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Subsea Production Control Systems for All-Electric Xmas Trees

Project Summary

When looking at a time line from the earliest days of offshore oil and gas production developments, present day development projects and field layouts have changed tremendously. Within the offshore oil and gas industry technology industry, there has been a high level of innovation with regards to many aspects. Some of the most radical differences over time have been in the design of surface facility and platforms shown in the diversity of structures illustrated in Figure 1. The idea for this thesis was born out of an interest in systems and their functionality. Through research into offshore and subsea production systems, common goals in research and development projects regarding these systems identified certain trends. Examples of these are

- to increase automation of production systems and controls
- to reduce production system components
- to reduce dependency on external supply of power
- to increase production system response capabilities
- to increase reliability of the production system

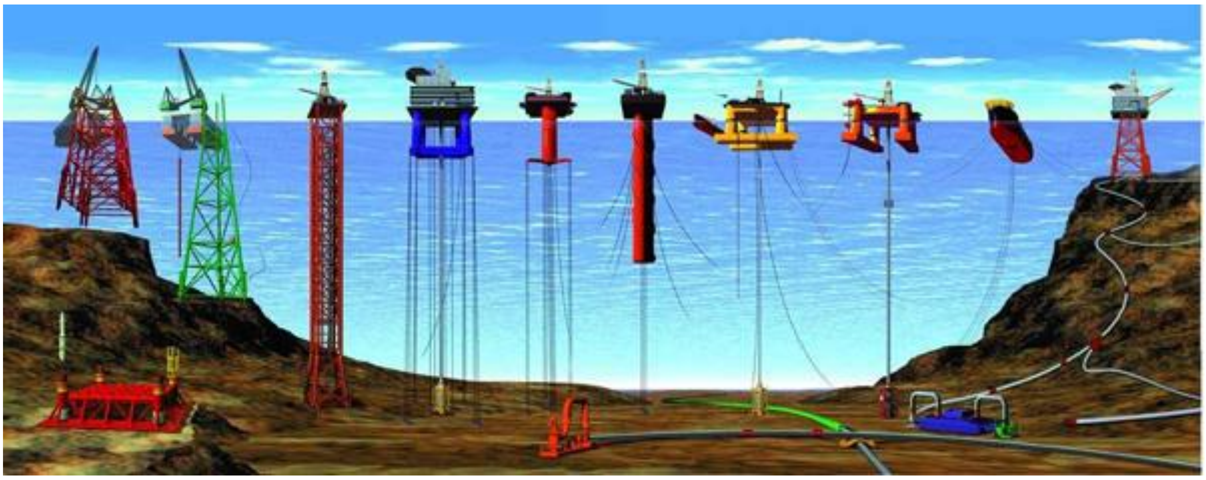

Figure 1: Surface facility designs used in oil & gas production systems (National Oceanographic and Atmospheric Administration, 2012)

With all-electric control systems, an attempt appears to have been made to satisfy the above goals. Electric actuators could enable an overall reduction in system weight and number of components. The implications of increases in water depth and wellhead offset distances could be reduced with respect to network complexity and control capabilities.

Currently, the majority of subsea production systems operate using electro-hydraulic multiplexed power and controls. Increases in hydrostatic pressure and hydraulic transmission distances require increased system complexity due to depth-compensation of hydraulics (accumulators) and control response delays.

This thesis is proposed in order to establish the current state of the art level of all-electric production control systems, address their weaknesses and influencing factors and suggest system improvements.

Contents

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Abbreviations

AC	Alternating Current
AET	All-Electric Tree
AMV	Annulus Master Valve
ASV	Annulus Service Valve
API	American Petroleum Institute
DC	Direct Current
DCV	Directional Control Valve
E-H	Electro-Hydraulic
EPU	Electric Power Unit
ESCCSV	Electric Surface Controlled Safety Valve
ESCM	Electric Subsea Control Module
HCR	High Collapse Resistant
HIPPS	High Integrity Pressure Protection System
HPU	Hydraulic Power Unit
HXT	Horizontal Xmas Tree
IMR	Intervention, Maintenance and Repair
ISO	International Organization for Standardization
LCC	Life Cycle Cost
MCS	Master Control Station
MCU	Master Control Unit
MUX	Multiplexed
NCS	Norwegian Continental Shelf
OCC	Open-Communications Controller
PIV	Production Injection Valve
PMV	Production Master Valve
PSV	Production Service Valve
PT	Pressure Transducer
RAMS	Reliability, Availability, Maintainability, Serviceability
RVA	Reliability Value Analysis
SCM	Subsea Control Module
SCSSV	Surface Controlled Subsurface Safety Valve
SEM	Subsea Electronics Module
SPS	Subsea Production System
TT	Temperature Transducer
TUTU	Topside Umbilical Termination Unit
SUT	Subsea Umbilical Termination
UKCS	United Kingdom Continental Shelf
UPS	Uninterrupted Power Supply
VXT	Vertical Xmas Tree
XT	Xmas tree

Symbols

A_V	Pressure action area
A_P	Actuator piston area
A_{OS}	Override stem area
A_{VS}	Valve stem area
C_S	Spring constant
D	Diameter
F_{CO}	Net force requirement for valve to crack open with full bore pressure at surface
F_{DR}	Dynamic friction force
F_{PB}	Bore pressure force
F_{PC}	Cavity pressure force
F_{SR}	Static friction force
F_V	Valve force
L	Length
P	Power
p_{PC}	Cavity pressure on actuator stem
S_P	Spring preload (closed valve)
S_{PR}	Seal packing friction
T	Torque

1 Introduction

Subsea all-electric actuators and subsea all-electric control systems have been under development for many years, both within the technological research environment (Jernström, et al., 1993) and within the subsea technology supplier industry (Cameron, Kongsberg, FMC Technologies, Aker Solutions, Parker et cetera).

The evolution in offshore electric and electronic control system technologies made oil and gas field development models significantly different in comparison to no more than thirty years ago. The development of electro-hydraulic controls throughout the seventies and eighties and subsequent system design refinements has led to decreases in required wellhead system and subsea field infrastructure weights and sizes. The more recent developments in all-electric controls technology over the nineties and the last decade have brought even further benefits in respect to system weights and sizes.

With regard to subsea production control systems for All-electric Xmas trees, this thesis aims to

- establish the current state of the art of control systems for all-electric subsea x-mas tree systems
- address technical limitations with respect to water depth and wellhead offset distances
- identify system weak spots and influencing factors

1.1 State of the art level of subsea control systems for all-electric subsea Xmas tree systems

A description of the current state of the art level of subsea control systems for all-electric Xmas tree systems requires a thorough reading and literature research. There are several academic articles published that have covered to varying degrees the control systems for subsea all-electric Xmas trees. These have been used to the extent possible to describe the development process.

Offshore oil service providers and industry suppliers have been contacted to obtain documentation of available systems. Several of the industry technology suppliers have made available all-electric control systems that are used for subsea applications.

1.2 Technological limitations with respect to water depth and wellhead offset distance

Water depth and wellhead offset distances from surface facilities will influence a field development. Control systems that depend on hydraulic power have an increase in depth-compensating equipment required for power delivery at increased water depths. With satellite developments and wellheads that have large single step-out distances from surface facility, valve control delays can become significant.

The hydraulic power distribution system has redundancy requirements which can increase the weight of the umbilical supply lines significantly. Additional chemical injection lines can drive the total umbilical weights even further up. According to Søgård, hydraulic umbilicals can handle a maximum step-out range of approximately 200 kilometres with the use of local capacitors (Søgård, 2008). These capacitors represent installation and intervention, maintenance and repair (IMR) costs that would not be part of an all-electric system.

There are several issues that have been identified with respect to electrical systems as well. Electrical systems will be influenced by:

- Control and sensor signals degradation due to amplitude dampening
- Power supply voltage drop which becomes greater along with increased step-out distances
- Durability of chemical injection supply solutions and the redundancy options available
- Failsafe solutions with respect to possible control system electrical power loss

1.3 Identification of weak spots

With the development of the new electric control system technologies, focus has been on risk management and on improvement of reliability, availability, maintainability and safety of subsea production systems. The weak spots shall be identified by literature review and theoretical calculations to ascertain the potential issues that are present in all-electric technologies.

2 Traditional production control systems

The subsea industry was born in the early 1960s. Cooper Cameron was the company that designed and installed the first subsea XT in the Gulf of Mexico (GoM) in 1961. This means that the industry is now 52 years old. In this space of time, the offshore oil and gas exploration and production industry has had to evolve. In the early period of subsea systems development, control system technology was transferred from the aerospace supplier industry.

The aerospace industry would become the primary supplier of control system technologies to the early subsea technology industry. Direct hydraulic and sequenced hydraulic control systems used in in aircraft system designs were redesigned to establish subsea control systems. The trend to use aerospace industry parts continued for several decades, and created subsea systems that had a high capital cost.

First use in industry	Flight Control Systems	Subsea Control Systems
	Mechanical	
	Hydro-mechanical	
1961		Direct Hydraulic
1964	Fly-By-Wire(Apollo LLRV*)	
		Electro-Hydraulic
2008		All-Electric(Total, K5F)

Table 1: In Table 1 a comparison of flight control and subsea production control system technologies are listed for comparison of times of industry implementation. *LLRV=Lunar Landing Research Vehicle utilised a pure electronic control system without hydraulic back-up systems.

By the time of the mid-1980s, the subsea control system suppliers had markedly changed their component suppliers from the aerospace to the information technology industry, which could offer less expensive components with equal reliability, availability, maintainability and serviceability (RAMS). There had also been significant gains in knowledge within the subsea control system supplier companies enabling more independent industry technology development.

The link between aerospace and subsea controls technologies can still be seen, as the main developments in aerospace controls appear in subsea controls afterwards.

With increased water depths, traditional field development models that used fixed platform types such as fixed leg steel platform or concrete gravity structures become impractical in many cases with respect to capital expenditure and flexibility of further field development. A gradual change in facility structural design philosophy has gone from alterations in fixed platform design such as compliant towers to semisubmersible vessels (SSVs), tension leg platforms (TLPs) and SPAR platform designs to ship shape floating production and storage structures (FPSOs).

At the same time as the surface facility designs have developed beyond simple fixed leg platforms, more and more components of the production systems have in the last two decades been shifted towards the seabed. At the production extraction point, the wellheads have gone through a very rapid development in respect to reliability and availability. The serviceability and maintainability has been improved rapidly as well.

2.1 Subsea Xmas trees

The subsea Xmas tree (XT) is located on the wellhead. It is composed of a set of valves that are used to manipulate and control the flow of product, injection of chemicals and water or gas from a well. A XT has several functional requirements. The primary function of it is to act as a barrier between the reservoir and the environment. Other main functions include the accommodation of various systems and measures that enable safe well production. The injection system, production control system, down-hole control system and monitoring systems as well flow control technologies are all utilised through XT valve connections. The following set of functional requirements is commonly defined for subsea XTs:

- Allow for well intervention
- Control hydrocarbon production
- Act as a barrier between the marine environment and reservoir
- Act as a barrier for the produced and injected fluids
- Facilitate down-hole valve control
- Facilitate down-hole gauge electrical signals transfer
- Facilitate chemical injection to the well or flow line
- Provide access for well intervention and work-over operations

A XT will have to be designed for the individual reservoir conditions and for the possible facility solutions available. This means that the size and configuration of a XT will not be the same from one offshore field to another. However, there is a strong trend toward smaller, more compact XTs in general.

There are two primary XT design configurations, namely the vertical XT (VXT) or conventional XT and the horizontal XT (HXT). There are also several intermediary XT design categories in use. The most significant differences of the HXT and the VXT within a well production and maintenance context will be described in the following paragraphs. Many differences in XT designs are due to valve locations and control system connections to valves. The well pressure and temperature dependent piping connections and gaskets options chosen for various designs also play a role.

Typical valves found in a XT system are SCSSVs, production master valve, production wing valve, annulus master valve, annulus wing valve, crossover (injection valve), methanol/chemical injection valve, scale inhibitor injection valve, corrosion-inhibitor injection valve, production choke valve, injection choke valve, manifold valve and chemical-injection control valve. Master valves and wing valves employed on XTs are typically gate valve, although in some cases they can be designed as ball valves. The loading on gate valves in different operational states (open from fully closed, open from partially closed, close from partially open, close from fully open) determines the powering requirement of the individual valve. A calculation of the worst case loading for a gate valve will be followed by a calculation of powering requirement using relevant standards.

2.1.1 Vertical subsea Xmas trees

The earliest and most extensively used type of subsea XT in the world at the present is the vertical Xmas tree. It is also referred to as a conventional XT. Another type of vertical XT can also be referred to as a dual bore XT. The location of the production and annulus line valves in the vertical plane is what identifies a VXT system. In vertical XTs, the production and annulus master valves, abbreviated to PMV and AMV respectively, are located in the vertical plane above the wellhead-XT connector. The tubing hanger is laid down before the XT structure. This has an impact on the capacity for work-over operations that can be conducted with the Xmas tree still in-place. The production and annulus wing valves (PWV and AWV respectively) are located after the point at which the production and annulus lines cross into the horizontal plane. Production and annulus swab valves that allow for well work-over and intervention are included in the system through a T-joint located in between the master and wing valves of the Xmas tree production and annulus lines.

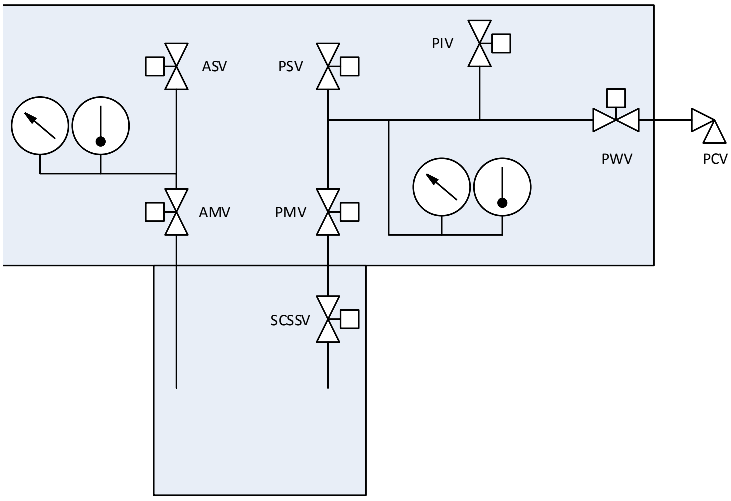


Figure 2: VXT main production and annulus line valve arrangement

VXTs have been used in oil and gas industry, first as dry trees where they are located on the derrick deck, then as wet trees where they are located on top of the wellhead. Today XT suppliers offer standardised XT modules with standardised connectors to their subsea control modules (SCM) or flow control modules (FCM).

2.1.2 Subsea horizontal Xmas trees

Subsea HXTs are easily distinguished from the subsea VXTs by observing that the production and annulus master valves are located on the side of the tubing hanger. On a VXT the tubing hanger is located below the master valves. The main benefit of this is easier access for well intervention or well work-over operations since removal of the tubing hanger does not necessarily have to require removal of the XT. There are also areas where offshore oil and gas extraction compete with other more traditional industries such as fisheries, shipping and fish or shellfish farming. The risks of accidents and incidents due to collision impacts or pulling and snagging events have been considered large enough in consequence to cause the development of protective structures. For these regions, HXTs have been considered more suitable, as the tree pipeline connections are in the horizontal plane and are less tall than VXTs.

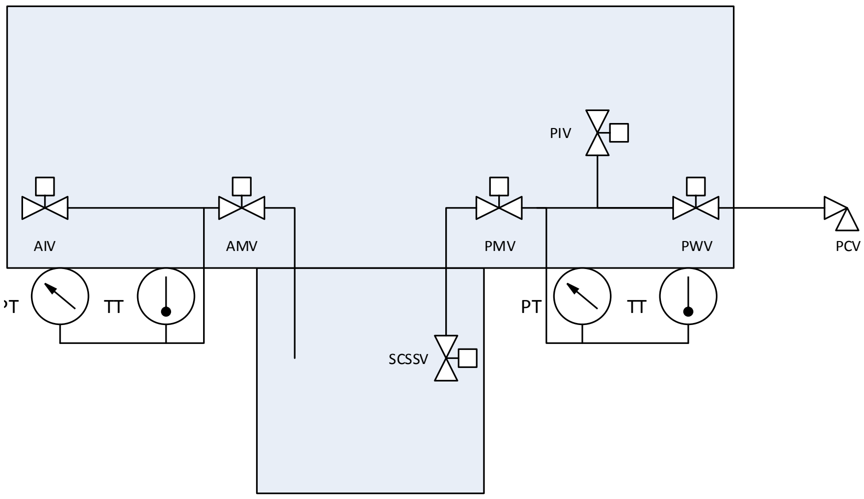


Figure 3: VXT main production and annulus line valve arrangement

With farther distances from existing infrastructure to potential fields, the development models need to take into account that hydraulic actuation methods for subsea control systems will take longer to respond to control commands. Therefore the requirements for more rapid control system technologies have risen. The latest trend is to develop all-electric control systems. Marginal field development models require small capital expenditure with minimal operational maintenance and minimal lost or deferred production.

