechanical fault symptoms related to gear wear or sudden damage can be detected using the accelerometer's increased sensitivity to higher-frequency vibrations.

The 330400 accelerometer is suitable for most gearbox monitoring applications, and the user should verify that the frequency response of the chosen accelerometer is capable of detecting the gear-related frequencies of interest. The 330400 has an upper amplitude range of 50 g peak. Alternatively, the 330425 accelerometer has an amplitude range of 75 g peak for installations where higher amplitudes are expected.

Accelerometers should be mounted on a flat surface of sufficient area to provide full contact with the accelerometer's base. The surface should have a maximum roughness of 16 micro inches (0.4 micrometers) Ra (arithmetic average roughness). A hole for the accelerometer mounting stud should be drilled and tapped perpendicular to the mounting surface (±5 minutes of an arc) in the center of the mounting surface that will accommodate the accelerometer stud thread, and to sufficient depth to prevent the stud from bottoming out in the hole. Neither the mounting stud nor any housing used should interfere with full and complete contact of the accelerometer base with the gearbox surface described above. A thin layer of coupling grease (such as silicone grease) applied between the accelerometer and the mounting surface is recommended. The accelerometer manufacturer's minimum and maximum torque requirements should be followed to prevent accelerometer looseness and damage. Cable and connector characteristics should meet the physical and environmental requirements of the installation. Refer to API Standard 670 and the accelerometer manufacturer's installation manual for detailed information.

For integrally-geared compressors, two accelerometer transducers should be installed on the bull gear housing. The transducers should be located on each side of the casing, and be mounted radially on, or adjacent to, the bearing boss with axis aligned as close as practical to the principal load direction (OEM should advise recommended mounting orientation). If bearing bosses are not available, the accelerometers should be mounted horizontally at a location that provides direct transmissibility of bearing vibration from the bearing support to the transducer. The accelerometers should be mounted below the split line unless otherwise specified. This placement allows the machine to be disassembled without requiring removal of the instrumentation.

8.7 Temperature Sensors

Temperature measurements provide immediate and corroborating indications of bearing wear and damage due to vibration, misalignment, high load, lubrication problems, and other malfunctions. Bearing metal temperatures in compressors and gearboxes should be monitored using resistance temperature detectors (RTDs). Thermocouples (TCs) may be used if dictated by user preference. Temperature elements of varying styles are available from several manufacturers.

For best temperature detection, the sensing elements should be embedded in the metal backing of the pads, as close as possible but not penetrating into the babbitt. Spring-loaded temperature elements that hold the sensor tip against the surface to be measured are preferred. Sensors that are potted into place should be avoided, as this complicates replacement.

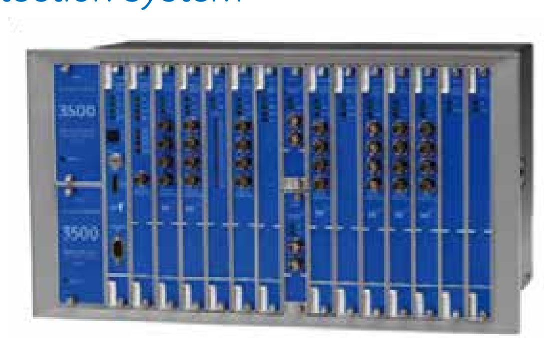
For radial bearings, depending on the length to diameter ratio, installations should use one or two sensors at the calculated maximum load deflection point on the bearing under normal conditions. For thrust bearings, the end user should install temperature sensors in each of two shoes in both the normally active and normally inactive thrust bearings, with equal angular separation between sensors. Dual element sensors are recommended, with one lead connected to the monitor and the other serving as an installed spare. Refer to API Standard 670 for further details and requirements.

8.8 Speed Sensors

Speed is considered a primary measurement, and compressors and their drivers typically have continuous speed indication in revolutions per minute (rpm). Machine speed measurements can come from a Proximitor sensor or magnetic pickup. Optical speed sensors are typically used for temporary diagnostic instrumentation only.

For permanent installations, the Proximitor sensor is recommended. All of these transducers can observe a single or multiple number of events-per-revolution of the shaft. Either signal can be used for the speed indication, but the multi-event per revolution signal, such as on a gear or toothed wheel, provides better resolution at speeds below 300 rpm. Speed wheels are typically located on the shaft of the driver, with once-per-turn Keyphasor signals providing speed for driven shafts. Specific sensor requirements for speed and overspeed detection are described separately in the best practices for the driver machine.

9 Bently Nevada 3500 Series Machinery Protection System



9.1 3500 System Overview

The 3500 system provides continuous, online protection for critical and highly-critical machinery applications. This system complies fully with API 670 and provides our best technology, developed over 50 years of experience, for protection of your most critical assets.

In addition to the solid foundation, many options exist to further increase fault tolerance such as SIL-rated modules and redundant power and signal pathways. The 3500 system also serves to capture all information for online condition monitoring and feeds directly to System 1 software for diagnostics and monitoring via separate digital pathways.

The system's highly modular design consists of:

- 3500/05 instrument rack (required)
- One or two 3500/15 power supplies (required)
- 3500/22M transient data interface (required)
- 3500 rack configuration software (required)
- One or more 3500/XX monitor modules (required) (The available 3500/XX are discussed below)
- One or more 3500/32 or/33 relay modules (recommended)
- One or more 3500/92 communication gateway modules (optional)
- Internal or external intrinsic safety barriers, or galvanic isolators for hazardous area installations (where required)

9.2 System Component Selections

The 3500 Series monitoring and protection system has several required components to create a functioning system.

9.2.1 Instrument Rack

The 3500/05 system rack design holds all 3500 monitor modules and rack power supplies. It allows the various 3500 modules to communicate with one another and the power supplies to distribute power to each module as required.

3500 racks are available in two sizes:

Full-size Rack – 19-inch EIA rack with 14 available module slots

Mini-Rack – 12-inch rack with 7 available module slots

3500 racks are available in three formats:

Panel Mount – This rack format mounts to rectangular cut-outs in panels, and secures to the panel using clamps supplied with the rack. Wiring connections and I/O modules are accessible from the rear of the rack.

Rack Mount – This rack format mounts the 3500 rack on 19-inch EIA rails. Wiring connections and I/O modules are accessible from the rear of the rack.

Bulkhead Mount – This rack format mounts the rack against a wall or panel when it is not possible to access the rear of the rack. Wiring connections and I/O modules are accessible from the front of the rack. The 3500/05 Mini-Rack is not available in this format.

Note: *Please see the latest 3500/05 Instrument Rack data sheet for more information (www.ge-mcs.com).*

The power supplies and TDI module must occupy the far left rack positions. The remaining 14 rack positions (7 rack positions for the mini-rack) are available for any combination of modules.

Best Practice Recommendation

For highly critical and critical machinery, each 3500 monitoring and protection rack should contain modules for only a single machine. This allows dedicated monitoring and protection functions for an individual machine and provides the following benefits:

- Service carried out on the 3500 rack will not affect other machines
- Failure of any component of the 3500 will not affect other machines
- Configuration changes can be carried out without affecting other machines
- Required for various functional safety certified configurations

9.2.2 Power Supplies

The 3500/15 power supplies are half-height modules and must be installed in the specially designed slots on the left side of the rack. The 3500 rack can contain one or two power supplies (any combination of AC and/or DC) and either supply can power a full rack. The second supply is highly recommended and acts as a backup for the primary supply. When two power supplies are installed in a rack, the supply in the lower slot acts as the primary supply and the supply in the upper slot acts as the backup supply. Removing or inserting either power supply module will not disrupt operation of the rack as long as a second power supply is installed.

The 3500 power supplies accept a wide range of input voltages and convert them to voltages acceptable for use by other 3500 modules. Three power supply versions are available with the 3500 Series machinery protection system as follows:

- AC power
- High voltage DC power supply

- Low voltage DC power supply

Note: *Please see the latest 3500/15 Power Supply data sheet for more information (www.ge-mcs.com).*

Best practice recommendations

- Use two power supply modules with separate power feeds for highest failure tolerance. In this scheme, the rack will continue monitoring in the event of loss of a single power feed, or loss of a single power supply module due to failure or removal of the module.
- Use of two power supply modules with a single power feed coupled to both inputs is also possible, and is a suitable solution when the single power feed is from an uninterruptable power supply (UPS). In this case, the benefit of having two power supply modules is for continued operation if a single module fails or is removed from service.

9.2.3 Transient Data Interface Module

The 3500/22M transient data interface (TDI) is the interface between the 3500 monitoring system and GE's System 1 machinery management software.

The TDI operates in the RIM slot of a 3500 rack in conjunction with the M series monitors (3500/40M, 3500/42M, and so on) to continuously collect steady-state and transient waveform data and pass this data through an Ethernet link to the host software. Static data capture is standard with the TDI, however using an optional channel enabling disk allows the TDI to capture dynamic or transient data as well. The TDI features improvements in several areas over previous communication processors and incorporates the communication processor function within the 3500 rack.

Although the TDI provides certain functions common to the entire rack, it is not part of the critical monitoring path and has no effect on the proper, normal operation of the protection function of the monitoring system. Every 3500 rack requires one TDI, which always occupies Slot 1 (next to the power supplies).

Note: *Please see the latest 3500/22M TDI data sheet for more information (www.ge-mcs.com).*

Best practice recommendations

- Security of the TDI module should be configured to comply with local site regulations and best practices.
- Trip multiply (TM) input contacts should be connected to the control system to inform the 3500 system of a startup condition so that normal channel alarms can be given "headroom" during startup. This prevents trips during transient events such as passing through first and second critical (where applicable). The TM factor should be set to bring alarm levels above normal transient vibration peak levels. The best way to check this is by using System 1 software to monitor startup plots (bode plot and direct/1X trends).
- TM should also be enabled for shutdown to prevent unwanted alarms.
- Rack reset input contacts should be connected to the control system to allow remote reset of rack alarms after acknowledgement from the operator/engineer.
- Rack OK contacts should be connected to the control system to alert the operator when a rack fault exists or certain other events warrant operator attention.

9.3 Monitor Module Selection

9.3.1 Vibration Monitors

As a key indicator of compressor condition, vibration is critical to understand how the compressor is running and whether or not it is running safely. The 3500 Series has two choices for vibration monitors.

