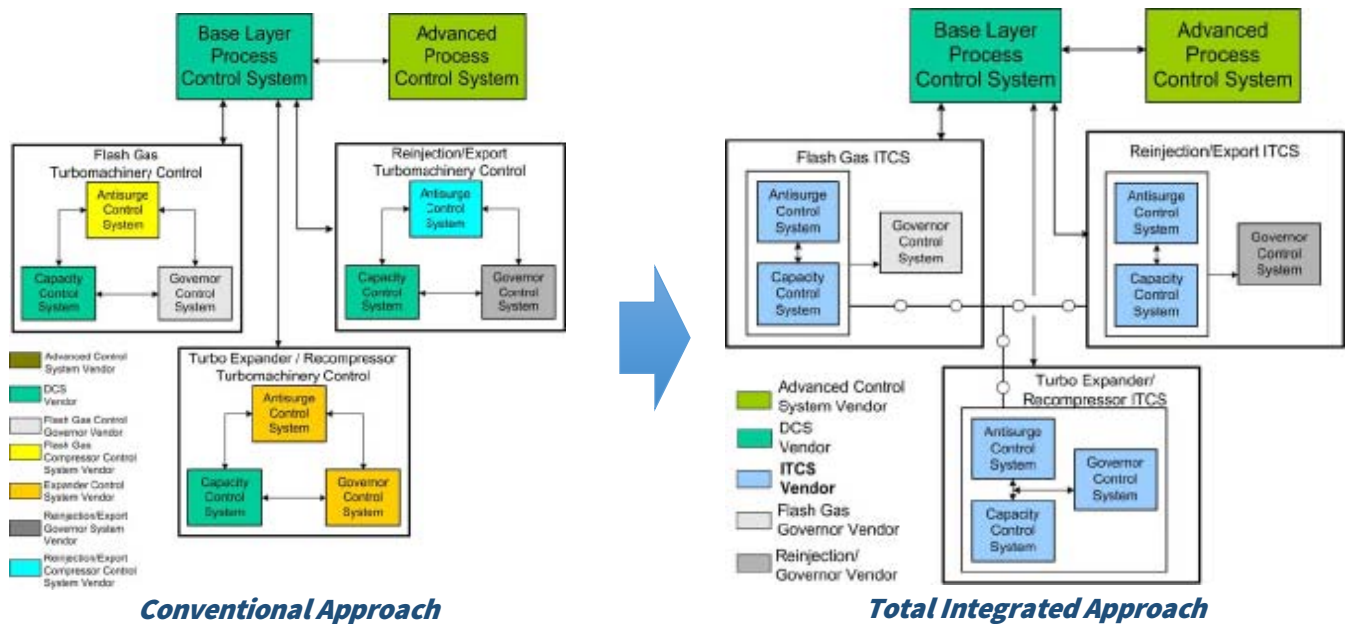




A Total Integrated Approach



Publish Date: 1/18/2012
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A case study describing how total plant turbomachinery control was used to maximize production at the ConocoPhillips Bayu-Undan project.

Introduction

The Bayu-Undan platform is a unique world-scale offshore gas processing platform handling over 1.1 billion cubic feet per day of gas. The platform extracts over 115,000 barrels per day of combined condensate, propane, and butane and produces over 950 MMSFCD of dry natural gas.

The project was implemented in two phases. Phase 1, achieving production in early 2004, involved processing the wet gas to separate and store condensate, propane, and butane; and reinjecting dry gas back into the reservoir. Phase 2, realizing production in early 2006, involved exporting the gas via pipeline to a liquefied natural gas (LNG) facility near Darwin, Australia.

Process Overview

Gas from the wellheads is fed to the production separator where heavier hydrocarbons drop out as liquids. The glycol contactors remove water entrained in the gas stream. The gas is further processed by the cold process trains to remove condensate. The liquid from the production separator feeds the second stage separator, where light hydrocarbons flash out and feed the second stage of the flash gas compressor and the remaining liquid is further processed by the fractionators. Light gas from the fractionators is compressed by the flash gas compressors and sent back to the production separator. Gas from the re-compressors is compressed for reinjection into the reservoir and/or export to the pipeline.

