

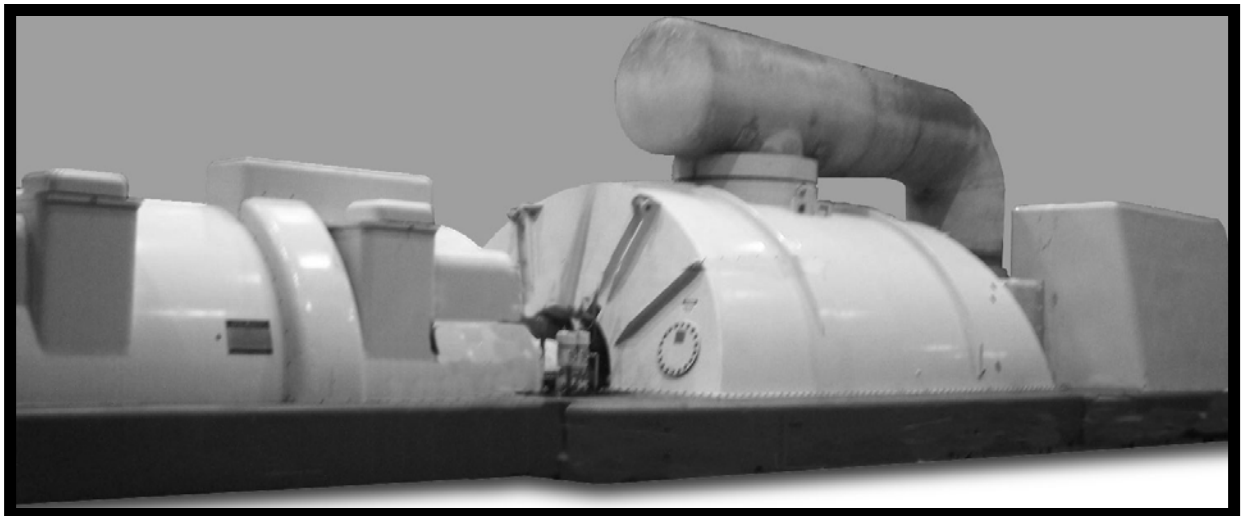
Designing Overspeed Trip Systems for Large Power Plant Steam Turbines

- An in-depth discussion of the issues that should be considered when designing a retrofit emergency overspeed trip system for a large reheat steam turbine
- Descriptions of hydraulic system options for improving the performance of emergency overspeed trip systems

Invensys Turbomachinery Controls

Invensys Process Systems

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Turbine Overspeed System Design Challenges

Turbine overspeed events have been identified by insurance company experts as the single biggest cause of equipment damage and personnel casualties in industrial plants. One recommendation by these experts that has been adopted by the turbine manufacturers and control system suppliers is the use of triplicated electronic overspeed trip systems. The electronic systems provide significant improvements in online monitoring and testing of the overspeed detection components and allow the entire overspeed protection system to be tested without actually subjecting the turbine (and generator) to overspeed conditions. This change alone significantly improves the safety of the system, but is not the only issue that should be addressed when considering a retrofit application that replaces a mechanical overspeed detection device with an electronic system.

The primary goals of a replacement electronic overspeed protection system should be the following:

1. Prevent overspeed under all loss-of-load conditions
2. Avoid nuisance trips

In order to achieve these design goals, several design criteria must be imposed. Additionally, these two goals can result in designs that can violate one goal by meeting the other. The protection system must be designed to not only protect equipment and personnel, but to also protect the owner's operating revenue and profits.

Loss of Load Conditions

The condition that causes a reheat steam turbine to overspeed is an imbalance of torque; the torque created by the steam turbine rotor exceeds the torque of the load. There can be numerous reasons for this imbalance, but the result is always dangerous. In most cases, the torque of the

load cannot be predicted or controlled.

