Overspeed Protection System Design, Verification and Testing

Technical White Paper

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Overview

Turbomachinery overspeed events occur throughout the industrial sector on a regular basis, most events are kept within design limits - with some of the events actually exceeding the design limits. Fortunately, overspeed events that cause catastrophic damage, injuries, or fatalities are becoming quite rare. This is due to many advancements in their design and the manufacture of emergency overspeed protection systems, in the last few decades.

Successful turbomachinery overspeed protection not only ensures the safe shutdown of the turbomachinery system when it is being stressed beyond its recommended limits; but, seeks to avoid exceeding those limits to begin with. Design of robust overspeed protection begins with a thorough understanding of the physical design limits of each turbine system and ends with the design of a complete control system capable of preventing a catastrophic overspeed event. Nexus Controls has decades of experience modernizing and improving upon older turbomachinery controls - including overspeed protection methods.

Figure 1 - Destroyed steam turbine due to overspeed

Normal vs. emergency overspeed protection

Safety is a key factor in choosing a control system. The primary control system is the first line of defense against overspeed, typically referred to as Normal Overspeed (NOS) protection. It is an essential element in ensuring safety of the machinery.

Figure 2 is a graph of turbine speed versus time. The y-axis starts at 100% rated speed and shows the typical profile of overspeed on instantaneous loss of full load with a fully functioning primary control system. The x-axis is elapsed time in seconds. Normal Overspeed is the range between

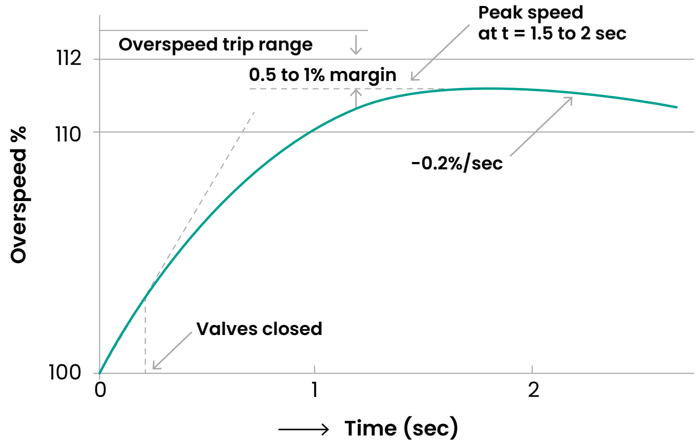

Figure 2 - Normal overspeed (typical) on loss of full turbine load with all controls working properly

100% and just under the Emergency Overspeed (EOS) trip setpoint, typically between 110% and 113%. The primary control systems will try to keep turbine speed from reaching the Emergency Overspeed trip setpoint by fast closing the controlling valves. The controlling valves are critical as the first line of defense against overspeed.

The primary control system regulates machine speed and load output by regulating the amount of energy input (in the form of hot gas) to the rotating machinery. This energy input drives speed and load output for either electrical power generation or mechanical work performed through pumps, compressors, and blowers. As increasing power output is required for higher loads on driven machinery (like generators or compressors), the risk of machine overspeed - upon sudden loss of load - increases proportionally.

Figure 3 is a graph of typical overspeed, over time, on a slowly accelerating unit on loss of full load showing what is supposed to happen when the turbine exceeds the Normal Overspeed range and an Emergency Overspeed trip occurs. Assuming the emergency trip system works as designed, it will prevent the turbine rotor from exceeding 120% (typical) of rated speed - which is the maximum design limit for most large utility turbines.

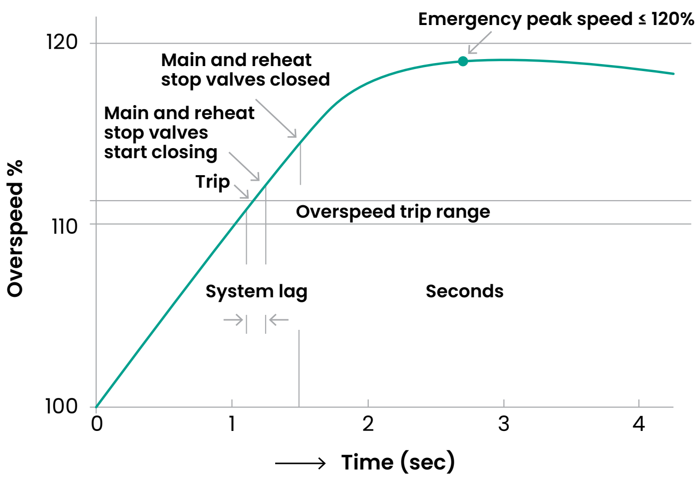

Figure 3 - Emergency Overspeed of a "Slowly Accelerating" Unit on (typical) loss of full turbine load with the first line of defense not working properly

