Troll Pilot control system for a subsea separator

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Introduction

This paper describes the design of a subsea control system for controlling and monitoring a subsea water separator, for use by Norsk Hydro in the Troll field, 100 km west of Bergen in Norway. Situated in Blocks 31/2 and 31/5, the Troll field contains large quantities of oil and gas together with significant amounts of water. It was therefore decided to install a subsea separator in order to avoid installing additional topside processing equipment and to maximise useful flow-line capacity. *Figure 1* shows the location of the installation and the subsea arrangement.

The separator, a self-contained seabed unit based on ABB Offshore Systems' SUBSIS (Subsea Separation and Injection System) technology, is located between two conventional production manifolds and the Troll C platform. It uses a gravity separator to extract water from produced fluids. This water is then re-injected into a disposal well via a subsea variable-speed pump.

The control system comprises topside computers and fibre-optic communication, together with a subsea control module to control separator valves and monitor pressure, temperature and separator water-level sensors. The system operates in a closed loop, with water level measurements resulting in control of the water injection pump speed.

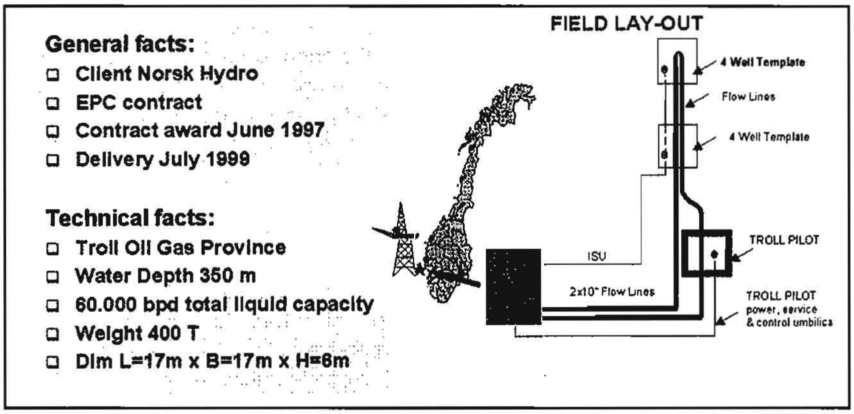

Figure 1: Troll C location and field.

A key feature is fibre-optic communication at 1.5 MHz, primarily for immunity from interference from the pump electrical supply, operating in half-duplex mode on a single fibre. Full redundancy is provided for all electrical and optical equipment, including sensors with four redundant communication channels.

The level sensors use a combination of technologies to give accurate and reliable, long-term measurements in the hostile separator environment. A redundant high-speed general-purpose Fieldbus (DC power and communication) is provided subsea for connection of complex level sensors plus others as required in the future.

Topside computers, which are fully integrated with the Troll C facility network, provide analysis of the data from dual level sensors to detect the interfaces between water, oil and gas in the presence of emulsions and foam. This is used to control the pump speed in order to maintain a constant water level in the separator.

The equipment began integration and land trials in the last quarter of 1998, and was installed subsea in September 1999.

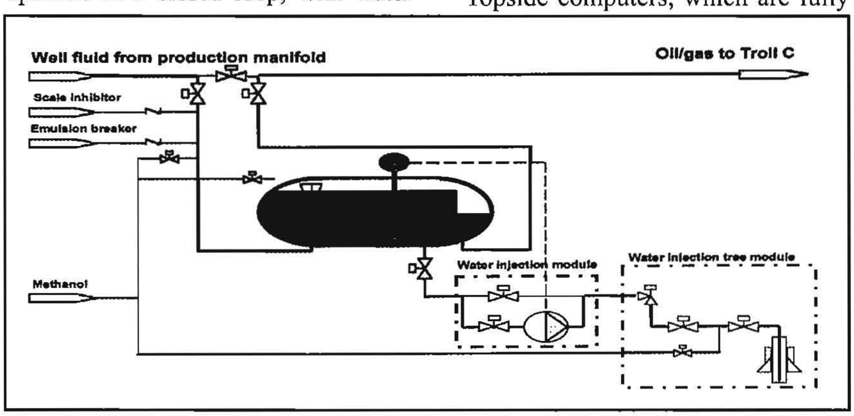

Figure 2: Simplified separator P&ID.