When a sudden load reduction occurs, the controls and protection system must act to reduce the torque produced by the steam turbine to match the torque of the load. As long as the torque imbalance exists, the turbine speed will increase. The acceleration of the turbine will be a function of the magnitude of the torque imbalance. The ultimate speed reached by the turbine rotor during an overspeed event is the time integral of the torque imbalance.

$$N_f = N_i + \int_i^f (\tau_t - \tau_l) dt \quad \text{Eq. 1}$$

Where:

- N_f Maximum speed attained by turbine rotor
 N_i Rotor speed at the beginning of the load imbalance
 f Time when the maximum speed is attained
 i Time at the beginning of the load imbalance
 τ_t Instantaneous torque produced by the turbine
 τ_l Instantaneous torque of the load
 t Time

In the above list of variables that affect the maximum speed of the rotor during an overspeed event, the overspeed protection system can influence the time and the instantaneous torque produced by the turbine. The instantaneous excess torque produced by the turbine is in part a function of the position of the intercept valves and/or the reheat stop valves and main stop valves.

It's All About Speed

In designing an overspeed protection system, reaction times of the various components of the trip circuit must be considered. These reaction times can be

broken down into four serially occurring events:

1. Detection of the torque imbalance
2. Initiation of countermeasures
3. Removal of the mechanical force that is holding the valve open
4. Closure of the steam valves (fully open to fully closed)

Obviously, the design objective should be to minimize the duration of each of these events, but in a retrofit situation, the designer might have practical limitations that will prevent adjusting the time required for some of these events. Since the electronic components of the new electronic overspeed protection systems are usually just replacing the mechanical bolt of an older system, a lot of discussions have focused on the latency issues of the electronics. Many turbine controls designers believe that if a mechanical bolt initiates a trip at the same speed setpoint of the electronic system, the mechanical bolt will always win the race. This is not necessarily correct. It is assumed that because of the time delay inherent in the digital system due to the series of events that must take place in the digital system logic, plus the time required for the mechanical action of the solenoid valves used by the electronic system, that the mechanical bolt is faster. In reality, there are a number of actions that must take place in the mechanical system that also take time, but cannot be readily measured. The chain of mechanical events that must ensue prior to dumping the trip header pressure can take up to 200 msec.

So, as long as the latency of the new electronic overspeed protection system is not much greater than 100 msec, the new system will not allow the turbine to accelerate to a higher maximum speed than the old mechanical bolt system, during the same load rejection. Of course this assumes that the mechanical bolt reacts

Mechanical Trip Latency—How fast is a mechanical bolt?

The chain of events that take place in a mechanical overspeed trip system are not evident because they are not readily measurable. The “speed” of a mechanical overspeed trip system can be an illusion.

When a turbine with a mechanical bolt reaches the speed setpoint for the overspeed trip, the first event is the extension of the bolt. The bolt extends out its cavity and strikes a lever. If this extension occurs just after the bolt passes the lever, there will be a delay equivalent to one revolution. The lever must swing through an arc of about 10 degrees to clear the knife edge. Then a plunger has to slide far enough to shift the spool in a hydraulic direction control valve. Once the direction control valve shifts, low pressure hydraulic oil dumps from a hydraulic relay or shuttle valve that is holding the pressure on the trip header. The first evidence of the trip action is usually the loss of pressure in the trip header.

All of these steps that led up to the loss of trip header pressure take time..

precisely at the same speed at which it is intended to react.

And the electronic system can make improvements on the performance. One of the characteristics that determines the setpoint of the old mechanical bolt is its lack of predictability. The turbine OEM’s must allow some margin above the “normal” speed range of the turbine to prevent inadvertent action of the mechanical bolt. Electronic trip systems, on the other hand, are very predictable and will usually initiate a trip within a few rpm of their setpoint. It is therefore prudent for the owners of the turbines to use an electronic overspeed trip setpoint that is slightly lower than the setpoint of the mechanical bolt. Invensys recommends using a setpoint that is no greater than the lowest acceptable test speed of the mechanical bolt system. This will allow a quicker response without risking a nuisance trip during a load rejection.

