New measuring sensor for level detection in subsea separators

A new sensor developed by ABB for measuring the water/oil interface level in subsea gravity separators used in offshore oil and gas production allows better control of the separators' water outlet pumps. Designated ILMS, for Inductive Level Monitoring System, it represents a key technology for subsea processing. In addition, it can provide information on the quality of the separation process, enabling the amount of separation-enhancing chemical additives to be reduced. Operating costs and environmental impact are lower as a result.

ABB launched a development project called SUBSIS[1)] at the beginning of 1996 with the goal of finding a subsea technology that would increase recovery and allow more economic offshore oil and gas production while reducing the environmental impact of such operations [1]. Based on the initial results, Norsk Hydro awarded in June 1997 the world's first commercial contract for such a system. Delivery of the installation **1** – for the Troll Pilot subsea separation project in the North Sea – is scheduled for late 1999.

Norsk Hydro specified for this first SUBSIS application the use of two independent level measuring principles. Subsea environments make special demands on the installed instruments, and as a result their specifications differ in several important respects from those used in topside separators. Several measuring principles were subsequently evaluated.

1) SUBSIS = Subsea Separation and Injection System

For the project it is planned to use a nucleonic densitometer and an inductive level monitoring system (ILMS) to measure the conductivity. The ILMS was developed at ABB Corporate Research in Norway in close cooperation with ABB Offshore Systems, who owns the system and has overall responsibility for the project. It is currently being prepared for industrial use. Both instruments are due for delivery in 1999.

Subsea separators rely on accurate level monitoring

Gravitational separators rely on the principle that immiscible fluids separate if left to rest, with the lightest fluids on top and the heaviest ones at the bottom. In separators of the kind used in SUBSIS [1], a mixture of oil, water and gas enters the tank from the reservoir. At the other end of the tank the gas and oil float freely over a weir-plate into the production line, while the water collects in front of the weir and is pumped back into the reservoir. Although its working principle is simple, the separator needs to be able to control the mixed fluid inflow and the separated outflows of the separator tank. Closed-loop control is being used for the SUBSIS installation for the Troll project. The data measured by the level instrument in the separator tank are fed via fiber-optic cable to the platform, where they are used to automatically adjust the speed of the water injection pump and so maintain the required levels in the tank. The inflow from each well is adjusted by means of a choke at the wellhead.

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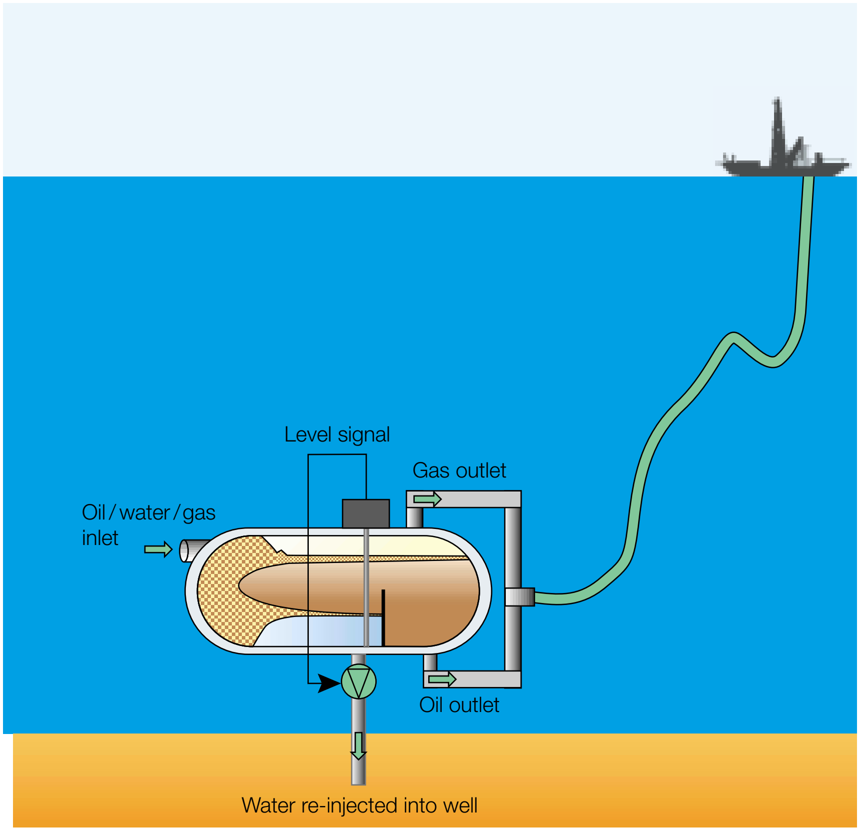
It is extremely important to know the water level in order to avoid pumping oil into the reservoir. At the same time, a low water level will ensure that the oil flowing topside is as clean as possible. However, the critical factor here is the quality of the water being re-injected into the well, since even quite small residues of oil can clog the porous rock, making any further injection of water impossible. Avoiding small amounts of water in the oil and gas flow-line is not as crucial, as further separation anyway takes place topside. The level sensor for the Troll Pilot project therefore needs to be most sensitive in the water layer of the separator.

