Abstract

The objective of this work is to analyze the dynamic performance of a Subsea Electro-Hydraulic Actuator integrated with a Hydraulic Power Unit (HPU). This system is designed to operate on a Wet Christmas Tree (WCT) installed in a depth of 3,000 meters. The parameters evaluated are the pressures in the hydraulic cylinder chambers and the system energy consumption. The simulation aims to evaluate the operational feasibility and the ability to achieve the requirements established for equipment developed to the offshore oil and gas exploration sector. The results can guide the designers to get better information for component selection and performance improvement. Another contribution of this study is to implement onshore solutions as an alternative to the development of hydraulic systems for subsea operations.

Keywords: Marine and Offshore Systems, Ultra-deep Water, Hydraulic Actuators, Energy Consumption, Subsea Oil & Gas.

1. Introduction

The Brazilian oil and gas industry is growing fast in recent years with the discovery of new oil reserves in the pre-salt layer. Recently the ANP (National Agency for Petroleum, Natural Gas and Biofuel) announced that 54.4% of Brazil's oil and gas production comes from wells of the pre-salt. One consequence is an increase in demand for equipment to operate in oil exploration, but one of the great challenges for exploration in the pre-salt layer is the

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operating environment of the equipment for extraction. The pre-salt reserves are in a region that lies more than 2,000 meters deep, called ultra-deep waters. Such depth has peculiarities for the project of oil exploration equipment which they can mention: the high external pressure, difficulty to perform maintenance with use of ROV's (Remote Operated Vehicles) and AUV's (Autonomous Underwater Vehicles). Due to the difficulties presented these equipment should be designed for operations with low corrective interventions and maximum safeguard correct operation.

One of the important equipment for oil exploration in deep waters is the Wet Christmas Tree (WCT), which is connected to the wellhead of exploitation. The purpose of the WCT is to control the flow of fluids extracted from or injected into the well and thus ensures the correct operation of the activity. It is noteworthy that WCT has another important function which is the total closure of the well in emergency situations, such as leakage or failure at flow to Unit Production and Storage. Usually the control of actuators is performed at the Floating Production, Storage and Offloading (FPSO) on the surface. In this unit is installed the Master Control Station (MCS), the Electric Power Unit (EPU) and the Hydraulic Power Unit (HPU) and it knows as Multiplex Control System. The disadvantage of the system is the long lines for transporting hydraulic fluid and consequently high weight that results in a complex control system with high production process costs.

2. Subsea Control

The use of a hydraulic system is due the following points: high energy density, compact size, low maintenance. The result of this combination is a reliable for several applications under hostile’s conditions and the maintenance is requires it would be a risk for the staff and for the environment. An example of the application of this technology is the compact hydraulic actuators, which are better known by the terminology EHA (Electric Hydrostatic Actuator). It consists of a linear actuator coupled to a hydraulic power unit which is controlled by variation of rotation of the pump. Its application was initially within the aeronautical industry for flapping (Navarro, 1997; Bildstein, 1998), where it proposes the decentralization process of the hydraulic systems, i.e., a constructive integration into a single element of all hydraulic components. In this solution, there is a supply unit installed for each actuator and it’s reducing the amount of lines for the transport of hydraulic fluid and the
volume of hydraulic fluid applied to the system. The layout for operation of a system in the offshore industry is shown in Figure 1 which demonstrates the main elements of a decentralized subsea control system. The system consists of three levels: Topside, SCM (Subsea Control Module) and actuators. The architecture is similar to the All Electric Control System but the mechanism responsible for moving the gate valve is an electrohydraulic system.

![Diagram of the control system](image)

Figure 1. Schematic diagram of the control system to open and close gate valves in the subsea production.

The topside refers to all equipment installed in the FPSO and it has two units: the Main Control Stations (ECP) and the Electric Power Unit (EPU). The EPU is responsible for the supply of electrical energy for the equipment present in the production process which is installed on the platform as well as the equipment installed underwater. However, the supply of energy to the submarine equipment is done through the umbilical. The umbilical also transfers information from the MCS which monitors the production system and sends the command signals to SCM. The information that arrives at the Subsea Control Module is processed and converted into voltage signals for the HPU drive, which is coupled to the hydraulic cylinder. According to the signal that is received, the movement of the cylinder will open or close the gate valve.
The possibilities of hydraulic circuits capable of carrying out such an activity are numerous, but in this work we sought to use a hydraulic system concept with control in the hydraulic pumps and sought to reduce the number of solenoid driven valves. These systems are known for reliability, robustness, high strength, high transmission, good overload protection, ease of use, low maintenance effort, good efficiency, no hydraulic fluid conditioning system, compact, with regenerative capacity of energy and in most situations is presented as a plug-and-play device (Weber et al., 2016). Figure 2 shows the layout of the hydraulic circuit used in this work where the control in the pump is performed with the variation of the rotational frequency of the electric motor that drives the hydraulic pumps of two hydraulic pumps with fixed displacement. The insertion of systems with rotational frequency variation is possible with the reduction of the costs of power electronics and servo motors. Thus, it encourages research in the field and applications within the industry. Helduser (2003) and Helbig (2015) point out in their works that it is possible to manufacture precise hydraulic units with good dynamic response and to be constructed and maintained at an affordable cost when integrating the hydraulic system with digital electronics.

