Proceedings IRF2018: 6th International Conference Integrity-Reliability-Failure
Lisbon/Portugal 22-26 July 2018. Editors J.F. Silva Gomes and S.A. Meguid
Publ. INEGI/FEUP (2018); ISBN: 978-989-20-8313-1

PAPER REF: 7053

RELIABILITY ASSESSMENT OF A SUBSEA ELECTRO-HYDRAULIC CONTROL SYSTEM

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ABSTRACT

This work aims to perform a quantitative and qualitative analysis of the reliability of the subsea multiplex control system applied in oil and gas production. In the development of the research, a functional analysis of the control system was made to define the function to be analysed through the fault tree, and failure rate data was obtained from OREDA. The failure probabilities when the system achieves 7,400h and 26,500h are, respectively, 17.35% and 67.52%. In other words, the reliability at the observed points is 82.65% and 32.48%.

Keywords: control system, reliability analysis, subsea equipment, fault tree.

INTRODUCTION

The oil industry plays an extremely important role in the Brazilian economy. In 2014, for example, the oil and gas sector accounted for 10.9% of Brazil's industrial GDP. Most of this oil has been and will be supplied from offshore reservoirs (Petrobras, 2016). To produce and transport oil from offshore reservoirs in deep and ultra-deep waters require underwater production systems. The technology developed for subsea equipment used in oil and gas production is a highly specialized field of application that demands specifics solutions for engineering.

The subsea production system has some unique aspects related to human access for installation and maintenance, what demands complex and unusual resources. Subsea equipment requires high availability, that means they must be reliable enough to operate in safe condition to environment and people, beyond that avoid, as much as possible, subsea intervention or maintenance (Dash, 2012).

Reliability is the ability of an item to perform the required function under specified conditions, over a given time interval (Kiran, 2017). The purpose of reliability analysis is to define the main points and failure modes associated to the system components and the statistical behaviour of these failures over time.

A reliability analysis aims to identify and maintain within acceptable limits the uncertainties regarding the costs involved in the exploration of the oil fields. This will result in information that will help planning, operation, and maintenance areas define properly necessary resources to keep production and system availability in high levels, increasing business profitability.

This paper presents a quantitative and qualitative study on the reliability of automatic control systems for subsea equipment applied to offshore oil and gas production and identifies the critical components and most likely failures modes in operational life cycle.

METHODOLOGY

A fault tree analysis was made following the flowchart (Lin, Yuan, and Zhang, 2014). Calculation and fault tree representation runner using R software. The top event considered was the Loss Well Control. The quantitative analysis calculated numerically for the approximately three years period of operation, from failure rate data that were considered constant, as well as in RBD analysis.

The qualitative analysis of the failure tree sought to identify the basic events that, when they occur, lead to the top event. The sum of the products of these identified basic events integrates the minimal set of cut or minimal cut sets (Čepin, 2011). A cut set can be formed by one or more elements, and the larger the number of basic events present in the set, the lower the probability of failure.

The graphical representation and calculations of the reliability model through the fault tree were made using the software R version 3.4.1 for Windows. R is a free software, built based on a language developed for analysis and statistical and graphical computing, maintained by the nonprofit R Foundation (R Core Team, 2017). This software, as well as its manual, can be obtained at https://www.r-project.org.

For fault tree analysis it was necessary to obtain an additional package for the R, called FaultTree in version 0.2.8 revision 71, which was developed by (Silkworth, 2017). In this tool, a fault tree is constructed from a script such that each node of the tree is described by command-line input. The visualization of the tree can be made continuously during the development of the tree by a defined command, different from the tools that have graphical interface.

The main information for the study is the failure rate of the components, which was obtained from OREDA. In OREDA, data collection is done during the life or actual use in the equipment field, so the failure rate tends to approach a constant value. This is because at this point the quality of the component has reached maturity and the failures that occur come to be originated from intrinsic random causes (Torell and Avelar, 2004).

In addition, submarine equipment can be considered subjected to rigid performance and quality control requirements during the component qualification, fabrication and integration testing phases, so it is acceptable to consider that failures in the initial life stage are greatly reduced. This feature reinforces the premise of constant failure rate adopted.

DATA SOURCE DESCRIPTION

The Offshore and Onshore Reliability Data project was started in 1981 with the collaboration of Norwegian Petroleum Directorate, which later changed its name to Petroleum Safety Authority Norway. In 1983, a cooperation group was formed consisting of several oil and gas companies, and OREDA's scope included a broader range of surface and submarine equipment used in the exploration and production of oil and gas (Oreda, 2015).

OREDA, for collecting data from various facilities, makes a statistical treatment to estimate the failure rate due to the multi-samples of the various facilities, which were submitted to the different operational and environmental conditions. In this case, the usual failure rate calculation for homogeneous samples dividing the number of failures by the total time in service may not bring an adequate result (Oreda, 2015).

Thus, the mean failure rate, measured by 106 hours, estimated with a 90% confidence interval will be used. It should be noted that the methodology adopted by OREDA for estimating the failure rate is not part of the discussion scope of this work. More information can be found in (Oreda, 2015).

MULTIPLEXED SUBSEA CONTROL SYSTEM DESCRIPTION

The multiplexed subsea control system (SCS) has topside components, on the production platform, and the subsea components installed in manifolds and subsea trees. Figure 1 shows a schematic representation of the main subsystems: MCS, EPU, HPU and SCM. In addition, there are auxiliary equipment such as TUTA, EFL, HFL, distribution boxes, junction boxes, subsea electrical and hydraulic connectors, sensors and transducers. Following is a brief description of the main equipments.

