ABSTRACT

This paper chronicles a control system retrofit for a 38,000 horsepower refrigeration compressor drive at Novacor's Ethylene #1 Plant, Red Deer, Alberta, Canada (Fig. 1). The changes were designed to meet a 3-year continuous operation requirement. When the plant was constructed in the late 1970's, annual turnarounds were considered normal operating procedure.

The project replaced original electronic controls on a 23,500 horsepower G.E. Frame 5, Model R gas turbine and a 18,300 horsepower Elliott 2 NV starter/helper steam turbine. Both turbines are connected at opposite ends of a single compressor drive shaft (Fig. 2). Because of the cost associated with any control system malfunction, a programmable triple modular redundant controller was selected as the replacement.

Among the modifications performed to enhance system reliability were wiring dual exhaust thermocouples directly into the system and triplicating critical field devices. Another important aspect of this upgrade was replacing deteriorating underground field instrumentation wiring with cabling in overhead cable trays. The original wiring was over stressed by "frost heaving," causing several unplanned shutdowns. In April of 1991, the project team initiated a schedule to meet an early August delivery. System specification, checkout, and start-up, as well as its first year of performance are discussed.

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INTRODUCTION

The key component in a modern Ethylene plant is the Propylene refrigeration system. The critical propylene compressor is driven by two turbines — a gas turbine and a steam turbine — one on each end of a single drive shaft. When this unit shut down, it causes a complete plant outage with the associated environmental and economic consequences. Extensive flaring of costly hydrocarbon feed stocks and intermediate products as well as losing opportunity to sell finished products usually result. In addition, the risk of having an incident increases significantly during shutdowns and startups, when fluctuating flow rates, pressures, and temperatures are likely to occur in the process train. To avoid accidents, unplanned shutdowns and inadequately controlled startups, a full Hazardous Operations (HAZOP) analysis was performed by the project team.

Performing this analysis led to requirements that sought to achieve single fault-tolerance for the turbine and compressor operation. Turbine control systems turbine that met the fault-tolerance objective were investigated and triple modular redundancy was selected as the preferred system architecture. This approach is designed to tolerate single faults through a voting approach to fault coverage and masking. In addition, the voting results are used for diagnostic reporting to system maintenance personnel and system logs. (See the control system block diagram, figure 3.)

Another area affected by the hazard analysis was the type, number and location of field devices critical to the operation of the turbine. These devices were duplicated or in some cases triplicated. Replacing the field wiring to the turbine skid, was also seen as essential to meet the new availability objectives. The replacement of the skid instrument wiring, while not part of this project, was accommodated by placing new field junction boxes above the walkways and wiring them to the existing junction boxes below the walkways. Other aspects of the system from power sources to trip systems were examined and most were modified.

Major turnarounds, however, are often scheduled months and sometimes more than a year in advance. Since this schedule had less than 120 days to delivery on site, significant changes in scope were not considered. A section of this paper covers areas that must be addressed in later turnarounds.
PROJECT SCOPE

Field Changes

Wiring. In the years since its original commissioning, the turbine had suffered a number of wiring related shutdowns. One reason the wiring became a problem is that it was installed in the ground. Weather in Alberta can be severe and earth routinely freezes and thaws to a depth of one meter. The freeze-thaw cycle, which causes “frost heaving,” had stretched and twisted the conduits and cables enough to crack insulation and jeopardize electrical integrity. To lower the risk of wiring related failures, all 1100 feet of wiring, from the control room to the turbine skid, was replaced with eleven multi-conductor Tech (armored) cables. The cables are approved for hazardous locations by Canadian Standards Association (CSA). To keep these cables out of the earth, 500 feet of new overhead cable trays were added to the existing tray system. New junction boxes were added at the skid to terminate all the new wiring. The original junction boxes were preserved and new wiring was run point to point between the old and new. New sensors and switches were brought directly into the new junction boxes. This was done in anticipation of rewiring the Skid during a future turnaround. The original junction boxes will be removed at that time. Easy access to the new terminations was an important consideration for selecting the locations of the new junction boxes. Another benefit of rewiring was bringing field wiring drawings up to date and placing the information in an easily accessible database.

