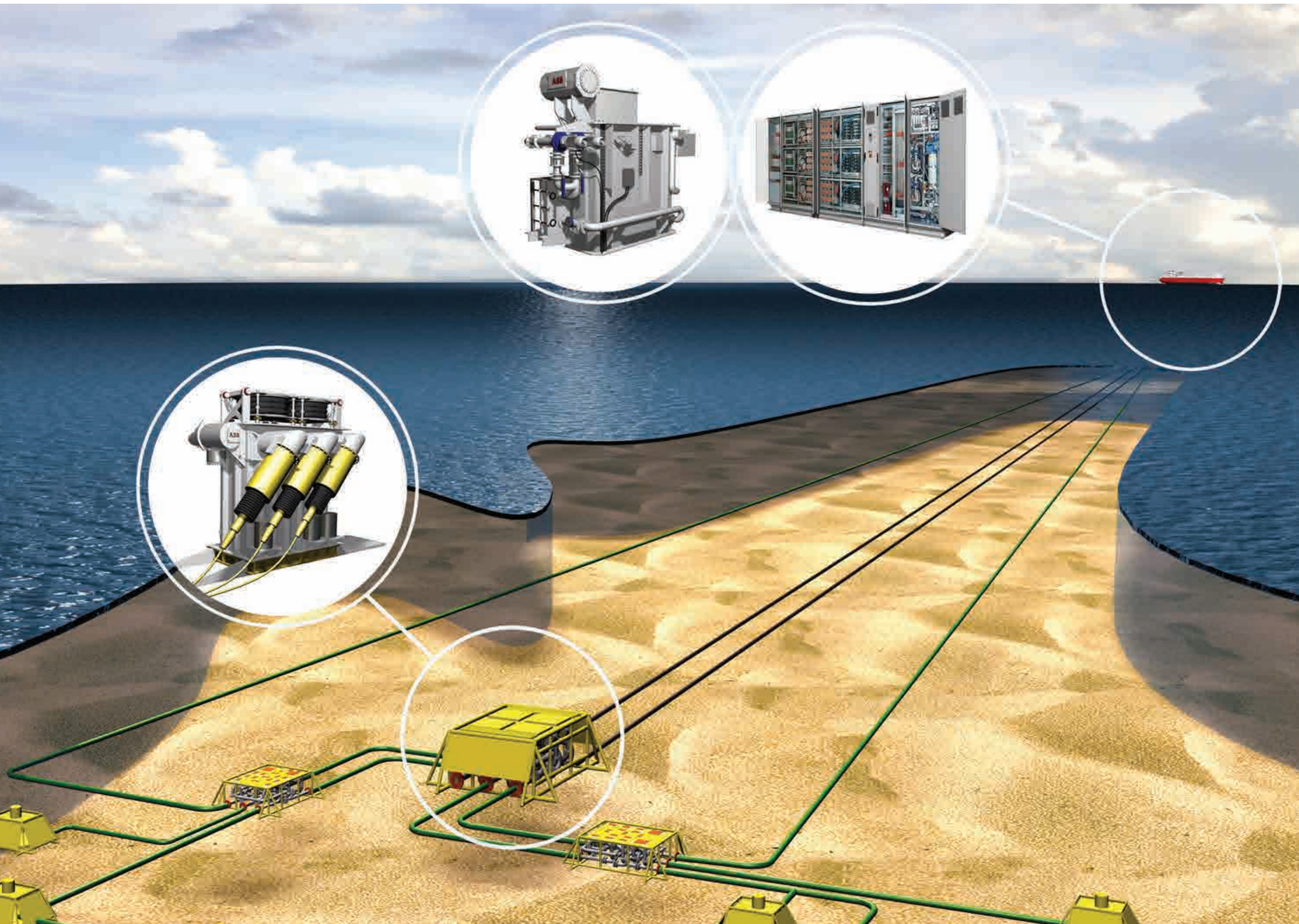
WHITE PAPER

Long step-out systems for subsea pump and compressor applications

Economic hydrocarbon recovery under extreme conditions



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Executive summary

Subsea processing, and gas compression in particular, are important advances in the development of fields in deep waters and harsh environments. This white paper explains the principles of applying a long step-out system to subsea pumping and compression applications. It discusses the features and the benefits of the system when applied to new (greenfield) and existing (brownfield) sites. While this paper is targeted primarily at engineering and design staff in oil and gas companies and EPCs, it is also relevant to all buyers and influencers. The aim is to stimulate discussions about future sites that can benefit from this technology.

1.0 Market forces demand new approaches

For much of the new millennium, oil prices were characterized by steep increases and a considerable amount of volatility. During these boom years, the focus was on production. The oil price crash in late 2014 has heralded a heightened interest in cost reduction and efficiency. Traditional responses to the downturn, such as industry layoffs and rig shutdowns, may no longer be sufficient to sustain a competitive advantage going forward.

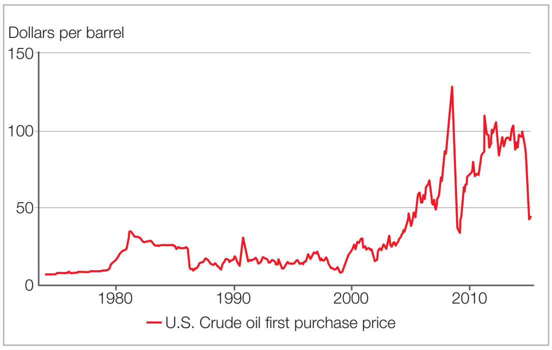

Figure 1. U.S. Crude Oil First Purchase Price[1].

