DAS Departamento de Automação e Sistemas
CTC Centro Tecnológico
UFSC Universidade Federal de Santa Catarina

Instrumentation, Electrical Drive Specification and Software Concept for an Electro-Hydrostatic Subsea Valve Actuator

Relatório submetido à Universidade Federal de Santa Catarina
como requisito para a aprovação na disciplina
DAS 5511: Projeto de Fim de Curso

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Lohr am Main, Julho de 2016.

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Esta monografia foi julgada no contexto da disciplina
DAS5511: Projeto de Fim de Curso
e aprovada na sua forma final pelo
Curso de Engenharia de Controle e Automação

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Acknowledgements

Throughout the preparation of this document, it has occurred to me that it is also a very well defined milestone of one peculiar period in my life. The conclusion of my academic graduation comprises much more than accumulated technical knowledge. In the last five years, while living with different people, I have witnessed a lot of thought divergence at times. But all that clash certainly contributed to build me a diverse and respectful personality. This gives me just as much confidence to live and work in society with responsibility, as the academic formal knowledge that I've acquired does.

That being said, I acknowledge and am thankful for uncountable people that helped me directly and indirectly. I dedicate my efforts to all of them. Unfortunately I can't name them all, so I'll highlight the most significant individuals, without whom I would definitely have stalled. First of all, I thank my parents, Amadeu Plácido Filho and Márcia Gonçalves Plácido for basically everything I have and am in life (self-determination seems to be an inheritable trait). I thank my sisters Juliana Gonçalves Plácido and Carolina Gonçalves Plácido who have also provided (and keep providing) me much love and support for as long as I can remember. And I thank my girlfriend, friend and partner Bárbara Galle Lopedote, who listened to me whenever I needed, gave me advice, comfort, love, motivation and never hesitated to support me.

I thank my employer Alexandre Orth, who trusted me with the wonderful opportunity to work in this very interesting project with adequate responsibility and much respect. I thank my work colleagues, especially my supervisor Alexander Drikitis who supported me in all technical or bureaucratic matters, gave me valuable life advices and made the work environment so pleasant and comfortable to me. I thank my hosts Ruth Feige and Heinz Stegerwald for treating me like part of their family and making me feel at home even in foreign lands. I thank my professors at UFSC, specially my advisor Prof. Victor Juliano De Negri, for having provided me with the knowledge that I extensively used here inside and outside the work premises. And finally, I thank my old friends and the friends I met here for sharing their shoulders and companionship at all times.

„Wenn gute Reden sie begleiten,

Dann fließt die Arbeit munter fort."

Das Lied von der Glocke (1799), Friedrich Schiller

Resumo

A Bosch Rexroth AG é uma companhia de engenharia especializada em acionamento e controle de todo porte, para aplicações industriais e móveis. Atualmente ela é a unidade de Negócios de Tecnologia da Automação da Robert Bosch GmbH, sendo uma subsidiária integral da última.

Dentre os setores industriais da companhia, o setor Marine & Offshore desenvolve soluções de atuação e controle nos processos de exploração e produção de petróleo e gás offshore, também na instalação, comissionamento e decomissionamento de plataformas e turbinas eólicas offshore.

Recentemente, com mais descobertas de campos petrolíferos em águas profundas (> 1000 m de profundidade), novas tecnologias buscam reduzir os custos da extração e maximizar a produção. Para isso, uma tendência no setor está propendendo em transferir a infraestrutura das plataformas na superfície para o fundo do mar. No entanto, as elevadas pressões, grandes distâncias de transmissão de energia/informação e o ambiente quimicamente agressivo da zona batipelágica, são alguns dos grandes desafios no desenvolvimento da tecnologia para este setor.

Neste trabalho será proposto um novo conceito de um atuador compacto eletro-hidrostático para válvulas em árvores de Natal molhadas, manifold e chokes. Primeiramente será dado uma perspectiva geral da exploração de petroléo offshore e será ilustrado o estado da arte dos atuadores no mercado, e as vantagens do projeto proposto sobre as tecnologias atuais. Finalmente, serão explicadas as metodologias de projeto utilizadas no decorrer do trabalho.

No capítulo seguinte serão esclarecidos todos os requisitos de projeto, os quais foram definidos à partir de uma descrição da aplicação, amparado em normas internacionais de engenharia, padrões internos da Bosch Rexroth, e acordos entre os parceiros de desenvolvimento de projeto.

O terceiro capítulo cobrirá a etapa de especificação e seleção dos atuadores, transdutores e demais elementos eletro-eletrônicos que compõem todas as partes do sistema, bem como a elaboração dos mecanismos do sistema elétrico. Nesta seção também serão descritos os sistemas de acionamento elétrico e monitoramento do sistema.

O início do desenvolvimento conceitual do software para o controle e interface do sistema será descrito no capítulo quatro. Nele serão descritos através de diagramas formais a arquitetura básica, o funcionamento do software, a abstração do sistema, e a funções necessárias para cumprir os requisitos de projeto.

Os resultados da avaliação do cumprimento dos requisitos através das soluções propostas serão discutidos no quinto capítulo. Por fim, este documento se concluirá com uma breve explanação dos trabalhos futuros para a finalização do projeto como um todo.

Palavras-chave: Subsea, Electro-Hydrostatic Actuator, Instrumentation, Valve Actuator, Offshore, Oil & Gas.

Abstract

Bosch Rexroth AG is an engineering company specialized in drive and control technologies, including for the Marine & Offshore industry. Recently, with the growing discovery of oil and gas fields in deep waters (> 1000 meters depth), new technologies seek to reduce the extraction costs and maximize production. To achieve these goals, a trend in the sector is transferring the surface infrastructure to the seabed. However, the high pressure, long distances of energy and material transport and the chemically harsh environment of the bathypelagic zone are great challenges to overcome while developing technologies for this sector. In this thesis, it is exhibited a proposition of a novel concept of compact electro-hydrostatic valve actuators for subsea Christmas trees, manifolds and chokes. It's illustrated the state of art in valve actuators available in the market and the advantages of the proposed project over the current technologies. This work focuses primarily in the synthesis of the electrical drive system design, the system instrumentation and the control software concept.

Keywords: Subsea, Electro-Hydrostatic Actuator, Instrumentation, Valve Actuator, Offshore, Oil & Gas.

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Symbols

AC	Alternating Current
ACM	Actuator Control Module
ADC	Analog-Digital Converter
BG	Linear position encoder (IEC 81346-2)
BLDC	Brushless Direct Current (Motor)
BM	Water contamination detector (IEC 81346-2)
BOP	Blowout Preventer
BP	Pressure transducer (IEC 81346-2)
C_{ACT}	Actual seawater concentration in the hydraulic fluid [ppm]
C_{MEAS}	Measured seawater concentration in the hydraulic fluid [ppm]
$C_{\%ERR}$	Maximum percentage of reading error of seawater concentration [%]
CAN	Controller Area Network
CDR	Critical Design Review
CF	Data logger (IEC 81346-2)
CI	Configuration Item
CM	Configuration Management
DAQ	Data Acquisition System
DC	Direct Current
EHA	Electro-hydrostatic actuator
EMC	Electromagnetic Compatibility
EMF	Electromotive Force
EMI	Electromagnetic Interference
F_{stem}	Stem force, the axial force on the stem due to well pressure at stem head
F_{drag}	Drag force, the friction of gate valve due to pressure difference over the valve
F_{seal}	Friction force due to the stem seals
F_{sp}	Spring force, the force required for safety closure
F_{fric}	Friction force, the friction due to the cylinder seals

F_{cyl}	Cylinder force, the hydraulic force due to oil pressure in A and B compartments
F_{vac}	Vacuum force, force due to vacuum chamber
F_{enc}	Enclosure force, force due to the enclosure pressure acting on the shaft
FAT	Factory Acceptance Test
FCR	Final Contract Review
FMEA	Failure Mode Effects Analysis
FPSO	Floating Production Storage and Offloading
HPU	Hydraulic Power Unit
HW	Hardware
IEC	International Electrotechnical Commission
IP	International Protection Marking (IEC 60529)
ISD	Intelligent Subsea Device
ISO	International Organization for Standardization
KF	PLC unit (IEC 81346-2)
LVDT	Linear Variable Differential Transformer
MA	Electric motor (IEC 81346-2)
MCS	Master Control System
P_{COMP}	Additional compensated pressure
$P_{COMPmax}$	Maximum additional compensated pressure
$P_{COMPmin}$	Minimum additional compensated pressure
P_{EXT}	External absolute pressure [Pa]
P_{INT}	Internal absolute pressure [Pa]
PDR	Preliminary Design Review
PEEK	Polyetheretherketone
PLC	Programmable Logic Controller
POU	Program Organization Unit
PRR	Production Readiness Review
ROV	Remotely Operated Vehicle
QA	Electric motor driver (IEC 81346-2)
QB	Relay (IEC 81346-2)
QM	Valve solenoid (IEC 81346-2)

S_{ACT}	Actual cylinder shaft position [m]
S_{MEAS}	Measured cylinder shaft position [m]
S_{N}	Nominal working stroke length [m]
S_{NERR}	Absolute stroke length tolerance [m]
S_{SPRING}	Difference of completely relaxed and completely compressed spring [m]
S_{TEST}	Small length to run system diagnostic procedures [m]
SAT	Site Acceptance Test
SCM	Subsea Control Module
SCSSV	Surface Controlled Subsea Safety Valve
SEM	Subsea Electronic Module
SFC	Sequential Function Chart
SIIS	Subsea Instrumentation Interface Standardization
SIL	Safety Integrity Level (IEC 61508)
SVA	Subsea Valve Actuator
SW	Software
TA	Power supply (IEC 81346-2)
T_{NCA}	Nominal time to actively close the valve [s]
T_{NCAmax}	Maximum time to actively close the valve [s]
T_{NCAmin}	Minimum time to actively close the valve [s]
T_{NCP}	Nominal time to passively close the valve [s]
T_{NCPmax}	Maximum time to passively close the valve [s]
T_{NCPmin}	Minimum time to passively close the valve [s]
T_{NCR}	Nominal time to close the valve via ROV override [s]
T_{NCRmax}	Maximum time to close the valve via ROV override [s]
T_{NCRmin}	Minimum time to close the valve via ROV override [s]
T_{NO}	Nominal time to open the valve [s]
T_{NOmax}	Maximum time to open the valve [s]
T_{NOmin}	Minimum time to open the valve [s]
TBD	To be defined
V_{ACT}	Actual hydraulic fluid volume (compensated for temperature and pressure variation) [m^3]
V_{LEAK}	Lost hydraulic fluid volume due to leakage [m^3]

V_{MEAS}	Measured hydraulic fluid volume (compensated for temperature and pressure variation) [m^3]
$V_{\%ERR}$	Maximum percentage of reading error of hydraulic fluid volume [%]
X_{CL}	Fluid cleanliness level threshold
XD	Electric connector (IEC 81346-2)
Δ_1	Maximum number of external connector pins in the SVA-V1
Δ_2	Maximum number of external connector pins in the SVA-V2
λ	SIL specified for the safety-related function
Ψ_{MAX}	Maximum peak power consumption [W]

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1. Introduction

As the world's population grows along with the economy and industries, so increases the demand for energy. Forecasts accounts an increment of 40% in energy demand by 2030. It is expected that China alone will raise its current oil consumption to over three times by the next two decades [1]. This scenario accelerates the necessity to find more energy sources, such as fossil fuel reserves, and the urge to explore them.

About 71% of the Earth's surface is covered with water, from that, approximately 62% are seas deeper than one thousand meters, as is shown in the bathymetric curve in Figure 1.1. In 2004, 34% of the oil production in the world occurred offshore, while the offshore gas production accounted for 28%. It is expected that most of the undiscovered oil and gas fields in the world lie in deep sea offshore environments. The current predictions state that, by 2030, 48% of all oil production and 42% of all gas production will occur offshore [1]. Following the trends, the progressive development of technology to enable further exploration of these resources more efficiently is inevitable.

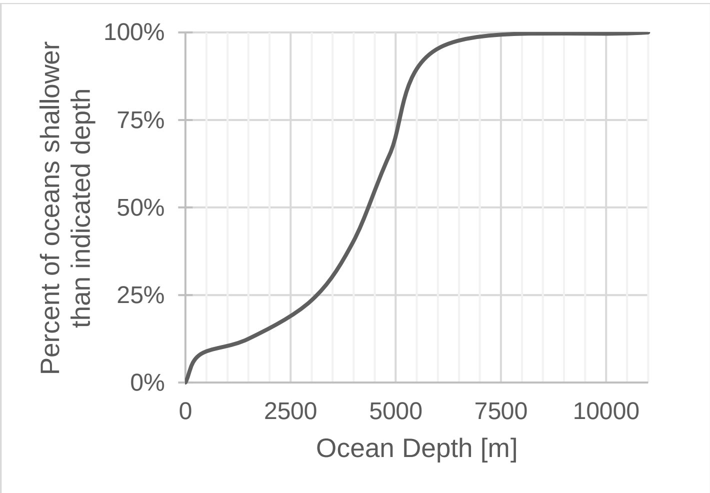

Figure 1.1: Bathymetric profile of the Earth's water bodies [2]

With the given background, this final term project report is an endeavor to stretch the development of subsea technologies, which are required to overcome the future energetic challenges of mankind.

This chapter will briefly introduce part of the offshore oil & gas production chain with a historical recollection in this industry branch, the main oil fields in the world and a description of the operation of a subsea factory and its main components. Then it will highlight the elements which require drive and control components, more specifically the production templates and manifolds. Afterwards, there is an explanation and depiction of the current technologies used in subsea actuators. The chapter is then concluded with the presentation of this project's proposal: a new concept of compact subsea valve actuators.

It is important to remark that, throughout the whole document, all component supplier names as well as system calculations, parameters and detailed diagrams were omitted or masked to preserve the intellectual property of the industry. Almost all of the work developed in this project has been removed from this document, leaving only the uncompromising line of thought to be evaluated. The scientific methodology employed, however, keeps the academic rigor and character of this thesis.

1.1. Offshore Oil & Gas Exploration

The exploration of oil & gas commodities over water bodies can be traced back to the 1930s, when the first marine geological surveys indicated the extension of onshore oil fields around the coastlines further underneath seabed [3]. For the next few decades, offshore oil & gas exploration quickly evolved along as new technologies were created to enable the development of this industry.

As new oil fields were discovered in deeper waters, the industry paradigm had to shift in order to pay off the increasingly costs of high depth exploration. The standard approach of keeping most of the production infrastructure on platforms in the surface, had to give place to a trend of moving the oil & gas extracting and processing equipment underwater while leaving only a few elements on a floating vessel [4]. In addition to this, the growing political pressure of environmentalist organizations inflicted more stringent governmental limitations to the fossil fuel exploration industry [4]. This new subsea environmental and ecological concerns provided great new challenges for oil & gas engineering designs.

Currently, there are fields beings explored of up to 7.000 meters below the surface, with the seabed depth at 2.200 meters beneath sea-level, as is the example of the Lula Field in the Santos Basin [6][7]. Some of the many factors that draw obstacles to subsea application design are the absolute pressure in the seafloor at such depth being around 22 MPa, temperatures as low as 4 ºC and the considerable length of umbilicals and risers.

1.2. Subsea Production System

1.2.1. Life Cycle of an Offshore Oil & Gas Field

The life cycle of the industrial exploration of an oil and gas field can be depicted in five main stages as is shown in Figure 1.2. It all starts with a geological survey, which begins with an exploration permit of an area, given to the oil companies by the local government. The survey is commonly carried out by seismic vessels and this process can take up to five years in average. After scanning an area, the likelihood of the presence of hydrocarbons in it is indicated by the observed rock formations and geological structures [8].

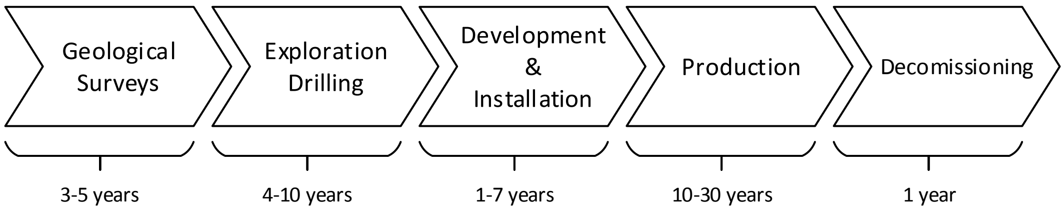

Figure 1.2: Life cycle stages of an oil & gas field (adapted from [8])

The next stage is the exploration drilling. In this stage, a drilling rig (semi-submersible, drill ship, jack-up, spar, etc…) is used to confirm the presence of hydrocarbons in the investigated field and study the economic viability of oil and gas production. It takes from four to ten years.

If the field is proven to be profitable, the third stage is carried out. It is where the industrial development of the field begins. In this stage the piping to channel the produced oil and gas is installed and the production wells are drilled and instrumented. The time required to equip the field with all the production infrastructure depends on the size of the field, and can take up to seven years.

After the field is tested and equipped, the fourth stage begins with the production of oil and gas. The complete depletion of a field takes from ten to thirty years, depending on the size of the field. Because of the high costs of subsea commissioning, all subsea components involved in the production must operate during this period without failure and only *in situ* maintenance. Thus, the service life required for these equipment is typically 20 years.

After the field exhausts, through which is called the natural decline of the field, the last stage takes part. This is where all equipment must be decommissioned and the wells cemented. This stage takes up to one year for a complete decommissioning, after which the license is removed by the competent authorities.

1.2.2. Subsea Factory Overview

Figure 1.3 illustrates a typical subsea production system, also called subsea factory. These are the equipment installed during the third stage of an oil field and operated throughout the fourth stage. A basic structure of a subsea factory is composed of production templates, manifolds, water injection templates, power distributor and process controller unit, oil and gas lift systems. In some fields, the produced fluid can also be separated and stored in specific subsea facilities.

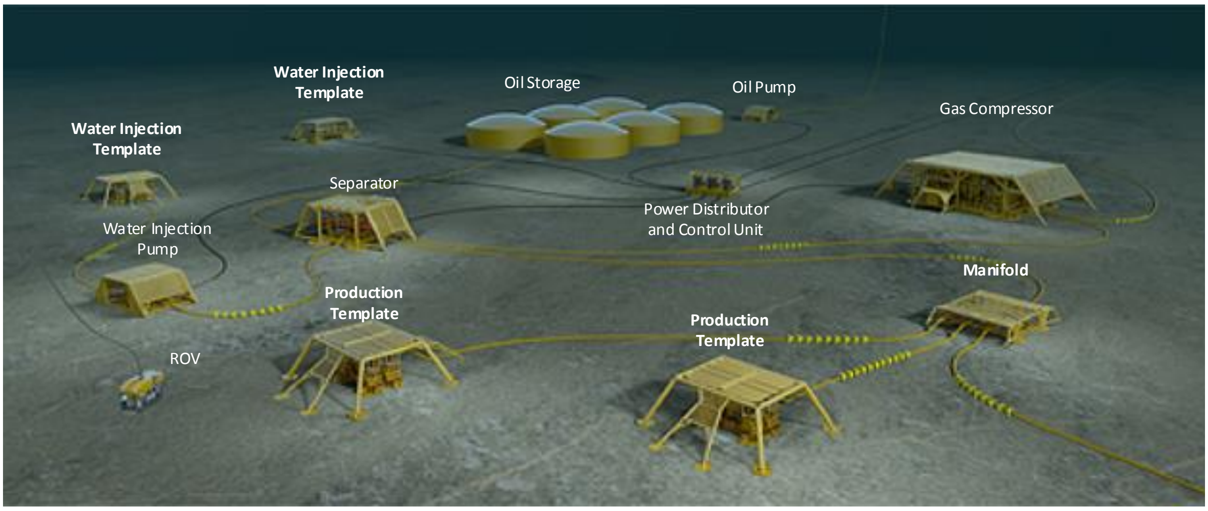

Figure 1.3: Subsea factory overview [9]

The oil and gas are extracted from the field in a mixture of sand, seawater and hydrocarbons in the production templates (also known as multi-well template). All production wells are then clustered in the manifold. From there, the extracted fluid can be either sent through a subsea separator, be stored or be pumped directly to the surface. It is more efficient to separate the mixture in the seabed, because less energy is spent pumping seawater and sand to the surface. Moreover, pumping oil and gas separately can be done more efficiently with specific equipment, a booster pump and a gas compressor respectively [10]. The oil storage facility functions as a production buffer for the offshore rig. The water obtained in the produced fluid is pumped back in the field in the water injection templates, in order to increase the field pressure.

The connection between a subsea factory and the surface rig is done via what are called risers and umbilicals. The risers are pipes through which the produced hydrocarbons are transported to the surface and injected fluids are transported back to the seabed, whereas an umbilical is a bundle of flexible cables and ducts through which all electrical and hydraulic power lines and control signals are conducted. Umbilicals can be as long as 100 km, for some of them extends throughout the whole field area [11]. All subsea processes are typically powered electrically and/or hydraulically from the surface rig, locally distributed and usually controlled by the subsea power distribution/control units. These units are typically subsea control/electronic modules (SCM/SEM) [12]. To allow manual intervention in deep sea environments, remotely operated vehicles (ROVs) are used to manipulate handles and interfaces in most of the subsea infrastructure [13].

1.2.3. Christmas Trees and Manifolds

For a better understanding of the theme of this report, in-depth explanation of some of the subsea machinery is necessary, namely the manifold and the Christmas trees. The latter are mounted in a production or water injection template.

1.2.3.1. Production Template

Starting off with the production template, in short, it is typically composed of a subsea wellhead and a subsea Christmas tree.