Since level monitoring is vital for operation of the subsea separator, several measuring principles for level monitoring were considered during the development of SUBSIS. These were based on ultrasonics, microwaves, capacitance, heatwires and floaters, etc, each of which has its pros and cons. For the Troll Pilot subsea separator it was decided to use two independent monitoring systems: one is



Subsea separation and injection system (SUBSIS). Level signals from the new inductive level monitoring system are used to control the water pump. (In the Troll Pilot project the gas exits through the oil outlet.) **1**

fitted with nucleonic sensor elements and the other is the ILMS.

Nucleonic (gamma) densitometers are widely used in the oil and gas industry, for example in topside separators and in multiphase meters for determining the constituents of produced fluids on the basis of their density. Since the handling of radioactive sources is not without risk, the arrangement for full subsea separator profile measurement tends to be complex and expensive. In addition, the lifetime of existing nucleonic level monitors, especially the detector part, is a matter of debate. Given this background, there are good reasons for looking for an alternative or supplementary method of measurement.

The other principle chosen for the Troll application is inductive level monitoring. Operation of the ILMS is based on the large difference in the conductivity of process water (typically 5 S/m) and oil (typically 10^{-6} S/m). While the principle of operation of the ILMS is generally well known and widely used for conductivity measurements, it is new to level monitoring in separators.

To fully understand the reasons for developing SUBSIS and the ILMS, some background knowledge of the subsea environment, gravity separation and properties of produced fluids is necessary.

Subsea environment, produced fluids and the separation process

The produced fluids constitute a complex mixture of chemicals, the behaviour of which varies according to the conditions along the flowline. The fluid may contain relatively large amounts of process water, in some cases amounting to as much as 90 % of the total. At some point between the reservoir and the end-user, the water has to be separated from the oil and gas. Traditionally, this has occurred topside. However, there are good reasons for moving the separation process closer to the reservoir and away from the topside installation. Key advantages include:

- The transportation piping, which is expensive, can be reduced in size when the water is removed from the fluid, thereby lowering costs.
- Oil and gas are easier to transport when the process water is removed since the risk of problems due to hydrates, scale, etc, is smaller.
- The fluid generally separates more easily when the separation process is close to the reservoir. This is because transportation intensifies mixing.
- Backpressure at the separator is reduced (water is considerably heavier than oil), translating into increased oil recovery.
- If necessary, the reservoir pressure can be maintained by injecting the separated process water back into the reservoir.

Separation-enhancing chemical additives are often added to the process to avoid thick foam and emulsion layers from forming. Additives for preventing scale and wax deposits are also commonly used. Besides being expensive, many of these additives are toxic, which makes them an environmental hazard. As mentioned, subsea separation has advantages for both the separation and transportation, so smaller amounts of chemical additives are needed. The minimization of these chemicals is in itself a good reason for subsea separation.