Data shows, for example, that while revenues of upstream, midstream and oilfield services companies declined 40 percent between the third quarters of 2014 and 2015, operating expenses (OPEX), only fell nine percent (Figure 2). This means that more drastic measures are required – particularly if low prices continue as long as expected. It is likely that an increased digitalization of existing operations will help tighten the revenue/OPEX gap[2].

One promising area to address such challenges is subsea exploration and production which decreases reliance on a key element of the equation: employees. If machines can largely do the work themselves, managed remotely by only a few technicians, companies can mitigate against high labor bills and a retiring workforce.

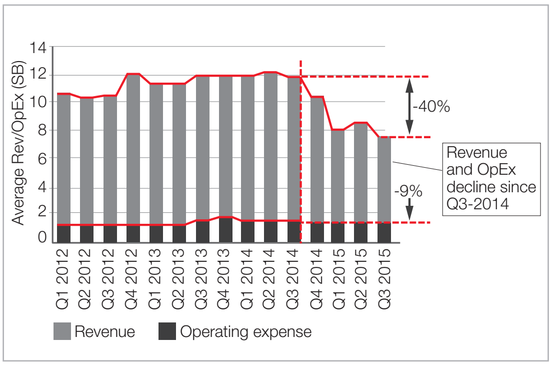

Figure 2. The growing revenue vs operating expense imbalance in O&G companies[3].

2.0 The need to go deeper and further afield

Oil and gas fields in shallow coastal shelves are becoming exhausted. The energy industry is now struggling to eke out as much as it can from existing installations and has begun to develop reserves in increasingly deep water. Fields more than a kilometer below the surface are becoming more common. The more depleted the existing reservoir, or the more inaccessible it is due to distance, the greater the need for subsea pumps and compressors and the technology that powers them.

Productivity challenges

- Squeeze more out of existing reservoirs
- Optimize tail production and extend field life
- Maintain high levels of production
- Develop difficult, previously unworkable, fields
- Separate, transport and reinject fluids and gas across long distances
- Control better what is going on in the subsea system
- Optimize maintenance in hostile environments
- Handle more data intelligently

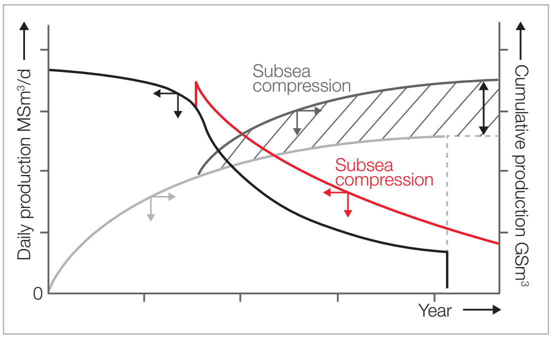

Figure 3. Benefit of subsea processing - raise production and increased recovery[5].

2.1 Increasing demand for subsea pumping and compression

A well's production depends on the reservoir pressure. During the early years of production, the reservoir pressure itself is sufficient to maintain the production rate. Over time, however, pumps and compressors are needed to boost the pressure in order to maintain a similarly high level of oil and gas production (Figure 3). This is crucial to extending the operating life of existing fields.

Gas-producing wellheads may be located on a production unit, offshore or onshore, or as a subsea-completed well tied into a production unit over a long distance. The majority of existing subsea-completed wells are within shorter distances, typically 50 km below the production unit.

Moving the required pumps and compressors from the topside installation to the seabed, increases the effectiveness of oil and gas extraction. Additionally, it reduces the number of people working in harsh environments offshore, cutting labor costs and enhancing safety at the same.

The required electrical power for pumps, booster stations or compressors is supplied from an offshore platform or an onshore facility. Due to the pressure drop during production, the frequency of the power supply needs to be controlled in order to change the speed of the pump or compressor. Most, if not all, motors for subsea processing require a variable speed drive (VSD) due to uncertainty in reservoir data, especially over the field's life time. This is where long distance step-out systems come in.

3.0 The move to long step-out systems

The journey to existing long step-out power systems started around 1996 when the oil and gas industry began looking into whether subsea compression and subsea multiphase pumping could be placed closer to the well. Boosting at the wellhead is much more energy efficient as this avoids the long suction pipe required (dependent on tie-back length). Compressors are installed to actively increase the flow and extract more gas and condensate from the geological formations.

The idea has been to minimize investments in new offshore production units by using existing rigs as a hub, with gas recompression equipment installed on the seabed by means of long step-out power system, or even running these sites from shore if possible.

During the 2000s, concerns over the unexpected diminishing gas levels in the Åsgard field (Figure 4) on the Norwegian Continental Shelf, elevated the need to explore ways of maintaining the volumes that were initially forecast (Figure 3). An approach was a subsea gas compression system using a VSD power system that is called a “long step-out system”.