What About the Torque Imbalance?

The accepted method of judging the inevitability of an overspeed event is by the turbine reaching the setpoint of the overspeed detection system. This will in no way predict the maximum speed attained by the turbine rotor during the overspeed event. One protection system that was added to reheat turbines to attempt to deal with the torque imbalance of a load loss is the so-called power/load unbalance system. If the steam pressure at the reheat section compared to the generator current is beyond a certain ratio, steam valve action is initiated to attempt to contain the reheat steam energy and thus reduce the torque imbalance. But one inherent

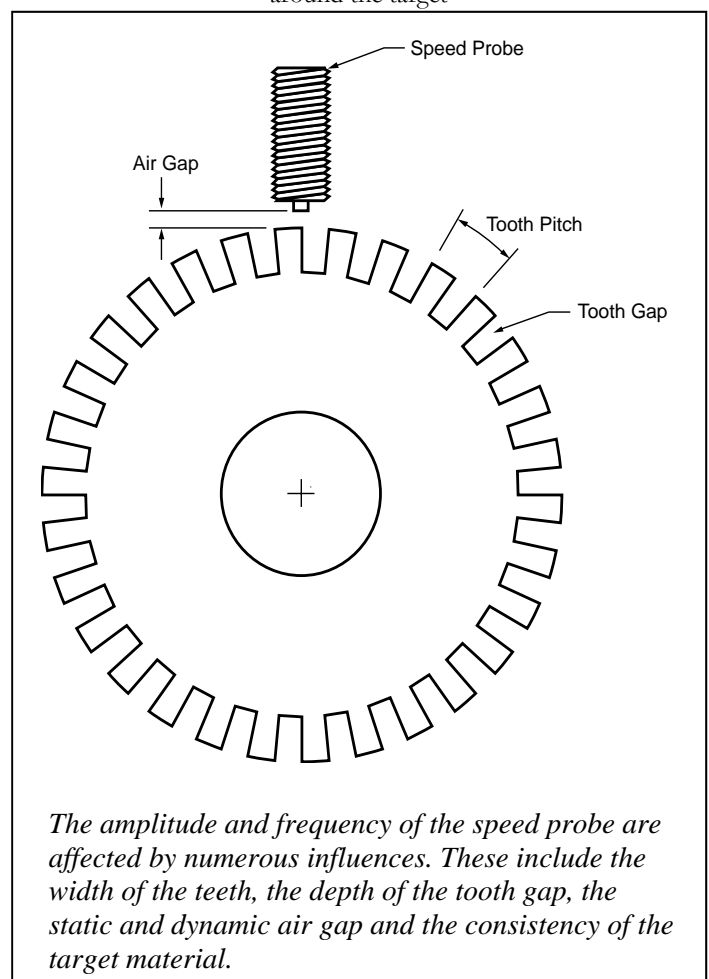
limitation of the power/load unbalance scheme is that it is disabled below about 40% power.

A full load rejection at 38% power can create enough of a torque imbalance to provoke an overspeed event, so it is important to have an overspeed trip system that will reliably measure the turbine speed and react quickly enough to limit the acceleration of the rotor. Since the net result of a torque imbalance is an acceleration of the turbine rotor, being able to measure acceleration of the rotor can provide evidence that an

overspeed event is about to happen well before the overspeed setpoint is actually reached. The greater the acceleration, the more likely the event is about to happen. And since the speed is a time integral of the acceleration, reacting to acceleration will allow the system to get a jump on minimizing the extent of the overspeed.