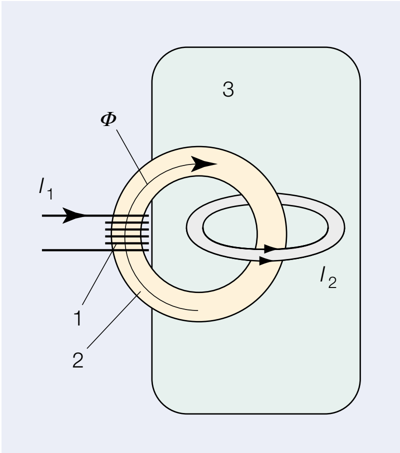
The actual separation process is highly sensitive to minute changes in fluid constituents as well as to variations in the flow rate, pressure and temperature during production. In addition, the way fluids from different reservoirs separate may vary greatly. A thorough understanding of these processes is important, particularly for the transportation and treatment of produced oil and gas. Unfortunately, no single theory exists to explain all the phenomena involved. Consequently, field experience as well as the results of comprehensive experimental investigations have gone into the design and operation of SUBSIS.

Requirements subsea level instruments have to meet

Level instruments have been in use for years in gravity separators on offshore platforms and in land-based processing plants. The sensor elements in these instruments usually have to be re-calibrated and cleaned regularly, and other routine maintenance is often necessary. When installed topside, the instruments are more or less easily accessible for maintenance, and providing the instruments are reasonably priced even the regular replacement of whole systems can be considered.

The maintenance of subsea equipment, on the other hand, is relatively complex. All kinds of subsea intervention require the use of remotely operated vehicles (ROVs) or other kinds of remotely operated tools. Such operations are expensive. Maintenance or replacement procedures may even involve shutting down production completely, making the overall cost extremely high. Maintenance-free operation and high reliability are therefore absolutely essential for subsea level sensors.

The pressure in the separators is normally lower topside than it is subsea due to the pressure drop in the subsea pipelines. Also, fluid sampling for laboratory analysis is common topside, but too expensive for regular subsea use. Realizing that copying topside solutions for subsea separators is unattractive or even impossible, ABB thoroughly investigated different subsea level monitoring systems during development of the ILMS for the Troll Pilot project.



Inductive principle and possible arrangement for detecting the conductivity of a surrounding medium **2**

I_1 Applied current
I_2 Induced current
Φ Magnetic flux
1 Coil
2 Ferrite core
3 Medium

Operating principle of the inductive sensor

As already mentioned, the idea behind the ILMS was to utilize the large difference in the electrical conductivity of process water and oil. This property can be measured in a number of ways. The direct way is to place two electrodes in the medium being measured; however, this is not feasible due to possible build-up of insulating layers of different kinds in the separator tank and on the electrodes. An alternative method is to set up an alternating magnetic field which induces a current in the medium as a function of the medium's conductivity. The operating principle of such an inductive sensor element is shown in **2**.

In this schematic a coil wound around a ferrite core has a current I_1 applied to it which sets up a magnetic flux Φ in the core. This flux induces a current I_2 in the surrounding medium, the value of which depends on the conductivity of the medium. The induced current causes a counter-acting flux in the core, resulting in a lower circuit inductance or, viewed from the source of the current I_1, in a lower impedance. Thus, measurement of the impedance of the sensor element reveals the conductivity of the surrounding medium.