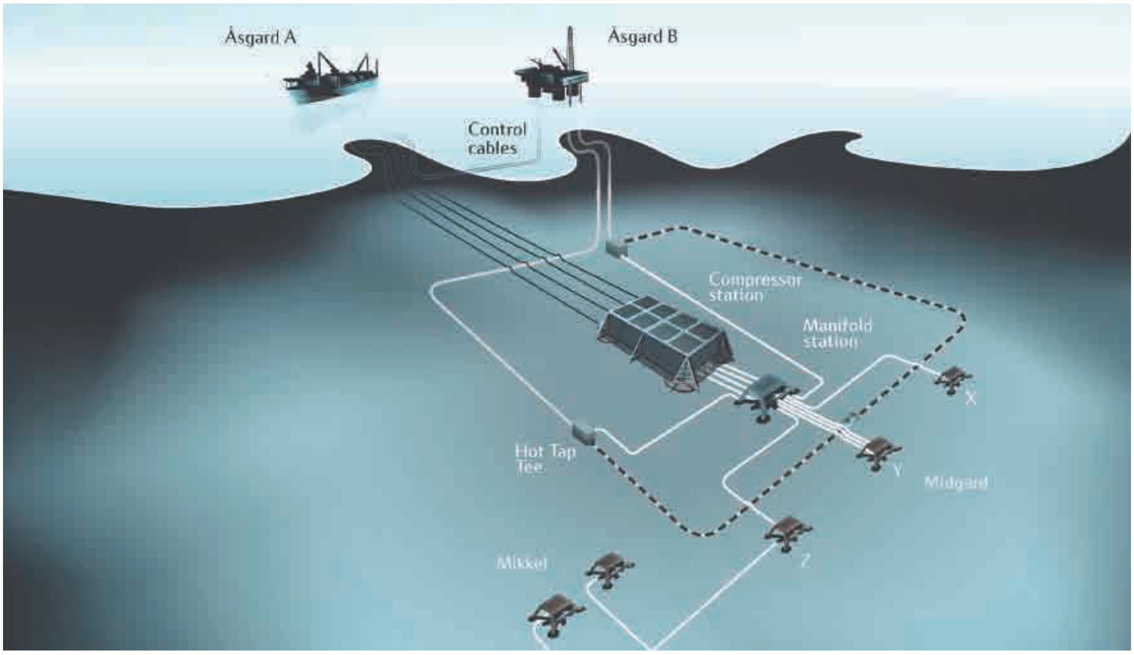

Photo: Statoil ASA

Figure 4. The Åsgard system involves one subsea template containing two parallel compressor trains installed in 300 m depth of water in the Norwegian Sea. At Asgard, gas needs to be boosted from the Mikkel and Midgard satellite fields to the Åsgard B platform to maintain stable production rates and avoid accumulation of mono-ethylene glycol (MEG) in the flowline[4].

4.0 Long step-out systems

With a standard VSD system, used in shore-side industries, there is a very short distance between the VSD and the machine, typically some hundreds of meters. However, in a long step-out system, the length is typically from 10 to 50 km, or longer depending on required power. Using long step-out systems enables accurate speed control of subsea machines from far away.

In a long step-out system, the VSD is located topside together with a step-up transformer. The VSD governs the speed of the subsea pumps and compressors. Additionally, remote control and monitoring is achieved by utilizing a VSD. The power is fed though a long cable to a step-down subsea transformer, which adjusts the voltage to fit with the nominal voltage of the motor. Compressors typically demand a higher power rating and higher speeds compared to pumps. The torque speed envelope is also wider for compressors versus pumps.

4.1 Qualification of long step-out systems

To ensure the reliable operation of compression equipment subsea, significant project-specific technology qualification activities must take place earlier than ever before. In fact, such activities have been taking place since the 2000s, building on decades of technology development. The work at the K-lab at Kårstø includes performance and endurance testing to ensure that robust systems are delivered.

Qualification of a long step-out system includes testing motor and topside VSD, using a cable simulator in order to confirm electrical stability for a range of operating conditions over the relatively long step-out.

For example, in the Asgard project, the three-phase cable simulator represented the actual condition of a 47 km subsea power cable using 10 pcs section operating at 52 kV, 300 A, 200 Hz, as this system was designed to test and qualify different compressors up to 200 Hz. The ABB drive was a standard ACS5000. However, the corresponding software was developed during the qualification. The qualification tests confirmed electrical stability over the relatively long step-out for a range of operating conditions.