3500/40M Proximitor Monitor – The 3500/40M Proximitor Monitor is a 4-channel monitor that accepts input from Bently Nevada proximity transducers, conditions the signal to provide various vibration and position measurements, and compares the conditioned signals with user-programmable alarms. The user can program each channel of the 3500/40M with the 3500 rack configuration software to perform any of the following functions:

- Radial vibration
- Axial (thrust) position
- Differential expansion
- Eccentricity

Note: *The monitor channels are programmed in pairs and can perform up to two of these functions at a time. Channels 1 and 2 can perform one function, while channels 3 and 4 perform another (or the same) function.*

The primary purpose of the 3500/40M monitor is to provide:

- Machinery protection by continuously comparing monitored parameters against configured alarm setpoints to drive alarms.
- Essential machine information for both operations and maintenance personnel.

Each channel, depending on configuration, typically conditions its input signal into various parameters called "static values." The user can configure alert setpoints for each active static value and danger setpoints for any two of the active static values.

Note: *The 3500/40M has no 4/20 mA recorder outputs.*

3500/42M Proximitor Monitor – The 3500/42M Proximitor/seismic monitor is a 4-channel monitor that accepts input from proximity and seismic transducers, conditions the signal to provide various vibration and position measurements, and compares the conditioned signals with user-programmable alarms.

The 3500/42M contains the functions of the 3500/40M with some additional features, including support for seismic transducers and configurable 4-20mA recorder outputs.

Note: *Refer to the latest 3500/40M and 3500/42M data sheet for more information (www.ge-mcs.com).*

The user can program each channel of the 3500/42M using the 3500 rack configuration software to perform any of the following functions:

- Radial vibration
- Thrust position
- Differential expansion
- Eccentricity
- Acceleration
- Velocity
- Shaft absolute
- Circular Acceptance Region
- Smax is available if requested by the end user (usually dependent on regional geographical preference)

Note: *The monitor channels are programmed in pairs and can perform up to two of these functions at a time. Channels 1 and 2 can perform one function, while channels 3 and 4 perform another (or the same) function.*

The primary purpose of the 3500/42M monitor is to provide:

- Machinery protection by continuously comparing monitored parameters against configured alarm setpoints to drive alarms.
- Essential machine information for both operations and maintenance personnel.

Each channel, depending on configuration, typically conditions its input signal to generate various parameters called "static values." The user can configure alert setpoints for each active static value and danger setpoints for any two of the active static values.

Best practice recommendations

Either the 3500/40M or 3500/42M should be used for protection and monitoring on compressors covered in this document. The 3500 rack will need to contain enough modules to cover the number of installed radial vibration and axial (thrust) position probes. Although the 3500/42M card has 4-20mA recorder outputs, it is always recommended that relay outputs are used for alarming/protection services. Refer to the relay card information section below for further information.

WARNING: Barriers/Isolators in Hazardous Areas

Double check whether transducers are installed within hazardous areas. If so, the transducers should be certified for the required zone/division, and barriers or isolators will be required to isolate the transducers (hazardous area) from the monitoring system (safe area). If unsure about the requirements, contact GE's Bently Nevada Technical Support (bntechsupprt@ge.com) and specify the instruments used (such as probes and monitors), the site hazardous rating, and any other information requested by Tech Support.

9.3.2 Keyphasor/Speed/Overspeed Monitors

The 3500 Series has two choices for Keyphasor measurement and two choices for speed measurements. The 3500/53 is an overspeed detection system (ODS). An alternative to the 3500/53 ODS is the 3701/55 emergency shutdown device (ESD) that also provides overspeed detection. A general overview describing the capabilities of the two choices follows.

3500/25 Keyphasor Module – The 3500/25 enhanced Keyphasor module is a half-height, 2-channel module used to provide Keyphasor signals to the monitor modules in a 3500 rack. The module receives input signals from proximity probes or magnetic pickups and converts the signals to digital Keyphasor signals that indicate when the Keyphasor mark on the shaft coincides with the Keyphasor transducer. The 3500 machinery protection system can accept up to four Keyphasor signals for normal configuration and up to eight Keyphasor signals in a paired configuration.

Note: *A Keyphasor signal is a once-per-turn pulse from a rotating shaft or gear used to provide a precise timing measurement. This allows 3500 monitor modules and external diagnostic equipment to measure shaft rotative speed and vector parameters such as 1X vibration amplitude and phase. The installation of a spare Keyphasor sensor is highly recommended because the Keyphasor is a vital element in performing machine management and diagnostics.*

Note: *Refer to the latest 3500/25 Keyphasor module data sheet for more information (www. ge-mcs.com).*

3500/50M Tachometer Module – The 3500/50M tachometer module is a 2-channel module that accepts input from proximity probes or magnetic pickups (except as noted) to determine shaft rotative speed, rotor acceleration, or rotor direction. It compares these measurements against user-programmable alarm setpoints and generates alarms when these setpoints are violated. The 3500/50M tachometer module is programmed using the 3500 rack configuration software and can be configured with four different options:

- Speed monitoring, setpoint alarming, and speed band alarming
- Speed monitoring, setpoint alarming, and zero speed notification
- Speed monitoring, setpoint alarming, and rotor acceleration alarming
- Speed monitoring, setpoint alarming, and reverse rotation notification

Note: *Refer to the latest 3500/50M Tachometer module data sheet for more information (www.ge-mcs.com).*

The 3500/50M can be configured to supply conditioned Keyphasor signals to the backplane of the 3500 rack for use by other monitors, thus eliminating the need for a separate Keyphasor module in the rack. The 3500/50M also has a peak hold feature that stores the highest speed, highest reverse speed, or number of reverse rotations (depending on channel type selected) that the machine has reached. These peak values can be reset by the user.

Best practice recommendation

For highly critical and critical compressors, Keyphasors must be installed following transducer recommendations. It is recommended that the monitoring system should use the 3500/50 tachometer module to bring in Keyphasor and high resolution speed (where available).

3500/53 Overspeed Detection Module – GE's Bently Nevada electronic overspeed detection system for the 3500 Series machinery detection system provides a highly reliable, fast response, redundant tachometer system intended specifically for use as part of an overspeed protection system. It is designed to meet the requirements of API 670 and 612 standards pertaining to overspeed protection.

3500/53 modules can be combined to form a 2-out-of-2 or a 2-out-of-3 (recommended) voting system. The overspeed detection system requires the use of a 3500 rack with redundant power supplies. ODS is only applicable to the driver, not the driven machine.

Note: *The 3500/53 product has been included in this application guide to support our existing installed base of these units. The 3500/53 is no longer available for new installations and 3701/55 ADAPT* ESD should be considered for all future Bently Nevada overspeed detection and emergency shutdown applications.*

3701/55 Emergency Shutdown Device – The two types of modules in a 3701/55 ADAPT ESD are processor modules and relay modules. Three of each type of module are inserted into the terminal base. Processor modules fit into the slots on the left side of the terminal base and perform system wide supervisory functions, including maintaining an event and alarm list. Relay modules fit into slots on the right side of the terminal base. The 3701/55 ADAPT overspeed and emergency shutdown device is certified for use as a microprocessor-based logic solver in a SIL 3 certified safety system.

The 3701/55 operates by receiving input signals (speed pulses) from field sensors, applying pre-programmed logic to these inputs, and then outputting the results of this logic to relays. The relays, in turn, operate final control elements such as an actuator shutdown valve and other emergency shutdown devices. Each processor module controls relay channels on one of the relay modules. Each processor module/relay module pair operates independently and separately. This redundancy increases the availability of the 3701/55. The three processor/relay module sets can be configured to operate as a 2 out of 3 (2oo3) triple module redundant device. Each of the three relay modules in a 3701/55 contain five relays – one protection fault relay (OK relay) and four programmable relays. The logic that drives these programmable relays is identical for each module and is programmed using the ADAPT ESD monitor configuration software.

The contacts for all five relays are on the side of the relay module. All relays are single pole/double throw (SPDT) relays and the connectors use standard labels (NO, ARM, and NC). Normally open (NO) and normally closed (NC) refer to the contact condition when the relay is not energized.

The protection fault relay indicates the status of the processor/relay pair. This relay is normally energized. An asserted protection fault relay indicates that the protection function for the channel (transducer input, monitor and relay) has been compromised. The protection fault relay indicates the operating status of the processor /relay pair and is not programmable.

Note: *The output of the protection fault relay should always be connected into an operator warning system so that any fault can be immediately addressed and repaired by the end user.*

Caution: Due to the extremely open and unrestricted configurability of the 3701/55 ESD overspeed detection system, it is imperative that the specific logic configuration of the trip function be completely understood, documented, and tested. Thorough validation is necessary to be certain that the system responds as desired to all possible input scenarios under all machinery operational conditions.

Refer to the separate Overspeed Detection System Application Guide for more details on ODS.

9.3.3 Temperature Monitors

As a key indicator of compressor condition, temperature is important to understand how the compressor is running and whether or not it is running safely. The 3500 Series offers the following choices for temperature monitors.

3500/60 and /61 Temperature Monitors – The 3500/60 and 3500/61 modules provide six channels of temperature monitoring and accept both resistance temperature detector (RTD) and thermocouple (TC) temperature inputs. The modules condition these inputs and compare them against user-programmable alarm setpoints. The 3500/60 and 3500/61 provide identical functionality, except that the 3500/61 provides recorder outputs for each of its six channels, while the 3500/60 does not.

3500/65 Temperature Monitor – The 3500/65 monitor provides 16 channels of temperature monitoring and accepts both resistance temperature detector (RTD) and isolated tip thermocouple (TC) temperature inputs. The monitor conditions these inputs and compares them against user-programmable alarm setpoints.

Note: *Refer to the latest 3500/60, 3500/61 and 3500/65 Temperature Monitor data sheet for more information (www.gemcs.com).*

The monitor is programmed using the 3500 rack configuration software. The 16-channel temperature monitor can be configured to accept isolated tip thermocouples, 3-wire RTD, 4-wire RTD, or a combination of TC and RTD inputs.

Best practice recommendation

Temperature sensors should be connected directly to the 3500 rack if possible. If not possible, information from the DCS can be provided digitally to System 1 software, or via analog output cards into the 3500 rack inputs.