Measuring acceleration for an overspeed event has traditionally been a problem due to the nature of the speed signal; it is generally considered a “noisy” signal. A control system cannot reliably calculate a time integrated value over a short period if the signal is noisy or inaccurate. The noise and inaccuracy in a speed signal are caused by both mechanical and electronic issues. These include:

- Uneven tooth spacing of the speed probe target
- Irregular shape of the teeth
- Variations in the magnetic properties around the target



- Variations in the gap between the speed probe and the target
- Physical difference in the location of each of the speed probes
- Inaccuracies introduced by signal converters and analog-to-digital converters
- Non-linearity of speed sensing circuit
- Variations or imprecision of the time base
- Rotor radial displacement
- Rotor torsional oscillations

Invensys has solved most of these problems associated with speed detection. The patented speed detection circuits and software of our Triconex Overspeed Protection System are able to provide extremely accurate frequency measurements over extreme variation in the operating conditions of the turbine.

We have speed detection systems that actually monitor and record the time at which each tooth on the target passes an individual speed probe. Starting with this level of detail allows the software to accommodate variations in the mechanical conditions of the turbine and eliminate the sources of signal distortion that are inherent in traditional designs. We can even detect if a tooth (or the pulse generated by a tooth) is lost or missing.

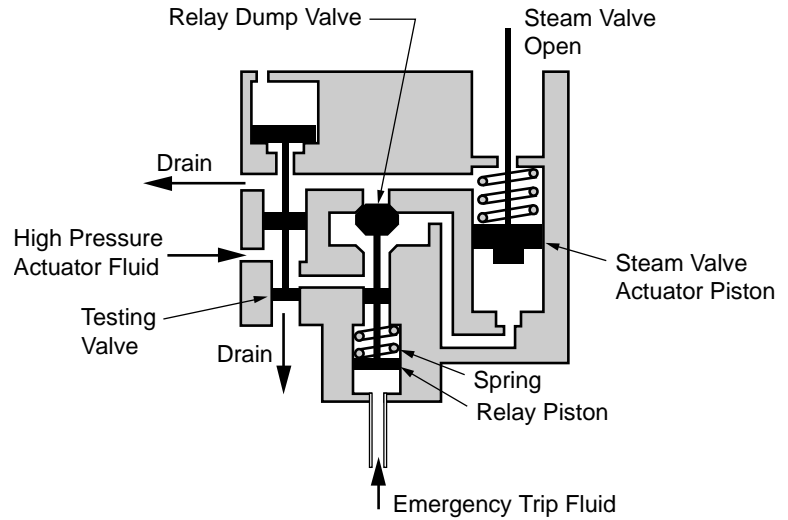
Improving Performance of the Trip System

Electronic systems have been accepted as the preferred solution for overspeed trip protection due to their reliability, reparability and testability advantages over the mechanical systems. Invensys has developed the speed detection portion of the system to eliminate the inherent disadvantages of traditional electronic systems and has even introduced improvements that exceed the performance of the mechanical systems.

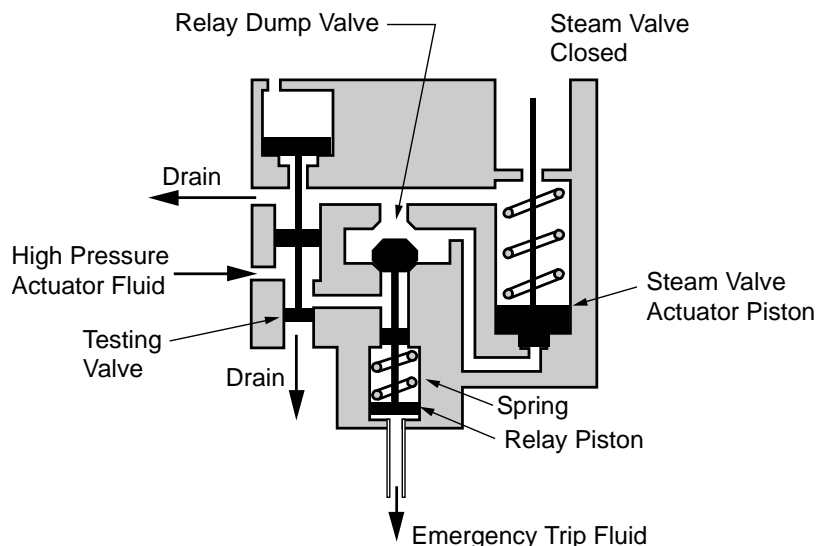
Once an electronic overspeed trip system is selected to replace a mechanical bolt, there are new opportunities available to the designer to improve the system performance. By minimizing the length of the trip oil circuit, the hydraulic latency of that circuit can be minimized.