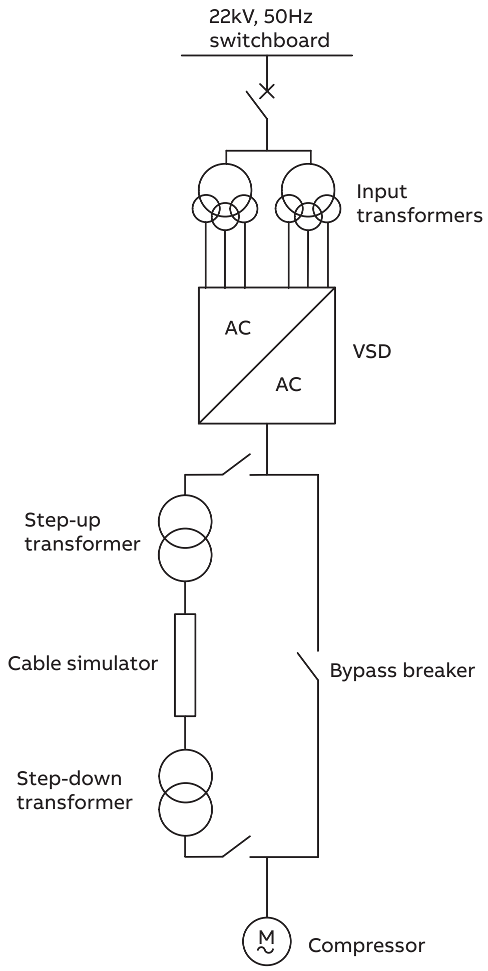

Figure 5. Single line diagram of the test setup used at the K-lab testing facility. This was for the subsea compressor testing at the Kårstø processing plant near Stavanger.

Figure 6. Cable simulator utilized during qualification of the Åsgard subsea gas compression system. Some flexibility included in the lumped components for different cable sizes and lengths.

4.2 Long step-out systems for subsea application
Long step-out systems have become one vital part to enable subsea pumping and compression. A long step-out system provides efficient and reliable electric power over a large distance from an offshore facility or offshore platform to subsea stations, such as a subsea gas compression station. A long step-out system normally utilizes a control approach without sensors. However, in future, a communication link for control can be implemented.

The distance from the production unit to the subsea pump or compressor, and the required power, has been increasing over the years. The first system delivered by ABB was rated approximately 1 MW with a step-out distance of around 7 km (Topacio and Ceiba subsea projects).

Nowadays, long step-out systems are delivering up to 20 MVA electric power to subsea loads and at a distance up to 43 km (Åsgard subsea project). Power system studies have shown that feeding 20 MVA up to a significantly longer distance of 120 km is feasible (Figure 8).

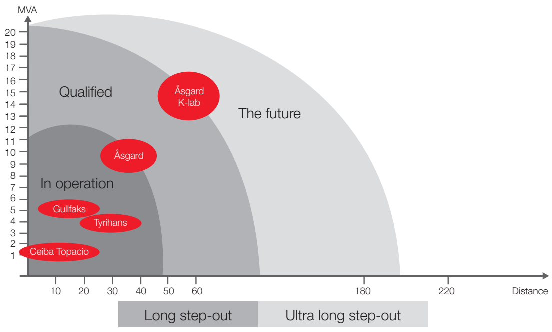

Figure 8. Feasible and achievable long step-out system in terms of power and distance.

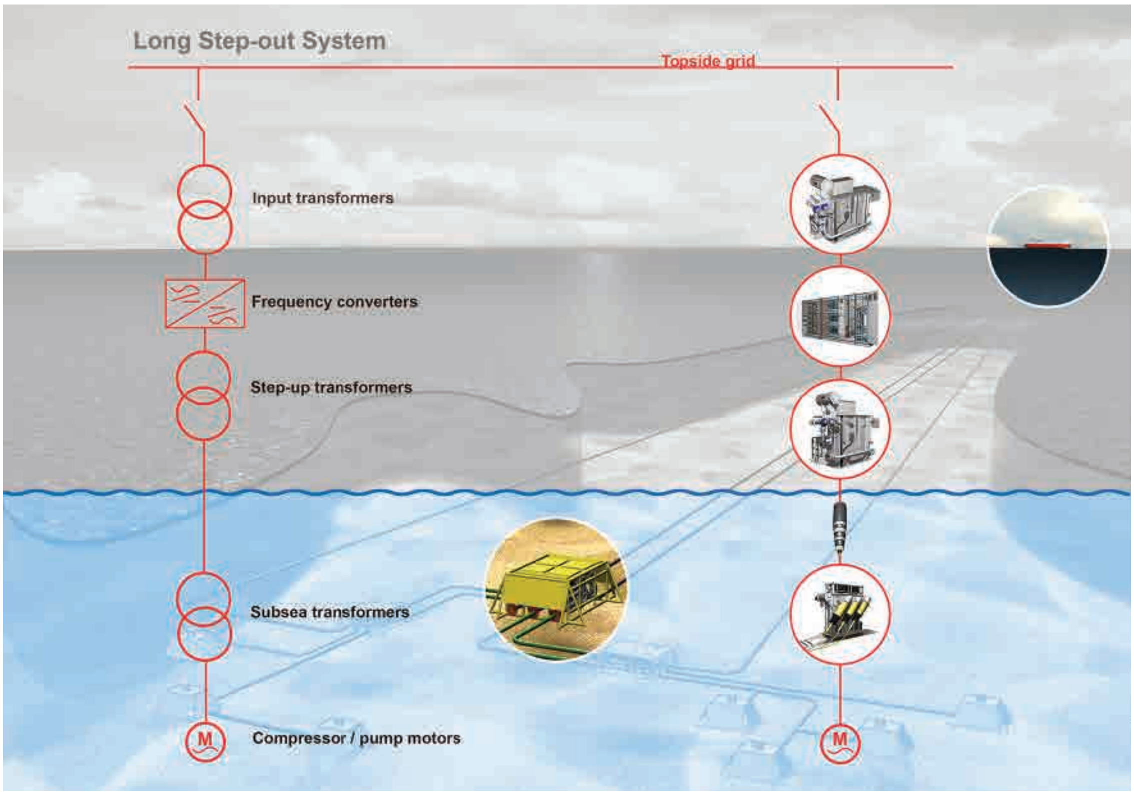

Figure 7. Schematic diagram showing a typical long step-out power system. Here, the load is either a subsea pump or compressor. Step-up transformers are utilized to raise the voltage level and increase the maximum electric power and length of transmission. The subsea step-down transformer is installed close to the subsea load and both are equipped with wet mate connectors on the secondary side in order to enable the subsea transformer and load to be retrieved.

