Bookazine by Istec

SPEED

The protection of rotating machinery using speed measurements

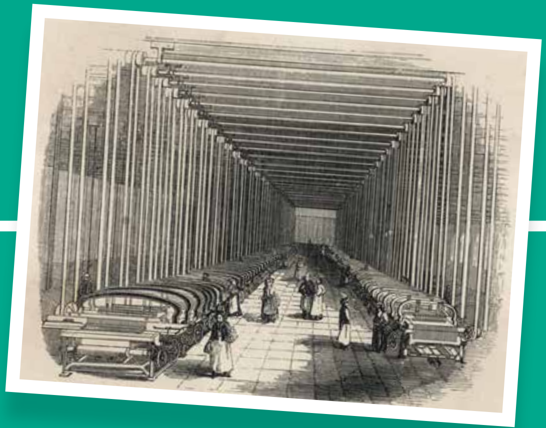
SPEED

First edition, May 2021

A brief history of speed measurements

Speed has been an important parameter for rotating machinery for centuries. Historically, it mostly served the purpose of finding the ideal operational speed to increase the production quality and efficiency. This required a solution, which has become known as the tachometer.

A tachometer is a measuring instrument that indicates the rotational speed of a shaft. The frequency that indicates the rotational speed is Hertz, the official SI-unit, but for vehicles and machines we usually work with revolutions per minute (RPM).



1817

Present

Future

History

The German engineer Diedrich Uhlhorn, best known for his invention of the coin press, developed the first mechanical tachometer in 1817. He could never have imagined that his invention would be used in every vehicle and on many machines.

Historical data shows that Uhlhorn did not originally develop the tachometer for vehicles but was looking for a solution to find the ideal operational speed for machines that were used for the spinning and weaving of cotton.

As with many inventions, the tachometer has become increasingly compact. Uhlhorn's tachometer must have been a bulky instrument; according to installation instruction documents; it was "mounted to the ceiling of the room". Around 1835, due to the rise of steam locomotives, tachometers grew increasingly relevant for vehicles and became a standardized instrument for locomotives.

Present

The first speed measurements were executed with mechanical tachometers, where the instrument had direct physical contact with the rotating object (e.g., a spinning wheel). Due to high maintenance costs and the demand for higher accuracy, a non-contact tachometer solution was sought. This led to the non-contact sensing technologies we use today; Hall-effect, eddy current and variable reluctance (VR).

Nowadays these measurement principles are incorporated in compact sensors and widely used in various industries to monitor and protect machines for (over)speed and acceleration. Increasing safety guidelines requires machinery with high rotational speed, such as turbines and compressors, to be protected by an overspeed protection system.

Future

Due to stricter requirements for speed monitoring and protection, speed measurements are becoming increasingly more important. As speed is often not a dedicated expertise within an organisation, the demand for systems and sensors offering simplicity and useability is growing. ■

1 Speed measurements on rotating machinery

2 Overspeed protection

3 Functional safety

4 Best practice guide

A guide for system and maintenance engineers about overspeed protection systems and speed measurements.

Preface

Before you lies our bookazine SPEED, a compilation of articles on the protection of rotating machinery using speed measurements. After the great success of VIBRATION, this is our second bookazine, and those of you who have read VIBRATION will recognize the format. With every book that is written, the publisher envisions a setting in which the reader could benefit from its contents. We focused on the engineers that are tasked with managing speed protection systems as part of a job description that is ever growing in both complexity and size. We hope to enrich their technical sources with accessible information and to provide them with the arguments to help their companies make solid decisions on speed protection.

In 1974, when our company was founded by my grandfather, it was all about the supply and technical support of Jaquet speed sensors and measurement systems. Throughout the years, we were involved in all aspects of these systems, including development, supply, engineering and consultancy. We played different roles as a distributor, integrator, consultant, and even a while as a branch office, but we have always stayed close to the end user. Now, at the date of writing, almost 50 years later, it is safe to say that speed measurements are at the roots of our company; it is a part of our DNA that helped us grow and grew with us.

Recently we went through another growth cycle with the development of SpeedSys®, a new generation of overspeed protection systems. This is a line of products that makes functional safety systems accessible to smaller rotating equipment, and increases overall plant protection levels, designed to meet the latest safety standards and incorporating our decades of field experience.

A special note of thanks to my father Dé, who has built the company to what it is today and laid the foundation for our ongoing developments and growth. His everlasting focus on quality of service has brought us the unique experience and expertise that we hold today.

I would also like to thank the Istec team for all their efforts in creating this bookazine. A special recognition to Michel and Daniël for their great editing and design work, and Koos and all other contributors for sharing their knowledge and experience.

I hope that this bookazine will provide you with valuable insights, and that you enjoy reading.

W. Verschuren

Wouter Verschuren
Managing Director

EDITOR'S NOTE: This bookazine is a compilation of our most popular articles and blog posts on the subject. It is not meant to be your new maintenance encyclopaedia and we do not claim it to be the complete story. However, we do hope that it supports the general awareness of the subject, offers a solid piece of information to those who are not familiar with it, and even provides some new insights to those who are. Read it like a magazine, choose the pieces you like and have fun.

Speed measurements on rotating machinery

1

What is speed and how do you measure it?

Speed can be defined as the rate at which an object changes its position, or as a ratio of the travelled distance within a certain timeframe. The parameter speed has a slightly different definition when related to rotating machinery, where we speak of rotational speed. Rotational speed is the rate at which an object rotates around a fixed axis and is expressed in the number of revolutions per minute (RPM). Measuring this type of speed is essential in every industry. This bookazine focusses solely on rotational speed measurements on rotating machinery.

Measuring rotational speed is quite complex as it is a high frequency dynamic measurement which can be subject to rapid changes. To measure rotational speed on rotating machinery, a speed sensor is used. There are different suitable types of sensors, which will be discussed later in this bookazine. Each speed sensor is contactless and uses a certain measurement principle to measure the rotational speed of a rotating object. These rotating objects must have teeth or slots for the sensors to be able to generate a speed signal.

Signal

The signals (pulses) of the speed sensor are sent to a speed measurement system, which converts it into a block signal for further processing.

Speed measurements are critical for both the protection and control of rotating machinery. Time is crucial when it comes to accurate measurements. Therefore, speed measurement systems count the time between pulses as opposed to counting the number of pulses after one revolution. ■

What is the purpose of speed measurements?

Speed is an essential parameter in the industry. When the rotational speed has been determined, several functions can be executed. The main functions are discussed:

Monitoring

Gaining insight into the rotational speed to validate the correct functioning of a process.

For practically every rotating machine, from small conveyor belts up to large turbines, the rotational speed is monitored.

Using a distributed control system (DCS), programmable logic controller (PLC) or local display, the values are monitored and the process can be verified with the measured speed value.

Controlling

Gaining insight into the rotational speed for process control.

Turbines and compressors typically have their own speed control system which controls the various stages of operation like start-up, operation, run-down and load control. During start-up, amongst others, it keeps the thermal expansion of turbines within its design limits and prevents running at resonance frequencies.

These systems also react to feedback from the DCS/PLC to optimise the process conditions of the machine.

Protecting

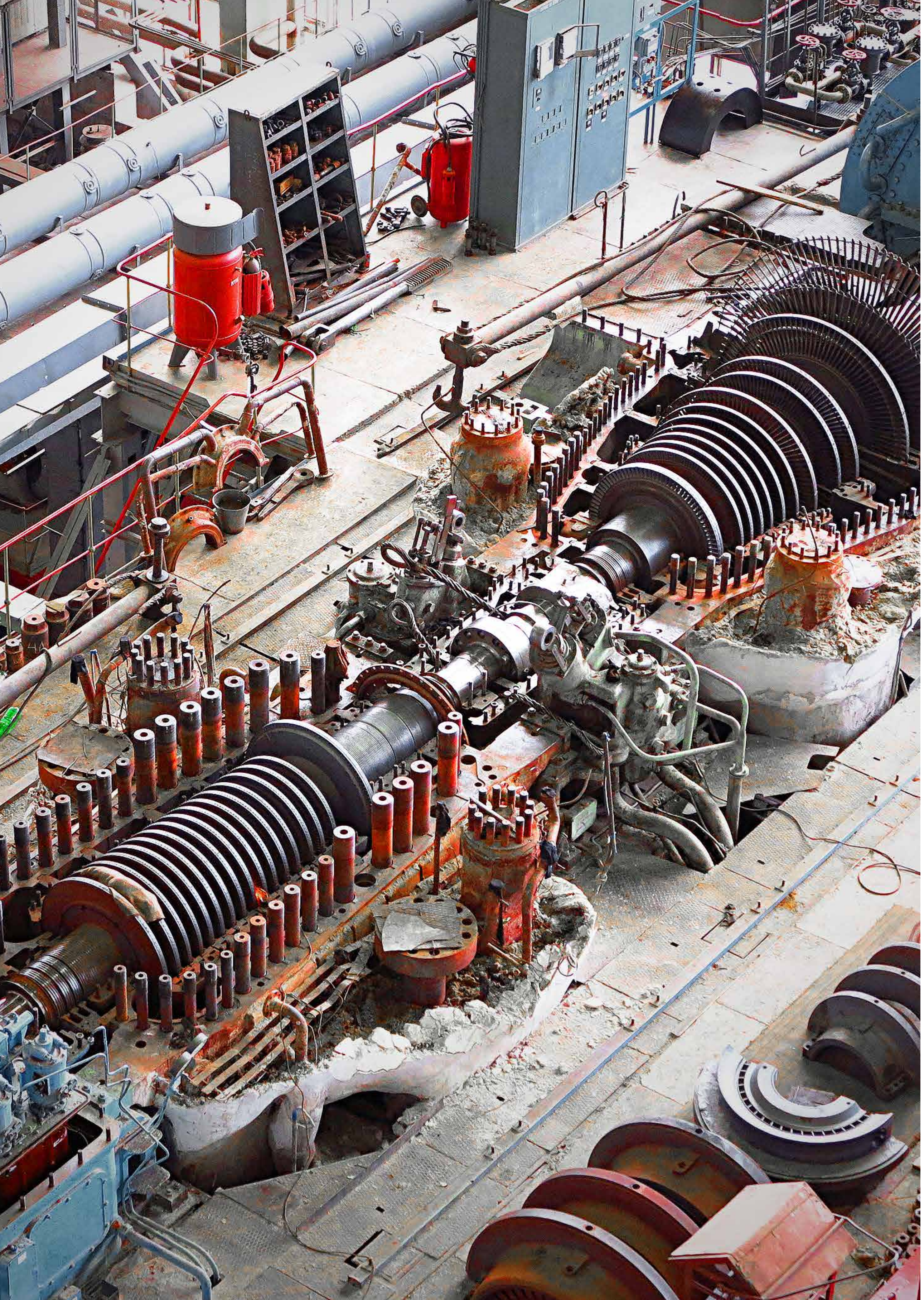
Gaining insight into the rotational speed to trip a machine when it runs too fast (overspeed) or accelerates excessively.

"An overspeed protection system tripping a machine is like a runaway truck ramp. Not ideal, but it's the last resort."

Machinery, such as turbines, and (some) compressors which, due to the nature of their process, can rapidly go into overspeed, are generally equipped with an overspeed protection system. When these machines operate with a rotational speed that is above their design specifications, it could lead to dangerous situations which should not be underestimated.

It could have catastrophic consequences for humans, the environment and the machinery. It is therefore essential that the overspeed protection system quickly detects and automatically intervenes when the machine runs or accelerates faster than allowed according to its design specifications. These protection systems are stand-alone systems to create an independent layer of protection. ■

Measuring speed has different functions in the industry. However, from this point forward, this bookazine focuses solely on speed measurements for protection purposes.



Speed-related conditions in rotating machinery

Rotating machinery such as turbines, pumps and compressors are continuously subjected to major mechanical forces. As most of these machines are critical to the process, systems are implemented with protection and/or monitoring functions to prevent failures. A few common speed-related conditions that may occur in rotating machinery are highlighted.

Speed protection

Overspeed

The construction of rotating machinery is designed to withstand a certain rotational speed. When overspeed occurs, the shaft of the machine rotates faster than the machine construction can withstand. The forces increase exponentially with the rotational speed which can cause parts to come loose. This could have a catastrophic impact on both the process, plant personnel, and the environment. Risk analyses therefore show that in most cases it is required to have a suitable overspeed protection system.

As mentioned in previous chapters, the rotational speed can be determined through speed measurements. An overspeed protection system ensures the rotational speed to stay within certain limits, to prevent damages to the machine. If the predefined limit values are exceeded, the machine is switched off (tripped) immediately (figure 1). These machine trips need to happen within a very short timeframe. According to the current machine guidelines and industry practices, overspeed protection systems must have a response time < 40 ms.

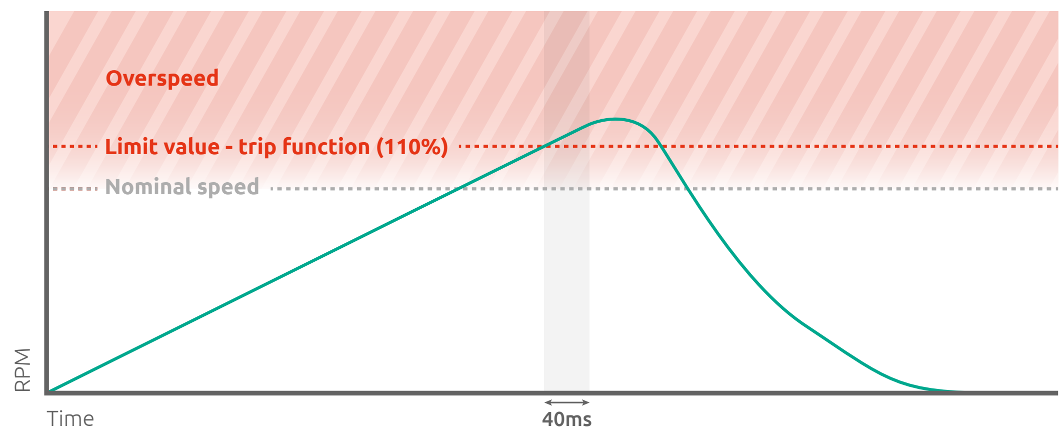


FIGURE 1 - THIS FIGURE SHOWS HOW A TRIP FUNCTION WORKS. AT 110% OF THE NOMINAL SPEED THE MACHINE IS TRIPPED, CAUSING AN IMMEDIATE SHUTDOWN.

Overspeed is the biggest fear of any operator of rotating machinery. Not responding in time or the malfunctioning of an overspeed protection system could cause turbine blades or rotor parts to come loose. In the worst case, these parts can penetrate the turbine housing, compromising personnel safety and causing major damage to the equipment powered by the turbine.

When the machine is tripped at its limit value of 110% of the nominal speed, the remaining energy in the machine can still cause it to accelerate further and exceed the limit value of 110% (figure 2). As a result, the machine reaches a critical rotational speed, with damage as a possible result.

Stopping the driver of a machine will not immediately lead to a decrease of the rotational speed

Acceleration

Excessive acceleration can cause a rotating machine to go into overspeed, and despite the present overspeed protection system, cause a dangerous situation. When an overspeed protection system detects excessive acceleration, it will take some time for the acceleration to disappear due to the driving force (fuel or steam) already available in the machine. During this short period, the machine could still reach a dangerous speed level. Therefore, it is essential to have in-depth knowledge of your machine and know which accelerations are acceptable at every speed.

During the start-up of a rotating machine, depending on the available energy, acceleration should be a protected parameter. Unlike with overspeed protection, acceleration protection does not only look at the rotational speed, but at the increase of the speed within a predetermined time frame. When the speed sensors detect an excessive acceleration increase, the protection system will trip the turbine.

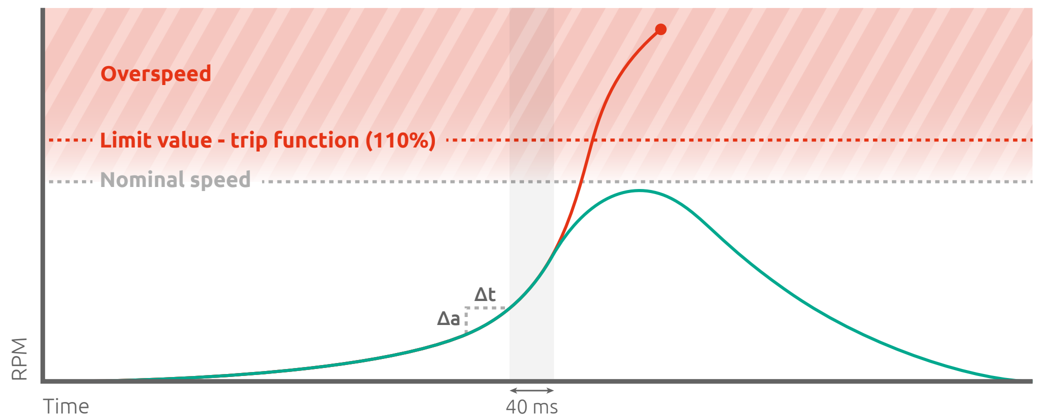


FIGURE 2 - THE GREEN LINE SHOWS HOW AN ACCELERATION TRIP FUNCTION WORKS.

When an excessive acceleration increase is detected, the protection system trips the machine. The red line shows what could happen when acceleration is not a protected parameter, making it unable to detect excessive acceleration. Even though the overspeed protection system will trip the machine (at 110% of the nominal speed), the machine may still increase its speed for a short while. For this reason, it is highly recommended to implement acceleration protection.

Speed monitoring

Reverse rotation

It may occur (e.g., in the case of a compressor driven turbine) that the pressure from the process causes a compressor to rotate in the wrong direction while the turbine that drives this compressor is in its run-down phase or when it is not operational. This is known as reverse rotation. This pressure can occur because the check valve does not close properly, causing a leak. As a result, the barring wheel can be damaged.

When the turbine is started up during this condition of the compressor, this can lead to damage. The speed that is built up because of reverse rotation and the speed from the turbine will counteract each other, which may cause damage to (e.g.) the coupling. This often concerns financial damage but does not pose a direct danger to personnel and the environment.

Standstill / Creep

It is important that a turbine is in an actual standstill situation before e.g., a turnaround or maintenance activities are started. After all, the enormous mass of a turbine could cause dangerous situations if maintenance work is started while the turbine is still rotating slowly. To monitor this, speed measurements must be made over a longer period than normal speed measurements because the turbine is running at a very low speed during its shutdown process.

Underspeed

Underspeed is the opposite of overspeed. To keep a process running, an installation must maintain a minimum rotational speed. The process can no longer be driven safely with a lower rotational speed. Even though underspeed is highly undesirable due to a disruption of the production process, it does not have the same catastrophic impact as overspeed. Limit values can be set to trigger an alarm when the minimum rotational speed to keep the process running is reached. This allows the operator to prevent underspeed from occurring. Underspeed measurements can also be used to indicate, for example, that a jog engine can be switched on. ■

Sensors for speed measurements

Choosing the right speed sensor for an application is of crucial importance for an accurate and reliable measurement. After all, the signal of the sensor is the input for an overspeed protection system. A faulty sensor leads to an unreliable input signal, which has a negative influence on the accuracy and reliability of the protection system.

There are several considerations that must be made to select the right sensor, which can be categorized in environmental and machine-related considerations.

Machine considerations:

1. What is the expected min and max speed?
2. What is the target that is measured and what are its specifications?
3. Are there any limitations on the weight and size at the mounting location?
4. What is the necessary cable length?

Environmental considerations:

5. What is the expected ambient temperature?
6. Does the measurement take place in explosion hazardous areas (ATEX)?
7. Are strong electromagnetic fields present?
8. Does the measurement take place in a corrosive environment?

For industrial speed measurements there are three main types of measurement principles:

- Variable reluctance (VR) sensors – also known as: passive sensors, electromagnetic sensors or magnetic pickup sensors (MPU).
- Eddy current sensors – also known as: proximity sensors or displacement sensors.
- Hall-effect sensors – also known as: active sensors.

Variable reluctance (VR) sensors

A VR sensor uses a magnetic field to measure changes in the distance between the sensor tip and the target object. The sensor contains a coil that is wrapped around a magnet which causes a change in the magnetic field (flux) and the coil as the teeth of a gear pass the sensor. The moving gear creates a varying flux that induces a voltage in the coil; the frequency of which is related to the rotational speed. The signal is a sinusoidal wave of which the amplitude is dependent on the target size, speed and distance.