Redundant Sensors. While many field devices were reused without any changes, to consider a fault-tolerant system without examining failures in the field devices, would have been an oversight. All switches and sensors that can cause a nuisance shutdown by failing were considered for replication. As previously mentioned, some devices simply could not be installed in the time allotted for project execution. Many signals were, however, duplicated or triplicated. Those triplicated were:

- Pcd (compressor discharge pressure) transmitters (Fig. 4)
- fuel gas pressure transmitters
- seal oil differential pressure switches
- low bearing oil pressure switches

In addition, the five existing magnetic pickups are now all used for the reliable determination of shaft speed for both control and electronic overspeed trip protection.

Redundant Exhaust Thermocouples. Exhaust thermocouples, for example, were replaced with internally redundant paired thermocouples. By connecting each thermocouple to the control system directly, exhaust temperature used by the control and trip logic gives a more accurate and reliable reading. The measurement selection and processing is described in the control software section of the paper.

Actuator Servo Loops. The existing servo actuators for both steam and gas turbines were reused including the electrical-hydraulic interface. Position feedbacks for the stop/ratio and fuel gas control valves were a different matter. They employ linear variable differential transformers (LVDTs) and the standard electrical excitation and demodulation circuitry that came with the new control system had to be modified to reuse these devices. For the fuel gas valve, two input signals were used to interface with the existing dual-coil torque motor used to drive the pilot. A circuit incorporating two servo amplifier boards was developed using a voted digital output to switch from one amplifier to the other upon a divergence of the control command and valve position feedback.

Redundant Power Sources. The HAZOP analysis identified power supply interruption from a single motor control center as a source of a single fault that could shutdown the plant. The turbine control system has two independent power input channels either of which can be AC or DC fed. To provide the highest integrity power supply in the project time frame, one feed was supplied by 130VDC station batteries. An uninterruptible power supply (UPS) provided the second independent power feed to the system.

Control Room Changes

The major change in the control room was finding a place for the new control system and graphic operations terminal.
Since the turnaround was scheduled to last only two weeks, most of the work was done prior to the shutdown. New equipment was set, mounted, and terminated before existing systems were removed. Existing panel mounted devices were wired to the new system during shutdown.

**Control System Changes**

**Integrated Control.** By bringing the data for all three machines into a single control system, the ability to control the system with the least obtrusive action can be exploited. The control system I/O included:

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type K thermocouples</td>
<td>56</td>
</tr>
<tr>
<td>Analog inputs</td>
<td>13</td>
</tr>
<tr>
<td>Analog outputs</td>
<td>12</td>
</tr>
<tr>
<td>Digital inputs</td>
<td>51</td>
</tr>
<tr>
<td>Digital outputs</td>
<td>23</td>
</tr>
<tr>
<td>Pulse inputs</td>
<td>5</td>
</tr>
</tbody>
</table>

In the previous control approach, information was split between the governors of each machine. These original independent controls could not be tuned properly, due to interaction between the two systems.

To improve the control of this dual-turbine configuration, the new system uses a single speed controller and a split ranged output to both the gas and steam valves. This algorithm loads the gas turbine and operates it on true temperature limit control, while compensating for disturbances and load changes using the steam turbine. This approach is elegant in its simplicity (Fig. 5).

Total horsepower demand is determined each computation cycle. Then, using the contribution of the gas turbine as a given, the algorithm maintains temperature limit control while the steam turbine is used to equalize the horsepower requirement.

When there is excess steam available to the drive train, the gas turbine’s horsepower contribution is curtailed by simply lowering the exhaust temperature limit if operations wishes to adjust the plant’s steam balance.

**Triplicated Sensor Processing.** These signals are voted in the new control system and erroneous devices can be detected with extremely high confidence. For triplicated transmitters, a simple median value selection provides the first level of protection against a failure of any single sensor. Furthermore, it is not uncommon for a sensor to drift from the actual value. The deviation of each sensor from the median of the three devices is continually compared to a threshold selected through the graphic screen. If the acceptable deviation is exceeded several things occur. The sensor selection algorithm immediately reverts to a low or high selection, depending on the measurement, and the exact device is indicated to the operator, alarmed, and logged to the printer.