5.0 Benefits of long step-out systems

As outlined previously, the objective of installing subsea pumps and compressors is to extend the lifetime of an existing field, or in the longer term, to build up a subsea factory instead of an offshore platform and manage subsea production from far away onshore.

The benefits of long step-out systems include:

- **Cost efficiency**
  Increasing the amount of oil and gas that can be recovered from new and existing fields by deploying compression or pumping systems at the seabed decreases overall costs per unit
  – Statoil's Åsgard project , the world's first subsea gas compressor system, 300 m below the surface, is predicted to enable an additional 306 million barrels of oil equivalent, corresponding to a medium-sized field on the Norwegian continental shelf (NCS) and to extend the field 's life to 2032.

- **Reliability with less risk**
  Using proven technology such as VSDs, as well as cables and transformers that have been rigorously tested, designs out the likelihood of any failure.

- **Sustainability**
  Maximizing the output from existing fields is essential to enabling more sustainable hydrocarbon recovery in economic, safe and environmental terms.

6.0 Process for designing and testing a long step-out system

Each subsea pump or compressor requires extensive engineering in order to select the most suitable system. There are many parameters to consider and the delivery must be tailored to the intended application. For a long step-out system, it is necessary to simulate the characteristics of the power umbilical.

Specialist engineers prepare a system concept or front-end engineering and design (FEED) for the electrical system. The following system analyses provide sufficient input for dimensioning equipment:

Steady state and dynamic performance calculations
- Fundamental load-flow of each system component
- Voltage drop within the system in steady state for a defined load condition
- System impedance curve
- Transfer function of motor voltage/converter voltage
- Flux correction factor
- System resonance
- Pulse pattern optimization of the VSD

Start-up calculations
- Calculate boost factor for motor, subsea transformer and step-up transformer for defined breakaway torque
- Verify start current
- Verify that the specified breakaway torque is achieved during start-up

Operational results
- Voltages and currents
- Harmonic analysis of voltages
- Transformer flux at start-up

7.0 Technical challenges faced by long step-out systems

Among the technical challenges faced by a long step-out system are:

- **Distance** between VSD and subsea loads.

- **Frequency** - an increase of frequency raises the cable losses significantly. This influences the physical size of equipment and sensitivity to load variations.

- **Harmonics** - introduce high frequency components. Waveform distortions in currents and voltages are created due to the harmonics. These harmonics can cause problems ranging from telephone transmission interference (electromagnetic compatibility problems) to an increase in power losses and winding temperature in motors and transformers. Consequently, degradation of conductors and insulating material of the components is accelerated.
  - When using an ACS5000 medium voltage drive for the long step-out system, the drive is equipped with a 36-pulse diode rectifier to minimize harmonics. It meets the most stringent requirements for current and voltage harmonic distortion as defined by IEEE, IEC and EN. This eliminates the need for costly harmonics analysis or installation of network filters when applying a new drive.

- **Resonance point** in the electrical system is one of the biggest challenges faced with a long step-out system. These resonance points can be excited by harmonics (multiples of the fundamental sine wave) since the long step-out system is equivalent to an electrical circuit comprising inductors and capacitors. One of the most important aspects is managing and mitigating these resonance points. The importance of avoiding these resonance points is vital to ensure correct system performance. Exciting the resonance points means voltage escalation, torque oscillations and reduced lifetime and system performance. Through mitigation analysis of the converter control system, ABB will optimize the harmonics out of the VSD.
  - For instance, the 7th or 15th harmonic excites the resonance points. By using optimized pulse patterns in the frequency switching strategy, the harmonic content can be shifted from the 15th to the 23rd. This means that, while the total harmonic distortion factor is the same, it is distributed over the frequency spectrum. Therefore, the resonance points are avoided and a good power quality to the subsea motor is provided.

- **Current and voltage at receiving point:** ABB has developed an algorithm that estimates the current and voltage on a subsea motor and allows the machine to be optimized by controlling the output power of the subsea load.
  - As the algorithm is integrated in the control system of the frequency converter, it tunes the voltage modulation of the frequency converter. This algorithm has been rigorously tested in a full scale qualification program.

8.0 Long step-out systems versus subsea power distribution systems

There are two options to deliver electric power (variable voltage and frequency) to subsea multiphase pumping and gas boosting loads for completed wells:

1. Using topside VSD and transfer power through a long subsea cable
2. Utilizing subsea VSDs close to the subsea load

Long step-out systems were originally designed to avoid having advanced equipment, such as VSDs, subsea. While 90 percent of the existing demand for brownfield long step-out solutions is within 40 km, feasibility studies have revealed that systems in excess of 120 km are attainable, albeit considerably more challenging. Once these challenges are overcome, there will be a significant rise in interest for super-sized long step-outs for the reasons outlined already in section 5.