The force required to accelerate a volume of hydraulic fluid through a filled pipe is directly

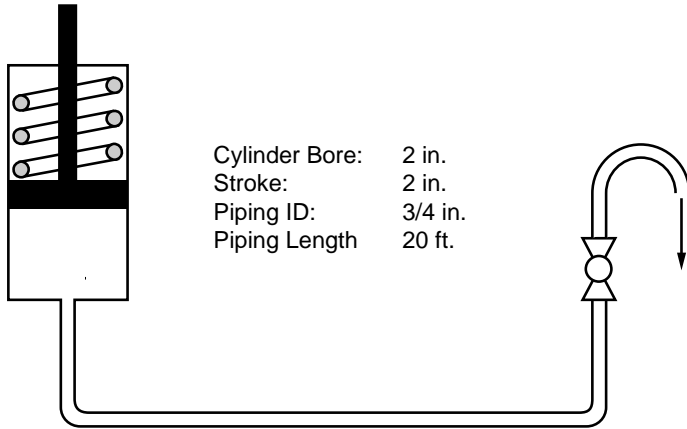
TRIP VALVE OPERATION



For the steam valve actuator to maintain the steam valve in the open position, the Emergency Trip Fluid supplies the pressure against relay piston that compresses the relay piston spring and keeps the relay dump valve in the “run” position (up). To trip the turbine, the emergency trip fluid must exit the relay piston cylinder, allowing the relay dump valve to shift to the trip position (down). The relay piston spring supplies all the force for moving the piston. In order for the piston to move to the trip position, the spring must also force all the fluid from the relay piston cylinder. A volume of fluid in the trip circuit piping that is equal to the displacement of the relay piston must be moved through the piping out the end of the trip circuit. The entire mass of the fluid in the piping must be accelerated the equivalent length of this volume of fluid in order for the piston to travel the required distance. The longer the trip circuit drain pipe, the greater the mass that must be accelerated. This mass acts as a retarding force against the spring and thus increases the time required for the dump valve to travel its required distance for a trip action.



EFFECT OF TRIP CIRCUIT PIPING ON TRIP TIME



Cylinder Bore: 2 in.
Stroke: 2 in.
Piping ID: 3/4 in.
Piping Length: 20 ft.

In the above sketch, the volume of fluid that must exit the cylinder in order for the piston to move to the bottom of the cylinder is 6.28 in³. That same amount of fluid must exit the end of the piping. For the piping in this example, 6.28 cubic inches occupies a slug of liquid in the pipe that is 14.2 inches long.

For the piston to stroke fully, the entire mass of liquid in the pipe must move 14.2 inches. If the fluid has a density of 60 lb/ft³, the average force that the spring must exert on the piston to move this mass of liquid through the pipe in 1/10 of a second is about 27 lbf.

The same spring can stroke the piston in about 30 ms if the length of the drain piping is shortened to 2 ft.

equivalent amount of fluid must exit the other end of the trip oil piping in order for the fluid to exit the relay cylinder. That means that the spring in the relay valve must push the entire mass of fluid in the pipe some length equivalent to the volume of the fluid in the relay cylinder. The acceleration that is required to move this fluid in a short amount of time can exceed 100g. The designer of the original trip system had little choice in this matter, but with an electronically activated system, this piping can be substantially shortened by moving the solenoids as close as

and easier to test.

How Much Hydraulic Redundancy?

A single SOV is obviously inadequate for preventing spurious trips and curtailment. With two solenoid valves, the spurious trips can be minimized and curtailments reduced. The downside of the dual SOV arrangement is that the probability of failure on demand is higher. Also, a failed component cannot be replaced on line without compromising safety or tripping the associated steam valve.

