PROCESS CONTROL OF A SUBSEA PROCESSING PLANT

Audun Faanes*, Helge Mordt/***, Gisle Otto Eikrem*, Kristian A. Høisæther****

** Statoil ASA, Trondheim, Norway, **FMC Technologies, Asker, Norway, ***Østfold Engineering College, Sarpsborg, Norway and Prediktor AS Fredrikstad, Norway*

Abstract: *The Tordis subsea separator station is the first commercial processing plant in the world that is located subsea. The station will be installed 200 m below sea level, and will be remotely operated from the Statoil operated Gullfaks C platform, which is located in a distance of 12 km from the Tordis oil field. Operation of the subsea separator station with pumps is a challenge for the design of the control system. By use of dynamic simulation different control strategies have been investigated, and the control system is also tested with the real pumps and instruments connected to the dynamic simulator. Copyright © 2007 IFAC*

Keywords: Dynamic modelling, Level control, Pressure control, Process control, Simulation, Tests

1. INTRODUCTION

The aim of this paper is to emphasize the use of extensive engineering, dynamic simulations and integrated testing prior to installation of a subsea process plant.

The Tordis subsea field at the Norwegian Continental Shelf has been producing since 1994. In 2007 a subsea processing plant will be installed in order to increase the oil recovery by lowering the well head pressure. Thereby the driving force for the oil production is maintained even at lower reservoir pressures. The installation consists of a separator for removal of most of the water from the production, a water pump to inject this water into a disposal well at the Utsira reservoir, and finally a multiphase pump to transport oil, gas and remaining water towards the Gullfaks C platform, 12km away. Removing the water from the production reduces the need for an upgrade of the platform water treatment, reduces the disposal to sea, and reduces the pressure loss in the existing production pipelines. A pilot installation has earlier been installed at another field at the Norwegian Continental Shelf, (Horn et al., 2003), but this is the first commercial subsea processing plant. A broader view on the project is given by Gjerdseth et al. 2007.

In the paper we will describe the process further (Sec. 2), and present the control system and control philosophy (Sec. 3). Dynamic simulations (Sec. 4) and testing (Sec. 5) are very important for a plant to be placed at 200m below the sea level.

2. SUBSEA PROCESS

An illustration of the system is shown in Fig. 1.

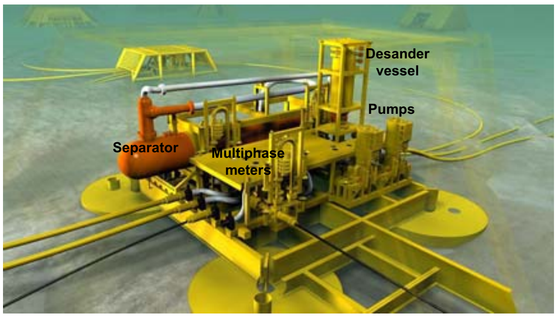

Fig. 1. The Tordis Subsea Separation Boosting and Injection Station.

The well fluid from Tordis Central Manifold enters the separator through two flexible jumpers. Each incoming line is equipped with a hydraulically operated block valve to be able to isolate the Subsea Separation Boosting and Injection station from the pipelines, i.e. to operate the Tordis field in bypass of the separator. The commingled production from the two flow lines is routed to the inlet cyclone on the subsea separator. Several injection points for chemical injection including emulsion breaker, corrosion inhibitor and MEG is available throughout the subsea processing plant.

The gas phase from the cyclone is routed in bypass of the separator and back into the separator at the combined oil/gas outlet of the separator. The separator is equipped with a level profiler for measurement of water and liquid levels. In addition, the level profiler will also give an indication of emulsion layer and foam in the separator. Pressure and temperature are also monitored.

2.1. Multiphase Pumping

The hydrocarbon phase and the remaining water are boosted to the required pressure for transport to the platform by a multiphase pump located downstream the separator. Downstream of the multiphase pump, the flow is split into the two flow lines to the platform. The operating pressure of the subsea separator is maintained by speed control of the pump.

As a pump lubricating system and in order to prevent leakage from the production side into the pump motor, a barrier fluid system is included. A topside pump and a dedicated line in the umbilical enable a continuous small leakage of the fluid the "correct direction" across the pump seals.

A pump monitoring and protection system is included to ensure no leakage of well fluid into the barrier fluid system, and to protect the pump from running outside the acceptable operating envelope (e.g. to avoid surge operation of the pump).