In order to do qualifications for longer distances, ABB has already begun investigating the interconnected complexities relating to:

a. Subsea motor starting conditions
b. Control and protection
c. Breakaway torque
d. Higher required VSD rating power
e. Higher topside feeding voltages
f. Voltage drops along cable
g. Transformer saturation
h. Harmonic resonance points

As an alternative to the long step-out power system, ABB formed a joint industry development program (JIP) in 2013 with Statoil and partners to develop new subsea power solutions which will be able to transmit power (from shore) up to 100 MW over distances up to 600 km and to power equipment at depths of up to 3,000 m. The target is to develop subsea power distribution, meaning all power system components (transformer, switchgear and MV drive) are located subsea. It is anticipated that this solution will be ready for the market by 2019, enabling operators to extract oil and gas in considerably longer and deeper areas than currently achievable. Given the inaccessibility of such environments, life cycles will need to be longer, with lower maintenance and higher reliability over current standards.

ABB foresees that both these solutions (long step-out power systems and subsea power distribution systems) will be utilized by the oil and gas industry and the preferred solution will depend on the field layout, feasibility and cost.

9.0 Successful installations of long step-out systems

Owing to the difficulties inherent within a long step-out power system, there are currrently 40 such installations. While there are several companies providing short step-out drive systems up to 12 km, ABB is the only long step-out system supplier with qualified technology and expertise for step-out distances beyond 40km.

9.1

2006-2009 - Tyrihans oil field – seawater injection pump 31 km tie-back subsea electrical system

Background
One of the first successful long step-out systems is at the Tyrihans oil field, off the coast of Norway. Tyrihans delivers oil and gas by pipeline to the existing Kristin oil and gas platform. Production at the Tyrihans oilfield employs five subsea skids installed 300 m underwater. One skid houses a 2.5 MW, 70 Hz pump motor to inject raw seawater into the oil reservoir, raising pressure in the field to facilitate oil extraction.

Challenge
Statoil needed to inject water into an existing well to get more oil out of the reservoir. Motors and converters are usually in the same room, not separated by 31 km of open sea and a 300 m dive to the seabed.

Solution
For the Kristin platform, ABB supplied specially designed transformers, VSDs and a controller with newly developed software to control subsea motors, and ensure optimal operation of two seawater injection pumps. Figure 9 shows the single line diagram for the project.

The system uses an underwater cable to connect a pump motor on the seabed of the North Sea to a VSD on an oil platform. The distance separating the motor and converter meant extensive dynamic simulations were undertaken to determine how the electrical system would behave. The simulations supplied important input for the design of additional equipment including transformers and control software for the frequency converter.

Benefits
The VSD ensures that the pump motor on the injection skid gets safe, high quality power and stays in peak working order underwater.

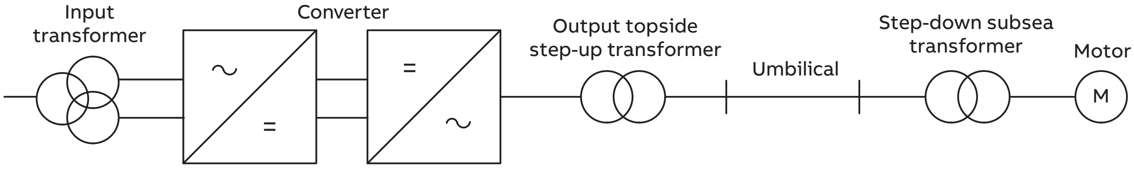

Figure 9. Single line diagram of Tyrihans Subsea Raw SeaWater project. ABB delivered combined topside transformers, subsea transformers and an ACS1000 topside frequency converter. Host platform: Kristin

9.2

2011 - Åsgard subsea gas compression project Long step-out, 2 x 15 MVA, 43 km, 120 Hz

Background

Åsgard is located on the Haltenbanken of Norway at depths of 240-310 m. The Midgard and Mikkel gas reservoirs in the Åsgard field are developed as subsea field installations. The well streams from both fields, located 50 and 70 km away respectively, are sent in the same pipeline to the Åsgard B platform. Analyses showed that, by the end of 2015, the pressure in the reservoirs would have been too low to ensure stable flows and satisfactory production on the Åsgard B platform. Compression was needed to ensure high gas flows and recovery rates.

Challenge

The closer the compression is to the well, the higher the efficiency and production rates become. By carrying out compression on the seabed, improved energy efficiency was attained. A dry gas compressor system is used on Åsgard. Gas and liquids are separated before boosting. The liquid is boosted by a 750 kW pump and the gas by a 11.5 MW compressor. After boosting, gas and liquids are mixed into the same pipeline before transport to Åsgard B.

Solution

ABB was commissioned to provide power to the gas compression system (see Figures 10 and 11). The Åsgard long step-out power system consists of two compressor strings and two pump strings. The overall subsea power system for the compressor string is composed of transmitting 15 MVA of electric power at 34 kV/120 Hz over a subsea cable of 43 km long. This has been a world record for distance, voltage, power and frequency between a drive on a floating production facility and a seabed compressor.

