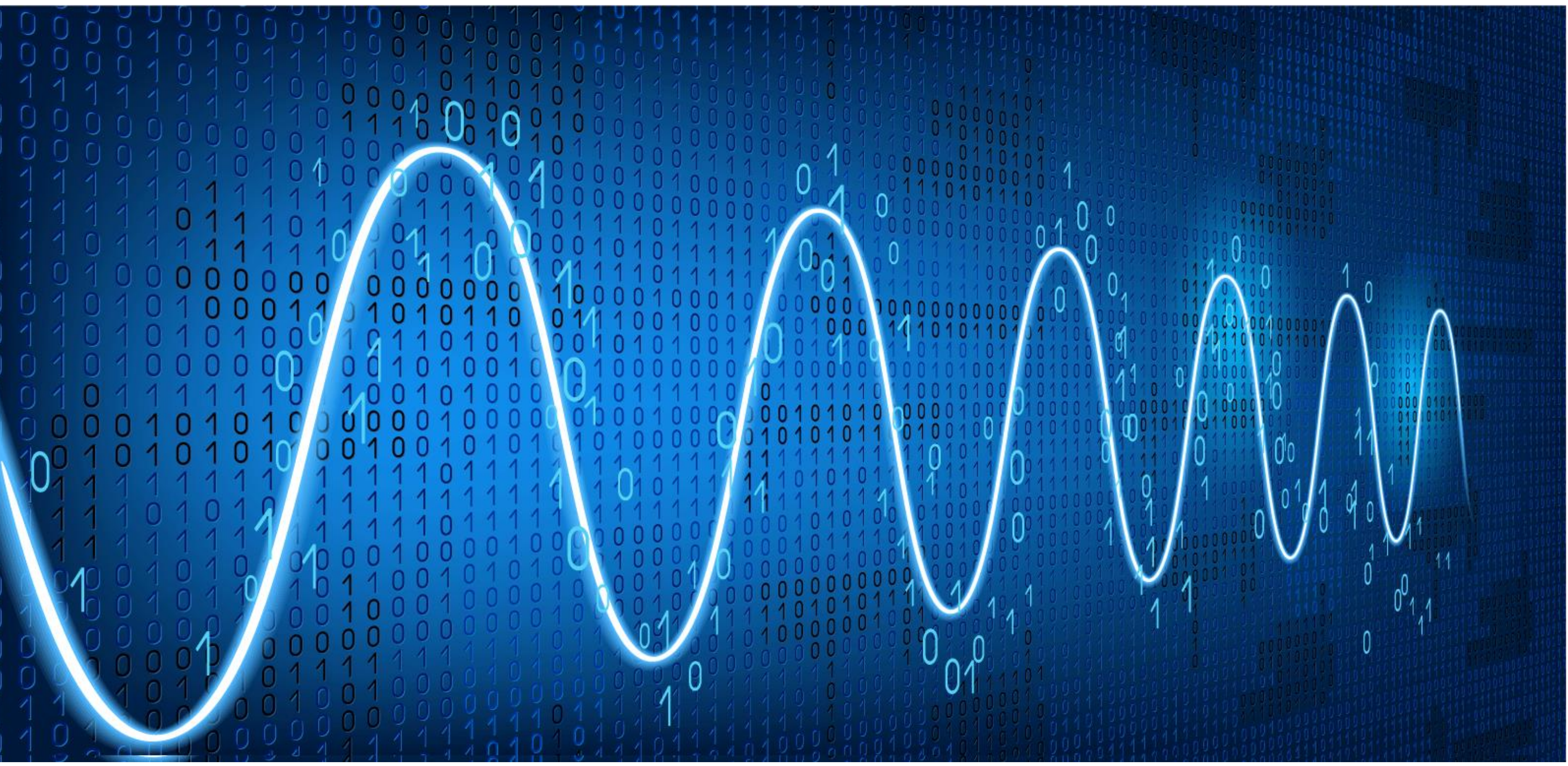
CENTRIFUGAL FANS AND VARIABLE FREQUENCY DRIVES

Risks and Mitigations



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INTRODUCTION

Variable frequency drives (VFDs) have become a preferred method of process control for electric motor driven equipment ranging from vertical water pumps to centrifugal air fans. Their use allows for a more energy efficient operation than controlling process flows with valves and dampers. However, the improper implementation of VFDs can lead to a number of other problems and increased maintenance costs. The following is a basic discussion of risks of using a VFD with direct driven centrifugal fans and methods of mitigating those risks to maintain equipment reliability.

DISCUSSION

Natural Frequencies

All objects have frequencies at which they tend to vibrate, called “natural frequencies.” If forced to vibrate at a natural frequency, an object will amplify the vibration to greater amplitudes. This forcing, or “excitation,” can be from the speed, or frequency, that a motor or fan rotates. An amplified vibration as a result of excitation of a natural frequency can cause catastrophic equipment failure. The Tacoma Narrows Bridge disaster is a notable example, where the bridge shook violently until it collapsed because the wind passing over it excited the bridge’s natural frequency.