Process system

A simplified P&ID of the separation process is shown in *Figure 2.* Essentially water, oil and gas flow into a large gravity separator tank where the water sinks to the bottom and the oil floats on top, with gas filling the void at the top. The oil and gas flow over a weir plate on to the Troll C platform under the driving pressure of the wells. The water is drawn out of the bottom of the tank and injected into a disposal well by a large 1.6 MW subsea pump. *Figures 3* and *4* show the pump and overall separator assembly.

The separator is operated so that the water level in the tank remains constant, irrespective of the quantity of oil and water entering it. The optimum water level is set by balancing the desire for maximum separation time with high production throughput. This is achieved by monitoring the water level and controlling the pump speed to maintain this optimum level, in the presence of changes in the total and relative proportions of oil, water and gas inflow, in both the short and long term. Algorithms have been developed and modelled to implement this process, illustrated in *Figure 7.* Fluid pressure and temperature measurements are also taken to refine these calculations.

Separator control system

The control system for the separator has a number of unusual challenges, compared to a conventional subsea production system, and the client also had a number of special requirements. The main design constraints which had to be accommodated were:

- Operation in the presence of very severe electrical interference from the subsea motor supply (1.6 MW variable-frequency motor drive).
- High data rates from the separator-tank level sensors.
- Fully dual redundant electrical system and sensors.
- Two different technologies for the redundant level sensors.
- All critical sensors to be subsea replaceable.
- Stable closed-loop operation.
- Topside computer system integrated with Troll C platform system.
- Make use of existing installation and test equipment from Troll Oil project.

Equipment

The equipment needed to control the separator is as follows:

Subsea control module (SCM)

This provides control of the process line isolation valves on the separator structure in order to direct and isolate flow as required. These comprise a mixture of double-acting ball valves and fail-safe gate valves, which are operated via conventional dual-coil, solenoid-operated, fail-safe directional control valves (DCVs) in the SCM. This also provides the means to monitor pressure and temperature sensors mounted on the tank and pump. It incorporates dual redundant electronics for interfacing to these sensors and to the water-level sensors, which are also duplicated. The sensors are connected to the SCM via ROV (Remotely Operated Vehicle) installed electrical jumpers.

The SCM contains dual redundant subsea electronics modules (SEMs) which provide the necessary control signals and data acquisition functions for the sensors. It is based on the use of standard ABB Advant electronic modules, ruggedised for the application, and employs a standard operating system and proprietary software customised to the Troll Pilot application. The SEM is controlled from the Troll C topside facility via redundant, high-speed, fibre-optic communication links.

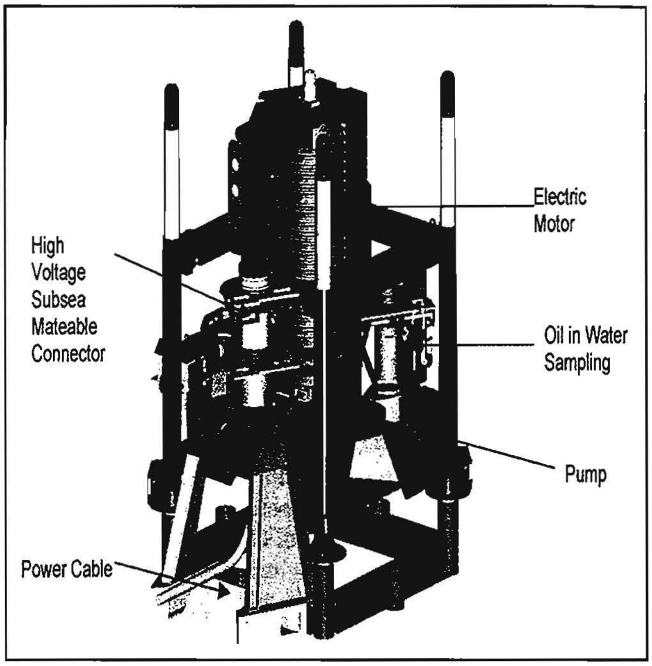

Figure 3: Framo water injection pump.