The subsea wellhead system, in turn, is a piece of equipment which consists, at first, of a wellhead housing that is fixed in the top of a well’s conductor before drilling it. During the drilling process, a blowout preventer (BOP) is mounted on the wellhead housing to protect the environment from possible oil spills caused by blowouts. After the well is drilled, the BOP can be removed and casing hangers with sealing assembly are installed in stack on the wellhead housing. Figure 1.4 shows a typical subsea wellhead system with its constituting elements. The casing hangers supports the cemented tubes through the wellbore. Finally, the wellhead housing functions as an interface to the subsea Christmas tree [14]. A temporary cap is used while the Christmas tree is prepared to be installed, so it prevents subsea debris from clogging the wellhead.

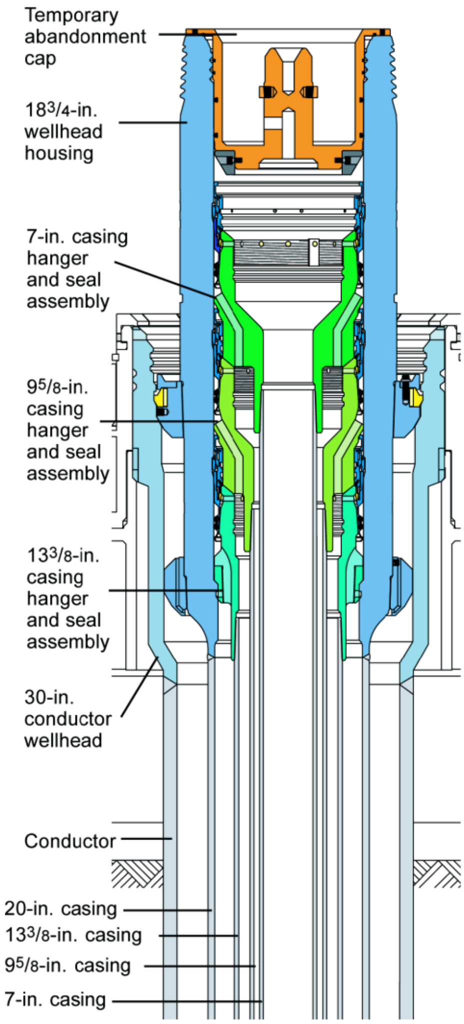

Figure 1.4: Wellhead components (colored) [15]

The subsea Christmas tree is an assembly of valves whose function is to allow flow control, well closure, safety closure, well maintenance/test, chemical injection and monitoring of production parameters. Historically, the array of valves in series used in onshore wells resembles a Christmas tree, hence the name. The subsea trees, as they are also called, can be classified as vertical or horizontal trees, and the vertical trees can be further named as a mono-bore or dual-bore tree. The classification depends in the orientation of its master valves in the assembly (vertical or horizontal) and the amount of annulus/production bores they have. The production bore and its valves are related to bulk hydrocarbon extraction. The annulus bore and its valves are used for troubleshooting, well servicing, conversion operations and chemical injection (to liquefy crude oil, for instance) and usually have a smaller diameter than the production bore. Both bores are usually isolated from each other. Regardless of the tree type, the general valve assembly in a Christmas tree has the following valves:

- **Surface Controlled Subsea Safety Valve (SCSSV)**

  An ON-OFF valve, which is directly actuated from the surface, when the well outflow is uncontrolled. It is the first valve in the production bore flow and is the main safety barrier during production [16].

- **Master Valves**

  They are ON-OFF valves. Their function is to completely shut their respective bore tubing of the well. The production master valve opens/closes the production tubing, while the annulus master valve latches the injection flow, and normally it remains closed during production. They are arranged in a redundant structure to improve reliability/availability. Typically the production master valve is the valve next to the SCSSV in the production flow. The annulus master valve is the first valve in its piping.

- **Wing Valves**

  These are continuously controllable valves, whose function is to control the flow of its bore. They are located between the master valves and the external outlets. When the well must be closed, these valves are the first to be shut. The annulus wing valve is normally closed.

- **Swab Valves**

  Swab valves are used during workover processes. They provide a controllable and safe re-entry into the well structure when the workover equipment is being installed on top of the well. They are only opened when the workover equipment is properly attached and sealed.

- **Cross Over Valve**

This valve allows the communication between the annulus and production bores. It can be used to bleed up a pressure rise for instance [14].

All valves used in a Christmas tree are fail safe, that means that in the event of system failure, the valves return to a safe-state to mitigate hazards. In average, a subsea tree contains 8 valves. Typically they are all gate valve types. The subsea tree is attached on top of the wellhead housing through a support interface piece called tubing hanger. In Figure 1.5 and Figure 1.6 there are schematics of both horizontal and vertical trees, respectively. In Figure 1.7 there is a picture of a vertical subsea Christmas tree.

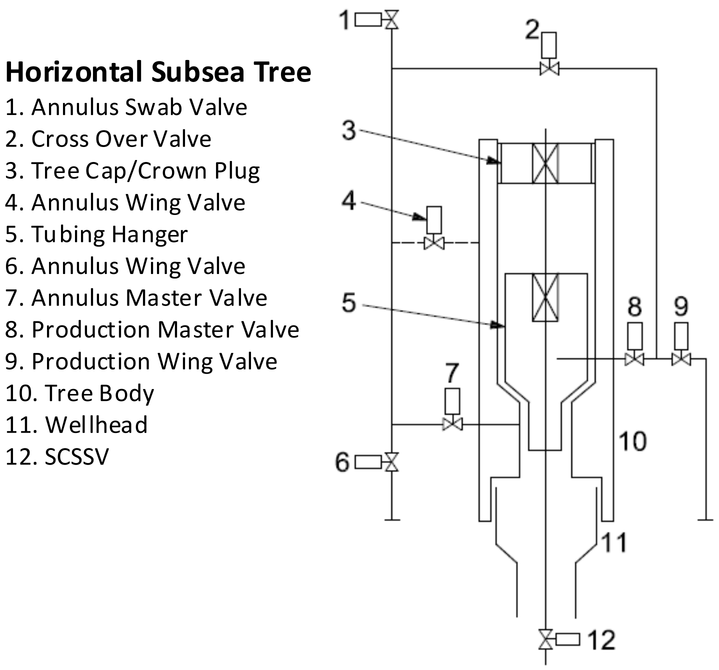

Figure 1.5: Main elements in a horizontal subsea Christmas tree [14]

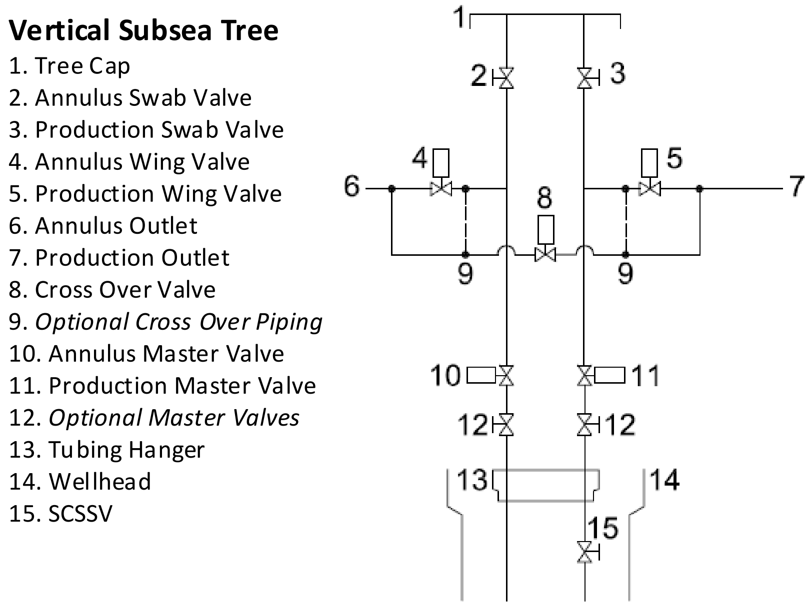

Figure 1.6: Main elements in a vertical subsea Christmas tree [14]

Figure 1.7: An actual subsea vertical Christmas tree, the GE VetcoGray D-Series DVXT

A template itself is a passive part that offers the structural framework and foundation for the installation of the subsea functional machinery, such as wellhead and Christmas tree pairs, manifolds, completion equipment, and all other subsea infrastructure [17]. The production template is specifically a template system composed of a wellhead and a Christmas tree (active parts). Although a water injection template also has its own peculiar structure (won't be detailed in this document), many of the valves in its system are of the same type as the production template.

1.2.3.2. Manifold

The hydrocarbons extracted in the production templates have to be clustered to be distributed to the other processing facilities. In a subsea factory, the unit that gathers the production flow, distributes injection flow and normalizes the pressure is called manifold. A typical manifold is an array of valves and chokes to control the flow and pressure of each well outlet that is connected to it. It is usually mounted on a central template and connected to multiple production templates and/or water injection templates, as shown in Figure 1.8.

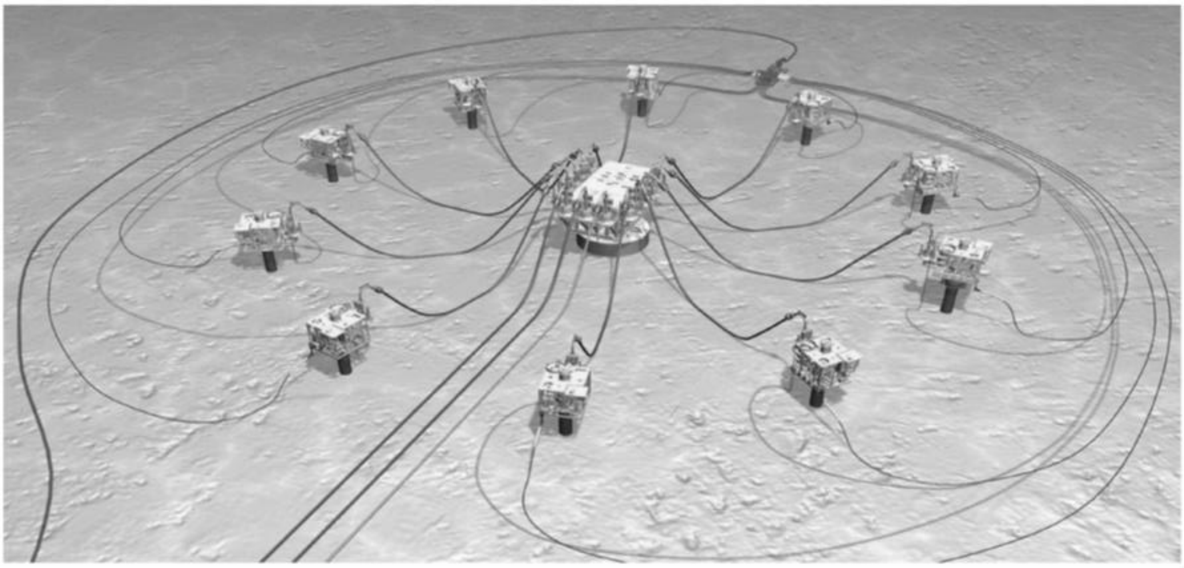

Figure 1.8: A central manifold connected to production templates [18]

There are several different types of manifold systems, each with adequate complexity for the field and function it is designed. The valves are arranged in parallel in respect to each production/injection template. Currently, most manifold valves are hydraulically piloted, ON-OFF valves [4]. For every production template linked to the manifold, there are at least two valves: one for production line and other for well test line. Meanwhile, injection trees requires one valve each. Each different fluid line in the manifold also has its own shut valve. Figure 1.9 illustrates a typical manifold schematic.

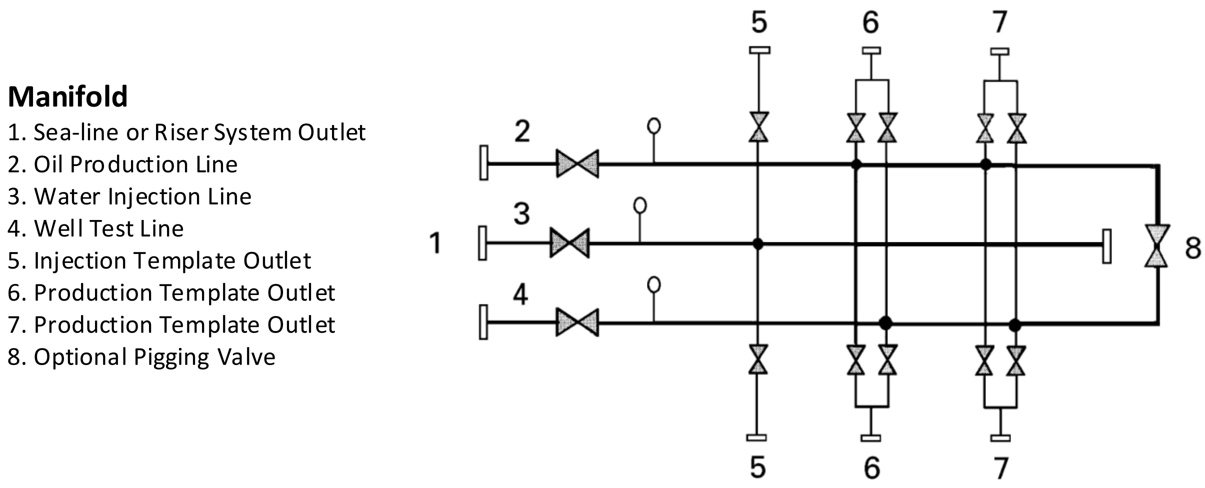

Figure 1.9: Main elements in a subsea manifold [17]

To normalize the various pressure levels coming from the flow of each production template, devices known as chokes as used. The subsea chokes are located after the production wing valve in the Christmas trees and before the production line valves in the manifold. The device can be either mounted in the production template or in the manifold. Similar to the wing valves, choke actuators can be continuously positioned to enable fine pressure control. In Figure 1.10 there are illustrations of different subsea choke types.

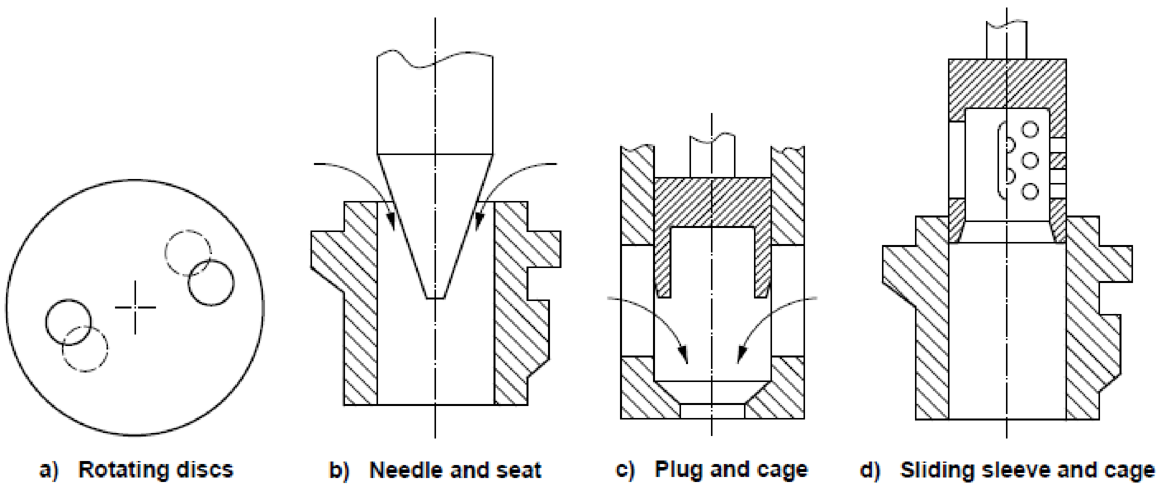

Figure 1.10: Different types of subsea chokes [14]

1.3. Subsea Actuator Systems

All valves utilized in the production and injection templates as well as the manifolds need a driving element and its controlling system unit. As aforementioned, the chokes are also moving machinery that require drive and control systems. A solution-neutral structure for a local drive and control system is given in the diagram of Figure 1.11.

The primary energy source is the element that supplies the energy to actuate over the material flow. It also provides energy to the control unit. Common forms of primary energy source in subsea applications are electrical and hydraulic energy. The energy transformation mechanism is a system that transforms the primary energy into the final form of energy used to actuate, which in this case is mechanic (kinetic) energy. The control unit is a regulatory mechanism which formats the transformed energy output to a desired profile. The resulting controlled actuation energy is what effectively exerts control over the material flow.

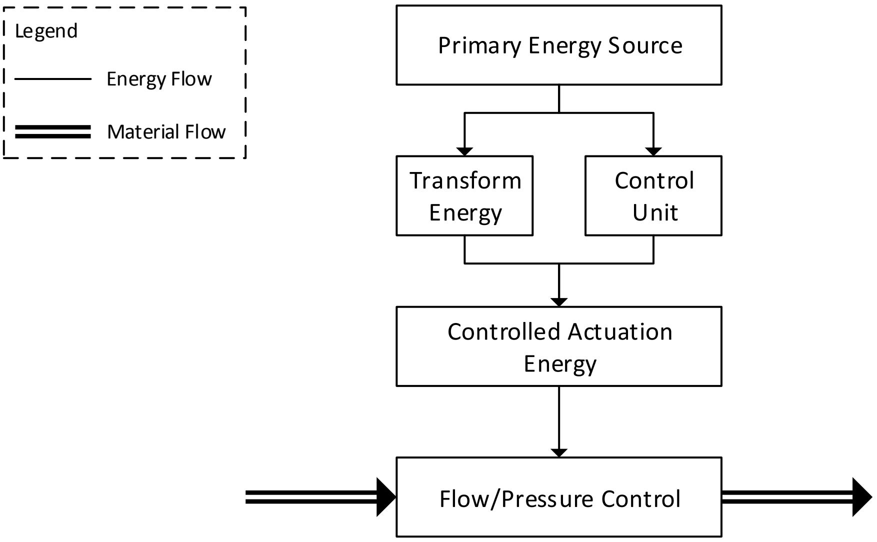

Figure 1.11: Solution-neutral drive and control strategy diagram

Currently, there are several types of drive and control approaches in use in subsea applications. They differ in the form of their primary energy source, the transformation mechanisms and the control signal transmissions. They are described in the following subsections as the state-of-art concepts [19].

1.3.1. Direct Hydraulic Control System

The simplest strategy of drive and control is the direct hydraulic system. For its extensive use, it's regarded as very robust and reliable strategy. Here, the subsea valve (either in the manifold or in the production/injection template) is actuated by a subsea hydraulic cylinder. The primary energy form is hydraulic, only to be transformed into work in the cylinder. It is generated in a hydraulic power unit (HPU) at the surface and is transmitted all the way to the cylinder in the seabed through the umbilical. The control unit is a valve, also located in the surface. The control signal in this case is the manual switch in the control valve. Figure 1.12 shows the basic diagram of this approach.

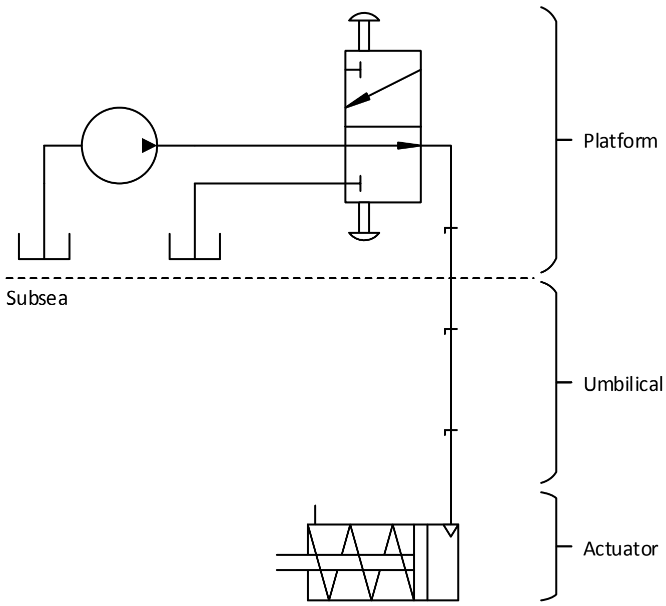

Figure 1.12: Direct hydraulic drive and control strategy (adapted from [19])

Although the low complexity and low implementation cost of this method are appealing, there are inherent disadvantages. Because the hydraulic flow is carried through a long umbilical, the cylinder displacement is rather slow due to pressure drop. For ultra-deep waters, this method becomes unpractical and expensive. Moreover, for each valve employing this strategy, there must be a separate hydraulic line in the umbilical. Eventual leakage in the hydraulic power line may also add up to the costs.

1.3.2. Piloted Hydraulic Control System

An improvement of the previous method is the piloted hydraulic control system. This strategy still uses hydraulic power as primary energy source. However, to eliminate the slow behavior from the direct hydraulic system, a hydraulic accumulator is placed in the seabed, near the cylinder. The flow of the accumulator is controlled by a hydraulically piloted valve, also placed underwater. In the umbilical there is now only one power line, which the HPU in the surface uses to constantly fill the subsea accumulator. Multiple subsea hydraulic cylinders can be driven with a single power line, provided that each cylinder has its own subsea hydraulically piloted control valve with a control line in the umbilical. This is also known as valve sequencing. Figure 1.13 shows the diagram with the elements of this approach.