In established offshore oil and gas production regions such as GoM, the Persian Gulf and the North Sea, there is a significant level of subsea infrastructure present. Both in the form of pipelines and umbilical lines that offer many tie-back options as well as increasing the flexibility of field developments. In regions where offshore oil and gas production has not been present for as long, the amount of and nature of the subsea infrastructure present varies. It is not uncommon for companies considering new or satellite field developments to connect these to existing networks so capital expenditures (CAPEX) are reduced.

2.2 Introduction to production control systems

The production control system is responsible for valve control and monitoring of the XT production parameters through feedback from sensors located at all relevant positions within the production system. Typical parameters that are measured using the XT production control system sensors are production pressure, choke downstream pressure, annulus pressure, manifold pressure, production temperature, manifold temperature, hydrocarbon leak detection, tree valve position (direct or inferred), production choke position, production choke differential pressure, sand detection, down-hole monitoring, multiphase flow, corrosion monitoring and pig detection.

According ISO 13628-6, the functional requirements of the subsea production control system are:

- Provide for individual or multiple operation of all remotely controlled subsea valves;
- Provide sufficient data feedback information to operate the system safely and to react promptly to conditions requiring production shutdowns (PSDs);
- Provide emergency shutdown (ESD) capability that ensures the subsea system will shut-down production safely within the time specified by ISO 13628-6 (2006) or by applicable

regulatory authorities for all production scenarios, including simultaneous drilling, completion and work-over operations.

The control system equipment that is used on fields where the wellheads have subsea XTs is divided into two parts: topside and subsea. A simplified breakdown of where the production system equipment is located in the two parts has been described in Figure 4.

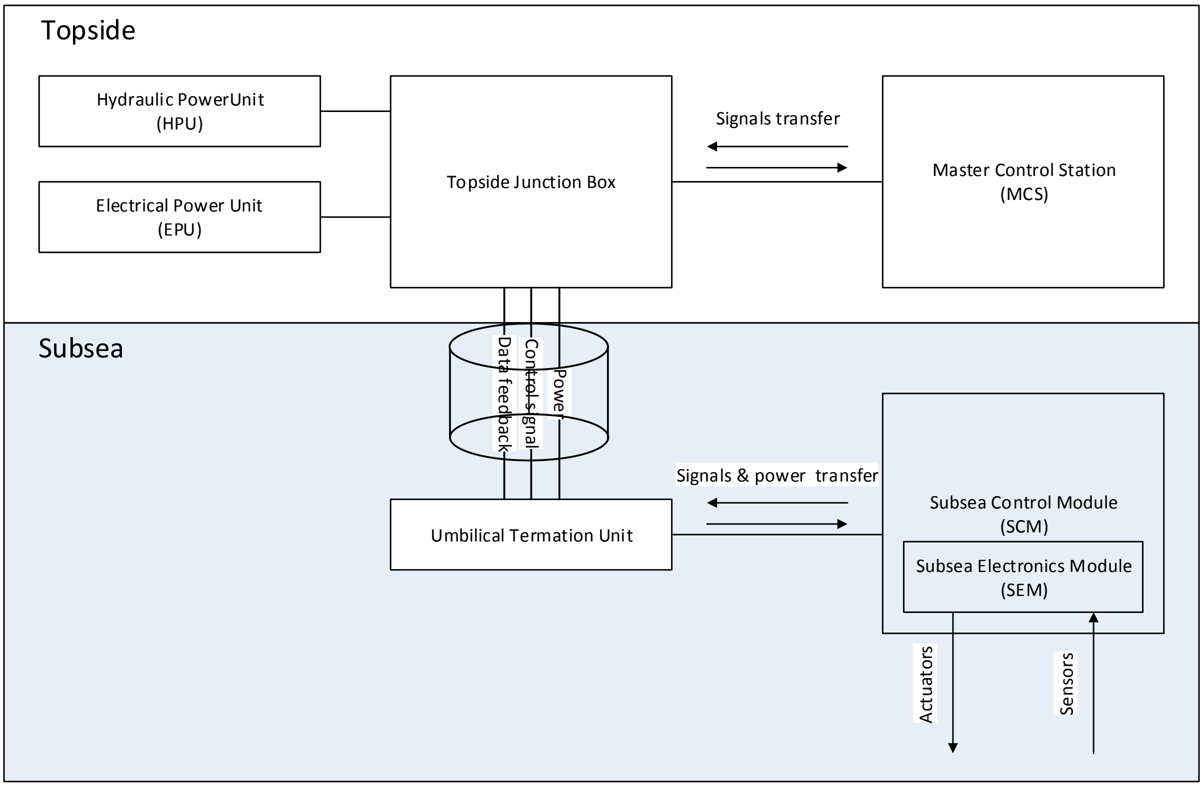


Figure 4: Breakdown of control system topside and subsea equipment

The overview from Figure 4: Breakdown of control system topside and subsea equipment has neglected many of the components in the subsea production control system. The complete subsea production control system will consist of many more systems and subsystems that are necessary in order to fulfil the functional requirements in a safe and satisfactory manner. A description of the common set of control system components encountered in industry is given in the following sections. Several of the components are encountered in both topside and subsea system components, but will appear as either topside or subsea equipment category equipment.

2.3 Hydraulic Control Systems

A hydraulic system functions on the principle of transmission of energy through fluid flow and fluid pressure. The flows and pressures of working fluids are generated using hydraulic pumps. The generated flows and pressures of working fluids will then be convertible to torque and displacement by use of a hydraulic motor. A simple schematic can be used to describe this principle.

The following components are required to establish a hydraulic system:

- A hydraulic actuator or pump
- A hydraulic motor

- A motor-actuator connection

The various types of pumps commonly encountered in offshore production systems are categorised as either centrifugal (fixed displacement) pumps or positive (variable) displacement pumps. The working principle of centrifugal pumps is to transfer kinetic energy to the liquid medium in the system through axial, radial or semi-axial motion of impellers mounted on a shaft. The working principle of positive displacement pumps is to move the liquid medium in the system through mechanical means.

Hydraulic pump or motor components used in fluid power systems will commonly be positive displacement or hydrostatic units. The most common positive displacement units are gear, vane and piston type pumps and motors. Gear type pumps and motors are classed as either external gear or internal gear type. External gear units are characterised by simplicity, low cost, good suction performance, low contamination sensitivity and relatively low weight. Internal gear units are similar in pressure capabilities to the external gear type pump or motor, and offer a decreased operating noise level.

A hydraulic system will require a power source to drive the hydraulic pump that supplies the hydraulic motor with a pressurised working fluid flow. Examples of power sources are electrical power generators, internal combustion engines and external combustion engines such as steam engines, steam turbines, wind turbines or water turbines.

Subsea hydraulic system power sources are typically located on board a host facility that has multiple functions vital for field operations. This facility is typically located topsides, and will be either a fixed or floating platform. The hydraulic power source is called the Hydraulic Power Unit (HPU), and the signal lines that provide subsea field feedback data and control feed to the subsea system is called the master control station (MCS) or master control unit (MCU). Subsea production system chemical injection hydraulic power units will also commonly be located topsides.

2.3.1 Direct Hydraulic Systems

This is the earliest and simplest hydraulic system. The direct hydraulic system have the controls divided into individual hydraulic lines connected to

- pressure sensors
- valve actuators or
- Other subsea functions.

This system requires a dedicated hydraulic line for each function and will quickly become very large in terms of umbilical size and weight. Therefore it can be said to be limited by field subsea system size. It is also limited by distance and water depth without the use of accumulators for hydraulic pressure boosting and safeguard measures. The accumulators will have to be integrated either for each dedicated hydraulic line or through more complex multi-pipe connections to the entire hydraulic umbilical network for leaner system design. This option limits the redundancy of the direct hydraulic system for larger subsea production system in comparison with alternative hydraulic, electro-hydraulic or all-electric control systems.

2.3.2 Piloted Hydraulic Systems

Piloted systems include a subsea control module that contains an arrangement of pilot valves that are actuated using local hydraulic accumulator tanks. The accumulator tanks receive hydraulic power from the HPU. The hydraulic signals from the master control station are used to activate the pilot valves that are used as pressure switches. These can be arranged in a series assembly to decrease the amount of piping involved for controls, with redundant supply lines for increased system reliability. This creates a lighter umbilical and less complex piping arrangement than the direct hydraulic systems.

2.3.3 Electro-Hydraulic Control Systems

In an electro-hydraulic system, an electric motor with a local reservoir is used instead of a hydraulic pump to act as a driver. This creates the hydraulic force which enables a hydraulic motor to perform as an actuator. A simple schematic can be used to illustrate this principle. This system eliminates the hydraulic connection requirement of the pure hydraulic system, reducing the weight and the possible sources of hydraulic leaks in the system.

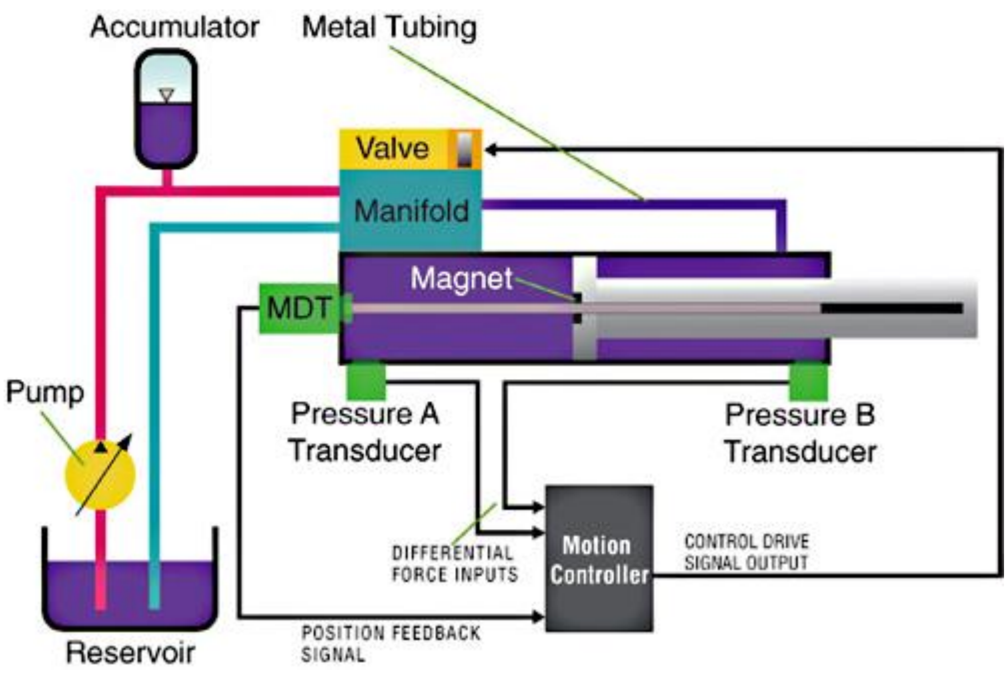


Figure 5: Electro-hydraulic valve control (Nachtwey, Peter; Delta Computer Systems Inc., 2010)

2.4 Topside equipment

2.4.1 Electrical power unit

A subsea E-H production and control system generates hydraulic and electric power that delivers a supply for electric monitoring and control equipment and other electric systems within the subsea production system. Hydraulic power is supplied from a hydraulic power unit (HPU) whilst electric power is supplied from an electric power unit (EPU). Common electrical power generators use electric or diesel engines mounted on skid supports which facilitate simplified handling and installation for transportation and installation on offshore facilities.

Suppliers of EPU and HPU technology for the offshore oil and gas industry include Aker Solutions, Caterpillar, MAN B&W, National Oilwell Varco (Electric brushless synchronous generator sets), Olympian, Wärtsilä (SSV and FPSO Market), Weatherford (Diesel engine generator sets and electric generator sets).

With reference to Figure 4: Breakdown of control system topside and subsea equipment on page 7, the electrical and hydraulic power generation for subsea systems is shown to be generated topside on a platform type facility. This is the most common arrangement at present. There is also a possibility for electrical power generation onshore with umbilical supply to the topside facility. One such solution is currently under development by Total E&P Norway to be employed at the field previously called Hild, now Martin Linge field. Other development models may have electrical power generation subsea with or without redundant surface facility. In the latter case, electricity is generated through the use of seawater batteries or thermoelectric couplers.

2.4.2 Hydraulic power unit

The typical present subsea production systems operate using some category of hydraulic production control system either direct/piloted/sequenced piloted or E-H-MUX. The working principles of the various hydraulic system designs will be described briefly later in this chapter. All hydraulic system will require a generator of hydraulic power however. The hydraulic power unit (HPU) is a generator assembly that creates hydraulic power, usually by means of a constant velocity electric motor which is powered by the platform EPUs. Electrical motors are used as HPUs. Both fixed speed and variable speed AC electric motors are available. The power generated is used to perform control functions throughout the production system by the use of hydraulic pipes and tubes. It is used to actuate valves directly and activate other hydraulic control functions using pilot valves. They can also be automated to activate valves in conjunction with electrical and electronic equipment.

2.4.3 Accumulators

The HPU is required to deliver hydraulic power to the rest of the control system during normal operation of the control system. The hydraulic accumulators that are located topside have to operate in conjunction with the HPU in order to deliver the required hydraulic power to the control lines. There are several foreseeable events that may occur that cause a reduced function, irregular production of pressure or even shutdown of the HPU system hydraulic pumps. In the case of such events, the topside accumulators are required to boost, compensate or enable safe shutdown of the rest of the control system. This is done by delivering stored hydraulic power, a safeguard against more severe consequences to events that could potentially occur to the Hydraulic power system.

Some of the hydraulic energy that is created by the HPU is stored in accumulators. This enables a supply of hydraulic energy In case of a drop in pressure of the hydraulic control lines. It is also used to boost the flow and increase the pressure of the hydraulic control lines with the intention of creating rapid response controls.

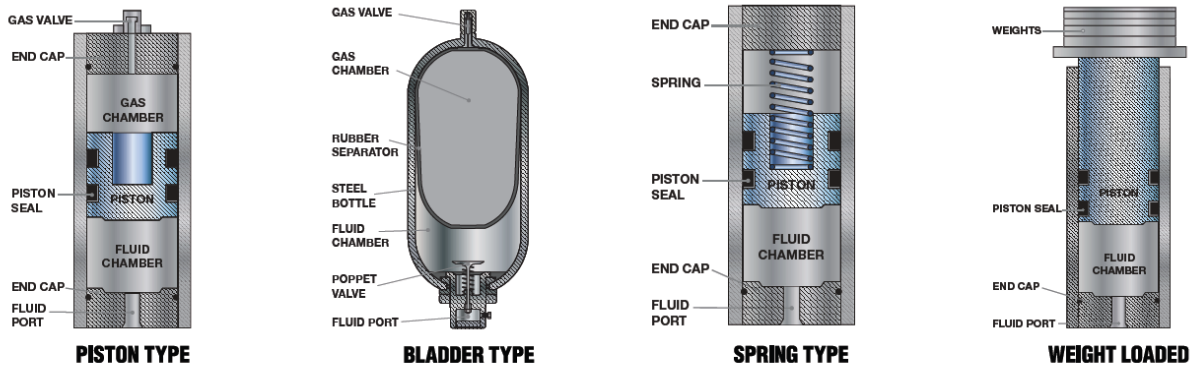


Figure 6: Overview of common hydraulic accumulator type designs (Source: Tobul Accumulator Inc.)

There are four types of accumulators in use topside. These are the bladder, weight loaded, piston and spring type. There are several differences in the design and the operational capabilities of these designs, as can be seen in Table 2.

Accumulator type	Bladder	Weight loaded	Spring loaded	Piston
Application with respect to pressure	High pressure	High pressure	High pressure or low pressure	High pressure

Table 2: Description of accumulator characteristics by type (Source: Tobul Accumulator Inc.)

The hydraulic accumulator type is selected based on a series of parameters, such as application, flow rate, maximum operating temperature, maximum and minimum pressures and fluid compatibility. Chemical coatings are widely used to ensure fluid compatibility. In addition, some metal alloys have been developed that are particularly well suited for common hydraulic fluid handling.