There are some triple SOV designs available that require two of the three SOV's de-energize in order for the system to trip. The systems used for steam turbines rely on flow restrictions to set the trip pressure. These SOV's are plumbed in parallel. The flow rate through one SOV is not sufficient to allow the trip pressure to drop low enough to allow the relay dump valve to shuttle. Obviously, this type of system is dependent on the viscosity of the fluid remaining within a certain narrow range. Plus, these triplicated systems can be tested online but not repaired without isolating (tripping) the steam valve.

For customers that want to improve on the availability and reliability of a dual system, Invensys offers a four-SOV trip system called the Quadvoter™ Hydraulic Trip System. This system is fully testable online, has no single point of failure, is easy to diagnose and allows all the active components to be replaced online without compromising safety or curtailing the unit.

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proportional to the length of the pipe. With the implementation of an all-electronic trip system, it becomes possible to substantially shorten the hydraulic circuits that relieve the latching pressure on the steam valve actuator.

During an emergency trip action, the high pressure hydraulic fluid that holds the main stop valves and reheat stop valves open is dumped to the drain through some type of relay dump valve or dump disk near the actuator cylinder. The emergency trip oil circuit supplies the hydraulic pressure to maintain the relay dump valves in their closed position. The relay dump valve includes a spring that pushes the valve open once the emergency trip oil pressure on the other side of the relay valve diminishes. This same spring must supply all the force to push the hydraulic fluid out of the relay valve and into the trip drain piping. An

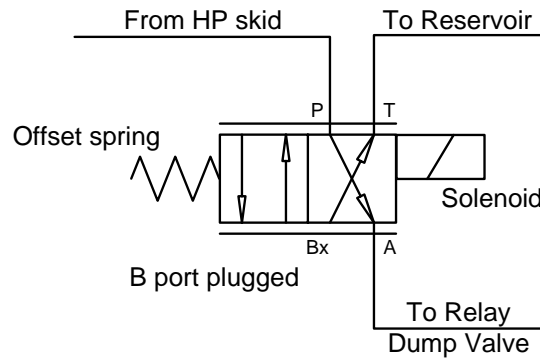
possible to the relay dump valve.

Just by moving the trip solenoid near the relay dump valve, the time required to shuttle the relay dump valve during a trip can be cut to less than a third of the time required by the mechanical system.

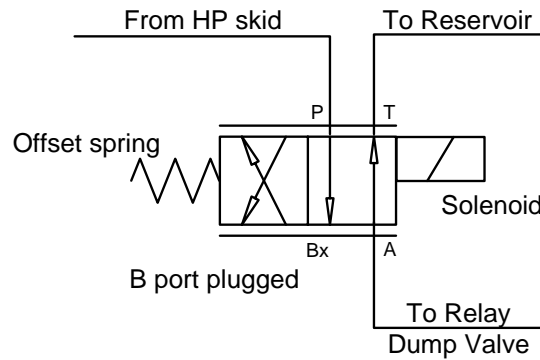
Depending on the piping arrangement used for the actuator drains for the stop valves, there can be opportunities for performance improvements on this part of the system as well. If the drain system from the actuator is restrictive, a local accumulator or dump tank can be added to relieve the back pressure.

In general, these improvements in performance that can be achieved by reviewing all parts of the trip system can more than offset any latency that is inherent in a new electronic overspeed protection system. And in the process the system can be made easier to maintain, more reliable

