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# Improve Safety and Reliability with Dynamic Simulation

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*Chemical companies face a major transition as the current workforce ages and the number of retirements accelerates resulting in many years of lost operating experience. It will be challenging to maintain and improve the reliability and safety of operations as some of the best operators leave the workforce. Faults due to operator errors can be addressed by improving the operator's training and increasing the robustness of the control system to operator variability. In this article, we demonstrate how operator variability can be detected as a first step toward measuring and improving the control system's robustness. The characterization of a typical operator procedure caused transition, a reflux pump switch, and the resulting control system response was analyzed using the dynamic process simulation tool Honeywell UniSim Design. The best operator response and potential errors for other daily operator activities such as pump switches, reboiler switches, and similar operational transitions can be obtained offline by studying process history.* © 2014 American Institute of Chemical Engineers Process Saf Prog 00: 000–000, 2014

*Keywords: process transition; fault detection; transition monitoring*

## INTRODUCTION

Operator turn-over and training issues are becoming more and more critical as the workforce grays with the potential for a much younger and more inexperienced workforce in the very near future [1]. Many facilities are moving to address this issue by investing in training including high-fidelity operator training systems based on dynamic process simulators such as Honeywell UniSim Operation. We support operator training, but we believe that a complementary effort to improve the robustness of the control system to operator variability should be carried out simultaneously. Procedure modifications should be identified that make errors easier to recognize and correct before they result in significant process upsets. During transitions in continuous process, control system procedural steps and manual valves and other equipment requires direct human involvement. Thus, procedural errors involving both inside and outside operators is a major contributor to safety incidents in process industries.

Operating companies must address the increase in operator variability caused by the loss of more experienced workers. They can characterize what is considered a good transition (best operator) and what types of errors are possible if mistakes are made by the operator during the transition procedure. Errors during transition can destabilize process steady state for a longer time, which can decrease production and/or increases off spec products. Major faults during transition may also lead to unexpected situations including accidents. Thus, it is desirable to capture what is a good transition. Operating companies can assess their specific control system's capability to compensate for operator-assisted transition errors using dynamic simulation. Monitoring and fault detection during transitions can be very useful to avoid those abnormal situations.

Many chemical manufacturing plant reliability and safety incidents result from abnormal situations associated with errors in operator-assisted transitions. Transitions occur daily in continuous chemical process operations due to maintenance or regeneration requirements of different equipment (e.g., furnaces, absorbers, pumps, compressors, valves, etc.). Operator-assisted transitions range in complexity from simple operations like pump switches, reboiler switches, and bypassing control valves to more complex transitions such as the start-up or shutdown of reactor systems or even the entire plant. Operator-assisted transitions can also be completely board driven such as adjusting an automatic control strategy based on current operating needs. All of these transitions are a necessary part of continuous chemical plant operations and all transitions cause disturbances or oscillations in plant process variables. They may also be susceptible to errors that increase the disturbances and lead to more significant reliability and safety exposures.

In this project, dynamic simulation-based study of process transition is performed for a simple reflux pump changeover operation. Analysis from the simulation data helps to find a process variable which can be used for monitoring transition for faults using trend comparison technique. Enhanced trend analysis-based monitoring [2] is used for comparing trends with standard transition trends for its dynamic feature synchronization capability. A dynamic simulation case of reflux pump change over in a distillation tower during normal operation was chosen to study the behavior of simple transitions in process operation using Honeywell Unisim Design. We first simulated the transition case using a normal operating procedure. Different fault scenarios were generated from the normal procedure and simulated to get the fault transition behaviors. The dynamic simulation allowed us to observe the effects of this transition on process variables and implement an effective fault detection technique. The monitored variables were used to detect any fault during the changeover for several different fault scenarios.

## TRANSITIONS IN CONTINUOUS PROCESSES

Several studies have been performed concerning transition monitoring of plant state changes. Process states can