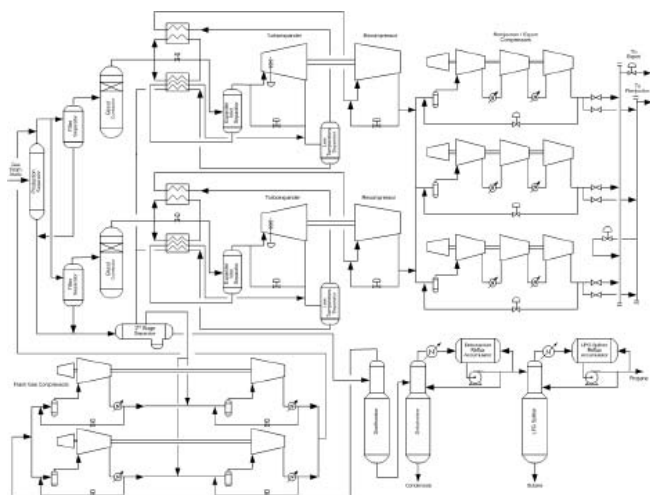


Figure 2: Process Flow Diagram

The critical turbomachinery driving the process include the following:

- Two parallel single-stage turbo-expander/re-compressor trains
- Two parallel gas turbine-driven two-stage compressors (7.5 megawatts each)
- Three parallel gas turbine-driven three-stage compressors (23 megawatts each)

Turbomachinery Control System

The performance of any compressor is limited by several constraints. Typical constraints include surge limit, process limit, minimum speed, maximum speed, power limit and sometimes stonewall or choke limit. By added control margins the actual available operating zone is shown in Figure 3.

The better the control system the closer you can operate without sacrificing reliability. Conventional control systems are typically based on simplistic algorithms with programmable logic control (PLC)-based hardware. These generic control systems require extra control margins and thus further reduce the compressor's operating envelope. Advanced compressor control systems, on the other hand, are based on application specific algorithms in purpose built hardware. By utilizing adaptive open-loop and closed-loop techniques, such systems are able to reduce the control margins without sacrificing reliability and thus maximize the compressors' actual available operating zone.

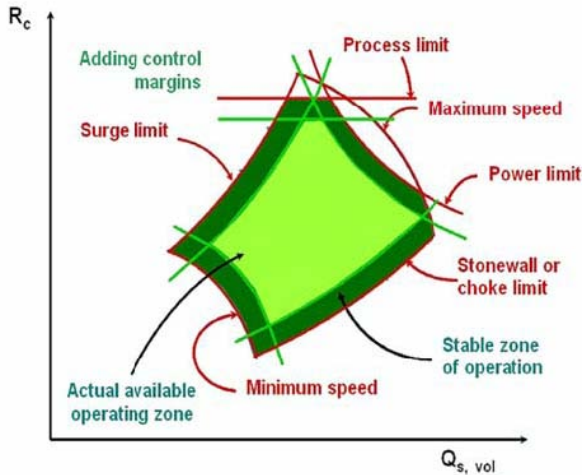


Figure 3: Compressor Performance Envelope

Integrated Turbomachinery Control System (ITCS)

The primary objectives of an ITCS are given below:

- 1) Provide maximum reliability of the machinery and process by:
 - Preventing unnecessary process trips and downtime
 - Minimizing process disturbances
 - Preventing surge, over-speed and associated damage
 - Automating startup and shutdown
- 2) Provide maximum efficiency of the machinery and process by:
 - Operating at lowest possible energy level
 - Minimizing anti-surge recycle
 - Optimizing load-sharing of multiple units

In order to achieve the above, the ITCS consists of integrating at minimum the anti-surge control and capacity control loops.

The ideal ITCS consists of integrating the compressor and driver controls. However, in some cases, such as with new gas turbine driven compressors, it may not be practical to integrate governor control system. An ITCS should be implemented by using deterministic hardware platforms in order to satisfy the desired execution requirements such as 40 milliseconds for anti-surge control. Advanced control algorithms using adaptive open-and closed loop responses must be employed to prevent surge. Dynamic decoupling

between anti-surge and performance loops must be utilized to minimize process disturbances.

Conventional Approach

The conventional approach to designing multiple turbomachinery control systems is to either resort to original equipment manufacturer (OEM)-supplied control systems or to implement the turbomachinery controls in the distributive control system (DCS).

Another approach is to integrate the turbomachinery control system with the emergency shutdown (ESD) system. All three approaches have inherent deficiencies as discussed below.