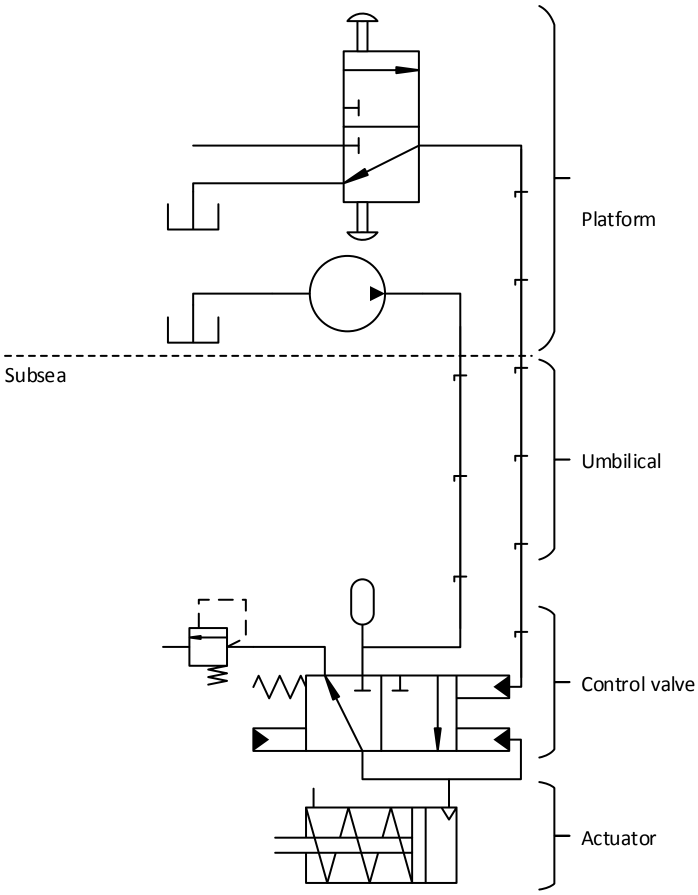

Figure 1.13: Piloted hydraulic drive and control strategy (adapted from [19])

The advantages observed in this approach comes with the onus of higher complexity and higher costs. Even though the hydraulic control lines utilizes less room than hydraulic power lines in the umbilical, hydraulic lines are generally costly. In addition to this, the hydraulic control lines are also affected by length of the umbilical, making the control signal transmission from the surface to the seabed very slow. This strategy is also unfeasible for ultra-deep waters.

1.3.3. Direct Electro-hydraulic Control System

To enable faster control response and reduce the hydraulic lines in the umbilical, the direct electro-hydraulic control strategy replaces the hydraulically piloted valves with a solenoid piloted valves to control the accumulator flow into the hydraulic cylinders in the seabed. In this strategy there is only one hydraulic line, used to fill the accumulator. Each subsea valve requires an electrical control signal. Figure 1.14 depicts the basic diagram of this approach.

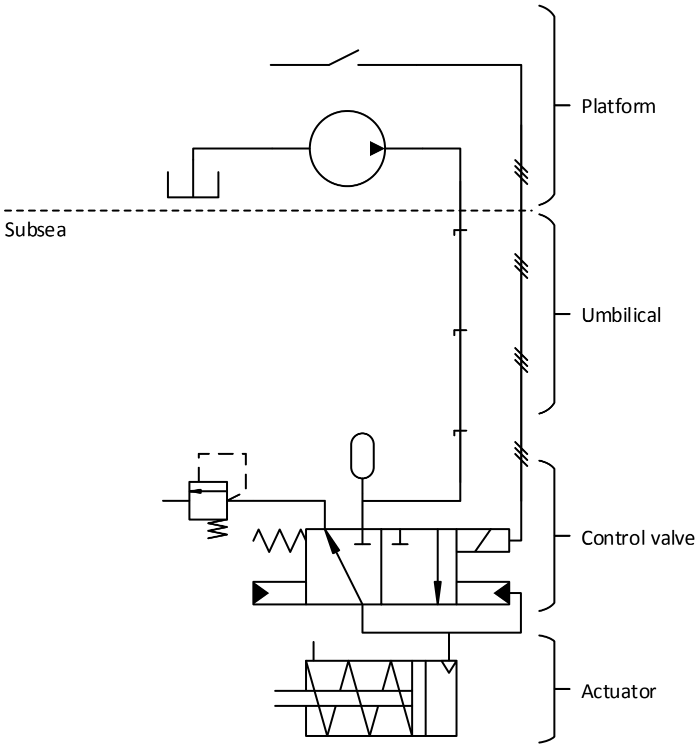

Figure 1.14: Direct electro-hydraulic drive and control strategy (adapted from [19])

The addition of electrical elements in the subsea environment, requires a special electrical umbilical, which may increase costs. Electrical systems require a better assessment of its failure modes to ensure reliability and availability of the system. The electrical signals are also degraded throughout a long umbilical, making this solution not suitable for ultra-deep waters as well.

1.3.4. Multiplexed Electro-hydraulic Control System

A step further in the previous approach would be to replace the multiple control lines with a single communication bus and adding a local control module in the seabed. This is achieved in the multiplexed electro-hydraulic control strategy, where a single control module can locally control the flow in the cylinders much faster and with less power loss in the umbilical. The local controller makes the system more flexible, expansible, and enables its employment in deep waters. Figure 1.15 shows an implementation of this strategy.

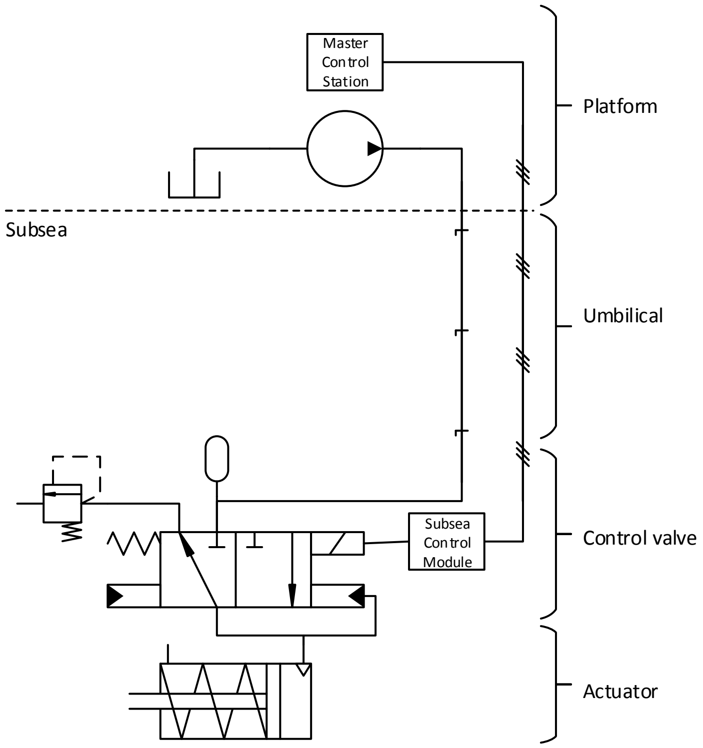

Figure 1.15: Multiplexed electro-hydraulic drive and control strategy (adapted from [19])

The main drawback of this method is the high complexity of the system, which might make it more susceptible to failure. Manual intervention also becomes less feasible, since the system is computerized.

1.3.5. All-Electric Control System

The last currently available control strategy for subsea actuators is the all-electric system solution, as defined by the diagram in Figure 1.16. Here, the hydraulic cylinder is commonly substituted with a fast linear electric actuator that drives the subsea valves and chokes in the templates and manifolds. To power the actuator, electricity is used as the primary energy source, which is typically generated in the surface. The actuator is controlled by a local subsea control module. The umbilical is then reduced to an electrical power conductor and a communication bus line. In this approach there is no risk of hydraulic fluid leakage, for all hydraulic components are disposed. Furthermore, the simple electric interface allows the scalability of this strategy to be easier than other hydraulic approaches.

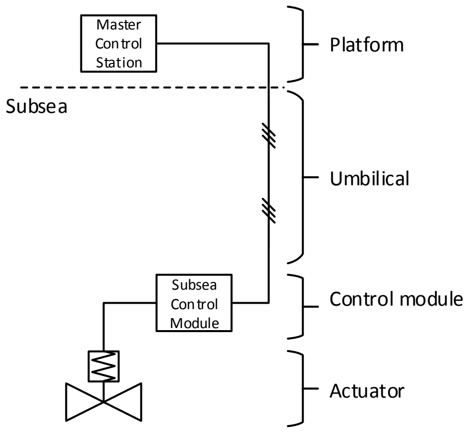

Figure 1.16: All-electric drive and control strategy (adapted from [19])

This technology, however, is the most financially costly among all solutions, both in implementation and maintenance. Moreover, the failure modes in electric systems are harder to assess. Since electrical systems have a lower power density than the hydraulic counterparts, the additional weight and volume may be problematic. As a recently developed technology, there is also not much experience in field and some doubts regarding its reliability and safety. Since the oil & gas industry is rather conservative, this solution is still not widely adhered.

1.4. Proposed Actuator

In the Compact Electro-Hydrostatic Subsea Valve Actuator project at Bosch Rexroth, it is proposed a novel concept of subsea drive and control strategy. It comprises the advantages of all-electric solutions, such as scalability, fast control and eliminates the hydraulic lines in the umbilical. The primary energy source is electrical, yet it is used to power a local HPU in seabed. The HPU, on the other hand, drives the hydraulic cylinder that moves the valve stem. Because hydraulic systems have a high power density, this actuator can be more compact in contrast to the all-electric systems. The local hydraulic circuit provides more controllable failure modes and, thus, it represents a more reliable solution than the all-electric solution [19]. The proposal also intends to reduce the manufacturing costs in comparison with the all-electric drive systems.

In order to optimize power consumption, the solution uses a variable speed pump. This type of servo pump allows a controllable speed of pumping, which is directly utilized to control the hydraulic cylinder displacement. This approach is defined as a hydrostatic circuit [20]. In contrast, hydraulic circuits have a central HPU which provides fluid flow at a constant pressure. The flow is controlled by proportional servo valves. The exceeding flow bleeds back to the fluid reservoir through a relief valve, however the unused power is wasted, partially as heat.

In Figure 1.17 there is a simplified diagram of the drive and control strategy proposition.

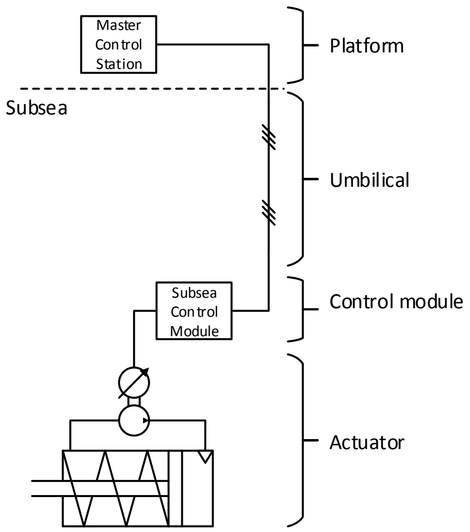

Figure 1.17: Electro-hydrostatic drive and control strategy

To incorporate this new approach of drive and control, this project puts forward the complete design of a subsea valve actuator and its interface module. This tackles multi-disciplinary areas of engineering.

The product is an instrumented hydrostatic cylinder actuator with solid and fully integrated mechanical, hydraulic and electric subsystems and a control cabinet designed specifically to provide the electrical interface to the actuator. The actuator is named Subsea Valve Actuator and is referenced with the acronym SVA, likewise the control cabinet is named Actuator Control Module and is referenced with the acronym ACM. To illustrate the design products within this project, Figure 1.18 shows a simplified layout of the components involved in the drive and control of the valve elements in the subsea templates and manifold. The components developed in this project are highlighted in blue color.

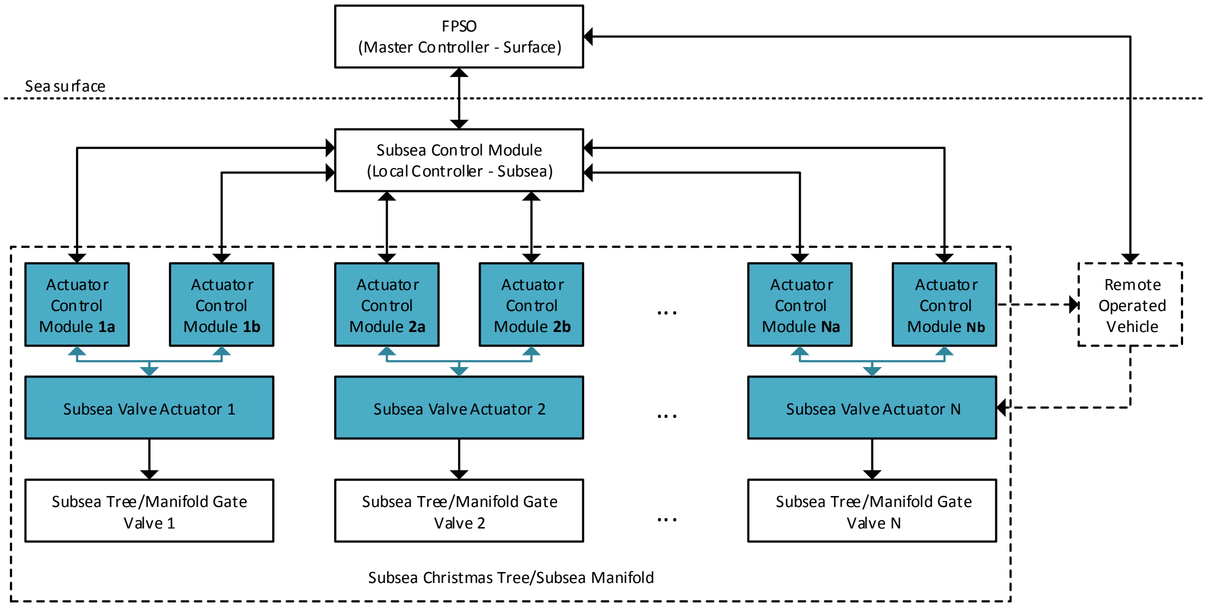

Figure 1.18: The proposed components to be designed (blue shaded) and their adjacent components

Along with this new drive strategy, the project intends to assimilate new industrial trends, such as condition monitoring capabilities. Condition monitoring consists in the measurement of machine parameters to foresee system failures, and optimize control [21]. Moreover, to enhance the manual intervention interfaces, the proposed system shall feature ROV override interfaces.

1.5. Project Development Methodology

The project development follows guidelines from a configuration management planning model for systems engineering, known as the V model. From that, the Marine

& Offshore department of Bosch Rexroth follows a local structure documentation for each project area, allocated in this methodology. The following sections clarify both the methodology utilized and what parts are presented in this document. The terminology utilized in this section is based off in the definitions given in ISO 9000, ISO 9001 and ISO 10007 [22][23][24].

1.5.1. Configuration Management Planning

Configuration Management (CM) is a management activity that applies technical and administrative direction over the life cycle of a product, its configuration items and related product configuration information. A configuration item is understood here as any entity or product within a configuration that satisfies an end use function. CM applies to the outputs of both the requirements engineering process and the systems engineering process, and also documents the product's configuration. It provides identification and traceability, the status of achievement of its physical and functional requirements and access to accurate information in the phases of the life cycle.

In Figure 1.19 there is a flowchart for the CM planning applied in this project. It is an alternative depiction of the standard V model.

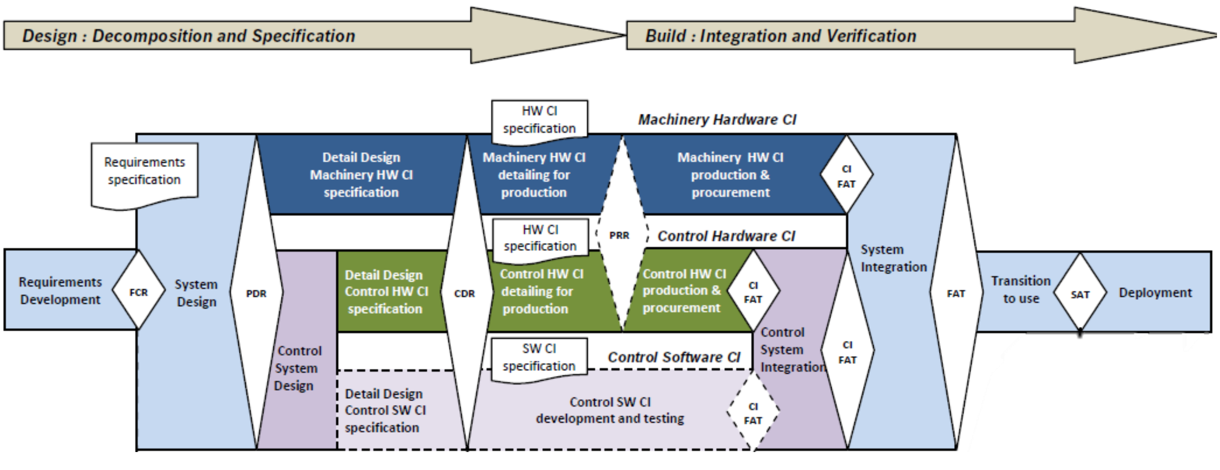

Figure 1.19: The configuration management plan flowchart employed

1.5.2. Scope of the Thesis

From the beginning of this work, the requirements specification was already documented and available under the applied CM plan. In respect to the CM plan, the only stage involved during this work is the system design. Nonetheless, because of the high degree of coupling between the machinery and control system, the specification of these subsystems in parallel, frequently interfered with each other. Likewise, the control software can only be implemented when all the available interfaces and operating modes of the physical system are defined. This demanded a refactorization of the requirement specification to enable a more clear boundary and independence of the subsystems. In between the term this work was developed, a preliminary design review (PDR) was performed to validate all project requirements and their relationships.

This thesis focus primarily in the electrical system design (that includes both the control system hardware and the electric elements in the machinery hardware) and initial concepts for the control software. According to the CM plan, the specific stages covered here are the “Detail Design HW CI specification”, part of the “Detail Design Machinery CI specification” and part of the “Detail Design SW CI specification”. This part of the project was made by myself and is thoroughly disentangled in Chapter 3, Chapter 4 and Chapter 5. The technical report completed by the end of this thesis is the Control System HW CI specification, split in two parts: one for the hydraulic actuator and other for its control module. The results allowed the project to advance its maturity level, reaching the final stages of design.

Following the methodology with technical and academic rigor, it shall be given all the theoretical background, the analyses and simulation results from the other project areas, and the project requirements that affect the electrical system development and are necessary to clarify the trail of the performed work. These are mostly covered in Chapter 2, and were made by other members of the project. All normative references that are related to the electrical system theme are also reviewed and mentioned throughout the thesis.

The patent applications for some of the technologies presented in this thesis are still pending (until the date of publishing). Naturally, sensitive industrial data has to be omitted or changed for being considered intellectual property of the company.

2. Project Requirements & Inputs

To validate the proposed concept, there are two variants of prototypes to be developed. The first one, referenced as SVA-V1, intends to validate the performance aspects of the novel drive and control strategy employed. The second one (SVA-V2) is a more mature version of the first prototype, stacking more functional requirements upon the ones in the first variant. Regardless of the prototype variant, both are submitted to design constraints which involve the environmental conditions and the physical boundaries of the interfaces of mechanical or electrical nature. Moreover, both variants have to comply with safety and reliability standards [25].

The ACM will be designed as a separate object with a compatible interface for both variants, however there will be no differentiation in the requirements, as the ACM is an obligatory component for the operation of the system as a whole. All requirements pertinent to the control will be refined and assimilated as software functional requirements in future software design phase. Independently of which variant, the general targets to be achieved with a complete system (SVA + ACM) were listed, specifically the ones related to the electrical drive/instrumentation are:

- To actuate gate valves of subsea trees and manifolds with the same performance as the current hydraulic and all-electric valve actuators;
- To be compliant with the industrial standards pertinent to these components;
- To reach a higher degree of safety and reliability performance as existing actuators, with fail safe functionality;
- To provide the standard electric interfaces in the current subsea trees and manifolds without adaptation in these facilities;

These targets will be refined in functional and nonfunctional requirements. To start the definition of the requirements, one fundamental premise to be noted is that the SVA has as design reference another existing valve actuator with a nominal stroke length of S_N [m], to which it is intended to be replaceable with no modifications in any of the interfaces.

In this chapter it shall be presented the functional requirements for each prototype variant, and specifically noted the relevance for the electrical system design. Afterwards, the nonfunctional requirements are defined, being divided in design constraints and safety, reliability and availability standards. Finally, the last two sections contain the analyses and simulation results for each variant, and the hydraulic circuits designed to cope with the performance requirements for the two variants. These are used as inputs to engineer the electrical system.

2.1. Functional Requirements

The functional requirements are functionalities that define objectively what tasks the system has to perform. They can be defined as function containing a task description, a set of inputs and a set of outputs which result from the performed task. A good set of requirements should meet the following criteria: correctness, unambiguousness, completeness, verifiability, consistency, modifiability and traceability [26]. These criteria are ensured under the aforementioned project methodology and loosely based in the suggestions from ISO 13628-6 (Section 7.3).

2.1.1. SVA-V1 Functional Requirements

In the first variant, six functions were defined as functional requirements and are detailed in relation to their inputs, outputs and, when suitable, their limits. They are detailed in Table 2.1. All functions that are directly or indirectly related to the electric system design are shaded in blue color.