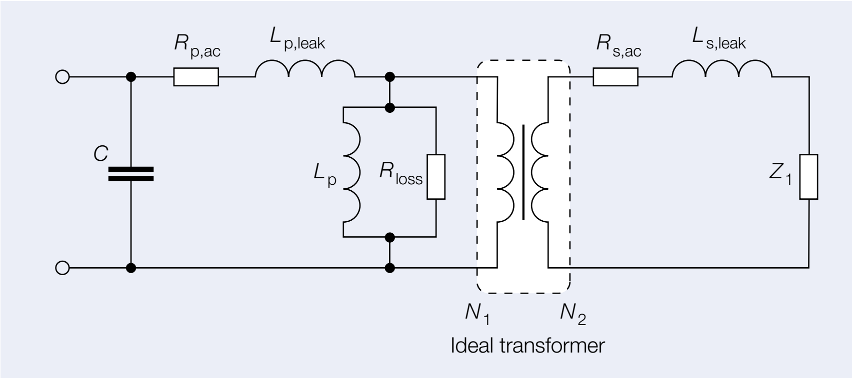
The induced current is distributed in the medium according to the magnetic field distribution and the conductivity of the medium. It is worth noting that if the frequency of the applied current is high enough, the skin effect will limit the current distribution to a shallow zone close to the linking flux in the core. However, for subsea applications what is required is low sensitivity to the possible build-up of different kinds of layers, ie a bulk sensor. The ILMS therefore makes use of a current frequency at which the skin depth is greater than the size of the core.

The skin depth, d, is given in [2] by:

$$d = (2/\mu\sigma\omega)^{1/2} \qquad (1)$$

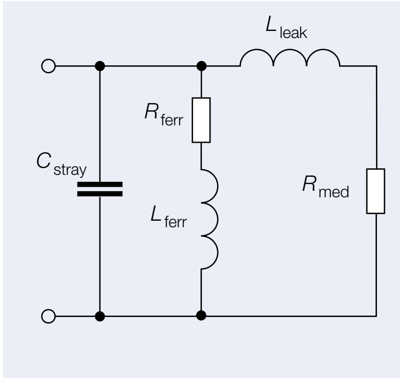
under the condition that $\omega \ll \sigma/\varepsilon$ and where μ is the permeability of the medium into which the magnetic field penetrates, σ is the conductivity, ε the permittivity and ω the angular frequency. The skin depth in process water with a conductivity of approximately 5 S/m is about 30 cm at 1 MHz[2]. The diameter of the core for the Troll application is less than 10 cm; a bulk sensor can be obtained for practical frequencies as discussed in the following.

[2] As the conductivity of the medium decreases (eg, due to a high oil content in the process water) the skin depth increases, so that if a high frequency is chosen the condition in eqn (1) may no longer apply.



Equivalent circuit diagram of the 'transformer' used to explain the inductive sensor principle **3**

C	*Coil capacitance*
L_p	*Coil self-inductance*
$L_{p,leak}$	*Primary leakage inductance*
$L_{s,leak}$	*Secondary leakage inductance*
$N_{1,2}$	*Primary and secondary winding turns*
R_{loss}	*Loss resistance*
$R_{p,ac}$	*Primary winding resistance*
$R_{s,ac}$	*Secondary winding resistance*
Z_1	*Load impedance*



Simplified schematic of the equivalent circuit diagram in Fig. 3 **4**

C_{stray}	*Stray capacitance*
L_{leak}	*Leakage inductance*
L_{ferr}	*Core inductance*
R_{ferr}	*Core loss resistance*
R_{med}	*Load resistance*

The sensor principle can also be explained by looking at the way the magnetic flux links two circuits, here given by the coil and the current induced in the medium. This situation can be viewed as a transformer in which the coil acts as the primary and the induced current as the secondary 'winding'. A conventional equivalent circuit diagram for this 'transformer' is shown in **3**.

Looking first at the primary side, coil capacitance C is composed of capacitance between the turns of winding, the capacitance between turns and ground potential, and capacitance between the turns and ferrite core potential, etc; $R_{p,ac}$ is frequency-dependent coil winding resistance; L_p is the (open-circuit) coil self-inductance; $L_{p,leak}$ is the leakage inductance and R_{loss} represents the sum of all the loss mechanisms involving the ferrite core. $R_{s,ac}$ and $L_{s,leak}$ are the respective frequency-dependent winding resistance and leakage inductance on the secondary, while Z_l is the load impedance. This ideal 'transformer' has primary and secondary winding turns N_1 and N_2, respectively.