(PLC)-based systems have been proven inadequate for anti-surge and performance control. With different OEMs for each set of machines, the result is different PLC systems utilizing various algorithms and control strategies. This makes integration between the systems virtually impossible.

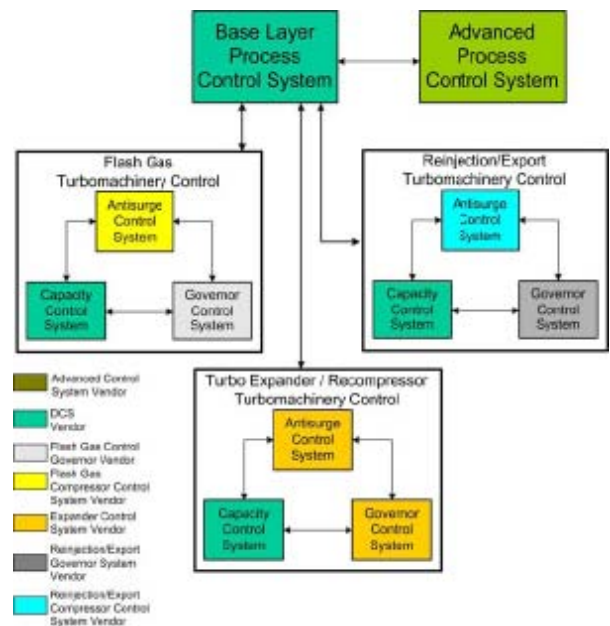


Figure 4: Conventional Approach

Utilizing the DCS for anti-surge control has also proven to be inadequate. Despite this, the DCS approach appears attractive as it greatly reduces the number of control interfaces. However, the success of this approach relies heavily on DCS engineers' limited turbomachinery experience.

The last approach is to integrate the turbomachinery control system with the ESD system. This approach is being promoted as economically attractive but has several flaws. Firstly, this approach violates the practice of keeping basic process control systems and ESD systems separate. Process control systems are designed to keep process running while ESD systems are designed to trip the plant. Typically, this approach utilizes triple modular redundant (TMR) systems and the perception being promoted is that the highest availability is realized. In reality the ESD system, while achieving the desired safety level of the system, sacrifices the process availability by causing unnecessary process trips. Often too much focus is given to control system hardware and not the quality of control. These systems fall short in adequately integrating anti-surge, load-sharing and performance control to maximize availability of the turbomachinery. A properly designed ITCS (as described in the following sections) actually minimizes the safety integrity level requirements through improved basic process control.

Total Integrated Approach

This approach involves determining the overall process control needs with respect to turbomachinery control for all machines. This involves providing an ITCS for each service focused on meeting the performance control objectives for the process. For practical purposes the ITCS for both flash gas and reinjection services included the anti-surge and performance control loops while the governor control loops remained with the OEM.

As the machines are interconnected in the process, it is prudent to look at how further integration between machines can be beneficial. Such systems can be integrated with each other by internal controller communication to allow for feed forward control actions where necessary.

This approach requires extensive field-proven experience in designing, engineering and commissioning various turbomachinery control systems for different applications.

This integrated approach served the basis for Compressor Controls Corporation (CCC) design when supplying ITCS solutions for all machines.