2.4.4 Master control station

The master control station (MCS) is where the main human – machine interface (HMI) of the production control system is located. In many production systems, additional remote work stations can be connected to the production controls using satellite communications systems. The MCS is composed of a range of electrical and electronic devices, such as

- Industrial computer servers that are used to run all the production control system applications topside and subsea.
- Communication protocols which are used for communication with topsides production system equipment and subsea production system.
- A logic controller to allow monitoring of the EPU functions and the ESD system.

A modem unit establishes the connection between the MCS and the subsea production system (SPS). The modem unit receives all data feedback from the entire range of sensors and sensor systems distributed throughout the production system network. These data are subsequently transferred to the designated MCS server for data acquisition, logging and storage. Real-time system data is also relayed to designated human-machine interfaces at the MCS to enable monitoring of production.

2.4.5 Uninterruptible power supply

The uninterruptible power supply (UPS) system is a safeguard against immediate loss of power supply. The UPS is an arrangement of equipment consisting of

- A battery bank that supplies the system with electricity.
- An inverter that transforms the incoming direct current (DC) from the UPS battery bank into alternating current (AC).
- A rectifier that adjusts the phase angle of the alternating current passing through the system. This is important in order to arrange the correct form and wave frequency of the voltage (and RMS) of the exiting alternating current.
- An electrical distribution panel that allocates electrical supply to connected systems and equipment that are affected by electrical power loss.
- Serial and/or Ethernet communications protocol(s) that offers the possibility of remote monitoring, diagnostic and shutdown of the UPS system.

The equipment is all placed inside boxes or cabinets that protect them against possible situations that may affect the functional or operational capacity of the UPS system. Typically they will be located topside in the case of a loss in power from the EPU. The size of the battery bank(s) is designed for the individual field production system. The communications protocol can be of either open source or of a proprietary origin.

2.4.6 Chemical injection unit

To ensure a more safe and reliable production from hydrocarbon reservoirs, chemicals need to be injected. This is because the unprocessed well-stream fluid commonly contains varied proportions of potentially hazardous substances. It is common for offshore production systems to include injection to prevent the formation or onset of undesired phenomena that will inhibit or reduce operability of the production system. The chemicals prevent the following processes: Corrosion, erosion, precipitation, fouling, scale, wax or emulsion. A range of chemicals are injected to target and mitigate these potentially expensive and hazardous bi-products.

The chemical injection unit (CIU) system consists of chemical injection pumps, reservoirs that store the chemicals that are used. It is connected to control and monitoring systems that enable control and monitoring possibilities from a HMI at the MCS. The well stream is analysed using flow metering devices that will show flow conditions subsea. Analyses topside are used to determine injection requirements. Substances are typically stored in reservoirs on-board a field surface facility. From there they are pumped through umbilical lines to the various wells subsea (Carstensen, 2012).

2.4.7 Topside junction box and umbilical termination unit

The electric and hydraulic power generated topsides, along with control signals are transmitted to the subsea network after joining up at the topside junction box and passing through the umbilical termination unit (TUTU). The TUTU connects the platform equipment with the riser solution that supplies and receives data and power to and from the subsea network of the production system.

2.5 Subsea equipment

2.5.1 Subsea Hydraulic Systems

A typical present-day subsea system infrastructure will use an electro-hydraulic multiplexed (EH-MUX) umbilical to provide subsea system management. This type of umbilical contains an alternating electrical current (AC) line to power the subsea electric equipment, a hydraulic line that supplies hydraulic pressure to the subsea hydraulic equipment and a signal line that is used to accurately and correctly manage the subsea system. The requirements and recommendations for design, fabrication, storage, transport and installation of umbilical lines are specified by ISO standard 13628 part 5. Selection of construction material for the umbilical insulations or internal components are either specified or references are made to the sources which are relevant.

The electric power source for the umbilical is called the Electrical Power Unit (EPU). The hydraulic power source is called the Hydraulic Power Unit (HPU). The signal line terminus is at the Master Control Unit (MCU) or Master Control Station (MCS). The MCU, HPU and EPU will typically all be located at a surface facility.

Typical E-H umbilical line designs are made from duplex and other steel types which can be designed both for E-H and pure hydraulic umbilical lines. Another E-H umbilical design material range is thermoplastic and High Collapse Resistant (HCR) hose for including deep water chemical injection lines. Integrated subsea power and control umbilical lines solutions are usually tailor-made for any individual development. Relevant system requirements for hydraulics, electric power supply and signal are considered with respect to ambient conditions such as terrain, offset distances and water-depths in question.

2.5.2 Hydraulic or injection fluid supply line

The umbilical line typically facilitates delivery of hydraulic pressure, electrical power and injection fluids. Examples of service line flow media are given in the description of chemical injection units in the previous section of this paper. Subsea umbilical lines will typically include several hydraulic service lines that supply chemicals that aid field production. The specified construction material for the hydraulic tubing in subsea umbilical lines is austenitic stainless steel, specifically A269-08 grade 316 (NORSOK M-630). It also facilitates a conduit for transfer of control and sensor signals between the subsea Xmas tree and the surface facility HMI located at the MCS.

In the subsea system, the common types of accumulators are bladder and piston type accumulators. I refer to Table 2: Description of accumulator characteristics by type for a description of these. The bladder and piston type accumulators have high pressure capacity, they are flexible in design with regards to flow rate, and they can perform better when submerged and influenced by water depths. In the last decade, several new patents have been filed and new types of depth compensated accumulators have been taken into use, notably in BOP control systems. These accumulators also have application in production control systems, enabling rapid response controls.

2.5.3 Subsea electrical systems

2.5.4 Electrical power distribution

The electrical conductor component of the umbilical line is typically composed of copper wire. Electrical and signal components of the umbilical line are covered by section 7.2 of ISO 13628-5. For electrical power conductors, a high conductivity copper wire fabricated from annealed circular copper wire is specified. Coaxial copper cables have a good electromagnetic compatibility with respect to multiple conductor umbilical arrangements compared with twisted pair copper wire. This is because it forms a dielectric with only an interior electro-magnetic field, with much reduced exterior electric and magnetic field discharges.

2.5.5 Signals transfer and data acquisition

For signal cables several conductor construction materials exist. Examples are twisted pair copper wire, coaxial copper cable and fibre-optic cable. A coaxial cable represents a robust and reliable for both signal on power and separate signal and power component umbilical line designs. The coaxial cable structure is such that electromagnetic interference to signals is reduced in comparison to twisted pair copper wire.

For further reduction in signal interference and enhanced data transfer capacity, fibre optic cables that are constructed from glass tubes isolated inside a polymer fibre insulation tubing represent the present state-of-the-art data communications cable.

For some applications, the conductor cable has a dual purpose in delivery of electrical power and transport of signals. This type is designated as a “signal on power” cable. For this type of cable the common conductor/signal cable construction material of choice is coaxial copper cable.

The typical insulation materials for copper power and signal cables that are installed with subsea power and signal transfer umbilicals are polymer based compounds, such as high-density poly-ethylene. These have the capacity to efficiently insulate even large power transmission cables without experiencing more than negligible electrical field discharges. A theoretical calculation showing this is given in Chapter 4.

For long distance power and signals umbilicals a separation of power and signals components using coaxial cables for power supply and fibre-optic cables for signals transfer and data acquisition can be used.

2.5.6 Subsea Control Module (SCM)

The subsea control module (SCM) is an assembly of systems that are tasked with well production management at the wellhead location on the sea bed. The vast majority of current subsea control modules in operation are operated using E-H systems supplied using multiplexed E-H umbilical lines supplying both electric and hydraulic power typically from an offshore surface facility.

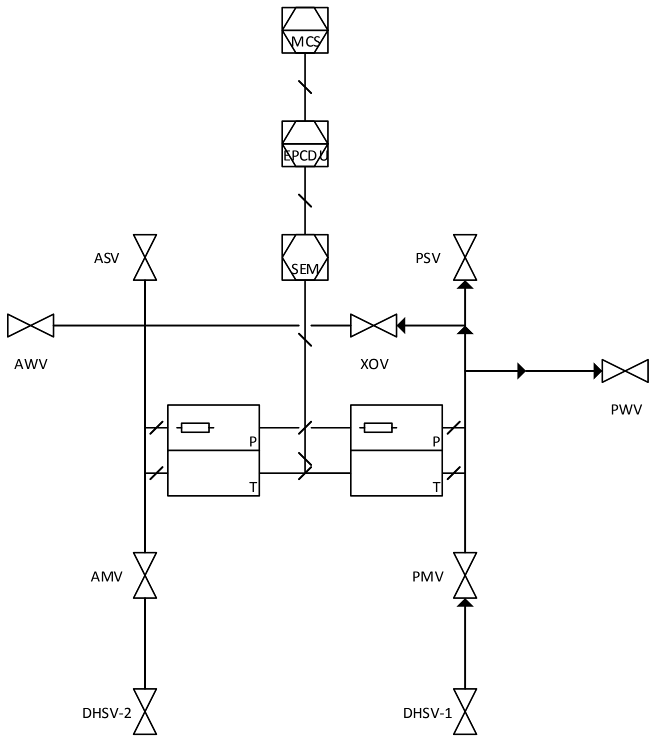


Figure 7: Diagram showing the Xmas tree sensor signal transfer route

3 All-electric subsea production control systems

3.1 Introduction

All-electric production control systems will be distinguished from hydraulic and electro-hydraulic production control systems by the system prime mover working principle. The prime movers and the control and power umbilical lines deliver electrical power throughout the production system. Separate signal cables or integrated signal on power cables transfer system data and control commands back and forth from the field systems to the surface facility HMI at the MCS. The hydraulic power supply unit and pipes are replaced by electrical cables. The production systems also require injection lines to supply chemicals as described in the previous chapter concerning traditional production control systems, so some hydraulic units and supply lines will still be required in the system.

The actuators in the production control system will be driven by electrical motors, so the type and design of the electrical motors are important. Electric motors transfer electrical energy into mechanical energy. There are several electrical driver options available. The differences are in the working principle used to create mechanical energy. The following three working principles on which electrical motors function are magnetic, electrostatic and piezoelectric.

The majority of electrical motors in use at present utilize magnetic interaction to establish mechanical motion due to electromagnetic energy. They are composed of a stator, rotor and some sort of commutation, for example by means of slip rings. These three components are assembled in a manner as to utilize the repulsion and attraction properties of magnetic interaction to establish a mechanical motion. Both alternating current (AC) and direct current (DC) motors include the mentioned three components. They each contribute to the definition of a DC motor, which is an assembly of;

- an armature circuit that carries the load current
- a field circuit that produces a magnetic field to establish the electromagnetic induction
- a commutation technique

DC motors can be split into different assemblies that in different manners utilize the desired properties of electromagnetic force. A selection of different types of DC machines that can be used in connection with subsea production control valve actuators will be described in chapter four. First a description of the loading conditions in a subsea gate valve needs to be obtained.

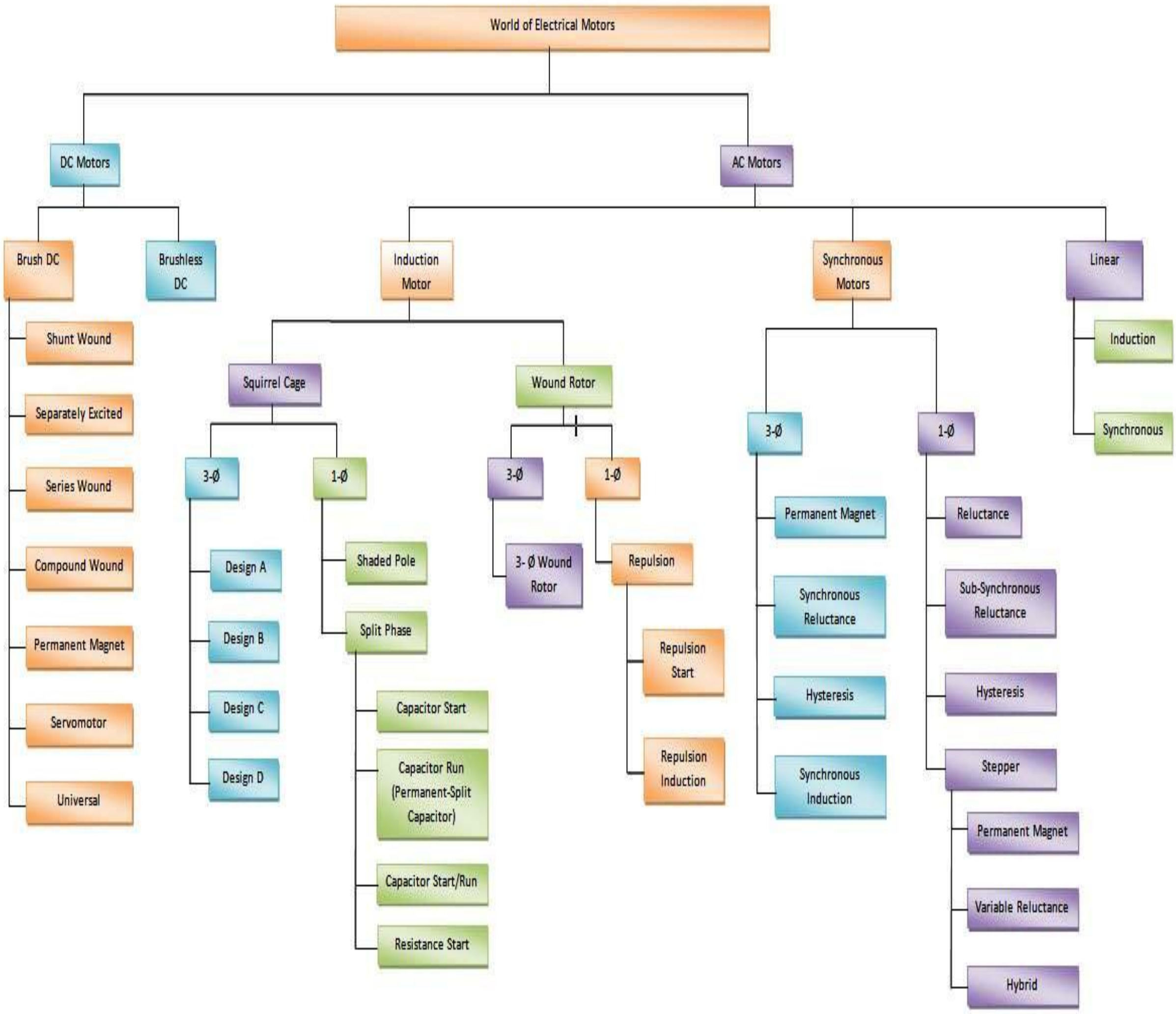


Figure 8: Overview of electric motor types categorised by current supply and working principles (Anon., 2012)

At present subsea electrical power supply over small or medium distances up to about 25-30 kilometres is typically done using alternating current. This is due to the fact that alternating current can be transformed into direct current in a much simpler manner than direct current can be transformed into alternating current. The alternating current transformers are also less susceptible to problems than direct current power supply systems. The voltage drop is also very much increased over large transmission distances due to the AC complex impedance (Z). Direct current is better suited as a power transmission method over long distances due to the form of resistance. This is illustrated in chapter four.

AC motors and generators can be run with either fixed or variable speed. The speed of AC machinery is controlled by two parameters, the frequency of the current supply and the number of stator pole pairs surrounding the rotor of the motor or generator. A variable speed AC motor can be accelerated and decelerated using these parameters.

Electric motors that are supplied by alternating current can also be designed for synchronous or asynchronous operation. This specifies whether the motor is rotating at a specific integer number of AC supply cycles (synchronous) or not (asynchronous). Universal motors can be run on either DC or AC supply.

3.2 Systems development and state of the art

The international nature and economy of scale invoked by the size of investments and returns of the offshore oil and gas industry has advanced the subsea technology utilized in offshore oil and gas development projects significantly in the last half a century since the first subsea x-mas tree system was installed in the Mexico Gulf.

Reduction of the weights and sizes of subsea systems have been a continuous work process that has lasted for decades. The technologies employed in the offshore exploration and production industry illustrate this process in the equipment used.

1961-1969	Direct Hydraulic
1971-1985	Sequenced Hydraulic
1985-2012	Electro-Hydraulic
2008-	All-Electric

The evolution of subsea systems has come about both through research & development and field experiences on a global scale. The subsea systems available compose a very large and diversified set of system designs developed for a diverse range of conditions. Weight, size, reliability, production capacity, economic, health, safety & environmental (HSE) considerations are factors that are continuously considered in subsea system design and field development projects.