9.3.4 Relay Modules

The 3500 Series has three choices for relay modules to serve different annunciation requirements. A general overview describing the capabilities of the primary two modules (the third is a TMR module and not listed here) follows.

3500/32 Relay Module – The 4-channel relay module is a full-height module that provides four relay outputs. Any number of 4-channel relay modules can be placed in any of the slots to the right of the transient data interface module. Each output of the 4-channel relay module can be independently programmed to perform needed voting logic.

Each relay utilized on the 4-channel relay module includes "alarm drive logic." Programming for the alarm drive logic uses AND/OR logic, and can use alarming inputs (alert and danger statuses), Not-OK, or individual PPLs from any monitor channel or any combination of monitor channels in the rack. Users program this alarm drive using the 3500 rack configuration software to meet the specific needs of the application.

3500/33 Relay Module – The 16-channel relay module is a full-height module that provides 16 relay outputs. Any number of 16-channel relay modules can be placed in any of the slots to the right of the rack interface module. Each output of the 16-channel relay module can be independently programmed to perform needed voting logic.

Each relay used on the 16-channel relay module includes "alarm drive logic." Programming for the alarm drive logic uses AND/OR logic, and can use alarming inputs (alert and danger statuses), Not-OK, or individual PPLs from any monitor channel or any combination of monitor channels in the rack. Users program this alarm drive using the 3500 rack configuration software to meet the specific needs of the application.

Note: *Refer to the latest 3500/32 and 3500/33 Relay Module data sheet for more information (www.ge-mcs.com).*

Best practice recommendations (for relay annunciation or trip)

Radial Vibration - Radial shaft vibration is monitored with orthogonal X/Y paired proximity sensors. The vibration shutdown system is field configurable to shut down when either a single sensor exceeds the danger alarm setpoint (one-out-of-one logic (1oo1)) or when both sensors are exceeding their danger alarm setpoints (two-out-of-two logic (2oo2) or dual voting logic). The end user must make an informed decision to use single logic or dual voting logic based on a risk analysis and the economic impact of a missed shutdown compared to a false shutdown. An excellent discussion of this trade-off consideration is presented Section 7.4.1 of API 670.

> **Note 1:** *Voting a radial vibration X/Y pair increases the risk of failing to shutdown on high vibration if the machine is experiencing a severely elliptical orbit which can occur due to a heavy preload condition.*
>
> **Note 2:** *When 2oo2 dual voting is applied, if one channel shows an alarm and the other does not, the end user should immediately determine the root cause of the alarm and take appropriate corrective action.*
>
> **Note 3:** *When 2oo2 dual voting is selected, a channel Not-OK with one of the vibration signals demands immediate action from the end user to rectify the cause of the Not-OK condition. Failure to rectify this condition may have the consequence of either having unprotected operation or reverting to a single logic protection (1oo1) based on the remaining OK channel. Field changeable options allow the end user to establish the correct response based on their operational needs.*
>
> **Note 4:** *End users need to be aware that logically OR-ing the*

channel Not-OK with the channel alarm in relay logic could lead to false shutdown if an event causes a momentary Not-OK condition on one channel (if 1oo1 voting is applied) or both channels (if 2oo2 voting is applied). A nearby lighting strike or other fast electrical disturbance could cause this condition. The input spike event is capable of exceeding the channel OK limits nearly instantly, while that same channel's alarms may not be driven due to the momentary nature of the disruption combined with the inherent measurement delay, and the configured alarm time delay. The Not-OK response of the channel has no delay.

(See Appendix 6 for further discussion on voting.)

Timed OK Channel Defeat – This feature defeats the channels alarm capability when the transducer is in a Not-OK state. When the transducer returns to an OK state, a 30 second delay occurs before the channel alarm capability becomes active. The OK channel defeat provides additional immunity to false alarms or trips due to a detectable fault that may occur in the sensor and monitor path such as intermittent field wiring. This option is available only if the OK mode is set to non-latching. The OK LED on the front of the monitor will flash at 2 Hz (two times per second) to indicate that the monitor has been in a Not-OK state. The end user should immediately investigate this to determine the cause of the temporary Not-OK state to avoid the initiation of a false trip. The end users' operating practices will best dictate when this option is selected.

Note: *This feature is not available for axial thrust monitoring.*

Axial (thrust) Position – Many years of field experience have shown that the best practice is dual voting thrust (2oo2) for shutdown. This voting requires both sensors to exceed their danger set-point to initiate a shutdown. API 670 Section 7.4.2 covers this consideration in detail. API 670 makes an allowance for end users to choose single logic (one-out-of-two or 1oo2) for axial position shutdown based on needs and preferences.

Note 1: *When dual voting is applied, if the two channels show a different reading, immediate action should be taken to determine the root cause driving the difference and then corrective action should be taken.*

Note 2: *When dual voting thrust is applied, a channel Not-OK caused by a transducer fault will drive that channel's alarms, resulting in a vote for shutdown. A second vote from the remaining channel will activate the shutdown relay. (Refer to API 670 7.4.2.5 b).*

Note 3: *The end user is encouraged to thoroughly understand and verify voting logic at the time of commissioning and after any change in configuration.*

(See Appendix 6 for more information about voting.)

Temperature – Temperature alarms should be annunciated via relay contacts to the control system for operator intervention.

Note: *All alarms should be set to latching mode. In this mode, when an alarm is triggered, it will remain in this state until it is reset by the operator/engineer. If latching is not enabled, alarms may disappear and the operator may miss the annunciation.*

9.3.5 Alarm Setpoints

This section provides general guidance on the processes that service engineers can use to obtain alarm set-point levels in the absence of any other procdures. This information is not intended to define alarm levels or recommend any machine limits.

Alarm setpoints are generally obtained by:

- OEM limits established in machine datasheets or OEM direct recommendations
- Site-specific monitoring philosophy and experience
- Relevant ISO/API standards or standards applicable to the jurisdiction

In the absence of the above sources of information, and as a good starting point to determine approximate alarm levels, API 617: Axial and Centrifugal Compressors and Expander-Compressors for Petroleum, Chemical and Gas Industry Services provides reference calculations to determine the acceptable vibration limits for OEM testing. These calculations can be used as a guideline when no other information is available. In any case, alarm set-points and relay logic configurations should be checked and signed off by site management.

Radial Vibration Alarms

When normal operating levels and limits have been defined – alert (H) and danger (HH) levels – the radial vibration channels should be set to alarm based on these levels. End users may elect to use either single logic or dual voting logic to initiate radial vibration alarms. The same considerations concerning alarm voting that were presented above, when discussing shutdown voting, apply to vibration alarms indication (see **Notes** above).

Note: *When dual voting is applied, if one channel shows an alarm and the other does not, immediate action should be taken to determine the root cause driving the alarm.*

Radial Position (Gap) Alarms

When normal operating levels and limits of gap voltage have been defined – gap high alert (H) and gap high danger (HH) set-points, and gap low alert (L) and low danger (LL) setpoints – the radial gap channels should be set to alarm based on these levels. End users may elect to use either single logic or dual voting logic to initiate radial gap alarms. The end user must make informed decisions concerning voting as explained in the **Notes** above.

Axial (Thrust) Position Alarms

When normal operating levels and maximum bearing clearances have been defined – alert (H) and danger (HH) levels, and alert (L) and danger (LL) levels – the axial position channels should be set to alarm based on these levels. Because of the rapid nature of many thrust failures, alarming only on thrust position is rarely used. Many years of field experience has shown that the best practice is dual voting thrust (2oo2) for shutdown. This voting requires both sensors to exceed their danger set-point to initiate a shutdown. API STD 670 Section 7 also covers this consideration in detail.

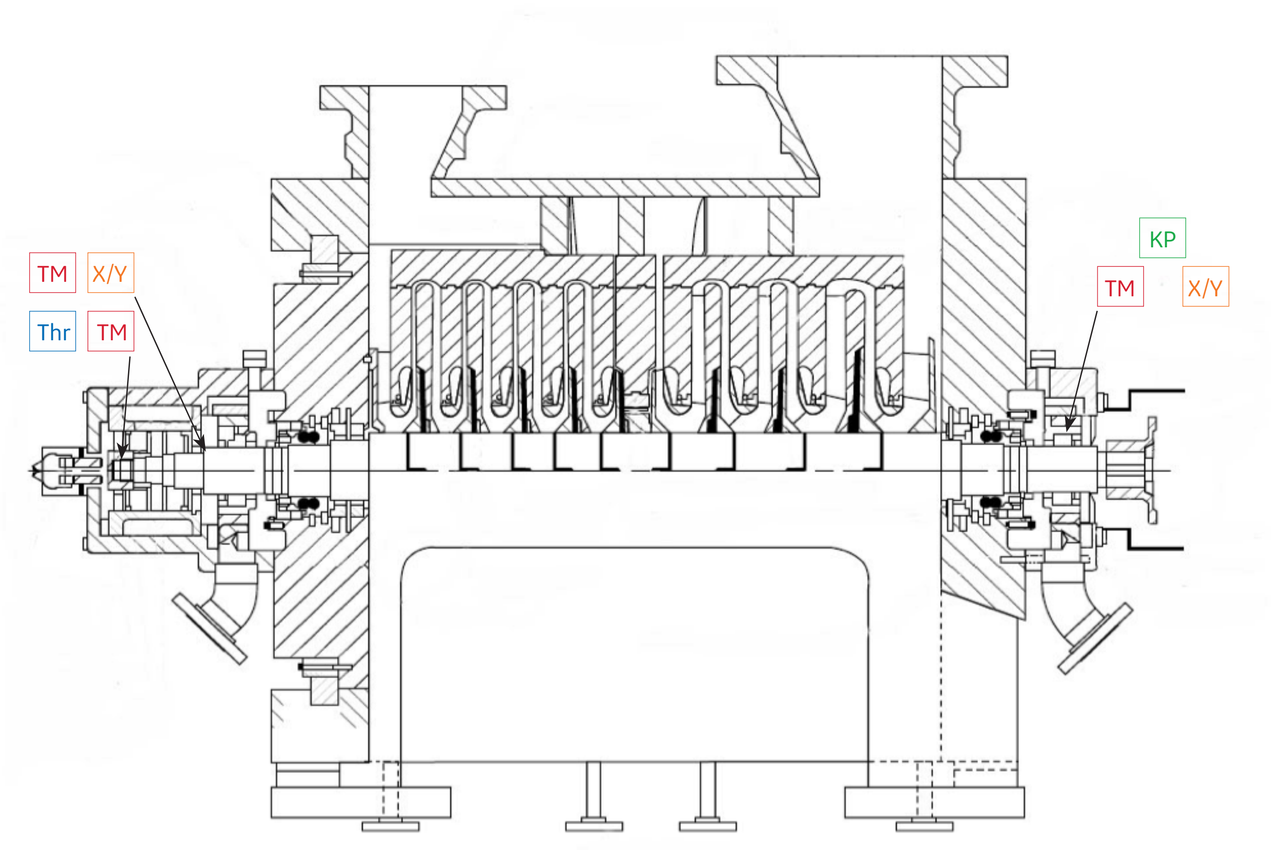
Additional monitors can be chosen based on required measurement capabilities. The following list of available monitors covers needed functions for centrifugal and axial flow compressors.