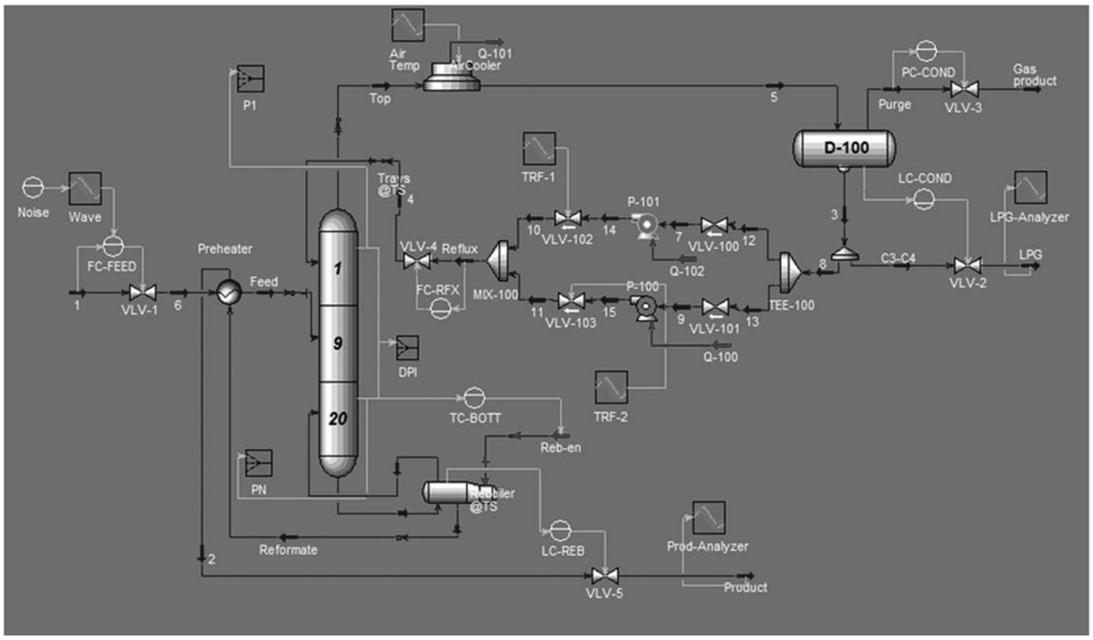


**Figure 1.** PFD of the stabilizer column used for dynamic simulation.

change due to changes in operation mode, feedstock, throughput, etc. Model-based technique were proposed [3,4] using nonlinear and multilinear models, respectively, for detecting state transition changes. Deviations from the proposed models were measured by open loop observers to identify faults using kalman filters. However, the application of model-based technique is limited by the complexity of model identification for specific process transition.

Data-based transition monitoring is proposed to use historical operational data to identify standard transition process. Several techniques like—neural network, dynamic Principal Component Analysis (PCA), trend analysis, and dynamic signal comparison were proposed to monitor transitions in process operation. Dynamic PCA (DPCA) was used by Ref. 5 to classify normal and transition states using multivariate statistical analysis from historical transition data. Comparison with normal modes and transition states for standard transition were used for identifying faults. Neural network-based state classification for transition state identification was proposed by Ref. 6. Transition monitoring using qualitative trends was proposed by Ref. 2. Trends were identified from historical data to describe qualitative pattern of transition process. Enhanced trend analysis method was proposed to compare online trends to dictionary trends. A signal comparison method was proposed by Ref. 7 using dynamic locus analysis, based on dynamic programming of online signal comparison. This technique has the ability to perform multivariate process monitoring for normal/abnormal conditions in transition process.

In this project, we have used enhanced trend-based comparison for monitoring equipment changeover transitions. Transition in continuous process due to equipment changeover is very common in daily operation. Different equipments like furnace, absorbers, compressors, pumps etc require regeneration or maintenance after certain runtime to maintain safe and continuous operability. During those transitions, the process goes through changes and those changes are reflected in process variables associated with the unit of operation. In transition, one or more variables change from its normal operating point and the transition operation is carried out in a way to minimize changes of process variables. Often these transitions are performed manually and in a short period of time. During short transition processes, disturbances occurring because of the transition are not significant enough to make state changes which can be observed using multivariable state monitoring technique. Also, in a continuous process, the main objective of process operation is to maintain steady state condition of process variables. Automatic control of process variable also makes it harder for changes in variables to be observed. Usually, standard operating procedure (SOP) is followed to ensure safe and steady changeover. A trend comparison technique can be very effective in this scenario by identifying appropriate variables for transition monitoring.

Due to the advancement of Distributed Control System (DCS) technology, plenty of data are collected from the process monitoring and control system. However, only a few critical parameters can be followed by operators in process operation, especially during transition. During transition, relevant data (or process variables) linked to transition can be monitored for proper transition changes and can be used as a fault detection tool to assist the operators with safe and fault free transition (or to avoid unwanted circumstances).