The multiphase pump has a power rating of 2.2 MW and the supply voltage is 6.6 kV. The speed of the pump is adjusted by using a high voltage variable speed drive (situated at the platform). Maximum speed is about 4000 rpm.

2.2. Water Injection

The water phase is fed into a centrifugal pump, which boosts the water to the pressure required for injection into the Utsira reservoir. Likewise the multiphase pump, a barrier fluid system and a pump monitoring and protection system are included. Normally, the pump will be operated at maximum capacity in order to minimize the amount of water being transported to Gullfaks C. The separator is, however, equipped with a level controller that will maintain the water interface level by adjusting the speed of the water injection pump in the event of a drop in the water production.

A water flow meter and a ROV-operable sample point are included downstream the pump in order to monitor the amount and quality of water being injected into the Utsira reservoir.

The power rating for the water injection pump is similar to the multiphase pump.

2.3 De-sanding operation

Sand from the wells will settle in the separator, and therefore the separator is equipped with a sand removal system. A de-sanding system is designed in order to remove the sand from the separator by exploiting the force of the water injection pump. A vessel for collecting the sand from the separator is installed in order to avoid sand transport through the pumps. The de-sanding operation is a two steps operation. High pressure water from the water injection pump is used to drive an ejector which reduces the pressure in the de-sander vessel compared to the separator. Sand is thus sucked from the separator to the de-sander. The next step is to close the connection between the de-sanding vessel and the separator, and then to pressurize the de-sanding vessel before injecting the sand into the Utsira reservoir.

The de-sanding operations are implemented as automatic sequential batch operations. The operator will only have to monitor the sequence run, with a possibility to intervene. The sequences deal with valve operations and timing, and they make sure that the correct forward pressure from the water injection pump is available. If the pressure at the outlet of the pump is too low, a minimum pressure control loop is activated reducing the opening to the injection reservoir and thus increasing the pump backpressure.

3. CONTROL SYSTEM

A 12 km service umbilical connects the subsea separator station to the control system topside. This umbilical provides electrical and hydraulic power to the subsea process control system. All subsea control valves are hydraulically operated. The communication is primarily fibre optical, but as a backup control signals can also be sent on the power line.

The subsea control system is redundant. There are two separate subsea electronic modules (SEM) and all transmitters subsea are dual to ensure the accessibility to the process. The subsea control module (SCM) is connected topside to the Subsea Power and Control Unit (SPCU), which in turn is connected to the sub sea process control node (SCU) for the process control system. The make and type of this system is the ABB 850 IndustrialIT. The outline of the process control system is given in Fig. 2.

A dedicated unit (PCU) controls the pump and the variable speed drive (VSD).

The pipelines have a pressure limit of about 200 bar, and to prevent hazardous operation, a SIL-2 rated protection system is located subsea. This system comprises of a redundant PLS and three dual pressure transmitters located at the separator inlet. The subsea protection system is directly connected to the high voltage circuit breakers for the pumps, and in case of an over pressure situation both pumps are stopped by disconnecting the high voltage supply to the pumps.

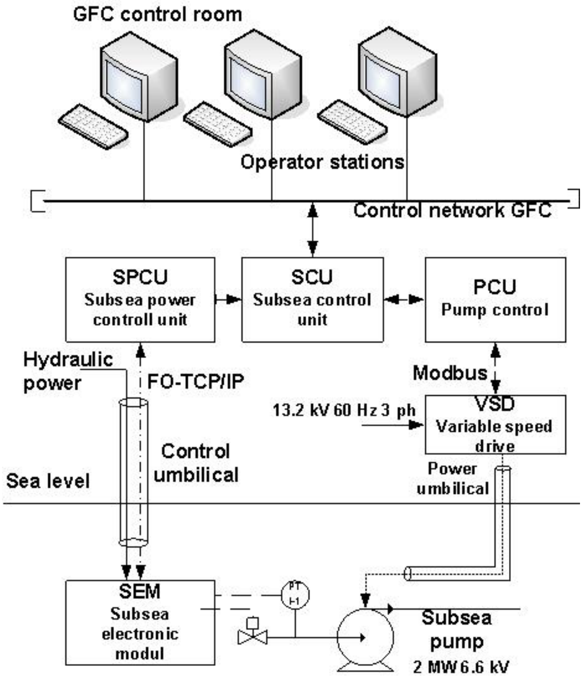

Fig. 2. Control system overview

The speed of the multiphase pump controls the pressure in separator. The outlet of the separator is designed as an overflow drain enabling a self-regulating liquid level control. The liquid flow rate to the multiphase pump is therefore driven by the liquid level, whereas the gas flow rate will be determined by the pump speed.

