How Soft Sensing Using Simulation Enhances Plant Process Management

By applying a high-fidelity dynamic simulation model for soft sensing, organizations can cost-effectively supplement actual process measurement instrumentation in noncritical areas.

Executive Summary

Measurement of operating parameters using physical instrumentation plays a critical role in controlling process plants and ensuring optimal and safe plant operations. However, some process plant parameters are not measured because of their complex instrumentation requirements, practical infeasibility or the need to reduce capital and maintenance costs.

There are techniques that can leverage the information available from existing measurements, and estimate the process parameters that are not physically measured in the plant. Soft sensing is one such technique, as it augments the physically measured parameters using mathematical and first-principle-calculation-based methods.

One novel approach to soft sensing is to use a high fidelity online dynamic simulation model connected to the plant information system. In this approach, the dynamic simulator takes a direct feed of information from the plant process instrumentation and control system, and can then predict process parameters that are not physically measured in the plant. The model can also estimate key equipment and process performance indicators, which can be archived in the plant historian system and used in generating performance dashboards and reports.

This white paper highlight how a dynamic simulator-based, online soft sensing system can provide a cost-effective alternative to physical measurement in non-critical sections, where requirements are not as stringent as the main process plant.

Soft Sensing Defined

Soft sensing is a technique to predict process parameters using mathematical and first-principle-based models, which are not measured using physical instrumentation in the plant. The system takes information available from physical measurements to calculate an estimation of the desired process parameter. It broadly entails:

- **Analytical techniques**, which rely on using first principle models based on physical laws such as mass and energy balance and physical and chemical equilibrium calculations, and utilizing suitable approximations to estimate the process parameters.

- **Empirical techniques**, which utilize available plant historical data to generate correlations using statistical regression methods, which are then used for estimation and prediction of process parameters.

Apart from estimating the missing process parameters in a plant, soft sensing can also be used to project key process and equipment per-
formance parameters that cannot be directly measured in the plant. A soft sensing system can thus measure in real time process performance indicators such as motor and turbine driver power conversion efficiency, furnace firebox thermal efficiency, heat exchanger fouling or thermal effectiveness, pump and compressor operating efficiency, reactor catalyst activity, etc.

The soft-sensed parameters can also be archived in the plant historian system along with the physically measured parameters, and later used for reporting in plant performance dashboards.

Online virtual sensors can thus effectively supplement missing physical instrumentation, and provide a cost-effective alternative for physical measurement in noncritical sections and utility units, where the requirements are not as critical compared with the main process plant.

Introduction to Process Simulation

Simulation is the imitation of an actual physical phenomenon of a real-world process in a virtual system using mathematical representation. Process simulation is a mathematical-equation-based representation of chemical, physical and unit operations of a process plant in a software environment. The simulation model can be used for various activities pertaining to design, operation and optimization of a process plant.

Process simulators are not new to the process industry, and have been in vogue for more than five decades. The first software programs developed for chemical industries were custom packages built to suit specific industry segments and applications, and they typically ran only on stand-alone systems. Over the years, the industry built software applications capable of handling large, multiple chemical systems, equipment and processes. They evolved into what we today know as steady state simulators. This software is capable of carrying out heat and material balance, and can model all types of unit operations and unit processes typically encountered in a chemical industry. They can be used to design new chemical manufacturing processes, size equipment for new or existing plants, increase operating and energy efficiency, perform plant de-bottlenecking or retrofitting studies, etc.

Once steady state simulators emerged, the next challenge was to model the transient or dynamic state conditions encountered in a plant. The need for a simulator that was capable of modeling actual process behavior in “real time” led to the development of dynamic simulators. A dynamic simulator has multifarious applications that include study of process transient behavior such as start-up, shutdowns, upset conditions, critical failure scenarios, operator training to ensure safe plant operations, process safety studies, hazard and operability analyses, offline controller tuning, evaluation of control strategy, etc.

Dynamic Simulation

Conventional dynamic simulation technology has also existed for some time and has been effectively used by process industries in offline applications. A rigorous, first-principle-based dynamic simulation model can accurately predict how a process and associated control system will behave when subjected to the actual operating conditions of the plant. The capability to mirror process response in real time or faster than real time (i.e., future condition prediction), without endangering the plant, makes dynamic simulation a very attractive tool for carrying out operator training, engineering studies and process safety analysis. The ability to perform in-depth analysis of control system strategy and response to
process transients before the physical plant is set up also makes dynamic simulation an effective process design aid.

A rigorous dynamic simulation model is, however, computationally intensive, requiring software and hardware systems capable of running the model faster (three to five times quicker) than real time. Advancements in hardware and software such as multicore processors and modular, object-oriented software have allowed easy access to cost-effective rigorous dynamic simulators that can be quickly configured and more easily deployed, which has also opened new avenues to applications such as online soft sensing.