3500 Series Measurement Capabilities

Monitor Modules

Measurements	3500/25	3500/40M	3500/42M	3500/45	3500/50	3500/53	3500/60/61/65	3500/62
Phase reference	●				●			
Radial vibration (proximity probes)		●	●					
Radial position (proximity probes)		●	●					
Axial position (proximity probes)		●	●					
Eccentricity (proximity probes)		●	●	●				
Seismic vibration (velocity/ accelerometers)			●					
Shaft absolute (proximity and seismic)			●					
Differential expansion		●	●	●				
Ramp differential expansion				●				
Complementary differential expansion				●				
Valve position				●				
Rotor speed	●				●			
Rotor speed rate-of-change (acceleration)					●			
Rotor zero speed (turning gear engagement)					●			
Overspeed						●		
Temperature (direct/average/differential)							●	
Process variable signals (4–20 mA, 1–5 vdc, etc.)								●

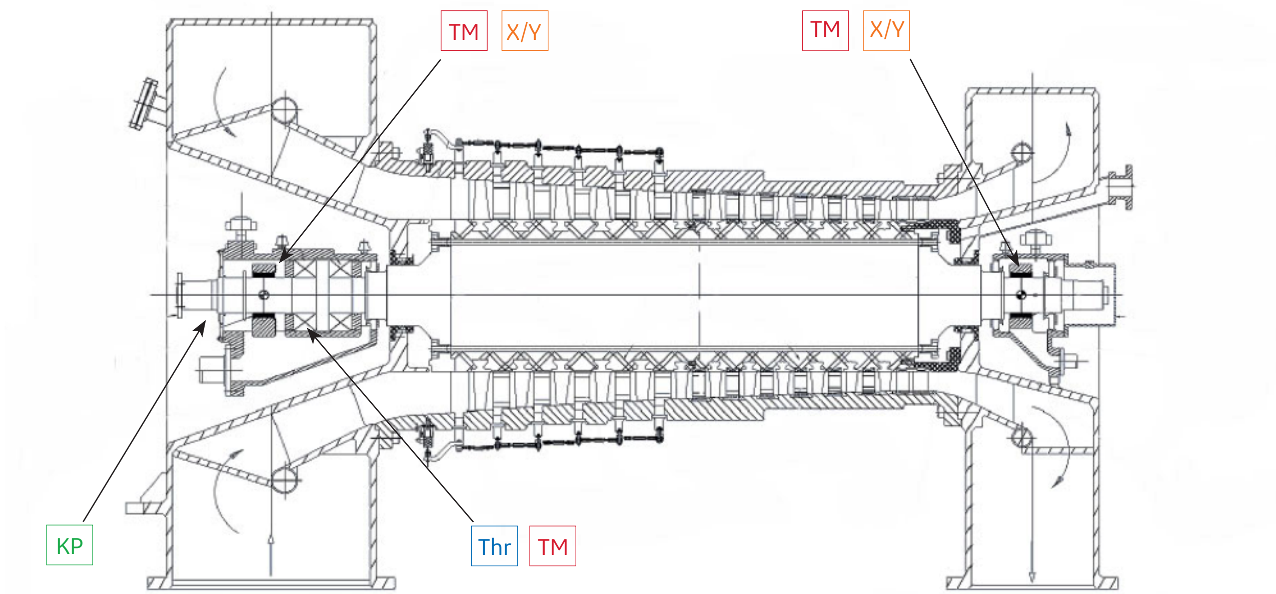
9.3.6 Vibration Instrumentation Diagram for Dual Flow Centrifugal Compressor



Key

KP	KeyPhasor – Redundant
X/Y	Radiat Proximity Probes – Dual
TM	Temperature Probes
Thr	Axial (Thrust) Position
AC	Accelerometers – Single

9.3.7 Vibration Instrumentation Diagram for Axial Flow Compressor



Key

KP	KeyPhasor – Redundant
X/Y	Radiat Proximity Probes – Dual
TM	Temperature Probes
Thr	Axial (Thrust) Position
AC	Accelerometers – Single

The following is the recommended rack layout for centrifugal and axial flow compressors:

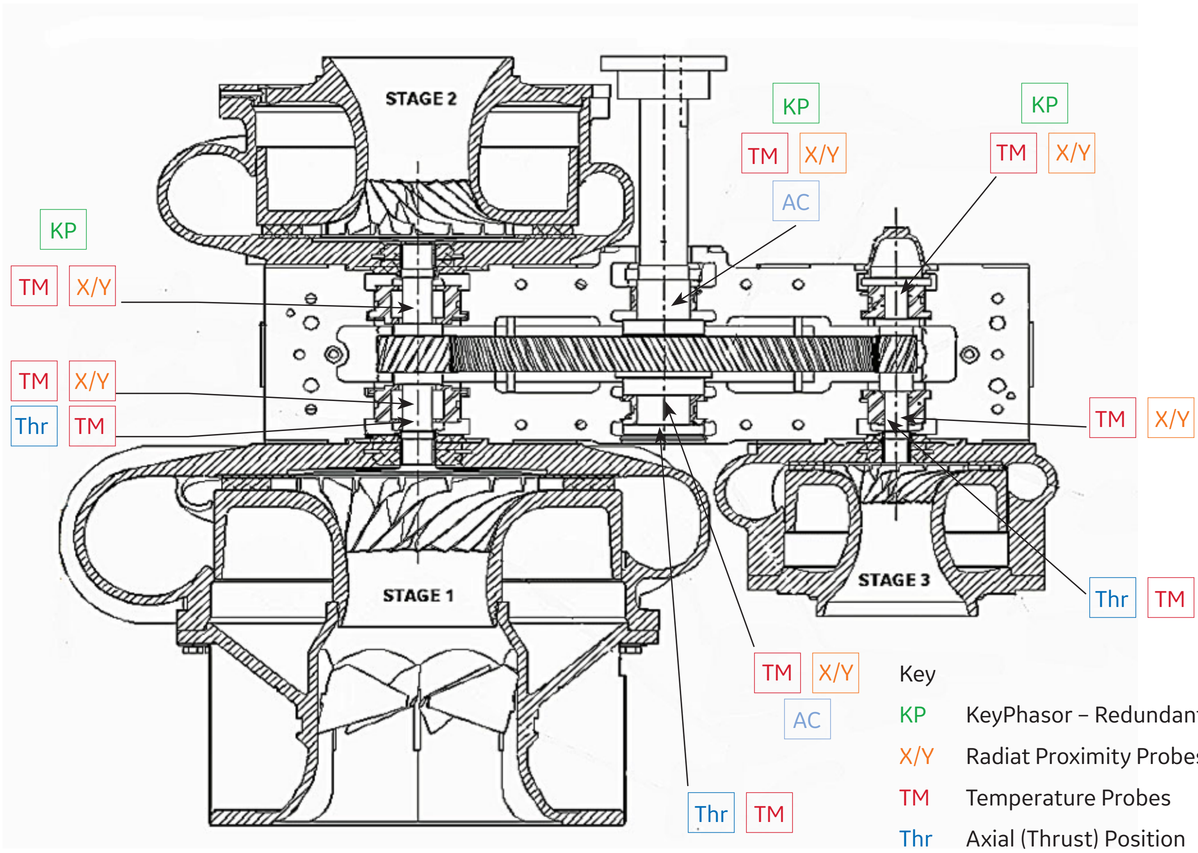
Note: *For details about the configuration of the various modules and settings, please refer to the 3500 Installation and Setup manual.*

Slot No.	Transducer Location	Transducer Type	Monitor Type
SLOT 2	Compressor Inboard Radial Y	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	Compressor Inboard Radial X	3300 XL Proximity Probe	
	Compressor Outboard Radial Y	3300 XL Proximity Probe	
	Compressor Outboard Radial X	3300 XL Proximity Probe	
SLOT 3	Compressor Thrust A	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	Compressor Thrust B	3300 XL Proximity Probe	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
SLOT 4	Compressor Keyphasor A	3300 XL Proximity Probe	3500/50M Tachometer Module or 3500/25M Keyphasor Module
	Compressor Keyphasor B	3300 XL Proximity Probe	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
SLOT 5	Compressor Inboard Radial Temperature A	RTD Sensor (or T/C)	3500/60 or 3500/61 Temperature Monitor
	Compressor Inboard Radial Temperature B	RTD Sensor (or T/C)	
	Compressor Outboard Radial Temperature A	RTD Sensor (or T/C)	
	Compressor Outboard Radial Temperature B	RTD Sensor (or T/C)	
	Compressor Active Thrust Temperature A	RTD Sensor (or T/C)	
	Compressor Active Thrust Temperature B	RTD Sensor (or T/C)	
SLOT 6	Compressor Inactive Thrust Temperature A	RTD Sensor (or T/C)	3500/60 or 3500/61 Temperature Monitor
	Compressor Inactive Thrust Temperature B	RTD Sensor (or T/C)	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	

Table 1. Axial flow and centrifugal compressors

Note: *All possible transducers are shown in table above, but not all transducers may be installed in any given installation.*