Over the last two decades the limitations of older technologies using hydraulics and large installation vessels and longer project times have been reached, extended through the creation of hybrid system solutions and improved through experience and good engineering practice innovations in equipment designs.

Cameron Subsea Systems is one of the companies within the offshore oil and gas industry which have been at the forefront of all electric control systems technology. The Cameron "DC Technology" programme, initiated in 1999 has reached the following milestones in the development of an all-electric subsea control system for implementation in subsea systems:

Year	Milestone	Specific projects
1999	DC Technology Program Start	
2004	Electric Subsea Production Control System Pilot Trial	BP Magnus
2008	First All-Electric Production System Field Installation	Total K5F
2011	First Qualified ESCCSV designed by Halliburton available, awaiting field trial	
2012	2nd Generation DC AET system fully qualified	

Table 3: Cameron DC Program Milestones

The pilot trial, conducted in May 2004, was part of a joint study involving BP, Cooper Cameron and the Reliability Engineering group at Cranfield University. It was intended to create a model that would provide a comparison of a subsea MUX E-H production control system with a prototype subsea all-electric production control system that had been developed by the Cameron Control Systems Group. A model was set up using a 4-well cluster arrangement (Theobald & Lindsey-Curran, 2005).

The reliability of the modelled subsea system was investigated with the aid of a software package called BlockSim. This software enabled the system to be to be modelled as a hierarchical structure of reliability block diagrams and sub-diagrams. A block on the top-level diagram could thus represent a sub-diagram which is accessed from the representative block on the top-level diagram (Theobald & Lindsey-Curran, 2005).

The study provided limited reliability data for the all-electric control system but the limited data provided did indicate an increase in system availability due to improved system reliability. The study succeeded to establish a model that allows for the comparison of an electro-hydraulic tree (EHT) system reliability versus that of an all-electric tree (AET) system (Theobald & Lindsey-Curran, 2005). Other benefits identified from the study included:

- The AET system had much reduced duration for choke operations
- Elimination of the HPU reduced weight and gained deck space topside
- Elimination of hydraulic fluid vents for IMR or work-over operations
- Elimination of subsea actuator banks

This pilot trial was followed three years later by the Total K5F field development which was the first in the world to use an all-electric subsea production system. This development was very important in the qualification process of the subsea all-electric system. At the start of production one can mention areas of uncertainty with regard to the AET systems such as:

- Actual field subsea AET system feedback data
- Actual field subsea AET system reliability and availability
- Actual field AET system condition monitoring feedback
- Accurate long-term OPEX and maintainability

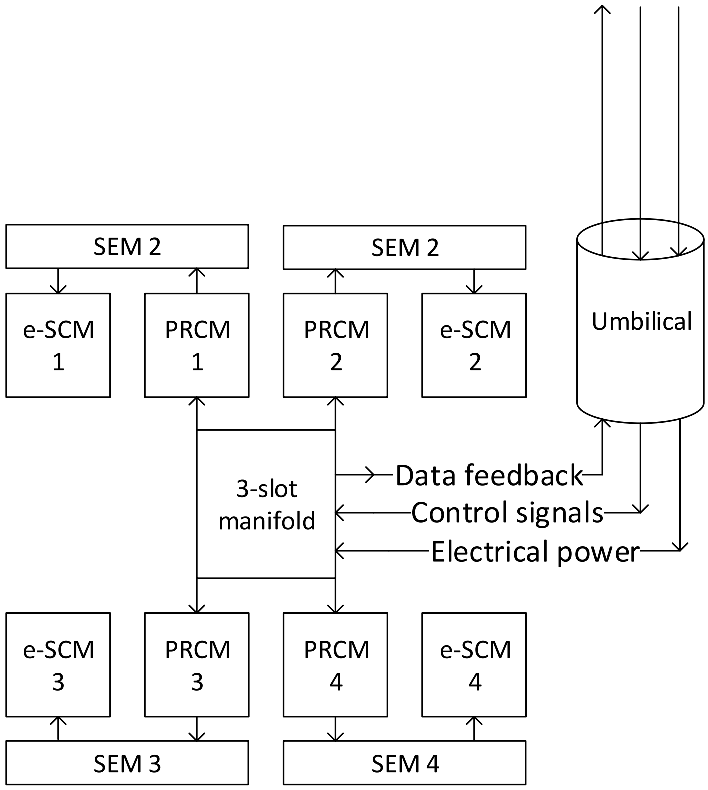


Figure 9: Diagram of the 1st generation CameronDC system installed at Total K5F field, Dutch North Sea

In the figure above the layout of the K5F field, which is situated in the Dutch North Sea, can be illustrated. DC electrical power with signals on power configuration using a coaxial umbilical line that runs 18 kilometres from the K6F platform ends at a three-slot manifold. The electricity and control signals are routed from the manifold to individual power regulation control modules that are attached to the CameronDC Xmas tree systems. Here the signals and the electrical power are relayed through the umbilical termination assembly (UTA) using jumper cables that connect to the subsea Xmas tree power regulation and communication modules (PRCMs). Signals are sent to the subsea electronic modules and commands relayed through to the subsea control module. The SEM then transfers commands for necessary steps in actuation of valves or to perform other control actions. The 1st generation CameronDC all-electric subsea Xmas tree electric production control system uses Ethernet communication protocols with a proprietary software package for communication of data and control signals throughout the production control system (Abicht & van den Akker, 2011), with CAN-bus protocols for control equipment communications in accordance with (IWIS, 2011).

It needs to be stated that the system installed at K5F does not rely entirely on electric controls. At the time of the project, there was no possible supplier of a qualified electric down-hole safety valve (DHSV) or surface-controlled subsurface safety valve (e-SCSSV). Halliburton Subsea were underway with development with an e-SCSSV solution at the time. The now qualified design of an e-SCSSV is a valve operated magnetically, which does not depend on a link to Xmas tree electrical supply. An image of the Halliburton e-SCSSV is shown in Figure 10.

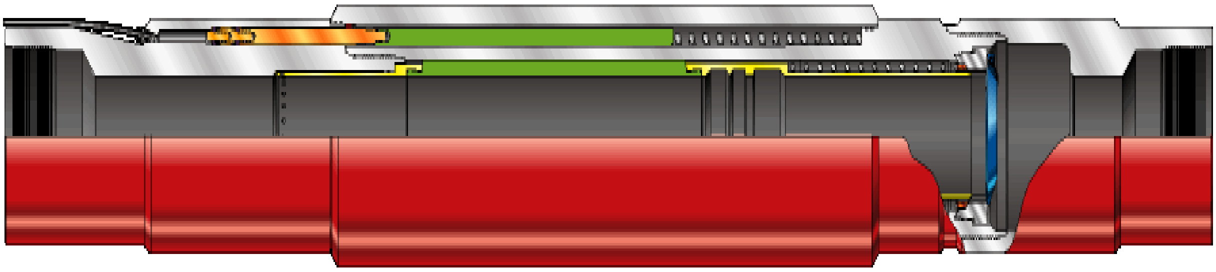


Figure 10: Halliburton E-SCSSV (Halliburton, 2008)

Experiences and feedback data recorded from the Total K5F field has proved Cameron DC and BP reliability data presented in 2005 (Theobald & Lindsey-Curran, 2005) to be relatively accurate in the prediction of availability and reliability.

In availability the actual field performance of the AET system designed by Cameron has been significantly better than anticipated. Before the K5F field entered into production, estimated availability of Cameron AET production systems was 94.8% (Theobald & Lindsey-Curran, 2005). The corresponding value for system availability after two years of field production for the Cameron subsea AET system was higher than 99.9% (Abicht & van den Akker, 2011). Currently, another all-electric production system is under consideration is for the Goliath field development project underway in the Barents Sea.

Although Cooper Cameron and Cameron Subsea Systems are the first to manufacture and install an AET production system, there are several other suppliers of subsea all-electric control systems. Weatherford, FMC Technologies and Aker Solutions have also been involved in electrification of subsea systems over the last decades. FMC technologies have developed several control systems that are all-electric, as well as ROV-retrievable electric actuators. These controls have been aimed at improving performance and increasing efficiency of existing fields by retrofitting such replaceable actuators on manifolds and choke valve assemblies (Sten-Halvorsen, Vidar; FMS Kongsberg Subsea, n.d.).

Cameron initially had plans to use direct current to supply their 1st generation subsea all-electric Xmas tree production system, then altered their design in order to utilise alternating current due to maintenance issues regarding transformers and rectifiers. The 2nd generation CameronDC subsea all-electric Xmas tree production system will also use alternating current to power the system, unless step-out distances over 50kms are considered. In this case, medium voltage DC supply networks are to be used.

3.3 Topside Equipment

3.3.1 Electrical Power Unit

For a subsea all-electric XT with an all-electric production control system, a safe and reliable electrical power supply becomes vital. Therefore, the reliability of the UPS and topside EPU will be a more important factor in field development. A power generation source with full redundancy should therefore be a requirement to maintain continuous production at an all-electric production facility.

3.3.2 Master Control Station

As in traditional production control systems, the master control station (MCS) is the principal access point for production control functions by the designated MCS staff.

Picture 1: Cameron DC MCS used for the 1st generation CameronDC field trial in 2005 (Lopez, 2005)

It is composed of a range of electrical and electronic devices, similar to the MCS for H-E MUX systems at the HMI. The 1st generation CameronDC subsea production control system uses an Ethernet communications protocol (Abicht, Daniel, 2011). A description of alternative communications protocols is given in chapter 4.

3.3.3 Uninterruptible power supply

In case of immediate loss of electrical power supply from the EPU, an UPS system needs to be in-place to create a safe-guard against loss of production system control functions. In order to increase the reliability and minimise lost/deferred production, The UPS system should have an included redundancy to guarantee delivery of the required system functions. The components that constitute the UPS system will be located in boxes or cabinets that are built to meet the satisfactory protection level required by relevant safety standards. An Example of standards that are used to describe protection level is IEC 60079. In this standard, equipment is designed to meet a certain equipment protection level (EPL) based on location of equipment and the hazards present there. This could be for example gas-or dust-related incidents such as explosions or particle-in-system interference. The design of the boxes or cabinets depend on the conceivable situations that can arise where the system is located. As the electrical generators and the UPS system will be the alternative sources of power to the subsea production system, the reliability of the topside power generation facility become paramount to overall system reliability.

3.3.4 Topside junction box and topside umbilical termination unit

The topside junction box and the topside umbilical termination assembly or TUTU for an all-electric system will become lighter due to the removal of the hydraulic power lines. The space requirement should also be reduced due to the decrease in numbers and sizes of pipes and cables that will join at this point before transmission to the subsea system components.

3.4 Subsea equipment

3.4.1 Subsea electrical systems

3.4.2 Subsea electrical distribution system

The all-electric umbilical line design concepts will be similar to the E-H umbilical line design concepts. However hydraulic power supply hoses for the subsea systems under development will be replaced by electric power cables. The same range of materials is available for all-electric umbilical line designs as for E-H umbilical line designs.

Umbilical line weight per unit length can be reduced with utilization of all-electric umbilical line supply, as a flexible thermoplastic/HCR thermoplastic integrated power and control system umbilical line. With all-electric umbilical lines, the subsea network complexity in number of wells/manifolds will have an impact on the weight of the umbilical. The transmission method, by either AC or DC will also affect the umbilical weight due to structural design of conductor, insulation, and shielding.

Picture 2: 2nd generation CameronDC electrical power and communication distribution unit (Abicht & van den Akker, 2011)

The combination of fibre-optic cable and copper coaxial power cable for umbilical signal and power transmission offer an alternative that is not the most common, but is used and readily available. The twisted pair copper wire offer a viable connection for signal delivery, but the bandwidth is much less than with use of fibre-optics. The twisted pair copper wire has a very limited signal bandwidth and carrier distance without signal enhancement. It has been made obsolete by coaxial copper cables from the 1980s onwards in use for subsea production control system in-field (between MCS and XT control system) communication functions. The coaxial cable offers an increased bandwidth for signals transfer in addition to a capacity to be designed for signal on power functions.

The subsea field umbilical line will connect to electric power and communication distribution units (EPCDUs) that act as distribution nodes for the subsea network.

3.4.3 Subsea Control Module

In an all-electric Xmas tree system, the electric subsea control module (ESCM) contains the assembly of control transfer functions used for well production management at the wellhead location on the sea bed. It is connected to the Xmas tree using a connector that enables the transfer of injection fluids and electrical power supply from the umbilical supply line to the Xmas tree. It will be connected with a power transformer and inverter that establishes the 24VDC that is used for valve control equipment. The power transformer-voltage regulator and communication assembly is called a PRCM, and has been described briefly in the distribution system section of this chapter.

Picture 3: 2nd generation CameronDC electrical subsea control module (Abicht & van den Akker, 2011)

3.4.4 Subsea Electronic Module

The subsea electronic module (SEM) is a one-piece input-output device that is either mounted on the Xmas tree structure as an integrated part of the subsea control module, or it can be connected to the Xmas tree structure as a separate module. Inside the SEM is an assembly of electronic circuit boards with processor units that are kept at atmospheric pressure and temperature. To ensure the integrity of the SEM interior, a continuous monitoring of pressure and temperature as well as electrical discharge is performed. The SEM is the electronic connection between the SCM and the MCS, and relays Xmas tree sensor data to the MCS for storage. It also runs continuous diagnostics of power and communications to and from the Xmas tree. Power to down-hole safety valves (DHSVs) are subject to ISO 13628 part 4 and IWIS recommended practices. Sufficient redundancy in electronics as prescribed by IWIS is shown in Figure 11.

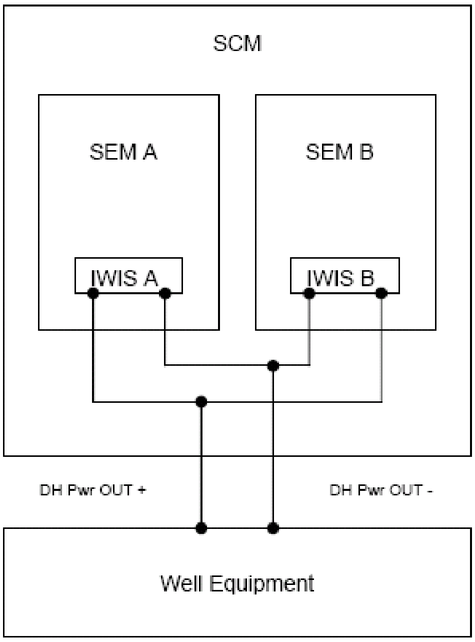


Figure 11: generic configuration for redundant electronic DHSV power supply (IWIS, 2011)

3.5 Production control system communications

The communication between the sensors of the PCS and the HMI or, in the case of intelligent/smart well systems, the automated controls of the subsea production control system is vital. There are several possible solutions available for the establishment of reliable communication over short distances. However, over longer distances there are major differences in satisfaction of modern large data size communication requirements. An as short as possible time from sensor measurement to completed required control response should therefore be the aim. The subsequent section deals with hardware-related as well as with network structure considerations that affect these conditions.

3.5.1 Data acquisition

The subsea control system utilizes a range of different sensors. These are used to record pressures and temperatures, flow characteristics and equipment or component condition monitoring. The subsea umbilical lines will have field signature method (FSM) sensor systems in place, that monitor umbilical or umbilical component corrosion over time. On the choke valve, pressure and temperature should be measured. On the subsea Xmas tree, several sensors should give feedback through the SEM about the pressure and temperature at the wellhead location.

The sensors used for pressure control will typically be piezoelectric

3.5.2 Production control system communication protocols

The production control system functions rely on rapid and error-free transfer of sensor signals and control response signals through the umbilical lines at the field. From a literature review of current communication protocols and their working principles a selection of communications protocols have been identified.

Common communication protocols used in production systems today are internet (IP), Ethernet and serial bus communication protocols. Other communication protocols are

- Token ring protocol,
- Fibre distributed data interface (FDDI) or copper distributed data interface (CDDI) protocol,
- Serial bus protocols,
- Synchronous optical networking (SONET) or synchronous data hierarchy (SDH),
- Asynchronous transfer mode (ATM).

The Ethernet communication protocol. The data is packed into variable size packets or frames

A token ring network consists of nodes that are connected in a loop or "ring" where signals are passed from node to node serially to end at designated physical addresses within the loop.

The CDDI or FDDI communication protocol is a ring-based token network. The differences between the token ring and the CDDI/FDDI protocols are that the CDDI and FDDI protocols utilize a double ring node-to-node communication process.