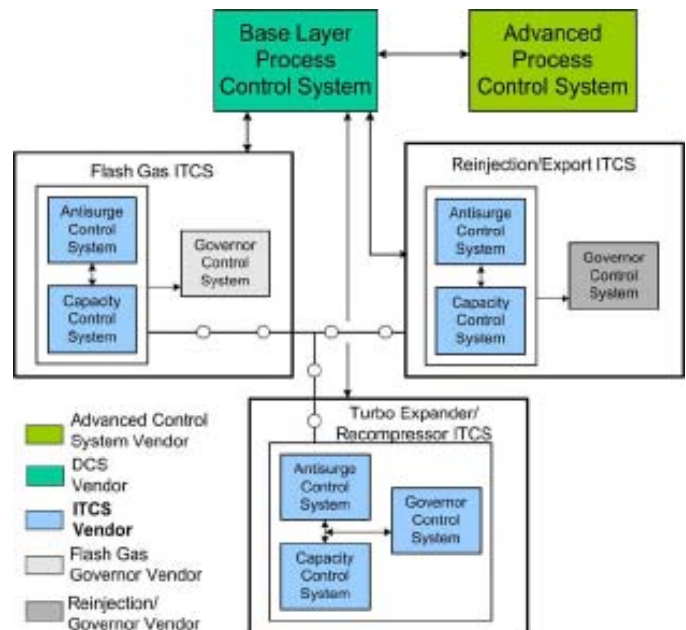


Figure 5: Total Integrated Approach

Project Execution

The design phase for the facility involved ConocoPhillips experts, EPC TIGA (joint venture between Fluor Daniel and WorleyParsons), the OEMs (Sulzer, Dresser Rand and GE Rotoflow), and the ITCS provider (CCC). The execution of the project required CCC's design effort to include:

- Review preliminary process control philosophy
- Provide preliminary control system design report
- Participate in setting up the dynamic simulation effort
- Review preliminary dynamic simulation test results
- Provide final control system design report
- Review final dynamic simulation results
- Provide final ITCS engineering manual
- Commissioning recommendations

Ideal interaction between all parties driven by ConocoPhillips was instrumental in developing and testing the ITCS strategies.

Overall Turbomachinery Control Design Basis

The basis for each ITCS design focused on meeting the overall process control objectives.

The primary control objectives identified during the preliminary engineering phase were:

- Provide maximum protection for each machine
- Maximize liquids production
- Maintain gas for reinjection/export

The secondary control objectives that were identified included:

- Necessary limiting control loops for each machine
- Balance the load between the machines to provide equal protection

The final control elements available to the ITCS were identified to be:

- Flash gas compressors speed and anti-surge valves
- Turbo expanders inlet guide vanes (IGV)
- Turbo expanders Joules Thomson (JT) valves
- Re-compressors anti-surge valves
- Reinjection/export compressors speed and anti-surge valves

Flash Gas Compressor ITCS

The primary objective of the flash gas compressor is to compress gas from the de-ethanizer and gas from the second stage separator. In order to maximize liquids production the first stage suction pressure and the interstage pressure of the flash gas compressor needed to be precisely controlled. This could only be done by a combination of operation of the anti-surge valves and the gas turbine speed. The challenge in real time is determining which pressure will be controlled by speed while the remaining one via the anti-surge valve. As the flow from the de-ethanizer and flow from the second stage are both very dynamic the need for optimized performance control was identified. The performance control loops within the ITCS were required to control speed and the anti-surge valve to meet the suction and interstage pressures based on efficiency, or in other words, least recycle. This

method of optimized performance control ensured that unnecessary recycling was avoided.

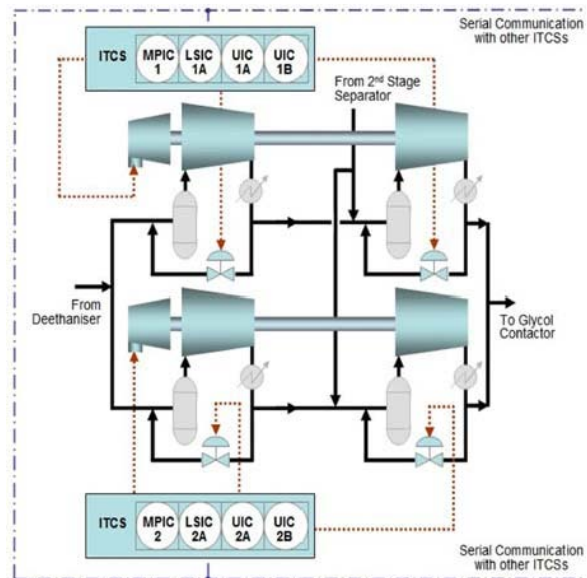


Figure 6: ITCS for Flash Gas Compressors

In summary, the flash gas compressors ITCS objectives were as follows:

- Provide invariant anti-surge control
- Optimized first stage and interstage pressure control
- Equidistant to surge load-sharing
- Decoupling between anti-surge and performance control loops
- Decoupling between anti-surge control loops
- Limiting control loops

Turbo-Expander/Re-Compressor ITCS

The primary objective of the cold part of the process (turbo-expander/re-compressor trains) is to maximize liquids production.