In addition, the SCM also contains separate redundant power modules, which supply high power DC to the level sensors. The SCM is replaceable using a standard Norsk Hydro running tool, supplied previously for the Troll Oil project.

In addition to the SCM, a separate accumulator module is provided to give local fluid storage for efficient operation of the valves. This module, based on the external dimensions of the SCM, can be replaced using the same running tool.

Umbilical termination electro-optical connectors and jumpers

Jumpers, which are replaceable by ROV and contain both electrical conductors and optical fibres, connect electrical and optical supplies to the SCM from the umbilical termination. These jumpers are terminated in hybrid electro-optical connectors, supplied by Ocean Design Inc, and allow mating and de-mating underwater. Redundancy is maintained by the provision of two identical jumpers.

ROV-replaceable electrical jumpers also provide connection to the redundant level sensors and pressure/temperature sensors on the injection pump.

Process sensors

Conventional process pressure and temperature transducers are fitted to the separator tank and to the pump module. These are used to measure the pressure and temperature in the tank

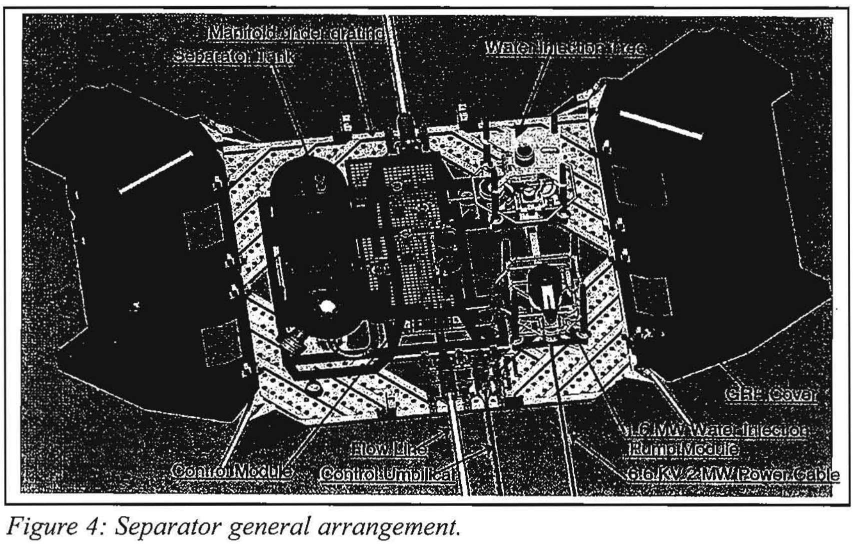

Figure 4: Separator general arrangement.

and suction and discharge pressures in the injection pump. Pressure and temperature sensors are also included in the pump body and motor for status monitoring purposes. All process sensors are duplicated for high availability.

Level sensors

A level sensor is used primarily to locate the interface between water and oil in the gravity separation tank, and secondly to locate the oil/gas interface. The device must be able to detect these interfaces unambiguously in the presence of a build-up of deposition products on the sensors, and of emulsion and foam layers at the interfaces.

Two independent devices are employed for redundancy. In addition, due to the critical nature of the level measurement, two completely different technologies were specified to eliminate potential common-mode failures.

The first device employs a vertical array of nucleonic sensors to provide the measurement, giving good resolution with the ability to replace the whole sensor without breaking the pressure integrity of the tank. This sensor essentially measures density (which is pressure and temperature dependent). A nucleonic source sends gamma radiation through the media into the sensor rod. The source decays with a half-life of 29 years. The second device, which comprises a vertical array of inductive sensors to detect the fluid interfaces, essentially measures conductivity (which is temperature dependent). In both cases the sensor arrays have 100 mm vertical spacing, giving a resolution of 100 mm.