Figure 2. Hydraulic circuit of the electrohydraulic actuator under analysis.
To understand the operation of the system is necessary to observe Figure 3-a which illustrates the direction of forces during the forward movement of the actuator. The resulting force is the sum of the forces involved, in this case are the forces: hydraulic (2), spring (3), due to the pressure due to the depth acting on the rod to the ocean (4), due to the internal pressure in the valve acting in the (5), the friction force between the gate and the upper seat (6) and the frictional force of the seals present on the actuator (7).

Consequently, the resulting force for opening the valve is obtained by electrification of the electric motor (M) which drives pump P1.1 and P1.2. The fluid pumped by P1.1 is directed to chamber A of the cylinder (A1.1), through filter Z1.1, check valve V5.3 and pilot valve V1.1. At the same time, piloting the pilot valve V1.2 allows the release of confined fluid in chamber B of the cylinder. Thus, the fluid also passes through valve V5.2 and subsequently through pump P1.2.

Note that the presence of the piloted valve assembly V1.1 and V1.2 is intended to lock the cylinder chambers when the electric motor is at rest. There is no need to use the electric motor or other mechanism to guarantee the position (open or closed of the gate valve). According to Bai (2012), the numbers of activities performed by submarine actuators are of three movements per day. Then, most of the time the system remains at rest and the energy consumption is given by the communication of the sensors with the MCS. In the return stroke of the actuator, the valve opening combination is similar, having only the mirroring of the valve openings as shown in Figure 4-b.

The presence of valves V2.1 and V2.2 in the circuit are given for reasons of safety of the hydraulic system and operating as internal pressure regulators of the lines. If the pressure exceeds a set value in the design, you have the valve opening and the fluid is directed to the reservoir until it reestablishes the correct pressure. Because it is a semi-closed circuit, at times the main circuit is communicated with the reservoir, so the check valves V3.1 and V3.2 have the function of allowing the passage of the hydraulic fluid when the pressure at the points $p_L$ and $p_R$ are below the reservoir pressure. Valve opening occurs when one of the following relationships is true:
Figure 4. Schematic simplification of the hydraulic circuit during the opening (a) and closing (b) movement of the gate valve.

\[ p_L(t) < p_{VL0} + p_S, \text{ for valve V3.1} \]  \hspace{1cm} (1)

and

\[ p_R(t) < p_{VR0} + p_S, \text{ for valve V3.2} \]  \hspace{1cm} (2)

where \( p_L \) and \( p_R \) are the pressures in the hydraulic circuit line, \( p_{VL0} \) is the preload pressure of the valve spring V3.1, \( p_{VR0} \) is the preload pressure of the valve spring V3.2 and \( p_S \) the internal pressure of the reservoir. Throughout the work the pressures are presented as gauge pressures, meaning that the pressures represent to the pressure at the discounted point the reservoir pressure.

Valves V6 and V7 are used only in emergency situations. With the suspension of electrical power supply to the actuator, the directional valve V6 returns to the normally open position. This position allows the communication of chamber A with chamber B and the pressures tend to match over time. Because there is a large amount of energy accumulated in
the springs there is the presence of the orifice (V6) which controls the return movement of the cylinder to the fully recessed position.

3. Methods Procedures and Process

As a basic requirement for the design of an actuation system for submarine equipment, it is necessary to present a life cycle capable of operating for a period equivalent to 25 years of operation. The equipment needs to present a robust and reliable system. In order to ensure compliance with some standards for submarine equipment, the following are examples: API 17-D, API 6-A, API 6-D, API 17-F. They helped in the design stages and construction of the mathematical model developed which allowed to present an approximate analysis of a real system.

The method used for evaluating the performance is the opening and closing conditions of the gate valve. In this study, a mathematical model is developed and the system performance evaluated using co-simulation. The model of the hydraulic system and the controller are implemented on the simulation software Simster S. In MATLAB Simulink, the forces acting in the gate valve, the effect of the pressure because of the water column and the pressure drop along the oil pipe are modeled. The two simulations run simultaneously in such a way that the system behavior can be analyzed. The main analysis focus is the performance evaluation under opening and closing conditions of the gate valve. The parameters used to construct the mathematical model are of industrial components available in the market and with the data published in the literature. More information about the selection of components and modelling can be found in Goularte (2017).