In conventional expander control systems speed is not typically controlled. Therefore during an upset turbo-expander speed may exceed allowable limits. Conventional control systems prevent over-speed based on primitive and often indirect methods, such as limiting the IGV position, limiting differential pressure across the expander or split range control between IGV and JT valve. These methods sacrifice liquids production.

Conventional control systems also ignore the importance of providing adequate anti-surge control for the re-compressor. However protecting the re-compressor against surge is just as critical as for any other compressor.

CCC's patented ITCS for turboexpander/recompressors provides maximum protection and utilizes control strategies that maximize liquids production². The JT valve is therefore used when absolutely necessary.

CCC's patented over-speed prevention strategy is based on direct control of speed, as well as acting on the re-compressor's antisurge valve to load up the train, then closing the IGV if speed continues to increase. This strategy maximizes utilization of the expander and minimizes use of the JT valve, thereby maximizing liquids production.

Load-sharing between turbo-expander/ recompressor trains is also critical. Operating close to surge demands equal protection (i.e. equidistant to surge load-sharing). However, operating far away from surge demanded shifting the load-sharing focus from the recompressor to the turbo-expander.

optimized load-sharing strategy was developed, providing equal surge protection across the re-compressor when in the vicinity of surge and equal efficiency across the turbo-expanders when far away from surge.

Unnecessary turbo-expander trips, in practice, greatly affect the process. CCC's patented JT valve prepositioning algorithm reduces the severity of the trip on the process. CCC "prepositions" the JT valve based on the capacity equivalent the turbo-expander's throughput immediately prior to trip. This strategy keeps the process online and minimizes temperature excursions in the low temperature separator (LTS) and in effect maximizes liquids production. The loss of one turboexpander requires the running train to take as much load as possible. The running train switches to flow control while the JT valve controls the production separator pressure to minimize loss of liquids production. This in effect minimizes loss of liquids production.

In summary, the turbo-expander/re-compressors ITCS objectives were as follows:

- Maintain production separator pressure
- Optimized load-sharing strategy
- Equidistant to surge load-sharing
- Decoupling between anti-surge and performance control loops
- Limiting control loops

Reinjection/Export ITCS

The primary objective of the reinjection/export compressors is to deliver gas at a suitable pressure and flowrate for either reinjection or export. More than six operating modes were identified depending on whether the upstream expander/recompressors were online and the export requirements. This required CCC to translate these operating modes into control modes for each individual compressor. The control modes were defined as follows:

- Mode A. Participates in a load-sharing scheme based on controlling suction manifold pressure, applicable when the compressor operates in either high speed mode (discharge pressure = 310 barg) or low speed mode

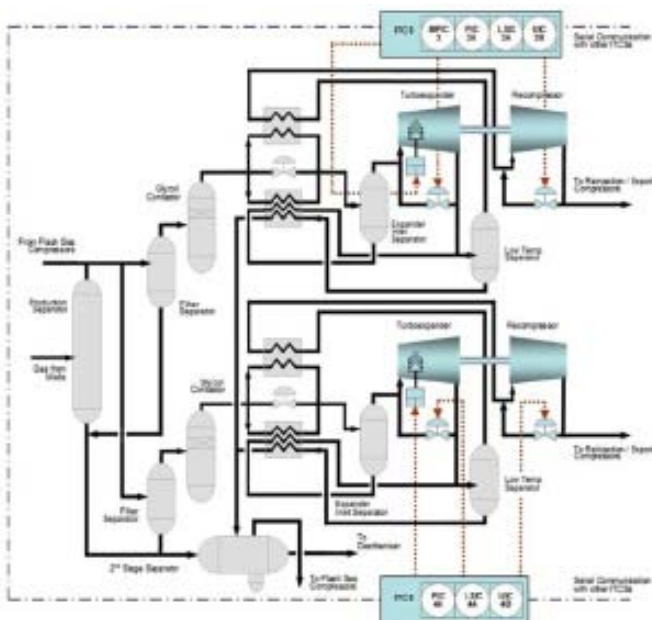


Figure 7: ITCS for Turboexpander/Recompressors

Equal efficiency across the expanders was desired when operating away from surge. As a result, an
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(discharge pressure= 190 barg). One, two or all three compressors may operate in this mode.