When the oil/water interface level passes an individual sensor element, there is a transition zone where the sensor gradually switches from indicating water to indicating oil (or *vice versa*). This transition zone is in the order of 10 mm for the nucleonic sensor, and 25 mm for the inductive. Thus when the level is within the transition zone, the resolution is in the mm range. During shallow water tests (*Figure 8*), it was shown that the level could be controlled at the middle of such a transition zone. Thus one can control the oil/ water level with mm precision although the nominal resolution is only 100 mm.

Data from each individual sensor element in the two arrays is transmitted to the topside computer where the level is calculated. The level sensor algorithm is designed to cope with individual sensor element failure, through interpolation techniques and comparison between the two sensors. Should one level sensor unit fail completely, operation can continue with a single unit.

The level sensors contain their own computer node, which connects to the AF100 fieldbus independently of the SEMs. DC power is supplied to them from two separate transformer rectifier units in the SCM.

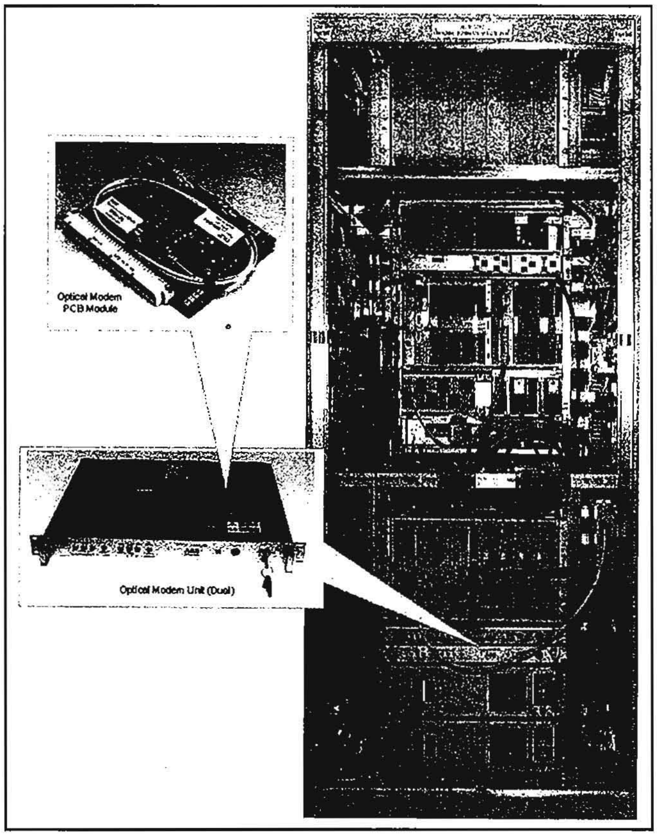

Figure 5: Subsea separator control unit.

Subsea separator control unit (SSCU)

The SSCU controls the operation of the separator and provides electrical power and communication to the SCM and level sensing devices. Figure 5 shows the complete unit, which will be located in the Troll C equipment room and operated from the control room via the distributed computer system (DISCOS) platform automation system. It contains the main process control computer, implemented with a Teleperm PLC (for commonality with the existing Troll C facilities) together with an Advant AC 410 PLC communication processor, two optical modem units (OMUs) and power supplies for the subsea equipment.

Each subsea power module is designed to provide independent, galvanically isolated, 500 VAC supplies to the separator SCM and level sensors, ensuring that the system will continue to operate correctly following possible damage or failure of one of these supplies.