Advantages

An advantage of VR sensors is their applicability to high-temperature applications. There are specific types of sensors that are suitable to function with temperatures of more than 300°C. Moreover, VR sensors are easy-to-use and highly reliable. Another advantage is that the sensor has a two-wire connection and therefore often fits within legacy infrastructures.

Best practice guide

Refer to the best practice guide for a detailed technical understanding of VR sensors.

Variable reluctance sensor → p 58

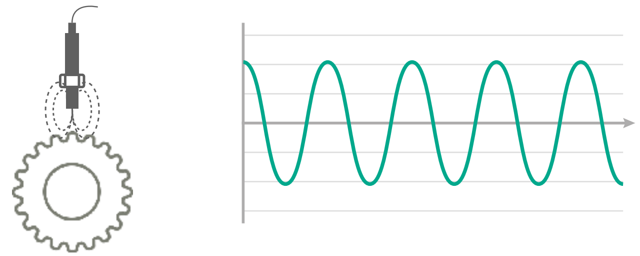


FIGURE 3 - A SINUSOIDAL OUTPUT SIGNAL FROM A VR SENSOR.

Disadvantages

A major disadvantage of VR sensors is that the amplitude of the signal depends on a factor of the size, speed and distance of the target. If the speed is too low, the gear tooth too small or the distance to the target material too big, the signal will be flattened and not usable. On the other hand, if the speed is high, the gear tooth large or the distance is small, the signal will show high pulses ($80V_{RMS}$). The application and positioning of VR sensors requires special attention and expertise to function properly. As these types of sensors do not function well with low speed, they are not suitable for low or zero-speed detection.

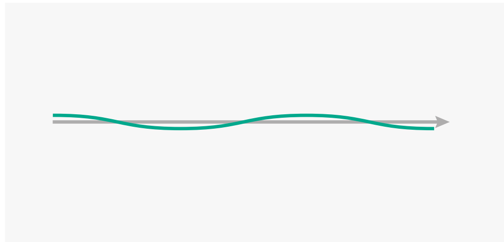


FIGURE 4 - WHEN THE SPEED IS TOO LOW, NO USABLE SIGNAL IS CREATED.

Eddy current (proximity)

An eddy current sensor uses an electromagnetic field to measure changes in the distance to an object. As a pole wheel moves past the sensor, it measures a variation in distance; close (tooth) and far (notch). The rotational speed can be determined based on the time between these events.

Best practice guide

Refer to the best practice guide for a detailed technical understanding of eddy current sensors.

Eddy current sensor → p 63

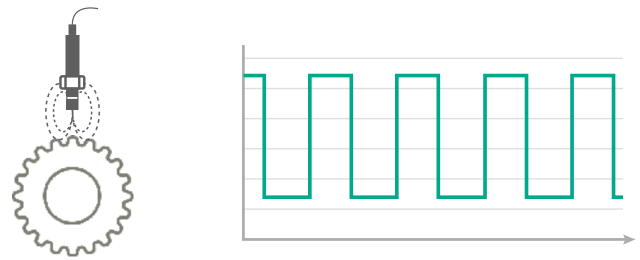


FIGURE 5 - AN EDDY CURRENT SENSOR ON A SLOTTED SPEED WHEEL GIVES A SQUARE WAVE OUTPUT SIGNAL.

Advantages

A major advantage of eddy current sensors is that the measuring principle shows both the pulses and the position with respect to the teeth. This provides insight into the set distance to the teeth of the target object.

Eddy current sensors are also available with a dynamic current output, which allows for long cabling (up to 1000m). Sensors with a dynamic current output are less affected by cable impedance as compared to Hall-effect sensors, eddy current sensors based on voltage signals, and VR sensors.

Disadvantages

The use of eddy current sensors for speed measurements has a disadvantage. At a high speed, saturation may occur, causing the signal shape to flatten increasingly. When the gear teeth move past the sensor at high speed, an eddy current sensor barely detects a difference in distances. The higher the frequency, the less effective an eddy current sensor will be for speed measurements.

Hall-effect sensors

A Hall-effect sensor measures changes in magnet's magnetic field, caused by the ferromagnetic target material. The sensors have built-in signal conditioners, which generate a clear square wave signal. In contrast to VR sensors, Hall-effect sensors are sensitive to the size of the magnetic flux rather than the speed at which it changes. Hall-effect speed sensors have a broad measurement range and can be used to measure both low-speed or stationary parts and high-speed parts.

> **Best practice guide**
> Refer to the best practice guide for a detailed technical understanding of Hall-effect sensors.
> **Hall-effect sensors → p 61**

Advantages

An advantage of a Hall-effect sensor is that the sensor directly provides a digital output which is easy to transmit and process. Another advantage is that Hall-effect sensors usually feature internal signal processing. The signal is digitalized and amplified, making it less susceptible to electromagnetic interferences (EMI).

Disadvantages

Due to built-in electronics, Hall-effect sensors are limited to applications that operate in temperatures ranging from -40 °C to +150 °C. Moreover, Hall-effect sensors require a 3-wire connection. Also, the trigger level is defined in the Hall-effect sensor and cannot be changed. ■

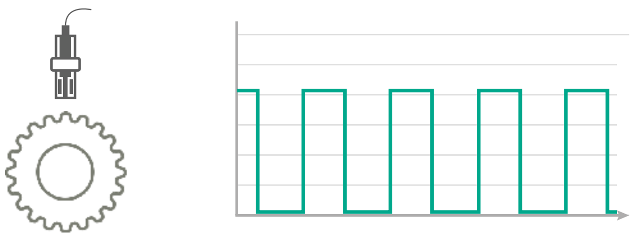
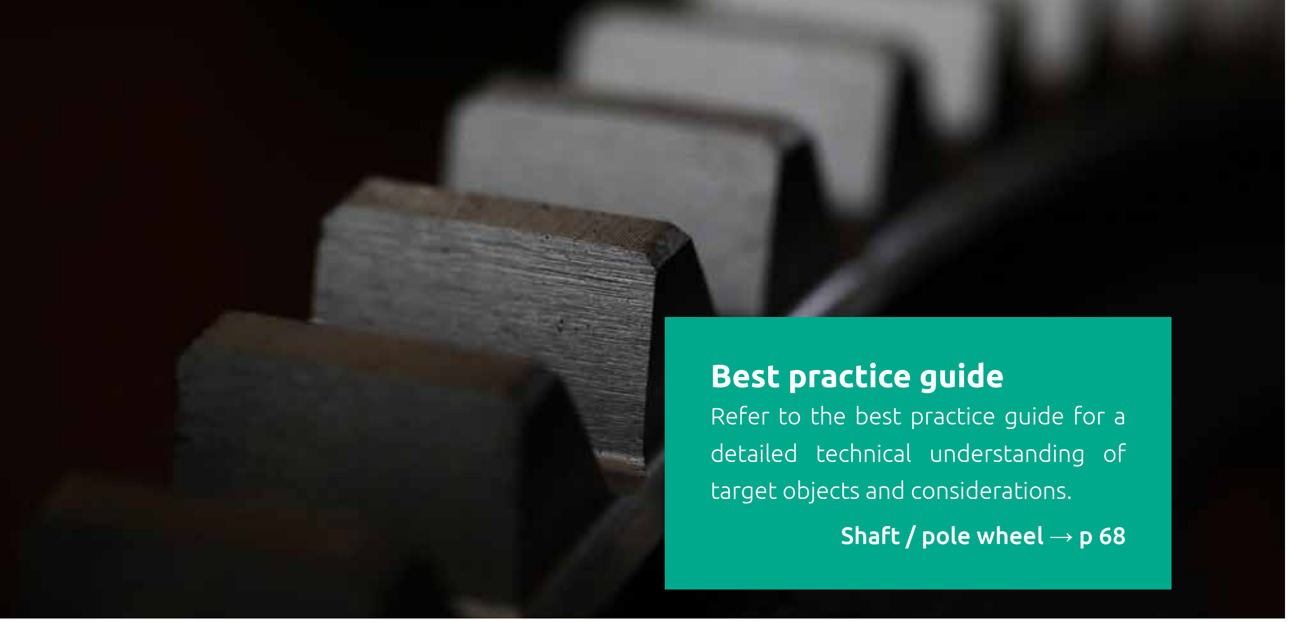


FIGURE 6 - A HALL-EFFECT SENSOR GENERATES A SQUARE WAVE OUTPUT SIGNAL.



Best practice guide

Refer to the best practice guide for a detailed technical understanding of target objects and considerations.

Shaft / pole wheel → p 68

Target objects of speed measurements

To measure the rotational speed of a shaft, it is necessary to use a suitable target for the contactless speed sensors to generate an accurate signal. In many cases an existing gear can be used for this, but when this is not present or within reach, there are various methods to enable speed measurements. Three different methods are described.

Pole wheel

A pole wheel can be used to perform speed measurements and supports both radial and axial measurements.

For radial measurements, the air gaps between the gear teeth are used to generate a speed signal. For axial measurements, the air gaps in the holes/notches of the pole wheel are used to generate a speed signal. Both the speed signals from axial and radial measurements are then used to calculate the rotational speed of the pole wheel, which is equivalent to the rotational speed of the shaft.

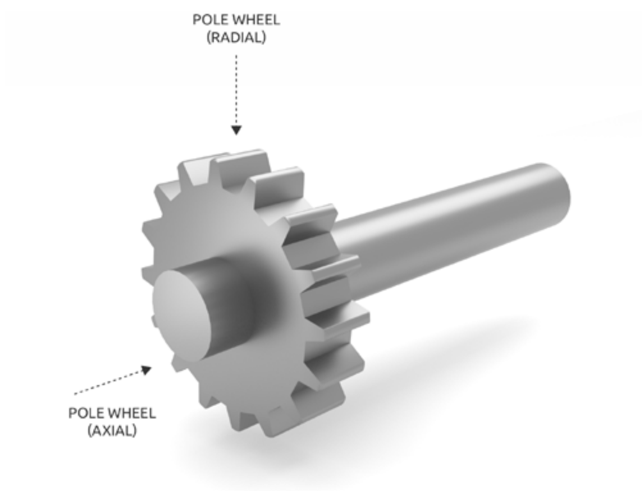


FIGURE 7 - THE RADIAL AND AXIAL MEASUREMENTS ON A POLE WHEEL.

Pole band

When a pole wheel is not an option due to the compact design of the machine, a pole band can be used instead. A pole band is mounted around the shaft and its profile has protrusions, notches or slots to be able to generate pulses. These pulses are used to calculate the rotational speed.

FIGURE 8 - A POLE BAND ON A SHAFT.

Integrated slots

The last commonly used method to generate speed signals are slots that are integrated in the shaft. This is only available when it is pre-engineered on the shaft by the OEM of the rotating machine. Generating pulses with integrated slots works the same way as with pole bands, using a similar profile as seen in figure 9.

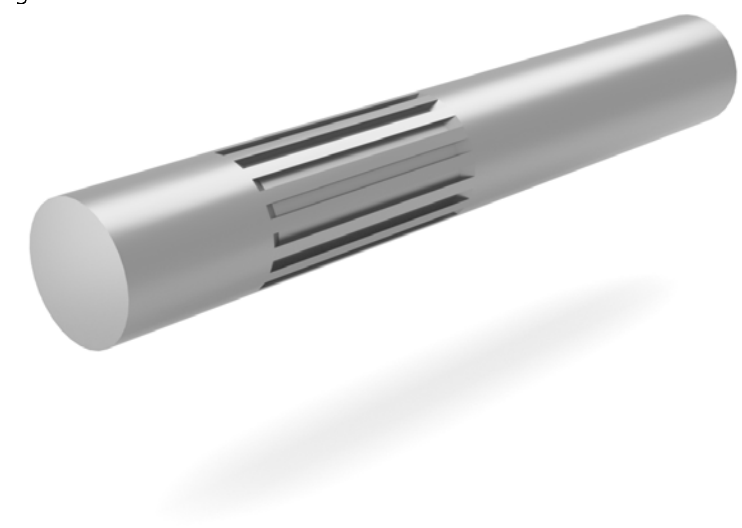


FIGURE 9 - INTEGRATED SLOTS ON A SHAFT.

Overspeed protection

2

What is overspeed protection?

To prevent dangerous situations and serious machine damage during an overspeed situation, an overspeed detection system (ODS) is installed. This system continuously measures the rotational speed of the machine. Based on IEC guidelines, API guidelines and the machine specifications provided by the OEM, the reaction time and limit values are defined in the system logic. These settings ensure that the system can trip/shutdown the machine in time when it is running faster than allowed by its design specifications. The ODS will send an alarm and initiate a trip that will cause the machine to be shut down by the emergency shutdown system (ESD).

The system logic also continuously monitors acceleration using the measured RPM data. When a rotating machine loses its load, due to a broken shaft for example, it will accelerate excessively, which will cause an overspeed situation. The software logic of an ODS recognizes this situation and intervenes by causing the machine to trip, even before the speed limit value is reached.

The potential effects of an overspeed situation can be catastrophic; The potential consequences for operational safety (i.e., personnel) and the environment are enormous. Moreover, the financial consequences can add up to millions of dollars because of damage, production loss and unplanned downtime. Therefore, having an ODS installed is required on many occasions.

Even though safety has the highest priority, machine uptime is of great importance too. It is therefore crucial that the ODS only intervenes when it is necessary, as a machine trip leads to costly downtime. A suitable hardware setup is essential, but just the beginning. Overspeed detection systems require proper engineering, commissioning and maintenance throughout their life to ensure machine safety and availability. ■

What causes overspeed?

Overspeed situations on rotating machinery should be prevented at all costs. Even the slightest overspeed could lead to mechanical stress that causes rotating machine parts to deform. More serious overspeed situations can cause the blade ends to rub against the housing. The most severe overspeed situations can cause the turbine blades to come loose, which results in machine parts penetrating the housing. This article describes the most common causes of overspeed.

> ***"An advanced overspeed detection system will initiate a trip function on speed acceleration even before an actual overspeed situation occurs."***

Broken shaft

When a drive shaft breaks, the turbine will suddenly experience minimal resistance. With the remaining driving force (fuel or steam), the rotor will be able to accelerate rapidly and exceed the machine's mechanical limits. An advanced overspeed detection system will detect when a rotating machine exceeds the maximum tolerable acceleration threshold, trigger an alarm and initiate a trip function even before an actual overspeed situation occurs. However, it will take some time for the driving force to disappear, during which the machine could still reach a dangerous speed level. Therefore, it is essential to have in-depth knowledge of your machine and know which accelerations are acceptable at every speed.

Valve malfunctioning

Control valves / safety valves are important mechanical parts of a machine. The consequences of failing control valves can be significant. When a control valve of a steam turbine is stuck or when one of its pressure valves remains opened, it could lead to excessive driving force on the shaft. Just as with a broken shaft, this could cause excessive acceleration and overspeed.

Testing mechanical overspeed devices

Mechanical / hydraulic overspeed protection can fail during an overspeed test. These systems have failure modes which can only be tested when performing an actual overspeed trip. When the system is stuck due to varnish or dirt, the mechanical overspeed device will not be able to shut down the machinery when required.

Human error

Even though most systems are automated, there is still room for human actions and interference. For example: leaving an override in place after a maintenance stop. Another example is an operator error. This has become less and less likely due to technological developments that require minimal human input, but it remains one of the main overspeed causes for rotating machinery.

Incorrect sensor input

The speed signal could be corrupted by an incorrectly mounted or adjusted sensor or system configuration errors, which causes an incorrect input in the system logic. An incorrect sensor input could also affect the control system, which could subsequently lead to an overspeed situation. This would leave the rotating machine vulnerable to undetected overspeed situations.

Control system failure

A failure of the speed control system can lead to an overspeed situation. A speed control system is used to regulate the speed of the rotating machine. An invalid input signal or programming error could set a failure of the speed control system in motion, which could subsequently cause overspeed. ■

Mechanical overspeed protection versus electronic overspeed protection

In the past, overspeed turbine protection systems were often designed by the turbine OEMs themselves, as part of the mechanical system. These mechanical protection systems are still in use, especially on medium-sized machines. However, electronic systems offer significant benefits and are becoming increasingly accessible, both financially and technically. The benefits of electronic protection over mechanical protection are discussed.

The principle of mechanical overspeed protection

To understand the difference between the two types of protection, it is important to understand how mechanical overspeed protection works. Mechanical overspeed protection systems use a weight on a spring, of which the spring force is known. Due to the centrifugal force, resulting from the rotational speed of the shaft, the spring is stretched further and further, and the weight moves out. If the rotational speed stays within the design specifications of the machine, the spring will not stretch too far, and the weight will not protrude. However, if it exceeds its design specifications, the weight will run out and hit the trip bolt. This will release the pin and the initiate the trip function.

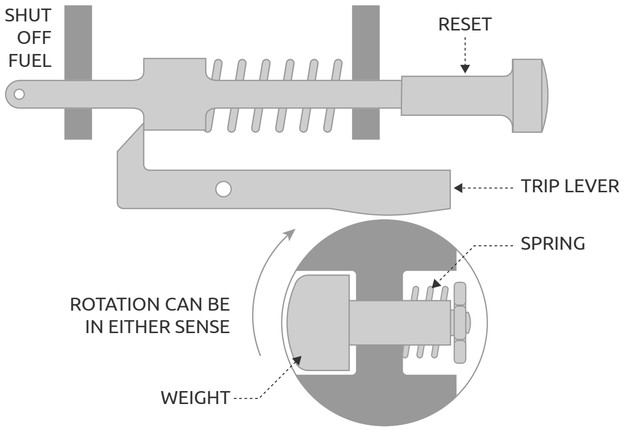


FIGURE 10 - THE OPERATION OF A MECHANICAL OVERSPEED PROTECTION SYSTEM.

The principle of electronic overspeed protection

Electronic overspeed protection consists of a gear or other measuring surface (e.g., a pole wheel), speed sensors, and a measuring system with trip logic and relay outputs. The speed sensors face the measuring surface and provide a sine or square wave signal, which are translated to pulses by the measuring system. The measuring system then counts the time between pulses to determine the rotational speed. The relay outputs are controlled by trip logic. To increase safety and availability, these protection systems are often built with redundant voting structures.

Why switch to electronic overspeed protection?

Switching from mechanical overspeed protection to electronic overspeed protection has significant advantages; verifiable safety being the primary argument. To illustrate: mechanical overspeed protection systems must be tested by creating an actual overspeed situation, while electronic overspeed protection systems can be tested by simulating overspeed. In addition to being much safer, a simulated test is quicker and easier to perform compared to testing during an actual overspeed situation.

TABLE 1: COMPARISION OF FORMS OF MACHINE OVERSPEED PROTECTION: MECHANICAL VS ELECTRONIC

Mechanical overspeed trip	Electronic overspeed trip
Inaccurate trip value determination due to inaccurate spring force (+ / a-50 rpm)	Highly accurate trip value determination
Trip value shifts slowly due to material fatigue of the spring	Trip value will not change
No possibility of user interface	Provides possibilities for DCS interface
Must be attached to shaft or mechanical lever	No physical contact with shaft or mechanical lever required
Lubricant build-up can block the operation of the mechanical trip	Lubricant build-up has no effect on trip function
Cannot be tested safely, except when disconnected from the driven equipment, which requires a shutdown	Possibility to test trip function safely by using a frequency generator to simulate overspeed
Overspeed required to activate trip	Can be tested at any speed and any channel can be tested during operation (online)
Requires multiple turbine start-ups to set trip value as accurately as possible	Does not require additional turbine start-ups

Switching to electronic overspeed protection is not complex. Firstly, the mechanical trip lever and all associated system components are removed. Secondly, a measuring surface (pole wheel) is mounted on the shaft if this is not already available, after which one or more sensors are placed around this measuring surface. The monitoring system can then be placed near the machine or in a cabinet. ■

Transmitter-based versus rack-based systems

A growing demand for overspeed protection on a wider range of rotating machinery has emerged alongside the general increasing industrial demands (API Standard 670). The imbalance between the criticality of a machine and the costs of the required protection system has created a need for less complex and more accessible solutions for overspeed protection on rotating machinery. Transmitter-based systems and rack-based systems are discussed.