**Soft Sensing Using Dynamic Simulator**

Traditionally, archived plant historian data was used in dynamic simulators by training operators in an offline mode. However, a high-fidelity, dynamic simulation model connected to the plant data system and distributed control system can also act as an effective analytical soft-sensing tool. The process boundary input conditions supplied by the process instrumentation, online data historian and controller positions supplied by the distributed control system allow the dynamic simulation model to replicate actual plant conditions in real time.

The simulation model calculates all relevant process parameters, and thus can be used to predict parameters that are not measured in the plant. The model can also estimate equipment performance indicators such as furnace efficiency, exchanger fouling, compressor efficiency, catalyst activity, etc. in real time, which cannot be measured using physical instrumentation. The soft-sensed parameters can be archived in the plant historian, along with other physically measured parameters, to inform plant performance reporting or process failure investigations.

Figure 1 depicts a typical dynamic simulation-based soft sensing system that consists of a data interface/administrator that coordinates data flow from process instrumentation for process boundary input data after filtering/reconciliation to the simulation model in real time. The same interface supplies controller position information from the distributed control system (DCS), along with offline data inputs, such as ambient...

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**A Dynamic Simulator-Based Soft Sensing System**

![Diagram of Dynamic Simulator-Based Soft Sensing System](image)

*Figure 1*
conditions and laboratory analysis data, and passes it to the dynamic simulation model in a synchronized fashion. The simulator will use the inputs and calculate all process parameters in real time. Parameters that need to be soft sensed will be communicated by the simulator to the interface, which will then be displayed in the control room display panel along with physically measured parameters. The simulator will also have an auto model tuning module, which will ensure the simulation model remains current with changing plant conditions and replicates the real process at all times. The soft-sensed parameters will be archived in the plant data historian along with physically measured parameters, and will be used in the plant performance reporting dashboard.

Dynamic Simulator-Based Soft Sensing at a Hydrocarbon Purification Plant

A section of a naphtha (lighter than petrol hydrocarbon fluid) sweetening plant demonstrates the efficacy of dynamic soft sensing. The process involves purifying naphtha of sulfur that is naturally present in the mixture, by decomposing the complex sulfur compounds present in the mixture in a hydrogen rich environment into H₂S (hydrogen sulfide), followed by stripping off H₂S to generate sweetened naphtha.

Process Details

Sour naphtha feed, containing complex sulfur compounds and dissolved oxygen, is fed to a stripper column, where dissolved oxygen is delivered using off-gas down below the recommended limit of 5 ppm, as higher oxygen content in naphtha will lead to heavy fouling in the downstream exchanger train. The stripper overhead is fed to the fuel gas system; the excess gas is flared off.

The de-aerated naphtha is pumped to an exchanger train where it is heated from reactor effluent stream and then fed to a fired heater. Here naphtha is vaporized, which along with hydrogen-rich feed gas is sent to the de-sulphurization reactor. The reactor effluent exchanges heat with feed naphtha in the P-heater exchanger train, and is then further cooled in an air cooler. The product is then sent to the next section of the plant for further processing (see Figure 2).

Applying Dynamic Simulation for Soft Sensing

To illustrate our thinking around soft sensing using dynamic simulation, we have created a proof of concept. Our first step was to generate a high-fidelity dynamic simulation model of the process plant on a commercial dynamic simulator platform, which was validated against the actual process.
plant data. Next, the model was tuned to match actual plant operating conditions at steady state.

The model was then linked with process instrumentation and distributed control-system feed using a compatible software interface. The interface was also linked to an input data module for supplying offline inputs such as ambient conditions, laboratory analysis of feed streams, etc. The interface was also connected to the plant historian, so soft-sensed and calculated parameters could be stored there for future use.

Once the connection was complete and the system was online, the process boundary feed compositions, temperature and pressure conditions were available to the simulation model, along with the controller positions. Once the linked simulation model was stabilized and settled in steady state, it mirrored the actual operating process.

The dynamic simulator then began predicting all the process parameters which were not physically measured in the plant, along with the equipment operating efficiency indicators.

Soft Sensing Using Simulation

Figure 3 illustrates how some of the soft-sensed process parameters, along with estimated equipment performance indicators, are computed by the simulation model.

The important parameters soft sensed by the model, and their relevance in the plant operations, include:

- **Dissolved oxygen concentration in naphtha liquid exit oxygen stripper**: A higher value than 5 ppm indicates fouling threat for the downstream P-heater exchanger train.
- **Oxygen stripper overheads gas flow rate**: A higher rate indicates more gas being fed to the fuel gas system, leading to the possibility of flaring of excess gas that is not utilized as fuel in the process.
- **Oxygen content in flue gas exit naphtha vaporizer**: A higher value indicates more flow of combustion air in the furnace, which will reduce the thermal efficiency of the process.