Table 2.1: Functional requirements for the SVA-V1 (blue shaded functions are electric system-related)

No.	Task Description	Inputs	Outputs	Tolerance
1	Open the gate valve by providing electric power	• Electric power signal AND • Electric control signal	• Displace cylinder shaft $+S_N$ [m] in T_{NO} [s]	• Position accuracy: $+S_N \pm S_{NERR}$ [m] • Time limit: $T_{NOmin} < T_{NO} < T_{NOmax}$ [s]
2	Close the gate valve by cutting electric power (fail-safe)	• No electric power signal OR • No electric control signal	• Displace cylinder shaft $-S_N$ [m] in T_{NCP} [s]	• Position accuracy: $-S_N \pm S_{NERR}$ [m] • Time limit: $T_{NCPmin} < T_{NCP} < T_{NCPmax}$ [s]
3	Compensate the external environment pressure	• External environment pressure (P_{EXT})	• Internal pressure $P_{INT} = P_{EXT} + P_{COMP}$ [Pa]	• Pressure limit: $P_{EXT} + P_{COMPmin} < P_{INT} < P_{EXT} + P_{COMPmax}$ [Pa]
4	Isolate the hydraulic fluid from external environment	• Reservoir filled with hydraulic fluid	• Hydraulic fluid leakage is avoided or minimized	• Volume leakage limit: $V_{LEAK} < V_{LEAKmax}$ [m^3]
5	Filter the hydraulic fluid from particles contamination	• Reservoir filled with hydraulic fluid	• Contamination in the hydraulic fluid is avoided or minimized	• Fluid cleanliness level according to a Class X_{CL} [27]
6	Continuously measure the actual position of the hydraulic cylinder shaft	• Position of the hydraulic cylinder shaft S_{ACT} [m] • Electric power signal	• Electric measure signal of the actual position of the hydraulic cylinder shaft	• Position measurement accuracy: $S_{MEAS} = S_{ACT} \pm S_{NERR}$ [m]

The tasks described in the first and the sixth requirements are the only that necessarily require direct attention in the electrical system design for the first variant. Notice that the closure of the valve (requirement number 2) is not actively controlled in this first variant, i.e., it shall close automatically via a passive hydraulic-mechanic system when no power is provided.

Also, in requirement number 3, it is stated that the internal pressure of the actuator must be compensated with the external pressure. This imposes a design requirement known as pressure-tolerant system. Pressure tolerant systems are designed to withstand the full ambient pressure. The external pressure is transmitted through an elastic mechanism, simultaneously preventing fluid leakage. This avoids the need of costly, bulky hulls. In contrast, pressure-neutral systems are designed to have its parts kept at a given pressure (usually atmospheric) with the help of a protective barrier. Because of the high hydrostatic forces, pressure-neutral systems are more susceptible to leakage [28].

Because of the high complexity of the electrical system within the ACM, it must be designed as a pressure-neutral system. The ACM shall be a mechanically separated part from the actuator, connected only electrically,

2.1.2. SVA-V2 Functional Requirements

As explained before, the second prototype variant shall inherit all the functional requirements designated for the first prototype and also include its own set of extra requirements. In Table 2.2 are the definition of the six additional functional requirements present in the SVA-V2 in the same way the first six requirements were defined. To preserve industrial secrecy, details regarding these requirements were omitted.

Table 2.2: Additional functional requirements for the SVA-V2 (blue shaded functions are electric system-related)

No.	Task Description	Inputs	Outputs	Tolerance
7	Close the gate valve by providing electric power	• Electric power signal AND • Electric control signal	• Displace the cylinder shaft $-S_N$ [m] in T_{NCA} [s]	• Position accuracy: $-S_N \pm S_{Nlim}$ [m] • Time limit: $T_{NCAmin} < T_{NCA} < T_{NCAmax}$ [s]

8	Condition monitoring-related function 1			
9	Condition monitoring-related function 2			
10	Condition monitoring-related function 3			
11	Condition monitoring-related function 4			
12	Condition monitoring-related function 5			

As it can be noticed, the functional requirements listed for the second variant are only the electrical system-dependent ones. Particularly, the tasks number 6, 8, 9, 10, 11 and 12 comprise the condition monitoring capabilities.

2.2. Design Constraints

Apart from the functional requirements, nonfunctional requirements are also imposed for both variants. Some of these nonfunctional requirements are classified as design constraints, which are the parameters bounded by application nature. Many other nonfunctional requirements, deemed irrelevant to the electrical system such as restrictions to sealing or hydraulic components, are also not mentioned here.

2.2.1. Mechanic Interface and Dimensions

As a gate valve actuator, it is important to highlight the basic component structure in a generic gate valve. In Figure 2.1 there is a diagram of a basic gate valve, component dimensions are not in proportion. The bonnet is a cover piece that seals the valve body and provides a supporting interface to the valve’s stem. The stem is the rod that transmits motion and physically connects the gate (or wedge) with the handle or, in this case, the valve actuator [29]. The valve bonnet and stem are the main supporting structures for the SVA. The SVA front face shall attach to the bonnet of the existing gate valves. The cylinder shaft shall be directly screwed to the valve’s stem.

As an integral part of the valve, the SVA and the ACM comprises the actuator and the positioner of the gate valve.

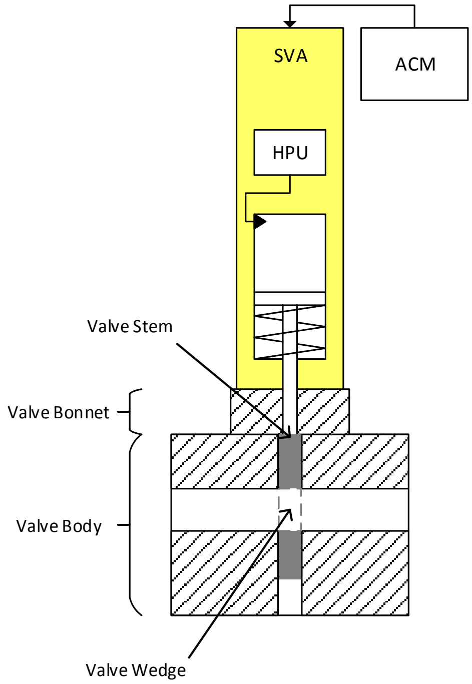

Figure 2.1: Basic elements in a gate valve with the SVA and the ACM as actuator and controller respectively

To fit in the current subsea template facilities, the SVA must have a cylindrical shape with a maximum length of L_{MAX} [m] and maximum diameter of D_{MAX} [m]. The total dry weight of the actuator must not exceed W_{MAX} [kg]. Analysis of the weight distribution and further mechanical aspects are of no concern for the comprehension of this document.

2.2.2. Electric Interface

2.2.2.1. Power Supply & Consumption

The available power supply lines in the current facilities are defined in the Annex E-4 of standard ISO 13628-6 [12]. The system must be able to operate using one of the options given, Low Power or Medium Power. The details of each option are reproduced in Table 2.3.

Table 2.3: Standard subsea electrical interfaces [12]

Power Requirements	**Low Power**	**Medium Power**
Power supply	24 [W]	500 [W]
Voltage operational window	20 [V_{DC}] to 28 [V_{DC}]	140 [V_{AC}] to 265 [V_{AC}]
Input frequency	N/A	47 [Hz] to 63 [Hz]
Power factor	N/A	> 0,95
Voltage ripple	1% up to 1 [MHz]	N/A
EMC	TBD	TBD
Input power transient	120% of max. input for 10 [ms]	120% of max. input for 10 [ms]
Cold start inrush power	120% of max. input for 500 [ms]	120% of max. input for 500 [ms]
Heat dissipation	Max. 6 [W]	Max. 100 [W]

Another nonfunctional requirement related to the power consumption is that the SVA must reduce its peak power consumption to a value Ψ_{MAX} [W]. That allows a power line conductor with smaller diameters, reducing the costs for subsea cabling and umbilicals.

2.2.2.2. Communication Protocol

The required network protocol to be used as communication interface is an implementation of the CAN bus protocol for industrial automation, known as CANopen. This follows the recommended practices of the Subsea Instrumentation Interface Standardization Joint Industry Project (SIIS) [30].

Because of the lack of technology-specific guidelines for communication network protocols in subsea environments (in the official standards [12]), the recommended standard for specification of the physical layer, according to SIIS, is the fault tolerant CAN bus according to ISO 11898-3. It contains more technology-oriented definitions, such as the topology that must be utilized for all CAN communicating devices and regulations towards the cable types and lengths [31].

2.2.2.3. Subsea Electrical Connectors

The electrical connectors utilized in all electrically operated subsea device for oil & gas industry applications must have a minimum of two barriers between seawater and any of its conductor. Furtherly, all subsea cabling should be repairable or replaceable by the use of an ROV [12]. Thus, wet-mate connectors shall be employed.

Subsea electrical connectors are relatively cost-sensitive elements in subsea engineering design [31]. For this reason, it was defined as a cost-related requirement that the SVA-V1 shall be limited to have its external electrical interface with Δ_1 electrical contact pins. Meanwhile, the SVA-V2 shall be designed to operate with a Δ_2 electrical contact pins external connector. The ACM, as stated previously, shall have a single Δ_2 pins external connector which is compatible to both variants. The connecting cables between the SVA and the ACM shall link the respective pins in each end.

2.2.3. Environment Conditions

The SVA must withstand the harsh subsea environmental conditions for normal operation, which include high hydrostatic pressure, low temperatures and chemically aggressive medium. Moreover, according to the functional requirements, as the SVA shall be a pressure-tolerant system, the high pressure is transmitted to all the system's elements. This implies that some of the electrical components must be adapted to high-pressure. Electronic components not suitable for high pressure environment may have its enclosure damaged due to implosion. This can cause short-circuits in capacitors for instance. Digital components which rely in crystal oscillators may also fail, as the high pressure can deform the crystal's structure leading to clock failure [32]. With this motivation, it was imposed that, whenever possible, the electro-electronic devices in the system shall be analog and pressure-tolerant. If necessary and possible, pressure-neutral chambers can be built in the actuator to accommodate non-adapted devices.

Overall, to avoid seawater contamination, the system must have an enclosure with protection degree IP68 rated for 3300 [m] of seawater column [34]. A relation of the local environmental conditions is given in Table 2.4, as provided by the international standards [12][14].

Table 2.4: Maximum ratings for environmental pressure and temperature [12][14]

	Operation		Design		Test	
	Min.	Max.	Min.	Max.	Min.	Max.
Pressure [Pa]	10^5	$3{,}0\times10^7$	10^5	$3{,}3\times10^7$	10^5	$3{,}3\times10^7$
Temperature [°C]	-5	+40	-18	+40	-18	+40
Temperature (electronics) [°C]	-5	+40	-18	+70	-18	+70

The considered EMI conditions for the subsea environment are detailed in the Annex F of the ISO 13628-6 [12]. Adequate EMI shielding shall be addressed for each component to improve control and avoid failures due to parasite signals. The general guidelines for EMC engineering are provided by IEC 61000-1-2 and IEC 61000-2-5 [35][36].

2.3. Safety & Reliability Requirements

The safety and reliability requirements are also part of nonfunctional requirements. These require special attention and detail, for they concern directly to the quality of the product rather than general functional performance and nominal capacity. The requirements here are split in topics of safety and reliability.

2.3.1. Safety

According to the standard IEC 61508-0, safety is defined as “the freedom from unacceptable risk of physical injury or of damage to the health of people, either directly, or indirectly as a result of damage to property or to the environment“[37]. Although catastrophes isolated in a subsea environment are not likely to cause direct human fatalities, potential oil spills and environment hazards may indirectly damage the lives of entire populations, negatively affect economies, among other disastrous outcomes [38].

The SVA is not designed to act as the last barrier against any safety risk related to the subsea production system or well (such as a SCSSV or BOP). However, a risk assessment of all subsystems has been executed by the project team members in order to identify potential risks.

In addition, it shall incorporate a fail-safe principle, as described in functional requirement number 2. This functional requirement must also be designed as a safety-related with SIL λ according to IEC 61511 [39]. A safety-related function is defined in IEC 61508-0:2005 as "systems that are required to perform a specific function or functions to ensure risks are kept at an accepted level. Such functions are, by definition, safety functions."

2.3.2. Reliability

Reliability concerns with the robustness of a system, or the ability of the system to keep operating successfully in the specified conditions for a given period of time [43]. Engineering for reliability may sacrifice safety degrees of a project. Design methods to enhance the reliability of the SVA shall be employed, such as redundancy, if worthwhile [12].

The service life required for the SVA is the same as the average service life for subsea tree equipment without intervention. In this period, the system must reliably be able to perform at least 1200 operating cycles under the tolerances specified in the functional requirements, following the recommendation of standard ISO 13628-1, Annex G.2.3 [17].

A *cycle operation* is understood in the scope of the SVA as a complete extension and retraction of the valve actuator. The cycle operation concept is not applied to functional requirements with continuous behavior.

Although the SVA is meant to be fixed permanently in the manifold or template, the ACM shall be designed as a ROV-retrievable module. This allows the SVA to be momentarily inactive in a fail-safe state in the event of a failure in the components in the ACM. It can then be replaced by a functional entity to resume operation of the valve actuator.

2.4. System Analyses and Simulation

This section presents the design choices originated to comply with the given requirements. Here is shown the engineering that was carried out in the other system areas, namely the mechanic design and the hydraulic design. It gives a brief insight in the final hydraulic-mechanic design and the calculated inputs to be used in the electrical system design process. Figure 2.2 illustrates the external mechanical design of the valve actuator attached to the valve bonnet and stem.

Figure 2.2: Current external mechanical design of the SVA [40]

2.4.1. Force Analysis

The project initiation phase starts off with a first hydraulic circuit draft for SVA-V1, which establishes a simple mechanism to fulfill the first 6 functional requirements. A simple depiction of the hydraulic circuit proposed is shown in Figure 2.3. It is based off in a patented invention [78], property of Bosch Rexroth AG. Obviously, the hydraulic circuit escalated quickly in complexity as the design fulfilled more requirements, functional and nonfunctional.

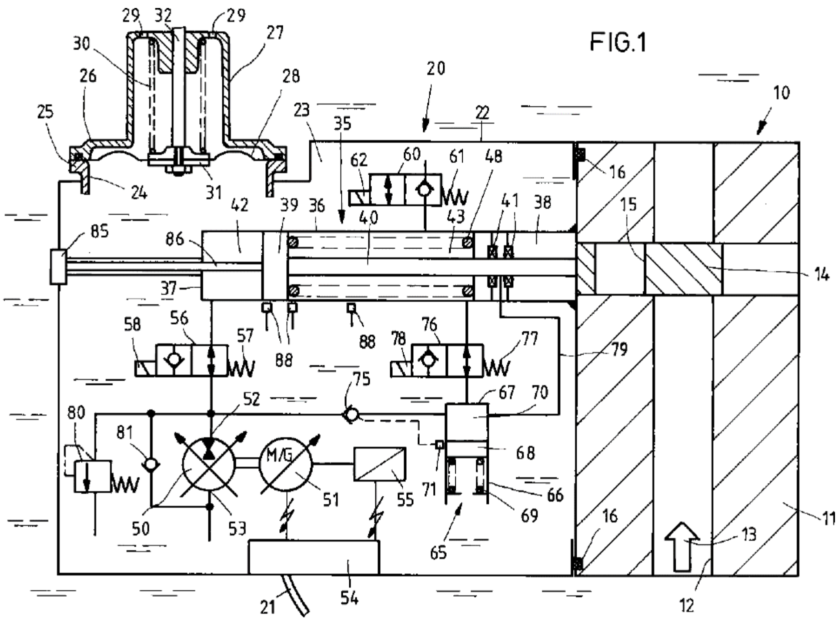

Figure 2.3: Initial draft for hydraulic circuit concept [78]

It was provided by industrial research the range of pressure in the well bore which the gate valve will be submitted, $P_{well,up}$, $P_{well,down}$ and $P_{well,ax}$. These values along with the friction constants of the materials in the well and the geometry of the valve wedge, results in the external forces applied in the valve actuator.

2.4.1.1. SVA-V1 Analysis

In the first variant, since the system must be fail-close, it was proposed the free-body diagram shown in Figure 2.4 as a dynamic physical model to calculate the applied forces. The moving part consists of the valve wedge, the valve stem, and the cylinder shaft. These elements are rigidly connected and act as a single body. The cylinder/actuator body is fixed and attached to the valve bonnet. The results led to the dynamic simulation of the hydraulic circuit.

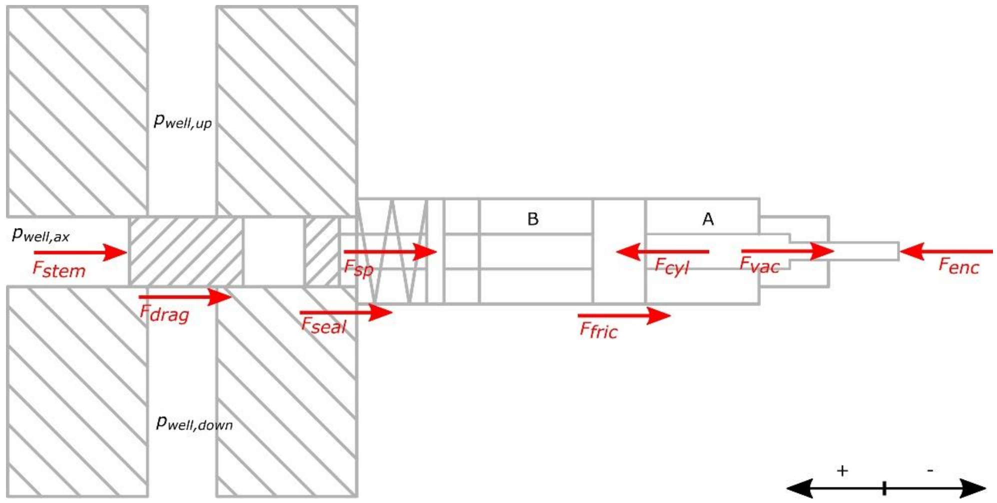

Figure 2.4: Free-body diagram for SVA-V1

2.4.1.2. SVA-V2 Analysis

Likewise, for the second variant, it started with a more complex hydraulic circuit draft. To allow the system to have a fail-close functionality and simultaneously enable active control of the valve, the second variant feature a novel spring clamp mechanism (patent applied). The best and worst-case scenario forces calculated for the second variant were also used as inputs in the hydraulic system simulation for dimensioning the hydraulic components.

2.4.2. Hydraulic System Simulation

2.4.2.1. SVA-V1 Simulation

The final hydraulic circuit design for SVA-V1 is shown in Figure 2.5 (details omitted for industrial property protection). The electrical components are referenced with a unique designator, which is also used in this document to specify a certain part.

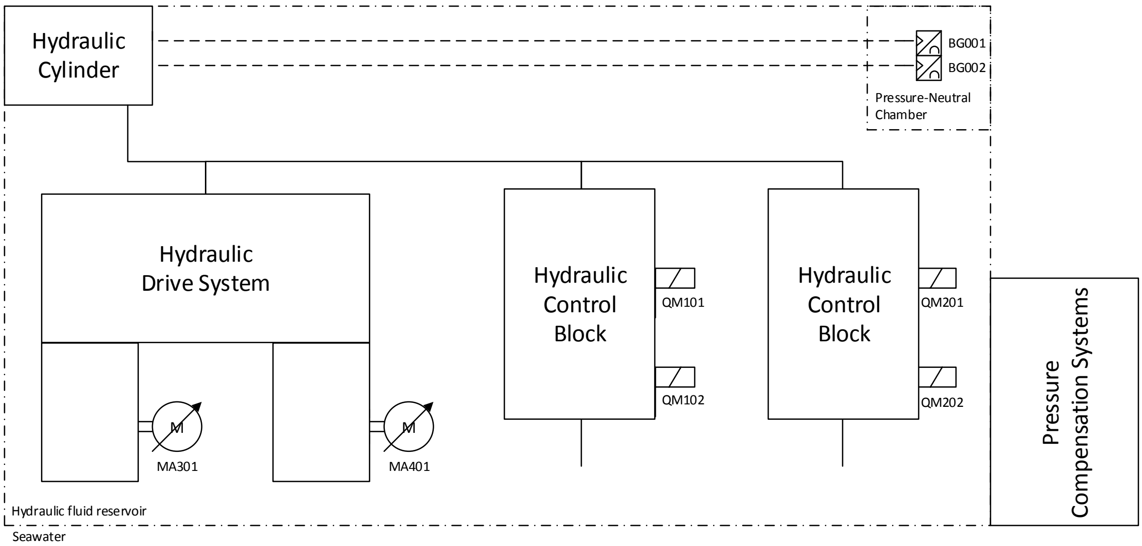

Figure 2.5: Final hydraulic circuit for SVA-V1

The hydraulic components were selected following mechanical design constraints, cost-related parameters, performance, available suppliers, interface flexibility, among other factors. The electrical elements up for design in the SVA-V1 are the electric motors, the valve solenoids and the cylinder shaft encoders.

Redundancy is applied in some parts of the hydraulic system where it was evaluated to increase the reliability of functionalities. If it is applied in measurement instruments, it can act not only as spare device in case of failure of one of the main instrument, but also the measurements of both instruments can be used with algorithms to mitigate systematic errors or detect drift rates [44].

It was observed that, in order to make a pressure-tolerant system, the valve actuator body should be used as the hydraulic fluid reservoir. With this design choice, the exposition of electrical components to a fluid medium narrowed the fluid options to comprise the ones which are sufficiently dielectric. The fluids were submitted to an electrical conductivity test, whose results were analyzed together with the electrical components geometry and electrical ratings.

The dynamic simulation of a complete operation cycle of the hydraulic system with the selected components resulted in the cylinder displacement profile as plotted in Figure 2.6 [45]. It shows a complete extension and retraction of the stem, with the worst-case scenario constant forces. All the time-related requirements were met. As required for the SVA-V1, the extension of the cylinder shaft (opening of the valve) is driven actively by the pump, which for this simulation was simply activated with a step input in an open loop. The closure is passive and happens between t_4 and t_5, where the valves are opened (or electric signal is cut) and the cylinder spring empties the cylinder chamber, moving the shaft backwards. The simulation was done by the project systems engineer in the proprietary software *Simster* from Bosch Rexroth AG [46].