FIGURE 11 - JAQUET FT3000

Rack-based systems

Rack-based overspeed protection systems have dominated the overspeed market for a considerable period. The rack layout was a perfect host for the bulky electronics required for these high-speed measurements. They were well suited for large machines that were already equipped with cabinets and could justify the large investments but offered less flexibility for other equipment. With the demand for overspeed protection systems extending to smaller and less critical machinery, the required investment for a rack-based system is often not proportional to the criticality, nor to the size of the machine.

Transmitter-based systems

Transmitter-based overspeed protection systems are stripped of all secondary functions and focus on the core of overspeed protection. With a much smaller financial and technical impact, transmitter-based systems offer a more accessible solution for smaller and less critical machinery. At the same time, extensive scalability and modularity options allow this type of system to be used for a much wider range of rotating machinery. Transmitter-based systems can be mounted close to machine even when there is no 19” rack cabinet. Plant-wide overspeed protection has become realistic due to the continuous developments that are driven by shifting market demands. ■

FIGURE 12 - ISTEC SPEEDSYS 200

PREVIEW P 38

Four reasons why overspeed protection systems should not be overly complex

It is evident that rotating machinery require advanced protection systems, as these have one of the most important functions regarding safety measures. However, advanced should not be mistaken for complex. Complexity does not necessarily mean that the system is better in its core function, on the contrary even. Four reasons why overspeed protection systems should not be overly complex are discussed.

Continue with this article ⟶ p 38

What does the API Standard 670 state about overspeed detection systems?

The API Standard 670 is an industry standard and describes the minimum requirements for a machine protection system (MPS). This includes, measuring radial shaft vibration, casing vibration, axial shaft position, shaft rotational speed, piston rod drop, phase reference, overspeed and critical machine temperatures.

This article is based on the authors' interpretation of the API Standard 670 5th edition, November 2014. Please refer to the standard for more information and context.

The standard includes requirements related to hardware (sensors and systems), installation, documentation and testing. This chapter focusses solely on the part that describes overspeed. The main elements are described.

The API Standard 670 only describes the requirements of electronic detection systems and defines them as follows:

An electronic overspeed detection system consists of speed sensors, power supplies, output relays, signal processing, and alarm/shutdown/integrity logic. Its function is to continuously measure shaft rotational speed and activate its output relays when an overspeed condition is detected.

Separate hardware and logic

The API Standard 670 describes that an electronic overspeed detection system must be exclusively dedicated to overspeed detection. The system must be isolated from other monitoring and protection systems and is not allowed to share components (with e.g., the control system). This ensures that the functioning of the system is verifiable and not dependent on other systems.

Response time

An electronic overspeed detection system, for those machines to which the API Standard 670 applies, must consist of three independent measuring circuits. To maximize the safety and availability of the machine, a two-out-of-three voting (2oo3) is used to activate the trip function. In other words, when at least two of the three sensors detect overspeed, the trip function will be activated.

It goes without saying that the response time during an overspeed event is of great importance. The API Standard 670 states that the system may take up to 40 milliseconds to detect overspeed and have the relay outputs switch. It should be noted that 40 milliseconds is not always fast enough to prevent the rotor from reaching a rotational speed that exceeds its design specifications due to the ramp-up.

The following actions must take place within these 40 milliseconds:

- All three measuring circuits (channels) measure the rotational speed.
- The measured values are independently compared to the set the trip value.
- The voting structure determines how many measurement circuits have determined an overspeed event.
- When at least two of the sensors have detected overspeed, the output relay should switch.

In figure 13 below, these steps are shown schematically. ■

Voting

Voting is related to the architecture of a trip system (1oo2, 2oo2, 2oo3, and so on). It can be defined as the minimum number of "paths" that should function out of the total number of paths available within the architecture.

For example, with a 1oo2 architecture at least one path should function, whereas with a 2oo4 architecture at least two paths should function.

Learn more about voting ⟶ p 32

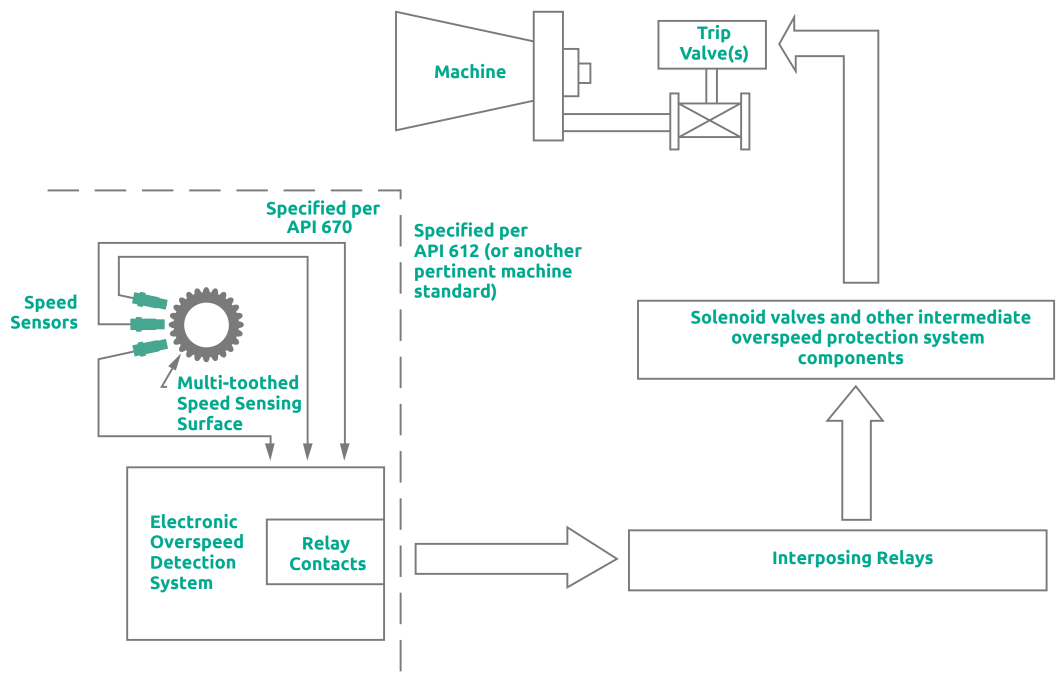


FIGURE 13. SCHEMATIC REPRESENTATION OF AN ELECTRONIC OVERSPEED DETECTION SYSTEM; THREE SENSORS POINTED AT THE MEASURING SURFACE, CONNECTED TO THE DETECTION SYSTEM WHERE VOTING TAKES PLACE WITH A RELAY AS OUTPUT. (SOURCE: API STANDARD 670)

Voting structures

Voting, regarding overspeed protection systems, can be defined by the number of safety loops that should switch to the safe state when an overspeed situation is detected. The desirable voting structure depends on the application. For highly critical machinery a 2oo3 voting structure is widely adopted and required by the API Standard 670, but for less critical machinery a 1oo1 voting structure may suffice. The reasoning behind this is the increased availability and safety that more complex voting structures provide.

The meaning of different voting structures is often misunderstood. This is due to the fact that the impact of a voting structure differs depending on the way you look at it.

What is considered a failure?

A failure occurs when the safety unit does not go to the safe state when the application requires it, or when it goes to the safe state when the application does not require it.

Two perspectives

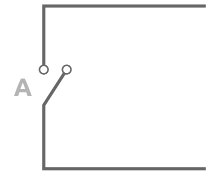
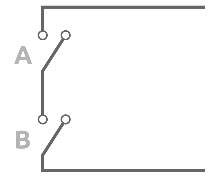
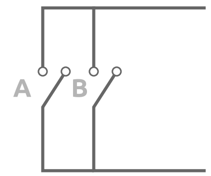
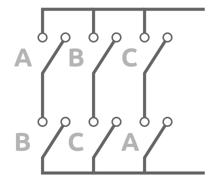
Two different situations should be considered; the situation from a safety perspective and the situation from an availability perspective.

- The safety perspective focuses on whether a machine remains protected when one or multiple safety units in the voting structure fail.
- The availability perspectives focus on whether a machine remains available if one or multiple safety units in the voting structure fail.

How to determine the voting structure?

- From a safety perspective: How many safety devices must remain functional for the machine to remain safe?
- From an availability perspective: How many safety devices must remain functional for the machine to remain available?

TABLE 2: VARIOUS (RELAY) VOTING STRUCTURES EXPLAINED BASED ON A SAFETY PERSPECTIVE VERSUS AN AVAILABILITY PERSPECTIVE.

Visualized structure	Safety perspective	Availability perspective
	**1oo1 structure:** If the unit fails, the machine protection may be impaired. This voting structure does not offer extra safety.	**1oo1 structure:** If the unit fails, the machine availability may be impaired. This voting structure does not offer extra availability.
	**1oo2 structure:** If one unit fails, the machine is still protected (safe). This voting structure does offer extra safety.	**2oo2 structure:** If one unit fails, the machine availability may be impaired. This voting structure does not offer extra availability.
	**2oo2 structure:** If one unit fails, the machine protection may be impaired. This voting structure does not offer extra safety.	**1oo2 structure:** If one unit fails, the machine is still available. This voting structure does offer extra availability.
	**2oo3 structure:** If one unit fails, the machine is still protected. This voting structure does offer extra safety.	**2oo3 structure:** If one unit fails, the machine is still available. This voting structure does offer extra availability.

Note: The figures in the table may cause confusion as the relays are depicted open, while they are energised closed during normal operation. However, this is how schematics of relays are generally shown as this provides a better overview.

The table shows that the voting structure differs depending on whether you look at it from a safety or availability perspective. Taking the second figure as an example it would be a 1oo2 voting structure from a safety perspective; only one of the safety units must function for the machine to remain safe. However, from an availability perspective: (2oo2 voting structure) if one unit fails the machine will not be available as both devices need to function properly. ■

⚠ In this bookazine voting structures are always used from a safety perspective.

Overspeed protection functions

Programming an overspeed detection system is done using software and can be divided in three phases: input, processing and output.

Input

To ensure that the software can make the correct calculations it is important to enter some basic data of the machine and the measurement surface, like a gear wheel (or pole wheel). For the machine data, the nominal and maximum speed should be set. As for the gear wheel, the number and the shape of the gear teeth should be set.

Programming the sensors starts by determining the measurement principle; eddy current, variable reluctance (VR) or Hall-effect. Subsequently the sensor settings are implemented, including limits for the sensor status (OK/Not OK) and a trigger level. A trigger level can filter any noise to make sure it is not counted as a pulse.

Processing

When the input signals are considered reliable, they enter the processing phase.

An overspeed detection system can trigger an alarm or switch for overspeed, acceleration and/or underspeed. Overspeed and underspeed require pre-set values (in RPM) for alarm and/or trip functions. Acceleration can be calculated using the following formula:

```
a = (speed2 - speed1) / (time2 - time1)
```

Output

The processed signal values are connected to external systems. The relay outputs and analogue outputs are most relevant to the protection functions. Relay outputs are used to transmit trip signals directly to a trip system, shutdown valve or interposing relays. Alarm statuses are connected to a monitoring system. The analogue outputs are used to send processed signals to external systems and/or local equipment for further processing. ■

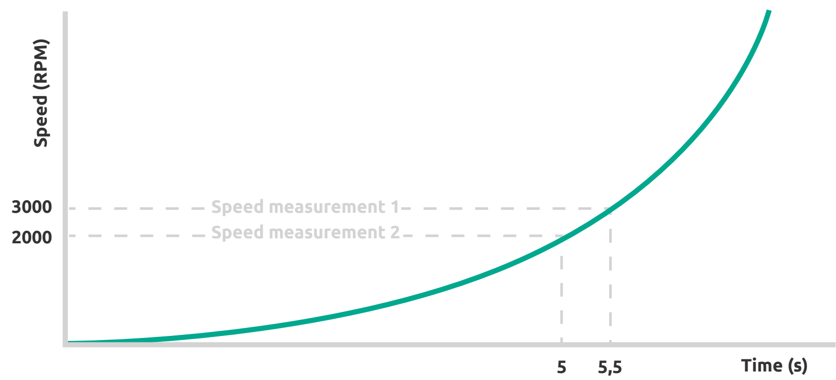
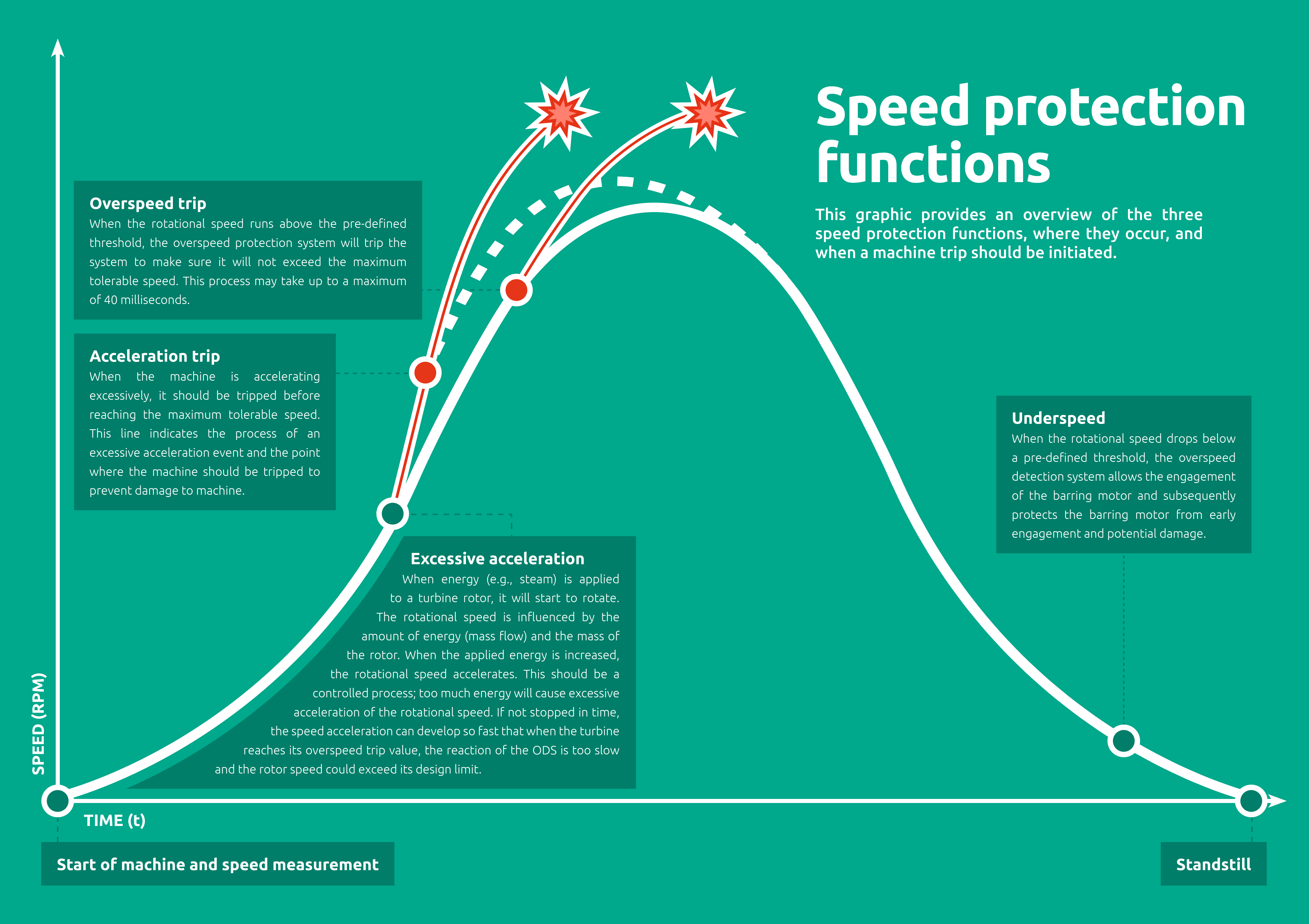


FIGURE 14


Speed protection functions
This graphic provides an overview of the three speed protection functions, where they occur, and when a machine trip should be initiated.
Overspeed trip
When the rotational speed runs above the pre-defined threshold, the overspeed protection system will trip the system to make sure it will not exceed the maximum tolerable speed. This process may take up to a maximum of 40 milliseconds.
Acceleration trip
When the machine is accelerating excessively, it should be tripped before reaching the maximum tolerable speed. This line indicates the process of an excessive acceleration event and the point where the machine should be tripped to prevent damage to machine.
Excessive acceleration
When energy (e.g., steam) is applied to a turbine rotor, it will start to rotate. The rotational speed is influenced by the amount of energy (mass flow) and the mass of the rotor. When the applied energy is increased, the rotational speed accelerates. This should be a controlled process; too much energy will cause excessive acceleration of the rotational speed. If not stopped in time, the speed acceleration can develop so fast that when the turbine reaches its overspeed trip value, the reaction of the ODS is too slow and the rotor speed could exceed its design limit.
Underspeed
When the rotational speed drops below a pre-defined threshold, the overspeed detection system allows the engagement of the barring motor and subsequently protects the barring motor from early engagement and potential damage.
SPEED (RPM)
TIME (t)
Start of machine and speed measurement
Standstill

Four reasons why overspeed protection systems should not be overly complex

It is evident that rotating machinery require advanced protection systems, as these have one of the most important functions regarding safety measures. However, advanced should not be mistaken for complex. Complexity does not necessarily mean that the system is better in its core function, on the contrary even. Four reasons why overspeed protection systems should not be overly complex are discussed.

Core of overspeed protection

Leading machine standards, such as the API Standard 670 and the IEC 61508 (functional safety), have one main requirement for rotating machinery: to be equipped with a suitable overspeed protection system. The core of overspeed protection is to detect overspeed and excessive acceleration situations and initiate a trip function when required. Any other functions are classified as add-ons and can be dealt with in other systems.

Costs

Complex systems with more functions are more expensive. Secondary functions, such as monitoring functions, do not directly contribute to the core function: overspeed protection. Additional functions require more hardware, which increases the costs of the system itself as well as the installation costs (e.g., wiring, instrumentation cabinets, etc.). In addition, hardware requires periodic maintenance; the more hardware the more maintenance-intensive the system becomes.

It is important that these systems are as straightforward as possible.

Such systems are often overly complex for smaller and/or less critical rotating equipment that requires simple overspeed protection. This leaves operators with the choice to either implement a system that is hardly financially justifiable for its application, or to leave the machine unprotected.

Complexity and expertise

With complexity comes a more demanding requirement for extensive know-how regarding the operation and maintenance of the overspeed protection system. Generally, the systems are only checked during turnarounds, making their reliability of utmost importance. As overspeed protection systems do not require daily attention, it is often not a dedicated expertise but part of a larger job description. As such, it is important that these systems are as straightforward as possible, and not dependent of a diminishing expertise. The more complex the system, the bigger the chance of human error. This is especially the case with overspeed protection systems, as nobody really gets the opportunity to gain experience due to the long maintenance intervals.

The more complex the system, the bigger the chance of human error.

Verification and testing

The more complex a safety system, the more demanding its testing and verification requirements are. To test and verify a safety system, the process is interrupted; a long proof test interval negates the need to interrupt the process regularly. A system that is focussed solely on the core of overspeed protection can reach test intervals of above 10 years, up to a point where it does not have to be tested before reaching end-of-life. It is important to note that the more functions an overspeed protection system has, the smaller the test interval becomes, and the more the process is interrupted. It is therefore important to have a suitable system for your specific application, rather than implementing a system that is "overkill" for the application. ■

A long proof test interval negates the need to interrupt the process regularly.

How SpeedSys changes the overspeed market

SpeedSys is a SIL-rated overspeed detection system for rotating machinery. It delivers the core layer of protection with a compact architecture. Its small technical footprint and low-impact installation enables advanced protection for a wide range of applications.

SpeedSys comes in two versions: Istec SpeedSys 200 for machinery that require SIL2 overspeed detection and vibro-meter (Meggitt) SpeedSys300 ODS301 for more critical machinery that require SIL3 overspeed detection.

SpeedSys is highly adapted to growing market demands and challenges overly complex rack-based systems. We describe 5 ways of how SpeedSys changes the overspeed market.