Complex objects such as an electric motor driven fan have a number of different natural frequencies that need to be considered [1][2][3]. Fans that run at a single speed without a VFD are typically designed to run at a speed that does not excite any of the natural frequencies present in the fan assembly. When one of these fans is then run using a VFD, which operates at a wide range of running speeds, there is a risk that one of the possible new running speeds of the fan will excite a natural frequency [4].

Fan Wheels

Fan wheels have their own set of unique natural frequencies that can cause issues separate from the rest of the machine. The warping and bending of the side rings and fan blades at natural frequencies can cause failure of the fan wheel, resulting in imbalance and loss of process efficiency. Before the fan wheel fails, excessive vibration caused by operating at a natural frequency can often be detected in the fan bearings [1].

Equipment Base and Foundation

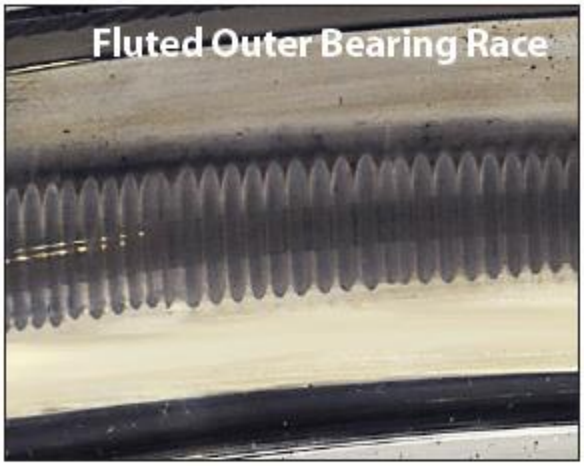
The foundation and base that the fan assembly rests on also has a unique set of natural frequencies. Similar to fan wheels, operating the equipment at one of these natural frequencies can cause failure of the base and foundation. However, because everything is directly mounted onto this part of the machine, vibration at a foundation's natural frequency can more easily cause excessive vibration in the fan bearings as well as in the motor [1][2].

System Ducting – Acoustic Natural Frequencies

When the vane pass frequency, or the running speed of the fan multiplied by the number of blades on the fan, matches the acoustic natural frequency of the ducting it feeds, the ducting can fail, resulting in process losses [3].

VFD Risks

Electrical Risk



The most common VFDs use Pulse Width Modulation (PWM) to modify the utility voltage wave. This method of frequency modification is achieved by essentially turning switches on and off very quickly to approximate an output voltage wave with a different frequency than the utility voltage wave. The higher the switching speed, the more closely the output wave approximates a pure sine wave, and the smoother the equipment runs as a result [5]. Low VFD switching speeds can generate unwanted vibration in the driven equipment. However, the switching action within a VFD generates voltage spikes, and the faster the switching speed, the larger the voltage spike [3][4][5]. Without proper insulation on the magnet coils in the motor, these voltage spikes can cause unexpected winding failure [5].

Another risk of stray voltage generated by VFDs is the presence of a motor shaft voltage. This will arc across the motor bearings, creating thousands of microscopic defects in the rolling elements and races which eventually results in a failed bearing with a pattern known as electrical fluting visible in the bearing races, shown in Figure 1 [6][7].

Small issues in the design and manufacture of VFD circuitry create variations, or harmonics, in the voltage waveform signal generated by the drive [4][5]. These harmonics have unwanted effects on the torque of the motor, making its running speed fluctuate if the effect is severe enough, creating noise. The voltage harmonics are also influenced by the total number of rectifiers in the drive circuit, which generates characteristic signatures in the voltage signal depending on that number. Typically, more rectifiers means higher frequency harmonics which have smaller effects on noise generated by the motor. The effects are exacerbated by the length of cable between the VFD and the motor. If there are two identical motors with identical drives but one has problems and the other does not, and the problematic motor has a longer cable, the length of cable is likely the source of the problems [5].

Operation Risk

If a VFD driven fan is connected with a common header to constant speed fans, there is a risk that the fan using a VFD would run slow enough to either be starved or be unable to generate enough air velocity to overcome reverse flow through its outlet produced by the other fans, effectively dead-heading the fan. In this situation, the VFD driven fan is running without contributing to the process flow.

