Upgrading To Fully-Electric Actuation and Control of Steam Turbines

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ABSTRACT

The use of an electric actuator for steam turbine governor valve operation is a cutting-edge technology in steam turbine control. With this design, the use of turbine oil for turbine speed control purposes is eliminated. This paper discusses the upgrade of critical mechanical drive steam turbines to fully electric control and actuation for improved controllability, efficiency and reliability.

The application at Saudi Aramco presented in this paper is pioneering in the Oil & Gas industry and the first regional application of this technology. Mechanical-drive installations in an Oil & Gas application environment present additional challenges to electric actuator retrofits; compared to other traditional applications, such as power generation. Moreover, the harsh weather conditions surrounding this pilot application called for extra precautions and special designs.

INTRODUCTION

The use of inverted screw electric actuators for direct control of steam turbine valves is relatively new, beginning around 2002. These are different from the electric actuators used with gas turbines and pilot valve actuation of steam turbines, as this application requires an order of magnitude higher force and works under considerably more challenging conditions. This application uses a powerful, fast and accurate electric actuator, directly replacing the main hydraulic actuator of the governor valves. This change also abolishes hydraulic oil usage for speed control, thus eliminating various associated costs, risks and reliability problems. The life cycle costs are also advantageous against pneumatic actuators.

At any rate, the subject upgrade is not a simple electronic governor retrofit, which had been done frequently in the past and considered an industry standard today (Rossi, 1979). With the availability of powerful and reliable electric actuators today, applying them for governor valves or extraction valve actuation reduces the traditional system complexity (Mansfield et al., 2006) resulting in fully-electric actuation and control of steam turbines that offers fewer components and higher reliability. The electric actuators used in the subject installation at Saudi Aramco utilize inverted roller screws assembled inside a threaded cylinder to convert the rotation to translational motion that drives the governor valve rack through a lever with closure springs. The electric actuator position is controlled by the electronic governor through electrical drives with position feedback thereby completely eliminating any hydraulic or pneumatic interfaces. This simplifies the system and reduces its components, thus adding inherent reliability.

The subject machines were installed in Saudi Aramco over 30 years ago and had mechanical governors with linkages, hydraulic pilot and actuator cylinders which are typical of that era. Due to aging and reliability issues, a decision was made at first to go for a typical upgrade to electronic governors and electronic over-speed protection, but leaving the hydraulic system with minimal change. After a comparative study between technologies available in the market today, a decision was reached to implement a comprehensive upgrade to fully-electric actuation and control of these critical machines. Nevertheless, this upgrade was both challenging and rewarding with a number of lessons learned. Additionally, the mechanical overspeed trip was upgraded to a redundant electronic overspeed trip system and new electro-hydraulic trip solenoids. Also, the original Trip & Throttle valve was maintained. The overall system meets API 612 (2003) and NEMA SM-23 (1991) requirements for performance and protection.

HISTORICAL WEAKNESSES OF HYDRAULIC VALVE OPERATORS

Typical original equipment turbine valve operators (often called servomotors) have historically evidenced several major shortcomings. Since stroke position control is performed by mechanical feedback, a hysteresis band exists for any change in position. If the previous changes were in the same direction (open or close) the "dead zone" of input vs. stroke change is small. If a direction change occurs, the "dead zone" can be significantly large. This condition is worsened by routine parts wear in pilot valves and linkage bushings, as illustrated in Fig. 1. At a critical wear factor the system becomes unstable, and requires highly complex mechanical maintenance to resume operability. Knowledge of these mechanical systems is difficult to maintain, often requiring assistance in timely service from OEMs or specialists. A dwindling pool of expertise on older hydraulics is being experienced as the engineering base ages. Fig. 2 shows the original servomotors in this case example. Since normal operating conditions usually leave governor valves in very narrow position ranges, all mechanical wear of the operating piston rings on cylinder walls is concentrated at that corresponding point, which leads to excess piston sealing clearance and cylinder blow by which reduces correction velocities and stability.