Compact architecture

The SpeedSys features a compact architecture while still being able to deliver high integrity overspeed detection. By sticking to the core of overspeed protection, Istec was able to use a DIN-rail housing as opposed to the traditional, 19” rack-based architecture, which mainly occupies the current overspeed market.

As the demand for high integrity (SIL rated) overspeed protection grows and extends to a wider range of machinery, the need for a more compact, yet scalable and modular system emerges. This has become part of the philosophy behind the SpeedSys; to protect what was previously left unprotected, both large and small, critical and non-critical rotating machinery. The compact architecture of the SpeedSys allows for a widely applicable overspeed detection system with a low technical impact.

SIL and proof-testing

SpeedSys is SIL-certified *by design* as opposed to *proven in use*. The difference between the two certification methods is reflected in the required testing frequency to maintain the SIL rating and the possibility to apply changes or future product updates.

Systems that are certified by proven in use generally require years of usage data and a high testing frequency to maintain their SIL rating. Changes to the system will invalidate this usage data and, subsequently its SIL certification. This could even lead to sudden obsolescence. The certified safety design of SpeedSys features advanced self-monitoring that enables a proof test interval of at least 10 years and acts as a solid basis for future developments in the product line.

Financially competitive

Complex rack-based systems are often overkill for less critical or smaller machinery and can thus not be financially justified. Depending on the desired voting structure, SpeedSys can be used standalone (1oo1) or scaled up to three modules (2oo3) in different voting configurations to suit any application. This increases its financial efficiency and machine applicability compared to rack-based systems. One system that fits all rotating equipment, with more efficient spare part management, less maintenance requirements and a lower organisational footprint.

> ***One stock, one procedure, one software pack, one training.***

Extensive support

SpeedSys differs from other overspeed protection systems, not only from a technical and financial point of view, but also due to its outstanding usability and structured support. The system comes with an extensive free online training environment, which includes instruction video’s regarding software and product use, valuable e-learning courses and knowledge articles.

Replacement solution

A growing obsolescence and the general discontinuation of overspeed detection systems by multiple OEM’s requires a replacement solution. SpeedSys is designed for low impact retrofitting of any existing overspeed detection system, to minimize the impact on the customer’s infrastructure. The small and scalable layout of SpeedSys allows for easy retrofitting and is adaptable to meet the existing measurement set-up. SpeedSys works with the three major sensor types (Hall-effect, VR and eddy current) and features built-in isolators to be integrated with any existing sensor infrastructure. ■

SPEEDSYS MODEL EXAMPLE:
ISTEC SPEEDSYS 200

Service and maintenance on machine protection systems

It is crucial that overspeed protection systems always function optimally; there is no room for error. Overspeed protection systems require frequent maintenance, verification and proof tests.

Maintenance to an overspeed protection system includes the following steps and procedures:

Step 1: Reviewing the current installation

Before a project is started the current system and situation are mapped and registered. The collected information is then substantiated by directives, industry standards and guidelines such as SIL and ATEX. Test procedures and conditions are collected and included in the scope of the project. Every deviation is registered, and the required adjustments, replacements, and spare parts are checked.

Step 2: Registering the system condition

The status of the overspeed protection system is examined both at the start and at the end of the turnaround project. Any discrepancies are recorded and checked to determine if action is required.

Step 3: Disconnecting sensors

The sensors are disconnected before any mechanical work on the machine is performed. During this process the sensors are labelled, visually inspected, and carefully stored.

Step 4: Inspection

The visual inspection is the first step in detecting possible damages and gives an impression of the current installation. Moreover, it contributes to the detection of structural flaws. Every sensor is examined, from the machine to the system. With the help of simulation equipment, the cabling and functionality of the overspeed protection system are verified.

Step 5: Calibrating sensors and measurement systems

In addition to the inspection, the whole measurement circuit in the field is thoroughly checked. Each speed measurement is verified for the correct functioning and output signal. All the data is recorded, including performance reports, type numbers, and serial numbers. These registrations are an important part of the required documentation, especially for ATEX and SIL environments.

Step 6: Re-installing sensors

When the mechanical work has been completed, the sensors are re-installed and accurately positioned. The tested sensors are installed in their original place.

Step 7: SIL proof test

If the overspeed protection system is classified by SIL standards, a functional proof test is required. This test is performed in accordance with both the test procedures as specified by the system supplier and with applicable guidelines. ■

Steam turbine overspeed test fail

This text is based on a report by The National Institute for Occupational Safety and Health (NIOSH). It is solely for illustrative purposes. As the facts are not verified, the company name and country are not mentioned.

In a plant, a steam turbine was put back into operation after maintenance and repairs. Before doing so, three overspeed trip tests had to be executed. However, during the second test a fatal error occurred resulting in a catastrophic outcome; loss of life.

The second overspeed test

The tests were executed with the guidance of three actors:

1. Personnel of the company that had performed maintenance and repairs to the turbine.
2. Turbine OEM personnel.
3. Personnel of the company that owned the turbine and performed standard maintenance activities.

The overspeed trip test consisted of an acceleration of the turbine to a predetermined rotational speed, to test whether the mechanical valve, which prevents the turbine from accelerating to a dangerous speed (overspeed), was functioning properly. During the second test the mechanical valve did not function, causing an overspeed situation. The rotational speed of the turbine exceeded its design specifications. As a result, hundreds of fragments from one of the 12 rings that were attached to the turbine shaft came loose.

"During the second test the mechanical valve did not function, causing an overspeed situation."

Research found that several factors contributed to the failed overspeed trip:

- There was no procedure to safely perform the overspeed trip test that complied with the OEM manual, industry standards, and consensus standards for steam turbines.
- Not a single employee of the three present companies was trained to perform these tests in a safe way.
- There was no clear delegation and definition of responsibility.
- The tests were conducted on a mechanical safety system without the presence of a redundant safety system that could intervene in the case of a failure in the first system.
- During the test, several unauthorized employees were in dangerous proximity to the machine, which put them at great risk should the test fail.

A series of recommendations were made:

- A procedure to inspect, report, execute, maintain and repair equipment and replace defective equipment should be developed, documented and implemented. This should be based on instructions from the OEM, industrial guidelines and consensus standards. An occupational safety analysis of all routine and non-routine activities should be included in these procedures.
- Employees should be trained to follow procedures that are established in accordance with OEM instructions, industry guidelines and consensus standards.
- A clear division of tasks and associated final responsibilities for each employee and manager should be developed.
- Malfunctioning equipment or defective parts should not be used.

CASE: OVERSPEED TEST FAIL

4 initial checks

when installing, commissioning and troubleshooting an overspeed protection system

It is essential to verify the functioning of every individual component of an overspeed protection system. This can be done during its installation, commissioning / turnarounds or troubleshooting. As this is a critical process and downtime is costly, it is crucial to have a solid step-by-step plan. This checklist provides an overview of the steps that should be taken to verify the safety and reliability of the sensors, installation, system and signal.

1. Sensor verification

The following checks can be done when the machine has stopped and the sensors are accessible:

Sensor specifications

- What is the type of sensor being used?
- What is the measuring range of the sensor?
  - ↳ ACTION Refer to the sensor's datasheet for this information.
  - ↳ ACTION Compare this information with the settings of the overspeed detection system.

Air gap

- What is the allowable distance of the used sensor and the pole wheel?
- How is the signal output affected by this distance?
  - ↳ ACTION Refer to the sensor's datasheet for this information.
  - ↳ ACTION Measure the gap between the sensor and the pole wheel.
    - ↳ TOOLS Feeler gauges or another type of depth measuring tool.

Alignment

- Does the sensor need to be aligned in a certain direction in relation to the pole wheel?
- What is the maximum side and angular misalignment that is allowed for this sensor?
  - ↳ ACTION Refer to the sensor's datasheet for this information.
  - ↳ ACTION Verify the alignment between the sensor and the pole wheel.

Stiffness

- How is the sensor mounted on the machine i.e., through the bearing casing or on a bracket?
- How rigid is this setup?
- Is the setup properly secured to a fixed point of the machine?
  - ↳ ACTION Verify the installation of the speed sensors and the stiffness of the bracket.
  - ↳ ACTION Verify the tightness of all bolts and nuts of the brackets and sensors.
    - ↳ TOOLS Torque wrench

Pole wheel

- What is the shape of the pole wheel?
- What is the *module* of the pole wheel?
- What is the height of the teeth on the pole wheel?
  - ↳ ACTION Verify the dimensions of the pole wheel on the actual machine, or through its drawings.
  - ↳ ACTION Compare the pole wheel dimensions to the specifications of the sensor and the overspeed system

2. Installation verification

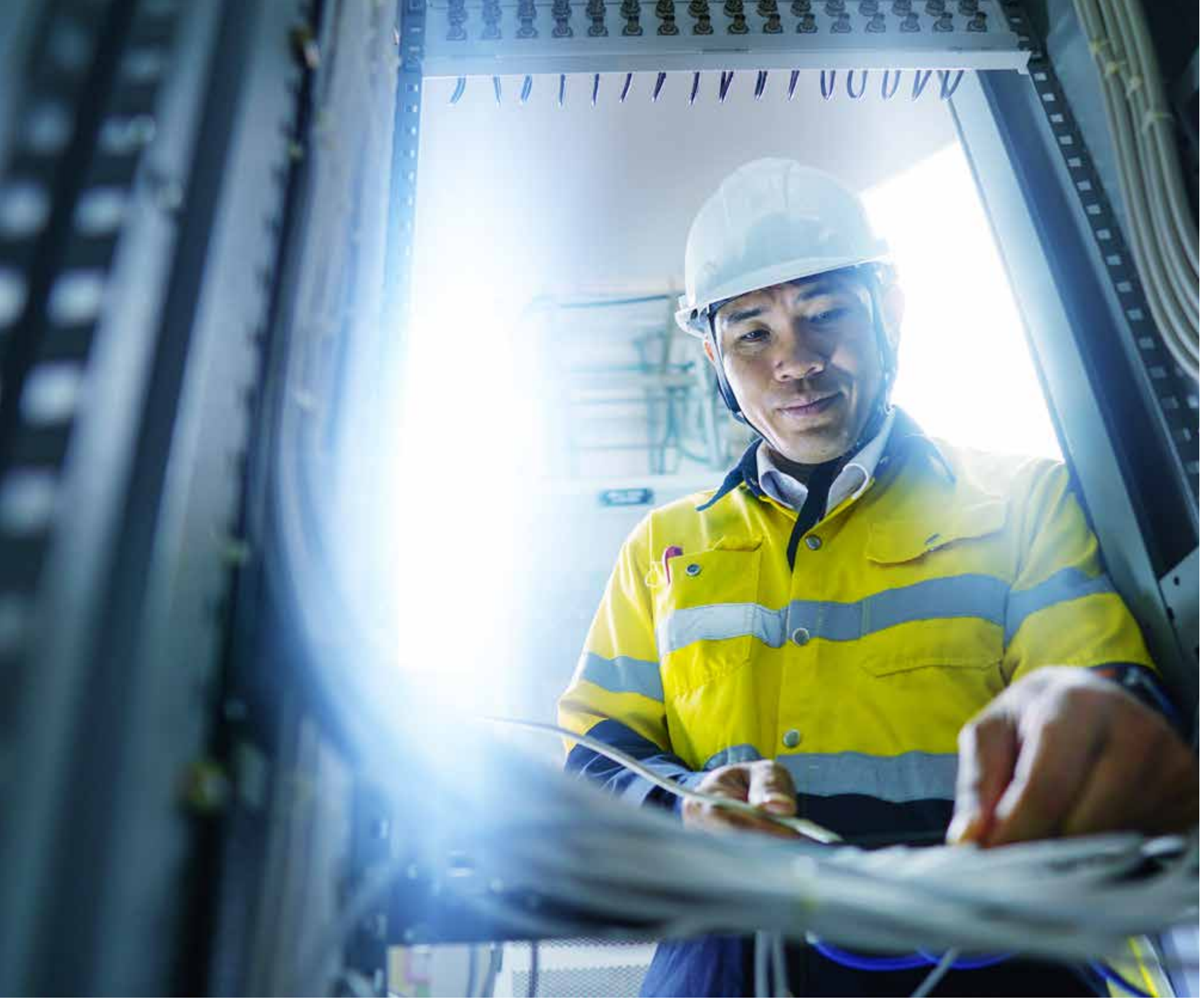
The following checks can be done when the machine is running. However, if there is an increased risk the machine should be stopped before doing these checks.

Sensor cables

- What type of cables are being used to transfer the signals from the machine to the overspeed detection system?
- How is the grounding and shielding of all the sensor cables? Is it connected as described in the user manual of the overspeed detection system?
- Is there a clear grounding philosophy with single ended shielding, to prevent ground loops
- Verify the clear differences in the installation between PE, IE and IS
  - ↳ ACTION Check the type of cable from the machine, in every junction box, to the overspeed system.
  - ↳ ACTION When the cable not shielded per overspeed measurement, consider replacing this cable.
  - ↳ ACTION Measure the resistance, current, and voltage between the shielding and the associated earth connections.
    - ↳ TOOLS Multimeter

Junction boxes

- How are the wires terminated in the junction boxes?
- Are the terminals properly fastened?
- Are the wire-end ferrules used correctly?
  - ↳ ACTION Check every junction box for proper connections.
    - ↳ TOOLS Screwdriver



3. System verification

Functional system check

- How is the device configured?
- Do all the in- and outputs work as its intended?
- What type of voting structure is used?
  - ↳ ACTION Go through the overspeed detection system configuration and look for anomalies and deviations from its standard functionality.
  - ↳ ACTION Inject a speed signal (simulation) into the overspeed system, with the same characteristics as the actual signal.
  - ↳ ACTION Check if the analogue and digital outputs change when certain values are met.
  - ↳ ACTION Verify the functionality of the voting structure by going through all the logical combinations.
    - ↳ TOOLS Configuration program of the overspeed detection system, speed simulating equipment, and a multimeter.

System wiring

- How is the overspeed system wired on the terminals?
- Does the system have internal wiring?
  - ↳ ACTION Verify all the wiring on and in the system for proper connections.
    - ↳ TOOLS Screwdriver

4. Signal verification

The following checks can be done when the machine is running:

Signal quality

- What shape does the signal have right before it enters the overspeed detection system?
- Is there noise present on the incoming signal?
- How stable is the sensor power supply?
  - ↳ ACTION Measure the shape, noise, and AC and DC levels of the incoming speed signals during a run-up and during nominal speed.
  - ↳ ACTION Store this data for future reference.
  - ↳ ACTION When replacing an overspeed detection system, measure the incoming signals on the old system first before replacing the system.
    - ↳ TOOLS Oscilloscope

Trigger level

- How do the measured signal levels compare to the trigger level of the overspeed detection system?
  - ↳ ACTION Measure the AC and DC levels of the incoming signal and verify this with the configuration.
    - ↳ TOOLS Oscilloscope and the configuration program of the overspeed detection system.

Pole wheel influences

- How stable and even is one revolution of the pole wheel?
- Verify the eccentricity of the pole wheel during different speeds.
- Does the pole wheel have enclosed magnetic fields?
  - ↳ ACTION Measure the eccentricity close to the pole wheel.
  - ↳ ACTION Measure the magnetic stability of the pole wheel with eddy current shaft vibration sensor on the pole wheel.
  - ↳ ACTION Measure the magnetic fields in the pole wheel when the machine is stopped and the pole wheel is accessible.
    - ↳ TOOLS Eddy current shaft vibration sensors (if already present) and a Gauss meter

Functional Safety

3

"The aim is to prevent accidents with human, environmental and financial consequences."

⟶ 52 - 55

This section (p 52 - p 55) was published before in the bookazine Vibration.

Functional safety

“Functional Safety is part of the overall safety that depends on a protection system or equipment operating correctly in response to its inputs”. (IEC 61508)

“Functional Safety is the detection of a potentially dangerous condition resulting in the activation of a protective or corrective device or mechanism to prevent hazardous events arising or providing mitigation to reduce the consequence of the hazardous event”. (IEC 61508)

By complying with functional safety standards, it is possible to identify hazardous situations or events that might lead to accidents. The aim is to prevent accidents with human, environmental and financial consequences. Predictive, preventive and/or corrective measures can be taken to prevent dangerous situations or to mitigate the impact of these situations.

By implementing functional safety, the risk of certain (dangerous) events must be reduced to an acceptable level, and the impact of potential consequences must be limited as much as possible. It is important to be aware that "risk-free" does not exist and therefore, cannot be a target. The risk calculation is based on the probability of the occurrence of an event, and the severity of its consequences.

You think safety is expensive?
Try having an accident!

Functional safety is achieved by implementing an active machine protection system, and by maintaining the minimum required availability of each safety function of the system. The machine protection system is designed to maintain the required safety level during its safety life cycle. Functional safety provides structure to the company's safety measures and is used to cover the responsibility for overall safety.

IEC standards

Functional safety guidelines are defined in the standards IEC 61508 and IEC 61511. IEC 61508 provides machine manufactures with guidelines for the specification, design and operation of electrical, electronic and programmable safety systems based on a life cycle concept.

The standard IEC 61511 is also based on a life cycle concept. The main difference between IEC 61508 and IEC 61511 is that IEC 61511 is not written for machine manufacturers, but for the end-users of the equipment and focuses on Safety Instrumented Systems (SIS) in the process industry.

Safety Integrity Level (SIL)

The Safety Integrity Level (SIL) is part of functional safety. It is used to design Safety Instruments (SI) and Safety Instrumented Systems (SIS). The safety integrity level is rated based on different risk levels, where the impact of system failures on humans, the environment and finances, and the likelihood of failure are considered. A high safety integrity level requirement increases the demand for functional safety measures and lowers and governs the chance of uncontrolled incidents.

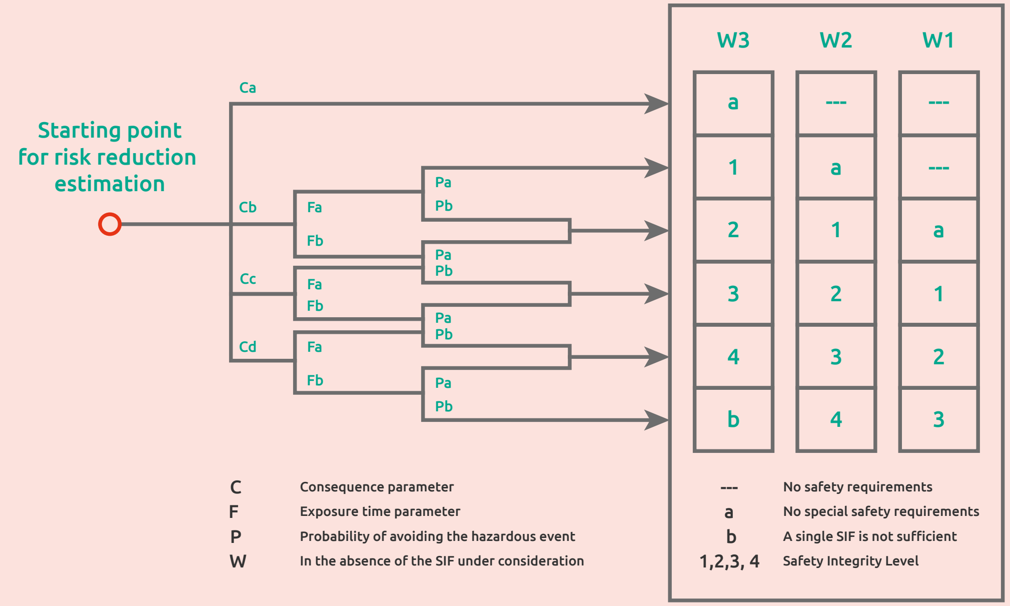


FIGURE 15 - RISK GRAPH TO DETERMINE THE RIGHT SIL.

The required safety integrity level differs for each application. The risk and the impact of the consequences of a failure determine the recommended SIL rating. The risk level and the consequences of a failure are determined using hazard and operability (HAZOP) studies, risk graphs and layer of protection analysis (LOPA) information.

A SIL-certified safety system must be maintained and tested properly to guarantee its availability. The SIL rating of a safety system decreases over time. By testing and maintaining the system according to a pre-set frequency, the rating can be (partially) restored. This test frequency is described in the safety documentation provided by the supplier of the system. The interval is based on the Safe Failure Fraction (SFF), Probability of Failure on Demand (PFD) and Hardware Fault Tolerance (HFT).