- Mode B. Non-load-sharing (stand-alone) choke control scheme, applicable only when the compressors operate in lowspeed mode (discharge pressure = 190 barg). One or a maximum of two export/reinjection compressors may operate inthis mode.
- Mode C. Non-load-sharing (stand-alone) compressor suction pressure control scheme, applicable when the compressoroperates in low- or high-speed mode. Only one compressor at a time may operate in this mode.

Using one of the operating modes as an example the control modes were defined as show in Figure 8, whereby onemachine is dedicated for export while the other machines for reinjection.

Based on the complex operating modes, unique challenges for the reinjection/export compressors ITCS were observed. The importance of not only anti-surge control but also operating one or more of the machines in choke region was of significant concern. The anti-surge control requirements for each compressor required providing adequate surge protection for each stage while utilizing one anti-surge valve. CCC’s experience in multiple anti-surge controllers sharing a single valve was utilized.

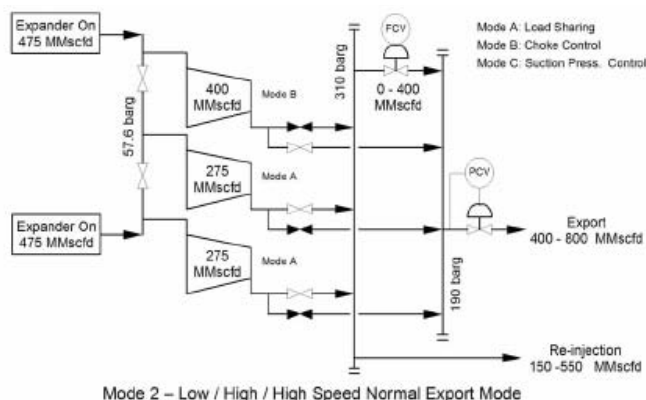


Figure 8: Reinjection/Export Compressor Normal Export Mode

The requirements for anti-choke control were identified early in the design phase. CCC’s knowledge

and experience were utilized to determine whether independent anti-choke control was required or integration within the anti-surge controllers was adequate. Anti-surge controllers with integrated anti-choke control were provided.

The integrated anti-surge and anti-choke control required an optimized load-sharing strategy. When the machines are close to surge, the equidistant to surge-load-sharing was desired; yet when away from surge, or in other words close to choke, equidistant to choke was required. This optimized load-sharing strategy and provided maximum protection for all parallel machines.

In summary, the reinjection/export compressors ITCS objectives were as follows:

- Maintain suction pressure
- Provide integrated anti-surge and anti-choke control for each stage
- Optimized load-sharing strategy
- Decoupling between anti-surge and performance control loops
- Limiting loops

The Role of Dynamic Simulation

Dynamic simulation played a pivotal role during the design phase of the project. The design simulation package used was Hysys, which included models of CCC controls.

With the help of CCC the project, team refined the CCC models to ensure that models emulated the ITCS system in this project. Once the system was setup, the dynamic simulation was instrumental in testing the control strategies listed above.

The dynamic simulation exercise provided a starting point for setting up each ITCS and the necessary interactions. The control strategies developed in the ITCS for each machine were tested and verified throughout the simulation process.

The extensive testing provided a benchmark for system performance. The overall dynamic simulation process provided no surprises during commissioning and contributed to shorter startup time.