In order to determine the production rates from a single well, this well is closed down, and the rates are obtained from the change in total production. For correct rate estimates, it is important that the well head pressures at the other wells are not changed due to the reduction in total flow and thereby pressure loss in the piping. Therefore, in this situation, a cascade control loop is employed. The outer-loop controller adjusts the separator pressure so that the wellhead pressure is kept constant. In this configuration the outer loop controller compensate for the change in pressure drop between the wellhead manifold and the separator.

The differential pressure across the multiphase pump is limited to about 30 bar (to protect seals). A differential pressure controller configured as a PD-controller with high gain supervises this pressure. The output from this controller is subtracted from the separator pressure controller output, and will therefore limit the pump speed.

The speed of the water pump is used to control the level in the separator. The operator can either select a direct level control or a cascaded controller scheme where the outer loop is the level control and the inner loop is water flow rate control.

To avoid that oil or even gas is let into the water pump in case of a rapid level drop in the separator, two protection systems are implemented. The first is a simple hidden level controller configured as a P controller with a high gain. This controller has a fixed set-point, and the output goes to the water injection pump speed controller through a minimum selector. In normal operation the output from this controller will be 100 %, which means that the speed of the injection pump is controlled by the ordinary level control loop. The main purpose of the additional controller is to avoid pump trips when the main level contol loop is set in manual. The second protection is tripping of the water injection pump when the liquid level is reaching a critical low limit detected by a level switch.

The control philosophy is partly developed in accordance with Åström and Hägglund (1988).

To ensure safe and proper operation of the pumps, automatic start and stop sequences are implemented. The start sequences make sure that a number of process conditions are met before starting is enabled, including production status, valve positions and separator conditions. When a sequence is running, timing of valve and choke operation, speed ramping and control loop behaviour are all taken care of by the control system thus reducing the work load for the operator. If the operator for some reason needs to monitor a start up more closely, the sequences can be run in a step by step mode controlled by the operator, or for safety reasons even be aborted leaving the complete control to the operator. The stop sequences enable an automatic shutdown of the pumps that is as gentle as possible. All the sequences are designed in accordance with the standard IEC 61131-3 (see IEC).

4. DYNAMIC MODEL AND SIMULATIONS

Dynamic simulations have been applied during the whole project. In early phases, Olga (Olga) simulations were used to study the multiphase flow through the pipelines and risers, and dynamic process simulations with D-Spice (D-Spice) and Assett (Assett) were performed. Sivertsen et al. (2005, 2006) have reported a study based on a combination of Olga and a simplified process model in Matlab. During detailed engineering a model combining Assett and Olga was developed. 9 wells and the two pipelines are modelled in 11 separate Olga models which are run from Assett where also the subsea process and the topside inlet separators are modelled. The simulations are used for verifications of the design, e.g. related to questions raised during the Hazops, development of the operational philosophy (start-up, stop, operational mode transitions, shut-down functions), and development and test of the automatic control (control loops, automatic control sequences, emergency shutdown, and process shutdown).

In the following an example from the simulations will be presented. In all figures, the variables are scaled from 0-100%. The case is a normal stop of the water injection pump, and the effect on the separator and the operation of the multiphase pump. In Fig. 3 the flow rate through the water injection pump is shown. In initial rise in flow rate is caused by opening of a recirculation loop. The effecting separator levels are shown in Fig. 4. Since the water after the pump stop will flow towards the platform and there is an overflow drain, the water level increases. The thickness of the oil level is decreased, which means that the oil production is reduced. The reduction in oil production can be explained by the raise in separator pressure (Fig. 5), which in turn raises the well head pressures and thereby reduces the driving force from the reservoir to the wellheads.

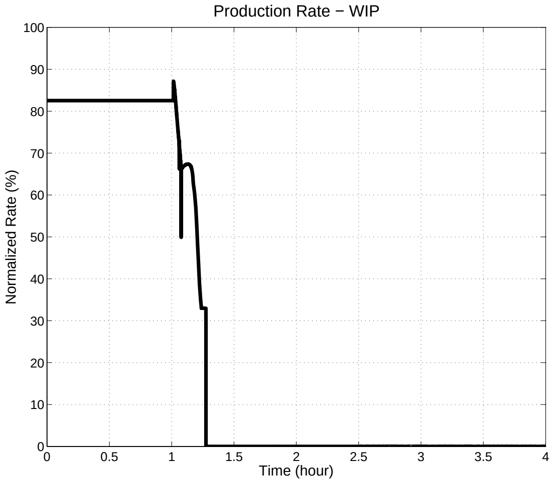

Fig. 3. Simulation example: Drop in flow rate through the water injection pump.