9.3.8 Vibration Instrumentation Diagram for Integrally Geared Compressor (3 or 4 stage)



Key

KP	KeyPhasor – Redundant
X/Y	Radiat Proximity Probes – Dual
TM	Temperature Probes
Thr	Axial (Thrust) Position
AC	Accelerometers – Single

Recommended rack layout for integrally-geared compressors

Note: *For details about the configuration of the various modules and settings, please refer to the 3500 Installation and Setup manual.*

Slot No.	Transducer Location	Transducer Type	Monitor Type
SLOT 2	Compressor Bull Gear Inboard Radial Y	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	Compressor Bull Gear Inboard Radial X	3300 XL Proximity Probe	
	Compressor Bull Gear Outboard Radial Y	3300 XL Proximity Probe	
	Compressor Bull Gear Outboard Radial X	3300 XL Proximity Probe	
SLOT 3	First Stage Compressor Bearing Radial Y	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	First Stage Compressor Bearing Radial X	3300 XL Proximity Probe	
	Second Stage Compressor Bearing Radial Y	3300 XL Proximity Probe	
	Second Stage Compressor Bearing Radial X	3300 XL Proximity Probe	
SLOT 4	Third Stage Compressor Bearing Radial Y	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	Third Stage Compressor Bearing Radial X	3300 XL Proximity Probe	
	Fourth Stage Compressor Bearing Radial Y	3300 XL Proximity Probe	
	Fourth Stage Compressor Bearing Radial X	3300 XL Proximity Probe	
SLOT 5	First/Second Stage Compressor Pinion Thrust A	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	First/Second Stage Compressor Pinion Thrust B	3300 XL Proximity Probe	
	Third/Fourth Stage Compressor Pinion Thrust A	3300 XL Proximity Probe	
	Third/Fourth Stage Compressor Pinion Thrust B	3300 XL Proximity Probe	
SLOT 6	Compressor Bull Gear Thrust A	3300 XL Proximity Probe	3500/40M Proximitor Monitor or 3500/42M Proximitor/Seismic Monitor
	Compressor Bull Gear Thrust B	3300 XL Proximity Probe	
	(Empty Channel)	N/A	
	(Empty Channel)	N/A	
SLOT 7	Compressor Bull Gear Accelerometer A	330400 Accelerometer	3500/42M Proximitor/Seismic Monitor
	Compressor Bull Gear Accelerometer B	330400 Accelerometer	
	Compressor Bull Gear Accelerometer A (Integrated)	330400 Accelerometer	
	Compressor Bull Gear Accelerometer B (Integrated)	330400 Accelerometer	
SLOT 8 (Upper)	Compressor Bull Gear Keyphasor	3300 XL Proximity Probe	3500/50M 3500/25M Keyphasor Module (Upper)
	First/Second Stage Compressor Pinion Keyphasor	3300 XL Proximity Probe	
SLOT 8 (Lower)	Third/Fourth Stage Compressor Pinion Keyphasor	3300 XL Proximity Probe	3500/25M Keyphasor Module (Lower)
	(Empty Channel)	N/A	
SLOT 9	Compressor Bull Gear Inboard Radial Bearing Temperature	RTD Sensor (or T/C)	3500/60 or 3500/61 Temperature
	Compressor Bull Gear Outboard Radial Bearing Temperature	RTD Sensor (or T/C)	
	Compressor First Stage Radial Bearing Temperature	RTD Sensor (or T/C)	
	Compressor Second Stage Radial Bearing Temperature	RTD Sensor (or T/C)	
	Compressor Third Stage Radial Bearing Temperature	RTD Sensor (or T/C)	
	Compressor Fourth Stage Radial Bearing Temperature	RTD Sensor (or T/C)	

Table 2. Integral Gear Compressors

Notes:

- *All possible transducers are shown in the table above, but not all transducers may be installed in any given installation (thrust measurements are shown on the two pinion gears, but are not configured in the table above.)*
- *When only one or two Keyphasor transducers are installed per rack, the 3500/50M tachometer module could be used.*

Best practice recommendations (cabinets)

Best practice for the installation of 3500 racks is placement in a standard industrial Rittal TS-8 series cabinet (800w x 800d x 2200h). The cabinet should be located inside a clean, climate-controlled room. Refer to document GEA-17562 for further information on 3500 installation, cabinets and integration.

10 The Industrial Internet

GE's new focus is about the convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet. It's about how the deeper meshing of the digital world with the world of machines holds the potential to bring about profound transformation to global industry, and in turn to many aspects of daily life, including the way many of us do our jobs. It's fundamentally about data – **Big Data** – and how it transforms and even revitalizes the dirty work of manufacturing, transportation, and energy production.

11 Management with System 1 Software

11.1 Overview of System1 Condition Monitoring and Diagnostics Platform

Widely used across many industries, System 1 condition monitoring software enables plant personnel to quickly identify important events, evaluate the situation, and respond. These abilities lead to increased equipment availability, enhanced reliability, and reduced maintenance costs.

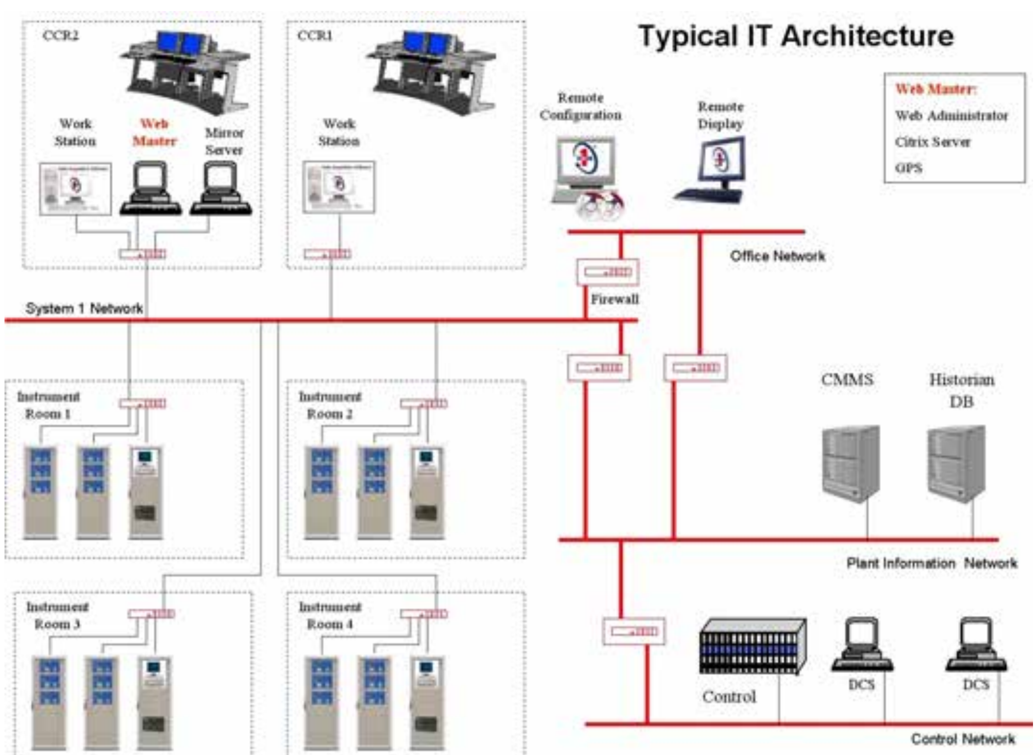
System 1 is GE's patented condition monitoring software platform for real-time optimization of equipment and selected processes, condition monitoring, and event diagnostics. Similar in concept to a process control system that allows users to understand, diagnose, and control their process conditions in real time, the System 1 platform provides this capability for the assets that drive your process.

Following is typical layout showing how System 1 software inter-relates with other devices in a plant environment network.

Section 7 of this document references typical machinery malfunctions associated with compressors, including System 1 software plots that are used to identify the various malfunctions.

Refer to Appendix 1 for further information regarding System 1 software and network connectivity .

For additional technical details regarding System 1 software, please consult the Installation Quick Start Guide (Part Number 181136, Rev. J (03/12)).



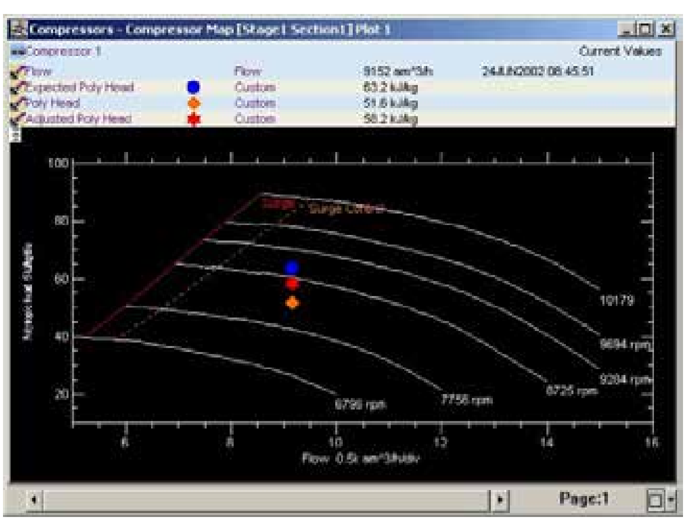
11.2 Thermodynamic Performance

Early phase degradation of critical process compressors is determined by thermodynamic machine performance. GE's Bently PERFORMANCE* SE* software extends System 1 software system functionality by providing online, real-time continuous calculation of machinery performance parameters. A graphical user interface displays performance cures and calculated performance parameters. Thermodynamic performance monitoring helps:

- Improve overall production capability
- Control costs through optimized maintenance activities
- Improve diagnostics and decision making
- Automate data analysis and advisories
- Provide fast and easy combustion problem diagnostics

Bently PERFORMANCE SE software integrates with System 1 software to display information about the condition of machines in combined mechanical and thermodynamic data presentations.

The Compressor Performance Module is available in versions suitable for single and multi-stage centrifugal compressors, axial compressors, and blowers. Gas calculations are performed using industry accepted computational methods with real gas equations of state for single gases and complex gas mixtures. Compressors with side load and side stream flows can be accommodated with section performance calculations as required. Design performance data is used to create a database from which expected performance is calculated and compared with actual performance. Available compressor performance indicators are isentropic and polytropic head, discharge pressure, and pressure ratio for variable speed and inlet volume flow. Isentropic and polytropic efficiency and gas (internal) power are also calculated for current operating conditions and compared to expected values.