Figure 3

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- **Hydrogen sulfide concentration in treated effluent exit foul water stripper:** A higher value indicates increased pollutant concentration in effluent water discharged from the plant.

Similarly, the equipment performance indicators estimated by the simulator that cannot be directly measured in the plant are:

- **Exchanger fouling in P-heater train:** A higher value indicates reduced exchanger heat transfer efficiency, leading to higher fuel consumption in the naphtha vaporizer and extra cooling load on the air cooler fans.

- **Naphtha vaporizer firebox thermal efficiency:** The ratio of heat pickup by the feed stream against the total heat released in the firebox. A lower number will indicate heat loss, and increased fuel consumption.

- **Pump power efficiency:** A lower value will indicate increased power consumption in the system, leading to poor energy efficiency in the process.

- **Reactor catalyst activity:** This indicates the effectiveness of the catalyst in the reactor. A low activity would require increasing reactor temperature, leading to increased fuel consumption and loss of catalyst working life.

**Soft Sensing Advantage: Reduced Off-Gas Feed Flow to the Oxygen Stripper**

The relevance of soft sensing can be appreciated by considering an actual plant scenario, where the soft-sensed parameters play a key role in improving process operations by empowering the operator with detailed insights and foresights.

The scenario considered here concerns a given plant operating condition, where the fuel gas demand has fallen in the plant, leading to flaring of excess fuel gas. The typical action taken by an operator will be to reduce the off-gas flow to the oxygen stripper to reduce the overhead gas flow rate, which in turn will reduce flaring of excess fuel gas. The plant operator will not observe any appreciable change in the physically measured parameters of the oxygen stripper, and hence the action of reducing the feed gas flow would appear to be a correct one.

However, reducing the off gas flow to the stripper will decrease the equipment stripping efficiency, leading to higher dissolved oxygen content of more than 5 ppm in naphtha, and subsequent fouling of the P-heater exchanger train, which will force premature shutdown of the plant for exchanger cleaning.

Estimating the stripper exit oxygen concentration using the simulation model and reporting it with other physically measured parameters helps the operator understand the impact of reducing the off-gas flow rate on stripper exit oxygen concentration. The operator would thus avoid reducing the off-gas flow to the stripper in light of the new information and avoid premature fouling of the exchanger train (see Figure 4).

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**Physically Measured and Soft-Sensed Parameters of the Oxygen Stripper Tower**

* Soft-sensed parameter

* Figure 4
**Auto-Tuning the Simulation Model to Ensure Soft-Sensed Parameter Fidelity**

There is always a gradual change in the plant because of operations, and equipment operating efficiency gradually deteriorates because of wear and tear. The process operating conditions also differ from time to time because of variations in environmental conditions or changes in input raw material composition. As with the aforementioned case, the dissolved oxygen content in feed naphtha can change. Similarly, changes in ambient conditions such as temperature and humidity will impact the cooling tower, air cooler and fired heater performance. The dynamic simulation model must therefore account for these changes to reflect the actual state of the plant and maintain the accuracy of the soft-sensed parameters.

The simulation model can directly account for changes in feed stream and environmental conditions, as it will pick up the latest values directly from the plant data input. However, the changes in equipment efficiency cannot be adjusted directly, and require tweaking of tuning factors such as catalyst activity, exchanger fouling factor, pump and compressor efficiency, etc. in the simulation model.

One approach is to make a manual adjustment to the offline mode to synchronize the simulation model. However, the manual adjustment will be time-consuming and require constant careful examination of the simulation model to decide when it requires adjustment. The manual adjustment mode would also force the virtual sensors to be offline throughout the adjustment period.

Another way to achieve this adjustment is to use an auto-tuning module embedded inside the simulation model. The tuning loops will automatically monitor the simulation model offset from the actual plant condition and adjust the tuning parameters in the simulation model so that it matches the actual process state.

**Looking Forward**

Soft sensing is a useful technique to estimate process parameters that are not physically measured in the plant. A high-fidelity dynamic simulation model can be used for soft sensing, when connected with processes in online mode. The model can also estimate process performance indicators that cannot be directly measured in the plant.

The simulation model can keep itself updated to changing plant conditions utilizing embedded auto-tuning loops, which will ensure accuracy of the soft-sensed parameters predicted by the model.

The soft-sensed parameters will enable the plant operator to make better judgments for operating the plant and run the plant in a more optimized fashion. The cost-effective use of simulator-based soft sensing can thus be effectively leveraged by process industries to improve plant operations and increase their profitability.

**References**

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