Figure 4 represents a fast accelerating unit that requires a "trip anticipation" function that begins to close 2nd line of defense stop valves below the Emergency Overspeed trip set point, in anticipation of an emergency overspeed trip event. If the trip anticipator does not work, the peak turbine rotor speed will exceed the maximum design limit. Exceeding the maximum rotational speed design limit typically requires extensive machinery condition inspections (which is very costly). Many turbomachinery design factors contribute to the level of risk for catastrophic overspeed events, including maximum design rotational speed, entrained energy levels (fluid pressure and temperature) within the machine, the driven load and potential for rapid loss of load, turbine rotor blade size and inertia, turbine rotor and casing materials, and control system capabilities - to name a few. All these factors must be accounted for in proper design of overspeed protection systems.

Theoretically, the NOS protection system should prevent any emergency overspeed events. But, in reality, the primary control system can't always prevent the rotational speed from exceeding the turbine emergency overspeed trip set point. Emergency Overspeed (EOS) protection is activated any time the turbine rotational speed exceeds the EOS trip set point. The EOS controller "fast closes" the stop valves and on reheat steam turbines, the reheat stop valves. When analyzing Emergency Overspeed scenarios, the conservative approach is to assume the first line of defense

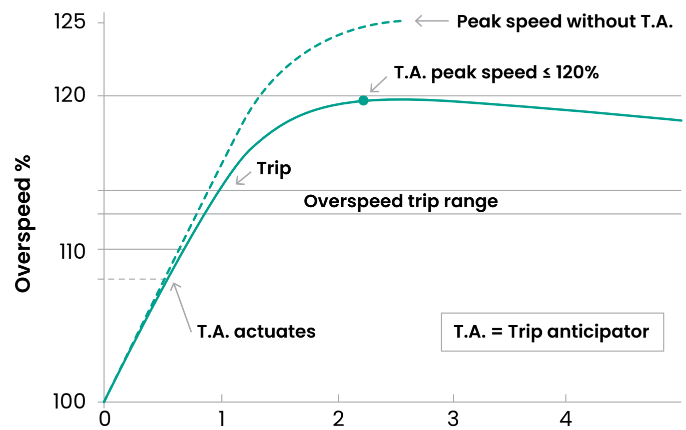

Figure 4 - Emergency Overspeed of a "Fast Accelerating" Unit with Trip Anticipator (T.A.) function (typical) on loss of full turbine load with all controls working properly (dark line) and without trip anticipation (dashed line)

system has completely failed. The Emergency Overspeed (EOS) protection system is an extra layer of protection that operates independently from the primary control system. It acts as a second line of defense and has the independent ability to determine if the machinery is headed for catastrophic overspeed.

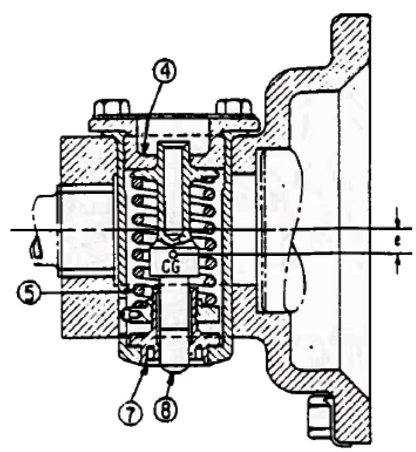

Figure 5 - Mechanical emergency governor

EOS protection systems for older turbomachinery are typically mechanical emergency governors (more commonly known as mechanical bolts), installed directly on the main turbine shaft. More modern control systems incorporate various forms of electronic overspeed protection systems including redundant digital electronics hardware, software, and mechanical components. These emergency systems are designed to respond when NOS protection systems fail to prevent the equipment from exceeding the approximately 110% of the design rated rotational speed of the turbomachinery.