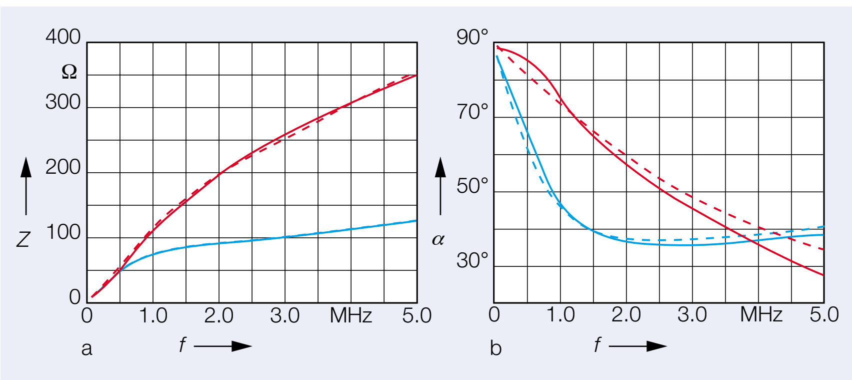
The mathematical treatment of the circuit given in **3** can be found in textbooks and therefore need not be gone into here. A look needs to be taken instead at those properties most relevant for the application under consideration. The secondary load impedance, being the impedance of the surrounding medium of the sensor, is observed on the primary side of the transformer as a change in the total impedance. The sensitivity of this measurement depends on good coupling between the primary and the secondary; this can be ensured, for example, by introducing a high permeability material as a linking core and minimizing the leakage inductances.

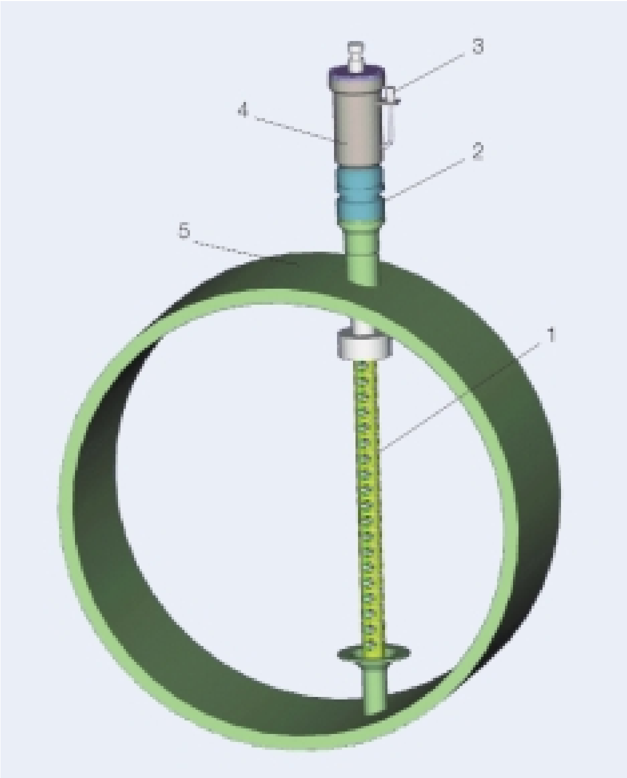
In 'simple' media, such as 'pure' process water or 'pure' oil, the relevant load impedance can be represented by a resistor. This allows the diagram in **3** to

Measured and theoretical impedance (a) and phase (b) for a sensor with a 5-turn primary winding **5**