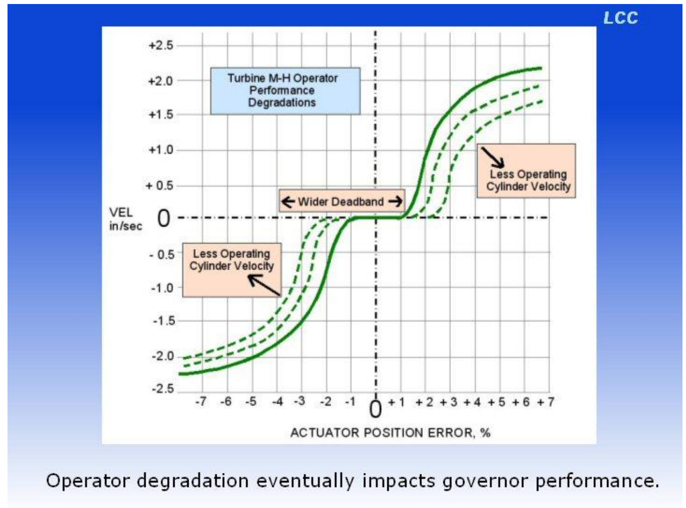

Figure 1. Mechanical-Hydraulic Actuator Degradation.

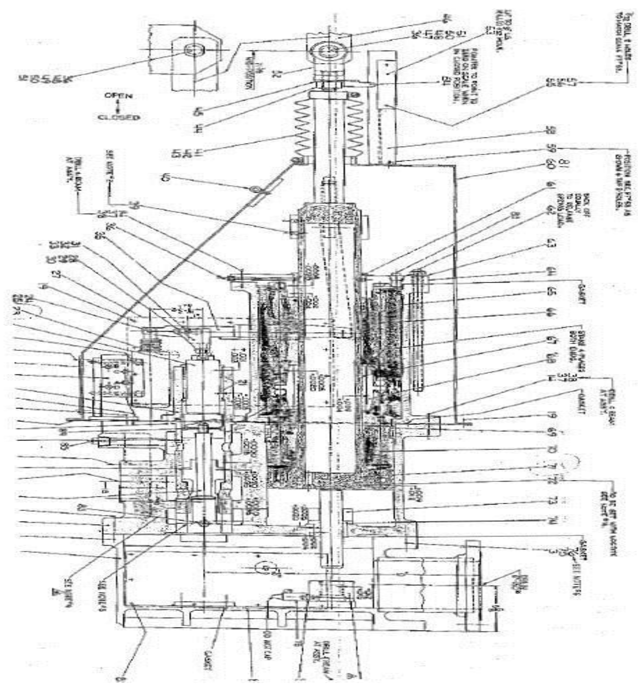

Figure 2. Hydraulic Servomotor Cross-section.

Further historical problems are experienced from hydraulic contamination (Sibul and Trygstand, 1999) where varnish, small particulates of rust, gasket materials, and even loosened reservoir paint lodge in pilot valve land areas and induce response lagging friction with resulting violent oscillations or "hunting." Mechanical drive turbine applications are much more susceptible to oscillations than generation turbines because they lack the stabilization of the grid load. A major drawback to hydraulic operators is the lack of condition monitoring information. Internal pilot valve positions and pressures, which would be useful in problem diagnostics, are unknown, and problems such as internal contamination and excess fit clearance from wear, cannot be determined short of teardown inspections.

Since the 1980s most manufacturers have "job-shopped" spare mechanical parts construction. This means that all but routine replacement parts are seldom in ready stock. When an order arrives the OEM provides a subcontract machine shop with the drawings and documentation. Unfortunately this has too often resulted in quality errors when the subcontractor is not familiar with the critical fits and properties of the part. The user then suffers the frustration of a high cost, long-lead time spare, which does not properly fit or function.