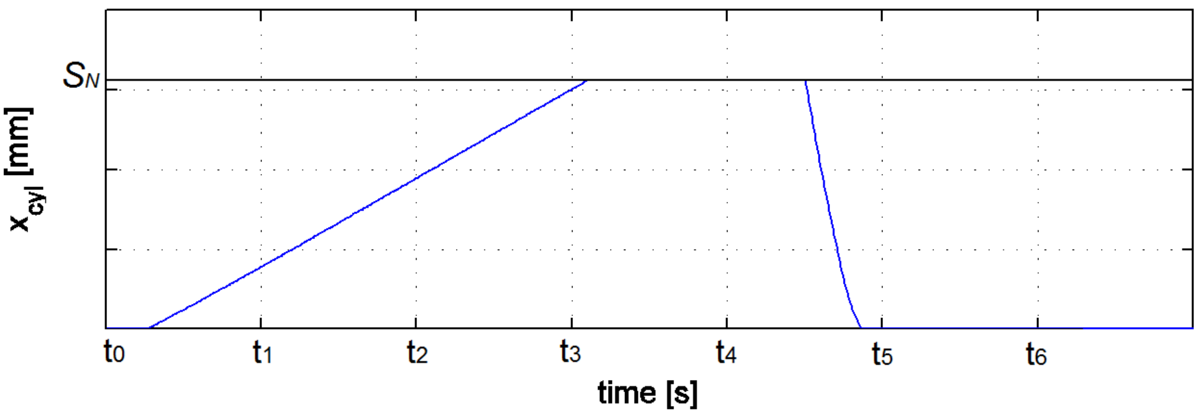

Figure 2.6: Cylinder displacement profile simulation for SVA-V1

With the selected pump, the simulation gives the first inputs for the electrical system, namely the pump's required nominal rotational frequency and nominal torque. The profiles for pump-motor rotational frequency is shown here in Figure 2.7, other plots are omitted to preserve industrial property. In the cycle operation of the SVA-V1, it was highlighted three working points over which a pair of values for rotational frequency and torque are assigned. These points intend to discretely cover the extremes (either in absolute value or in time length) of the range of operation parameters which the driving components are submitted in a normal cycle operation.

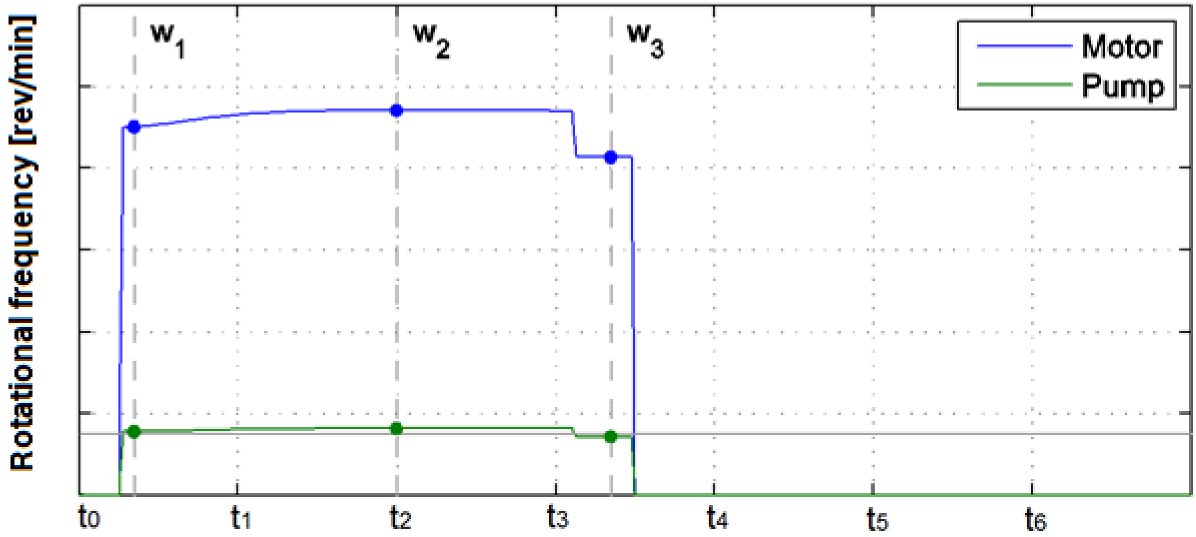

Figure 2.7: Rotational frequency profiles of the pump-motor pair in a cycle operation of the SVA-V1

2.4.2.2. SVA-V2 Simulation

In the SVA-V2, the hydraulic diagram is slightly more complex than the SVA-V1 in order to meet all the additional requirements. The additional electrical components are instruments used to enable condition monitoring. Their choice procedure is detailed further in section 3.3.2. Apart from that, the electrical components are the same as in SVA-V1.

Similar to the simulation done for the first variant, a cycle operation was simulated in the SVA-V2 model to give inputs for the electrical system design [47]. In this variant the closure is also controlled, and therefore the operation is more dynamic. To capture more accurately the range of values observed in a cycle operation of the SVA-V2, it was defined six working points of pump rotational frequency and torque. The plot with the torque profile of the motor and pump for a complete cycle is given in Figure 2.8.

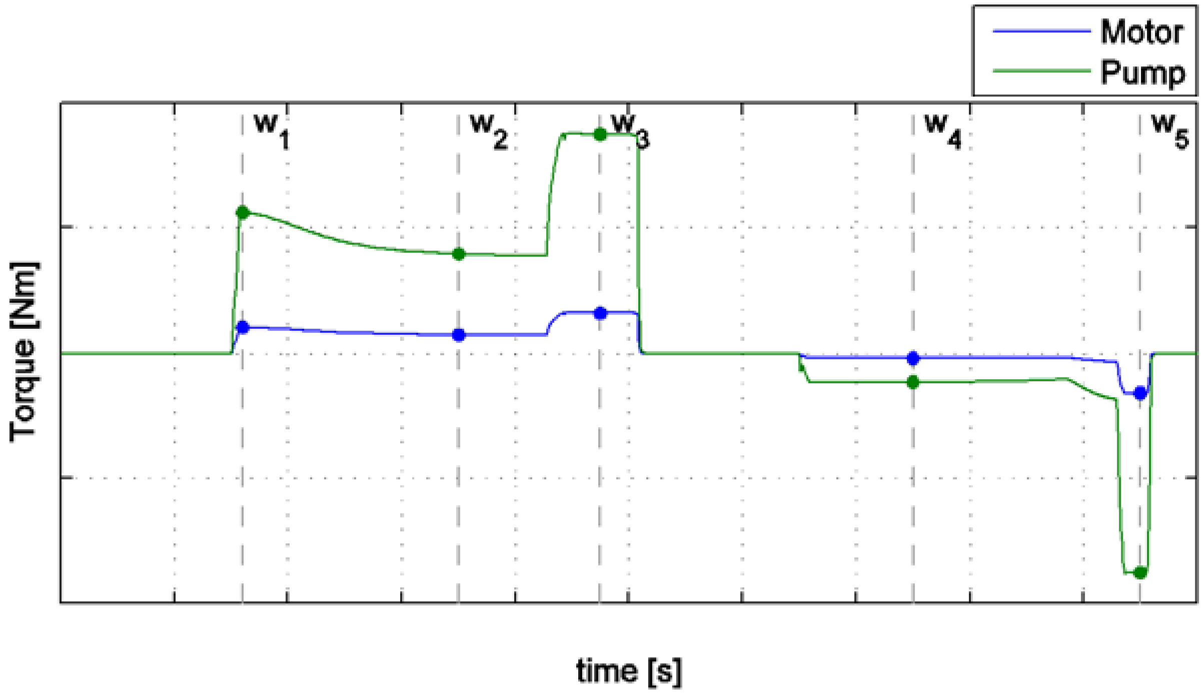

Figure 2.8: Torque profiles of the pump-motor pair in a cycle operation of the SVA-V2

This concludes the necessary background of requirement and system inputs to begin the walkthrough in the electrical system design process.

2.5. Summary

It was exposed in this chapter the design requirements necessary to lay down the project development plan and to guide the design process. A greater focus was given to the requirements that are directly related to the instrumentation, the electrical drive and the electrical system in general of this project. Furthermore, the current design of the project was briefly discussed, showing roughly what has been done in the other disciplinary areas of this project.

3. Instrumentation and Electrical Drive Specification

In this chapter it is explained the process of electrical system design, the technology selection for electrical drives, controls and instrumentation. This process is based off in the design requirements and inputs presented in Chapter 2. Moreover, it is provided normative and theoretic background for the proposed solutions presented in this chapter.

The first section covers the general design choices, as a framework to guide the development of both SVA variants and the ACM. The following chapters cover the specific electrical system development of each system in this project: the SVA-V1, SVA-V2 and the ACM. They are divided in a subsection for the general layout of the electrical components and another subsection to detail each particular component selection and purpose. For each system there is a final subsection showing the internal and external electrical interfaces. By the end of this chapter, all electrical elements composing the project will have been defined and explained, as well as the electrical mechanisms.

It is important to notice that, while designing the electrical systems, a nomenclature convention was adopted for the components. The letter codes are based in the designator list in standard IEC 81346-2. It names a component according to what it *does*, instead of what it *is* [48]. The designator acronyms are explained in the scope of this document in the symbol list. The three-number index in the designator is related to an internal convention. The first number is related to a group of components within a system, while the following two numbers are unique designators, to avoid ambiguity in the reference designators.

3.1. Design Choices

According to ISO 13628-6 and the SIIS Recommended Practices, the instrumentation in subsea modules have three standard architectures defined, all implementing some sort of redundancy [12][30]. These are depicted in Figure 3.1, Figure 3.2 and Figure 3.3, where the blue links are control signals and the red links represent power signals. To use the standard nomenclature, ISD stands to Intelligent

Subsea Device and corresponds to the devices inside the SVA, particularly the set of transducers. SCM/SEM is a generic Subsea Control/Electronic Module, which in this case is the data acquisition system within the ACM.

The architecture layout in Figure 3.1 implies that every component in the ISD group (SVA transducers) must have a separated redundant channel for each external ACM module.

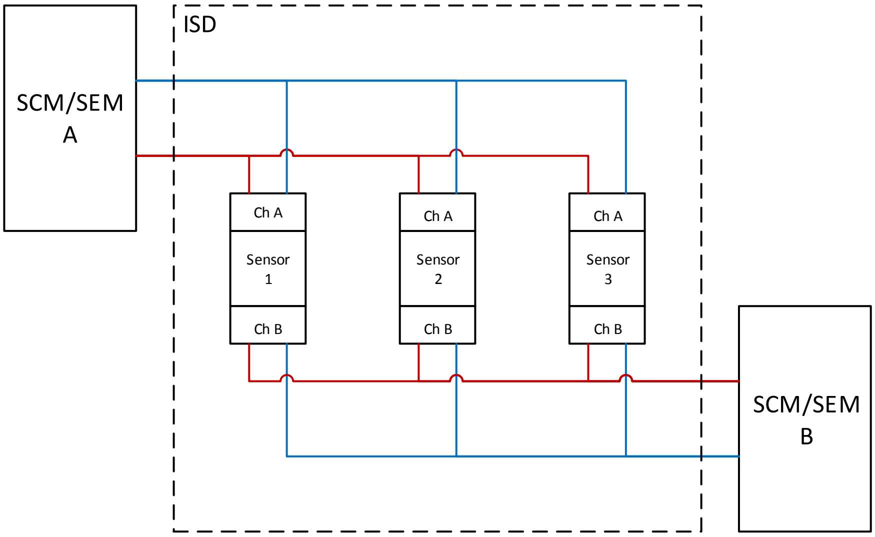

Figure 3.1: Double channel sensor output

In Figure 3.2 the system redundancy is achieved only in the SCM/SEM and sharing the same single channel sensor with both controllers. In this approach it is required a commutation protocol to avoid interference of the two control modules.

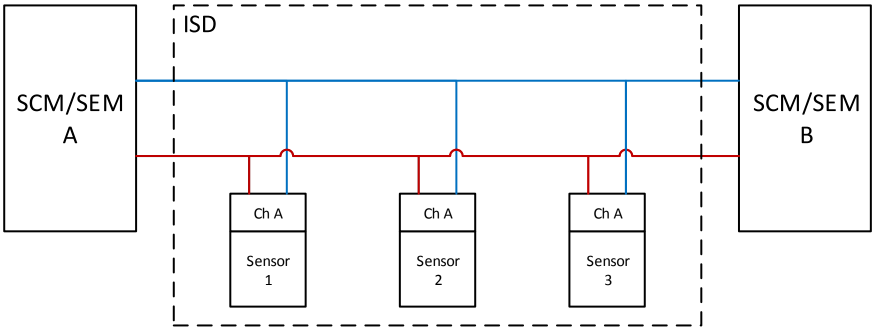

Figure 3.2: Parallel bus sensor output

ISDs redundancy is again provided in the architecture shown in Figure 3.3 by doubling the single channel sensors and providing their signals for each of the ACM.

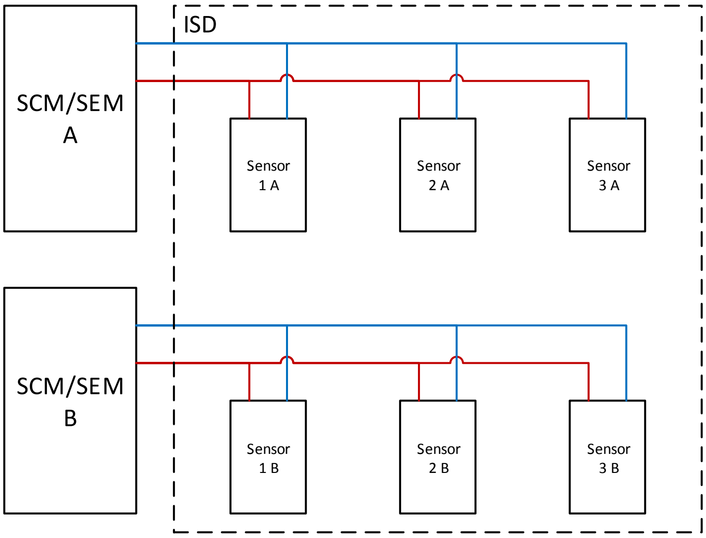

Figure 3.3: Duplicated sensors

Due to the limitation in external pins available in the SVA imposed as design requirement (see section 2.2.2.3), there is no room for exclusive channels nor exclusive sensor unit for each ACM. To comprise single channel sensors and redundant sensors while still achieving redundancy, the approach used in the ACM is a combination of all the three architectures, as shown in the Figure 3.4. In this layout, both redundant sensors and duplicated single output sensors can be utilized. All outputs are shared with both ACM. In this architecture, the system is robust against failures that may happen in one of the channels of a redundant sensor, in one of the duplicated sensors or even in one of the ACM. This is achieved with the system data bus entirely connected in parallel.

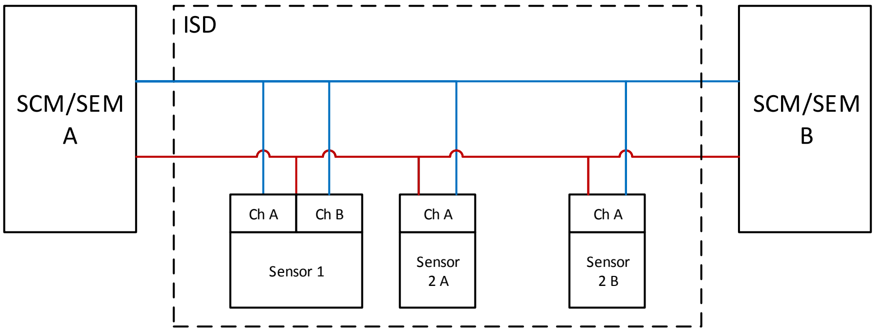

Figure 3.4: Double channel parallel bus sensor output and parallel bus duplicated sensors

3.2. First Prototype Variant (SVA-V1)

3.2.1. General Architecture

The electrical components pertaining to the first variant, as shown in the hydraulic circuit in Figure 2.5, are displayed in the component layout in Figure 3.5. Some components are motors, some are instruments and some are valve solenoids. No further details can be given because it is industrial property.

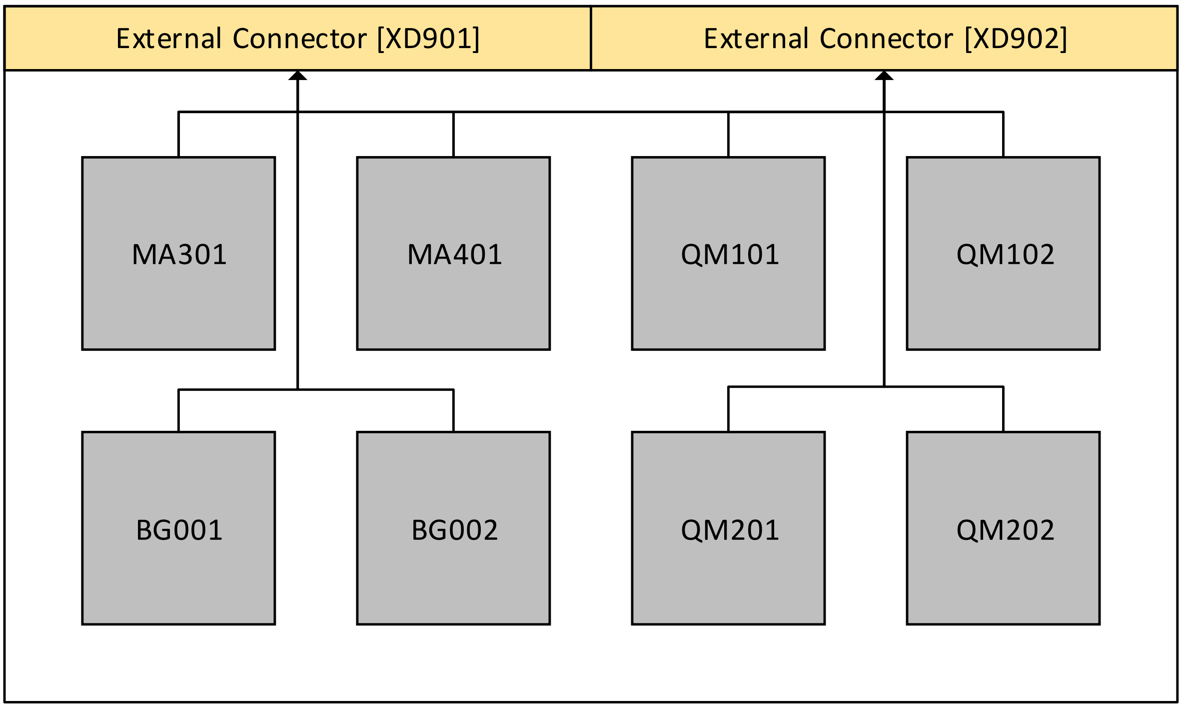

Figure 3.5: SVA-V1 electrical system architecture

Notice that each component is simultaneously connected to two external connectors. This corresponds to the design choice of having two redundant ACM for each SVA.

3.2.2. Components

The components selected for the first variant shall be the same as the ones used in the same mechanisms of the second variant. This improves the modularity aspect of the project. That was also a premise when the hydraulic circuit was conceived. Therefore the control valves, pumps, and all other components are the same for both variants. In the electrical system perspective, only the electrical connectors will differ in each variant. This was already required in section 2.2.2.3. In Figure 3.6 there is a Venn diagram depicting the similarities between the electric systems of both variants in terms of physical components.

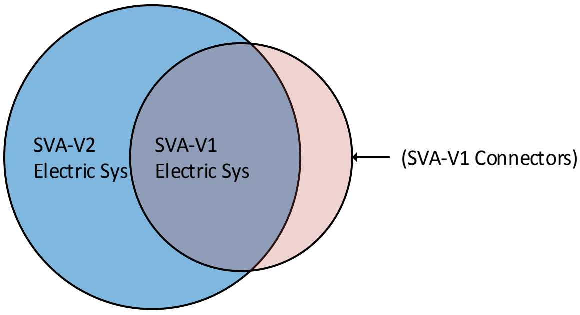

Figure 3.6: Similarities between the electric systems of the two variants

3.2.2.1. Electric Motor

The electric motor is the device which will convert the electric energy into mechanical energy. It shall be attached to the hydraulic pump. The electric motor must be able to have a variable velocity in order to control the hydraulic fluid into the system and, consequently, the position of the cylinder rod. According to the adopted classification in IEC 81346, its designator in the project is “MA”, because it is an object whose function is to “provide mechanical energy (rotational or linear mechanical motion) for driving purposes” and “drives by electromagnetic force” [48].

The electric motor must be able to transmit the required velocity-torque values defined in the working points of the hydraulic system simulation in section 2.4.2, which imply that it must be bidirectional. Moreover, the electric motor must have a sufficient efficiency to deliver the required power under the available power threshold defined in section 2.2.2.1. Finally, it must operate while immersed in hydraulic fluid under high pressure and resist eventual corrosive attack of the medium.

There are several different electric motor concepts, each has its own advantages and disadvantages. For this project it was considered the AC induction motors, brushed DC motors and brushless DC (BLDC) motors, since these technologies have a bigger range of options available in the market. Moreover, all these main technologies have options suitable to drive the hydraulic system in terms of performance. To find the best technology in overall terms, they were analyzed qualitatively in respect to their service life, efficiency, control method, cost, the required number of connector pins to power and control, and power-to-weight ratio [49]. There are also remarks regarding specific features of each technology and how these features affect the electrical drive system and adjacent subsystems of the SVA. In Figure 3.7 there is a generic comparative radar chart for each of the technologies considered [51][52]. The parameters are rated from the lowest score (middle of the chart) to the highest score (border of the chart) in respect to the SVA application.