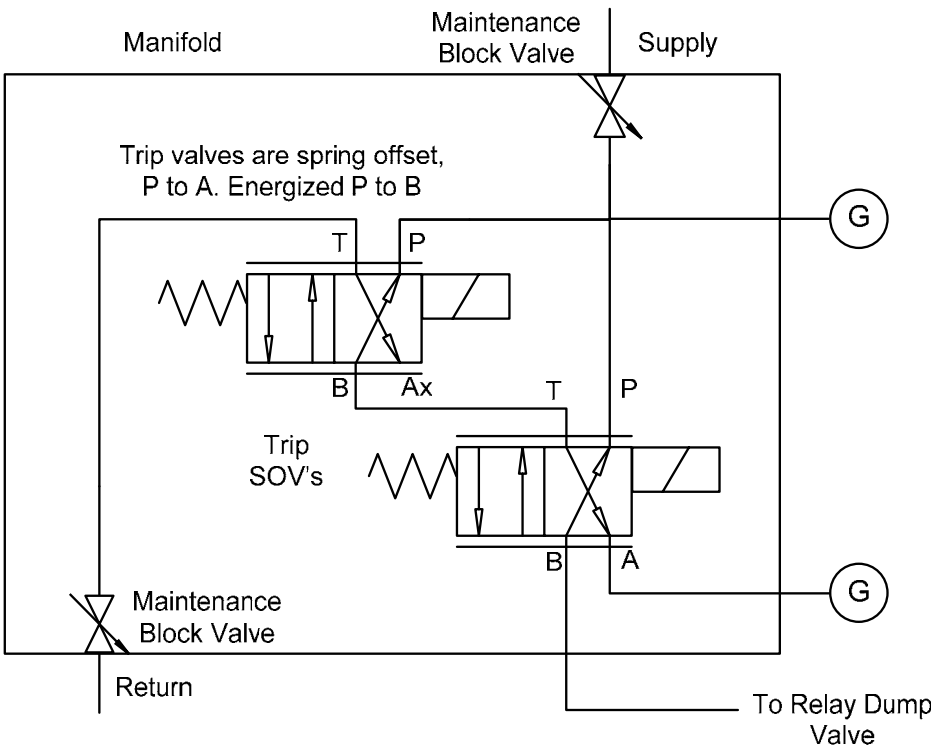
The simplest trip system is a single SOV that is energized to run. This arrangement is generally safe, but does not score well for availability. Additionally, the system must be tested frequently to assure that the valve is not stuck in the energized position. And testing this arrangement requires tripping the associated steam valve.