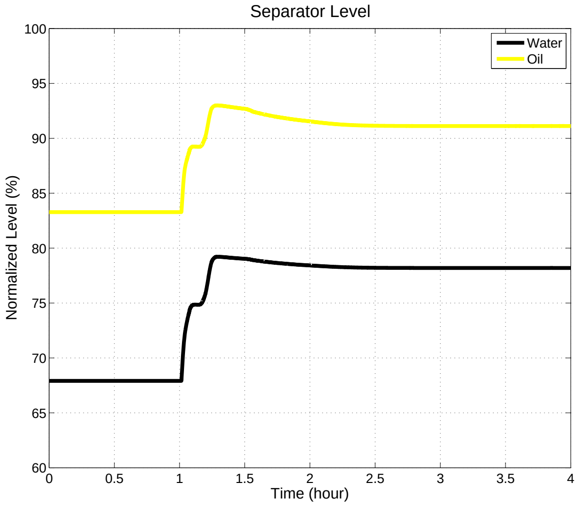

Fig. 4. Separator water and oil levels at outlet during and after a stop of the water injection pump.

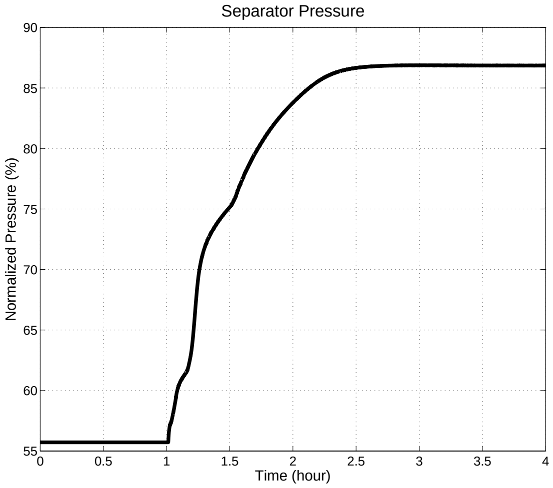

Fig. 5. Separator pressure during and after a stop of the water injection pump.

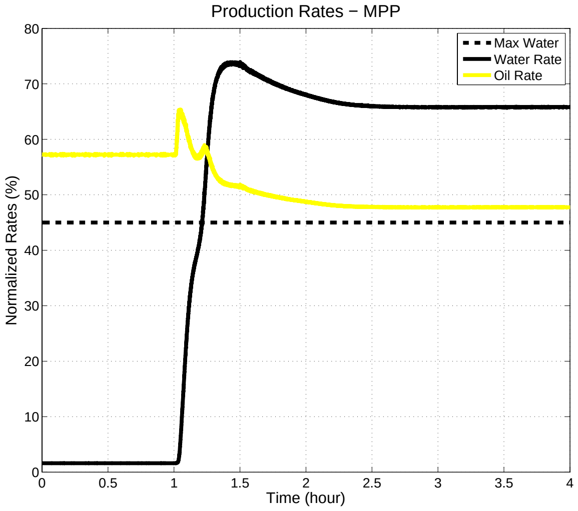

Fig. 6. Flow rates through the multiphase pump (MPP) during and after a stop of the water injection pump.

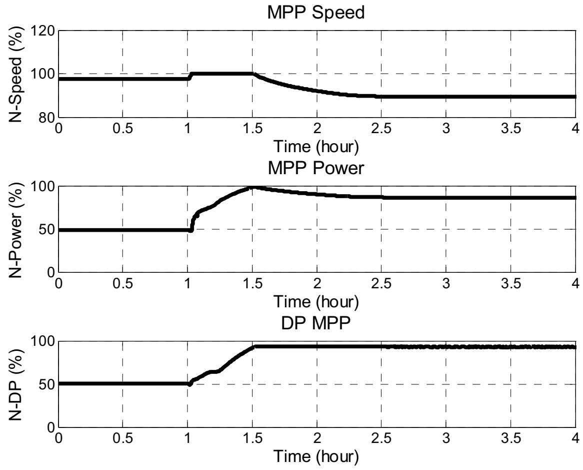

Fig. 7. Control of the multiphase pump (MPP) during and after a stop of the water injection pump.