High pressure synthetic fluid operated hydraulic systems have reduced contamination problems by fluid segregation from turbine lubricating oil, but they have evidenced problems of their own problem history in high EH converter and filter maintenance, and vulnerability of leaks in high pressure lines. Further complicating high pressure hydraulic systems is the trend to regulatory requirement for guarded lines to prevent spillage into the environment.

THE INVERSE ROLLER SCREW ELECTRIC ACTUATOR

The inverse roller screw electric actuator represents a new solution to turbine governor valve positioning, which solves the historical problems associated with hydraulic operators. It is also superior to ball screw actuators in terms of reliability and accuracy. The actuator consists of three major components: motor, roller screw assembly, and electronic feedback device. The motor is a brushless 3-phase unit supplied in a wide range of horsepower to meet valve load needs. The roller screw assembly, seen in Fig. 3, consists basically of a tube with an inside thread, longitudinal planetary gears, and a rod, which is in turn attached to the governor valve(s)/linkage.

Figure 3. Electric Actuator's Planetary Roller Screws (courtesy of Exlar Corporation).

Since load is applied over the full length of the planetary screws, the electric actuator does not suffer the point loading of hydraulic cylinders, and with careful engineering of correctly hardened engagement components, the long-term wear is minimal. Plus, the actuator stiffness is high and mechanical hysteresis is eliminated, providing superior performance when coupled to a modern digital governor. Moreover, in terms of energy consumption compared to hydraulic and pneumatic actuators, the electric actuator consumes 77 and 90 percent less energy, respectively (Pohl et al., 2012).

The electronic feedback device is a position encoder that provides motor rotational position to the servo drive unit. The complete assembly is shown in Fig. 4 and block diagram of control in Fig. 5.

Figure 4. Electric Actuator Assembly.

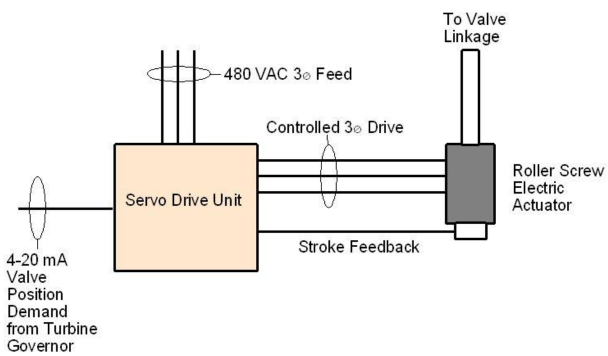

Figure 5. Electric Actuator Control Block Diagram.

Advanced Control Features Of Roller Screw Electric Actuators

The roller screw electric actuator is very precisely controlled by a Servo Drive Unit (SDU). This gives superior control of Speed, Position and Force. SDU have been developed over the past twenty years from variable speed drives with improvements in speed and resolution realized through the availability of faster, higher functioning Digital Signal Processor (DSP) circuit chips. SDU permit sophisticated high speed control strategies, most significantly for turbine governor valve control, including velocity profiling. When applied, velocity profiling produces very accurate position control by defining the exact controlled motor speeds proportional to the position error signal. As a new setpoint position is approached, high speed vector calculations in the DSP meter the motor current drive for a critically damped approach. Contrast this with the mandatory overshoot, then undershoot suffered in hydraulic cylinders (Fig. 6) and one can appreciate the electric actuator performance (Fig. 7) advantage.