11.3 Automated Machinery Diagnostic Functionality

Pre-configured diagnostic RulePaks automate the compressor failure mode and anomaly detection process within the machinery management system. A RulePak is a set of extraction, calculation, and diagnostic rules that work together to analyze static and dynamic data in real time. This real-time analysis provides continuous asset health feedback to the user.

Designed specifically to work with System 1 software, the RulePaks present System 1 supplied mission critical data in an actionable format. Conceptually, a RulePak can be thought of as a black box, with inputs coming in on one side and diagnostic results coming out the other. When an event occurs, these diagnostic results can trigger notifications to machine operators that indicate how severe the issue is, and provide suggested actions to mitigate the issue.

11.4 Centrifugal Compressor RulePak

The centrifugal compressor advanced RulePak contains algorithms that help diagnose the following machine malfunctions:

Anomaly	Description
Compressor Surge	The compressor is operating at flow rates significantly below the design flow rate, causing vibration and possible flow reversals
Compressor Near Surge	The compressor is operating near surge limits, based on pressure ratios and flow
Compressor Stall	The compressor is operating at flow rates significantly below the design flow rate
Whirl	Fluid induced instability is causing lateral rotor vibrations
Whip	Severe fluid induced instability is causing lateral rotor vibrations at one or more resonances
General Radial Preload	A unidirectional, steady-state force on a rotor is causing rotor operation at high eccentricity within the seal or bearing clearance boundaries
1X Runout	The slow roll vector magnitude exceeds the recommended level, indicating a non-concentric rotor surface at the plane of measurement
Sub-synchronous Rub	Rotor contact with a stationary part excites sub-synchronous radial vibration characteristics
Super-synchronous Rub	Rotor contact with a stationary part excites super-synchronous radial vibration characteristics
Synchronous Rub	Thermal rotor bow is induced by rotor-to-stator rub (Newkirk effect) or differential viscous shearing within the bearing (Morton effect)
Loose Rotating Part	Changes in the synchronous behavior of the rotor due to rotating elements coming loose *Example: Shrink fit elements losing the frictional force required to keep them locked onto the shaft*
Synchronous Rub or Loose Rotating Part	Non-specific determination of either a synchronous rub or a loose part
High Synchronous Vibration	Excessive vibration at running speed
Misalignment	Misaligned rotors between coupled machines
Rotor Bow	Bent rotor shaft

11.5 Axial Flow Compressor RulePak

The axial compressor advanced RulePak contains algorithms that diagnose the following machine malfunctions:

Anomaly	Description
Compressor Surge	The compressor is operating at flow rates significantly below the design flow rate, causing vibration and possible flow reversals
Compressor Near Surge	The compressor is operating near surge limits, based on pressure ratios and flow
Compressor Stall	The compressor is operating at flow rates significantly below design flow rate
Whirl	Fluid induced instability is causing lateral rotor vibrations
Whip	Severe fluid induced instability is causing lateral rotor vibrations at one or more resonances
General Radial Preload	A unidirectional, steady-state force on a rotor is causing rotor operation at high eccentricity within the seal or bearing clearance boundaries
1X Runout	Slow roll vector magnitude exceeds the recommended level, indicating a non-concentric rotor surface at the plane of measurement
Sub-synchronous Rub	Rotor contact with a stationary part excites sub-synchronous radial vibration characteristics
Super-synchronous Rub	Rotor contact with a stationary part excites super-synchronous radial vibration characteristics
Synchronous Rub	Thermal rotor bow is induced by rotor-to-stator rub (Newkirk effect) or differential viscous shearing within the bearing (Morton effect)
Loose Rotating Part	Changes in the synchronous behavior of the rotor due to rotating elements coming loose *Example: Shrink fit elements losing the frictional force required to keep them locked onto the shaft*
Synchronous Rub or Loose Rotating Part	Non-specific determination of either a synchronous rub or a loose part
High Synchronous Vibration	Excessive vibration at running speed
Misalignment	Misaligned rotors between coupled machines
Rotor Bow	Bent rotor shaft

11.6 Integral Gear Compressor RulePak

The integral gear compressor (IGC) RulePak contains algorithms that diagnose the following machine malfunctions:

Anomaly	Description
Compressor Surge	The compressor is operating at flow rates significantly below the design flow rate, causing vibration and possible flow reversals
Compressor Near Surge	The compressor is operating near surge limits, based on pressure ratios and flow
Compressor Stall	The compressor is operating at flow rates significantly below the design flow rate.
Gear Mesh	High vibration occurs at the frequency of the gear tooth mesh
Whirl	Fluid induced instability is causing lateral rotor vibrations
Whip	Severe fluid induced instability is causing lateral rotor vibrations at one or more resonances
General Radial Preload	A unidirectional, steady-state force on a rotor is causing rotor operation at high eccentricity within the seal or bearing clearance boundaries
Radial Preload—IGC Pinion Shaft	A unidirectional, steady-state force on a rotor is causing rotor operation at an irregular shaft centerline position
Rotor 1X Runout	Slow roll vector magnitude is greater than 40 percent of the compensated 1X vector, indicating a non-concentric rotor surface at the plane of measurement
Sub-synchronous Rub	Rotor contact with a stationary part excites sub-synchronous radial vibration characteristics
Super synchronous Rub	Rotor contact with a stationary part excites super-synchronous radial vibration characteristics
Synchronous Rub	Thermal rotor bow is induced by rotor-to-stator rub (Newkirk effect) or differential viscous shearing within the bearing (Morton effect)
Loose Rotating Part	Changes in the synchronous behavior of the rotor due to rotating elements coming loose *Example: Shrink fit elements losing the frictional force required to keep them locked onto the shaft*
Synchronous Rub or Loose Rotating Part	Non-specific determination of either a synchronous rub or a loose part
High Synchronous Vibration	Excessive vibration at running speed
Misalignment Possible Misalignment	Misaligned rotors between coupled machines
Rotor Bow	Bent rotor shaft

12 SmartSignal Integration

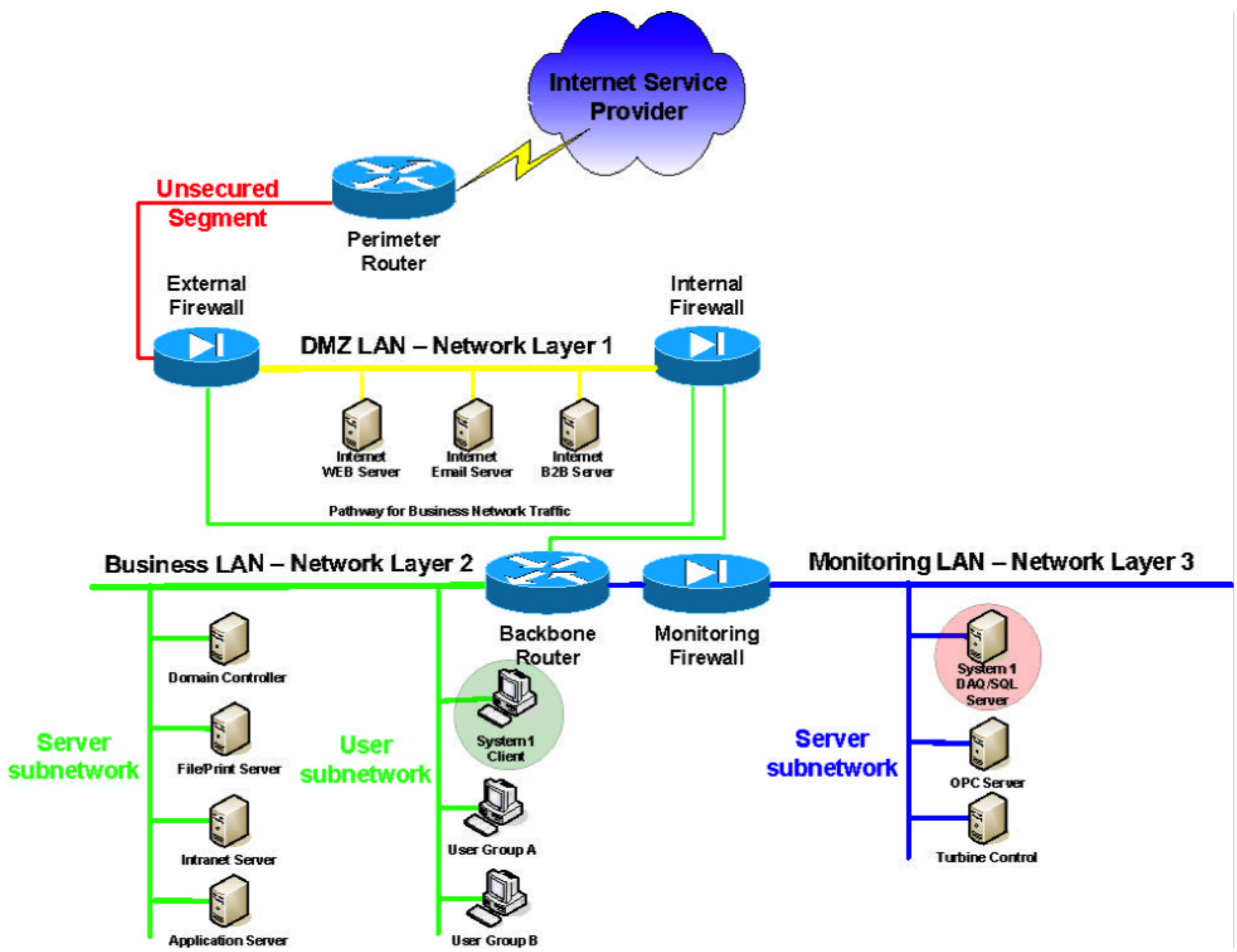
As part of any plant-wide monitoring solution, we recommend that compressors be tied into GE's SmartSignal predictive analytics software for the earliest possible notification of changes that indicate operation outside of normal parameters. Because SmartSignal software uses similarity-based modeling to warn of the smallest changes in machine behavior in any area (process, vibration, or electrical), it is an important tool underlying the foundation of the condition monitoring program. Note that SmartSignal software is an early warning/detection tool, while System 1 software is a detailed diagnostics tool.