4. Results and Observations

The first point evaluated with the results of the simulation was the power consumed by the system presented as shown in Figure 5 which presented the simulation results for operation at the depths of 2,600 and 3,300 meters. The consumption of the system is related to the depth of the system installed and consequently to the force acting on the rod exposed to the ocean. As shown in Figure 3 the depth value is part of the resulting forces in an underwater actuator. Therefore, the greater the depth, the greater the effect of the force acting on the rod exposed to the ocean. Thus, the hydraulic force required to move the hydraulic cylinder in the opening direction of the gate valve is smaller as the depth of installation of the actuator increases.
It is important to note that the power consumed to open the valve has a reduction with increasing depth, indicating that the water column assists in opening the valve. However, in the return it was not possible to notice a significant difference, as there is influence of the force of the spring in the return movement of the gate valve. The action of the hydraulic actuation system is opening the valve V1.1 by the pilot and the discharge / suction of the hydraulic fluid in the cylinder chambers. The change in the displayed power values during the open and closed movements is correlated with the working pressure of the hydraulic system, as shown in Figure 6 which shows the pressure curves ($p_R$) and ($p_L$). In the course of the forward movement there is an increase of approximately 30% in the pressure at the outlet of P1.1 to a depth of 2600 meters, which is a consequence of the increase of the torque of the electric motor to reach the minimum pressure for movement of the gate valve, as well as reducing the volumetric efficiency of the pump. In this way, the pump must operate at a higher rotational frequency to ensure adequate flow and compensate for internal leakage. The energy losses are rising due to the viscous friction and the internal component leaks.

The power consumed for both situations is below 230 W, which is the maximum power that can be delivered by the SCM to the electric motor of the system. Therefore, an
analysis of the energy efficiency of the system during the entire work cycle seeks to evaluate the amount of energy delivered to the system and the output energy in the form of movement of the gate valve. Figure 7 shows the flow of energy in each component and determine the components with the greatest energy dissipation. Note that the main power losses are: the pumps, the electric motor, and the valve V1.1.

![Diagram of distribution of energy losses of the system operating at 3300 meters depth.](image)

The loss of energy in the electric machine is equivalent to 22.3% of the total energy delivered to the system. It is important to mention that the losses from the frequency converter are not included in this value. According to Minav et al. (2015) electric motors have two types of dissipation sources: losses in the electric machine and mechanical losses. The losses in the electric machine are composed of the resistive losses of the stator and the rotor, magnetic losses, refrigeration and additional losses not known. Mechanical losses include friction in the motor bearings, which depends on shaft speed, bearing type, lubricant properties and applied load.

Another source of dissipation found in the system refers to the energy losses associated with valve V1.1. The behavior is shown in Figure 8, which shows the pressures on the three ports of the piloted check valve. In the range of 2 to 62 seconds where the gate valve is opened there is a small pressure differential between the upstream (A1) and downstream (A) ports of the piloted check valve, which demonstrates a small energy dissipation. In the time interval of 75 to 130 seconds, the return movement of the actuator is observed. By observing the pressures it is noted that there is a considerable difference between the pressures at the upstream points (A1) and downstream(A), indicating the existence of a restrictive effect on the passage of hydraulic fluid by the valve. The control of position is not being performed by the pair of pumps but the restricting effect during the passage of the hydraulic fluid. This is due to the low pressure in the pump discharge P1.2 (pR) it is insufficient for full opening of valve V1.1 via pilot, as shown in Figure 8. Consequently, partial opening of the valve causes a control of flow rate and the increase in
pressure difference between points A and A1, dissipating a considerable amount of energy. The presence of the restrictive effect reduces the energy efficiency of the electrohydraulic system by not allowing the energy recovery in the pump P1.1 during the return movement of the actuator.

![Pressure curves at points A, A1 and R of the proposed hydraulic circuit.](image)

Figure 8. Pressure curves at points A, A1 and R of the proposed hydraulic circuit.

5. Conclusions

The simulation model has identified the strengths and weaknesses of the system for application in submarine equipment and, mainly, to show its capacity for moving the gate valve and the energy consumption. The mathematical modeling of the electro-hydraulic actuation system allows the evaluation of the dynamic and static behavior. In addition, it is possible to evaluate different types of hydraulic component failures (degradation of sealants and leakage) of the subsea actuation system. These alterations can change the behavior of the system which allows the engineers to evaluate possible damages to oil production and environment.

The paper demonstrates that the simulation is a useful tool to evaluate and to consolidate the development of new mechanical systems and maybe the model can help to reduce the final costs of the project. In the next phase of this project, experimental tests should be carried out for improving and validating the developed mathematical model. The model will be used to determine energy consumption at other elements present in the system such as sensors and frequency inverter.

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