**Redundant Exhaust Temperature Processing.** By duplicating other inputs, a measure of protection from catastrophic failure and nuisance trips is obtained. Exhaust temperature, one of the most critical gas turbine measurements, can be made more accurate and fault-tolerant by using redundant thermocouples. The steps in the exhaust temperature computation follow:

- Each thermocouple element in a given pair measures the same temperature as the other element.
- 18 pairs of exhaust thermocouples are divided into 3 sectors.
- Up to 12 thermocouples in each sector are averaged for a sector temperature.
- “Exhaust temperature” is the average of 3 Sector temperatures.
- If the deviation in the readings of a redundant pair exceeds 20 degF, that pair is automatically eliminated from the sector average computation.
- An alarm indication is presented to the operator through the graphic interface and annunciation on panel and a logged message on the printer.
- Once the operator has determined the cause of the pair’s abnormal deviation, he may decide to place one of the disabled thermocouples back on-line.
- After a thermocouple has been manually enabled it will be used unless a burnout (open circuit) is detected or it is manually disabled.
By treating each sector separately, hot spots can be detected that might not elevate the average to a noticeable extent. All measurements are available on a graphic display that use color coding for the status of each of the 36 measurements (Fig 6). In addition to the manual enable/disable feature, limits are adjustable on the graphic screen.

**Control Software Changes.** Using a computer-based graphic editor to make changes to logic and control blocks allowed the control engineers to quickly adapt the system to the complex new machinery train. It is anticipated, however, that this capability will seldom be used during actual operation. Furthermore, it must be used with full knowledge of the system and unit operation.

**Tuning loops and Setting Trip Thresholds.** The system’s control loop responses, as well as trip and alarm limits are tuned or changed through the use of display entered constants and do not rely on changes to the logic or block software. Four starts were required to discover the time constants for the controllers. Responses to step changes in the steam and gas valve positions were measured. Approximate tuning was done on each loop and the process was repeated.

High acceleration (40 RPM/sec), from purge to minimum governor, is required to put the compressor through the critical vibration speed zones quickly. Initially, rapid acceleration caused flameouts on the gas turbine, which was corrected by adding “a little kick” to the fuel valve. The steam valve is given a kick for faster acceleration.

**PROJECT EXECUTION**

**Time Line**

With project kickoff on April 16, 1991, and a two week turnaround scheduled for the end of September 1991, the timing of every task in the project plan was critical. Most of the retrofit simply had to be done before the plant came down. The major milestones are shown in table I, Project Schedule.

**Startup Experience and Recommendations**

**Staffing.** Dedicated a team to an undertaking like this is essential. The purchaser cannot obtain a system that truly reflects his needs without involvement in every aspect of the project. The control system supplier cannot know the operation of the process plant, which is the reason that the turbine exists. The most difficult aspect may be in meeting approval
TABLE I. PROJECT SCHEDULE

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
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<tbody>
<tr>
<td>Kickoff</td>
<td>16 April</td>
</tr>
<tr>
<td>Manufacturing Began</td>
<td>15 May</td>
</tr>
<tr>
<td>Prelim. Installation Engineering Release</td>
<td>22 May</td>
</tr>
<tr>
<td>Cable Tray and Armoured Cable Installation</td>
<td>24 May</td>
</tr>
<tr>
<td>Final Specification Design Review</td>
<td>03 June</td>
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<tr>
<td>Training at Factory</td>
<td>03 June</td>
</tr>
<tr>
<td>Software Development Begins</td>
<td>04 June</td>
</tr>
<tr>
<td>Final Specification Approved</td>
<td>26 June</td>
</tr>
<tr>
<td>Manufacturing Complete</td>
<td>01 July</td>
</tr>
<tr>
<td>Acceptance Test Plan Approved</td>
<td>10 July</td>
</tr>
<tr>
<td>Factory Test Complete</td>
<td>02 August</td>
</tr>
<tr>
<td>Installation Engineering Package Approved</td>
<td>09 August</td>
</tr>
<tr>
<td>System Onsite and Installation Begun</td>
<td>12 August</td>
</tr>
<tr>
<td>CSA Site Approval Received</td>
<td>14 August</td>
</tr>
<tr>
<td>System Testing Begun</td>
<td>17 September</td>
</tr>
<tr>
<td>Installation Complete</td>
<td>20 September</td>
</tr>
<tr>
<td>System Commissioned</td>
<td>02 October</td>
</tr>
</tbody>
</table>

milestones. When time is of the essence, a two week period for drawing or specification review and approval takes a concerted effort of dedicated personnel. The control system vendor must likewise staff the project for an intense effort.