In Fig. 6, the oil and water flow rates through the multiphase pump are plotted. We see that the water production quickly exceeds the maximum topside water handling capacity. Thus, in the operational procedures some action, e.g. to close down some wells, must be implemented.

In Fig. 7, we see the control of the multiphase pump. Since the separator pressure increased, and the pump initially is not running at maximum capacity, the pump speed is increased up to 100% (upper plot). As the water rate and thereby total liquid rate increases, the required power to run the multiphase pump increases. In a short period at around 1.5hrs, the multiphase pump is limited by the maximum power (middle plot). The pump becomes also more efficient, in that the resulting pressure lift increases as the density of the medium increases. Finally, this pump differential pressure must be limited in order to protect the seals (lower plot).

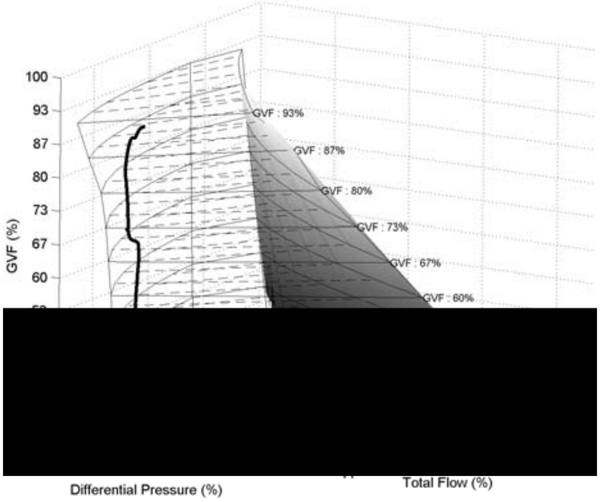

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Fig. 8. The 3-D pump curve of the multiphase pump. The trajectory shows how the differential pressure, flow rate, gas volume fraction (GVF), and pump speed, ps, for the pump varies during the stop of the water injection pump. All values are normalized (0-100%). The end point (last value) of the trajectory is marked with a circle. The surface is the limit for minimum-flow.

From the 3-D pump curve in Fig. 8, we see that as the water injection pump stops, the gas-volume fraction is decreasing, since the liquid flow is increased. We can also see that the flow is kept on the correct side of the minimum-flow surface, which is not surprising, but is more interesting to verify for other cases where low flow can be expected.

The model is also used in the System Operation Test as described in Section 5, and for training purposes on a training simulator made by connecting the Olga-Assett model to a copy of the process control system and the operator stations.

5. SYSTEM OPERATION TEST

The accessibility to the process is limited when the installation of the equipment at the sea bed is completed. It is important that one up front of the installation makes a complete test of the system. In this test, the pumps were placed in a dry dock that was eventually filled with sea water. The pumps were connected in a flow test loop, where two phase flow was created as a mixture of air and water through the multiphase pump. The principle for the test arrangement for the pumps is given in Fig. 9.

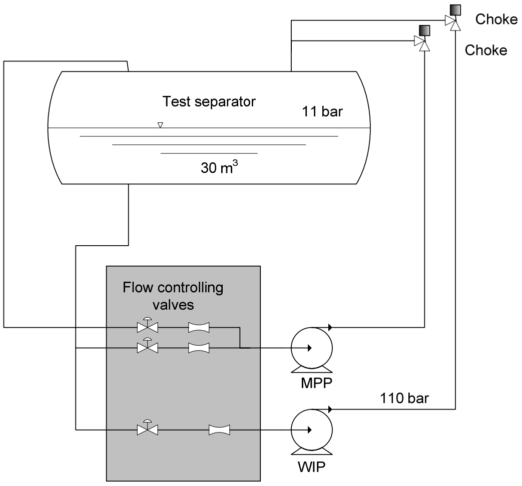

Fig. 9. Test set-up for the system operation test (MPP = multiphase pump, WIP = water injection pump)

Gas and liquid were circulated in a loop and by use of control valves the mixture between the two was controlled.

To make the test of the control system operation as realistic as possible, it was decided to use the dynamic simulator in the test. The actual pumps and control system were applied, and in addition the control system is connected to the same measurement system that shall be used subsea. However, since the large separator was not available, the real pressure measurement was installed in a small vessel, wherein the pressure could be controlled. The dynamic simulator then simulated the pressure in the separator, which was used as a reference for an auxiliary pressure control loop that controlled the pressure in the small vessel. The level measurement system was solved in the same way. In a small tank with a level control system, the level profilers were installed. The level in this tank then followed the water level in the simulated separator. Notice that the pressure and level tanks are not physically connected to the pump circuit shown in Fig. 9.