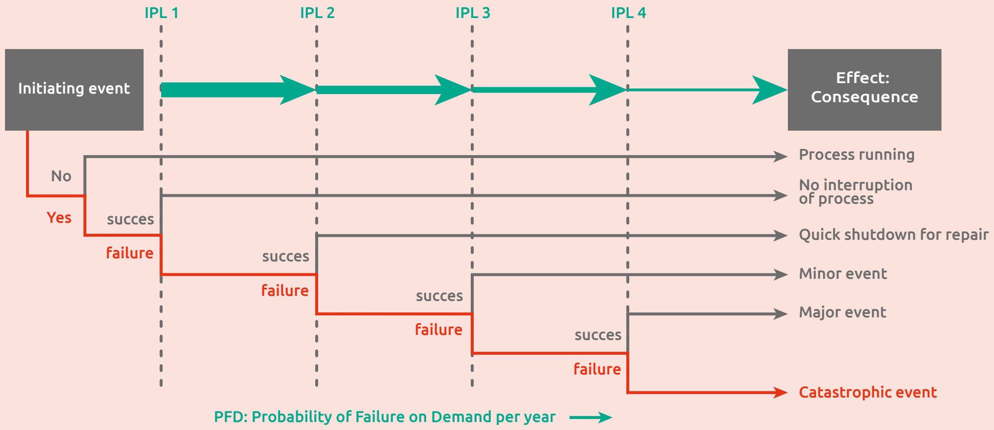


FIGURE 16 - INDEPENDENT PROTECTION LAYERS (IPL).

Safety Integrity Level proof tests

Proof tests are used to ensure the safety integrity level of a safety system throughout the safety life cycle. A proof test verifies the system function and availability, and covers failures like dangerous failures, diagnostic failures and parametric failures. Proof tests are an important part of the safety life cycle and a key act in covering the company's safety responsibilities. The tests are performed by competent engineers and require proper procedures and documentation.

Full proof test

A full proof test is an end-to-end test of the safety system, with maximum coverage of the safety parts and functions. The proof test is usually performed at a pre-defined test interval, according to the safety requirement specification. Depending on the safety conditions, the test can be performed with active process conditions or simulated process conditions, and in practice the latter is usually considered the only option. The purpose of the test is to reveal undetected faults in the safety instrumented system so that, if necessary, the system can be restored to its designed functionality. By testing the complete system, including the loops and all the safety functions, the test can cover all the dangerous failure modes, including diagnostic failures and parametric failures. Note: A full proof test should have 100% coverage, but this is usually not the case. The essence of a full proof test is that it covers all the parts and functions that can be tested, and that it offers the highest possible coverage for the application.

"A full proof test should have 100% coverage, but this is usually not the case."

Partial proof test

It is not always possible to do a full proof test, for instance if the test interval is not in parallel with other maintenance intervals. If a full proof test is impossible, or if it imposes unacceptable risks, partial proof tests are used as an alternative.

A partial proof test is a proof test that does not cover 100% of the parts and functions of the safety system. For various reasons, parts can be excluded from the test or the test can be divided into parts.

Example I: For practical reasons, the sensors of a safety system are not included in the test but simulated on the input of the protection system. This partial test covers the functionality of the system but does not cover all the parts.

Example II: During active process conditions, the 3 channels of a 2oo3 system are tested in sequence instead of in parallel, to avoid activating a trip. This partial test covers all the parts except for the combined functionality and the logic.

"A partial proof test restores the SIL rating of the safety system in proportion to its coverage ratio."

The proof test coverage is a measure to determine how many undetected failures are detected by the proof test. The IEC 61508 standard provides some equations as a guideline to determine the coverage ratio. A partial proof test restores the SIL rating of the safety system in proportion to its coverage ratio.

Diagnostic proof test

Diagnostic tests usually refer to integrated, online tests that are performed continuously or with a high frequency. In general, the diagnostic test is a self-test that focuses on the function of the instrument. Diagnostic tests can be done by integrated diagnostic and/or simulation hardware and software features, but might require external components as well. Diagnostic tests are designed to detect dangerous failures and change them to safe situations, either by generating an alarm or bringing the process to a safe state. The tests might have a lower coverage ratio, but are important because their high frequency can identify critical failures quickly. ■

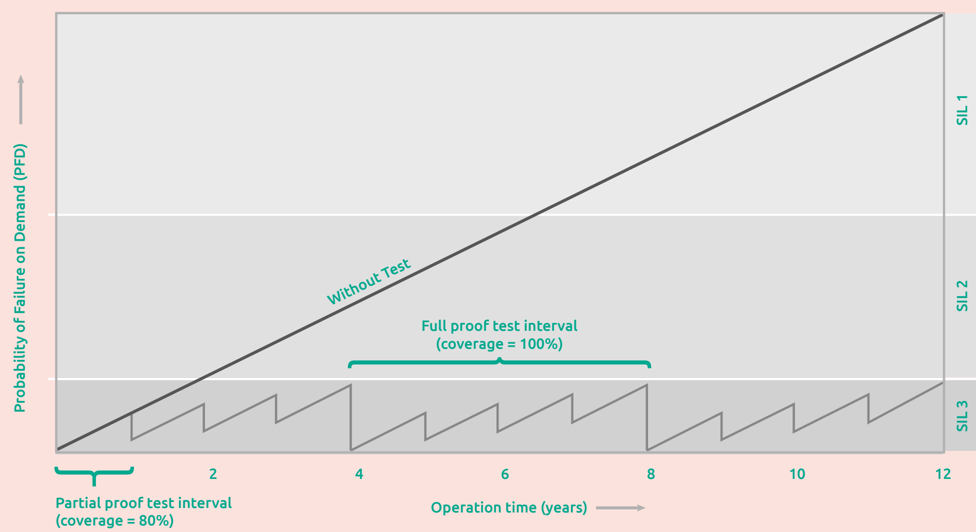


FIGURE 17 - SIL PROOF TEST INTERVAL.

Best practice guide

Introduction

The previous sections provide a general understanding of speed measurements and protection. This best practice guide is intended as a generic approach based on the extensive field experience from the Istec service staff. Its intention is to provide valuable in-depth information for engineers, but it does not cover all the installations, available solutions, and possible installation and application errors. It provides guidance in verifying and commissioning the overspeed protection system.

A typical overspeed protection consists of a series of individual components. Each component of an overspeed protection system is examined step-by-step, describing its function, design considerations, probable causes of failures and best practices. These components include:

- Sensors
- Shaft/pole wheel
- Sensor mounting bracket
- Cable
- Connectors
- Junction boxes
- Connection terminals
- Input interface (isolator/barrier)
- Overspeed detection system (logic solver)
- Output interface

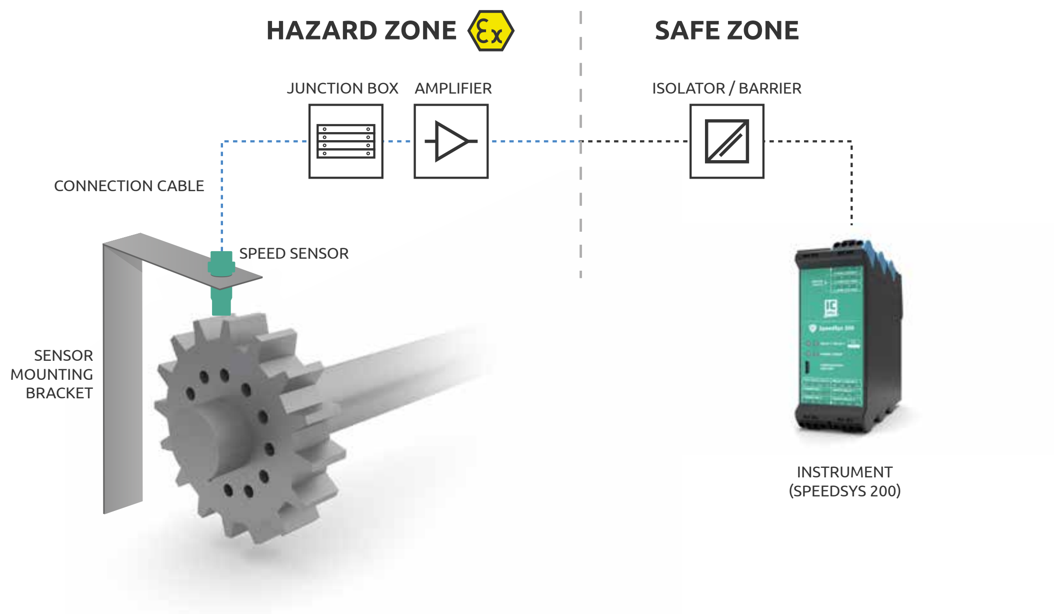


FIGURE 18 - OVERSPEED SYSTEM OVERVIEW

Speed probes

Speed probes are typically based on detecting changes in the magnetic flux. The sensors generate a magnetic field which is disturbed when the teeth or holes of the pole wheel pass the sensor. This disturbance is used by the sensor/measuring system to detect speed.

Note: Both the API Standard 670 and IEC 62061 specify that safety systems for overspeed detection should be a standalone system and not share components and or functions with e.g., the control system. This is to prevent a common failure to influence both systems at the same time. Therefore, the overspeed protection system and control system should have their own individual speed sensor.

Speed probe design considerations

Pole wheel geometry partially pre-defines the type of sensor that should be used. However, environmental and installation requirements are also important factors. Three commonly used speed sensors are:

- Variable reluctance (VR) sensors
- Hall-effect sensors
- Eddy current sensors

Variable reluctance (VR) sensors

VR sensors, also known as magnetic pick-up (MPU) sensors or electromagnetic sensors, are passive probes, generating an output voltage based on the size and rotational speed of the pole wheel. Due to their simple design this sensor type is most suitable for harsh environments.

A VR sensor cannot be used for low speed or zero speed detection. Also, the output voltage (amplitude), is based on speed and pole wheel geometry and can exceed 80 V_{RMS}. The advantages of VR sensors are the simplicity of their design and the high temperature range in which they can operate.

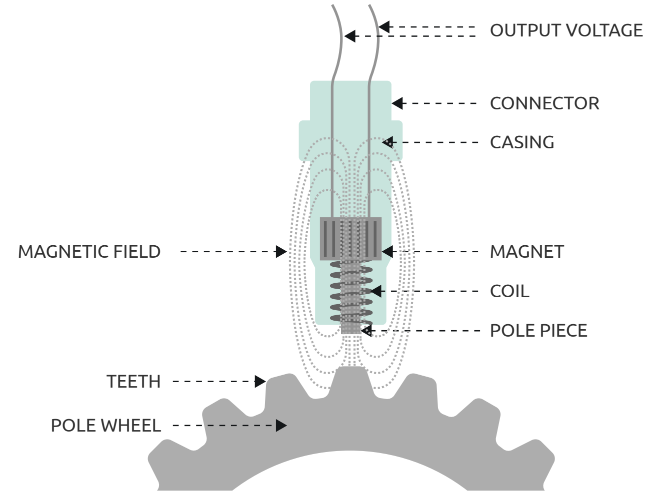


FIGURE 19 - OVERVIEW OF A VR/ MPU SENSOR APPLICATION

VR probe measuring principle

VR sensors are self-generating: they consist of a coil and a permanent magnet. When a ferro magnetic target (e.g., the tooth of a pole wheel) approaches the face of the sensor the magnetic flux changes through the coil, which then generates a voltage output.

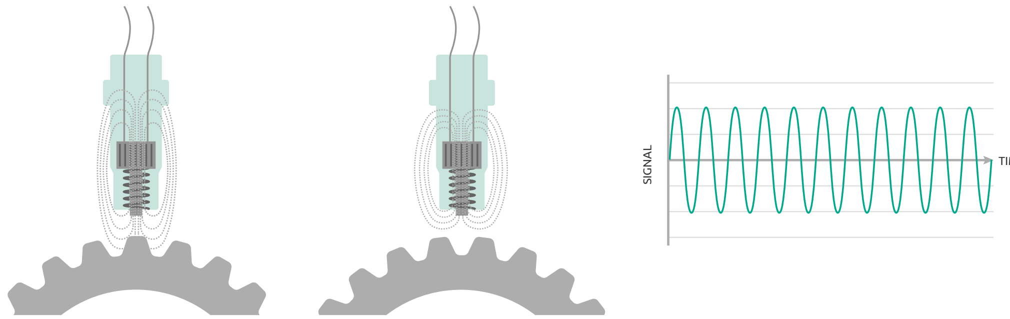


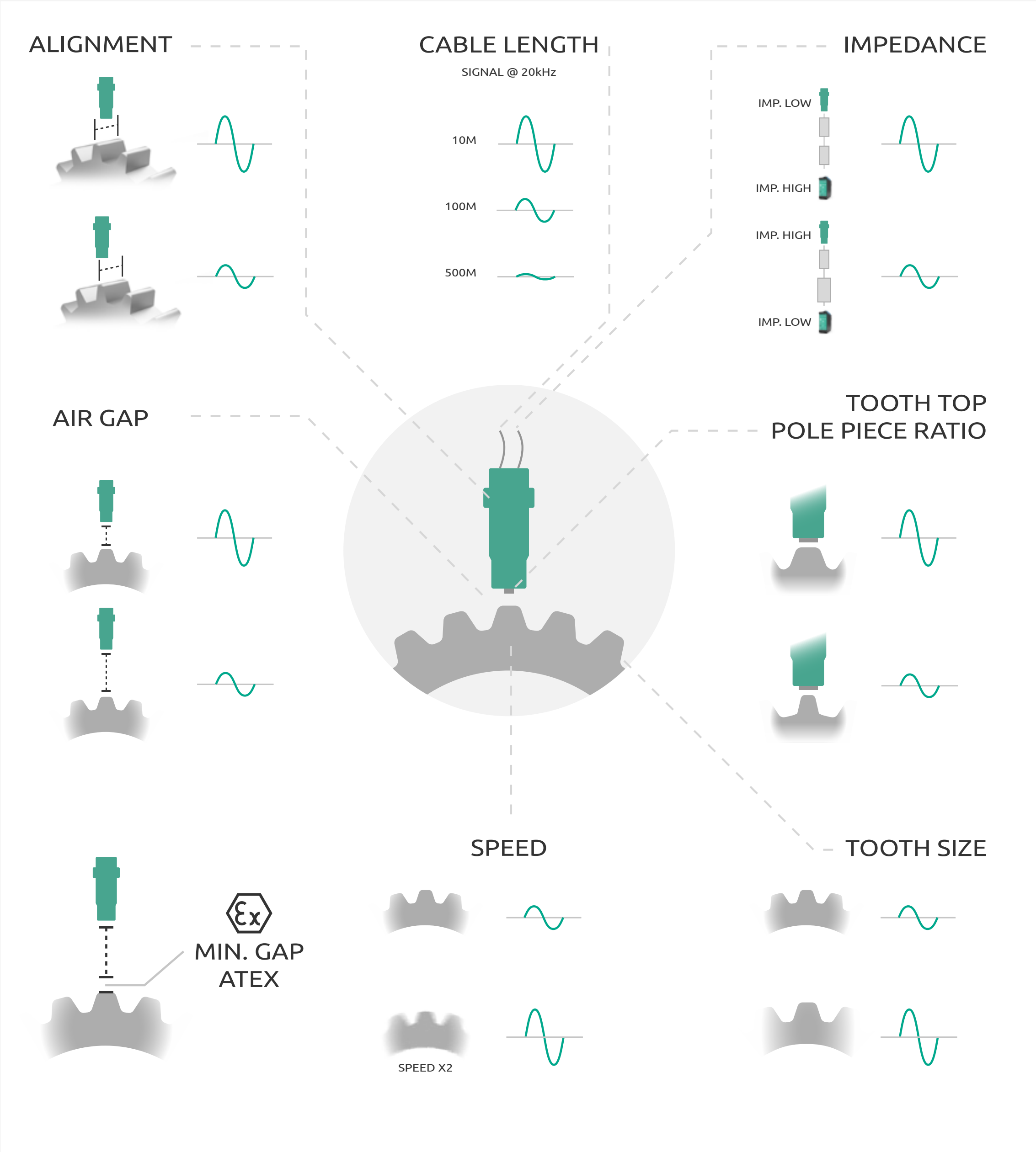
FIGURE 20 - SELF-INDUCED OUTPUT VOLTAGE BY A VR/MPU SENSOR

The amplitude of the output signal is related to the distance between the probe face and the pole wheel, the dimension of the teeth, and the rotational speed of the shaft.

Note: The diameter of the pole piece and inductivity of the coil are influencing the output level. These parameters are sensor model specific and embedded in the design of the sensor, the influence on the signal output is only generically discussed in this bookazine.

Note: For illustration purposes, all the situations are presented with a perfect sinusoidal signal. This can only be achieved in ideal situations. In practice the waveforms will be more complex.

Overview of the parameters affecting the VR speed sensor outputs.



Hall-effect sensors

Hall-effect sensors can detect changes in magnetic flux. When combined with an integral magnet, they can detect the changes caused by the teeth of a pole wheel. The advantages of Hall-effect sensors are the capability to detecting zero speed and a square wave output.

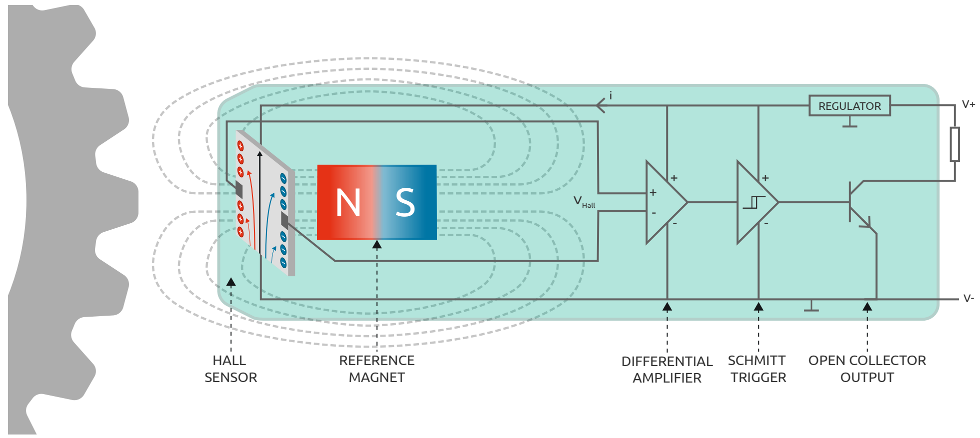


FIGURE 21 - THE HALL-EFFECT MEASURING PRINCIPLE.

Hall-effect measuring principle

The measuring principle of the Hall effect sensor is based on the influence of a magnetic field on a current. The basis is a current passing through a semiconductor (e.g., a rectangular slice of gallium arsenide). When the semiconductor is placed in a magnetic field non-parallel to the current, the current will be affected as a result of the Lorentz force. The electrons will be forced to move more alongside one edge of the semiconductors. This results in a potential difference between the two sides, known as the Hall effect.

The output (V_{Hall}) is proportional to the strength of the magnetic field and inversely to the alignment of the magnetic field with the current through the semiconductor. In the case of a speed measurement the sensor senses the passing teeth of the pole wheel as they are affecting the magnetic field, which is present because of the reference magnet, that passes through the Hall-effect sensor. This periodical signal (V_{Hall}) is fed through the integrated signal conditioner. This signal conditioner switches the output on when the V_{Hall} passes a predefined trigger level, and off when it drops below this trigger level. This creates a square wave output signal.