A range of communication protocols developed for process facility control systems, Serial bus protocols are polling based systems. They have been specifically designed to provide real-time data and control and are very high reliability of bitrate delivery and delay times. The maximum bitrate for serial bus protocols is rather limited, however. This could potentially be a problem with respect to upper tier subsea production control systems communications. This is because some of the data and control functions require larger bitrate capacities.

The SONET (North America) or SDH (the rest of the world) protocols were originally designed for optical transfer of acoustic and data traffic. The design basis is to emit laser or coherent light emitting diode (LED) photons acoustics in pulse code modulation (PCM) format through optical fibre. PCM is a method to digitally represent analog signals by assigning values to light wave amplitudes and frequencies. The conversion is performed by analog to digital converters (ADCs). After signal transfer, the light waves are then filtered through digital signal processors and converted into analog representation using digital to analog converters (DACs). The SONET and SDH protocols are "protocol neutral" and can be used in combination with one of the other communication protocols to establish a reliable data acquisition system for production control system condition monitoring.

ATM is a communication protocol developed by the telecommunications sector for delivery of acoustic, visual and data signals through a unique communication line. The protocol design basis is to utilise multiplexed asynchronous signal transfer with respect to time. Data is packed into fixed size "cells".

The method for assignment of network addresses of the well equipment, using IP communications protocols is specified by IWIS. Address negotiation is to be initiated from the surface MCS (active) to the wellhead SEM (passive) which will prepare to receive initiation signal, whereupon it stands by for reception of data from MCS. For subsea network communications, the intelligent well interface standardisation panel (IWIS) specifies a communication bitrate of 9600 bits per second as a default value. This rate can be increased if desired or required. With intelligent/smart well production control systems greater data transmission capacities might be necessary for efficient use of rapid response control mechanisms. Instrumentation and their functions are to use serial communication protocols that enable plug and play functionality.

4 Limitations of subsea all-electric production control systems

A subsea all-electric Xmas tree production control system should offer at least the same control and signals capabilities during production as a multiplexed electro-hydraulic production control system. To become a preferred system design option, it should also have advantages over the traditional production control systems. In this project the purpose has been to establish the state-of-the-art of subsea all-electric production control systems for all-electric Xmas trees. Limitations of the system with regards to water depth and wellhead offset distance or overall system distance are also to be addressed.

4.1 Subsea electrical power transmission

The choice between alternating current supply (AC) and direct current (DC) of electrical power supply for a subsea all-electric production system should be discussed. The different types of electrical motors and their functional components have been described earlier (see section 3.1). It is possible to use both AC and DC motors to run valve actuators and perform control functions within the subsea system. The factors that may create certain application disadvantages and advantages will be investigated.

Direct current transmission systems are characterized by a low voltage drop over long distances. This capability of a large transmission distance is offset by the fact that DC power and voltage regulators are more complex and costly than for AC. This may lead to higher maintenance costs and downtime for transformer repair/replacement operations.

Alternating current transmission systems are characterized by the ability to easily regulate the voltage but the electrical power suffers a large voltage drop over longer distances. According to Birkeland a subsea electrical power umbilical line of more than 100-200 km length would become unfeasible (Birkeland, 2008). Due to voltage loss, at 500km, an AC power line would only maintain approximately 20% of initial input voltage (van den Akker, 2008).

4.1.1 Comparison of AC and DC electrical power transmission methods

The effect of transmission distance for the electrical power supply to Xmas tree control system machinery and electronics should be efficient with regards to power loss. The electricity can be transmitted through the use of alternating or direct current transmission methods.

For direct current transmission systems, the following expression predicts the power transmitted:

$$P = \frac{V_s \cdot V_d}{Z_0}$$

For alternating current power systems, the following expression predicts the power transmitted:

$$P = \frac{V_s \cdot V_d}{Z_0 \sin \theta} \sin \delta$$

AC power (in Watts) is given by the equation $P_{AC} = PF_n \cdot I \cdot U$

In the equation, $PF_n$is the power factor, dependent on the phases of current supply denoted by the subscript '*n*'. '*I*' is the current passing through the cable cross-section, and '*U*' is the voltage.

DC power (in Watts) is given by the equation $P_{DC} = I \cdot U$

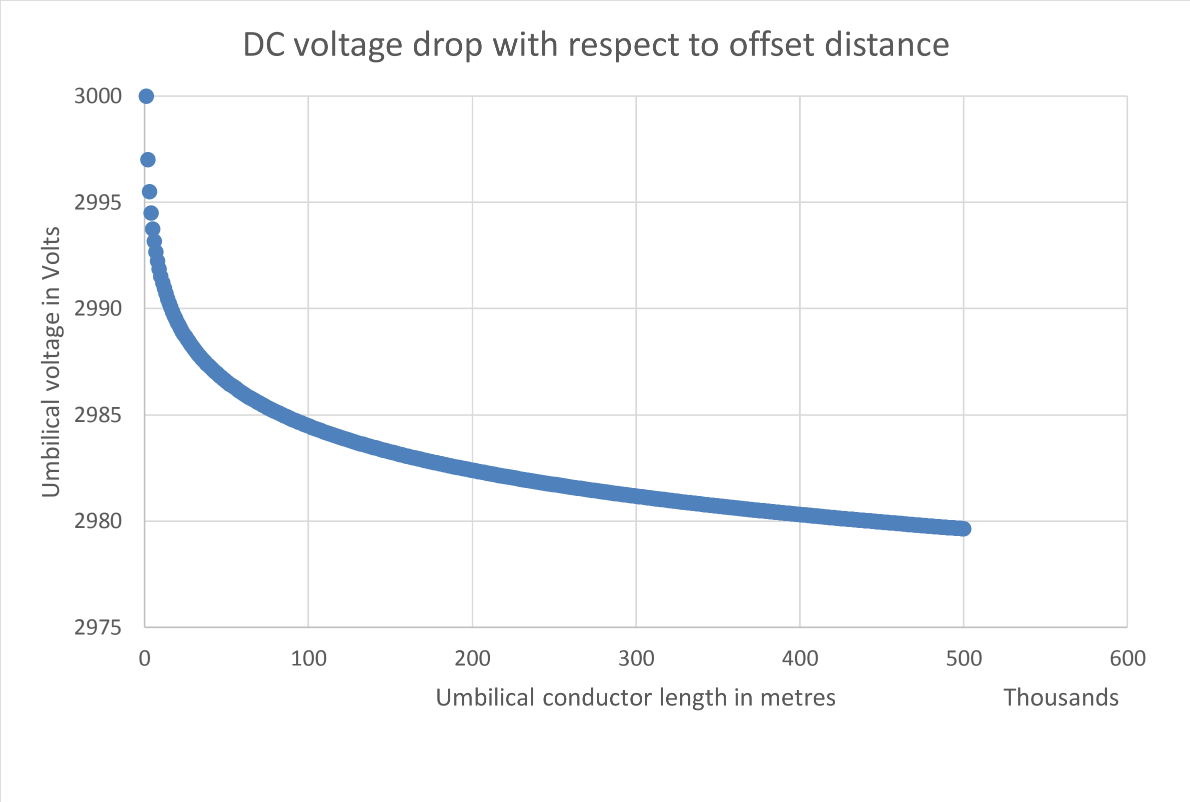


Figure 12: DC transmission voltage drop using a copper cable (Based on theoretical calculation given in Appendix B2.

It can be observed that with DC power transmission, an increase of the voltage will reduce the drop across the circuit. The insulation of the conductor and the radial location of conductor surface relative to electromagnetic shielding for a co-axial cable can be addressed to check for electric leakage and insulation condition monitoring.

4.1.2 Umbilical power cable insulation

The 1st generation CameronDC production control system is supplied by a DC electrical signal on power coaxial cable. The coaxial cable consists of two copper cables, one inner "core" conductor and an outer copper mesh acting as a "shield" against electric field discharge with insulation between inner and outer conductor, and insulation outside the "shield" mesh.

For reliable signal and electric power transmission, a coaxial cable requires a safeguard against electric field discharge, which can cause a short-circuit of the umbilical power supply circuit. The coaxial cable design is called a dielectric. The insulator between inner and outer conductor is commonly composed of some kind of polymer such as poly-ethylene. These are called dielectric materials, since they are particularly suited for use with electric field insulation.

With the transmission of electrical power through a coaxial cable, an electric field forms that has a varying strength along the radius of the cable. The field is largest at the surface of the inner conductor. The form of this electric field is given by the following equation:

$$E(r) = \frac{V_{Peak}}{r \cdot \ln(r_o/r_i)} \Rightarrow V_{Peak} = E_r \cdot r \cdot \ln(r_o/r_i)$$

The characteristic impedance of the insulating material of a coaxial cable is given by the subsequent equation:

$$Z_0 = \frac{\ln(r_o/r_i)}{2 \cdot \pi} \frac{\delta_0}{\sqrt{\varepsilon_R}}$$

The peak electrical power that can be handled using a coaxial cable with the given insulator is

$$P_{Peak} = \frac{V_{Peak}^2}{2 \cdot Z_0}$$

Hence the peak power the insulator can handle, expressed as a function of the coaxial cable geometry is given by

$$P_{Peak} = \frac{\pi \cdot E_d^2 \cdot r_i \cdot \ln(r_o/r_i) \cdot \sqrt{\varepsilon_R}}{\delta_0}$$

Explanation of parameters used above:

- $\delta_0$is the impedance of a perfect vacuum,
- ε_R is the relative dielectric constant with respect to the dielectric constant of a perfect vacuum,
- r, r_o and r_i are radii from the centre of the cable structure,
- E_r and$E(r)$ are electric field values,
- V_{Peak} represents the peak or maximum voltage for the cable,
- P_{Peak} represents peak or maximum electrical power capacity of the cable insulating material,
- Z_0 is the characteristic impedance of the insulating material around the coaxial cable.

For an example coaxial cable of specified outer and inner diameter, where inner diameter is where the peak electric field energy is located and the outer diameter is the outside of the insulation:

Outer radius	Inner radius	E(r)	Peak voltage	Char. Impedance	Peak power
0,0627 m	0,0313 m	24173186 V/m	525 kV	27,4235	4,970 GW

Table 4: Critical electric field strength (electric power required for electric field discharge through insulation) using HDPE of $\varepsilon_R = 2,25$

The result of a calculation which was based on peak power, peak voltage and electric field strength for a Nexans 525 kV subsea umbilical coaxial cable is shown in Table 4. It can be seen that with insulation made from HDPE that is completely insulating the electrical current, a power of 4,97GW can be handled by the dielectric HDPE before the electric field becomes too large for the insulator.

Outer radius	Inner radius	E(r)	Peak voltage	Char. Impedance	Peak power
0,0627 m	0,0313 m	24173186 V/m	525kV	27,4235	3,314 GW

Table 5: Critical electric field strength (electric power required for electric field discharge through insulation) using air of $\varepsilon_R = 1,00058986$

However, if the calculation is done for air and for water surrounding the conductor material (), the power that is required for electric conduction is much less. This shows the requirement for good insulation on the all-electric power umbilical. Common materials are polymers such as high density poly-ethylene (HDPE), which was used for calculating the peak power effect in table 6. The potential incidents are not only related to power loss through short-circuits, but signal interference as well.

Outer radius	Inner radius	E(r)	Peak voltage	Char. impedance	Peak power
0,0627 m	0,0313 m	24173186 V/m	525kV	27,4235	31,261 GW

Table 6: Critical electric field strength (electric power required for electric field discharge through insulation) using water of $\varepsilon_R = 89$ (~5°C)

4.1.3 Condition monitoring of umbilical power transmission

In the power transmission umbilical line, there are certain conditions that could arise that would present a hindrance to power delivery. Among them are two important conditions that should be monitored constantly:

- Discharge of electricity through the cable insulation
- Insulation breakdown, which has been described in the previous section of this chapter

To ascertain present umbilical line insulation conditions and electrical discharges or capacitance leakages, an umbilical monitoring device (UMD) will be used. These are supplied by the subsea production system suppliers. VetcoGray offers an UMD for power umbilicals that is able to measure the insulation resistance with relatively high accuracy for in-field umbilical lines, and even for larger power umbilicals, using FSM (General Electric Company, 2010). In addition it is used to detect capacitance leakage from the umbilical power transmission cable. The measurement of insulation resistance and detection of current leakages are taken using measurement signals. The measurement signal can be altered to ensure that the device is calibrated for its specific application. Both measurement signal frequency and pulse width can be varied through pulse-width modulation. The VetcoGray UMD is able to measure leakage capacitance between 100nF to 1µF. The table below shows the maximum measurement errors for given insulation resistances (General Electric Company, 2010).

Insulation resistance	Measurement error
10kΩ-5GΩ	<5%
5GΩ-10GΩ	<20%

Table 7: VetcoGray UMD measurement errors for given umbilical resistances

There will be more factors that need monitoring on the umbilical. Strains due to ambient environmental conditions can cause damage to the umbilical conductor and insulator materials. This should therefore be monitored using a strain gauge system which can take measurements along the length of the umbilical from end to end, as well as on the riser section of the transmission line, until the topside umbilical termination unit (TUTU).

4.1.4 Subsea electrical power connectors

The subsea power connectors are to be wet mateable, meaning that they have to be connectable in subsea conditions with respect to water depth, insulation against water and have safeguards against misalignment on contact surfaces. They should be designed for connection and retrieval using ROVs.

4.2 Umbilical signals and data transfer

The Xmas tree system consists of piping equipped with pressure and temperature sensors and actuator systems with an interface located on the SEM. This is either located in the subsea control module (SCM) or at a separate connection point on the Xmas tree.

The communication from the SEM is based on two different circuits. The direct circuit is one where sensors transfer a signal to the SEM which requires the SEM to take independent actions based on direct sensor data input. This could be for example to cut electrical power supply for a certain valve and cause the valve to close by spring-loaded default. The other circuit will be the normal operational circuit, where sensor signals are transferred from SEM to the MCS, control signals are returned and transferred to the Xmas tree SCM and control action is performed.

The sensor-SEM-MCS signal transfer to MCS-SEM-actuator control transfer time for large distances is one question that will be discussed. The sensor signal transfer time is dependent on several factors. These can be divided into material factors such as

- Signal cable types
- Connector designs

The signal cable types have been briefly described in chapters two and three, and are

- Twisted pair copper wire (electronic wave transport)
- Co-axial copper cable (electronic wave transport)
- Fibre-optic cable (light wave transport)

Copper and fibre-optic cables have several features that have to be taken into account both with respect to application and with respect to performance with respect to application. As copper conducts electricity, twisted pair and co-axial copper cables can be used for simultaneous power and signals transmission. The size, complexity and cost of signal on power umbilical designs are therefore limited. These advantages are offset by the fact that signal bandwidth is reduced due to electromagnetic interference from the electrical current that passes through the same copper cable. Another disadvantage of signal on power copper cables are that the distance over which signals can be transmitted without signal reinforcement is limited. Optic-fibre cables cannot be used in a signal on power transmission configuration. The size and complexity of the umbilical is then increased. A short summary of data transfer rates is given in Table 8: Bitrates for different signal cable types. All three cable types are in use in subsea communications at present.

	Twisted pair copper wire	Coaxial copper cable	Fibre-optic cable
Bitrate	100Mb/s	100Mb/s	10Gb/s

Table 8: Bitrates for different signal cable types

The signal transfer times are further influenced by how the network structure is designed. The Standard protocols have been mentioned in connection with the subsea production control communications system in the previous chapter. The subsea networks will follow recommended practices according to IWIS/SIIS that is mentioned in appendix A5. IWIS. However, these are guidelines, and companies that develop and supply subsea technologies will in many cases rely on good engineering judgment in network design and in software or hardware development. The CameronDC programme has been using Ethernet communications protocols with coaxial cable signals and power transmission in signal-on power umbilicals, separation of power and signals after passing through the PRCMs. For the 2nd generation systems, the data signals line will pass through fibre-optic cables. This should enable longer transmission distances without signal reinforcement, higher rates of error-free signal transfers.

4.2.1 Subsea signal cable connectors

Similar to subsea power connectors, signal connectors are to be wet mateable, meaning that they have to be connectable in subsea conditions with respect to water depth, insulation against water and have safeguards against misalignment on contact surfaces. They should be designed for connection and retrieval using ROVs.