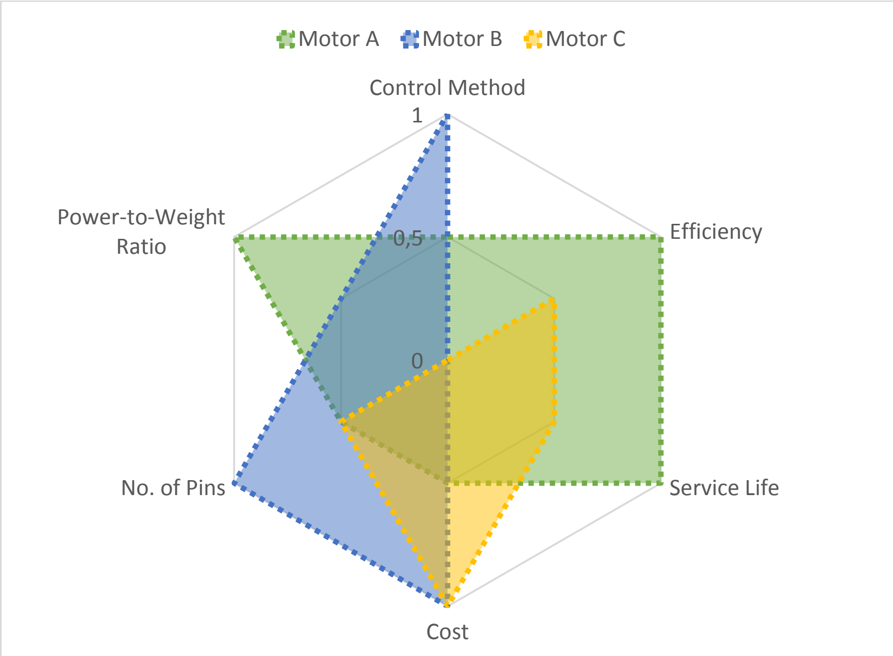

Figure 3.7: Qualitative comparison between electric motor technologies in the SVA application

The efficiency of any machine is given as ratio of the power output to the power input. In electric motors, the efficiency is a function of the load. The output power in a motor is given by the product of its rotational speed and the output torque, which changes with the load. All electric motors have inevitable power losses due to Joule effect in the windings and due to friction in the axis bearing. In brushed motors, there are also power losses because of the friction between the brushes and the commutator, which are non-existent in BLDC motors and induction motors. Induction motors have further power losses in the rotor core inherent to its construction. The power losses in the core are due to hysteresis and Eddy currents. BLDC also have losses due to parasitic currents, but depending on its construction, this effect can be mitigated [52]. Further power losses must also be considered together with the control method. Since induction and BLDC motors require an additional hardware piece to control their speed, it can affect the operation or limit the power output [53].

A brushed DC motor can be operated in many different manners, such as series excitation, shunt excitation, permanent magnet stator, and others. The open-loop control of the velocity of a brushed DC motor can be achieved by simply varying the voltage in the armature. By monitoring the current drained in the armature windings, one can apply a closed-loop torque control with fairly little effort [51].

To control the angular velocity in induction motors, it is required more sophisticated methods. It can be seem in the equation of the synchronous velocity in an induction motor:

$$\omega = \frac{4\pi f_s}{P} \; [{}^{rad}/_{s}]$$

Where ω is the synchronous angular velocity, P is the number of poles and f_s is the frequency of the voltage in the stator windings. The poles are a construction parameter of the motor and cannot be changed during operation. To control the frequency in the stator it is necessary a frequency inverter. An effective control of induction motors can make use of a plethora of methods such as field-oriented control, direct torque control, scalar control, among others [54]. However it must be remarked that some control methods are only applicable in three-phase induction motors.

Brushless DC motors, in the other hand, require a coordinated commutation of the winding currents in respect with the rotor position in order to control its rotation smoothly [51]. In practice, this requires an electronic commutator, which automatically switches the currents in the stator windings according to the rotor position. Since there are permanent magnets in the rotor of BLDC motors, typically, its position can be measured with Hall Effect sensors fixed in the stator. This would require additional contact pins to read the measurement signals from the control module. However, the position of the rotor can also be estimated using back-EMF signals [55]. This is a well-known method used in control of sensorless BLDC motors.

Particularly, brushed motors present a few inherent disadvantages. The first being its service life, which is mainly limited by the degradation of the brushes. The service life of the brushes depend on many factors, which are hard to predict accurately [56]. In contrast, the service life of BLDC motors is largely dependent of the bearing's service life, which is usually much longer and predictable. Induction motors' service life is mainly caused by thermal breakdown of the winding insulation, but this may also take longer times if the machine is properly operated. The brush commutation generates electromagnetic noise, a trait also undesirable in the proximity of analog signals. Although BLDC and induction motors also produce EMI, the frequencies are controlled and their interference can be better filtered in the DAQ with less information loss [57]. The wear of graphite brushes produces graphite dust. This contaminates the hydraulic fluid in which the motor will be immersed and may clog the hydraulic system. All these characteristics are not desirable in the SVA project, justifying the drop of the brushed DC motor choice.

Induction motors also have undesired particularities. These motors are susceptible to an effect called slip. The slip is the offset between the stator's rotational field and the rotor's velocity. This phenomena is caused by the load in the shaft. Additionally, induction motors have a very nonlinear torque-velocity characteristic curve, which makes the control more complex. To increase the permeability in the rotor, induction motors usually employ a ferromagnetic core, which also increases its weight and rotor inertia considerably, having a poorer dynamic characteristic [51].

After evaluating all the aspects, one of the motor technologies was selected to drive the hydraulic system in the SVA.

3.2.2.2. Control Valve Solenoid

The control valves were selected solely for their hydraulic function. For fail-safe reasons, the control valves are normally open. When open, they allow the cylinder spring to press the hydraulic fluid out of cylinder chamber, closing the gate valve. These valves, however, are driven through solenoids, which concern the electrical system. The solenoids selected are custom built for high-pressure environment, with IP00 housings to allow pressure-tolerant application [34]. The solenoids are designated with the letter code "QM", as specified by IEC 81346 for devices for "controlled switching or varying a flow of energy, of signals or of matter" specifically "switching of flow of flowable (sic) substances in closed enclosures" [48].

3.2.2.3. Cylinder Position Encoder

The last electronic components required in the SVA-V1 are the redundant position encoders for the hydraulic cylinder shaft. A position encoder is a device that measures mechanical position (in this case, linear displacement) and translates it to an electrical signal. According to IEC 81346, the adopted designator for this component is “BG” because its function is to “convert an input variable (physical, property, condition or event) into a signal for further processing”, specifically a “gauge, position or length” input [48].

There are several different physical principles for position encoders. Linear Variable Differential Transformer (LVDT) and magnetostrictive transducers were selected to be more thoroughly analyzed in this work. This is justified because both measurement principles are virtually frictionless, give absolute position measurement, can be built to withstand harsh environments and are regarded to have a relatively large service life [59][60].

Transducers using magnetostrictive principle rely in the following physical phenomena: the Wiedemann effect and the Villari effect. In practice, the transducer is composed of a waveguide rod with the length of the displacement course, a moving permanent magnet disc along the rod, and an electronic system in one of the ends of the rod as is shown in Figure 3.8. The rod is built in ferromagnetic material. The magnet is mechanically attached to the part whose position is to be measured. The measurement is done by transmitting a short pulse (approximately 1 to 2 [μs]) of electrical current through the waveguide rod. The combination of the Villari and Wiedemann effects explains that, when the current pulse reaches the permanent magnet, a torsional mechanical wave is sent through the ferromagnetic rod. This mechanical wave is detected in the electronic system through an electromechanical sensing element. The speed of the wave is a known parameter, which depends in the waveguide rod material and structure. Typically it is about 3000 [m/s]. The time elapsed between the current pulse emission and the torsional wave detection is counted in the electronic system. From this value, the position can be inferred. Since it is a time-based measurement, the position cannot be continuously measured. However, in practice, most of the available DAQ has sampling rates lower than the refresh rate of a typical magnetostrictive position transducer [60].

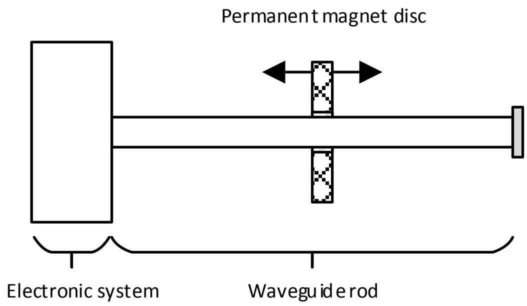

Figure 3.8: Composition of a basic magnetostrictive position sensor

A basic Linear Variable Differential Transformer sensor is composed of two parts: a moveable rod and a fixed tube. The rod, also called core, is attached mechanically to the moving part whose position is wished to be measured. The core is made of a highly permeable material. In the tube part there are typically two conductive coils separated by insulating disc-shaped flanges. The primary coil is placed in the middle of the tube, while the secondary coil is placed in the tube's extremities. Figure 3.9 shows a cutaway view of a basic LVDT sensor. To measure the position of the moving core, the primary coil in the tube is excited by an alternating voltage. This generates a magnetic field. As the core slides inside the tube, it creates an inductive coupling between the primary and secondary coils. Depending on the length of the core inside the tube, the induced voltage in the secondary coil changes proportionally. Thus, the position can be inferred from the strength of the signal [60].

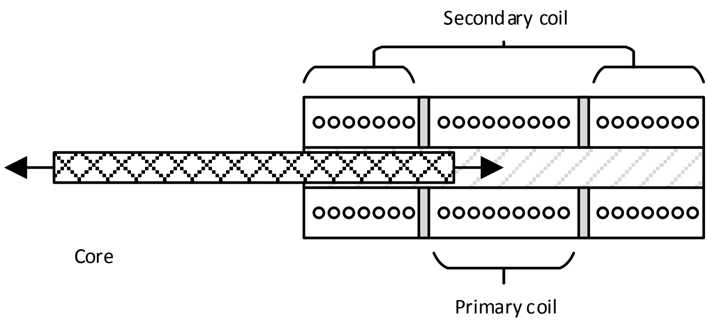

Figure 3.9: Cutaway view from a basic LVDT sensor

The positive and negative aspects of both technologies has been assessed in the project needs and the best suited technology was selected.

3.2.3. Interface

Internally, all devices will have a specific cabling to provide an electrical link with the external receptacle contact pins. Because all signals are routed to two ACM, each component will have a three-way cable. To calculate the nominal cross section of these cables, it is used the guidelines in the standards DIN EN 50565-1 (chapter 5.2 and 5.3), DIN VDE 0298-4 (chapter 5), DIN EN 60228 and ASTM B258-14 [61][62][63][64]. From these it's possible to define the cable type (single-wire or stranded), the jacket material for use in hydraulic fluid medium, the insulating material, the conductor alloy type and the conductor cross section. These parameters were chosen according to the rated nominal current and voltage of the components and the hydraulic fluid data.

The bifurcated ends of each cable assembly would be directly soldered to the contact pins of the external receptacles. Due to the origin of multiple signals from a single pin, as the ground reference pin and the cross-piloted valve solenoids, more than one wire may be soldered to a single receptacle pin. Figure 3.10 shows a diagram with this proposed solution.

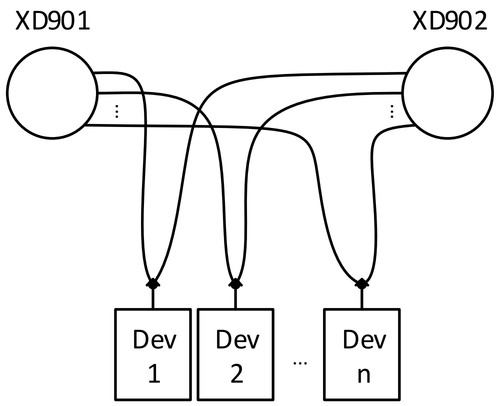

Figure 3.10: Internal cable structure between components and external connectors in the SVA

Seeking high mechanical stability in the soldered electrical joints under the actual extreme conditions, the most suitable tin solder was selected. It presents strong mechanical properties and is ductile enough to not break under pressure. Furthermore these metals were listed as compatible with the hydraulic fluid medium, i.e. resist corrosive attacks. Still, to mitigate chemical attack in the conductor metals and avoid short circuits due to eventual contact between the soldered joints, a heat-shrink tube of a protective high-end polymer shall be used in all soldered joints and exposed contacts.

The cable that connects the SVA to the ACM is limited to a length of L_{ACM} [m]. Because of the high commutation frequency and electrical current through some of the conductors, they may be an interference source for the adjacent wires. To mitigate the EMI effects, all wires must be covered by a conductive shielding foil or mesh. This shield cover shall be short-circuited to the ground potential in order to reduce the effects from capacitive coupling properly. If possible, there shall be an extra ground wire for each signal wire to be twisted in pairs. This reduces the interference caused by inductive coupling effect [49].

3.3. Second Prototype Variant (SVA-V2)

3.3.1. General Architecture

It was aforementioned that the SVA-V2 shall make use of the same electrical components used in the first variant with seven additional transducers. The only exception being its electrical external connector, which was settled in the requirements with a fixed number of contact pins.

The general layout of the electrical components in the second variant is depicted in Figure 3.11. The selection of transducers to meet the condition monitoring requirements is explained in the following subsections.

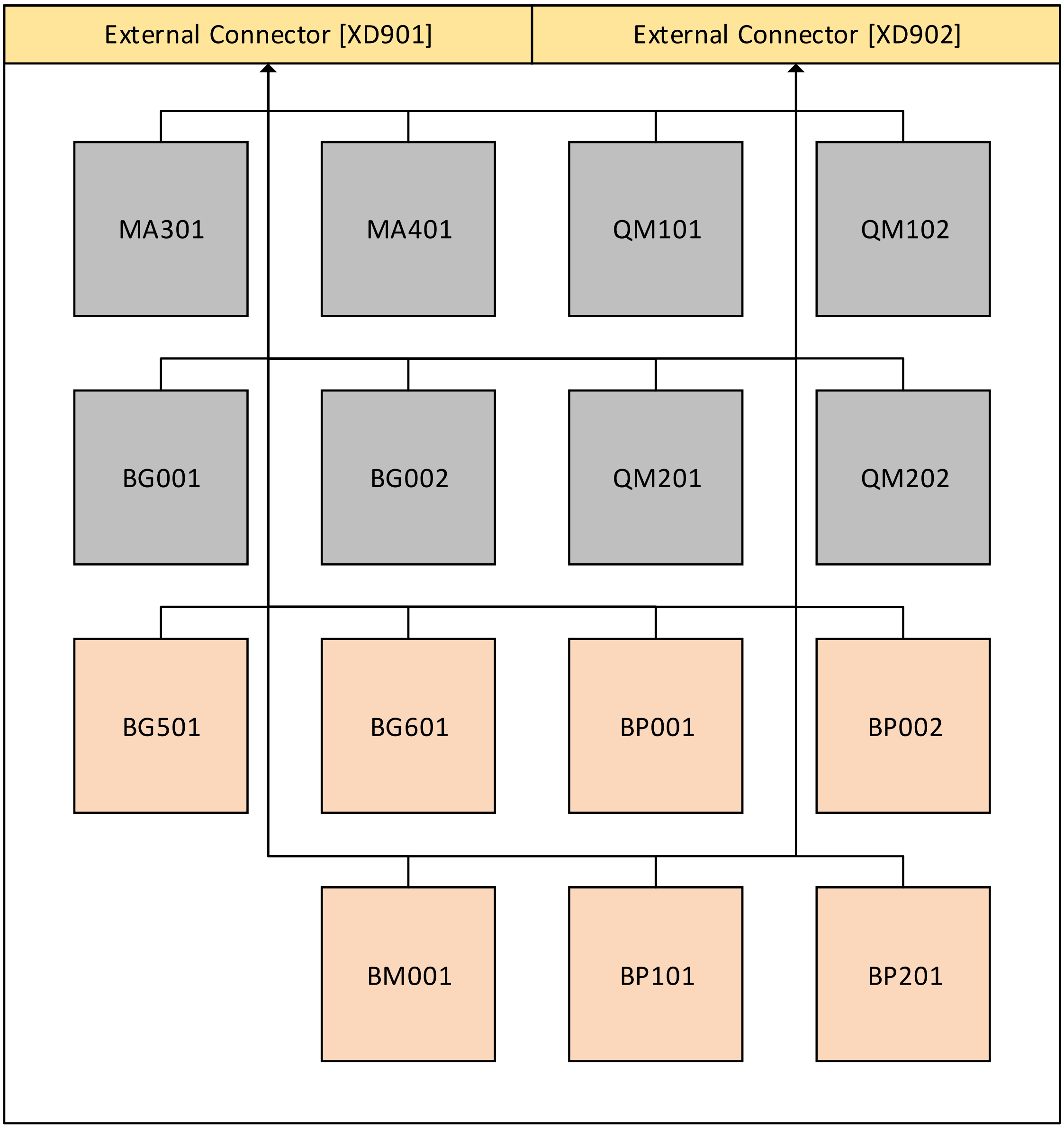

Figure 3.11: SVA-V2 electrical system architecture

There are no significant differences in the internal interconnection structure of SVA-V1 and SVA-V2, other than more internal cables to accommodate the extra instruments. The cable to interface the SVA-V2 and the ACM shall have a mating connector to the SVA-V2 connector, which is different from the SVA-V1.

3.3.2. Condition Monitoring Instrumentation

The additional instruments in the SVA-V2 serve the purpose to monitor the condition of the valve actuator. An effective condition monitoring system is able to detect the most likely failure modes in the process it is observing. The procedure to assess these failure modes is known as FMEA and is described in IEC 60812 [67]. In Table 3.1 there is a brief list of the components commonly used in subsea technologies and their respective most likely failure modes during operation. The information is based in the Offshore Reliability Data (OREDA) handbook [68].

Table 3.1: Likely failure modes during operation in common components employed in subsea technology

<table>
<tr><th>Component</th><th>Failure Mode</th><th>Effect</th></tr>
<tr><td rowspan="4">Electric Motor</td><td>Rotor does not move</td><td rowspan="6">Hydraulic fluid can’t be pumped</td></tr>
<tr><td>Load-free rotor</td></tr>
<tr><td>Short-circuit in winding wire</td></tr>
<tr><td>Open winding wire</td></tr>
<tr><td rowspan="2">Hydraulic Gear Pump</td><td>Gear does not move</td></tr>
<tr><td>Load-free rotor</td></tr>
<tr><td rowspan="3">2/2 Directional Control Seat Valve</td><td>Short-circuit in coil wire</td><td rowspan="2">Control valve is always open, hydraulic flow is free</td></tr>
<tr><td>Open coil wire</td></tr>
<tr><td>Seat does not close the flow completely</td><td>Control valve can leak flow when closed or be stuck open</td></tr>
</table>

To detect failures modes of the components in the SVA system, specific instruments were selected to be installed in the system. The positioning of the transducers allow many different check procedures to verify the condition of the system. A list of the check procedures has been written, however are not listed to protect industrial property.

3.4. Actuator Control Module (ACM)

3.4.1. General Architecture

The Actuator Control Module is the unit responsible to monitor the condition and to control the Subsea Valve Actuator. Its interface is designed to be able to control and monitor both variants of the SVA.

In order to fulfil its assigned tasks properly, the system layout must have a minimum functional architecture. A proposed architecture for the system is depicted in Figure 3.12. Among the components are power supplies, controllers, motor drivers and relays.

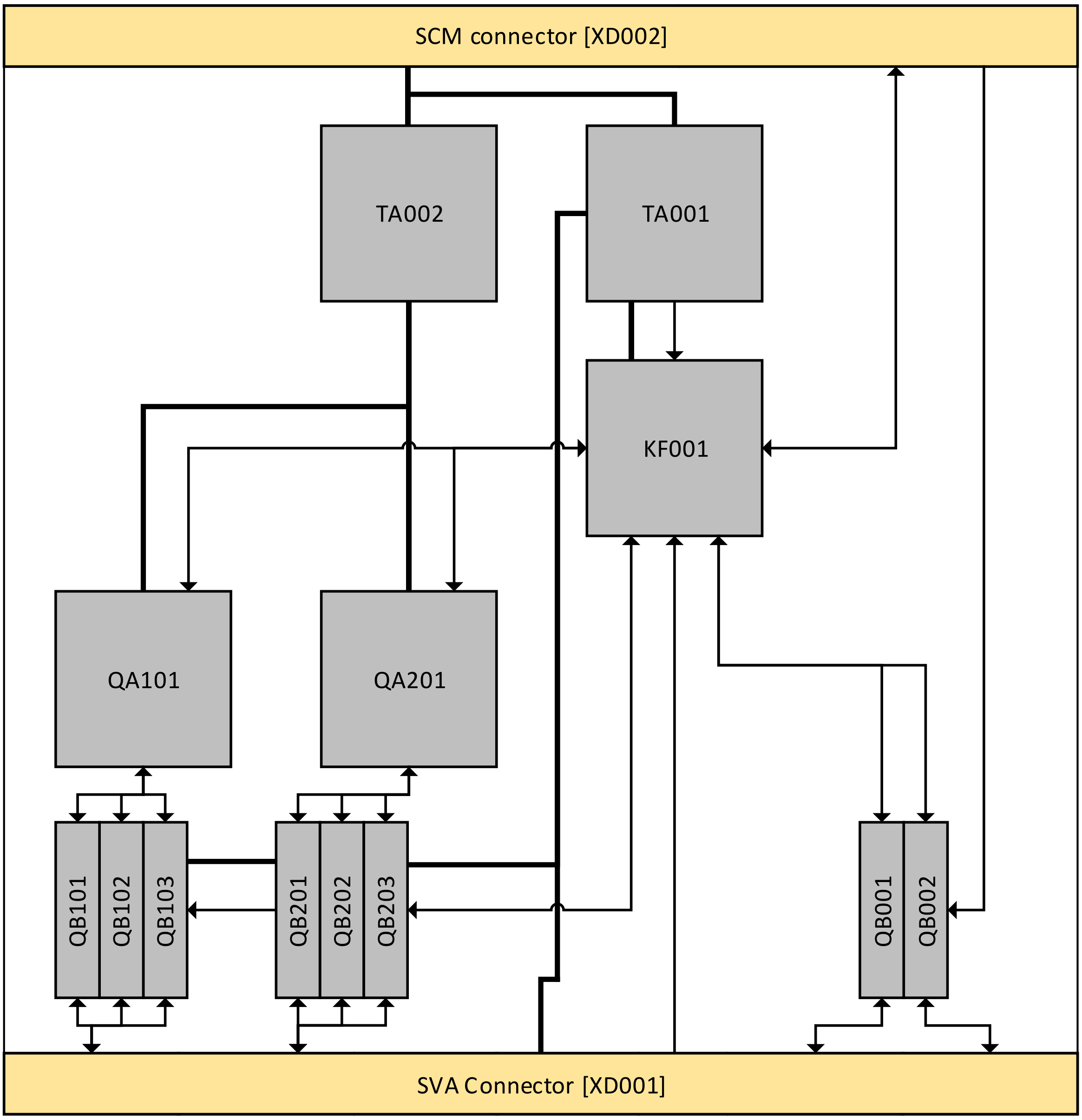

Figure 3.12: ACM electrical system architecture

In the lower part of the proposed layout is the SVA connector, which provides an interface to the components defined in the SVA variants specification. The upper part corresponds to the third-party SCM interface that connects to the ACM. It provides power, CAN interface with the local and/or surface control modules and safety signals to deactivate the control valves in the SVA (and consequently close the gate valve).