Energized Position
A port is routed to the HP supply

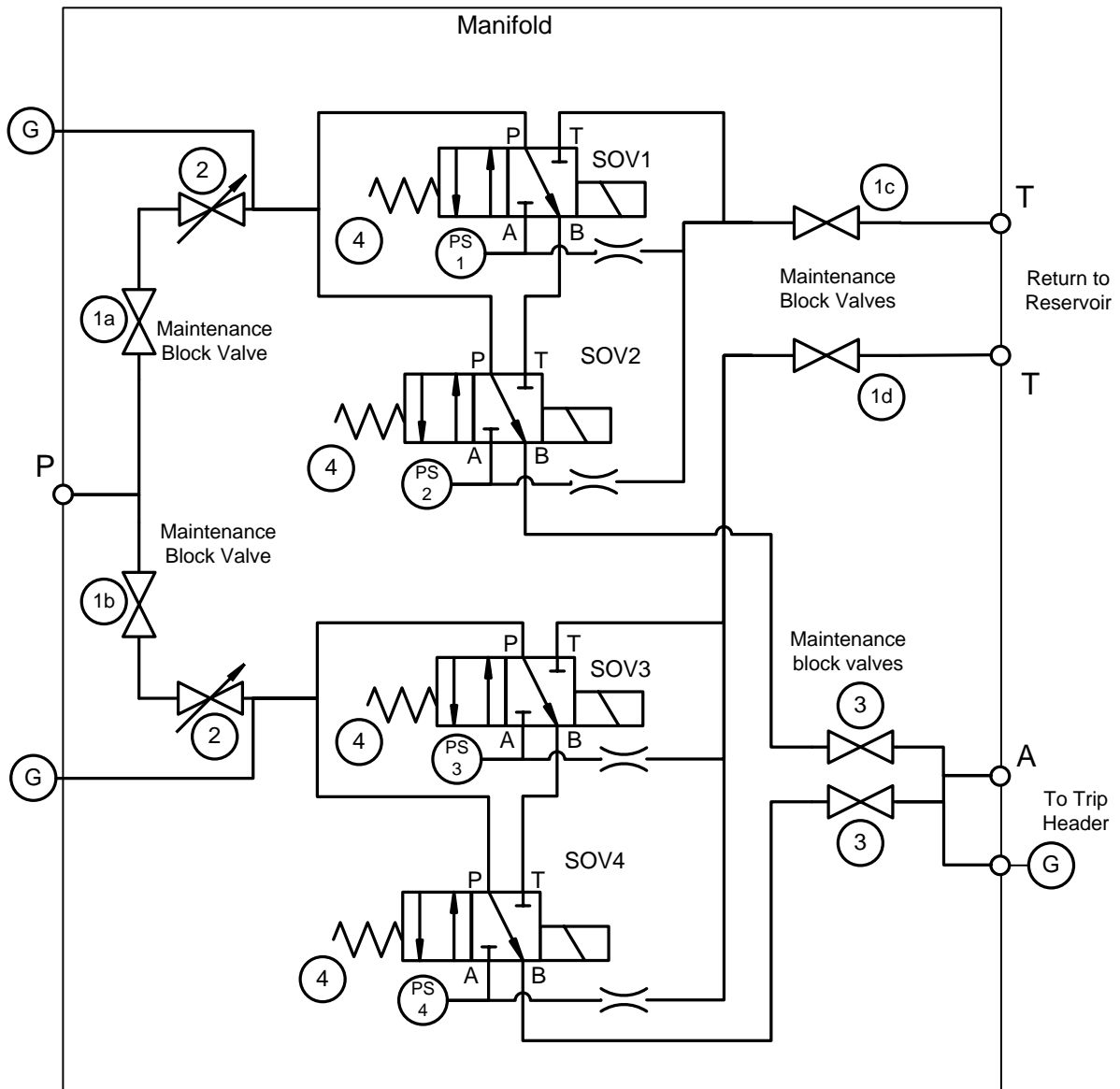


De-energized Position
HP supply is routed to the blocked B port
A port is routed to the reservoir



To improve the availability of the turbine, adding a second SOV in a serial arrangement eliminates spurious trips associated with a single component failure. This scheme also allows the individual SOV's to be tested without tripping the associated steam valve, reducing curtailment of the asset.

A disadvantage of this arrangement is that both SOV's must shift to their de-energized position in order for the steam valve to trip. In this regard, this scheme has the same problem as the single SOV configuration and since there are two devices that must function, the probability to fail on demand for the dual scheme is worse than for the single scheme. Of course, periodic testing of the SOV's will ameliorate this problem.



The Invensys Quadvoter™ trip system is available for either a pressure dump configuration or the pressure switching arrangement shown here. This is the ultimate hydraulic trip system providing both high reliability and high availability. Any single SOV changing state will not cause a trip and if a single SOV fails to change state when commanded during a trip, the system will still trip the turbine.

Maintainability was a key design criterion in the development of the Quadvoter™. Pressure gages and block valves are included to allow maintenance personnel to safely isolate the active components. All the hydraulic components are mounted on a single manifold; there are only three piping connections. All the components are either cartridge type devices or manifold mounted to assure reliable, leak-free operation and simple repair procedures. All electrical components are enclosed in a NEMA 4X junction box with all customer connections marshaled to terminal strips. If a fault is detected by the diagnostics, the offending component is identified by the controller for easy troubleshooting.

Even with this amount of redundancy, it is important to conduct periodic testing to allow detection of covert faults. The Quadvoter™ is fully testable without interrupting operation of the associated steam valve. No bypassing is required during testing, assuring that safety is not compromised. Pressure switches provide feedback that allows the controller to judge the success or failure of each part of the test procedure. The SOV's can also be provided with optional position switches that show if and how fast the valve spool has moved.



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