Subsea communication system

Of particular note is the surface-to-subsea communication system. This is implemented using ABB's standard

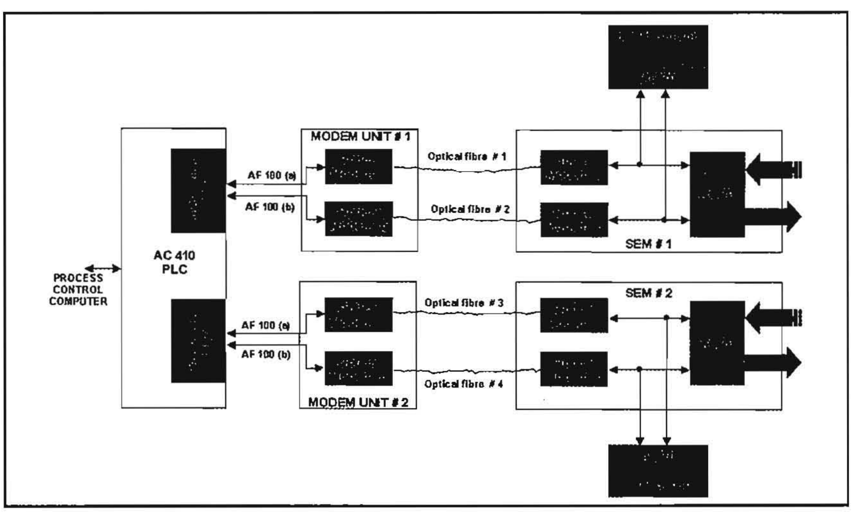

Figure 6: Central system communications topology.

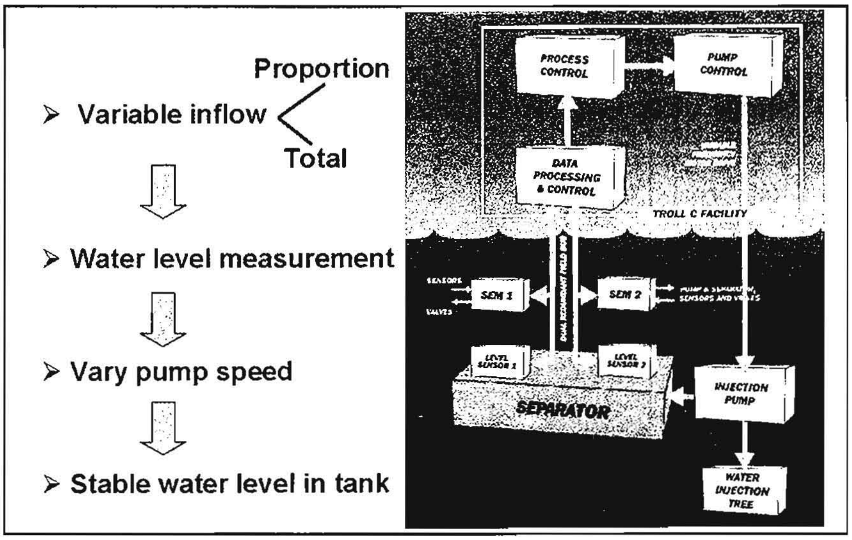

Figure 7: Closed-loop control.

AF100 Advant fieldbus system, transmitted on a 'transparent' optical-fibre communication system.

AF100 operates on RS 485 electrical circuits at 1.5 Mbits/sec, and is used to interconnect devices where a master device controls and monitors a number of slave devices. In this case the master device is the Advant AC 410 PLC in the SSCU, which controls two subsea slave devices, namely the separator SCM and the level sensor. A fibre-optic communication system is employed to transport the AF100 bus through the subsea umbilical in order to provide immunity from interference by the high-power, variable-frequency, electrical pump supplies.

The standard twisted-pair AF100 system employs two redundant channels for high communication availability, hence the 'transparent' OMU employs two separate optical modules to maintain this redundancy. *Figure 6* illustrates the communication system topology, while the optical modem unit installed in the SSCU is shown in *Figure 5*.

Two separate OMUs are used to provide a separate and isolated communication channel to each SEM within the SCM and to each level sensor. Also separate termination and jumper arrangements are employed to eliminate common-mode failure mechanisms. The system therefore possesses dual duplex communications, with four optical fibres being actively connected between the separator SCM and SSCU, only one of which needs to be working for full system capability to be maintained, resulting in a very high availability.