## REFLUX PUMP SWITCH EXAMPLE

To study simple transition in continuous process, we have used dynamic simulation of a stabilizer column (Figure 1). Stabilizer is used for removal of gaseous hydrocarbons and light liquid fractions from petroleum feed. For transition simulation, we have used the reflux pump changeover operation on the column. A simple modification was made to carryout changeover transition. One additional pump is placed parallel to the running pump and four valves were placed around the pumps (Figure 2). First, a standard transition procedure was made to minimize the disturbance on the reflux flow rate. From the standard operation procedure, potential faults during changeover are identified. Below are the SOP for pump changeover and potential faults.

### Reflux Pump Switch Procedure

1. Open the inlet valve of the reserve pump.
2. Start the reserve pump.
3. Make sure of the pressure build up in the pump outlet.

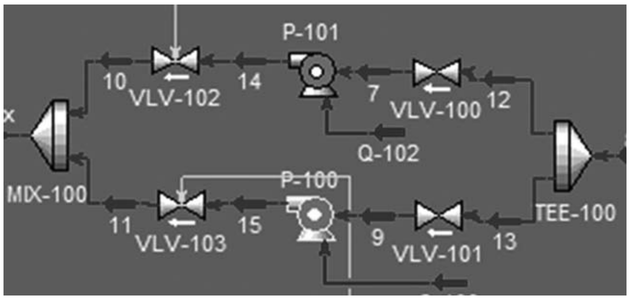


**Figure 2.** Reflux pump setup for switch simulation.

**Strip Chart Legend - FC-RFX-DL1**

| Curve Names | Colour | Line Style | Line Thickness |
|---|---|---|---|
| FC-RFX - SP | | Dotted | 2 |
| FC-RFX - PV | | Solid | 2 |
| FC-RFX - OP | | Dashed | 2 |
| Trays - Stage Temperature (1_ | | Dashed | 2 |
| Trays - Top Stage Pressure | | Dot-Dash | 2 |

**Figure 3.** List of variables and their color code.

4. Start opening the reserve pump outlet valve, simultaneously, closing the running pump outlet valve.
5. Make sure the reserve pump outlet valve is fully open.
6. And the running pump outlet valve is fully closed.
7. Stop the previously running pump.
8. Close the inlet valve of previously running pump

### Potential Faults During the Changeover

a. (@1) Reserve pump inlet valve is not opened.
b. (@1) Opened the wrong valve instead of inlet valve.
c. (@2,3) Pump failed to start/No pressure buildup.
d. (@4) Asynchronous opening and closing of the outlet valves.
e. (@4) Wrong valve operation during opening and closing of the outlet valves.
f. (@5) Pump outlet valve partially opened/did not open.
g. (@6) Closing the wrong valve.

The SOP for pump changeover listed above have manual valve and pump operation which requires manual operation through human involvement.

#### DYNAMIC SIMULATION TRANSITION ANALYSIS

Dynamic simulation can be a great tool for studying transition process behavior. Through simulation one can observe the transition process and analyze the movement of different variables due to transition. Appropriate variable(s) explaining the transition process can be used to monitor the process. The variables to be monitored for pump changeover transition are reflux rate change, top stage pressure change, top stage temperature change, actuator position (or reflux controller output) of reflux rate control valve (Figure 3).

At first, dynamic simulation transition was performed using SOP. Changes in process variables listed above are gathered in a strip chart (Figure 4). From the chart, it is noticeable that the variables start to change during the transition step 4. At step 4, the operators start swapping the pumps by simultaneously opening and closing outlet valves of reserve and running pumps. During this operation, pressure in the pump outlet is increased because both pumps