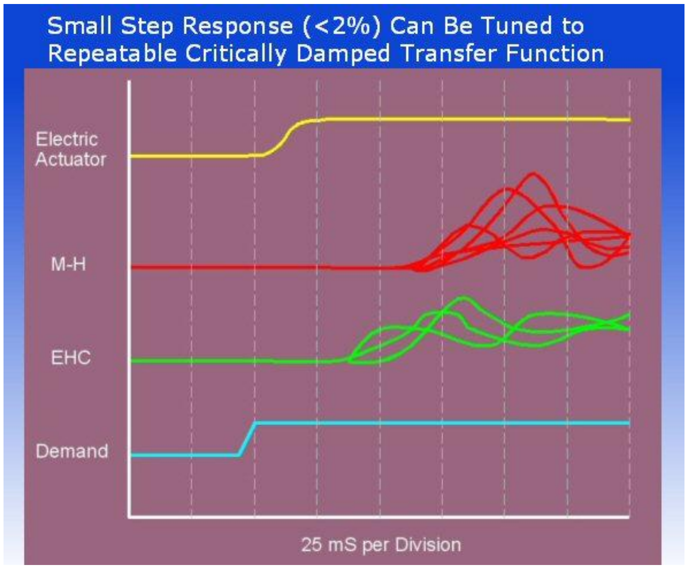

Figure 6. Performance Comparison to a Demand Signal.

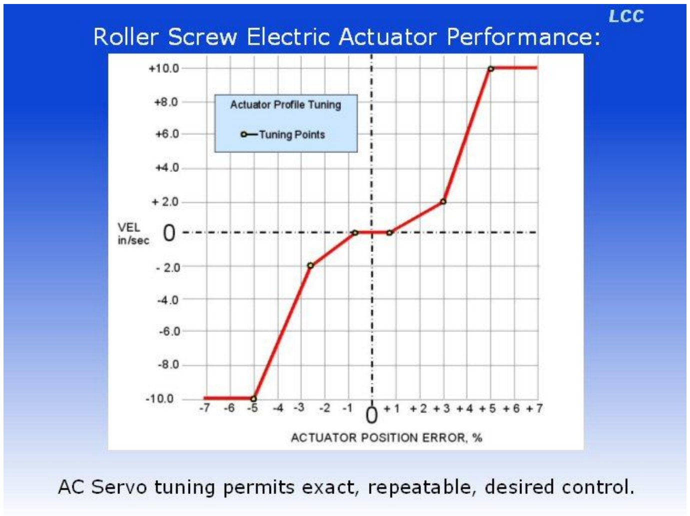

Figure 7. Electric Actuator Profile Tuning.

A property of electric actuators known as "backwind" defines the response of the actuator under load when the feed voltage to the SDU is removed. Careful actuator performance selection can result in desired failure responses of in-position, open, or closed as the application requires.

The SDU units monitor all electric actuator critical parameters and supplies a wealth of condition monitoring information. The immediate drive current is especially valuable in that it represents the load (force) on the actuator, and when compared to historical data, can be used to detect increases in valve linkage friction, which demand greasing of pivots. With the condition monitoring data, these maintenance tasks can be performed online before the problem upsets control performance and results in forced shutdown. In a similar fashion, condition monitoring detection of valve stem friction and valve sequence (lift bar adjustments) is available.

The combination of the SDU and Electric Actuator also improves the precision of governor valve stroke control. Position feedback is typically 2^12 or 4096 increments per turn. In the Saudi Aramco system, a 12.7 mm (0.5 inch) per turn roller screw pitch was selected yielding a controlled position resolution better than 0.0033 mm (0.00013 inch) for the full stroke range, a major improvement over hydraulic systems.

EXHAUSTIVE SYSTEM PRE-INSTALLATION TESTING

In some cases the introduction of new technology to older operating machines has been difficult due to the complexities of integrating new and diverse equipment. To be sure, pitfalls are present and caution must be exercised in the design stage. Caution in design is not sufficient to insure a successful start up, however, and full simulation factory testing fills this void. In this application, Saudi Aramco's experience in retrofit modernizations is evident by the option of fully simulated loop-closure testing of all component equipment prior to arrival at the ‘Uthmaniyah Gas Plant site. A testing regimen was devised to accomplish three validations:

(1) The design equipment met the application expectations.
(2) Discover and correct any performance deficiencies.
(3) Tuning was optimized to reduce start up sorting time.