	SmartSignal Early Warning for Compressors	Key Equipment Failure Modes									
		Performance	Efficiency Loss	Bearing Failures	Rotating Part Failure	Lubrication	Mech Damage/Wear	Leakage/Seal Failures	Fouling	Process Deviations	Intercooler
Machine Type	Centrifugal Compressors	●	●	●	●	●	●	●	●	●	●
	Axial Compressors	●	●	●	●	●	●	·	●	●	·
	Integrally Geared Compressors	●	●	●	●	●	●	●	●	●	●
	(Gearboxes)	·	·	●	●	●	●	·	·	●	·

APPENDIX 1 System 1 Software and Network Connectivity

System 1 communication across Network layers

The customer's information technology (IT) department typically defines network layers. Layers are often separated by functionality. Here is one example of a layer scheme:



- Layer 3 network for machinery monitoring/control equipment
- Layer 2 network for customer business needs like file sharing, corporate email, and Intranet applications
- Layer 1 network for the customer's Internet access, public websites, and business-to-business applications

Network devices such as routers, firewalls, and switches are common solutions used to physically separate the network layers. These devices may impose restrictions on the types of network communications allowed to cross the network layers. For example, between Layer 2 and Layer 1 (as shown above) the restrictions may only allow HTTP (web access), SMTP (email access), and FTP (file transfer) communication. This list is not comprehensive, but outlines some common restrictions in use on firewalls and/or routers.

Network Address Translation (NAT) – NAT is a technology to mask the IP address in network communications. The source and destination IP addresses are changed based on some pre-defined rules.

TCP/UDP Port Blocking – Some network devices have the ability to block traffic according to which port number it is using. If port 80 is blocked at a router, typical web browsing would not be possible as all requests for port 80 passing through the router would be discarded.

One-way Communication Rules – Some network devices have the ability to restrict network communication in a single direction – from Network Layer 2 to Layer 1, but not from Network Layer 1 to Layer 2.

Network Broadcasting – Network broadcasting involves network communication without a specific target destination. The requesting application asks a blanket statement such as “Are there any SQL Servers on my network?” It is common to prohibit this type of behavior across network layers.

Firewalls – A firewall is a system designed to prevent unauthorized access to or from a private network. Firewalls can be implemented in both hardware and software, or a combination of both. Firewalls are frequently used to prevent unauthorized Internet users from accessing private networks connected to the Internet, especially intranets. All messages entering or leaving the intranet pass through the firewall, which examines each message and blocks those that do not meet the specified security criteria. To control the flow of traffic, numbered ports in the firewall are either opened or closed to types of packets. The firewall typically considers the following transmission details for each packet:

- Destination port
- Source IP address
- Destination IP address

Some firewalls also consider protocol. If the firewall is configured to accept the specified protocol through the targeted port, the packet is allowed to enter.

UDP and TCP/IP

Some frequently used terms in this section include the following:

User Datagram Protocol (UDP) – This is a connectionless protocol that, like TCP, runs on top of IP networks. Unlike TCP/IP, UDP/IP provides very few error recovery services, offering instead a direct way to send and receive datagram packets over an IP network. It's used primarily for broadcasting messages over a network.

Transmission Control Protocol/Internet Protocol (TCP/IP) – This suite of communications protocols is used to connect hosts on the Internet. TCP/IP uses several protocols, and the two main ones are TCP and IP. TCP/IP is built into the UNIX operating system and is used by the Internet, making it the de facto standard for transmitting data over networks. Even network operating systems that have their own protocols, such as Netware, also support TCP/IP.

Directional Reference (Inbound Vs. Outbound) – In this document, inbound connections refer to the connections from the un-trusted side of the firewall to the trusted side. Outbound connections refer to the connections in the opposite direction – from trusted to un-trusted.

APPENDIX 2 RulePaks Process Inputs

The following table defines the process measurement inputs used by the RulePaks:

Measurement	Value	Req	Opt
Inlet Pressure	Pressure	✔	
Inlet Pressure Backup	Pressure		✘
Discharge Pressure	Pressure	✔	
Discharge Pressure Backup	Pressure		✘
Control Setting Angle	Degrees or Radians Closed	✔	
Inlet Flow Rate	Volumetric Flow	✔	
Inlet Flow Rate Backup	Volumetric Flow		✘
Bearing Metal Temperature[1]	Temperature	✔	
Bearing Metal Temp Backup #1	Temperature		✘
Bearing Metal Temp Backup #2	Temperature		✘

Note: *System1 Software provides all the information for a qualified diagnostician to perform the analyses performed in the RulePaks above.*

[1] *Metal temperatures for each bearing*

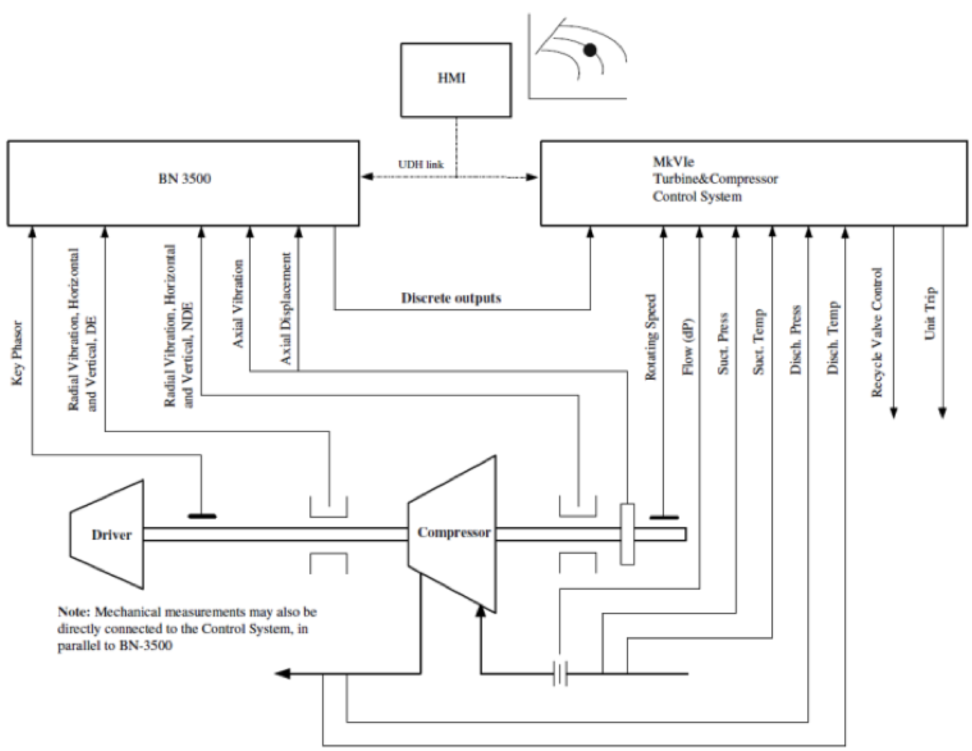
APPENDIX 3 OpitComp*-BN

The OptiComp-BN integrated turbine and compressor control solution delivers advanced compressor surge control, process performance control, load sharing/balancing, auto sequencing, and other auxiliary controls. In many cases, mechanical measurements of the radial vibration and axial vibration and displacement of the compressor rotor can show a clear indication of surge and incipient surge. Therefore, correlating the appearance of mechanical signs of surge with the process instability can help differentiate between normal operation and surging, significantly improving detection of surge and incipient surge.

OptiComp-BN combines thermodynamic and mechanical measurements in one integrated system. These measurements are used in algorithms designed to detect surge and incipient surge. OptiComp-BN can detect incipient surge when it is not visible by monitoring only the thermodynamic signals. Moreover, monitoring rapid changes in both radial and axial vibration and displacement signals, combined with any indication of process instability, significantly increases reliability in detecting surge cycles and surge severity. OptiComp-BN is applicable to GE's turbomachinery control, monitoring, and protection systems, which include the Speedtronic Mark* platform and Bently Nevada vibration monitoring.

OptiComp-BN provides the following benefits relative to traditional surge and incipient surge detection systems:

- **More reliable surge detection:** Mechanical and process monitoring enable you to avoid unnecessary process interruption.
- **Reduced risk of surging compressor and process shutdown:** Rotating stall detected and operators alarmed early; choose real-time manual or automatic response.
- **No need to cause compressor surge to establish field mapping of surge points:** Lower risk of compressor damage during commissioning; detect "stall" before surge
- **Risk assessment for continued operation:** Determine potential mechanical damage resulting from compressor surge.



OptiComp-BN Functional Diagram

I/O Points typically used in the OptiComp-BN system

	I/O Point Description	Notes
Process (Thermodynamic) Signals (per compressor section)		
1	Differential Pressure from Flow Measuring Device	Typically, most sensitive to compressor load changes. Used in anti-surge control algorithms, surge detection, performance calculations, diagnostics **Mandatory (see Note 1)**
2	Discharge Pressure	Used in anti-surge control algorithms, surge detection, performance calulations, diagnostics **Mandatory**
3	Suction Pressure	Used in antisurge control algorithms and surge detection, performance calculations, diagnostics **Mandatory**
4	Discharge Temperature	May be used in antisurge control algorithms. Used for performance calculations, diagnostics **Highly Recommended**
5	Suction Temperature	May be used in antisurge control algorithms. Used for performance calculations, diagnostics **Highly Recommended**
6	Compressor Shaft Rotating Speed	Used for start/stop sequencing, diagnostics **Mandatory for variable speed drives**
7	Motor Power	Applicable only to electric motor drive units. Used for start/stop sequencing, diagnostics **Mandatory for constant speed motors (see Note 1)**
Mark VIe Outputs		
	Modulating Output to Recycle (Blow-off) Valve	Typically, 4/20mA signal proportional to valve position **Mandatory**
	Solenoid Control of the Air to Recycle Valve Actualtor/ Positioner	Used to override modulating control signal and open to recycle valve **Optional**
	Unit trip on Multiple Surge Detection	Used to trip the unit if multiple surge cycles are detected within short period of time **Optional**
Mechanical Signals (per compressor case)		
1	NDE Radial Vibration, Horizontal	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
2	NDE Radial Vibration, Vertical	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
3	DE Radial Vibration, Horizontal	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
4	DE Radial Vibration, Vertical	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
5	Axial Displacement	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
6	Axial Vibration	Used by BN-3500 for alarm/trip. Used by OptiComp-BN to detect non-synchronous vibration **Mandatory for OptiComp-BN stall/surge detection**
7	Key Phasor	**Mandatory for BN-3500**
BN-3500 outputs for OptiComp		
	Discrete Output: Rotating Stall Detected	Used to signal rotating stall detection from BN-3500 to Mark VIe.
	Discrete Output: Surge Detected	Used to signal surge detection from BN-3500 to Mark VIe.