The control loops for the pressure and the level in the measurement tanks were designed such that they were 5 – 10 times faster than the simulated response of the level and the pressure in the simulator.

The mass flows through both pumps were measured and were used as input to the mass balance in the dynamic simulator. Thus, the control loops were closed.

In Fig. 10, the components in the test set-up are shown together with the information flow scheme of the closed loop. For signal interface with the simulator, OPC is used. The result from a test with increased inflow from the wells is shown in Fig. 11. We see that the water flow to Utsira is increased by raising the pump speed in order to keep the separator water level. The oscillatory behaviour of the closed loop indicates that a re-tuning of the controllers might be required. The increase in the production rate was set in the model.

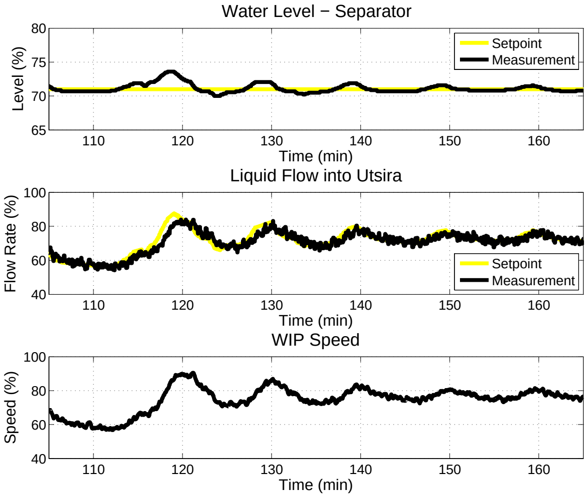

Fig. 11. System operation test result. Closed loop response after increase in production rate.

6. CONCLUSIONS

A subsea processing plant will be installed at 200m subsea level at the Tordis Field. Dynamic simulations have been a useful tool for evaluating different control strategies. The findings from the dynamic simulation have been used to develop the operational philosophy and the operation procedures. The pumps, control system and the most important sensors have been tested together with the dynamic model of the separator.

7. ACKNOWLEDGEMENTS

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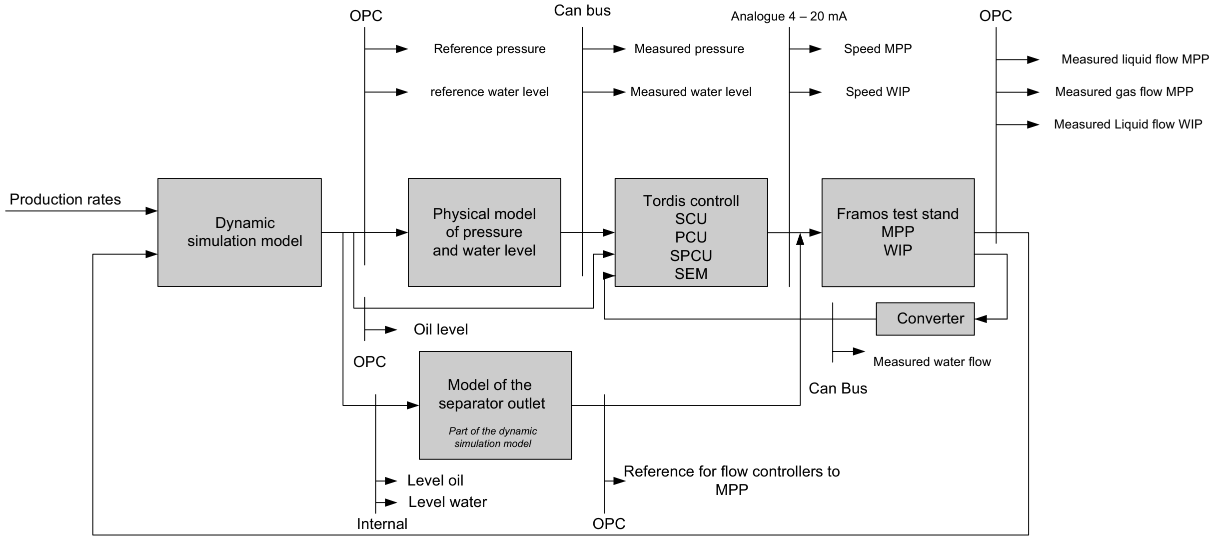

Fig. 10. System operation test: The float of information