To accomplish the testing regimen, a set of loop closure instrumentation was constructed (Fig. 8). For speed feedback, the turbine's speed response function for governor valve position changes was observed on the pre-upgraded operating unit. A turbine speed feedback simulator was built using governor valve actuator position input to a test PC, which generated a second-order speed output of timed pulses that mimicked the magnetic probes to be used on the installed system.

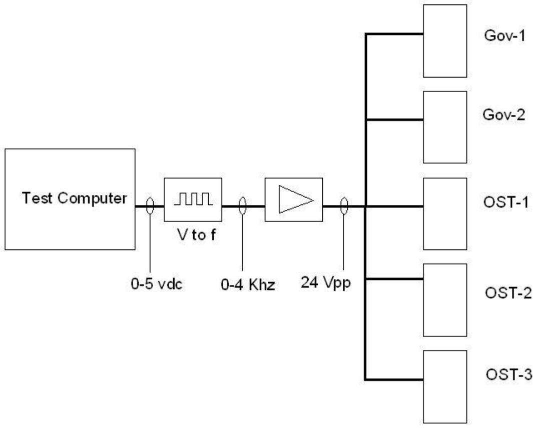

Figure 8. Turbine Speed Control Test Simulator.

For actuator load feedback (Fig. 9), a pneumatic cylinder was coupled to the electric actuator with the cylinder pressure controlled by the test PC through an I-to-P transducer, enabling actuator load simulation to 1 percent accuracy for varying startup and turbine speed situations.

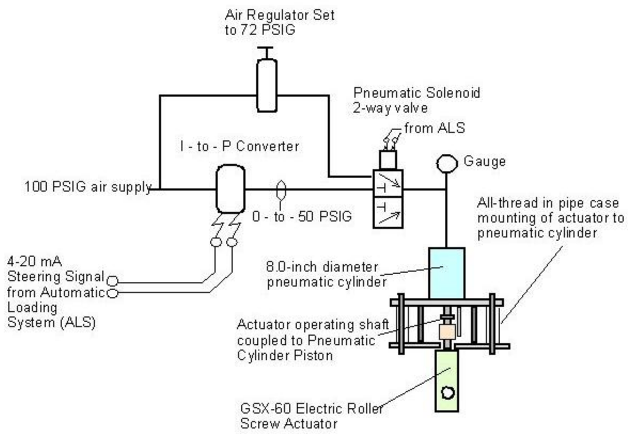

Figure 9. Actuator Load Feedback Setup during Testing.

The combination of speed and load simulations enabled the new digital governor and electric actuator systems to be operated under very representative conditions, as the application was tested in all modes of operation. The ensuing tests discovered a critical need that otherwise would probably have been overlooked.

In the situation in which a full load actuator closure occurs (possible from several initiating causes), it was determined in testing that the rapid closure rates of the electric actuator — under accurate simulated steam and closure spring forces — generated significant back-EMF voltage on the SDU bus to initiate an SDU trip. This condition was deemed unacceptable, since an SDU reset would require operator manual intervention of the remote units prior to restart. The discovery led to the inclusion of a brake resistor bank for the SDU, to dissipate the back-EMF generated under these events. Once testing resumed with the brake resistor bank, the system was proven to remain operational through all rapid valve closure scenarios. This illustrates the value of full simulation testing of retrofit systems. If a typical "ship to site" of the various components was utilized, this additional need would not have been detected and a major delay in startup would have been experienced to enact a back fit.

CASE EXAMPLE: SAUDI ARAMCO COMPRESSOR DRIVE STEAM TURBINE

The ‘Uthmaniyah and Shedgum Gas Plants are sister plants built and brought online in the late 1970s, for processing the natural gas associated with oil production. Four parallel feed gas compressors are used in each plant. Each compressor is driven by a 22 MW steam turbine, with pneumatic and hydraulic controls of the technology at the time of construction. The machines are categorized as “critical” service since they are unspared.

Figure 10. Old Mechanical Governor and Hydraulic Actuator.