Fibre-optic system

Each fibre-optic channel operates in half-duplex mode on a single fibre, with a compact single-board modem at each end (*Figure 5*). This modem, proprietary to ABB, is designed to fit with other standard modules in the SEM. Identical modules are used in the SEM and OMU. It operates at 1550 nm optical wavelength, on a single-mode optical fibre. Optical couplers are used to combine the transmit and receive signals at each end.

The optical modules employ self-regulating techniques to accommodate external changes in ambient temperature and ageing effects, and do not require laser temperature stabilisation with Peltier coolers. An operating range in excess of 50 km is possible, with acceptable safety margins and very-low bit error rates (<1 in 10^6 bits). The signals, transmitted at 1.5 Mbits/sec, are Manchester biphase encoded.

Separator control and software

The separator control system comprises seven programmed control units and two local operator stations. All the software for these systems has been written using standard, industrial control system languages. *Figure 9* shows the software functional blocks, and the processes performed by each of the controllers are summarised below.

Teleperm process controller

This is the master of the system and performs the separator closed-loop control. It receives the calculated separator fluid levels from the AC410 controller and then, using a closed-loop control function block, issues pump speed demands to the frequency controller unit (FCU) to maintain the correct water level within the separator tank. Algorithms are implemented within the controller to select which of the dual sensor readings are used and displayed at any one time.

The separator cause-and-effect safety control logic is implemented within this unit, and it also controls the operation of all separator subsea control valves operated by the SCM.

The Teleperm controller sits on the

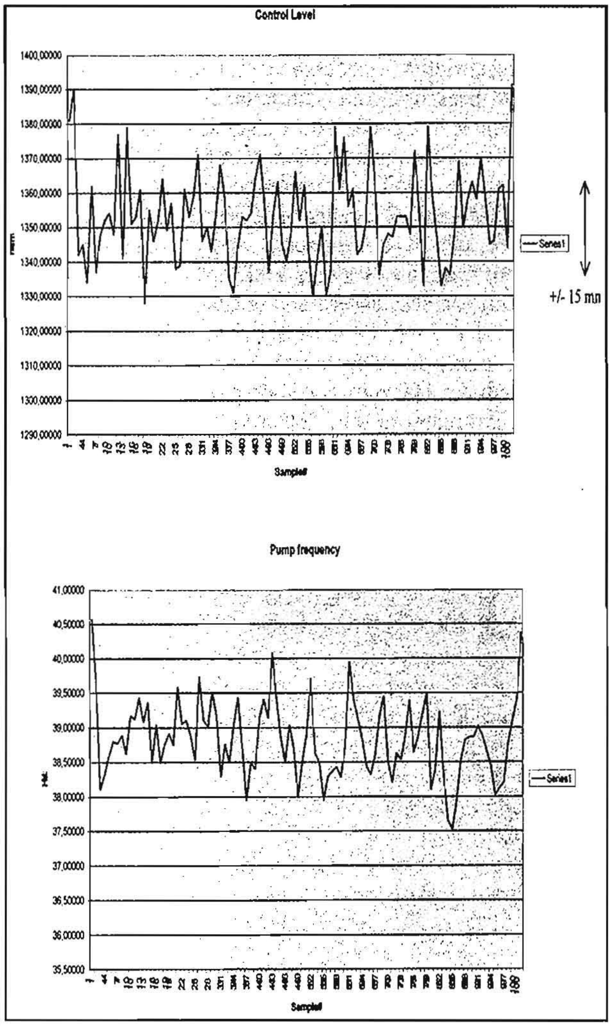

Fig. 8: Closed-loop control performance (at shallow water test).

DISCOS network, allowing the subsea separator to be operated from the Troll C control room in the same manner as all the other platform-installed separators. The system can also be operated from a local operator station, which again sits on the DISCOS network.