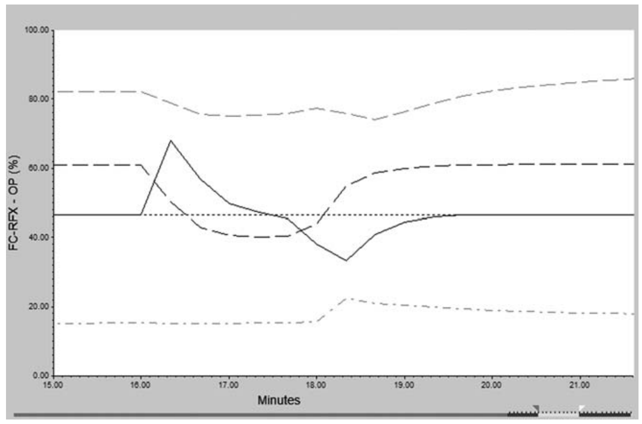


**Figure 4.** Strip chart of monitored process variables due to standard transition procedure.

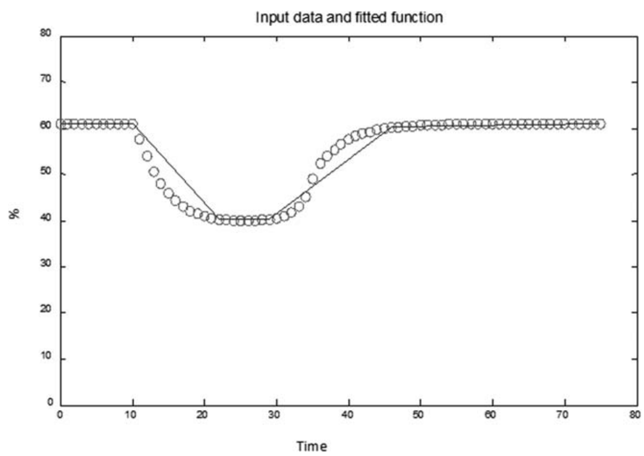


**Figure 5.** Monitored variable (controller output) data with fitted line.

are in operation at the same time. Hence, we see sudden increase in reflux flow in the trend. But, the reflux flow controller (FC-reflux) at the downstream of the pumps tries to maintain the flow to its set point by decreasing the output of the controller to the control valve. After the valve swapping is complete, pressure returns to normal state and control valve output returns to its original position (assuming both pumps have the same capacity).

From the trend changes, it is obvious that the controller output to the control valve has distinct yet simple changes with the transition steps for pump changeover operation. Other process variables like reflux flow (FC-reflux PV) show too much change to be used for trend comparison. Variables like top stage temperature and pressures show too little change to be used for monitoring.

To monitor the transition process for fault detection, the controller output to the control valve is selected for trend comparison. An enhanced trend comparison method proposed by Sundarraman and Srinivasan [2] is used for monitoring and fault detection. This method is suitable because to capture changes in the process, process states need not be changed. Only the variable changes, in this case an instrumentation variable, can be compared with the standard data. The data from standard transition simulation is fitted with several linear lines (Figure 5) which are identified as

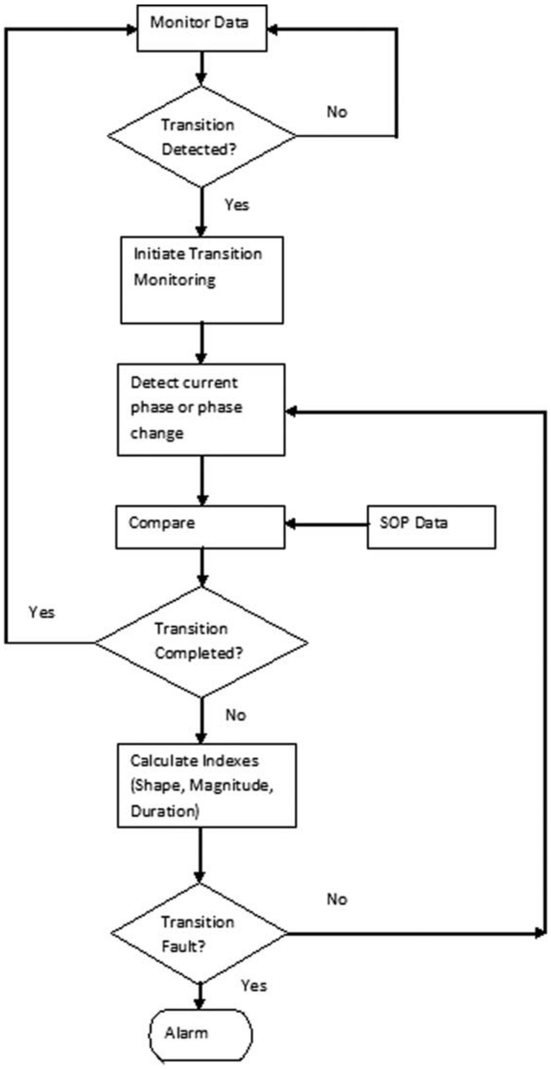


**Figure 6.** Block diagram of transition monitoring system.

standard trend of the transition process. Comparison with this linear simplified trend is used for monitoring the transition process.