The original mechanical governor receives a speed set-point signal from the plant control system that is “translated” to a pneumatic signal controlling the pilot valve, which then controls the main hydraulic cylinder or servomotor driving the governor valve rack. This setup is shown in Figure 10. Frequent failures of the mechanical governor and hydraulic circuit prompted ‘Uthmaniyah Gas Plant, and later joined by Shedgum Gas Plant, to search for a reliable solution that would put an end “once and for all” to the repetitive failures. Figure 11 shows the frequency of governor failures at ‘Uthmanyiah Gas Plant over the five years prior to the upgrade. The number of failures between the two plants averages to two shutdowns per machine per year.

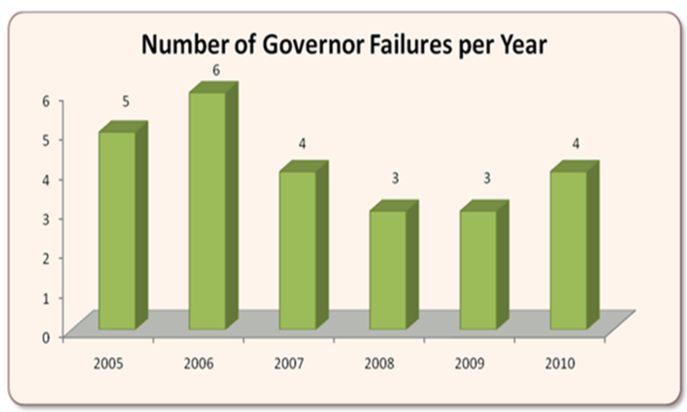

Figure 11. Pre-Upgrade Governor Failures.

Two large compressor-drive steam turbines were selected for a trial upgrade to fully-electric speed control. Several options available in the market were studied, including:

- Electro-hydraulic pilot/servo valve (several designs)
- Electro-pneumatic actuated pilot valve.
- Electro-hydraulic Power Cylinder.
- Hydraulic Pressure Unit dedicated to control oil.
- Electric pilot valve actuator.
- Electric main actuator (fully-electric).

After consideration of the advantages/disadvantages and costs of each option, a complete upgrade to a fully electric speed control system became obvious and the decision was made to go for this state of the art in steam turbine control. The electric actuator force rating was available to over 111 kN (25,000 lbf) and a stroke length to 25cm (10 inches), which facilitated the direct replacement of the main hydraulic actuator. This eliminated all hydraulic and pneumatic interfaces with the electronic governor signal thus considerably improving system reliability and accuracy.

Dual redundant electronic governors were used to control the turbine's governor valve electric actuator through a servo-drive with position feedback. Additionally, the original mechanical overspeed trip was upgraded to Triple-Modular-Redundant (TMR) electronic overspeed protection. The first trial installation commenced in 2011 at the 'Uthmaniyah Gas Plant followed by installation at Shedgum Gas Plant.

Design Challenges

A major challenge was the hazardous environment, due to flammable gas leak possibility, as well as the hot, humid and dusty weather. These conditions are not typically faced in power generation applications and required a unique solution for this pioneering oil and gas installation. The solution was to design and build a protective purged enclosure (Figure 12) that keeps out hazardous gases and provides a clean environment for even better reliability and longer service life. Reduced pressure instrument air was used for purging the enclosure.

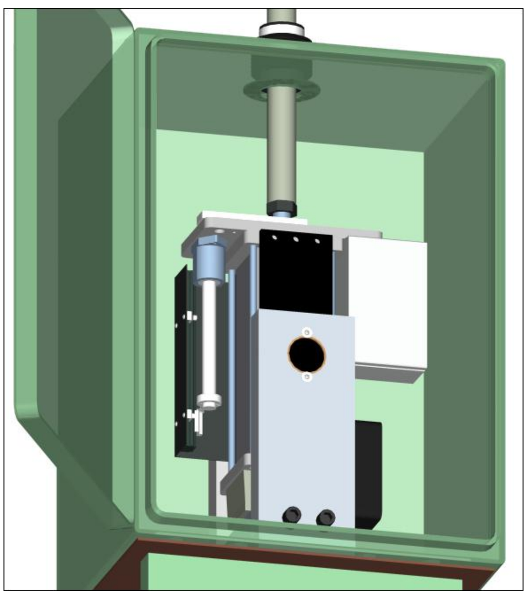

Figure 12. Electric Actuator in Enclosure.