Closed-loop control is implemented as a two-stage cascade control loop, with a power controller in cascade with the level controller. The underlying reason is that the system curve for a water injection well can be more or less 'flat' (i.e. a small change in pressure gives a large change in flow).

When the pump is running at a low-flow/high-head condition, the pump curve is also 'flat'. This means that a minute change in pump speed can give a large change in water flow. A small decrease in pump speed can then lead to the flow dropping rapidly, and tripping the pump due to low flow trip.

To avoid this, a high-speed power controller is cascaded with the level controller. The output from the level controller is fed as setpoint to the power controller (about once every 5 seconds). The power controller (which runs every 0.25 seconds) then maintains the pump power constant at this value by adjusting the speed. As the power is roughly flowxhead, any change in flow will be immediately detected by the power signal. If the speed drops, for example, the flow will begin to decrease, the power level will decrease with it, and the power controller will increase the speed to compensate. In this manner, much more stable operation is expected when running the pump close to the minimum flow condition.

During the engineering phase, several alternate control algorithms were also investigated; and the system described was selected as giving the best compromise between system performance and complexity.

Frequency control unit

This unit provides power to the subsea injection pump. It receives speed demands from the Teleperm and, by varying the frequency of the electrical supply, controls the pump speed. Diagnostic signals are returned to the Teleperm, and are also used within the closed-loop control and safety shutdown algorithms.

Advant AC410 control unit

This controller is used as an interface between the Teleperm and subsea controllers. It receives high-level commands from the Teleperm via its 3964(R) communication interface and performs checks to ensure that the operation is valid. If so, it then issues instructions to both SEMs to execute the necessary operations and validates their responses. Sensor readings and status returned from the SEMs are also transmitted to the Teleperm for display and alarm monitoring.

The AC410 also calculates the absolute separator fluid levels from both level instruments. Both instruments have similar level calculation algorithms. The main processes included in these algorithms are:

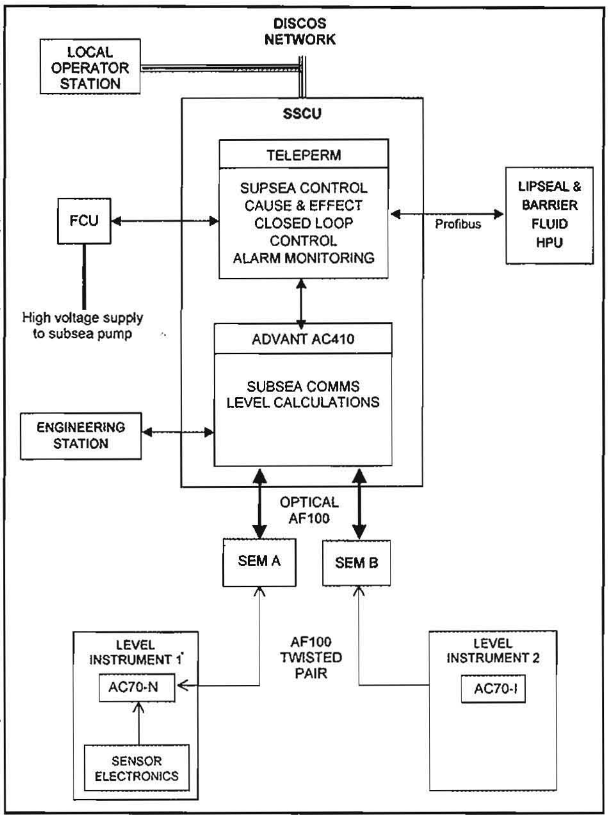

Figure 9: Software functional diagram.

- ❒ Filtering of data to remove errors.
- ❒ Interpolation to replace any failed sensor element reading.
- ❒ Correction to apply ageing coefficients to each sensor element (for the nucleonic sensor).
- ❒ Pressure and temperature correction.
- ❒ Calculation of 'Top of Water', 'Bottom of Oil', and mid-emulsion levels.