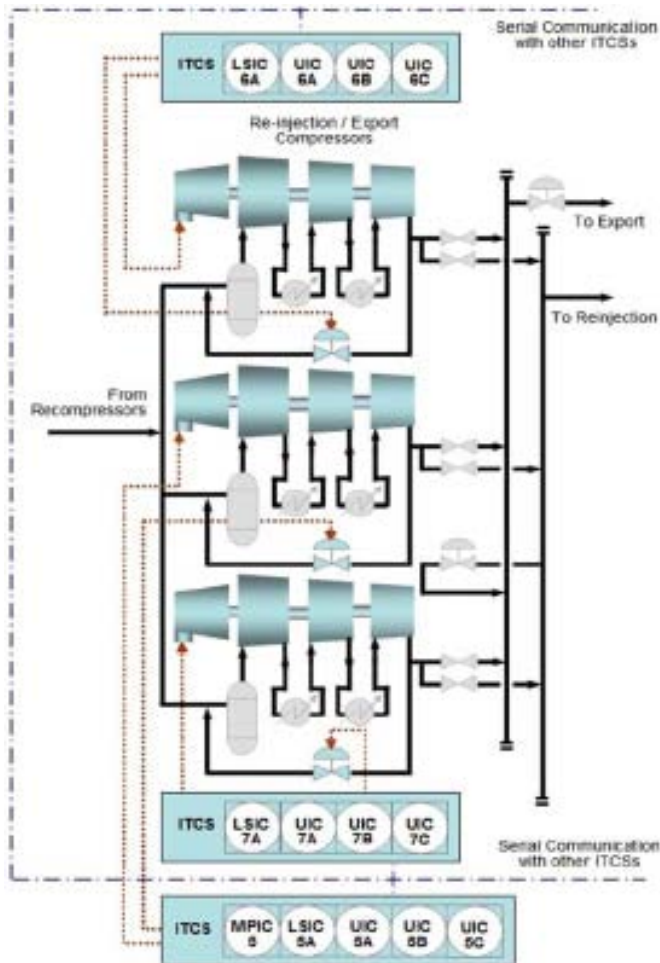


Figure 9: ITCS for ReInjection/Export Compressors

Total Integrated Approach in Action

The total integrated approach proved extremely beneficial. Figure 10 illustrates the total plant turbomachinery control, consisting of the ITCS for flash gas, turbo-expander and reinjection/export services.

One of the benefits realized by this approach was demonstrated during the design phase, when it was recognized that the flash gas compressors would potentially run into overload condition while running at maximum speed due to excessive gas coming from the de-ethanizer. It was determined that this condition could be alleviated by opening the turbo expander/recompressors’ anti-surge valves. Since communication between all ITCS was originally envisaged to be beneficial, setting this up in the system was not difficult.

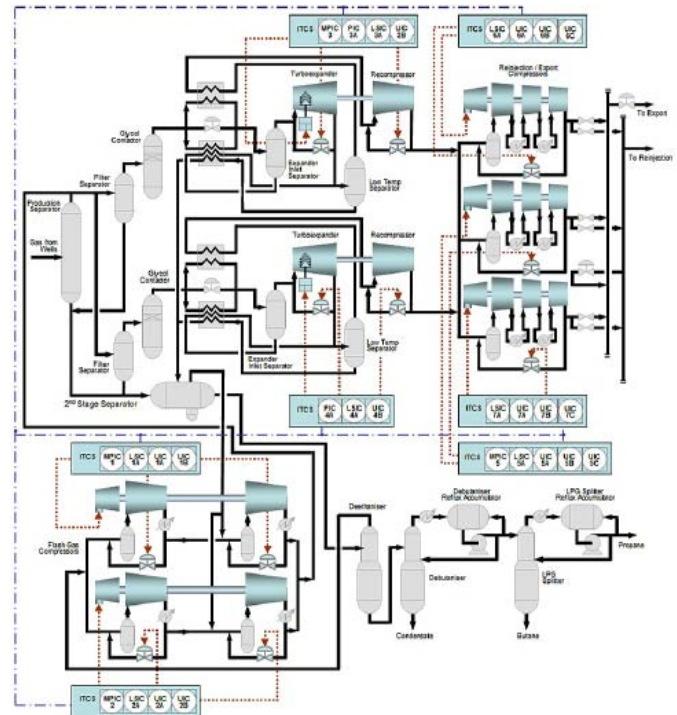


Figure 10: Total Plant Turbomachinery Control for Bayu-Undan Platform

Feedback from the Field

The total plant turbomachinery control was executed and completed to ConocoPhillips satisfaction. Feedback provided by ConocoPhillips from the field is given below.

With respect to the expander/re-compressors ITCS, “The trains run very well in both load-sharing, flow and pressure control, and both pressure control (preferred). With the improved IGV control it has meant that very low temperatures have been achieved. This has a flow effect of excellent recoveries. The stability of the control has allowed the plant to operate above design and meet both allocated and stretch targets for volumes over the last two years.”

With respect to the reinjection/export compressors ITCS, “With the compressors in export mode, this has allowed us to increase further raw gas rates to the facility, meaning increased volumes. The choke control mode, discharge pressure limiting and anti-surge pressure override functions all have been used with great success.”

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Acknowledgements

The author wishes to thank the management and staff of ConocoPhillips at Bayu-Undan for their support and permission to present the details of this article.