Although primary control and emergency overspeed protection systems must work independently, it is also highly desirable and advantageous to design them to work together effectively as layers of a total protection system.

A complete system level approach to overspeed

Overspeed protection failures are usually the result of controllers designed with inadequate responsiveness for modern requirements, inadequate periodic maintenance and testing of overspeed protection systems, human error, or a combination of all these factors. Sometimes, in fact, older primary control systems respond very well within normal operating speeds, where they perform “fine control,” but they are not adequately equipped to handle large and rapid system transients, such as rapid loss of load.

Effective, modern controllers are designed to perform well

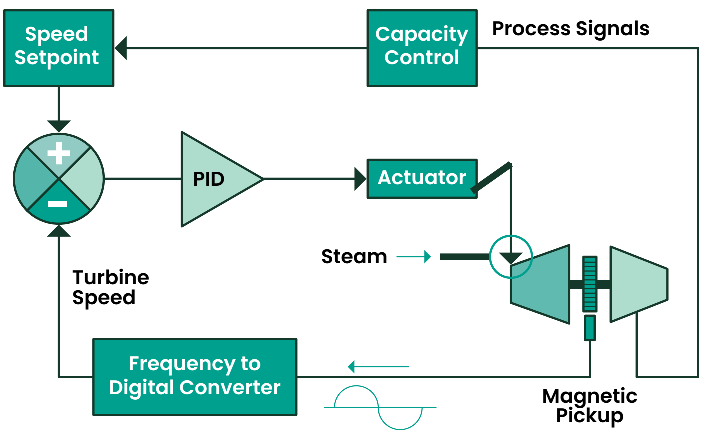

Figure 6 - Integrated control system design for optimized safety, reliability, and performance

with fine controlling ability and respond quickly enough to catch a rapidly accelerating piece of high-energy machinery.

They accomplish this by ensuring highest performance components and redundancy in all critical elements of the system. Older Mechanical Hydraulic Control (MHC) systems have fixed speed regulation that provides for fine speed control but aren’t ideal for large system transients, and most don’t have the ability to “anticipate” a potential trip condition like their modern counterparts. More modern digital Electro-Hydraulic Controls (EHC) can be designed for greater fault tolerance and trip anticipation without sacrificing frequency response and fine control. However, control systems are only as strong as their weakest links. The importance of effective design of mechanical control system elements such as hydraulic powered fuel control and safety valves, rotational speed sensing assemblies, high speed and high-resolution turbine sensory instrumentation, hydraulic trip manifold assemblies, levers and linkages, and hydraulic power units are often overlooked or underestimated as critical parts of overall control system performance.

Regardless of the control elements in place, it is essential to perform manufacturer specified periodic testing of key control elements to verify continued proper function. Testing is crucial to ensure that any latent failures of essential control elements are detected and repaired before safety is compromised. The reliability of overspeed protection systems depend greatly on the confirmation, through regular testing, that all critical system components remain in proper working order.

Older MHC systems have limited online testing capability including the type that require the main trip element (mechanical bolt) to be “locked out” and exercised without initiating a turbine trip. Potential failures in the “lock out” system can lead to an unwanted turbine trip while the unit is operating. To confirm the trip setpoint of the MHC system is working properly, turbomachinery OEMs generally require turbine rotor speeds to be increased above 110 percent of rated speed. Performing this type of periodic testing inherently introduces risk due to stresses on the rotor at the higher-than-rated speeds.

Other factors making this testing undesirable include the labor costs to perform overspeed testing, delays in operational startup (warm-up periods), and higher insurance costs. With more modern control and protection systems, overspeed testing can be performed without raising the turbine speed to above 100 percent of the rated speed. Therefore, many customers are choosing to engage Nexus Controls to upgrade their primary control and emergency overspeed protection systems. Ideally, a robust control system should anticipate potential trip conditions based on dynamic conditions and move controlling and safety (stop) valves, without tripping the turbine, in a rapid loss of load event. This is especially challenging in more modern turbines with higher operating pressures and temperatures and lightweight rotors. A well-designed primary control system should anticipate trip or loss of load events – giving itself valuable additional milliseconds to respond before an actual unit trip must take place.