Additionally, in this fulcrum rack design, the support of the electric actuator needs to provide rotational freedom, to allow tilting as the actuator rod extends and retracts. This was achieved with a pivoted trunion bearing support (Figure 13) that results in zero-deflection of the actuator rod.

Figure 13. Electric Actuator Support Bracket.

Finally, a "minimum stop" was designed and fitted onto the electric actuator to eliminate valve seat impact in case of total power loss. The electric actuator assembly with the minimum stop is shown in Figure 14. An additional protection against shutdown — due to power loss to the servo drive — is providing a redundant power supply from a different feeder.

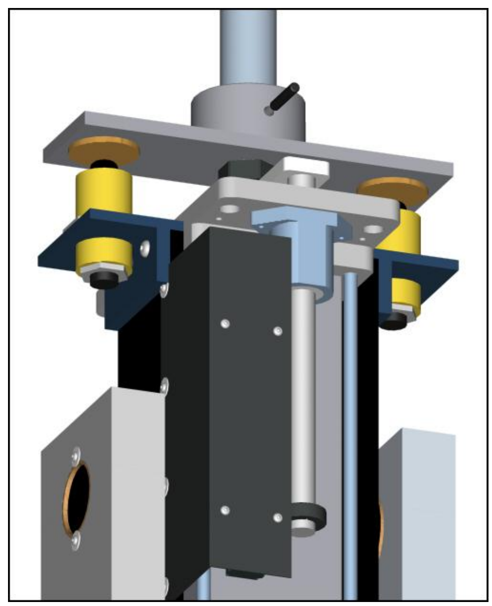

Figure 14. Electric Actuator Assembly with Minimum Stop.

Operational Experience

The previous design of the steam turbine speed control system, having a Mechanical Governor with Hydraulic Actuator, experienced speed oscillations and unnecessary shut downs due to mechanical wear and oil contamination. This necessitated repetitive maintenance that adds to the outage losses. The main disadvantages of the old system can be summarized as follows:

- Mechanical governors caused many shutdowns.
- The shaft-driven governor gear assembly caused abnormal vibration.
- Low servo motor/power cylinder reliability.
- Sensitivity to oil contamination.
- Several control oil leaks

- Mechanical overspeed protection prone to failure.
- High maintenance costs.

After upgrading (Figure 15) to fully-electric speed control and actuation, i.e., electric actuator and electronic governor, the system reliability was improved significantly. In the past year of operation, only a single relevant trip occurred that was actually due to complete power loss. This will be overcome by designing future installations to have redundant power supply. The main advantages of the new system can be summarized as follows:

- Not affected by oil contamination.
- Elimination of oil leaks.
- Speed fluctuations issues resolved.
- Reliable electronic overspeed protection.
- Lower maintenance costs.
- Condition monitoring of linkage and actuator “health” by electric current.

Figure 15. Electric Actuator Installed at Site.

CONCLUSIONS

Inverted roller-screw electric actuators are a proven economic, efficient and reliable control option. With careful engineering, selection, installation and tuning, the electric actuator provides superior performance with less routine maintenance. Based on our experience so far, these actuators eliminate many of the chronic problems associated with hydraulic cylinder positioned turbine governor valves.

With full electronic interfacing, electric actuators are compatible with plant distributed control systems and digital electronic governors. Additionally, they provide new means of troubleshooting via actuator current or load cells/strain gauges for monitoring the condition of the actuator and connected linkages. With future higher force ratings, they would cover the entire spectrum of large steam turbine direct actuation applications. With the current technology available today, electric actuators are feasible replacements for many aging hydraulic applications.

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