4.3 Subsea valve controls

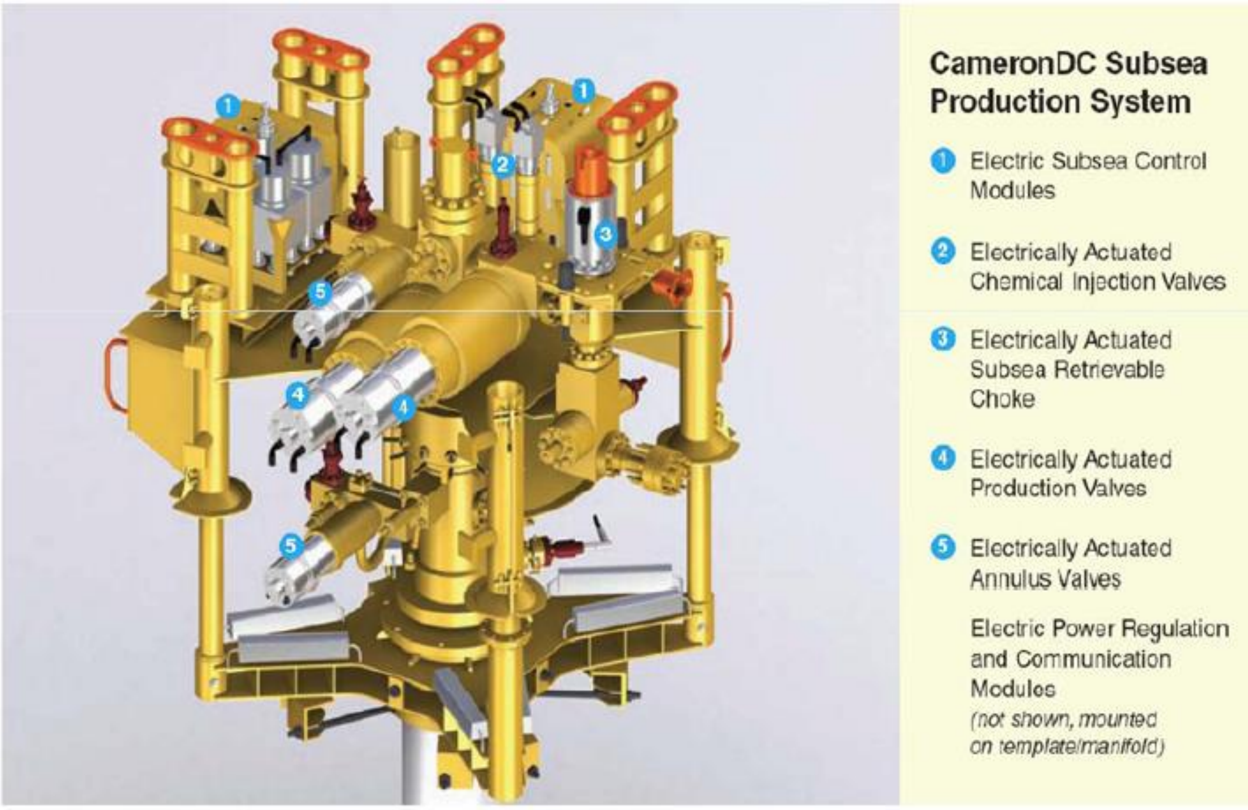


Figure 13: 1st generation CameronDC AET installed at K5F (MacKenzie, Rory; Total E&P, 2011)

4.3.1 Xmas tree gate valve functional requirements

The subsea Xmas tree valves perform several vital control functions for the production system. Gate valves can be used to control flow through the following Xmas tree piping systems:

- Production line through use of production master and wing valves
- Water (W), gas (G), water and gas (WAG) injection lines
- Annulus line through use of annulus master and wing valves
- Annulus injection line
- Service lines such as chemical fluid injection lines
- Isolation through use of cross-over valves (XOV) or down-hole safety valves (DHSVs)

The piping systems above will typically be constructed of piping of the following internal diameters:

Valve function	Valve diameter (inches)	Valve diameter (metres)
Production valve	5”-7”	

Annulus valve	2”
Chemical injection valve	3/8”-1”
Isolation valve	1/2”-1”
Blowback valve	1/2”-1”

Table 9: Overview of Xmas tree piping internal diameters by system (Søgård, 2008).

Hydraulically actuated valves require increased power to perform in deep water than in shallow water. This is due to the hydrostatic pressure increases. Developments in subsea hydraulic technology have been able to compensate for this effect through use of local hydraulic power storage. In the last decade, electric actuator designs have also been used to refit subsea manifolds and choke valve systems with electric control modules and ROV-retrievable electric actuators (Moe, Sigurd, FMC Technologies, 2011). The electrical power and control signals are transmitted to the electrical subsea control module at the Xmas tree. When a control signal to actuate a gate valve is transmitted through to the SCM, the command will be relayed onwards to the SEM. The power supply will be activated by electronic signal from the SEM. The electrical power is subsequently transmitted to the electrical prime mover of the gate valve which will actuate the valve to the desired position. The electric motors all deliver mechanical power in the form of rotary motion. It is therefore inherent to any design that mechanical losses and moving parts are in higher number than with an equivalent hydraulically powered valve actuator system. This is due to transformation of motion from rotary to linear. Theoretical calculations wll show this over the following sections.

4.3.2 Xmas tree gate valves

Xmas tree gate valves are composed of the following components:

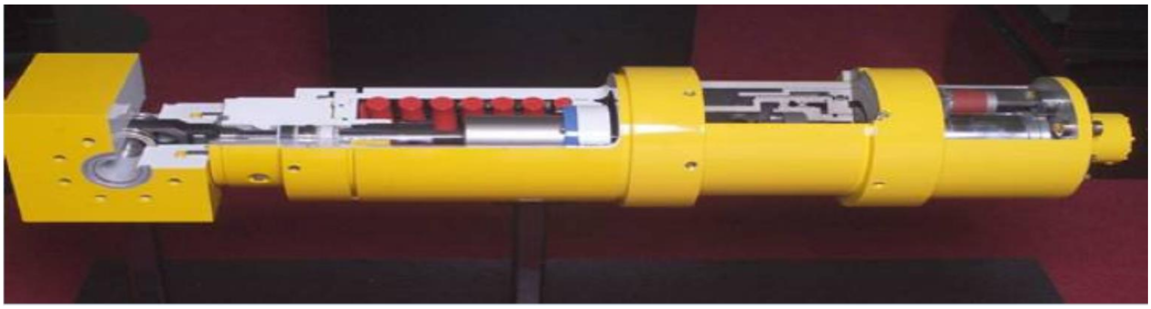
- Actuator
- Slab
- Transmission gears
- Driver

The components described are available in several designs depending on their applications. Gate valve actuators are required to move the valve from fully closed to fully open and vice versa. This can done by application of an in-line force or by application of a rotary torque onto a type of screw that will translate into a linear motion. Actuator designs operate on rotary, linear or rotary-linear motion. Gate valve actuators operate on either linear or rotary-linear motion. Using an all-electric configuration the motor-actuator connection will not involve hydraulic pressurization of the actuator. For a gate valve, a rotary-linear electro-mechanical direct or through-gear transmission of required actuation forces is used. This will enable the operation and control of valves. Examples of rotary to linear mechanisms are:

- Roller screws
- Ball screws
- Power screws

In the transformation from rotary to linear motion, mechanical losses will occur. These losses will occur with all the mechanisms mentioned above in various manners. A theoretical calculation of valve actuation based on a worst case loading on one gate valve has been performed to assess all-electric powering requirements and investigate electro-mechanical actuation. This is given in the following sections of this chapter. Additional mechanical losses will occur in the event that transmission gears are put into use. This will be beneficial compared with direct-driven options, however, as the power requirement for the actuator prime driver is reduced.

The valve calculations have been performed using equipment materials and dimensions according to the relevant current international standards (ISO 13628-4, 2010). In part 4 of International Standard 13628, master valves have different definitions for HXTs and for VXTs. The definitions relate to the location of the valves. VXT master valves are located in the vertical bore, HXT master valves are located in the horizontal bore of the production line. ISO 13628-4 specifies minimum requirements regarding the number and failure states of the master valves. There are to be two master valves in the XT production line. The failure state is the position the master valve should have in case of PSD or ESD situations. Master valves are specified to be fail-close, which means that in any shutdown event, master valves should move to a fully closed position. The Cameron electrical gate valve design is shown below, with indication of where the different components of the valve are located.



Valve slab | Spring failsafe solution | Gearbox transmission | Electric motor

Picture 4: Cameron all-electric gate valve (MacKenzie, Rory; Total E&P, 2011)

4.3.3 Xmas tree gate valve failsafe arrangements

The gate valves that are classified as master valves should be fully closed in the case of failures such as valve prime as valve prime mover power loss or system failures that require isolation of the well stream. Hence the master valve has the master valve has been considered as failsafe-closed type valves. A common failsafe arrangement is that in the case of is that in the case of actuator prime mover power loss, a spring will ensure that the valve is actuated into a fully closed into a fully closed position that isolates the well stream. This is the solution used with the 1st generation Cameron AET generation Cameron AET gate valves as can be seen in Valve slab Spring failsafe solution Gearbox transmission Electric motor

Picture 4: Cameron all-electric gate valve.

There are several other designs that offer a failsafe arrangement for gate valves. FMC Technologies, Oceaneering and Aker Solutions have in the last two decades been developing electric actuator control systems. These have been used to retrofit and provide emergency shutdown arrangement for several subsea applications. The applications have been mainly for choke and manifold valve actuators. These are also an additional failsafe option for AETs. In addition there is the option of installing battery packs on the XT for use in case of electrical power loss from the principal power supply source.

4.3.4 Xmas tree gate valve worst case loading

In order to estimate the powering requirement for a valve using electrical actuation, the peak loading of the valve needs to be calculated. The peak loading of a production master valve with the pressure rating, nominal bore size and type of valve already given, an excel spread-sheet has been set up. This has been used to calculate the forces acting on the valve and the required force to actuate the valve. The state that is considered to involve the largest forces through valve operation in atmospheric conditions and subsea conditions needs to be ascertained using valve loading conditions in the different positions.

The four different valve positions that have been considered for calculation are:

- Close valve from fully open position
- Close valve from partially open position
- Open valve from partially closed position
- Open from valve fully closed position

Of these four positions, the position that is considered to involve the largest forces on the valve is the position last mentioned; open valve from fully closed position. Gate valves can be of different designs. In this case, a flat plate valve has been considered.

A theoretical calculation based on a valve with given data has been used to test the differences between hydraulic and electrical actuator systems. This is in respect to defined limitations given in the introduction of the thesis. For the valve loading calculation, the parameters given in Table 10 and Table 11 have been used. On the Norwegian Continental Shelf or NCS for short, a common XT production line nominal bore size is 5 1/8 inches. The gate valve calculations has been performed for this bore size, with a selected working pressure rating of 10,000 psi.

A theoretical calculation performed for an electro-mechanical actuator system shows this.

Valve parameters	
Bore size	5 1/8 inches
Valve slab diameter (D_v)	6.3 inches
Valve pressure rating (p_v)	10,000 psi
Valve cavity pressure (p_c)	11,150 psi
Static friction factor (μ_s)	0.20
Dynamic friction factor (μ_d)	0.15

Table 10: Valve dimensions and parameters

Actuator parameters	
Actuator piston diameter (D_p)	9 inches
Override stem diameter (D_{os})	2.25 inches
Valve stem diameter (D_{vs})	2.50 inches
Actuator piston stroke (x_p)	5.89 inches
Spring constant (c_s)	4160.27 lb/inch

Table 11: Actuator dimensions and parameters

The two tables above represent the parameters for a production master valve of inner bore 5 1/8 inches in diameter. The hydraulic loading conditions when the valve is about to open from fully closed position will now be given.

Initial loading conditions

The gate valve in this calculation has a spring failsafe arrangement, which, in order to keep actuation linear, has been preloaded. The spring preload,

$$F_{sp} = 30202lb.$$

The valve force is given by the valve slab surface area (A_v) and the pressure (p_v) acting on it, and is expressed

$$F_v = A_v \cdot p_v$$

$$A_v = \pi \left(\frac{D_v}{2}\right)^2$$

The friction force on the valve before movement is initiated is given by the coefficient of static friction (μ_s) and the valve force F_v:

$$F_{sf} = \mu_s \cdot F_v$$

When the valve is in motion, the friction force is lowered as the coefficient of dynamic friction will be lower than the static friction coefficient.

When the valve is about to open, the pressure from the production line (p_v) on the valve stem area (A_{vs}) acts with a force F_{bs} given by

$$F_{bp} = p_v \cdot A_{vs}$$

$$A_{vs} = \pi \cdot \left(\frac{D_{vs}}{2}\right)^2$$

The pressure from the cavity space (p_c) on the valve stem area acts with a force F_{cp} which is given by

$$F_{cp} = p_c \cdot A_{vs}$$

The actuator is required to overcome the combined loads from the static friction, cavity pressure, failsafe spring stiffness and the spring preload. The expression for the hydraulic actuator loading required to begin to open the valve then becomes

$$F_o = F_{sf} + F_{spf} + F_{cp} + F_{sp} + (c_s \cdot 1in)$$

The calculation sheet is given in appendix B1. For a linear hydraulic actuator, this load will have to be overcome to open the gate valve. Losses in hydraulic actuation will occur from friction and pressure drops. For an electro-mechanical rotary-to-linear actuator, the load that is to be overcome will experience loads due to friction losses between mechanical components through the rotary-to-linear motion transformation and through gear box transmission of actuator forces.

4.3.5 Electro-mechanical mechanism

With power, ball or roller type screw actuation mechanisms, the applied torque *T* from the prime driver is converted into a linear force *F*. The symbol η represents the torque losses due to the transformation of motion from rotary into linear. It is called the mechanical efficiency. It is derived from the ratio between frictionless motion and motion with mechanical friction. The applied linear force is given by the equation

$$F = (2\pi T/l) \cdot \eta$$

The symbol *l* in the equation above stands for lead. The lead is the axial distance travelled by the nut per revolution of the screw or actuator stem. It can be represented mathematically with the expressions

$$l = \pi\alpha \cdot d_{ms} = n \cdot p$$

The logic and method used to obtain the torque expressions with use of the three different screw actuator mechanisms is shown in appendix B2. They are in general for screw designs and for power screw designs:

$$T_{Travel} = \frac{d_{ms}F_o}{2}\left[\frac{\mu_s + \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos\,(\tan^{-1}(\cos\alpha\tan\theta)) - \mu_s\tan\alpha}\right] + \frac{d_{mc}\cdot\mu_c F_o}{2}$$

$$T_{Return} = \frac{r_{ms}F_c}{2}\left[\frac{\mu_s - \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos\,(\tan^{-1}(\cos\alpha\tan\theta)) + \mu_s\tan\alpha}\right] + \frac{d_{mc}\cdot\mu_c F_c}{2}$$

The friction forces will depend on contact surfaces between the rotary mechanism and the screw actuator that drives the gate valve into the desired position.

4.3.6 Electro-mechanical prime driver

At present, it is common for electrical gate valve actuator designs to use brushless DC permanent magnet motors. According to Borchgrevink this is due to better torque performance (Borchgrevink, et al., 2009). The 2nd generation Cameron DC Xmas tree systems uses a brushless permanent magnet DC motor as well (Abicht & van den Akker, 2011). To maintain the open position, an arrangement of two stepper motors are arranged to work in opposite directions along the axis of the actuator stem. This enables a low power maintenance of position with high accuracy due to the unique DC stepper motor property of integer steps/revolution.

5 Further developments

5.1 Comparison of traditional and all-electric subsea control equipment

There is a wide array of equipment that may be included in a subsea production system, as the description of component systems in the previous sections illustrate. The equipment used will also depend on the system driver selection. The direct hydraulic, piloted hydraulic, electro-hydraulic and all-electric system working principles can be compared in terms of the equipment required for safe and reliable operation. This section will present a comparison of equipment requirements on the basis of system working principles. There are four main categories of production systems based on these working principles, and they are

- Direct hydraulic systems
- Piloted hydraulic systems
- E-H MUX control systems
- All-electric control systems

The direct and piloted hydraulic systems have been used for production control subsea for more than three decades. They can be used for very small subsea developments. But as the weight and complexity of the system grows significantly with number of wellhead systems, they can be eliminated from further consideration. Solely the multiplexed electro-hydraulic and all-electric controls shall therefore be compared. E-H MUX production control systems typically utilise hydraulic machinery through electronic controls.

The power is supplied through multiplexed electronic control and data transmission networks that also supply hydraulic fluid and chemicals for flow assurance. Hydraulic power is generated using HPUs with actuators for pressure or hydraulic power boosting and power rectification topside before umbilical transmission.

The hydraulic power loss caused by the water-depth increase down to the subsea infrastructure level is further compensated by subsea accumulators located at SHDUs. The hydraulic power fluid is subsequently transmitted to individual Xmas tree systems which have their own hydrostatic pressure-compensating accumulators.