#### TRANSITION MONITORING AND FAULTS

As mentioned earlier, transition monitoring is performed by comparing the real-time trend with the trend for SOP using enhanced trend analysis. In practice, the transition monitoring software can either be activated manually when a procedure is started or it can be configured to automatically detect the beginning of a procedure when one or more criteria of the transition are met (e.g., backup pump start). As described earlier, the standard transition process is divided into different phases to compare with real time data.

In enhanced trend analysis, comparison in each phase is performed by computing three matching degrees—shape matching degree, magnitude matching degree, and duration matching degree—from standard and real time trends. During monitoring, the real time data are gathered from the DCS (or low latency history) and a slope is calculated to detect a trend in each phase or to detect change of phases. From the calculated slope, the trend in each phase is characterized as increasing, decreasing, or no trend. To take into account the variations due to process disturbances, three consecutive data points showing a dissimilar trend are required to detect a phase change. Also, a slope below a certain threshold is considered zero and used to detect that there is no trend in a given phase. After detecting a trend and determining the phase in the transition process, the trend in the current phase is compared by calculating a shape matching index relative to the standard transition data. The index value is either zero if no match is found or one if the data matches the trend.

The magnitude of the change in the process data observations in a particular phase of the trend is compared with the magnitude of the standard trend at that respective phase and equivalent time by calculating the ratio $\frac{P_{\text{now}} - P_{\text{start}}(i)}{P^{\text{ref}}_{\text{eqv}} - P^{\text{ref}}_{\text{start}}(i)}$. In this ratio, $P$ represents the magnitude of the process data and $P_{\text{start}}(i)$ represent the magnitude at the start of the current phase $i$. The superscript ref represents the magnitude of the standard transition data. $P^{\text{ref}}_{\text{eqv}}$, the expected value of the process data based on the standard trend, is calculated using a linear interpolation from the standard transition data. If the duration of the trend is longer than the standard phase duration, then the value of $P^{\text{ref}}_{\text{eqv}}$ is taken as the magnitude at the end of phase $i$. If the slope is zero, the value of $P_{\text{start}}$ and $P^{\text{ref}}_{\text{start}}$ are taken as the start value of the previous phase.

A duration index is only calculated when either there is an early termination of a phase or when a phase continues to persist beyond the standard phase duration. This index is calculated as the ratio of the real time phase duration and the standard phase duration.

The standard values of these three indexes (shape, magnitude, and duration) are one when compared with the SOP. However, for fault monitoring, the absolute values of the differences of the indexes from their standard values are multiplied with a factor for comparing with each other. These factors can be chosen based on the different penalty of each type of deviation. A fault signal is generated if the maximum of the above calculated values exceeds a threshold limit.

Using the transition monitoring algorithm (Figure 6), the monitoring and fault detection was tested on different transition fault scenarios listed as potential faults during a pump changeover. Three different cases for faults with different degrees of match with the standard transition are discussed below.

The first fault transition scenario is due to no pressure increase in valve swapping step (step 4). No pressure increase at step 4 can be caused by wrong valve operation (faults a, b, c, e) or pump failure during transition. The net effect of these scenarios is decrease in reflux flow since the running pump outlet valve is closing during this step. As the reflux controller is in automatic mode, the controller output to the control valves increases to maintain reflux flow at the set point. When low reflux rate is detected by an alarm or an operator, the fault is fixed and the reflux rate brought to normal condition. The response from the scenario is shown in Figure 7.

In this figure, a fault is detected due to a shape mismatch of the trend in phase 2. It is important to note that transition monitoring can prevent an upset in the process state by detecting a fault early in the transition process before it is obvious from a low reflux flow alarm. Monitoring can help assist operators in detecting faults early in the transition process using process variables which DCS operators may not monitor during normal operation.

In the second and third type of scenario, fault transitions are simulated by asynchronous opening and closing of the outlet valves (fault d). In Figure 8, a fault is generated in phase 3 due to a duration mismatch degree. For this particular fault scenario, closing the running pump's valve takes longer than opening the reserve pump's outlet valve.