Mitigation

Determination of Natural Frequencies

Avoiding exciting the natural frequencies of a centrifugal fan first requires determination of those natural frequencies. This information is often available, especially for the fan wheels, from the manufacturer of the fan. If this is not available, the first step in determining possible natural frequencies is typically conducting some type of impact test. The most basic type of test to get a rough estimate of the natural frequencies is referred to as a "bump" test. A bump test is done by simply impacting the fan using a block of wood or a dead blow hammer, which in turn causes the system to ring and you observe (or measure) the vibration response. Where the fan rings or vibrates the most will be at the Natural frequencies, so this is a quick and fairly simple rough evaluation. If bump testing does suggest that there is a natural frequency that could be problematic, then Impact or Modal Testing would be the next step. This involves placing accelerometers on the equipment at key locations to measure the system's response, and striking it with an instrumented force hammer. This allows you to accurately measure the resulting force/response vibration signatures and identify the natural frequencies of the fan (or system). The terms Impact testing and Modal testing are often interchanged however Modal testing is more involved since it includes not only the natural frequencies but also the vibration's associated deformation or "shape" typically shown as a 3D model. It is important to note that any type of Impact testing should only be performed *when the equipment is not running*.

If the equipment in question is already running using a VFD, other tests such as Start-up and Coast-down and negative averaging can be used to determine the critical speed and other natural frequencies of the fan wheel. Start-up and coast-down testing is best performed with a VFD to control the rate of speed change during equipment start-up and coast-down. Otherwise, without a reduced rate of speed change, fans often start up and coast down too quickly to collect useful data. This test involves using two, preferably 4, sensors on the fan shaft bearings separated by 90 degrees and a tachometer signal. Proximity probes can be used to generate a plot of the shaft's orbit. Sudden changes in the shape of the orbit at a given running speed would indicate a natural frequency. Velocity and acceleration sensors can be used to generate a Bode Plot which displays vibration amplitude and phase versus RPM. A significant increase in amplitude with a corresponding phase change indicates a natural frequency.

Equipment Design and Modification

If an output setting of a VFD driven fan makes the fan turn at or close to a natural frequency, there are a number of possible solutions. The first, and easiest, is to consider a programming change to keep the fan from operating at that speed for any significant period of time or to shift the speed setting away from the natural frequency. If, however, the process the fan is feeding requires the fan to run at a natural frequency, physical modifications would be required to shift the equipment's natural frequency away from the fan speed. Examples of typical modifications to change natural frequencies include adding mass and/or installing stiffeners [1][2][3]. Typically, it is more cost effective to stiffen equipment and supporting structures than to add mass. Figure 2 is an example where mass was added to a vertical pump motor to lower the natural frequency of the machine. Below are some general rules of thumb to help avoid equipment structures that would be prone to excessive vibration and natural frequency excitation [1][2].

1. Total weight of the foundation should be greater than 5x the weight of all the equipment supported on the foundation, including housings, ducts, and other structures. The foundation weight should never be less than 3x the equipment weight.
2. Total weight of the foundation should be at least 10x the weight of the rotating parts of the machine. The foundation weight should never be less than 6x the weight of rotating parts.
3. The width of the foundation should be at least 2x the distance measured from the base of the foundation to the center of gravity of the whole machine including the foundation.
4. The thickness of the foundation should be at least 33% of the clear distance between the inboard and outboard bearing pedestals.
5. The height to thickness ratio of the outboard bearing pedestal should not exceed 3. The flexural stiffness of the outboard bearing pedestal, assuming rigid constraint at the foundation, should be at least 5,000,000 lb/in in both the axial and horizontal directions.
6. The span/depth ratio of any beam that supports equipment should not be more than 10. For example, the minimum depth for a beam spanning 20 feet would be 24 inches (2 feet).
7. Web stiffeners should be provided in steel wide flange beams at all locations where equipment is bolted. Web stiffeners connect the upper and lower flanges of the beam. The web stiffeners increase torsional stiffness of the beam and minimize deformation of the flanges.
8. Lateral supports and bracing should be provided to yield a slenderness ratio no larger than 100 for any beam or column that supports a machine. Concrete floor slabs should not be considered as lateral support.
9. A deeper beam should never be framed into a shallower beam.

The above rules of thumb are not meant to replace engineering calculations, but only to serve as guidelines for identification of robust and reliable machine supports.

While faster switching speeds within a VFD smooth out inherent motor vibrations, the risk of electrical damage to the motor is increased. Therefore, an acceptable compromise must be found between elevated vibration due to slower switching speed and increased risk of electrical damage. However, the risks of electrical damage to motors and bearings can be reduced by doing the following [5][8]:

1. Ensure a motor to be driven by VFD has insulation rated for VFD applications.
2. Keep the cable length between the motor and the VFD to a minimum.
3. Use a shaft grounding device such as an Aegis Pro grounding ring.
4. Insulate motor bearings.

Operation

As mentioned above, one of the easier methods of avoiding exciting natural frequencies with a VFD is to prevent the VFD from running at a natural frequency for any significant amount of time. It is acceptable to allow the rotating speed of the equipment pass through natural frequencies to change output, but not to linger there.

To prevent inadvertently starving or dead-heading, at least one of the following should be done. First, it is ideal that all fans connected with common headers be driven the same way, either all fans using single-speed drives or all fans using VFDs [3]. Second, there should be a minimum speed set for VFD driven fans such that the minimum speed still allows the fan to avoid starvation or a dead-head condition.

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