The power, signals and data collection is done through multiplexed coaxial cables or through separate coaxial cable for power and fibre-optic for data and control signals. With an all-electric control system the valve actuation and connected control systems are powered from EPUs through connections made at subsea power EPCDUs. The electric power is delivered to AC or DC motors on commands given by the SEM. The electronic control systems that give commands also relay data on the subsea Xmas tree sensors back to a HMI at the MCS and is stored on servers for later analysis and condition monitoring purposes.

The requirements of the system functions indicate that with larger water-depths, the hydraulic components of the subsea E-H MUX production system substantially increase in terms of weight due to distance and water-depth. The main increases in weight are caused by

- Accumulators required for hydraulic power boosting and rectification and

- Umbilical line weight and diameter required for hydraulic power transmission

A simple summary comparing the effects of water-depth and offset distance on traditional production control systems to those on either an AC and DC production control systems is given in Table 12: The effect of water-depth and offset distance on power umbilicals for controls.

Parameter	E-H MUX subsea umbilical	DC all-electric subsea umbilical	AC all-electric subsea PCS
Larger water-depth	More subsea accumulators because of hydrostatic pressure effect	Negligible effect of hydrostatic pressure on signal dampening and umbilical material electrical field discharge properties	Negligible effect of hydrostatic pressure on signal dampening and umbilical material electrical field discharge properties
Longer offset distances	More accumulators because of hydraulic power transmission speed loss over long distances	The initial voltage drop is significant, however at distances greater than 100-150 km the rate of voltage loss decreases rapidly.	Significant voltage drops over distances greater than 100-200km. At step-outs this with distance 60-70% reduction in peak voltages would occur.

Table 12: The effect of water-depth and offset distance on power umbilicals for controls.

In terms of equipment, the potential gains in reduction of heavy production control system components carry a substantial cost-reduction both with regard to both capital expenditure and operating costs.

From the description of traditional and all-electric production control systems in chapters two and three, principal components in subsea production systems have been described. This breakdown of the system into components required for both systems shows that for an all-electric system several components will be eliminated. A comparison of principal subsea production system components in Table 13 also makes this clear.

	Traditional E-H MUX PCS	All-electric PCS (AC umbilical)
Power generation equipment	EPU	EPU
	HPU (with accumulators)	
	CIU (with accumulators)	CIU (with accumulators)
Power transmission equipment	TUTA	TUTA
	EPCDU	EPCDU
	HPDU (with accumulators)	
	Manifolds (with accumulators)	Manifolds (with accumulators)
	EH-MUX umbilicals	Power and signal umbilicals

Table 13: comparison of necessary equipment for E-H MUX and All-electric subsea production controls

Utilisation of all-electric controls exchange the pressure-related issues with a different set of main production system design and development issues, such as

- Altered production system weight concentrations
- Power transmission method (AC/DC)
- Electromagnetic compatibility of electrical and electronic umbilical components
- Xmas tree valve failsafe solutions
- Reliability of subsea communications and control

- Condition monitoring
- Alternative chemical injection solutions

5.2 Altered production control system weight concentrations

Starting with the first point on the list, the overall weight of an all-electric subsea production system will be smaller than a traditional E-H MUX design. A range of design solutions are responsible for the weight loss:

- Due to the elimination of hydraulic lines in umbilicals there will be significant decreases in distribution system weight per unit length. Use of alternative chemical injection methods could eliminate chemical injection tubing in addition. A graphic representation of an all-electric along with a traditional SPCS would show a remarkable difference in complexity. This is illustrated by the comparison with traditional and all-electric umbilicals in Figure 14.

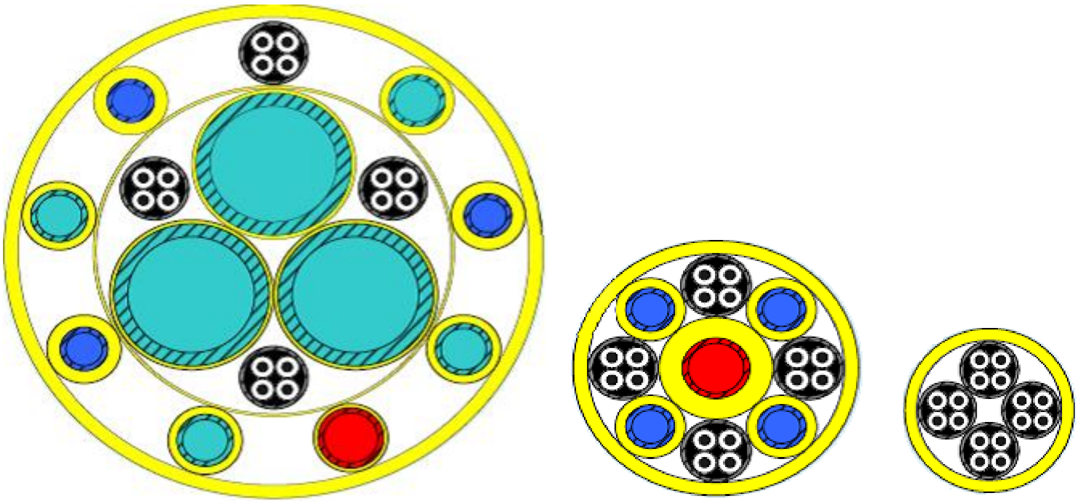


Figure 14: Comparison of electro-hydraulic, all-electric with chemical injection lines and all-electric umbilical (MacKenzie, Rory; Total E&P, 2011)

- Elimination of HPUs and affiliated piping which leads to a decreased weight of TUTU regains topside space that can be used or other purposes.

5.3 Power transmission method (AC/DC)

Transmission of AC power is more reliable with regards to electrical equipment failures over time. A disadvantage is that the step-out distances that can be achieved with AC transmission methods are limited without significant voltage losses. A subsea AC power network supply requires the inclusion of rectifiers, choppers and converters at XT locations. This increases the number of electronic components on the XT. This is currently the configuration of the CameronDC XT system. The complexity is then increased at a single point of the system. Total E&P has brought up issues with the electrical power distribution as a weak point in the system (MacKenzie, Rory; Total E&P, 2011). The results of analysis regarding these issues are not yet published, as the events of downtime are still under investigation (Abicht & Braehler, 2010).

Using DC transmission methods the wellhead offset distances from the surface facility and MCS have a much lower rate of voltage drop over large distances in comparison with AC transmission cables.

This is supported by the theoretical calculations performed in the previous chapter. A return to earth line could be to prevent corrosion of umbilical material or equipment using anode-cathode principle. High voltage DC (HVDC) cables are utilised in many applications onshore. Offshore, low and medium voltage lines are more common, as the powering requirements for conventional XT are usually between At the XT system umbilical power connector more complex power regulation and control modules need to be included, however, if DC power transmission is to be used.

5.4 Electromagnetic compatibility of electrical and electronic umbilical components

The increased complexity of the subsea production control equipment also includes added electronics and sensor equipment. Subsea control system can utilize signal-on-power configurations featuring copper co-axial cables or copper wiring and still perform well. However, with longer and longer distances, there are several issues that arise from those two transmission media.

With more complex data acquisition and electronic communications from the SEM, signal transmission through co-axial cables do not allow the bitrates and the long travel distances that fibre-optic cables can achieve. The connectors for fibre-optic cables have suffered a bad reputation due to failure to connect in several occasions, but have a low rate of failures in comparison with other subsea distribution system components.

5.5 Xmas tree valve failsafe solutions

The failures that can occur that disable the valves from functioning properly on a XT can arise from either mechanical or power distribution failures. In the case of power supply failure, the failsafe solution should therefore be to use backup methods such as a preloaded spring or an ROV-operated override torque mechanism that enables failure position of the valve to be engaged. This ROV torque mechanism could be either a battery-powered electric torque tool or a hydraulic torque tool with an integrated accumulator package.

The electro-hydraulic control system will, since it is supplied by both electric and hydraulic power, have two distribution failures that could lead to control system shutdowns; electric or hydraulic power loss. The all-electric production system has one; the loss of electrical power supply.

A spring failsafe arrangement needs to be dimensioned for the water depth of operation.

5.6 Reliability of subsea communications and control

With the first generation Cameron DC subsea production control system, downtime incurred during the first years of production were due to modem network communication failures. Not a lot of information regarding subsea all-electric production system performance have been published, so therefore a detailed discussion of system reliability is not possible. However, CameronDC has chosen fibre-optic communications for umbilical communications with the 2nd generation AET controls. One of the main advantages of fibre-optics over co-axial for signals transfer is the negligible effect of electro-magnetic fields on light pulse signals.

5.7 Condition monitoring

The corrosion of pipes and the material degradation of pressure vessels that compose the subsea production control system can be monitored using field signature method (FSM). This method will detect changes in the electron circulation of the system materials. This will give state of degradation of equipment such as pressure vessels containing control equipment. The MCS will receive such information real-time. The data collected can be used over time to register degradation rates. Maintenance or replacement of degraded equipment and material can then be organized without events.

The positions of all valve actuators and hence valve positions need to be known in order to operate the valves into the required and desired positions at any given time. To manage this production conditions need to be established. This enables accurate and safe control system management. Points in the system where control valves are located should have flow, pressure and temperature measurement devices that deliver real-time feed of conditions. Control feedback of actions made should also be as rapid as possible to ensure that control action decisions have been correct. For this purpose, magnetic sounding sensors are employed.

5.8 Alternative chemical injection solutions

As has been mentioned before, umbilicals will typically contain chemical fluid injection lines. There are possible solutions that could eliminate the components required for fluid injection from the umbilical. An illustration has also been shown in Figure 14 of an all-electric umbilical. This shows the potential umbilical weight and size reduction possible. Several concepts such as patent applications by Baker Hughes Incorporated illustrate some of the possible means of umbilical free fluid injection into the subsea field production pipe. The patent involves storage of chemicals for injection in reservoirs located at the wellhead. A logistics solution where ships transport chemicals to maintain the chemical fluid volumes is then organised. The ships then connect to refill the reservoirs using a buoy-riser system.

This is a concept that is also taken seriously by operator companies, as this would have a beneficial effect on operational costs. Operating fields with umbilical injection fluid lines can be quite costly as there have been cases where the chemical injection service lines become blocked due to different combinations of poor operating conditions such as:

- Low temperatures with respect to viscous properties of chemical fluid
- Chemical compatibility problems between chemical fluid and service line material

6 Summary

Through the course of this paper the goals have been to establish current level of AET production control systems development, address the technical limitations with respect to water depth and wellhead offset distances, and identify weak points.

The literature review that has been conducted for this paper has been substantial, and multi-disciplinary in nature. From this the different approaches to electrical controls have been apparent. In the case of Cameroon a have attempted, and succeeded in establishing a complete AET production system that has been qualified by operators. Other companies and organizations have developed tools that aid in raising the performance and improving the production in existing fields since 2001. Weak spots and improvement possibilities have been identified.

Long distance transmission of power requires additional signal reinforcement stations. With fibre-optics, single-step out distance without reinforcement is approximately 160 kilometres. Comparison of AC and DC power transmission methods shows that DC power has a reduced voltage drop over distance than AC. However, AC transformers are much simpler in maintenance and operational aspects than DC transformers. Failsafe solutions for the XT valve controls are still unaltered in the case of Aker Solutions electrical actuators and Cameron electrical gate valve actuators. Predictive maintenance for electrical control systems has been based on company experiences with similar systems in traditional controls.

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Appendices

Appendix A. Standards applicable to subsea control systems development

A1. ISO 13628 Petroleum and natural gas industries – Design and operation of subsea production systems

This standard contains general requirements, recommendations and guidance for subsea production systems development. The purpose of this ISO standard is to offer any individual project development a manner in which to deliver an optimal solution using recommended practices, ranges and limitations for safe and economic subsea production systems design.

It encourages users to utilise standardised connections and interfaces with respect to intervention and work-over possibilities and a minimalized requirement for specialised Intervention, Maintenance and Repair (IMR) equipment and methods. A focus on Reliability, Availability, Maintainability and Serviceability (RAMS) of the production system during the design process is also recommended. With a maintained focus on RAMS and IMR requirements and options as well as on the use of standardised connections and interfaces, life cycle costs (LCC) and reliability will be reduced and predictable.

A1.1. ISO 13628-4: Subsea wellhead and tree equipment

In part 4 of the above mentioned standard various subsea wellheads and subsea trees are specified- It also lists the tools and equipment required for installation and tests of the wellheads and trees.

Specifications and recommendations for design, fabrication, storage, transportation, quality control and marking code for subsea tree assemblies and sub-assemblies are also covered by part 4 of the standard. An additional reference that contains similar specifications and recommendations as well as guidance regarding above-mentioned areas of the development process is American Petroleum Institute (API) specification 17D.

A1.2. ISO 13628-5: Subsea umbilicals

In this part of the standard the guidelines and requirements for subsea umbilicals are specified. It offers recommendations and requirements for different signal cables, electric cables, hoses and tubes to be used for umbilical designs. The design, fabrication, storage, transportation, testing and installation stages are also covered by this part of the standard.

A1.3. ISO 13628-6: Subsea production control systems

Part 6 of ISO 13628 is applicable to the design, fabrication, testing, installation and operation of subsea production control systems. It covers surface control systems and subsea installed control systems. This equipment is utilized for control of subsea production of oil and gas and for subsea water and gas injection services.

A1.4. ISO 13628-8: ROV Interfaces on subsea production systems

This part of ISO 13628 specifies functional design requirements and guidelines for ROV interfaces on subsea production systems for the oil and gas industry. Selection and use of ROV interfaces with regards to standard equipment and design principles are assisted. It also presents guidelines for interface design for specific conditions and specifications of use.

A2. ISO 10423 Petroleum and natural gas industries - Drilling and production equipment - wellhead and x-mas tree equipment

A2. ISO 10423 specifies requirements and gives recommendations for the performance, dimensional and functional interchange-ability, design, materials, testing, inspection, welding, marking, handling, storing, shipment, purchasing, repair and remanufacture of wellhead and x-mas tree equipment for use in the oil and gas industries. This standard is based on the old API specification 6A seventeenth edition.

A3. NORSOK U-001 Subsea Production Systems

The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety and cost effectiveness for petroleum industry developments and operations. Furthermore, NORSOK standards are as far as possible intended to replace oil company specifications and serve as references in the regulations of relevant authorities.

A4. IEC 61508/61511 - Functional safety of electrical/electronic/programmable electronic safety related systems

IEC 61508 covers aspects to be considered when electrical, electronic or programmable electronic systems are to be used in safety functions. An objective of this standard is to enable development of safety-related systems that utilize the electrical, electronic and programmable electronic systems for which international standards may not exist. IEC 61511 gives requirements for the specification, design, installation, operation and maintenance of a safety instrumented system, so that it can be confidently entrusted to place and/or maintain the process in a safe state. This standard has been developed to implement a process industry version of the IEC 61508 standard.

A5. IWIS

The Intelligent Well Interface Standardization (IWIS) panel is a number of oil companies organized to assist the integration of down-hole power and communication architectures, subsea control systems and topsides by providing recommended specifications (and standards where appropriate) for power and communication architectures, and associated hardware requirements. This will give possibilities to implement more down-hole ’smart’ equipment in a timely and cost-effective manner. Improving compatibility should also eventually benefit reliability, and transparency when tackled as an industry group.