ABB was responsible for system engineering including power system study, design, commissioning, qualification tests and measurement systems. ABB was also responsible for delivery of the topside high voltage power apparatus and the subsea transformers.

Benefits

ABB's long step-out system helps extend the productivity, profitability and lifespan of existing offshore oil and gas fields. In September 2015, Åsgard became the world's first subsea gas compression facility to commence operation. The technology is expected to increase recovery from the Mikkel and Midgard structures by around 280 million barrels of oil equivalent[6].

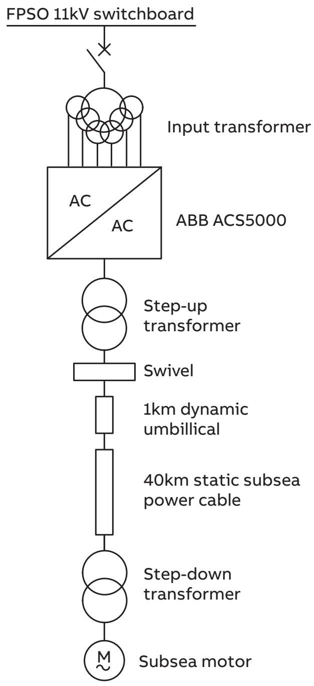

Figure 11. Single line diagram of Åsgard subsea compressor string.

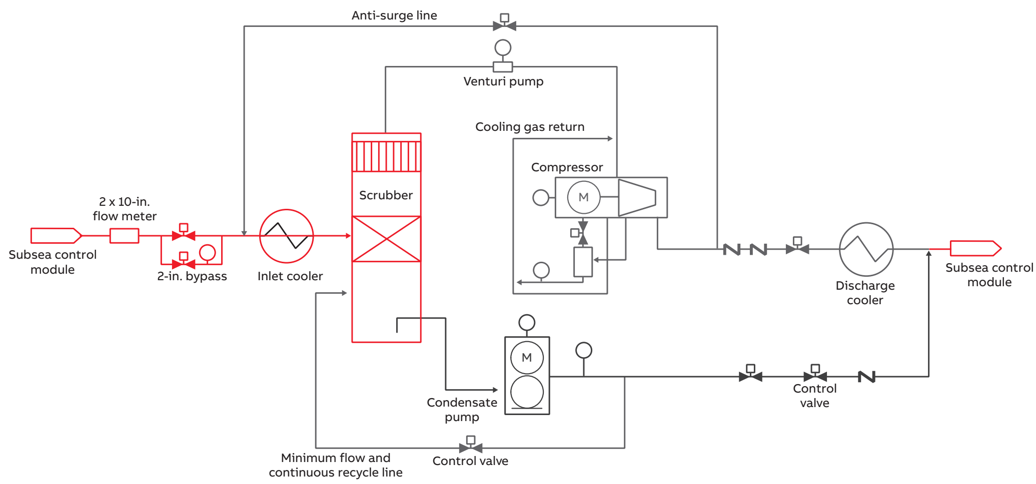

Figure 10. The process flow diagram for a compression train within the Åsgard subsea compression system illustrates the flow of well fluid through a scrubber, the separation of the fluid into gas and liquid streams, and their eventual recombination into a multiphase stream. Source: OTC 27197.

9.3

2012 – Gullfaks WGC Long step-out, 2 x 9 MVA, 15 km, 75 Hz

Background
Statoil installed the first subsea wet gas compressor (WGC) in the world at the Gullfaks C platform in the North Sea. The 420 tons protective structure and compressor station (the 2 x 5 MW compressor and cooling modules, weighing 650 tons) were installed 135 m deep and 15 km from Gullfaks C in early May 2015. This was the first compressor of its kind in the world to maintain gas production, raising pressure in the pipelines and accelerating gas flow to the platform (Figure 12).

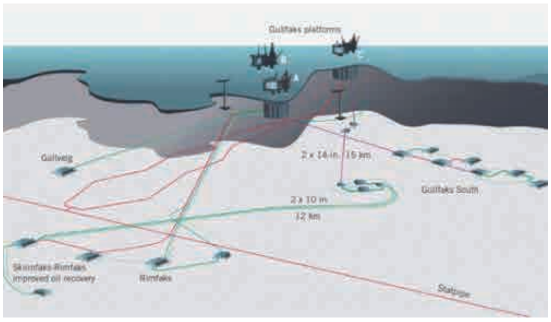

Figure 12. The Gullfaks system provides a multiphase compression model for smaller fields, where simplicity and relatively low-boost pressure drive investment decisions[4].

Challenge
Like with Åsgard, the primary goal with the Gullfaks system was to boost the well stream in order to increase the production rate and ultimate recovery over the remaining life of the field.

To meet the requirements of Statoil's design criteria, the system needed to include two compressors with common section and discharge lines. Each compressor needed its own recirculation line with a choke, allowing the startup and shutdown of one compressor while the other was in operation.

Solution
The VSDs for each compressor are installed on the topside of Gullfaks C, thus limiting the complexity of the installation of each subsea component.

ABB was chosen to provide power to the WGC system. ABB was responsible for long step-out system design including power system study, design and commissioning. The Gullfaks long step-out system delivers electric power to two multiphase compressors (WGC4000) with individual recirculation systems. The overall subsea power system of compressor string is composed to transmit 9 MVA electric power at 23.4 kV/75 H. The compressor station is located at the M and L templates and the tie-back distance is about 15 km.