In the interpolation stage, 'dead' sensors are estimated using the neighbouring values. In this manner, one can lose every other sensor and only have reduced resolution; the system will still be operative. If too many sensors in the lower (and most critical) part of the sensor rod are lost, then the whole sensor is declared as dead (and the system switches automatically to the other sensor).

Often an emulsion layer forms at the oil/water interface. The algorithms are designed for the worst-case emulsion behaviour (i.e. when there is a gradual transfer from pure water to pure oil, with no distinct phase interface anywhere). Ideally one would like to measure the level where the oil-in-water content is 1000 ppm (i.e. the upper limit allowed for Troll Pilot). In the best of circumstances, the inductive meter can measure the level where there is 3% oil-in-water (30,000 ppm), and the nucleonic meter can measure the level where there is 10 % oil-in-water (100,000 ppm).

Two level signals are calculated for each level sensor: one for control purposes and one for shutdown purposes. These are calculated with different algorithms, as they have different requirements.

The signal used for control needs to have a fast response so that a sudden change in conditions is picked up rapidly. Noise content is not so important (if the level makes a sudden jump, the pump accelerates or decelerates, but it will not change speed much before the next level measurement arrives). The worst-case condition is if the inflow is suddenly cut (e.g. one well trips), and the level begins to fall rapidly.

The signal used for shutdown purposes needs to have a much better signal-to-noise ratio. One single glitch in the signal will cause a trip. This signal is thus more filtered than the control signal, and has a slower response. The filtering time has been carefully selected so that worst-case process disturbance will still be detected quickly enough.

The calculated levels are then forwarded to the Teleperm for use in the closed-loop pump control algorithms.

For diagnostic purposes, the raw data for each sensor element is also forwarded to the Teleperm unit where it is displayed on a detailed VDU picture.

Subsea electronics modules

The dual redundant SEMs (A & B) both run the same software. The functions performed by this software include:

- ❐ Monitoring of sensor values.
- ❐ Control of valves on command from AC410.
- ❐ Valve position detection.
- ❐ Self-test and health monitoring.
- ❐ Valve pressure profile storage and processing.

Level instruments

The level instruments each contain an AC 70 controller, which collects data from the individual sensor units. This data is checked for errors and then stored ready for transmission to the SSCU, on command of the AC410 controller.

System integration testing

Before subsea installation, the separator system was subjected to an extensive campaign of testing.

Shallow water testing

All system concepts were proved during a 3-months shallow water testing phase at Fusa in Norway. This brought together all active elements of the system, working with a small test separator and an automated test loop to provide a simulation of flow through the separator. The water injection pump was driven under closed-loop control from the SSCU for the first time, and the performance and calibration of the level measurement system were checked out *(Figure 8)*.

The pump was operated over most parts of the allowed envelope. Some limitations were imposed by the test loop so that, for example, it was not possible to run the pump at max. head/min. flow.

Site integration testing (SIT)

The Troll Pilot site integration took place during the summer of 1999. The SIT allowed testing of the entire control system, in its full dual-redundant configuration, using the complete separator manifold. This included assessing the effect on the control loop of switching between the redundant level instruments. The SIT was completed successfully before load out of the equipment at the end of July 1999.

Conclusions

The Troll Pilot subsea separator represents the first full-scale use of subsea water separation, bringing together a number of innovative technologies in a cost-effective solution for increasing production and flowline capacity, and thus enhancing the economics of large water producing developments. This has been recognised by the Offshore Northern Seas Conference, in Norway, with the Troll Pilot separator winning the 1998 Innovation Award; and by OTC, with the high-power electrical connector winning the 'Best Mechanical Engineering Achievement Award' in 1999.

The separator control system is an essential element in this fusion of technologies, applying optical-fibre communication for noise immunity and high data rates, together with a high-speed, general-purpose, subsea fieldbus for connection of intelligent sensors, with potential for significant expansion. It embodies a sophisticated computer system to implement safe and stable closed-loop operation.

Troll Pilot came on-stream earlier this year as the first full-scale subsea separation system.