Appendix B. Theoretical calculations

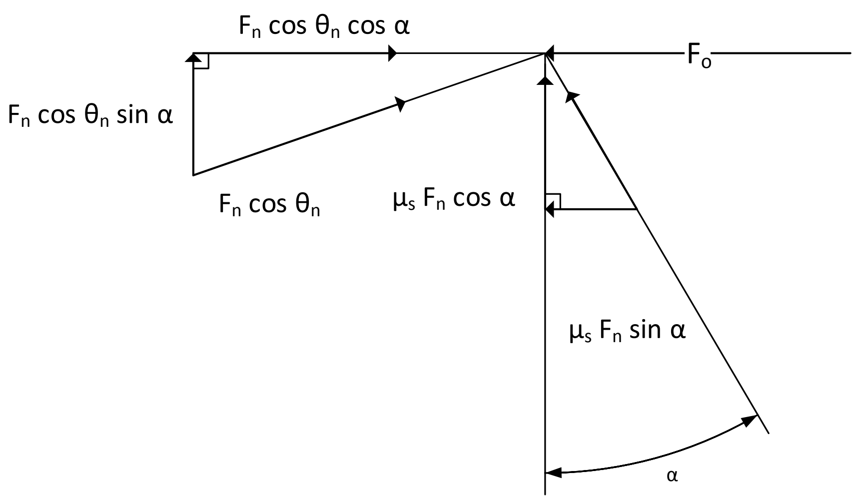
B1. Worst case loading for a VXT PMV with 10 000 psi pressure rating:

Valve parameters			Actuator parameters		
Valve diameter	5,125	inch	Actuator piston diameter, D_P	9	inch
Valve sealing diameter, D_{VS}	6,30	inch	Override stem diameter, D_{OS}	2,25	inch
Valve pressure rating, p_V	10000	psi	Valve stem diameter, D_{VS}	2,50	inch
Valve cavity pressure at crack open, p_{VC}	11150	psi	Actuator piston stroke, S_t	5,89	inch
Static friction factor, μ_S	0,20		Spring constant, c_S	4160,27	lb/inch
Dynamic friction factor, μ_D	0,15				

Seal packing friction			Valve pressure acting area		
$F_{SPF} =$	6000	lb	$A_V = \pi \cdot (D_{VS}/2)^2 =$	31,17	in^2
Spring preload			Actuator piston area		
$F_{SP} =$	30202	lb	$A_P = \pi \cdot (D_P/2)^2 =$	63,62	in^2
Valve force			Override stem area		
$F_V = A_V \cdot p_V =$	311725	lb	$A_{OS} = \pi \cdot (D_{OS}/2)^2 =$	3,98	in^2
Static friction force			Valve stem area		
$F_{SF} = F_V \cdot \mu_S =$	62345	lb	$A_{VS} = \pi \cdot (D_{VS}/2)^2 =$	4,91	in^2
Dynamic friction force					
$F_{DF} = F_V \cdot \mu_D =$	46759	lb			
Gate Valve Forces Bore pressure force on valve stem					
$F_{BP} = p_V \cdot A_{VS} =$	49087	lb			
Valve cavity pressure force on valve stem					
$F_{CP} = p_{VC} \cdot A_{VS} =$	54732	lb			
Net required force to initiate motion					
$F_{CO} = F_{CP} + F_{SF} + F_{SPF} + F_{SP} + (c_S \cdot 1in) =$	157440	lb			
$=$	61984	kg			

B2. Torque transmission and net linear actuation force yield through use of various screw designs

The electro-mechanical rotary-to-linear actuation mechanisms can be represented by the following free body diagram:



Forces in the vertical direction are assumed to sum to zero.

The equilibrium of forces in the horizontal direction of the above diagram is

$$F_n \cos\theta_n \cos\alpha = F_o + F_f \sin\alpha$$

Since $F_f = \mu_s \cdot F_n$, the equilibrium equation reduces to

$$F_n = \frac{F_o}{(\cos\theta_n \cos\alpha - \mu_s \cdot \sin\alpha)}$$

To obtain an expression for required torque for moving the loading along the screw, the moments about the centreline of the screw are taken:

$$T_r = F \cdot r_m = r_m(\mu_s \cdot F_n \cos\alpha + F_n \cos\theta_n \sin\alpha)$$

In addition there is a friction torque originating from friction force on the thrust block. This is assumed to be acting along the mean radius of the thrust block collar. Hence,

$$T_r = r_m(\mu_s \cdot F_n \cos\alpha + F_n \cos\theta_n \sin\alpha) + r_{mc}(\mu_c \cdot F_o)$$

By substitution of the expression obtained for F_n above into the torque equation, the following expression is presented:

$$T_r = F_o \cdot r_m \left(\frac{\mu_s \cos\alpha + \cos\theta_n \sin\alpha}{\cos\theta_n \cos\alpha - \mu_s \cdot \sin\alpha}\right) + r_{mc}(\mu_c \cdot F_o)$$

The torque expression can be further simplified by dividing of the first term numerator and denominator with $\cos\alpha$:

$$T_r = F_o \cdot r_m \left(\frac{\mu_s + \cos\theta_n \tan\alpha}{\cos\theta_n - \mu_s \cdot \tan\alpha}\right) + r_{mc}(\mu_c \cdot F_o)$$

$\theta_n = \tan^{-1}(\cos\alpha \tan\theta)$, hence the following expressions for torque with the screw mechanisms are obtained:

In general for screw designs and for power screw designs in particular:

$$T_{Travel} = \frac{d_{ms}F_o}{2}\left[\frac{\mu_s + \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos\left(\tan^{-1}(\cos\alpha\tan\theta)\right) - \mu_s\tan\alpha}\right] + \frac{d_{mc}\cdot\mu_c F_o}{2}$$

$$T_{Return} = \frac{d_{ms}F_c}{2}\left[\frac{\mu_s - \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos\left(\tan^{-1}(\cos\alpha\tan\theta)\right) + \mu_s\tan\alpha}\right] + \frac{d_{mc}\cdot\mu_c F_c}{2}$$

For ball screw and roller screw designs:

$$T_{Travel} = \frac{d_{ms}F_o}{2}\left[\frac{\mu_s + \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos(\tan^{-1}(\cos\alpha\tan\theta)) - \mu_s\tan\alpha}\right]$$

$$T_{Return} = \frac{d_{ms}F_c}{2}\left[\frac{\mu_s - \cos(\tan^{-1}(\cos\alpha\tan\theta))\tan\alpha}{\cos(\tan^{-1}(\cos\alpha\tan\theta)) + \mu_s\tan\alpha}\right]$$

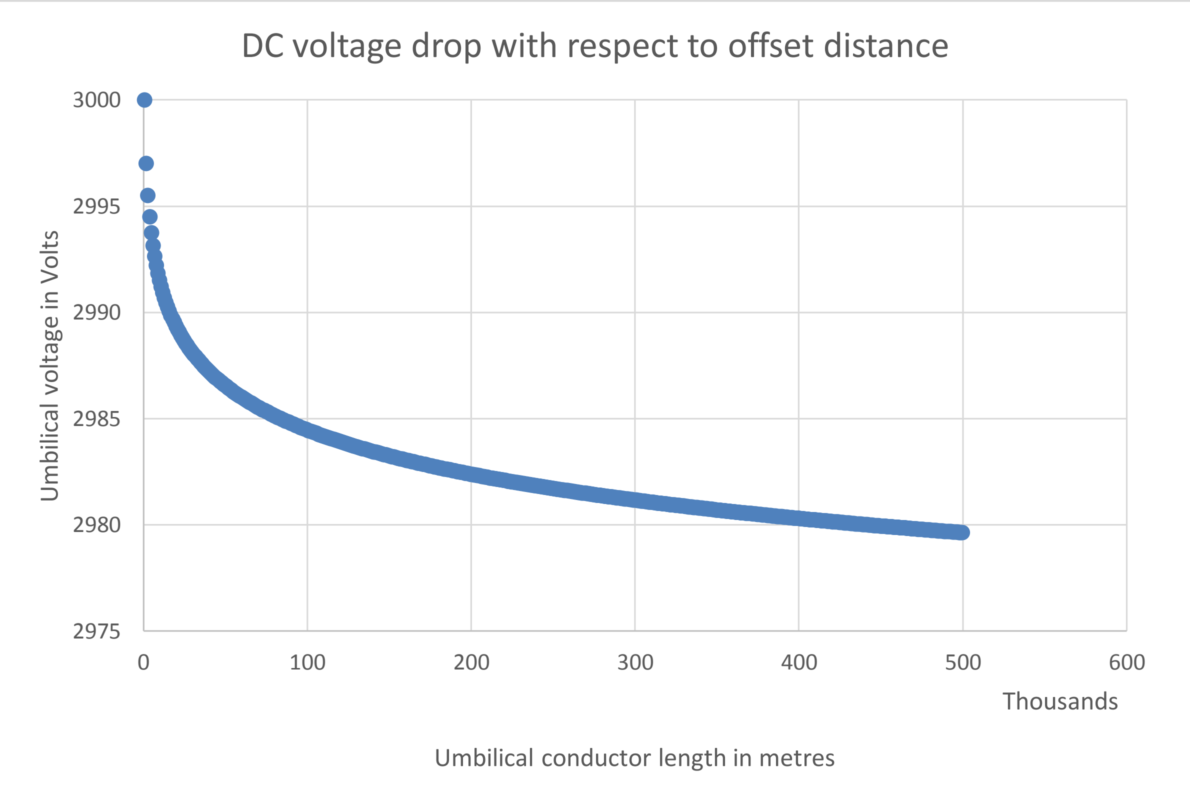
B3. Dielectric field strength and power handling calculation

Umbilical dielectric insulation

High-density poly-ethylene (HDPE)		
Relative dielectric constant	2.25	
Peak voltage (Vpeak)	3000.00	Volts
Outer radius (ro)	0.20	metres
Inner radius (ri)	0.10	metres
Electric field strength E(r)	43280.85	Joule
Impedance of a perfect vacuum	377.00	Ohm
Char. Impedance Z0	27.73	Ohm
Peak power (Ppeak)	162299.37	Watt
Resistance at peak power	324598.7369	Ohm
Air		
Relative dielectric constant	1.00058986	
Peak voltage (Vpeak)	3000.00	Volts
Outer radius (ro)	10.00	metres
Inner radius (ri)	0.01	metres
Electric field strength E(r)	43429.45	Joule
Impedance of a perfect vacuum	377.00	Ohm
Char. Impedance Z0	414.35	Ohm
Peak power (Ppeak)	10860.31	Watt
Resistance at peak power		
Water		
Relative dielectric constant	89	(at 5 degrees Celsius)
Peak voltage (Vpeak)	3000.00	Volts
Outer radius (ro)	5553.00	metres
Inner radius (ri)	0.01	metres
Electric field strength E(r)	22680.43	Joule
Impedance of a perfect vacuum	377.00	Ohm
Char. Impedance Z0	84.13	
Peak power (Ppeak)	53490.42	Watt
Resistance at peak power		

B4. DC Power transmission distance calculation using 3kV voltage and 400mm² conductor cable

Direct-Current (DC) Power Umbilical			
Umbilical parameters	**Value**	**Unit**	**Note**
Umbilical length	20000	metres	
Diameter of conductor	0.011283792	metres	
Conductor sectional area	0.0004	square metres	
Conductor material	**Copper**		
Resistivity	1.724E-08	Ohm metres	(at 20 degrees celsius)
Conductor resistance	0.862	Ohm	
Voltage	3000	Volts	
Current	3480.278422	Amps	
Power	10440835.27	Watts	



Power transmission distance	Voltage drop
1	3000
1000	2997
2000	2995.5
3000	2994.5
4000	2993.75
5000	2993.15
6000	2992.65

7000	2992.221429
8000	2991.846429
9000	2991.513095
10000	2991.213095
11000	2990.940368
12000	2990.690368
13000	2990.459599
14000	2990.245313
15000	2990.045313
16000	2989.857813
17000	2989.681342
18000	2989.514676
19000	2989.356781
20000	2989.206781
21000	2989.063924
22000	2988.92756
23000	2988.797125
24000	2988.672125
25000	2988.552125
26000	2988.436741
27000	2988.32563
28000	2988.218487
29000	2988.115039
30000	2988.015039
31000	2987.918264
32000	2987.824514
33000	2987.733605
34000	2987.64537
35000	2987.559656
36000	2987.476322
37000	2987.395241
38000	2987.316294
39000	2987.239371
40000	2987.164371
41000	2987.0912
42000	2987.019772
43000	2986.950004
44000	2986.881822
45000	2986.815156
46000	2986.749938
47000	2986.686108
48000	2986.623608
49000	2986.562384
50000	2986.502384
51000	2986.44356
52000	2986.385868
53000	2986.329264
54000	2986.273709

55000	2986.219163
56000	2986.165592
57000	2986.11296
58000	2986.061236
59000	2986.010389
60000	2985.960389
61000	2985.911208
62000	2985.862821
63000	2985.815202
64000	2985.768327
65000	2985.722173
66000	2985.676719
67000	2985.631943
68000	2985.587825
69000	2985.544347
70000	2985.50149
71000	2985.459236
72000	2985.41757
73000	2985.376474
74000	2985.335933
75000	2985.295933
76000	2985.256459
77000	2985.217498
78000	2985.179037
79000	2985.141062
80000	2985.103562
81000	2985.066525
82000	2985.02994
83000	2984.993795
84000	2984.958081
85000	2984.922787
86000	2984.887903
87000	2984.85342
88000	2984.819329
89000	2984.785622
90000	2984.752288
91000	2984.719321
92000	2984.686712
93000	2984.654454
94000	2984.62254
95000	2984.590961
96000	2984.559711
97000	2984.528783
98000	2984.49817
99000	2984.467867
100000	2984.437867
101000	2984.408164
102000	2984.378753

103000	2984.349626
104000	2984.32078
105000	2984.292209
106000	2984.263907
107000	2984.23587
108000	2984.208092
109000	2984.180569
110000	2984.153296
111000	2984.126269
112000	2984.099483
113000	2984.072935
114000	2984.046619
115000	2984.020532
116000	2983.99467
117000	2983.969029
118000	2983.943605
119000	2983.918395
120000	2983.893395
121000	2983.868602
122000	2983.844012
123000	2983.819621
124000	2983.795428
125000	2983.771428
126000	2983.747618
127000	2983.723996
128000	2983.700559
129000	2983.677303
130000	2983.654226
131000	2983.631325
132000	2983.608598
133000	2983.586042
134000	2983.563653
135000	2983.541431
136000	2983.519372
137000	2983.497475
138000	2983.475736
139000	2983.454153
140000	2983.432724
141000	2983.411448
142000	2983.390321
143000	2983.369342
144000	2983.348508
145000	2983.327819
146000	2983.307271
147000	2983.286863
148000	2983.266592
149000	2983.246458
150000	2983.226458

151000	2983.206591
152000	2983.186854
153000	2983.167246
154000	2983.147765
155000	2983.128411
156000	2983.10918
157000	2983.090072
158000	2983.071084
159000	2983.052216
160000	2983.033466
161000	2983.014833
162000	2982.996314
163000	2982.977909
164000	2982.959617
165000	2982.941435
166000	2982.923363
167000	2982.905398
168000	2982.887541
169000	2982.86979
170000	2982.852143
171000	2982.834599
172000	2982.817157
173000	2982.799816
174000	2982.782575
175000	2982.765432
176000	2982.748386
177000	2982.731437
178000	2982.714583
179000	2982.697824
180000	2982.681157
181000	2982.664582
182000	2982.648099
183000	2982.631705
184000	2982.615401
185000	2982.599185
186000	2982.583056
187000	2982.567013
188000	2982.551055
189000	2982.535182
190000	2982.519393
191000	2982.503686
192000	2982.488061
193000	2982.472517
194000	2982.457053
195000	2982.441669
196000	2982.426362
197000	2982.411134
198000	2982.395983

199000	2982.380907
200000	2982.365907
201000	2982.350982
202000	2982.33613
203000	2982.321352
204000	2982.306646
205000	2982.292012
206000	2982.277449
207000	2982.262956
208000	2982.248533
209000	2982.234179
210000	2982.219893
211000	2982.205675
212000	2982.191524
213000	2982.17744
214000	2982.163421
215000	2982.149468
216000	2982.135579
217000	2982.121754
218000	2982.107992
219000	2982.094294
220000	2982.080657
221000	2982.067083
222000	2982.053569
223000	2982.040116
224000	2982.026723
225000	2982.01339
226000	2982.000116
227000	2981.9869
228000	2981.973742
229000	2981.960642
230000	2981.947598
231000	2981.934611
232000	2981.92168
233000	2981.908804
234000	2981.895984
235000	2981.883218
236000	2981.870506
237000	2981.857848
238000	2981.845243
239000	2981.832691
240000	2981.820191
241000	2981.807742
242000	2981.795346
243000	2981.783
244000	2981.770705
245000	2981.75846
246000	2981.746265

247000	2981.734119
248000	2981.722022
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250000	2981.697974
251000	2981.686022
252000	2981.674117
253000	2981.66226
254000	2981.650449
255000	2981.638684
256000	2981.626965
257000	2981.615292
258000	2981.603664
259000	2981.592081
260000	2981.580543
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262000	2981.557598
263000	2981.546191
264000	2981.534827
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266000	2981.512229
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268000	2981.489799
269000	2981.478646
270000	2981.467535
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274000	2981.423498
275000	2981.412588
276000	2981.401719
277000	2981.390889
278000	2981.380097
279000	2981.369345
280000	2981.35863
281000	2981.347954
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283000	2981.326715
284000	2981.316152
285000	2981.305625
286000	2981.295136
287000	2981.284683
288000	2981.274266
289000	2981.263886
290000	2981.253541
291000	2981.243232
292000	2981.232958
293000	2981.222719
294000	2981.212515

295000	2981.202345
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298000	2981.172042
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