Even though every effort was made to checkout the system and control logic during design implementation and factory test, some items went undiscovered until field checkout. Following are observations and, in some cases, problem resolutions which came up during the installation and precommissioning portion of the project.

Control System Operation and Software

- A 3 second time delay on the seal oil differential pressure switch indication eliminates nuisance trips during startup oil system surges.
- Because changes are easy to accomplish and nearly inevitable during startup of a complex set of machinery, diligent software change management is necessary to prevent surprises upon reload.
- Percentage horsepower along with percentage valve opening indications were added to the startup screen.
- A new graphic screen was required to bypass lube oil and seal oil differential pressure switches. Because these devices were triply redundant, a switch may be disabled when its state disagrees with the other two switches. Upon disabling a switch, a valid trip is not signaled until both remaining switches indicate a trip — 2-out-of-2.
- Operating procedure now requires an operator to press the "proceed" button (see figure 7.) to continue with each startup step until warm-up step is reached. Transition from warm-up to run is automatic.
- Historical data storage and retrieval corrected.

Field Hardware Problems

- The servo amplifiers were modified to fail safely when the control system is taken out of service for downloading software. A shutdown contact was wired in fail safe mode with the shutdown trip solenoids. Furthermore, the steam turbine's trip & throttle valve can not be latched open again until slow roll has been selected by the operator after a "mode 0 - trip state" is reached.
- Stop ratio valve leaked so it was removed, the sealing surfaces were lapped, and the valve stem replaced and repacked.
- Over tightening of fittings caused leaks at the valve blocks for lube oil and seal oil differential pressure switches. Fittings were replaced.
- UV flame detector amplifiers are 300VDC (!) at the terminals and require appropriate shielding.
- Control system vendor's drawing overlays did not match user's format, requiring reformating of the software based drawings.

Control System Hardware Problems

- Canadian electrical code required removal of nylon washers, for mount components chassis.
- Panel alarm assembly had faulty soldier joint -- caused intermittent communication alarms.
- Two I/O modules failed, perhaps due to static discharge, and were replaced during precommissioning.

Future Enhancements

Areas were identified (using a HAZOP analysis) that could not be addressed by this project due to the time available. Some are tentatively planned to be addressed during the turnaround scheduled for 1993. The areas identified for future reliability-motivated modifications are:

- duplicate stop/ratio valve actuator LVDT
- add 2nd set of station batteries and charger
- install redundant fire detectors for GT housing
- add limit switch on GT exhaust/ bypass louver
- compressor interstage propylene accumulator level switches.
RESULTS AND CONCLUSIONS

As of this writing, the unit had suffered no nuisance trips during the year after its control system retrofit, nor had it failed at any time to control the turbines and compressor properly. This record represents a reduction from about two per year prior to the upgrade — saving about $250,000. This record was established in spite of component failures in an analog I/O processing circuit. Because the system is fault-tolerant, however, the problem, which has been corrected, did not cause a system level malfunction.

Diagnostic tools such as the exhaust thermocouple and seal/lube oil switch bypass screens protect the turbines and improve on-line maintenance of the complete system. Multiple field element processing enables operation of the turbines even with field element failures identified.

The controllability of the machinery train is improved due to the coordinated steam and gas turbine controls. Thus, a source of process variations is greatly reduced, which increases product quality. Even major disturbances do not jeopardize the operation of the train since a single control action is taken by the system. Smoother start-ups reduce the risk of surge and bring the product “on spec” quicker.

New information about the machinery is available to the operators and maintenance personnel through the graphic display interface. This promotes better operating decisions and quicker diagnosis of abnormal conditions.