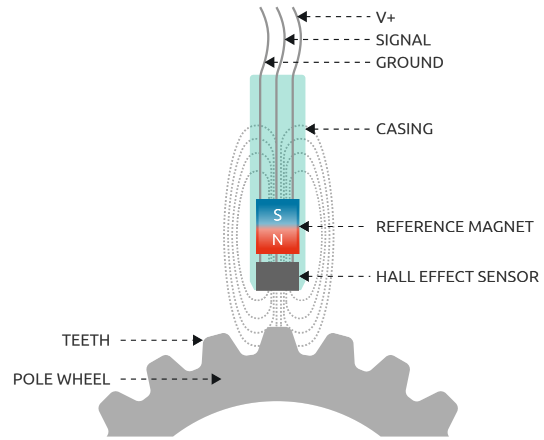
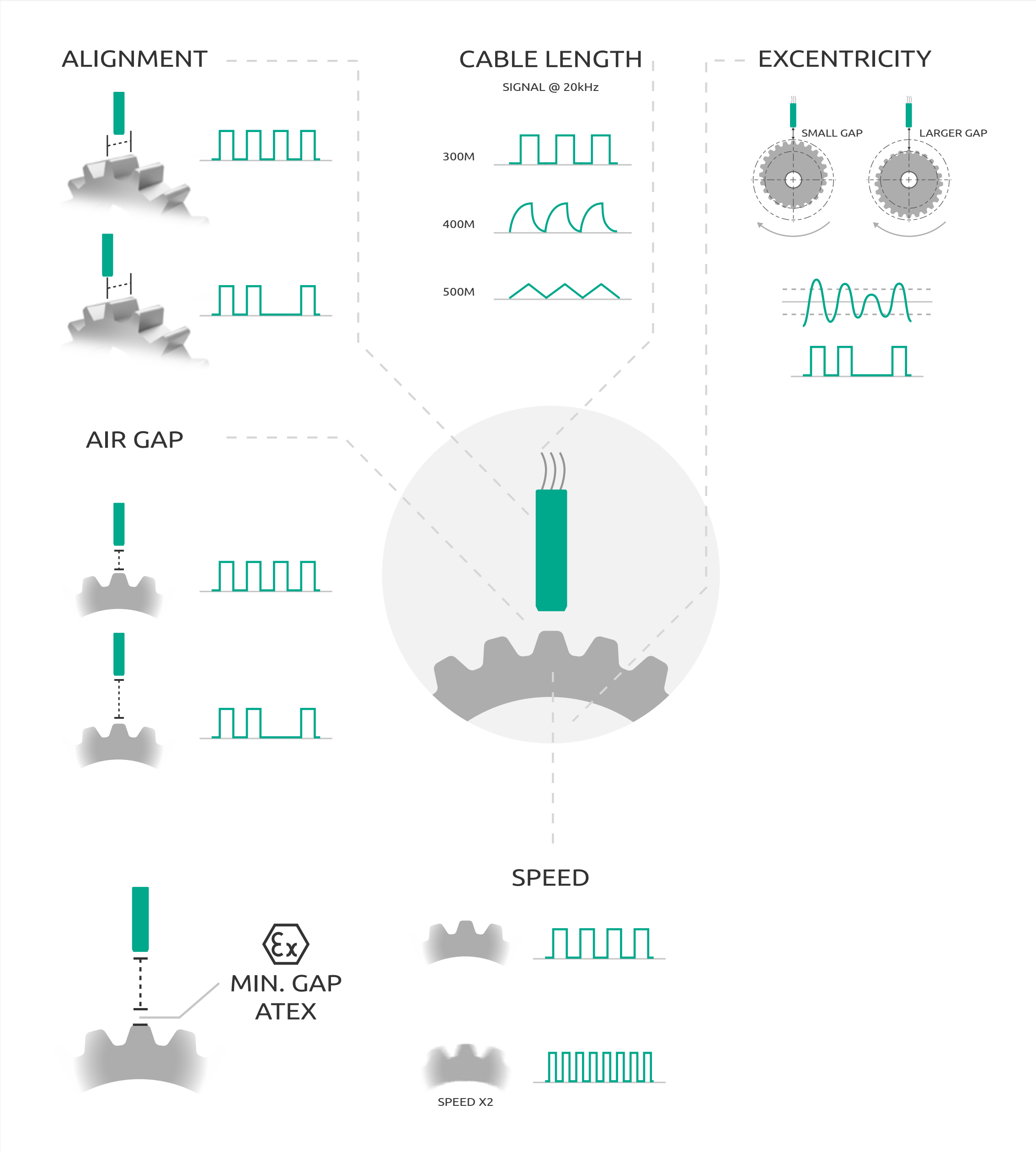


FIGURE 22 - THE HALL-EFFECT SPEED PROBE.

Overview of the parameters affecting the Hall-effect speed sensor outputs.



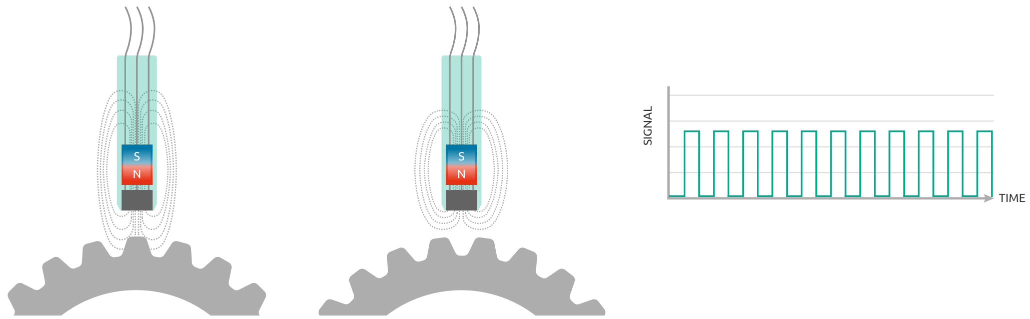


FIGURE 23 - OUTPUT SIGNAL OF A HALL-EFFECT SPEED PROBE

The rising edge of the output signal occurs when the teeth approach the speed sensor, the falling edge occurs when the teeth move away from the sensor.

Eddy current sensors

Eddy current sensors generate their own oscillating magnetic field. The oscillating frequency of the magnetic field changes with the presence of metals. The advantages of eddy current sensors are the capability to measure the distance of the pole wheel when dynamic current drivers are used. The signals can be used for very long cables.

Note: the information below is based on the dynamic eddy current probe. The reason for this is that there are voltage-based and current-based probes available, with different wiring and characteristics. The current-based probe allows for more cable length and is a 2-wire system as opposed to a 3-wire system thus allowing to use standard two wire cabling. The dynamic eddy current probe features internal diagnostics to reach the highest SIL-rating (SIL 3 in a 2oo3 configuration).

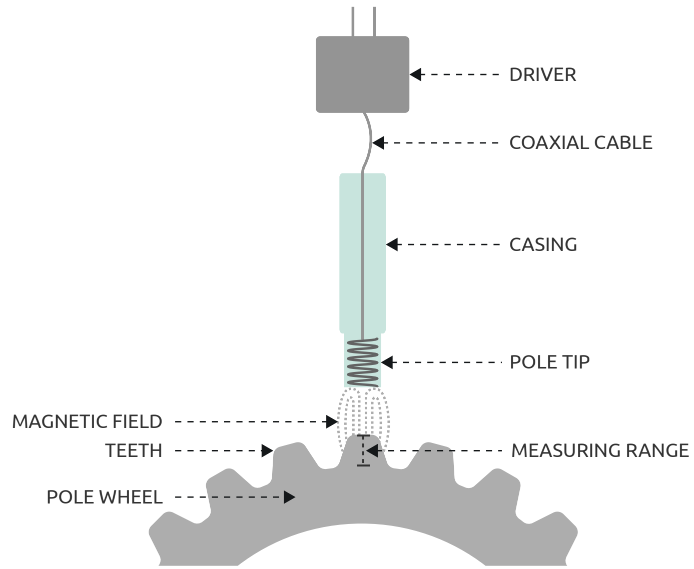
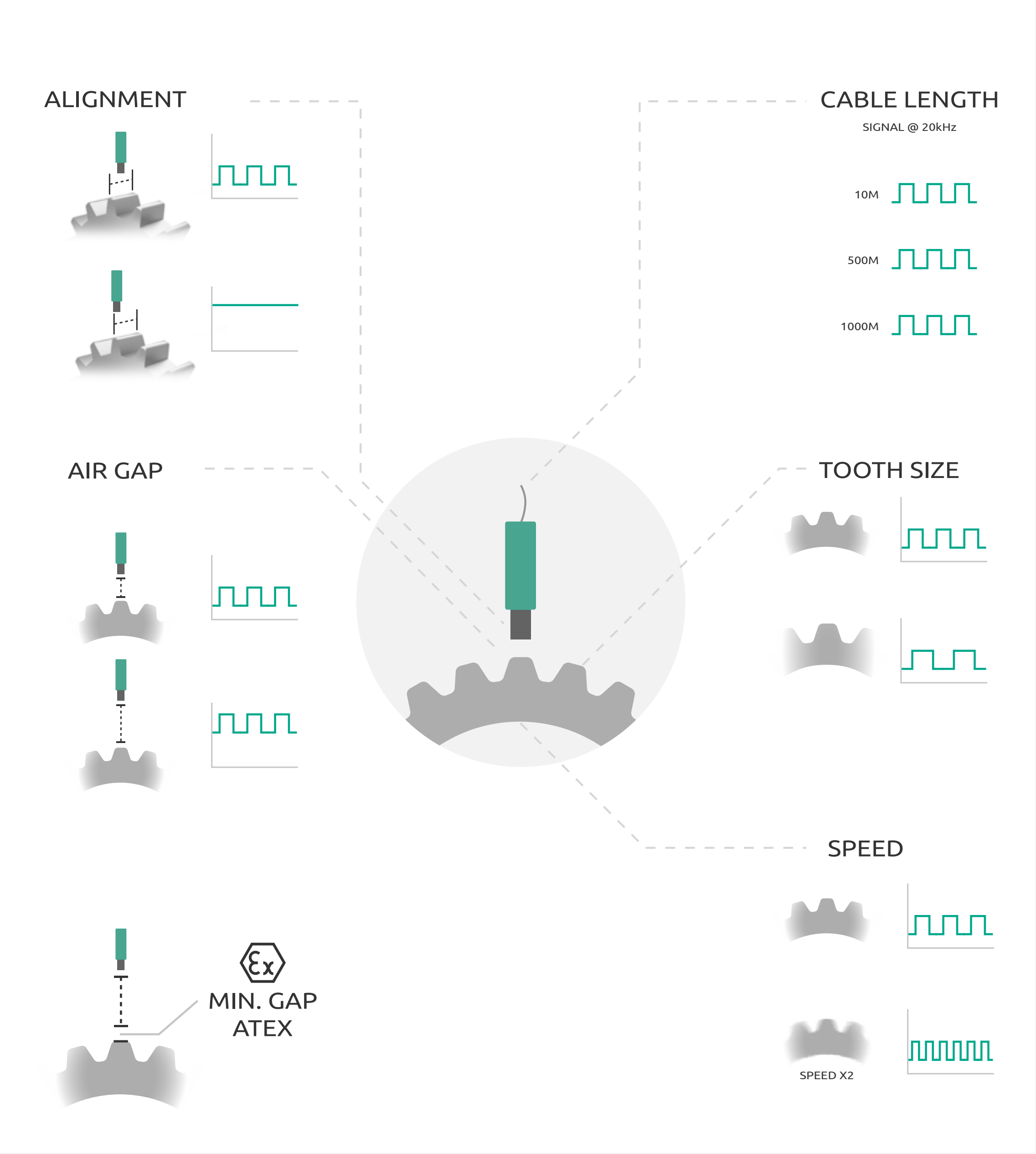


FIGURE 24 - OVERVIEW OF AN EDDY CURRENT SPEED SENSOR APPLICATION.

Overview of the parameters affecting the eddy current speed sensor outputs.



Eddy current measuring principle

Eddy current sensors consist of a probe, connection cable and a driver (oscillator). The driver generates an oscillation frequency which is dependent of the cable length and coil inductivity but is significantly higher than the frequency coming from the rotating pole wheel. When the coil is facing a metal object the oscillation frequency changes. This change is proportional to the distance between the target and the probe tip.

The amplitude of the output signal is independent of the distance between the sensor tip and the pole wheel, if the top of the teeth and the notch between the teeth are within the measuring range of the sensor.

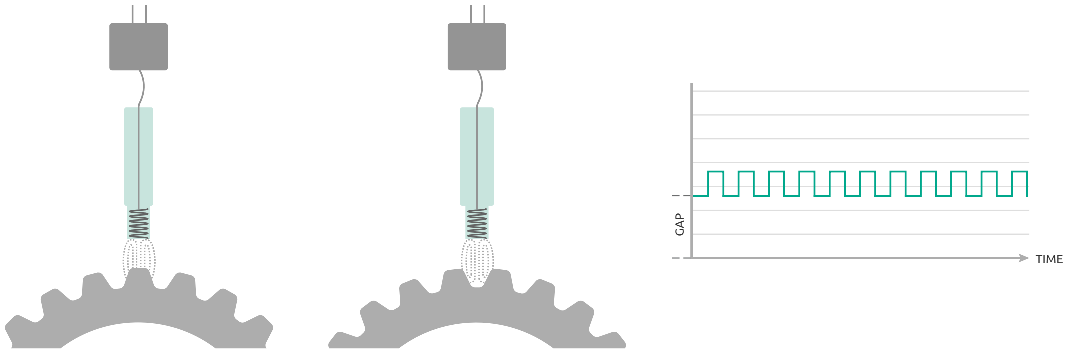


FIGURE 25 - EDDY CURRENT PROBE OUTPUT SIGNAL, BASED ON DISTANCE MEASUREMENT.

Note: eddy current probes come with a pre-defined measuring range. Industry standards are 2mm, 4mm or 12mm. To select the right eddy current probe type it must be considered that the distance from the sensor tip to pole gap bottom shall fall within the pre-defined measuring range of the probe.

Note: All the situations are presented with a square wave signal. This can only be achieved in ideal situations. In practice the waveforms will be more complex.

Note: When the tooth is too small and the measuring range of the eddy current probe in relation to the tooth to large, this signal will look like a sinusoidal signal with a small amplitude.

Output relative to the gap position

- The signal amplitude is constant and independent of the distance between the sensor and the measurement surface; When the distance increases too much the sensor will detect a “sensor not OK”, disable itself and drive the output to a sensor not OK level.
- The static distance from the probe to the pole wheel can be verified by monitoring the DC value of the output of the driver.

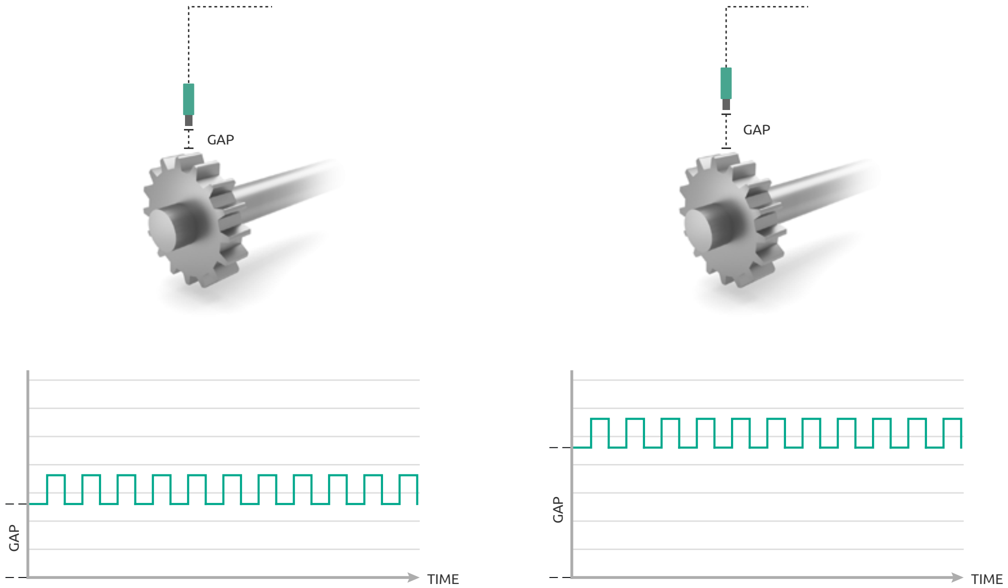


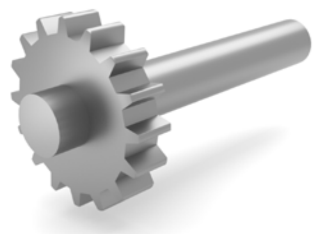
FIGURE 26 - THE GAP AFFECTS THE OUTPUT OF THE SIGNAL AS LONG AS THE DISTANCE BETWEEN THE TIP OF THE PROBE AND THE BOTTOM OF THE POLE GAPS ARE WITHIN THE MEASURING RANGE OF THE SENSOR.

Shaft/pole wheel

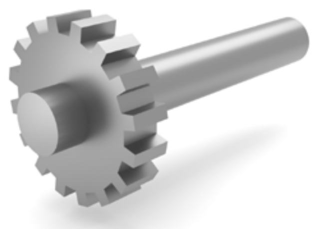
A pole wheel is designed to provide a speed sensor with a suitable target to generate a signal with enough resolution to adequately perform speed control or detect overspeed and enough body to have a solid signal-to-noise ratio.

Pole wheel design considerations

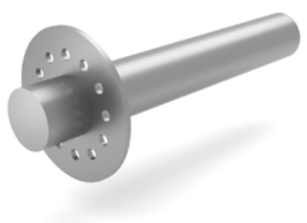
- The notch/ hole size must be suitable for the sensor type.
- The notch/ hole shape must be suitable for the sensor type.
- Pole wheel edges should be rounded off and have a smooth surface.
- Pole wheels should, in the case of Hall or VR probes, generate sufficient magnetic flux for the speed sensor to detect the passing teeth.



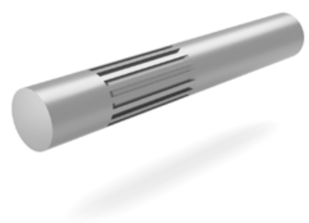
Pole wheel with involute teeth



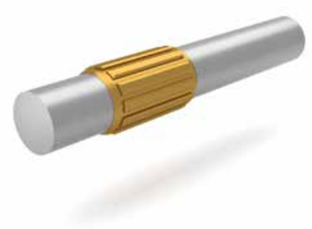
Pole wheel with squared teeth



Pole wheel with holes



Slotted pole wheel



Pole band

“Module” of a gear

The size and shape of the teeth of a pole wheel have a significant impact on the reliability of a speed measurement. For an overspeed detection system (ODS) a higher number of teeth makes the detection of overspeed faster. On the other hand, more teeth on the same diameter makes the size of the teeth smaller. When the teeth are too small, the amplitude of the signal will be too low, which may result in the system failing to detect individual teeth.

Pole wheel geometry

Due to the measuring type and sensor design, each type of speed sensor has its own specific physical limitation. For each sensor type and model the allowable pole wheel dimension is specified. This is generally done with a parameter called module (M). The module (M) defines the compatibility of two involute shaped gear wheels to fit each other.

DIN 780 specifies how the “module” number defines the gear wheel dimension.

For involute gear wheels the following simplified geometric relationship is applicable: $M = d_k/(Z+2)$

M = module
d_k = outer diameter
Z = number of teeth.

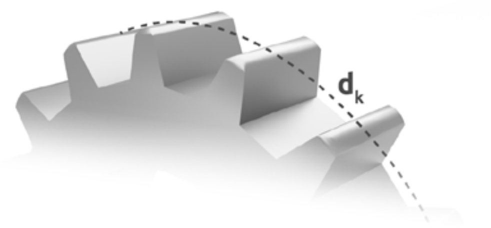


FIGURE 27

This shows that gear wheels with the same module almost have the same tooth dimensions regardless of the wheel’s diameter. For equal circumferential velocity they will generate almost the same output.

Note: for involute gear wheels, the “module” automatically defines the tooth height and dimension of the tooth top. When used for other pole wheel shapes like slotted pole wheels, the tooth height needs special attention to ensure that the tooth dimensions are suitable for the application.

Target material; Hall-effect sensor or VR probe

The reference magnet of a Hall effect speed sensor or VR probe maintains a stable magnetic field. The teeth of the pole wheel create continuous moving targets while rotating. For the probe to detect the moving teeth, they need to influence the magnetic field. This only happens when the teeth are made of a ferrous metal, such as:

- Iron
- All common carbon steel
- Ferritic stainless steel (e.g., 416, 430)
- Small magnets can be integrated in the blade tips to enhance the change of the flux.