The final system integration tests were carried out at Horsøy outside Bergen in 2014 before being prepared for installation and hook-up to Gullfaks C. The intention was to verify that all units of the new subsea compressor station work as expected.

Benefits
The Gullfaks technology is a WGC which does not require any treatment of the well stream before compression. This solution results in smaller modules and simpler construction on the seabed. Subsea WGC at Gullfaks C will add 22 million barrels of oil equivalent to the field and extend production by many years. In addition, the platform avoids extra weight and space required by a topside compression module. As such, the gas recovery rate from Gullfaks South Brent may be increased from 62 percent to 74 percent[7].

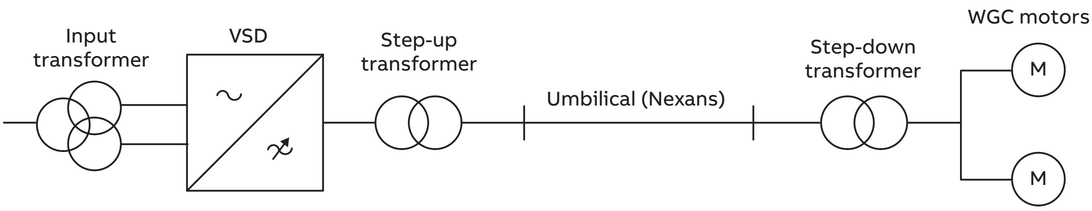

Figure 13. Single line diagram of one the two off Gullfaks WGC train.

9.4

2014 – Moho Nord Long step-out, 2 x 5 MVA, 7 km, 68 Hz

Background

The Moho Bilondo PEX is located off the Congo shore, approximately 75 km from Djéno terminal and 25 km from NKossa field. The production of Phase 1B will be developed via a tie-back to Alima FPU. This includes the addition of a new subsea loop with multi-phase pumps for the production of the alpha reservoirs. Total E&P Congo was the operator of the 3.5 MW subsea pump. It is the first deep water offshore project in Congo at water depths ranging between 650 m and 1,100 m.

ABB is responsible for delivery of the long step-out system. ABB's scope of work included validating the power system design based on confirmed parameters (or tested data) for the Moho equipment including the step-up transformer, VSD, step-down transformer, subsea umbilical high voltage cables and subsea motors. ABB is also responsible for delivery of the topside VSDs and combined transformers and the subsea transformers.

Challenge

Similar to the Gullfaks project, the primary goal is to boost the well stream in order to increase the production rate and ultimate recovery over the remaining life of the field. The water depth of 1000 m is one of the main challenges for design and manufacturing of the subsea transformer and pressure compensators.

Solution

The Moho Nord long step-out system delivers electric power to two multiphase pumps. The principal overview of the long step-out system is presented in Figure 13. It consists of two separate step-out systems (inner and outer system), where the power transmission from topside to subsea is going in two separate three-phase systems in the same subsea high voltage cable. The long step-out system transmitted 5 MVA of electric power at 23.4 kV/68 Hz. ABB utilized a standard ACS1000 MV drive with updated control software.

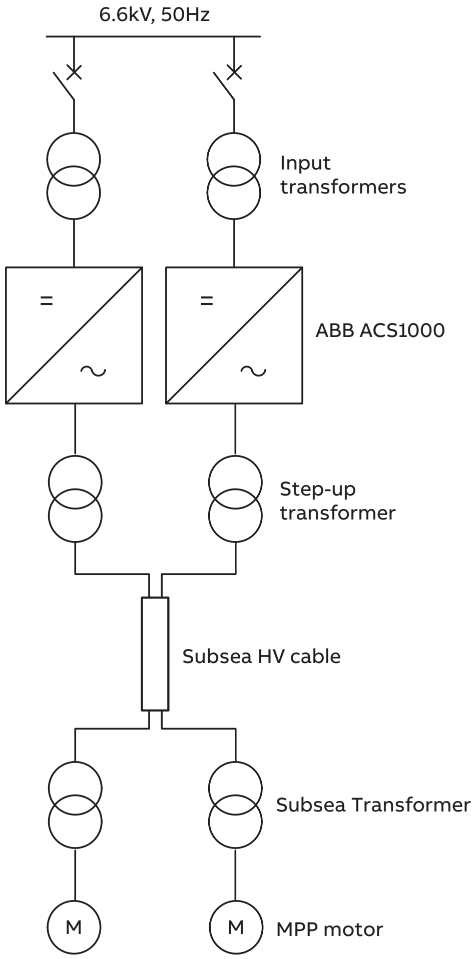

Figure 14. Principal overview of power system drive. Input transformer and step-up transformer are integrated into a combined oil-filled tank.

10.0 Conclusion

Utilizing the long step-out system results in the installation of entire production lines (compressors and pumps) on the seabed. This leads to an increase in the amount of oil and gas that can be recovered from new and existing fields. Compression on the seabed provides benefits compared to a conventional topside compressor, such as others reducing weight and space required for the topside compression module. Additionally, the advantage of a wet gas compression facility is that it does not require any treatment of the well stream before compression and this makes for smaller modules and a simpler construction on the seabed.

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