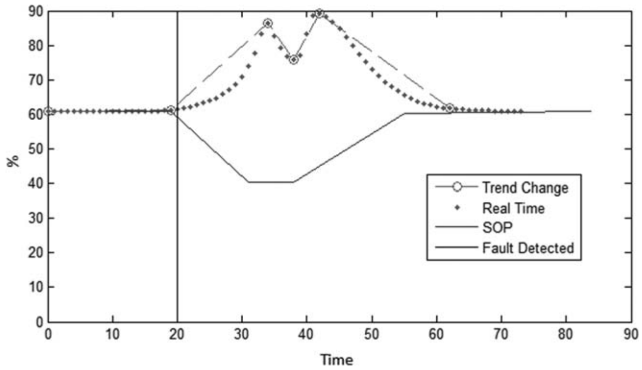


**Figure 7.** Trend comparison for first fault scenario (no pressure increase).

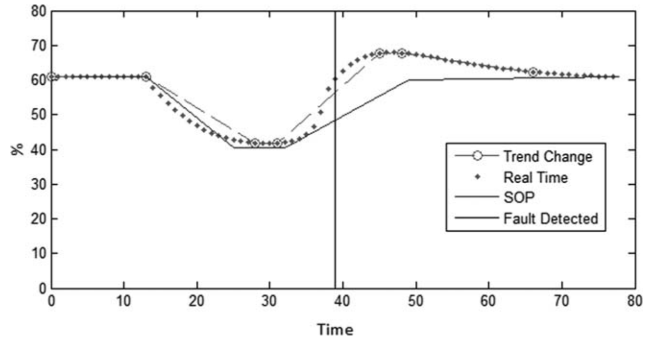


**Figure 9.** Trend comparison for third fault scenario (asynchronous pump changeover—opening the outlet valve of reserve pump takes longer than the opening the running outlet valve).

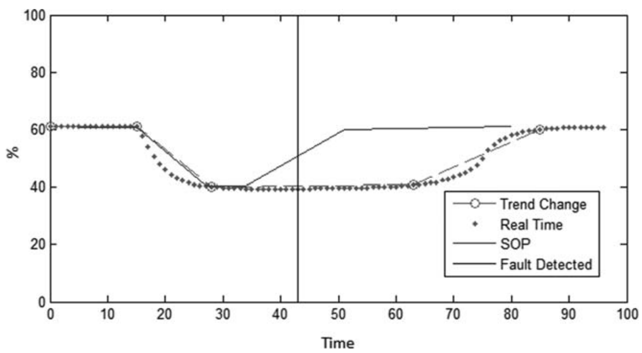


**Figure 8.** Trend comparison for second fault scenario (asynchronous pump changeover—closing the outlet valve of running pump takes longer than the opening the reserve outlet valve).

In the third case, a fault is generated in phase 4 due to a magnitude mismatch degree as showed in Figure 9. This simulation case scenario is opposite of the previous one. Opening the reserve pump's valve takes longer than opening the running pump's outlet valve.

The above examples show that transition monitoring can be used to identify when transition trends are significantly different from the standard trend expected for at given transition process. Deviation from standard transition procedures can happen due to differences in skills of different operators. This could be used to identify operators to be targeted for additional training in order to improve their skill. Using these transition monitoring indexes, to help operators follow the best operator SOP during transitions would lead to more consistent process operation. Consistency in process operation can help the plant run more safety and reliably.

#### DISCUSSION

Transition monitoring in continuous process operation can be a very effective strategy for detecting faults due to human factors or equipment failures. Faults in daily operation due to human factors are a major reliability and safety concern. Transition monitoring software can be designed to automatically detect the beginning of a transition, monitor the transition operation, and alert or alarm the operator in case of a significant deviation of the transition trend. In the case described above, the transition monitoring software used valve output data directly from the DCS; however, low latency process history could also be used. We expect that alerts or alarms from transition monitoring could also help the operators diagnose problems earlier than traditional process alarms (e.g., a low reflux flow alarm).

In this example, we simulated a pump switchover procedure as an example for transition monitoring. Failures during a pump switchover such as pump failures and incorrect valve sequences result in shape mismatches relative to the standard transition process. This mismatch can be detected by transition monitoring software and used to alarm or alert the operator with a more specific failure diagnosis than traditional alarms. This early fault detection can help operators avoid or minimize upsets due to transition errors. In addition, by identifying faults during transitions, operations can address differences between operator transitions which could lead to targeted operator training and more consistent transitions, leading to improved plant reliability and safety.

In this work, we used dynamic simulation to study a transition process. Dynamic simulation can be used to evaluate the control system's robustness to operator errors during routine procedures. Due to advancements in DCS technology, a wealth of data is available in process history to characterize best operator performance of daily transitions. These data can be easily accessed and used for monitoring transition process using trend comparison techniques. For the particular transition studied in this article, this simulation example shows that the reflux controller output to the control valve can be used to monitor the pump changeover transition. To improve plant safety and reliability, these tools also can be used to create transition performance indexes and improve the ability of the operators to consistently follow SOP during transitions.

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