α	*Phase*
Z	*Impedance*
f	*Frequency*

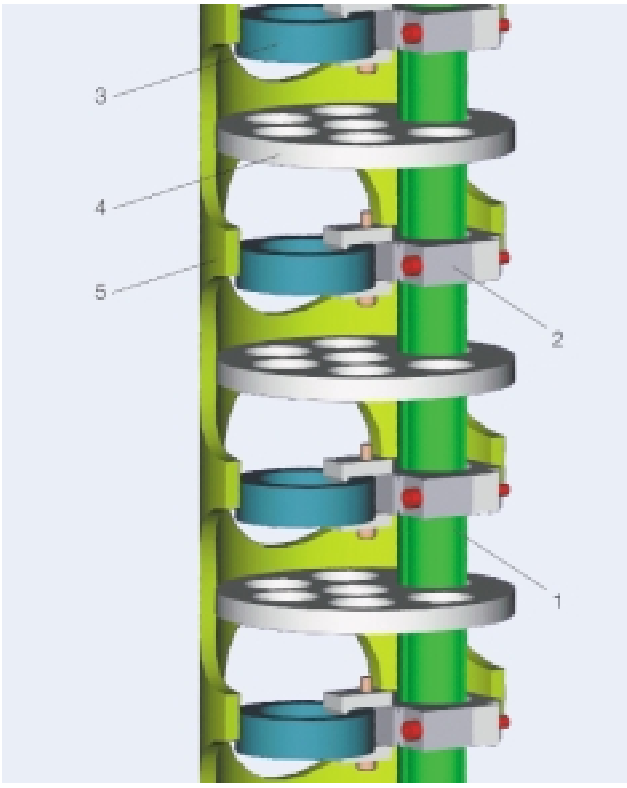
red solid line	*Measured in oil*
red dashed line	*Simulated in oil*
blue solid line	*Measured in process water*
blue dashed line	*Simulated in process water*





ILMS developed for use in subsea separators **6**

1 Sensor rod
2 Mechanical connector
3 Power and signal connections
4 Electronics canister
5 Separator wall



Details of the ILMS sensor rod **7**

1 Inner tube
2 Attachments
3 Sensor elements/ferrite cores
(coils are hidden by attachments)
4 Spacers for added strength
5 Outer shielding tube

be simplified as shown in **4**. It can be seen that while a somewhat different terminology is used for the circuit elements in **3** and **4** there are good reasons for this. For the purpose of this discussion it is somewhat imprecisely stated that C_{stray} is a capacitance that includes all stray capacitances on the primary side of the transformer as well as some capacitance resulting from the wires feeding current to the sensor. R_{ferr} and L_{ferr} are series representations of the loss resistance of the core and the primary inductance. L_{leak} and R_{med} are the leakage inductance and load resistance on the secondary side, respectively, as observed on the primary side of the transformer.

It can be seen from the equivalent diagram in **4** that the circuit has two resistive elements: the loss resistance of the core and the load or loss resistance of the medium, the latter being the element used by the ILMS. The measurement is based on the difference between the currents flowing in the branches of these two resistors. To ensure good measuring sensitivity irrespective of how the sensor electronic signal is processed, the core loss has to be reduced to the lowest possible value.

It should also be noted that the stray capacitance may actually short circuit the measurement device, especially at high frequencies. The system therefore has to be made robust. This is done by choosing appropriate dimensions for the wires and a suitable number of coil turns, as well as by ensuring that the frequency is not too high.

The design and optimization of the sensor included a mathematical model of **3** and **4** which considered, among other things, how the various elements depend on frequency, temperature and pressure. The predictions based on this model agreed closely with the measurements. An example is given in **5**, in which the total impedance amplitude and the corresponding phase are shown. The simulated values are hardly visible in the impedance plot since they agree so closely with the measurements. The results were obtained at room temperature and atmospheric pressure, all the data for the different parameters being known under these conditions and from the data sheets for the ferrite material that was used. Equally good results were obtained when considering the dependence on the number of turns. It should be mentioned here that the ferrite material selected for the Troll application exhibits significantly lower losses than the material used in 5 and offers considerably better sensitivity. In addition, its Curie temperature is higher than the 110 °C of the material used in 5, resulting in a better margin (the Troll separator temperature is about 70 °C).

From principle to product

Knowledge of the basic sensor principles, plus the mathematical tools that were developed, led to an optimized design for the Troll sensor. In addition to the core-sensing technology, attention was focused on ensuring a rugged design which can resist mechanical shock, high pressure and temperature as well as chemical attack by the fluids in the separator.