Non-ferrous materials are not suitable, such as:

- Aluminium
- Brass
- Austenitic stainless steel
- Materials with an 8%CrNi plating

The selection of a suitable material is important; a Hall-effect speed sensor will not work with a non-ferrous target material. The alternating passing of ferrous metal targets changes the flux and consequently the voltage output of the sensor.

Note: Enclosed “strong” magnetic fields in the pole wheel can also lead to the disturbance of the speed signal.

Target material; eddy current sensor

Eddy current proximity probes generate an oscillating magnetic field this oscillating magnetic field is influenced when electric conducting materials are within the range of the probe. The suitable target materials are required to be of a material that can influence the electromagnetic field generated by the probe, including:

- Iron
- All common carbon steels
- Ferritic stainless steel (e.g., 416, 430)
- Brass
- Aluminium
- Austenitic stainless steel

Pole wheel mechanical considerations

One of the key aspects is the clearance between the sensor and the pole wheel.

The following aspects need to be considered:

- Eccentricity (radial movement). For radial speed measurements it is important that the eccentricity of the pole wheel is known and incorporated in the design of the set-up.
- Axial movement of the pole wheel in combination with radial mounted probes (influencing the alignment of the speed sensor in a radial measurement set-up).

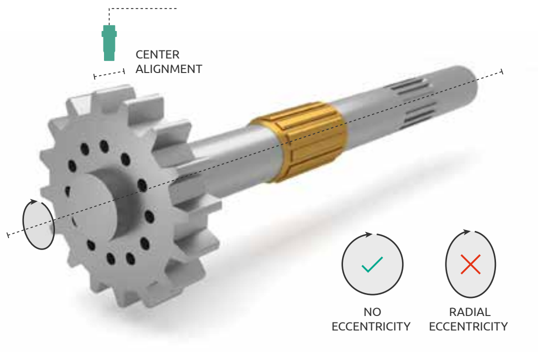


FIGURE 28 - ECCENTRICITY ON A POLE WHEEL.

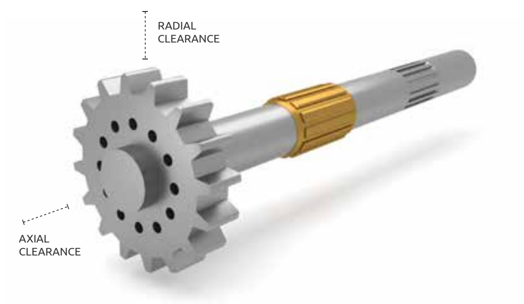


FIGURE 29 - RADIAL AND AXIAL CLEARANCE ON A POLE WHEEL.

- Axial movement. Both mechanical and thermal clearance may never result in the loss of the speed measurement.

Example 1: Hall-effect sensor output relative to eccentric or axial movement

Hall effect speed sensors measure the changes in the strength of the magnetic field. The sensor’s internal trigger level defines when a pulse is detected. The trigger level is fixed and defined in the design of the sensor.

In an ideal situation, the changes are only caused by the tooth of a pole wheel. However, in practice, especially with sleeve bearings, there is an additional eccentric or axial movement that causes a periodical offset. As a result, the air gap between the probe and teeth of the pole wheel varies once per revolution. The eccentric movement is superimposed as an amplitude change on the analogue signal. As a result, the frequency of the output signal can be influenced, if the eccentric movement is significant.

- Air gap changes mainly occur in sleeve bearing applications since sleeve bearings allow for a certain clearance within the bearing, both in radial and axial direction.
- When the eccentricity exceeds the allowable levels, the signal can drop below the trigger level and be lost. This leads to missing pulses.

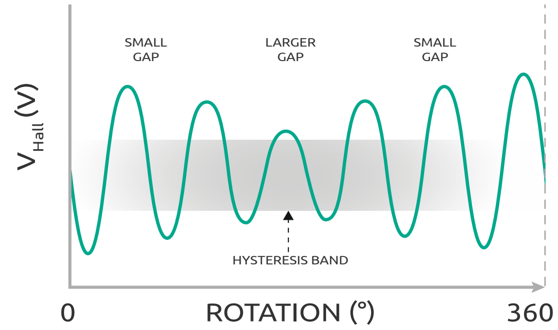


FIGURE 30 - INFLUENCE ON THE V_{HALL} VOLTAGE CAUSED BY ECCENTRIC RADIAL MOVEMENT.

Note: To have a defined pulse detection, a trigger level with a hysteresis band is used. The trigger needs to pass the upper level to be detected and to drop below the lower level to be released.

Note: When the speed probe is mounted in axial direction, axial movement of a shaft will show the same periodical behavior as radial eccentricity.

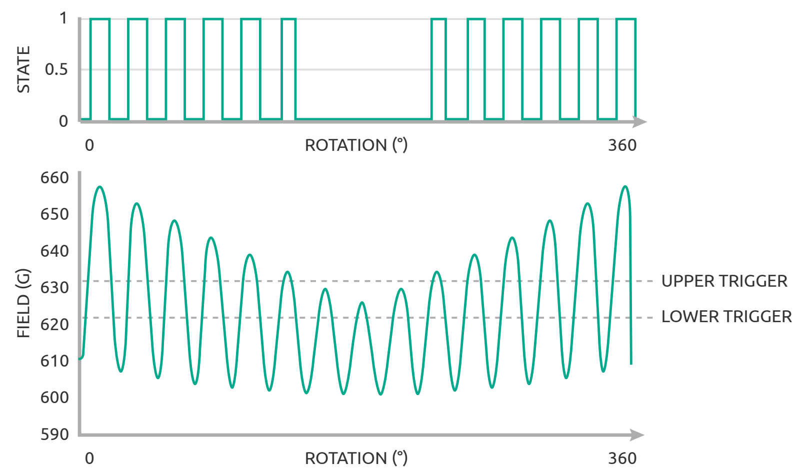


FIGURE 31 - INFLUENCE OF SIGNAL OUTPUT CAUSED BY ECCENTRIC RADIAL MOVEMENT.

Note: a typical maximum radial eccentric movement for Hall sensors is ≈ 0.2 mm.

Note: a typical maximum axial eccentric run-out for Hall sensors is difficult to define. The normal assumption is that, in the case of a sleeve bearing with axial positioned speed sensors, the shaft is always pushed to one side of the bearing and the axial run-out is minimal. In the case of high axial movement ≥ 0.2 mm, an axial positioned speed sensor should not be used.

Example 2: eddy current sensor output relative to eccentric or axial movement
Eddy current speed sensors measure the changes in the distance to the target. If changes in the distance are not only caused by the distance between tooth of a pole wheel relative to the sensor but also by eccentric movement the sensor will register the complete behaviour.

In an ideal situation the changes are only caused by the tooth of a pole wheel. However, in practice, especially with sleeve bearings, there is always an additional eccentric or axial movement that gives a periodical offset the whole pole wheel, which consequently narrows and widens the air gap. The eccentric movement is superimposed as an amplitude change on the analogue signal. As a result, the frequency of the output signal can be influenced, if the eccentric movement is significant.

Typically, the allowable eccentricity should be smaller than 10% of the amplitude of the measured dynamic signal. The pole wheel and application eccentricity can influence the output.

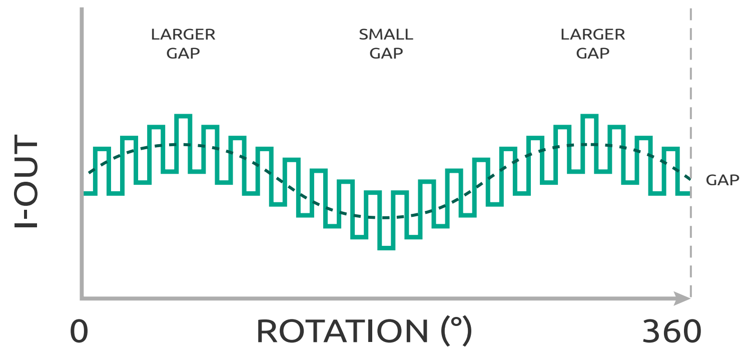


FIGURE 32 - EXCESSIVE ECCENTRICITY AFFECTING THE SIGNAL OF AN EDDY CURRENT SPEED PROBE.

Pole wheel failure modes

- Radial eccentricity must be as low as possible, typically less than 0.2 mm for Hall-effect sensors or 10% of the dynamic signal amplitude of eddy current probes. The eccentricity consists of the mechanical eccentricity and the bearing clearance. Excessive eccentricity can lead to unstable speed measurements or even the loss of pulses.
- Axial clearance (mechanical and machine expansion due to temperature changes) must be incorporated in the width of the pole wheel design and alignment of the speed sensor. Excessive axial clearance may lead to loss of pulses or additional pulses and could damage the speed sensor.
- Rough edges of the gear teeth may lead to additional or loss of pulses.

- The pole wheel or other target material must create a suitable change in magnetic flux in the sensing element. A permanent magnet is normally provided in the sensor for this purpose.

Pole wheel verification points

Position and alignment

- A non-contact speed sensor must be correctly aligned with the target. Axial movements of the shaft due to mechanical clearance or temperature changes may cause a positional offset that stops the sensor from functioning. This could lead to intermittent measurement problems.
- Check the shaft axial movement.
- Electromagnetic (VR) sensors induce a voltage output which is the result of the change in magnetic flux caused by the passing teeth of the pole wheel and of the gap between the probe and pole wheel. If the shaft is not running correctly or vibration is present, the sensor's output voltage may vary during one revolution, or additional pulses might be induced in the sensor. Excessive magnetic or mechanical shaft run-out may cause the permissible measuring range to be exceeded, resulting in the sporadic loss of signal.
- Check the shaft run-out and vibration.

Air gap

- Under all operating conditions, the air gap must be kept within the permissible range of the sensor, based on the pole wheel being used. Contact between the sensor and the pole wheel must be avoided.
- Check whether the air gap setting is appropriate for the sensor.

Note: in some set-ups insufficient clearances may be in conflict with applicable ATEX guidelines.

Pole wheel

- The pole wheel must not be magnetised or become magnetised during operation.
- For Hall-effect sensors and VR probes the pole wheel must be ferro-magnetic with low remanence. Stainless steel and plating with more than 8% CrNi are not suitable.
- For eddy current sensors the pole wheel needs to be suitable for electromagnetic signals.
- Check the material and whether the wheel is magnetised.
- Technical data of the sensors to use specifies which pole wheel shapes and dimensions are allowable. These parameters are expressed as a module number.

Tooth profile and geometry

- For Hall and VR sensors the centre of the sensor must typically remain within 3 mm of each edge of the pole wheel under all operating conditions. A pole wheel width of less than 10 mm is undesirable as this would impose tighter installation and operating tolerances.
- For eddy current sensors the pole wheel width needs to be at least three times the probe diameter.

Speed sensor requirements

The previous chapter describes the functionality of the various speed sensors. This chapter describes the additional behaviour and requirements of speed sensors.

Mounting requirements

The mounting requirements for a Hall-effect and eddy current speed sensors are straightforward:

- Radial and axial alignment must be within the specified tolerance of the sensor.
- All sensors require sufficient stiff mounting brackets.

For a VR sensor, additional parameters need to be considered to guarantee an output signal with a sufficient amplitude.

VR probe mounting considerations

Due to the measuring principle, VR probes require special attention to guarantee that during the full range of the operational speed the amplitude is compliant with the measuring system. Since VR sensors are self-generating, they are not depending on an external power source.

The output signal is not only affected by the pole wheel geometry, rotating speed, and distance to the pole wheel, but also by the sensor design and the load impedance (input impedance from the measuring device) applied to the sensor.

VR sensors designed for pole wheels with a low “module” number are typically small with a high impedance coil (e.g., 10.000 Ω). This is due to the number of windings, the pole piece diameter, and the wire diameter.

Sensors designed for a higher module numbers are more robust and have coils with a larger pole piece diameter, fewer windings and a larger wire diameter. This results in a lower impedance (e.g., 3000 Ω).

Coil Impedance	Compliance with pole wheel dimension
280 Ω	“module” 2-3-4
3.000 Ω	“module” 1-2-3-4
10.000 Ω	“module” 0,5-1-2

EXAMPLES OF SUITABLE POLE WHEEL DIMENSIONS RELATED TO THE COIL IMPEDANCE.

The examples in figure 33 show how the output signal behaves with respect to the gap and the gear wheel module, with a constant circumferential velocity of 15 m/s.

Note: the circumferential velocity is affected by the pole wheel diameter and the rotational speed.

General speed sensor and mounting considerations

- Minimum allowable probe distance to the pole wheel must be guaranteed.
- Alignment between probe and pole wheel must be guaranteed.
- Environmental conditions need to be compliant with the specification.
- Rapid thermal cycling needs to be prevented.
- Maximum allowable vibration levels should not be exceeded.
- Maximum cable length needs to be considered.

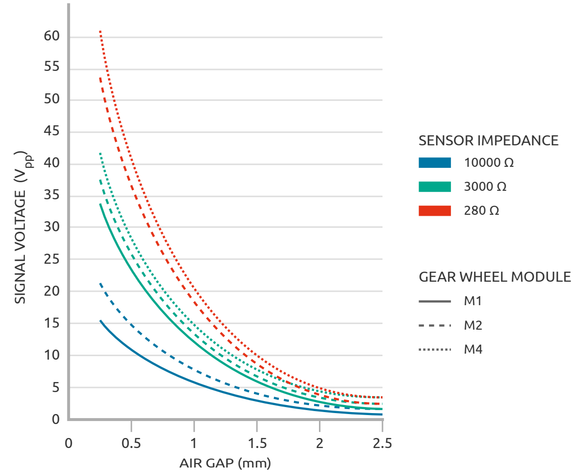


FIGURE 33 - FOR CLARITY ONLY
M1, M2 AND M4 ARE SHOWN IN THE FIGURE

Speed sensor and mounting verification points

Alignment of the sensor relative to the pole wheel

- Check alignment and gap.

Insufficient air gap

- Check the distance between sensor and pole wheel.
- Check whether the front of the sensor wall is damaged.
- In the case of ATEX requirements, verify if the required minimum gap is guaranteed.

Environmental conditions are exceeding the probe specification

- Check temperature range.
- Check vibration and impact level.

Unstable speed signal

- Check the mechanical mounting of the probe.
- Check if the distance between the probe and pole wheel is compliant with the sensor/application.
- Check supply voltage range.
- Check supply ripple & noise.
- Check current drawn.
- Check output signal levels over the speed range.

Electromagnetic interference

- Check for magnetic fields around the sensor.

Cabling / connector

A speed sensor can have an integral cable or a connector. The cable must be suitable for the temperature range, environmental and mechanical conditions, and transmission distance.

Cable design considerations

The cabling must be suitable for the environmental conditions but also needs to have the right electrical parameters for its application. Cable length, (possible) ATEX-zone and signal type are the basis to specify the suitable cabling:

- Voltage versus current signals
- Maximum cable length
- In the case of a VR probe, a possible impedance mismatch between probe impedance and cable/ system impedance
- Environmental conditions such as temperature and moisture
- Environmental conditions such as oil or aggressive fluids
- Required cable length, wire cross section, twisted pair, individual / overall shield.
- ATEX requirements
- Mechanical load
- Integral sensor cable or connector

VR probe impedance mismatch

The cabling impedance, system input impedance and sensor impedance can lead to signal interference and signal loss. Based on the coil impedance and a system input impedance of 10.000 Ω/nF, the cable length is limited. Exceeding the specified maximum cable length may lead to a false signal interpretation.

Coil	Compatible cable length
280 Ω	300 metres
3.000 Ω	50 metres
10.000 Ω	20 metres

EXAMPLE OF THE CABLE LENGTH RELATED TO THE COIL IMPEDANCE AND SYSTEM IMPEDANCE.

Example: signal behaviour of a VR sensor in relation to the cable length

- Inductance at 1 kHz: 360 mH
- Resistance at 25 oC: 1.000 Ω
- Pole piece diameter: 5 mm
- Applied load impedance: 10.000 Ω
- Pole wheel module: 2

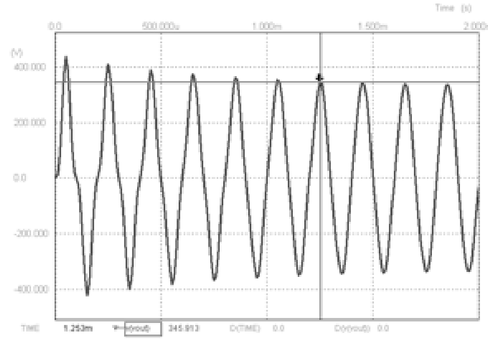


FIGURE 34 - OUTPUT SIGNAL 5M CABLE.

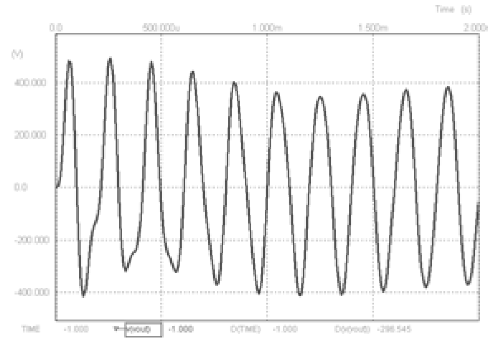


FIGURE 35 - OUTPUT SIGNAL 10M CABLE.

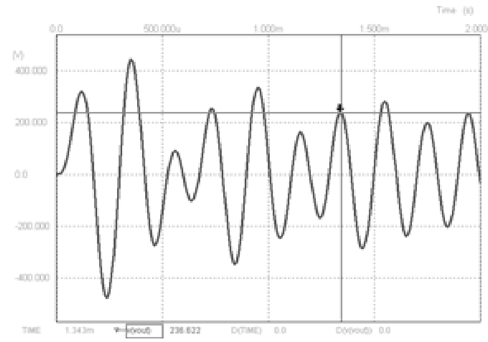


FIGURE 36 - OUTPUT SIGNAL 100M CABLE.

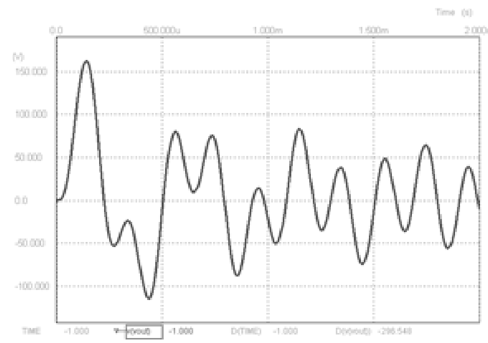


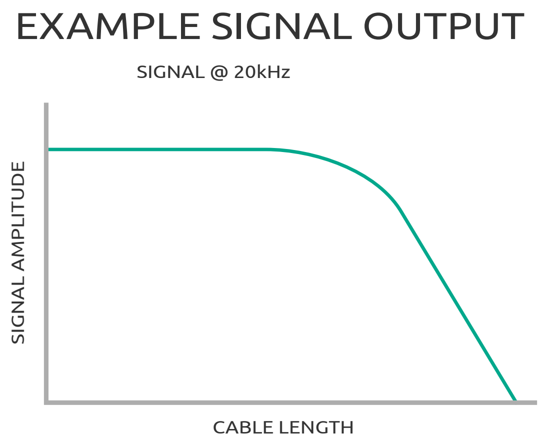
FIGURE 37 - OUTPUT SIGNAL 300M CABLE.

Low-pass filtering due to cable length

For 3-wire voltage eddy current probes the cable length has a different influence than for a 2-wire dynamic current eddy current probes.

Besides a possible impedance mismatch, cable length also has an impact on the maximum measurable speed. Due to the capacitive and resistive value of the cable, the cable can work as a low-pass filter. This means that the longer the cable, the lower the maximum measurable frequency will be.

A typical industrial data cable will have a low-pass filter frequency of 20kHz at 300m of cable. This means that for cables that are longer than 300 metres the signal amplitude is strongly reduced (-3dB/Octave).



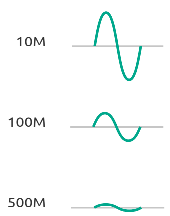


FIGURE 38A - EXAMPLE OF THE LOW-PASS FILTER FUNCTION OF A TYPICAL INSTRUMENTATION CABLE FOR A DYNAMIC SINUSOIDAL VOLTAGE SIGNAL.