Appendix 4 Thermodynamic Performance Required Data

Air Compressors

Online Process Data:

- Ambient Pressure
- Ambient Temperature
- Relative Humidity
- Inlet Filter Delta Pressure
- Wet Bulb Temperature (Optional)
- Suction Volume Flow
- Suction Pressure
- Suction Temperature
- Discharge Volume Flow
- Discharge Pressure
- Discharge Temperature
- Speed

Composition of Gas Mixture:

- Gas Constituent #1
- Gas Constituent #2
- Gas Constituent #3

Motor Data:

- Input Power
- Input Voltage
- Input Current
- Input Power Factor
- Motor Efficiency
- Speed

Process Compressors

Online Process Data:

- Ambient Pressure
- Ambient Temperature
- Suction Volume Flow
- Suction Pressure
- Suction Temperature
- Discharge Volume Flow
- Discharge Pressure
- Discharge Temperature
- Speed

Composition of Gas Mixture:

- Gas Constituent #1
- Gas Constituent #2
- Gas Constituent #3

Motor Data:

- Input Power
- Input Voltage
- Input Current
- Input Power Factor
- Motor Efficiency
- Speed

Appendix 5 3500 Thrust Measurement and API 670 Compliance

The design of a monitoring system must strike a careful balance between false trips of the machine and missing conditions where the machine should be tripped. Obviously missing a machine trip can be a serious event, but it must be recognized that incorrectly tripping a machine is also an event that could compromise safety, especially considering the complex processes that most of the machinery covered by API 670 supports. In both missed trip and false trip cases safety may be compromised and there is the risk of potential negative financial impact to the end user.

API 670 Requirements

API 670 outlines requirements for axial position measurements, calling for paired channels. The requirement allows for one transducer signal (single voting logic, 1oo2) or two transducer signals (dual voting logic, 2oo2), to exceed the danger set point to initiate shutdown relay actuation. Specifically, with regard to 2oo2 dual voting logic applications, the standard indicates that shutdown relay actuation should occur when:

- Both axial position transducers or circuits fail
- One channel has failed and the other has exceeded its danger set point
- Both channels exceed the danger set point

Transducer System Faults

The axial position measurement is distinct from other measurements covered by API 670 due to the critical nature of the measurement and the possibility that the transducer element can be destroyed under extreme machinery conditions. In this case, there is the possibility that the probe target can shift suddenly in the direction of the probes with sufficient magnitude to make contact with, and destroy the transducer. This may occur before the monitoring system measurement is capable of detecting the sudden shift and generate a trip signal.

In this scenario, if the protection system were to defeat alarming upon probe failure, the alarming capability would be defeated at the time that the machine is experiencing what is highly likely to be an operating condition requiring shutdown – the very type of situation that the measurement is put in place to protect against. The possibility that the loss of a transducer is very likely to have been caused by the machine resulting in the overall protection function being defeated is what is fundamentally behind the standard's requirement to trip upon loss of protection circuit function.

Monitoring System Faults

The design of the 3500 monitoring system thrust channel type considers the protection circuit outlined in API 670 section 5.4.3, to only include the probe and transducer system which are susceptible to machine-induced faults. The 3500 system is capable of differentiating between faults that occur with the transducer system and those that occur in the monitoring system itself. While the system drives for trip in the case of a transducer system fault, a fault at the monitoring system does not. Rather than driving for machine trip, the system design annunciates the fault, providing an opportunity for plant personnel to respond to the problem condition.

A protection system designed such that it generates a trip signal in the event of a system fault condition has a significantly increased tendency for false tripping of the machine, unless the fault can credibly be linked to a machine emergency condition such as is the case with axial position transducers. If those elements of the monitoring system that are "out of harm's way" were to drive a trip relay actuation upon failure (single logic), or drive a vote for trip in dual voting logic, the system would contribute significantly to reducing machinery availability. This is especially relevant considering the relative complexity of a typical monitoring system's architecture.

In effectively all cases, a fault at the monitoring system will not coincide with, nor be driven by a safety critical machine operating condition. Unlike the transducer portion of the protection path, there are no known credible cases where the machine is capable of compromising, or generating a fault in the monitoring system. Therefore, to drive for a trip in the event of a monitoring system fault will result in a false machine trip in effectively all cases for single logic applications, and have serious potential negative impact on the availability of the machinery in dual logic cases.

To accommodate for the possibility of monitoring system faults, the monitoring system has extensive diagnostic capability to self-diagnose and annunciate internal faults. In the event of an internal monitoring system fault, the system responds by providing visibility to the condition by means of a number of mechanisms to annunciate the condition. This provides for a more effective alternative response to a fault than simply tripping the machine or voting to trip. Visibility mechanisms include, monitor LED states, monitor channel states (available in Modbus registers, local and remote system displays, and in System 1), 4 mA to 20 mA outputs, and the 3500 rack OK relay. These allow plant personnel to immediately be visually informed of a protection system malfunction so they can quickly attend to the problem. In the case of a single point monitoring system fault, the second channel supporting the recommended dual channel 1oo2 configuration continues to protect the machinery without the user suffering a false trip of the machinery and the associated safety risk and process interruption.

Summary

The axial position measurement is critical and is adapted to the application-specific possibility of a probe fault being induced by a catastrophic machinery condition. Due to this possibility, API 670 requires that a transducer system fault results in that path's protection relay actuation or voting for trip in dual logic applications. The 3500 system meets these requirements by driving for trip in the event of a transducer system malfunction.

The possibility of a catastrophic machinery condition compromising the protection function does not extend to the monitoring system portion of the protection path. Therefore the 3500 system does not generate a trip signal in the case of a monitoring system fault. The 3500 system configured for thrust measurement is capable of differentiating between a fault at the transducer level and one that occurs within the monitoring system itself. This allows the system to avoid false trips that may otherwise result from monitoring system malfunctions. The 3500 monitoring system internal diagnostic coverage and numerous fault annunciation methods all support the availability of the protection function by making the status of the monitoring system channels known to plant personnel in real time. The protection function is maintained without potentially compromising the availability of the monitored machine and associated process.

The Bently Nevada 3500 system's axial position measurement is compliant to API 670 4th edition requirements.

Appendix 6 Voting Truth Tables for Normal AND and True AND voting

A. True AND Voting - Radial Vibration

Trip logic: CHA_{danger} AND CHB_{danger} = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	NOT OK	NO ALARM
DANGER	DANGER	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	NO ALARM
NOT OK	DANGER	NO ALARM

B. True AND Voting - Radial Vibration with Not OK

Trip logic: CHA_{danger} OR $CHA_{Not\ OK}$ AND CHB_{danger} OR $CHB_{Not\ OK}$ = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	NOT OK	ALARM
DANGER	DANGER	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	ALARM
NOT OK	DANGER	ALARM

C. Normal AND Voting - Radial Vibration

Trip logic: CHA_{danger} AND CHB_{danger} = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	NOT OK	ALARM
DANGER	DANGER	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	NO ALARM
NOT OK	DANGER	ALARM

D. Normal AND Voting - Radial Vibration with Not OK

Trip logic: CHA_{danger} OR $CHA_{Not\ OK}$ AND CHB_{danger} OR $CHB_{Not\ OK}$ = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	NOT OK	ALARM
DANGER	DANGER	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	ALARM
NOT OK	DANGER	ALARM

E. Normal AND or True AND Voting - Thrust Position

Trip logic: CHA_{danger} AND CHB_{danger} = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	DANGER	ALARM
DANGER	NOT OK	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	ALARM
NOT OK	DANGER	ALARM

F. Normal AND or True AND Voting - Thrust Position with Not OK

Trip logic: CHA$_{danger}$ OR CHA$_{Not\ OK}$ AND CHB$_{danger}$ OR CH$_{Not\ OK}$ = Trip

Channel A	Channel B	Result
OK	OK	NO ALARM
OK	NOT OK	NO ALARM
OK	DANGER	NO ALARM
DANGER	OK	NO ALARM
DANGER	NOT OK	ALARM
DANGER	DANGER	ALARM
NOT OK	OK	NO ALARM
NOT OK	NOT OK	ALARM
NOT OK	DANGER	ALARM

3500 RV and TP Voting Observations

1. Four truth tables define voting an RV XY pair and two truth tables define voting a TP pair. These are:
   A. RV True AND
   B. RV True AND OR-ed with channel OK
   C. RV Normal AND
   D. RV Normal AND OR-ed with channel OK
   E. TP True AND as well as TP Normal AND (**note:** these are identical)
   F. TP True AND OR-ed with channel OK as well as TP Normal AND OR-ed with channel OK (note: these are identical)
2. Timed OK Channel Defeat (TOKCD) prevents a trip on simultaneous loss of OKs (such as lightening) for voted RV channels when OK is not OR-ed for both True and Normal voting (see Truth Tables A and C).
3. If RV is OR-ed with the channel OK, a Trip occurs (see Truth Tables B and D).
4. The nature of the TP measurement does not allow TOKCD to be applied to that measurement (see Appendix 5).
5. If TP is OR-ed with the opposite OK, the OR-ed OKs will trip upon a momentary instantaneous loss of OK (see Truth Table F). A long term loss of OK – for approximately 0.1 seconds or longer – will cause a trip as shown in the truth table.
6. If TP is not OR-ed with the OK (see Truth Table E), a momentary instantaneous loss of both transducer OKs will most likely not cause a trip because of the time required by the monitor to calculate perceived axial position shift and the normal 0.1 second TP time delay. A long term loss of both transducer OKs, greater than the 0.1 seconds, will result in a trip (see Truth Table E).

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