According to the selected architecture required by norm, the ACM is designed to normally work connected in parallel to another hardware instance of itself, both connected to a single SVA [30]. Since the system will have two main controllers connected to the actuator components, i.e. two controllers actuating in the system simultaneously, there must be a law of precedence to ensure that there will be no conflicts in the controlling system.

Although CAN bus is a multi-master network protocol, in the adopted architecture, a master-slave management is adopted for its simplicity. As shown in Figure 3.5, one of the actuator control modules will be assigned as a master and the other as a slave.

The master is then able to send signals to actuation elements, i.e. motor drivers, relays and valves. The sensor inputs can be read simultaneously by the master and the slave, since the master may consult the slave's received data to confirm his own readings. Master and slave can be switched during operation, for test procedures or failure handling.

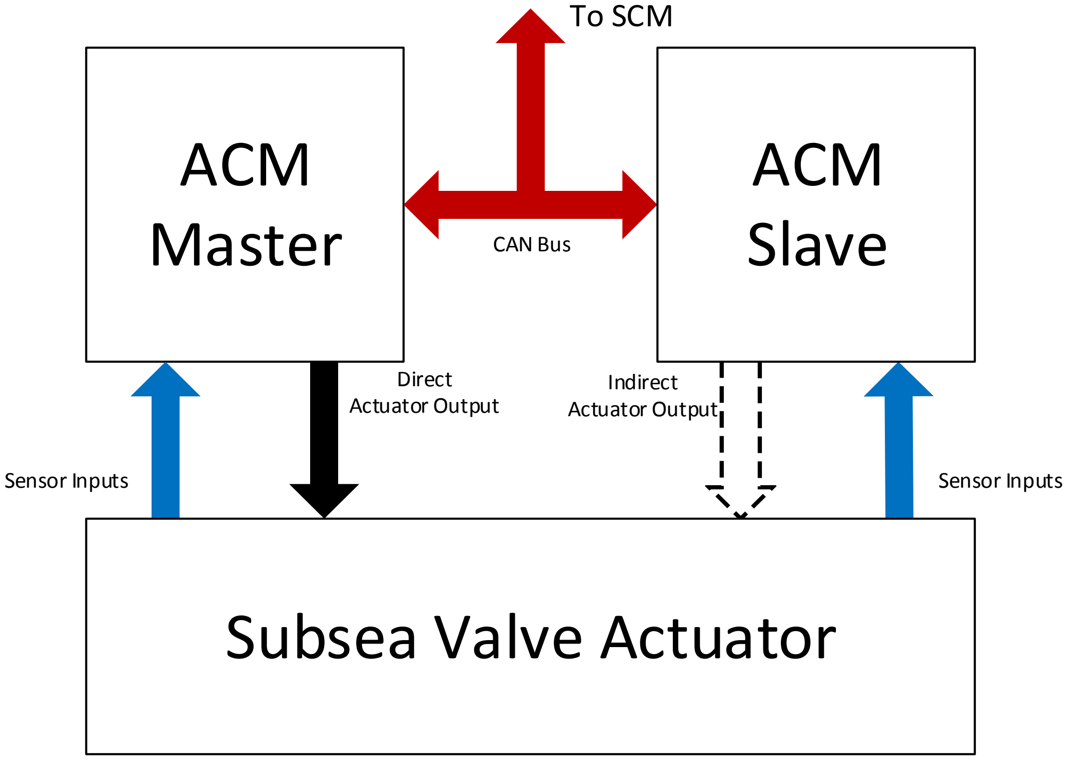

Figure 3.5: Information flow through the system components

3.4.2. Components

The components in the ACM won't be exposed to high pressure. The ACM enclosure is built to keep a pressure-neutral environment. More specifically, the mounting of all components inside the cabinet must comply with some requirements from the standard ISO 13628-6 [12]. The following requisites are listed:

- All active electronic circuits should be in enclosures filled with nitrogen gas at nominal 0,101 [MPa];
- SEM (ACM) shall be protected against water intrusion; the design should include two separate and testable barriers;
- Electrical distribution cabling and jumper cables from umbilical termination to the SCM should be repairable or reconfigurable by the use of an ROV;
- A minimum of two barriers should be provided between seawater and any conductor;

The following subsections contain specific remarks for the components listed in the architecture.

3.4.2.1. Power Supply

The power supplies, or more accurately the AC/DC converters, are the components which will transform the supply AC power line to a suitable DC level for all electrical components in the ACM and SVA.

From all the electrical devices selected to compose the SVA and ACM system, an estimation of the electrical power demand was made based in the operational modes of the components in a worst-case scenario (maximum demand).

3.4.2.2. Motor Driver

The motor drivers in this application are electronic modules that are able to commutate power signals in sequence to drive the motors embedded in the SVA. This device's function is described according to IEC 81346 as "controlled switching or varying a flow of energy or of signals", specifically "switching and variation of electrical energy circuits" [48]. Thus, its adopted designator is QA.

3.4.2.3. Controller Unit

The controller unit is the element which will process all input signals, actuate the valves and the motor drivers and also communicate with other instances of itself and the local SCM through a CAN module. The reference designator for controllers according to IEC 81346-2 is KF [48]. It must be a reliable unit equipped with analog and digital I/O, capable of running real-time applications and with CAN interface available. The chosen device is compact PLC unit with support to all standard PLC programming languages listed in IEC 61131-3 [70].

3.4.2.4. Decoupling & Safety Relays

The relays are critical components in the system for they are required to latch the physical connection between the motors' windings and the motor drivers, as well as to electrically disconnect the valves' solenoids from the power source in the controller, taking the actuator to a safe-state. The device designator according to IEC 81346 is QB. The function of this component fits in the description "controlled switching or varying a flow of energy or of signals" and "isolation of electrical energy circuits".

3.5. Summary

This chapter highlighted the selection of all electrical components, instruments, drives, controllers, etc. that compose the systems in the project. It gave explanations regarding the technologies employed and justified the choices with the design requirements previously presented, and relevant technical references from standards and research.

4. Software Conceptual Development

To provide an interface to the mechanism designed, a software must be designed. The software shall complete most of the functional requirements highlighted for the electric system.

It runs low-level control loops for the SVA namely the position control of the cylinder and the control valves switching. It is a communicating channel between an external user and the SVA functionalities, which utilizes the CAN module of the controller as primary interface. Finally it acts autonomously to check the condition of the machinery and act when an emergency actuation arises.

During the development of this thesis, only an overall concept for the software could be conceived, due to the length of the activities needed to define the hardware components. This section explains the development tools utilized and the process of initial synthesis.

4.1. Development Tools

4.1.1. Programming Language

The IDE utilized in the company is proprietary package which uses an implementation of the CoDeSys PLC language [71]. It implements all programming languages described in IEC 61131-3 [70] and allows cross-compiling for multiple proprietary platforms.

A software project in CoDeSys is built of Program Organization Units (POUs) and Actions. POUs consist a declaration and a body. The body can be written in any language. POUs can call other POUs, but recursion is not allowed. The different POUs data structures are Function, Function Block and Program.

4.1.1.1. Function

It is data structure that yield only one data element (which can also be an array), i.e. it returns only one value. It is declared with a type equal to its return value type and can be called as an operator. The local variables used in a function are deleted after it is finished.

4.1.1.2. Function Block

Function blocks can provide one or more values during its procedure. But it does not return any value itself. A function block can be reproduced multiple times, each being an instance with its own name (instance identifier), inputs, outputs and internal variables. All values are retained after processing a function block instance. The internal variables are only accessible in its own instance.

4.1.1.3. Program

A program is a POU which returns many values during operation. All of the data within a program is retained through the cycles. Programs can be called only from other programs and function block instances. Programs cannot be instantiated, therefore all changes in a program will be retained if another POU calls it.

In the CoDeSys there is a special predefined program POU called PLC_PRG. It is obligatory in every software project. This is an equivalent to the main function in ANSI C language [72]. This program is called exactly once per PLC control cycle. All the other POU and programming logic is inserted in it.

Notice that the relationship between the POUs is strictly in terms of memory share. Functions, programs, actions and other structures can be called in any task with any periodicity that the controller allows. This is handled by the scheduler, which is already built-in in the IDE.

4.1.1.4. Action

Besides the POUs, there is also an object called Action in CoDeSys. Actions are a set of instructions assigned to one specific POU. It manipulates only the local variables in the memory area of the POU it belongs to. They can be programmed in any of the supported languages and called multiple times in any POU’s body.

4.1.2. PLC Software Framework

At Bosch Rexroth, the development of software for PLC devices follows a proprietary framework. This is adopted to optimize the overall software performance and to enhance the modularity, platform-undependability and maintainability of the code. The framework structure is illustrated in Figure 4.1.

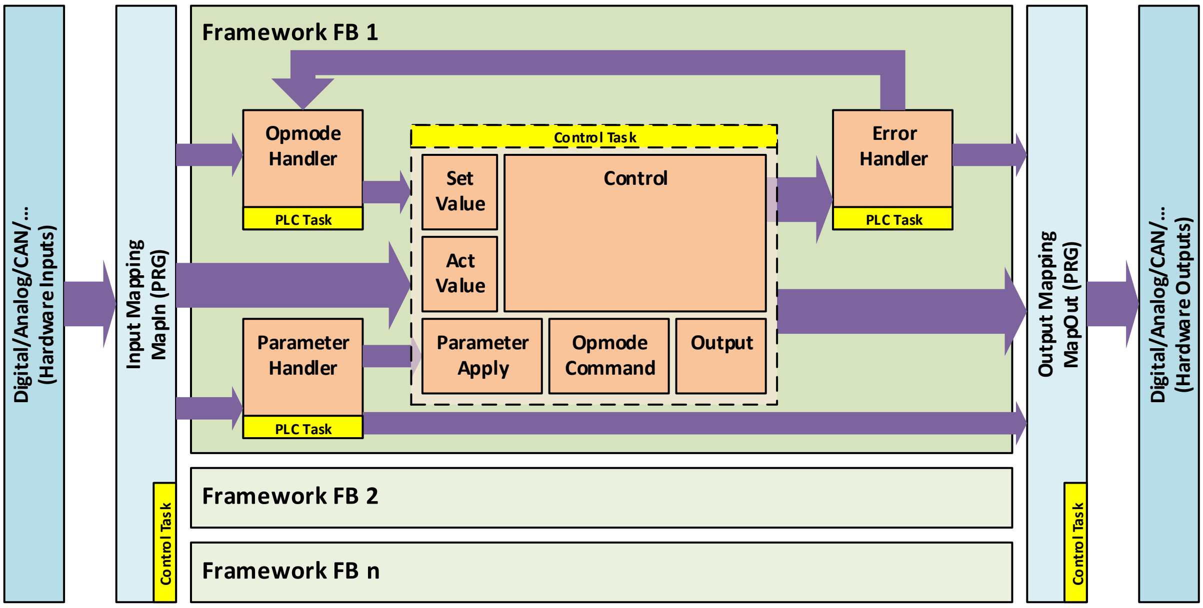

Figure 4.1: Bosch Rexroth PLC software development framework

There are two tasks running concurrently in this framework: the Control Task and the PLC Task. The PLC Task handles the software logic, states and long routines. The Control Task is responsible for handling hardware input and outputs and the control loops. There is no real parallel execution in the selected controller. The scheduler periodically calls the PLC Task and the Control Task. PLC Task is usually slower and is run more seldom than the Control Task. Because the Control Task is more critical and must meet hard real-time requirements, it can interrupt the PLC Task.

In the framework, the structure blocks are either called in the PLC or in the Control Task. A brief explanation of each block is given below:

4.1.2.1. Framework (Function Block)

This is the function block instance where the framework structure is contained. All of its variables and actions are set to run one specific application.

Typically in an application, for every machine part, there is a framework. In the SVA (one machine part), a single framework is sufficient to realize the software concept.

4.1.2.2. MapIn, MapOut (Program)

These are the maps that relates physical the I/O pins and internal registers to the respective variables in the memory. It functions as an abstraction layer. CAN bus data, ADC registers, digital I/O, RS232 registers, for instance, are all named to relate with their application purpose. For example, if the output of a pressure sensor is connected in a pin in the controller, the MapIn program maps the pin number to an internal variable for the pressure sensor. These blocks provide a generic interface to the framework. They run in Control Task, as they have to quickly refresh the I/O values.

4.1.2.3. Opmode Handler (Action)

This is where the main application sequence logic is. It is where the decision clauses are done and other actions are called. The content and structure of this block is completely application-specific and can be altered as necessary, except the data format. The I/O data must always be compatible with the framework structure.

4.1.2.4. Parameter Handler (Action)

The parameter handler is the action that controls the access and flow of the internal variables. It separates the variables in I/O data, machine data (length of stroke, cylinder diameter), process data (position set-point, relay feedback signal) and status data (error flags, state flags). These variables are structured in a standard format and accessed through the parameter handler. The information handled comprises all application constants, scaling factors, user levels, default values, error sentences, etc. The structure of this block is fixed, the content can be altered to fit the needs of the application.

4.1.2.5. Error Handler (Action)

It collects the outcome from other actions and verify whether they are in an erratic behavior. Then it sends a status data to the opmode handler, so it can react to the error. The structure of this block is also fixed. The content can be programmed to fit the application.

4.1.2.6. Control, Set Value, Act Value, Parameter Apply, Opmode Command, Output (Action)

These actions are run in the Control Task and are responsible for the quick operations in the application. They serve the purpose of manipulating the data, calculating control loops and performing computation in general.

The blocks communicate between themselves via arrays, which are represented by the purple arrows. In fact, these are local variables in the function block “framework”, which are accessible through the actions contained in it.

4.2. Synthesis Process

4.2.1. Finite State Machine

To start the development of the software architecture, a state-machine was synthesized from an operation cycle that would cover all the functional requirements needed. The following procedure steps were proposed:

1. The controller is powered up and the software begins in the initial state;
2. In the state 1, it runs a procedure to identify the devices it is connected with. In case of unsuccessful result or erratic execution, it goes to state X and returns to the initial state.
3. After that, it goes to the state 2. In this state it will run periodic diagnosis functions and listen to CAN requests. This is an endless loop routine. The periodic functions and CAN interrupts are scheduled with a prioritization order.
4. If an error happens during the scheduling or while handling the CAN messages, it goes to the state X. From there it may reset to the state 1 or go back to state 2.
5. When there is a function in the schedule, it goes to state 3.

6. If an error happens during the execution of the function, the software goes to state X. From there it can reset to the state 1, go back to state 2 or resume the function it was executing in the state 3.
7. If another function is scheduled for execution right afterwards, the software immediately begins the execution of the next function at the conclusion of the previous.
8. After the successful conclusion of the function(s) scheduled, the system goes back to the wait command state.

A visual representation of the explained behavior can be seem in the machine-state in Figure 4.2.

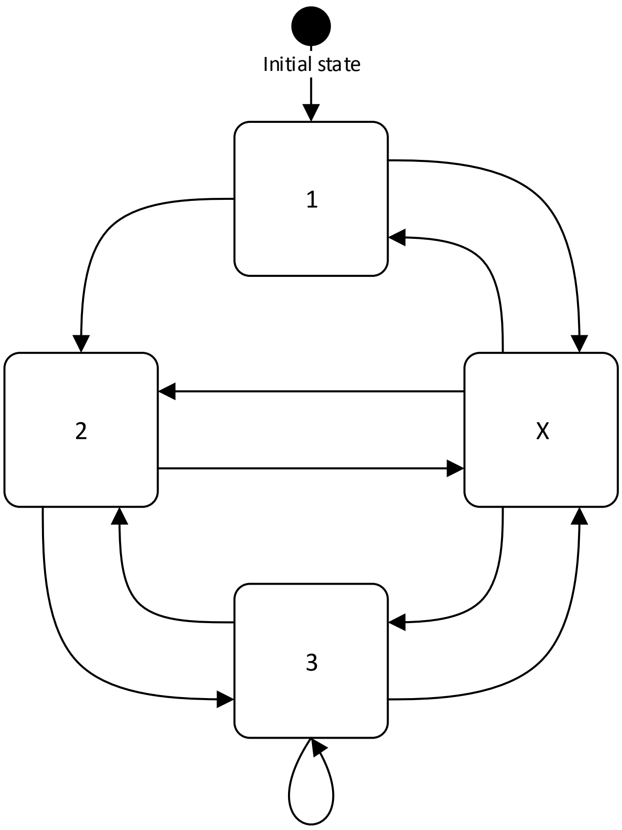

Figure 4.2: A state-machine representation of the proposed software behavior

4.2.2. Sequential Function Chart

To translate the state-machine into a PLC software shape and fit it into the proprietary development framework, a few steps are taken. At first, from the state-machine, one can derive the sequence logic of the software operation. This is substantially the content of the Opmode Handler in the framework. The Sequential Function Chart is usually the language preferred to program the Opmode Handler.

From the previous state-machine, a SFC for the whole Opmode Handler was conceived, shown in Figure 4.3. The proposed steps with the respective transitions are explained in the following subsections.

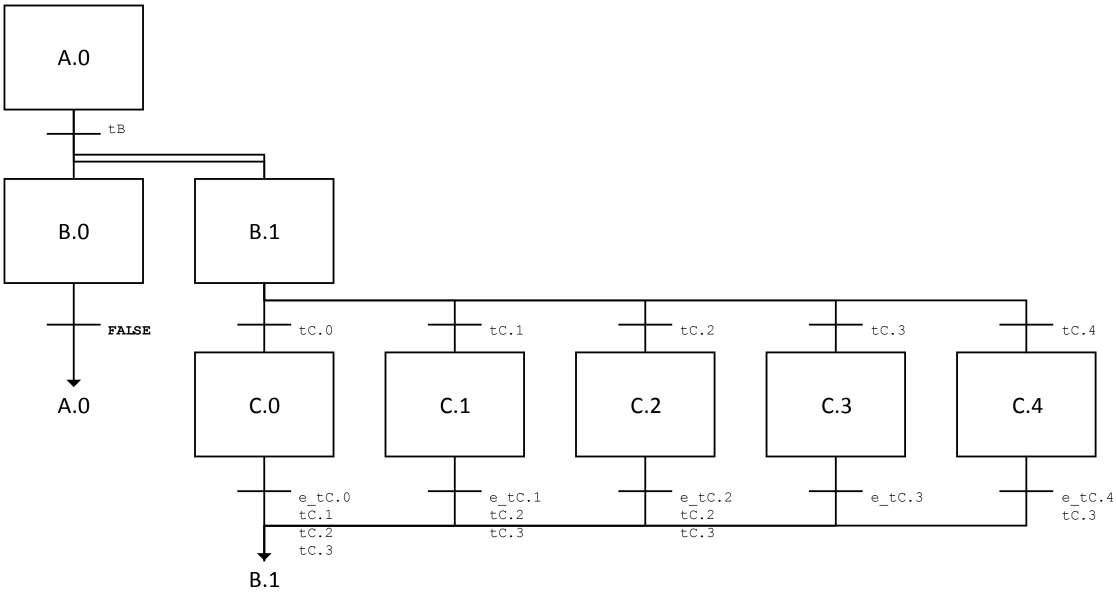

Figure 4.3: Concept of sequential function chart for the software

4.3. Summary

The fourth chapter comprises the software development tools and directives as well as presents the synthesis of a conceptual software for control and interface of the valve actuator. It shows the general software idea and how it was translated into a specific programming language defined by standard to fit in the desired software framework.

5. Results

With the proposed solutions in the hardware and software systems, the results obtained can be evaluated in two aspects: the functional aspect, which analyzes whether the requirements were achieved objectively, and the safety and reliability aspect, which verifies if the current system is safe and reliable in accordance with the standards and requirements.

This section gives a brief evaluation of both aspects, with remarks in specific system components and mechanisms.

5.1. Functionality Evaluation

The desired functionality, i.e. the capability to fulfill all functional requirements, was partially met because the electrical system was designed specifically to be able to cope with the results shown in the section 2.4. The time specifications, control loop tolerances and condition monitoring requirements, however, are requirements that can only be fulfilled with a complete design of the system’s software. This part is still in development.

5.2. Safety & Reliability Evaluation

The safety and reliability aspect of the electrical system are most importantly evaluated in parts where it is involved with a safety-related function. In this project, the closure of the valve gate is a safety-related function, which must be attended so it can always be able to return to that safe-state position.

However, reliability in its performance is also desired. The electrical system plays a special role in the drive system. The proposed design for the drive system is fault-tolerant, but a thorough analysis is necessary to ensure it.