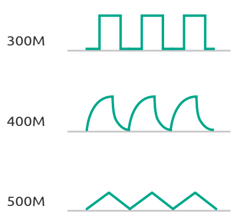


FIGURE 38B- EXAMPLE OF THE LOW-PASS FILTER FUNCTION OF A TYPICAL INSTRUMENTATION CABLE FOR A DYNAMIC SQUARE WAVE VOLTAGE SIGNAL.

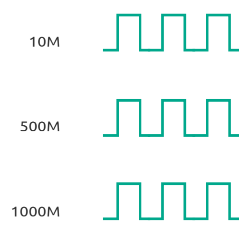


FIGURE 38C - EXAMPLE OF THE LOW-PASS FILTER FUNCTION OF A TYPICAL INSTRUMENTATION CABLE FOR A DYNAMIC SQUARE WAVE CURRENT SIGNAL.

Cabling properties

Field cabling has its own influence on the sensor output signal. The sensor wires are susceptible to radiated noise. The best engineering practices for field cabling are:

- The sensor cables must have a foil shield with 100% coverage and a braided outer shield with at least 80% coverage (mesh density) connected to the overspeed protection system.
- The cable capacity should be as low as possible. E.g., 90pF/metre
- The wiring cross section must be suitable for the distance and signal current.
- Cable bending radius / flexibility meeting the application requirements

Cable mounting requirements

After selecting the right cable, the cable needs to be carefully mounted to prevent signal distortion.

- The cable route should not be parallel to high voltage cables to prevent distortion.
- The cable shielding should be continuous, single-ended connected to ground.
- Cables should be mounted inside cable ducts or conduits to prevent mechanical damage.
- The cables should not exceed the maximum allowable bending radius.
- The cables should be protected from aggressive/ harsh environment influences.
- All speed signal cables for safety functions using a voting structure need to be installed separately, with separate paths. Thus, not in a single multicore or bundled together.

Cable failure modes

Cable length not suitable for application

- Verify signal shape.

Cable quality

- Check cable properties.

Open or short wired cables

- Check cable for damages, check for loose connections.
- Shielding issues: the most common problem with cabling is that the shielding is not properly handled. Signal shields should be run back to the instrumentation, without interruption and without being connected to any earth (or earth/shield rails). Improper screening can result in significant signal interference.
- Check signal screening all the way from the sensor to the instrument.

Harsh environments

- Check for aggressive fluids and or mechanical load.
- Standard PVC cables should not be used where oil is present. If this is the case, Teflon cables should be specified.
- When harsh mechanical conditions are present, verify whether a protective hose or special cable is used.

Cable routing

- Cable bending can lead to damaged insulation and or screens, leading to spurious speed measurement failures.
- Check cable data sheets for guidance on the minimum bending radius. These are static values.

Connectors

- Any form of termination represents a potential failure mode. Mechanical or environmental damage is normally self-evident.
- Check for loose/bent contacts.
- Check for moisture ingress.
- Check broken cable connection.
- Check for ultimate tensile strength of cable connection.
- Check for maximum bending radius of the cable.

Magnetic run-out

- Check for magnetic fields near the sensor.

Input interface

Input interfacing can have several functions:

- Signal isolation (e.g., improvement of signal-to-noise ratio)
- Signal isolation to meet the comply with ATEX guidelines.
- ATEX barriers, to comply with ATEX guidelines.
- Pre-amplifiers to enhance the measured signals

Input interface design considerations

Input interfacing is typically used to either meet ATEX requirements and/or enhance signals to achieve a better signal-to-noise ratio or being able to drive longer cables.

The interface can be either close to the sensor mounted in an enclosure, mounted inside an instrument cabinet or be part of the speed measuring device. The working principle is independent of its mounting location.

The following aspects need to be considered:

- Signal isolation. In the case of poor signal-to-noise ratio, select an Isolator to improve signal quality.
- Pre-amplifiers. Consider the min-max output signal for the application in relation with the cable specification and establish whether pre-amplification is required for the chosen pole wheel / speed sensor solution.
- ATEX requirement. Establish which limiting parameters are applicable based on the required zone classification and select the appropriate Zener barriers or isolators.

Input interface installation requirements

- The cable route should not be parallel to high voltage cables to prevent distortion.
- The single-ended screen concept must be maintained.
- Field mounted isolators / pre-amplifiers / barriers must be installed inside enclosures compliant with the environmental and/or ATEX requirements.
- Special measures need to be taken to ensure that the field installation is compliant with the ATEX directive. Specific items to consider are gas tightness of cabling and the field enclosure certification.

Note: in the case of isolators, many overspeed systems lose the ability to use sensor OK monitoring and can therefore not validate if the sensor signal is valid or not.

Isolators and barriers

When Hall-effect speed sensors are used in a hazardous zone with explosive atmospheres (gas or dust), special precautions need to be taken to reduce the risk of speed sensors becoming an ignition source. Two solutions are distinguished to avoid dangerous energy levels entering the explosive area: isolators and barriers.

Zener barrier
A Zener barrier is used to limit the maximum allowable energy that can enter a hazard zone (explosive area) by means of passive components.

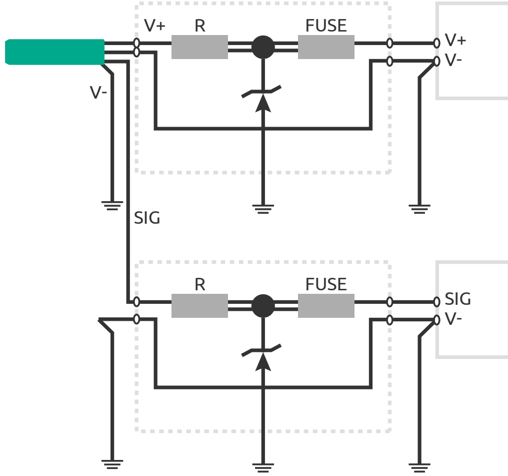


FIGURE 39 - TYPICAL ZENER BARRIER DRAWING FOR A 3-WIRE VOLTAGE SENSOR.

Isolator
An isolator is used to limit the maximum allowable energy that can enter a hazard zone (explosive area). An isolator also provides galvanic insulation between the hazard and non-hazard zone.

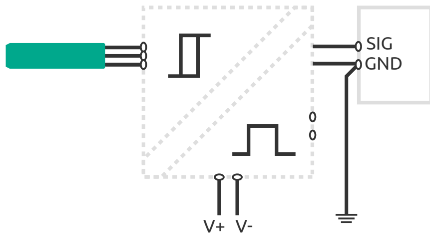


FIGURE 40 - TYPICAL ISOLATOR DRAWING FOR A 3-WIRE VOLTAGE SENSOR.

Note: The Explosive atmospheres – IEC 60079-14:2013: Electrical installations design, selection and erection section 16.3 Installations to meet the requirement of Equipment Protection Level (EPL) “Ga” or “da” states: “Associated apparatus with galvanic isolation between intrinsically safe and non-intrinsically safe circuits is preferred. Since only one fault in the equipotential bonding system, in some cases, could cause an ignition hazard, associated apparatus without galvanic isolation shall be used only if the earthing arrangements are in accordance with item 2) of 16.2.3. (16.2.3.-2 For TN-S systems only, connected to a high integrity earth point in such a way as to ensure that the impedance to the point of connection to the main power system earth point is less than 1 Ohm resistance.)”

Grounding and impedance
A major difference between a Zener barrier and an isolator is how the signal is transferred and connected to ground.

A Zener barrier is a passive pass-through device that increases the loop load. When unacceptable high voltages enter the hazard area through the barrier, the barrier drains the signal to the ground, or when the current is too high a fuse is blown. To be able to drain excessive voltages to the ground

the Zener barrier needs to be grounded intrinsically safe (IS). If the field is not galvanically isolated from the logic solver, it causes the risk of ground loops.

A Zener barrier cannot convert a voltage to a current signal which makes the signal less suitable for long cables.

An isolator is an active device and requires a supply voltage on the safe side to function. Due to the isolation, the sensor in the hazardous area is not connected to the same ground as the logic solver, eliminating the risk of ground loops. Also, an isolator normally reduces the loop load and therefore reduces the risk of losing signal quality.

An isolator can convert a current to a voltage signal, which makes the signal more suitable for long cables.

	Zener barrier	Isolator
ATEX certification	Available for all zone classifications	Available for all zone classifications
External Supply required	No	Yes
Reducing the risk of ground loops	No	Yes
Reducing the risk of influencing the signal quality	No	Yes
Signal conversion	No	Yes
Dedicated IS ground connection required which reduces inspection requirements	Yes	No
Auto recovering from high current	No	Yes
Reducing loop load	No	Yes
Improved noise level	No	Yes
Size	Typically, smaller than an isolator	Typically, larger than a Zener barrier

Integrated isolators
One of the disadvantages of an isolator is that the logic solver loses “sight“ of the sensor and is therefore no longer able to monitor the sensor behaviour. For safety systems this is a critical feature.

Using logic solvers with dedicated integrated isolators (by design) negates this issue and integrates the best of both solutions.

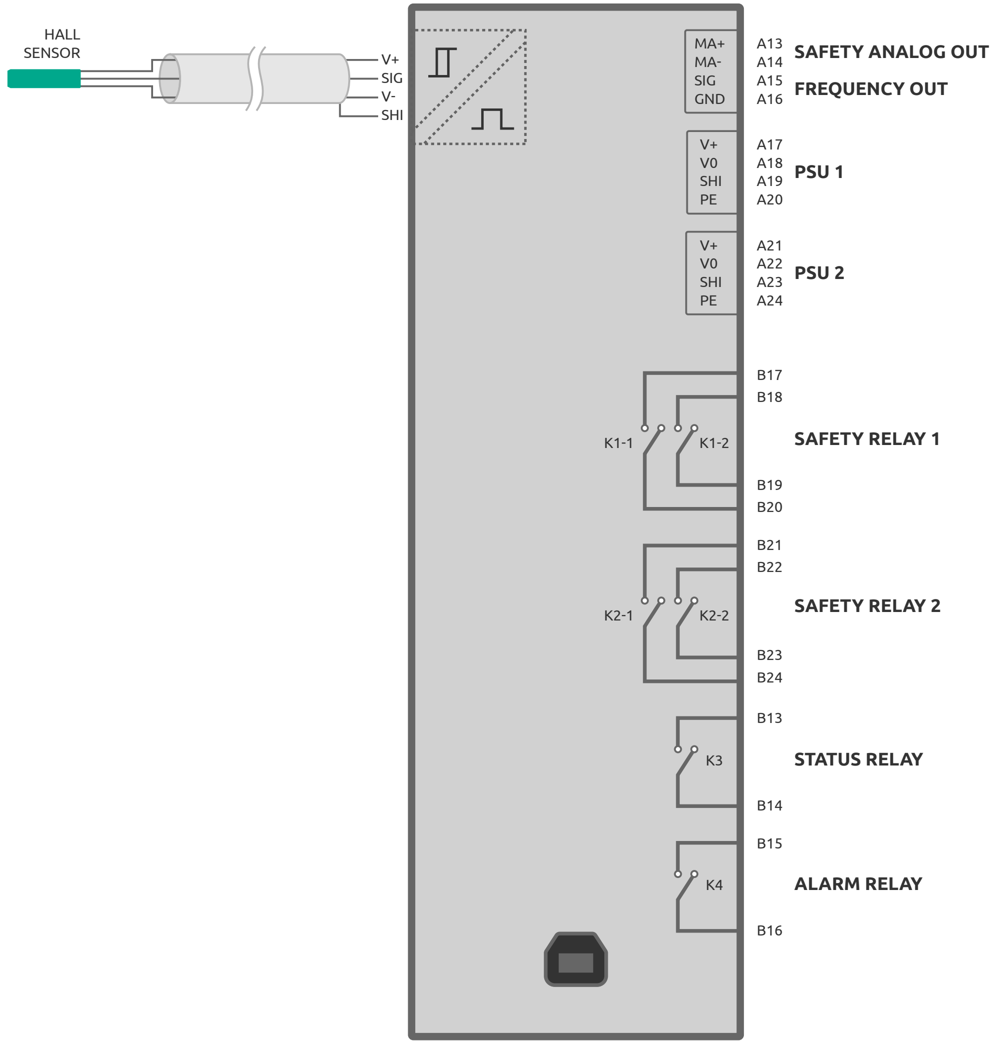


FIGURE 41 - EXAMPLE OF AN OVERSPEED PROTECTION SYSTEM WITH AN INTEGRATED ISOLATOR.

Input interface failure modes

Unstable speed measurements can be caused by a reduced signal amplitude caused by a signal drop over the Zener barriers, poor performance of pre-amplifiers, excessive cable length, crosstalk caused by either poor quality multicore cables or poor signal shielding.

If there is an unstable speed signal:

- Check supply voltage range.
- Check supply ripple & noise.
- Check current drawn.
- Check output signal levels over the speed range.
- Check cable quality.

Overspeed detection system

An overspeed detection system (ODS) can be seen as the logic solver of the overspeed protection system. It continuously measures the rotational speed of the machine by receiving data (frequency depending on signals) from the speed sensors. Using pre-defined system logic, the system can detect when a machine is rotating faster than allowed by its design specifications. To prevent significant damage to the machine, the ODS initiates a trip that causes the machine to shut down.

An overspeed detection system follows three phases:

- Input phase. During the input phase, the speed sensors provide frequency signals which, in combination with trigger levels, provide a pulse train. In combination with the number of poles of the pole wheel, rotational speed can be calculated. For further processing, values for nominal, maximum and minimum speed and speed acceleration are programmed.
- Processing phase. After validation by the ODS, the input signals enter the processing phase. The frequency data is then compared to the programmed values, in order to detect overspeed, underspeed, and/or excessive acceleration events.
- Output phase. The ODS digital safety outputs or analogue safety outputs are used to activate or deactivate the tailing equipment e.g., the emergency shutdown system and or emergency shutdown valves. This is typically done in a fail-safe configuration. Furthermore, alarm statuses can be connected to a monitoring system and non-safety analogue outputs are used for further processing by external systems or for display functions.

There are a few important things that should be considered for overspeed detection systems:

Critical safety functions versus other functions

According to leading machine protection standards, the core function of an overspeed detection system is to make sure no dangerous speeds are reached. To reach that goal, the system initiates a trip when the speed reaches its pre-defined speed limit threshold or when it accelerates excessively.

Any other speed related functions do not have the same criticality as overspeed and acceleration, as the potential consequences of their occurrence is of a different size and scale. These functions include reverse rotation detection, standstill/creep monitoring and general speed indication. These generally do not require advanced voting logics or frequent proof-testing and therefore, do not need to be embedded in the functional safety system. However, these functions can be part of the wider range of speed measurement equipment that includes monitoring and control. From a functional safety perspective, it would even be preferred to have these functions embedded in the control or monitoring layer and not in the safety layer, as any additional function and component can introduce new failure modes.

Sensor monitoring functions & self-monitoring

SIL-rated safety systems run continuous or frequent self-monitoring sequences to detect potential system failures. They aim for a high test-coverage to minimize the risk of undetected failures. Systems with a very high diagnostic coverage (near 100%) generally do not require intermittent testing.

Some systems are equipped with an on-board frequency generator to cover a gap in their diagnostic coverage. The frequency generator simulates the signal of a channel in order to check its response. As this function temporarily puts a channel out of order, it can only be applied in a redundant setup with 2oo3 voting logic. This clearly shows two weaknesses of this approach: (1) it only works for 2oo3 systems and therefore cannot be used on smaller equipment, and (2) the function can not be used if there is a faulty channel.

> ***To achieve high diagnostic coverage the system and sensor diagnostics should be embedded in the design of the overspeed system – it is not something you can fix later.***

An advanced ODS validates whether sensors are functioning properly. After all, defective sensor inputs should not compromise the safety of the machine. Depending on the voting structure, the system trips the machine when one or more sensors are not functioning properly. A point of attention on this subject is an internal versus an external ATEX isolator. An external isolator makes it impossible to monitor the sensor voltage, and subsequently the sensor status. This creates a gap in the diagnostic coverage for systems that do not have internal isolators.

A possible solution to circumvent this issue is dynamic sensor monitoring; a function that validates sensor input signals by internal value comparison. However, this too can only be used in a redundant 2oo3 voting structure, which makes it unsuitable for smaller equipment. In addition, it only works for sensor defects that appear on one sensor at a time. Failures on multiple sensors simultaneously will remain undetected, leaving another gap in the sensor monitoring. Therefore, for ATEX applications a system with an internal isolator can provide significant advantages over those with an external isolator. A system that does not need to rely on dynamic monitoring can have a better diagnostic coverage.

Proof-test intervals & lifespan

An overspeed detection system has a certain lifespan in which the OEM guarantees its proper functioning, given that the maintenance and commissioning guidelines are followed correctly. When the system has reached its end of life, it should be replaced for safety and reliability purposes.

To ensure safety and reliability during the useful life of the ODS, proof-tests should be performed. The frequency of these proof-tests depends on the instructions provided by the OEM, the SIL rating and the complexity of the system. Generally speaking: additional functions and components require additional testing. This underlines the argument to separate critical safety functions from other functions, to allow for longer proof-test intervals and to make a higher SIL-rating more accessible.

Response time

API Standard 670 5th edition states that an overspeed detection system may take up to 40 milliseconds to detect overspeed and switch the relay outputs. It is however expected that due to tightening safety guidelines the minimal response time will be shortened in future updates of this guideline. Modern overspeed detection systems are designed with faster response times and ready for the shifting demands of the safety guidelines.

The total time is a sum of the response time of the electronics and the measurement time:

- The response time of the electronics is fixed and mainly consists of the time it takes to switch the relays. In a 2oo3 voting structure all three measuring circuits (channels) measure the rotational speed, which is independently compared to set the trip value. The voting structure determines how many measurement circuits have determined an overspeed event. When at least two of the sensors detect overspeed (2oo3), the output relays should switch, and the machine is tripped.
- The measurement time depends on the measured time between pulses derived from the speed sensors and the averaging that is applied. This also means that the number of poles on the pole wheel and actual rotational speed have a significant effect on the measuring time.

Location & environment

With the growing demand for overspeed protection on smaller and/or less critical rotating machinery, the need for overspeed detection systems in decentralized plant architectures requires a system that can be placed directly next to the machine. Many applications do not have room for a cabinet to fit a 19” rack-based system, and long cables are often not an option due to the loss of signal. A transmitter-based system provides a more accessible solution in a decentralized architecture; it can be placed directly on the machine and does therefore not require long cables.

Overspeed design considerations

- What is the speed range? (min-max)
- Does it require digital or analogue outputs?
- Is the system suitable for the selected sensor?
- What voting structure is desired? (1oo1, 1oo2, 2oo2, 2oo3).
- Does it involve a single or redundant power supply?
- Are isolated inputs optional or required?
- ATEX compliance in the case of integrated isolators/barriers
- Does the system need to comply to the API Standard 670 / IEC 61506 / 61511?
- What is the required SIL level?

Overspeed system installation requirements

- Rack-based system (19”) or transmitter-based din rail mount?
- What is the required IP rating?
- Does the system have a sufficient heat dissipation capability as per the instrument specification?
- Serviceability should be included in the design of the cabinet / junction box
- When required, the configuration port should be accessible
- The system should only be accessible to competent staff (ATEX, IEC61508 and IEC 61511 requirement)
- ATEX compliance: when isolators/barriers are installed in the cabinet (e.g., 50 mm clearance between ATEX connections and other connections).

Overspeed failure modes

Unstable speed signal:

- Check supply voltage range
- Check supply ripple & noise
- Check power supply current drawn
- Check signal levels over the speed range
- Check trigger levels

Speed deviation in the case of voting structures

Relatively small speed deviations (<5% of nominal speed)

- Check for eccentric movement of the pole wheel
- Check for axial movement of the pole wheel
- Check if the trigger levels are compliant with the signal levels

Note: VR speed sensors will, typically, have a larger speed deviation than Hall or eddy current probes.

Relatively large speed deviations (>5% of nominal speed)

- Check compatibility between pole wheel versus speed sensor
- Check sensor installation
- Check for large eccentric movement of the pole wheel
- Check for large axial movement of the pole wheel
- Check cabling
- Check supply voltage both instrument and speed sensor level
- Check in trigger settings on the overspeed detection system

"Speed measurements are key in the critical balance between safety and availability"

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