The complete ILMS is shown in 6, and design details of the sensor rod in 7. The outer tube and the spacers, which are at 10-cm intervals, protect the ferrite ring cores during installation yet allow the separator fluids to flow freely around the sensor elements.

The ILMS sensor rod consists of a vertical stack of sensor elements that measure conductivity as illustrated in 8. The result is a full vertical conductivity profile of the separator contents. All the performed experiments and all theoretical evaluations consistently prove that the ILMS is capable of measurement in water and water-continuous emulsions. The oil-continuous and gas phases, on the other hand, exhibit practically no conductivity. Thus, the ILMS signal does not provide any information about interfaces in this region, eg between oil and gas.

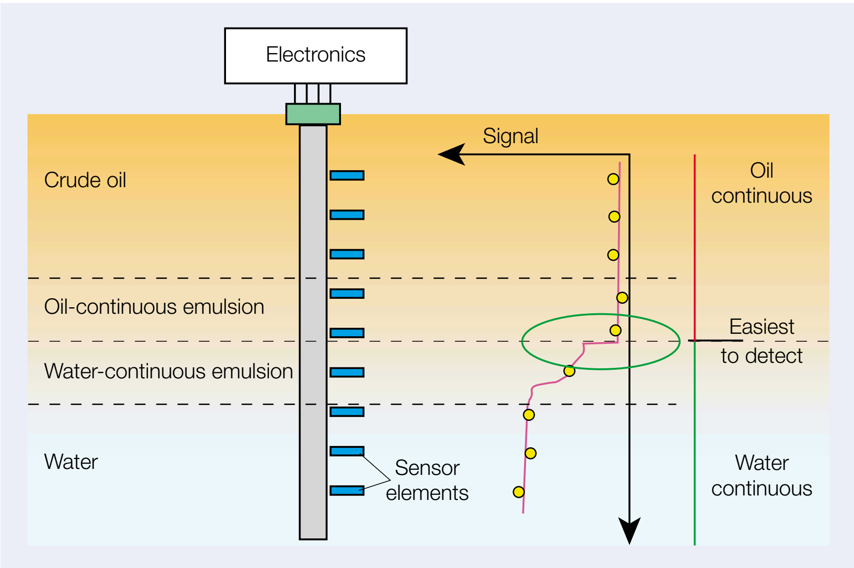
The ILMS used in the Troll project is designed to determine the most robust way of measuring the water level in the separator. The transition between water-continuous and oil-continuous emulsion represents the biggest leap in conductivity, and the level of this transition zone may be used to deduce the water level in the tank. By combining ILMS data with temperature readings from within the separator, it is also possible to obtain absolute measurements of the oil contained in the water-continuous phase. The water level can then be identified as the point at which there is a certain amount of oil (eg 3 %) in the water. The vertical profile of the oil content in the water-continuous emulsion can also be utilized for emulsion control.

Known theories concerning conductivity in emulsions have been confirmed experimentally by means of an ILMS sensor element. It is evident from the typical curves shown in 9 that the abrupt change in permittivity could be used instead of conductivity to determine the level of continuity inversion. For this and other reasons, pure capacitance meters are sometimes used in land-based and topside separators. However, the criterion on which the selection of the inductive principle is based is its highly robust and tolerant behaviour towards many different side-effects occurring in separators, paired with its ability to measure the oil content in the water-continuous phase. (Most capacitive principles have problems with this due to the high conductivity of the process water nearly short-circuiting the electrodes.)