5.2.1. Safety Shut-down Signal

The electrical system drives the control valves, which are responsible to hold the cylinder open. Since the control valves are normally open, they must be designed so that the user is able to cut the power of the valves in case of an exceptional event. The control lines of the solenoids were placed with two safety relays in series, as shown in section 3.4.2.4. These relays are also normally open, meaning that in case their control signals are cut, the control valves are also de-energized.

In Figure 5.1 there is a sequence of events where both the ACM controllers are in an “uncontrollable” state, i.e. with unpredictable outputs. Green lines are energized conductors. In this situation, the first relay solenoid is turned off, opening the control signal path, and consequently opening the control valves in the SVA (frame 1). If there’s a problem in the coil of the first relay (it can be mechanically jammed), a second signal can also deactivate all control valves (frame 2). It is a redundant design to improve safety.

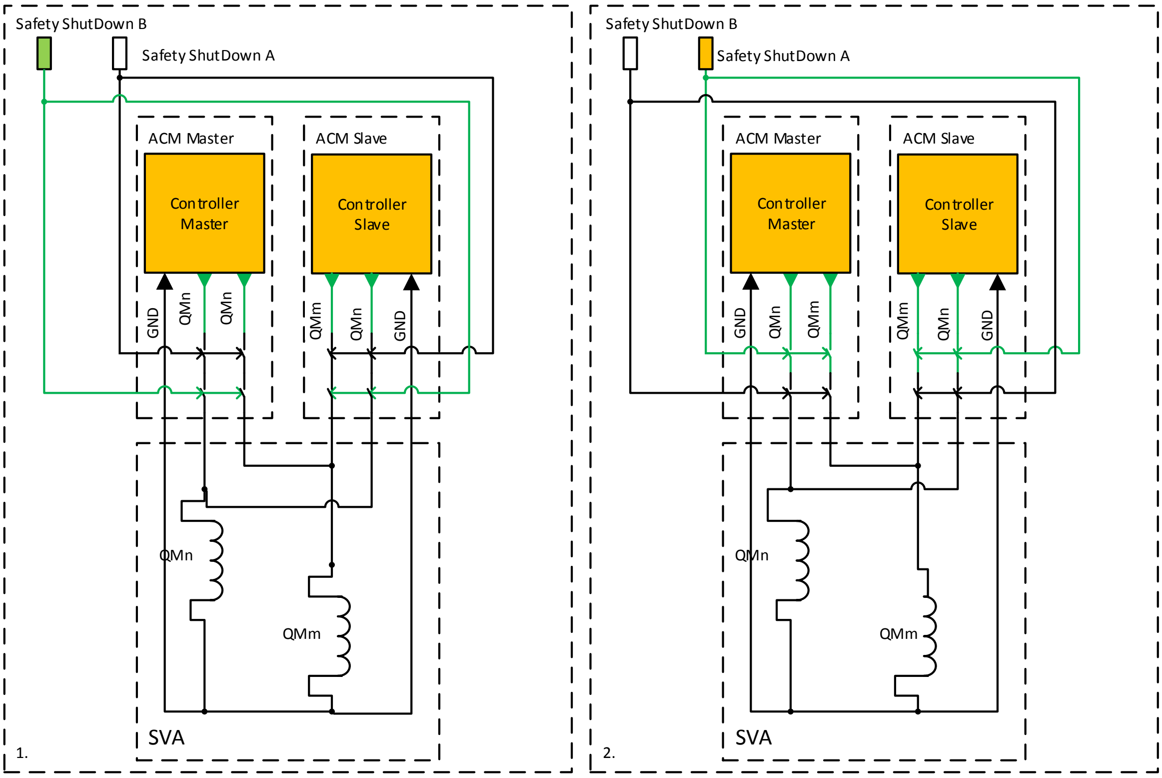

Figure 5.1: Safety power-cut system for the control valves

5.2.2. Redundant Drive System

For the drive system there is also an evaluation of the redundant design employed. In this situation it is desired to improve reliability. In Figure 5.2, it is shown a sequence of failures which the system can withstand and still run with full performance.

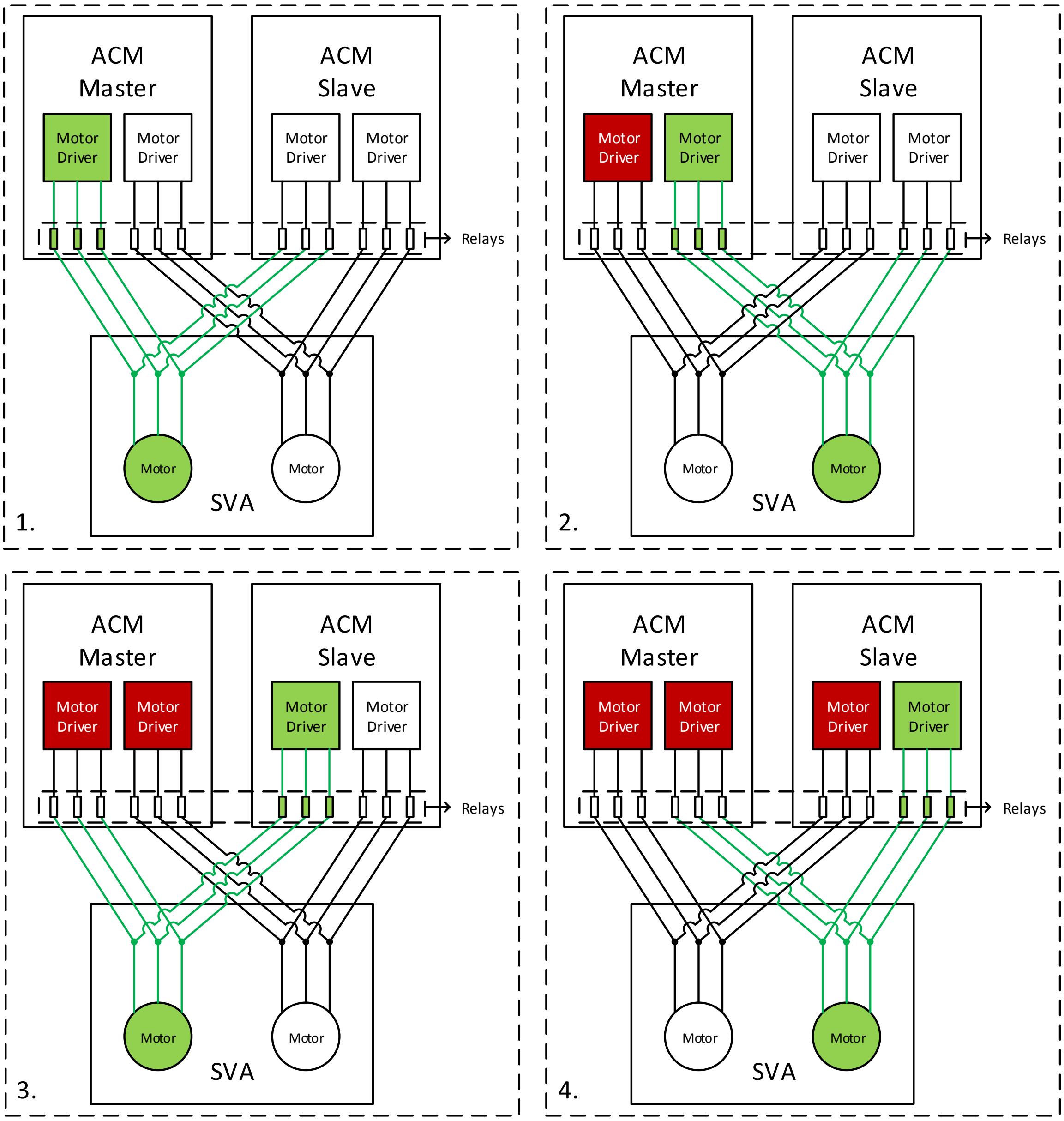

Figure 5.2: Redundancy in the motor and motor driver

In the first frame, there is normal operation of a single motor. The second frame depicts a failure in one of the motor drivers in one of the ACMs. The system detects the failure and starts driving the SVA with the second motor. The thirds frame shows a failure in both motor driver of the first ACM. In this situation, the second ACM takes over in the actuation and starts driving the SVA with the first motor again. At this point, an ROV can be deployed to retrieve the first ACM and substitute it for a fully operational one. In the fourth frame, after a failure in the first motor driver of the second ACM, the second motor drive takes over the driving while retaining full performance at all times.

This is one of the many possible failure sequences that may happen, to which the proposed design has shown a high level of robustness. It is necessary to make a full evaluation of the other possible scenarios to ensure the design is reliable enough.

6. Outlook

Following the project development schedule under the configuration management rules, many steps remain before the completion of this project. In this chapter it is briefly presented the main topics to be developed, directly related to control system (HW and SW) and the integration with the other subsystems, until the commissioning.

6.1. Software Realization

After finishing the software concept, remains the task of implementing it. Basically all the PLC programming must be written and properly documented.

6.1.1. Condition Monitoring Algorithm

Although condition monitoring guidelines are well established in international standards [73][74][21], the strategy for implementation has yet to be defined. In section 3.3.2 it was shown a few objective tests to monitor the condition of some of the components in the system. However, with data acquired from the instruments in the system, there may be numerous more effective ways to infer the condition of other parts of the system more accurately. Research on this topic reveals that many approaches using artificial intelligence methods have shown encouraging results [75][76][77]. These algorithms, however, must be well-tested before employment in a conservative industry sector such as the Oil & Gas industry.

6.2. Verification & Validation

According to the presented configuration management methodology, all stages of the project must be submitted to verification and validation. It consists in a collection of independent processes intended to check if the project requirements and specifications were properly met. It ensures the quality of the project and helps to detect design gaps [23].

In this theme, regarding the whole electrical system specification, there are much to be done. At first, the proposed solutions must be mounted in a test bench and submitted to a thorough examination of all the most likely and conceivable system faults. The metrological components of the system must be tested for accuracy and finely calibrated. Tests of environmental emulation must also be carried out to certificate the resilience of the system. Some of the tests for material compatibility were already performed, but none specifically regarding the electrical system.

Bibliography

[1] I. H. Fang, F. Cheng, A. Incecik, P. Carnie, *Global Marine Trends 2030 Report*. United Kingdom: University of Strathclyde, Lloyd's Register Group Ltd. and QinetiQ, 2013.

[2] R. Marquadt, "Five-Year Life Test Data on Pressure (10000 lbf/in^2) Tolerant Electronic Components," in *IEEE Transactions on Components, Hybrids and Manufacturing Technology*, USA, 1974, pages 365-371.

[3] F. J. Schempf, "*Special Anniversary – The history of offshore: developing the E&P infrastructure*", Offshore Magazine, vol. 64, 2004.

[4] Y. Bai, Q. Bai, *Subsea Engineering Handbook*, 1st Ed. Houston, TX: Gulf Professional Publishing, 2012.

[5] M. McConnell, E. Gold, "The Modern Law of the Sea: Framework for the protection and preservation of the marine environment" in *Case Western Reserve Journal of International Law*, USA, 1991, page 92.

[6] Petróleo Brasileiro S.A. (2016). *Pre-salt* [Brochure]. Available at: http://www.petrobras.com.br/en/our-activities/performance-areas/oil-and-gas-exploration-and-production/pre-salt/

[7] Petróleo Brasileiro S.A. (2016). *Santos Basin* [Brochure]. Available at: http://www.petrobras.com.br/en/our-activities/main-operations/basins/santos-basin.htm

[8] PA Resources AB. (2014). *Life cycle of an oil field* [Article]. Available at: http://www.paresources.se/en/Operations/Life-cycle-of-an-oil-field/%233

[9] Statoil ASA. (2011). *The subsea factory* [Brochure]. Available at: http://www.statoil.com/en/technologyinnovation/fielddevelopment/aboutsubsea/Pages/Lengre%20dypere%20kaldere.aspx

[10] *Subsea Pumping – Subsea technologies for unprecedented recovery and production*, FMC Technologies, USA, 2014.

[11] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 5: Subsea umbilicals*, ISO 13628-5, 2009.

[12] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 6: Subsea production control systems*, ISO 13628-6, 2006.

[13] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 8: Remotely Operated Vehicle (ROV) interfaces on subsea production systems*, ISO 13628-8, 2002.

[14] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 4: Subsea wellhead and tree equipment*, ISO 13628-4, 2011.

[15] PetroWiki. (2015). *Subsea wellhead systems* [Article]. Available at: http://petrowiki.org/Subsea_wellhead_systems

[16] *Petroleum and natural gas industries – Subsurface safety valve systems – Design, installation, operation and redress*, ISO 10417, 2004.

[17] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 1: General requirements and recommendations*, ISO 13628-1, 2005

[18] *Petroleum and natural gas industries – Design and operation of subsea production systems – Part 15: Subsea structures and* manifolds, ISO 13628-15, 2012.

[19] *Oil & Gas: Introduction to Subsea Production Systems – Production Control Systems*, DNV GL, Norway, 2013.

[20] J. Korn, *Hydrostatic Transmission Systems*, 1st Ed. Michigan: Int. Textbook Ltd, 1969.

[21] *Condition monitoring and diagnostics of machines – General guidelines*, ISO 17359, 2011.

[22] *Quality management systems – Fundamentals and vocabulary*, ISO 9000, 2015.

[23] *Quality management systems – Requirements*, ISO 9001, 2015.

[24] *Quality management systems – Guidelines for configuration management*, ISO 10007, 2003.

[25] “SVA Requirements Specification”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-0000-DRS-0000, 2015.

[26] A. M. Davis, *Software Requirements: Analysis and Specification*. Englewood Cliffs, NJ: Prentice Hall, 1990.

[27] *Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles*, ISO 4406, 1999.

[28] C. Thiede, M. Buscher, M. Lück, H. Lehr, "An overall Pressure Tolerant Underwater Vehicle: DNS Pegel,” in *OCEANS 2009 – EUROPE*, Bremen, 2009, pages 1-5.

[29] *Control Valve Handbook*, Fourth Edition, Fisher Controls International LLC, USA, 2005.

[30] *Subsea Instrumentation Interface Standardization Recommended Practices*, SIIS-RP-V008 MASTER, Draft.

[31] *Road vehicles – Controller area network (CAN) – Part 3: Low-speed, fault-tolerant, medium-dependent interface*, ISO 11898-3, 2006.

[32] G. E. Brown, "Operational Considerations for Underwater-Mateable Connectors," in *Proceedings OCEAN 2003*, San Diego, CA, USA, 2003, pages 1843-1848 Vol. 4.

[33] J. L. Sutto, “Pressure Tolerant Electronic Systems,” in *OCEANS ‘79*, San Diego, CA, USA, 1979, pages 460-469.

[34] *Degrees of protection provided by enclosures (IP Code)*, IEC 60529, 2001.

[35] *Electromagnetic compatibility (EMC) – Part 1-2: General – Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena*, IEC 61000-1-2, 2016.

[36] *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 5: Classification of electromagnetic environments*, IEC 61000-2-5, 2011.

[37] *Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 0: Functional safety and IEC 61508*, IEC 61508-0, 2005.

[38] V. S. Radovich, “Oil and gas in the Ocean – International Environmental law and policy,” in *OCEANS 2016*, Shanghai, China, 2016, pages 1-5.

[39] *Functional safety – Safety instrumented systems for the process industry sector – Part 3: Guidance for the determination of the required safety integrity levels*, IEC 61511-3, 2016.

[40] “Dimensional Drawing SVA-V1”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-1000-DDM-0001, 2016.

[41] “Force Analysis SVA-V1”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-1000-CAL-0001, 2016.

[42] “Force Analysis SVA-V2”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-2000-CAL-0001, 2016.

[43] P. O'Connor, A. Kleyner, *Practical Reliability Engineering*. Fifth Ed. New York, NY: John Wiley & Sons, 2002.

[44] E. O. Doebelin, *Measurement Systems: Application and Design*. Fifth Ed. New York, NY: McGraw-Hill, 2004.

[45] “Simulation Report SVA-V1”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-1000-REP-0001, 2016.

[46] Bosch Rexroth AG. (2016). *Simster* [Brochure]. Available at: https://www.boschrexroth.de/ en/xc/products/product-support/econfigurators-and-tools/simster-s/simster-s-index

[47] “Simulation Report SVA-V2”, Bosch Rexroth AG, Lohr am Main, Germany, Rep. SVA-02-53-2000-REP-0001, 2016.

[48] *Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Part 2: Classification of objects and codes for classes*, IEC 81346-2, 2009.

[49] W. C. Dunn, *Fundamentals of industrial instrumentation and process control*. New York: McGraw Hill, 2005.

[50] R. Krishnan, "Selection Criteria for Servo Motor Drives," in *IEEE Transactions on Industry Applications*, 1987, pages 270-275 vol. IA-23.

[51] T. Kenjo, *Electric Motors and their Controls: An Introduction*. First Ed. Eastbourne, UK: Oxford Science Publications, 1991.

[52] H. E. Jordan, *Energy-Efficient Electric Motors and Their Applications*. Second Ed. New York, NY: Springer Science+Business Media LLC , 1994.

[53] M. Miyamasz, K. Akatsu, "Efficiency Comparison between Brushless DC Motor and Brushless AC Motor Considering Driving Method and Machine Design," in *IECON 2011 – 37th Annual Conference on IEEE Industrial Electronics Society*, Melbourne, VIC, Australia, 2011, pages 1830-1835.

[54] P. T. Finlayson, "Performance Comparison of Digital AC and DC Drives," in *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, Houston, TX, USA, 1992, pages 365-369 vol. 1.

[55] L. Chunfeng, Y. Weibo, T. Wusheng, "Study on Rotor Position of Sensorless Brushless DC Motors Through Back Electromotive Force Detection," in *2010 International Conference on E-Product E-Service and E-Entertainment (ICEEE)*, Henan, China, 2010, pages 1-4.

[56] maxon motor AG. (2016). *With or without brushes?* [Video] Available at: http://www.maxonmotor.com/maxon/view/content/maxon-Knowledge

[57] M. K. Pandey, A. Tripathi, B. Dwivedi, "A Technique to Minimize the Effect of Current Harmonics in a Brushless DC Motor Drive," in *IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, Auckland, New Zealand, 2015, pages 702-706.

[58] N. J. Jameson, M. H. Azarian, M. Pecht, "Fault diagnostic opportunities for solenoid operated valves using physics-of-failure analysis" in *IEEE*

Conference on Prognostics and Health Management (PHM), Cheney, WA, 2014, pages 1-6.

[59] O. E. Voutilainen, P. Lappalainen, R. Parkkinen, M. Karras, "The Measurement of the Piston Velocity of a Hydraulic Actuator," in *IEEE Transactions on Instrumentation and Measurement*, 1989, pages 815-819 vol 38.

[60] D. S. Nyce, *Position Sensors*. First Ed. Haboken, NJ: John Wiley & Sons Inc. 2016.

[61] *Kabel und Leitungen – Leitfaden für die Verwendung von Kabeln und isolierten Leitungen mit einer Nennspannung nicht über 450/750 V (U_0/U) – Teil 1: Allgemeine Leitfaden*, DIN EN 50565-1, 2014.

[62] *Verwendung von Kabeln und isolierten Leitungen für Starkstromanlagen – Teil 4: Empfohlene Werte für die Strombelastbarkeit von Kabeln und Leitungen für feste Verlegung in und an Gebäuden und von flexiblen Leitungen*, VDE 0298-4, 2013.

[63] *Leiter für Kabel und isolierte Leitungen*, DIN EN 60228, 2005.

[64] *Standard Specification for Standard Nominal Diameters and Cross-Sectional Areas of AWG Sizes of Solid Round Wires Used as Electrical Conductors*, ASTM-B258, 2014.

[65] *Dattenblatt Sn-Ag-Weichlot*, TECHNOLIT GmbH, Germany.

[66] *Datasheet PEEK (polyetheretherketone)*, Polyfluor Plastics bv, Netherlands.

[67] *Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)*, IEC 60812, 2006.

[68] *Offshore and Onshore Reliability Data, Vol. 2 – Subsea Equipment*, Sixth Ed. DNV GL, Norway, 2015.

[69] *Information technology – Generic cabling for customer premises – Part 3: Industrial premises*, ISO 11801-3, 2016.

[70] *Programmable controllers – Part 3: Programming languages*, IEC 61131-3, 2013.

[71] *User Manual for PLC Programming with CoDeSys 2.3*, Sixth Ed. 3S-Smart Software Solutions GmbH, Germany, 2010.

[72] *Information technology – Programming languages – C*, ISO/IEC 9899, 2011.

[73] *Condition monitoring and diagnostics of machines – Prognostics – Part 1: General guidelines*, ISO 13381-1, 2015.

[74] *Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines*, ISO 13374-1, 2003.

[75] M. R. Mamat-Ibrahim, M. R. Tamjis, T. Lachman, "Condition Monitoring Algorithm for Induction Motor Drive" in *2004 IEEE Region 10 Conference TENCON*, 2004, pages 9-12 Vol. 4.

[76] Chuanchao Zhang, "Health Condition Monitoring of Aeroengine with Unknown Clustering Number Based on Ant Colony Algorithm" in *IEEE International Conference on Cloud Computing and Intelligence Systems (CCIS)*, Beijing, 2011, pages 510-514.

[77] Won-Chul Jang, Myeongsu Kang, Jaeyoung Kim, Jong-Myon Kim, Hung Ngoc Nguyen, "Reliable condition monitoring of an induction motor using a genetic algorithm based method" in *IEEE Symposium on Computational Intelligence for Engineering Solutions (CIES)*, Orlando, FL, 2014, pages 37-41.

[78] A. Orth, R. Knoell, A. Koertgen, G. Swagten, "Elektrohydraulisches System für den Einsatz unter Wasser und Prozessventil mit einem derartigen elektrohydraulischen System," Deutsches Patent DE 10 2015 213 695 A1, 2016.02.18.