Avoiding unnecessary trip events through effective turbomachinery control, without sacrificing robust machine protection, has become an operational imperative for most in the industrial markets. Once an avoidable trip event occurs, industry experience has shown that the cost of lost production can range from several hundred thousand dollars to several million dollars in lost production while waiting to get machinery back up and running – and that assumes there was no significant damage caused by the trip event. Modern control systems can provide highly reliable operation through use of redundant instrumentation, control circuits, and critical components that allow for single failures of components without causing an unplanned outage. The best control systems will predict, or at least detect, critical control element failures, and allow for online maintainability of critical components. Effective total control system design drives highest running reliability without sacrificing machine safety and protection features.

Best-in-class emergency overspeed protection systems must be fast, reliable, and have online maintainability of components most likely to fail more frequently to ensure optimal performance. Testing primary and emergency overspeed protection elements while machinery is running, ensures they are working properly without sacrificing unit availability. This requires that a certain amount of fault tolerance in system components and periodic response testing of those elements occur. It is imperative for overspeed protection control elements to have the fastest speed of response possible to prevent catastrophic machinery overspeed conditions. For this reason, redundant and triple modular redundant (TMR) systems have been developed to provide the best combination of running and tripping reliability. Also, an overspeed analysis is recommended to account for trip system element lag times, and determine the amount of entrained energy (the amount of high-pressure and temperature energy that is already past your safety and control valves) that will continue to accelerate a machine after an emergency trip event is activated.

Selecting a control system provider

Ideally, the primary control system and the emergency overspeed protection system are designed as a complete system - while maintaining key elements of independence. Most effective primary overspeed protection uses both controlling and stop valves in combination to provide the best effort at preventing rotating machinery from exceeding the emergency overspeed trip setpoint. The same valves are typically also used, through very high-speed closure elements, to provide for emergency overspeed protection. Integrated system design between digital electronic hardware, firmware, software, and mechanical control elements is crucial to provide for best control and overspeed protection.

To provide a reliable primary control system and emergency overspeed protection system, control system providers must know the following physics-based limiting factors:

- The mass and total inertia of the turbine and driven equipment rotating elements
- The amount of work performed at maximum load by driven equipment
- The amount and condition (pressure and temperature) of entrained (stored) energy already past controlling and safety valves
- How much additional entrained energy is expected to enter the machine post-emergency trip - based on how long it takes to close the valves

To be effective, control system providers must understand the physics and practices involved in designing and operating safe machinery. Turbine equipment designers and manufacturers recognize that it is essential to understand "how fast is fast enough" for overspeed protection and they incorporate that knowledge in their designs. Control system providers should be able to demonstrate the effectiveness of the overall overspeed protection system through analytics, such as overspeed calculations, direct testing or empirical measurement, or system modeling based on direct knowledge of the rotating machinery design.

On the surface, turbomachinery overspeed protection upgrades may seem simple or straight forward. However, it is critical for safety to ensure that controls providers understand potential issues and can demonstrate the effectiveness of their protection system designs.

Figure 7 - Nexus **OnCore™** is an example of a modern, next-generation control system from Nexus Controls

About Nexus Controls, a Baker Hughes business

Nexus Controls has a wealth of knowledge and experience due to its rich 150-year history, dating back to the founding of the Woodward Governor company. Nexus Controls, a Baker Hughes business, was officially founded over 62 years ago and has proudly been providing the control and safety systems you can trust - from experts you can trust.

Nexus Controls supplies control and safety systems for heavy duty and aeroderivative gas turbines, steam turbines, hydro turbines, generators, compressors, turboexpanders, excitation, balance of plant equipment, DCS and manufacturing operations. Many legacy systems are limited by the technology of their era and require an upgrade to deliver optimal turbine performance, operability, manufacturing performance, safety, and availability improvements; to modernize them consistent with the fourth industrial revolution (4IR).

About the author

Steven Foss is currently the Mechanical and Packaged Systems Engineering Manager for Nexus Controls, a Baker Hughes business, based out of Longmont, Colorado. Past roles include Quality Leader, Mechanical Systems Engineering Manager, Mechanical Systems Engineer, and Field Service Engineer. He has a Bachelor of Science degree in Mechanical Engineering from the University of Colorado, Boulder and 24 years of experience in the turbomachinery controls industry.

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