The robustness of the ILMS can be summarized as follows:

- The ferrite core may be covered by relatively thick layers of scale, wax, etc, which may grow over the years of operation, without compromizing its ability to detect the level. (Even magnetic layers, although very unlikely, would not upset the measurements.) This has also been verified experimentally.
- The instrument tolerates water ingress to some extent even if the stray capacitance does increase due to the high permittivity of water. However, if salt water comes into direct contact with the naked supply wires it will short-circuit the entire sensor and ruin the measurements. Providing suitable insulation materials are used, water ingress mechanisms will leave most salt ions

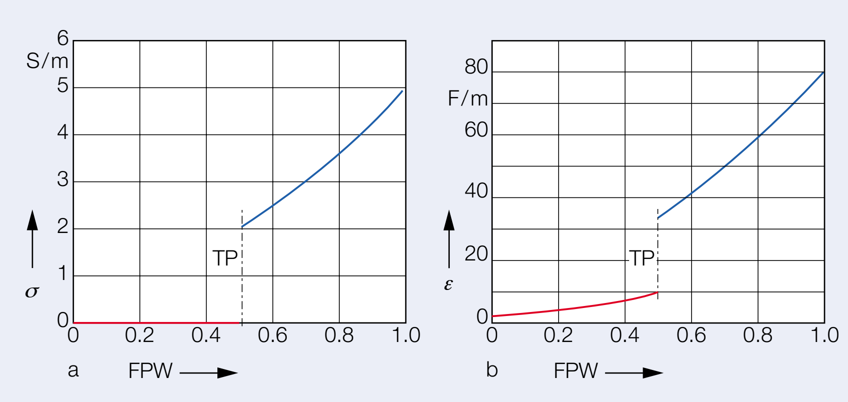
The ILMS is made up of a vertical stack of sensor elements, each measuring the conductivity in its vicinity. 8



outside the barriers and only distilled water will penetrate. Distilled water inside the instrument is not a problem.

- The instrument can easily be built with a high level of redundancy. In the system for the Troll application several of the single sensors in the stack **7** may be destroyed without the instrument losing its ability to determine the level in the tank.
- The electronics necessary for processing the signals can be situated outside of the hot, harsh tank environment. Multiple redundancy is also easily achieved for the electronics, and this option has been implemented for the Troll project. The electronics has the additional advantage of being simple and highly reliable.
- The wiring system is inherently as redundant as the sensor elements.
- No re-calibration is necessary during operation.
- No temperature and pressure measurements are necessary for safe detection of the level. (For higher-accuracy oil-in-water measurements, however, temperature measurements are required.)

The design chosen for the electronics is based on direct measurement of the loss represented by the resistance of the medium. The results obtained with this method are better than with the more usual bridge configuration since the method is more tolerant of stray capacitances and other parasitic effects.



Conductivity (a) and permittivity (b) in emulsions **9**

σ *Conductivity*
ε *Permittivity*
TP *Transition point*
FPW *Fraction process water*

Oil-continuous emulsion (red line)
Water-continuous emulsion (blue line)

The ultimate goal – full profile measurement

The inductive sensor is without doubt valuable for the detection of the water-phase in both subsea and topside separators. By combining ILMS readings with temperature data, it is also possible to achieve a profile of the oil content in the water phase. In later models, temperature-measuring devices may be incorporated in the sensor rod to make this feature independent of external measurements.

The ultimate goal is full profile measurement in the separator tanks. However, this cannot be achieved using the inductive principle only. Capacitive principles allow measurement in regions with low conductivity (oil, gas), whereas the ILMS does not. It is planned to carry out investigations to see whether an instrument combining inductive and capacitive measurements is suitable for full profile measurements.

The formation of emulsions is critical in subsea separators, while in topside separators foam layers are also important. Studies of the physical properties and measurements of both the conductivity and permittivity are needed if electrical full-profile instruments are to be successful. The inductive sensor in SUBSIS is currently being used for closed-loop control of the water outlet pump. If a full-profile system could provide more details about the emulsion, closed-loop control of the chemical injection system might also be feasible. Considerable interest is being shown by the offshore community in a further reduction and optimization of the use of chemicals injected into the production fluids.

References

[1] **R. Strømquist, S. Gustafson:** SUBSIS – world's first subsea separation and injection system. ABB Review 6/98, 4–13.

[2] **N. Tralli:** Classical Electromagnetic Theory. McGraw-Hill Book Company, Inc. 1963.

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