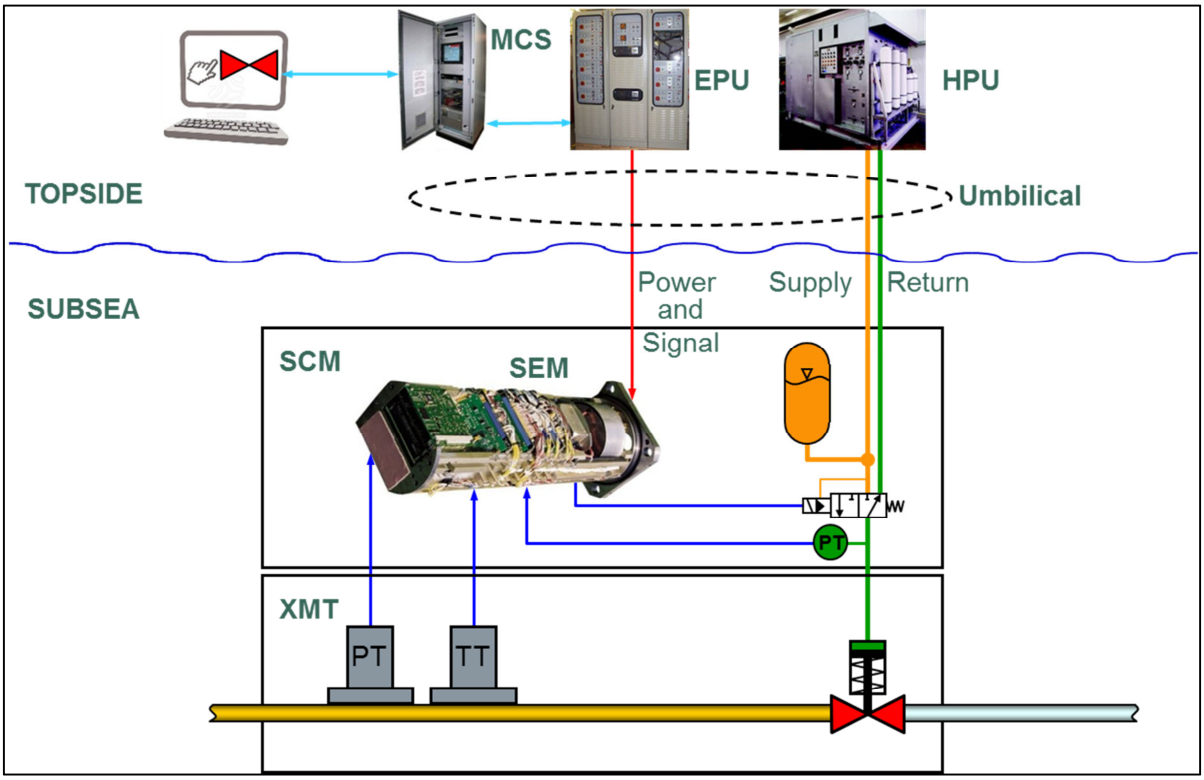

Fig. 1 - Schematic sketch of a multiplexed subsea control system.

- MCS: The master control station performs the logical control of the entire system: topside and subsea equipments. It consists of controllers, for example, PLC or industrial computers, network communication modules, analog and digital signal input and output modules. In addition to the control of subsea equipment, it integrates and communicates with the platform's supervisory system.
- EPU: The electrical power unit is responsible for the single-phase power supply of the underwater electronics. It also performs the last stage of communication between topside and subsea equipment by inserting, via frequency or amplitude modulation, the control signal on the same pair of cables that supplies electrical power to the subsea

system. For convenience, and depending on the concept adopted in the design, MCS and EPU may be together in the same physical structure (cabinet).

- HPU: The hydraulic power unit provides the hydraulic power to drive the functions of the subsea equipment. Usually delivered at two pressure levels, the lowest (LP) is for the equipment functions, typically valve actuation, and the highest level (HP) is for the functions inside the well. The control fluids are composed of water (percentage of water over 80%) and glycol. They also present other elements that guarantee some properties, such as anticorrosive, bactericidal and low compressibility. Due to the physical characteristics of the SCM, they must meet a strict level of cleaning.
- SCM: The submarine control module is responsible for controlling and monitoring subsea equipment. It is responsible for the multiplexing of the electrical signal in the submerged part of the system, and it communicates with the surface through a single pair of cables, which also promotes its electrical supply. The main components of the SCM are input transformers, subsea electronic module (SEM), directional control valves (DCV), filters, modems, pressure transmitters, flowmeters, check valves, hydraulic accumulator and dielectric oil.

RESULTS

For fault tree construction, loss well control was considered as failure of the system (top event), since this is the main goal of the subsea control system (SCS) and this event would cause operational restrictions or process safety incidents that could lead to temporarily interrupt production and, consequently, financial loss or any incident related to process plant safety. At this point, it is important emphasizes that this analysis did not model all possible system failures, only the most relevant ones that contribute directly to the occurrence of the defined top event.

Then, the fault tree structuring was divided into subsystems according to the discipline involved directly, as defined and represented in Figure 2. This step was done in order to facilitate the understanding of the whole system, besides allowing to identify the contribution of each subsystem in the total reliability. This approach can be visualized graphically in Figure 2, where the eight defined subsystems are linked to the top event by an OR gate.

Each of the events defined and linked to the top event were developed up to the level of the corresponding base event. The code lines used in software R to perform the analysis and construction of the trees are in (Silva, 2017) - Appendix B. The graphical representation of the failure tree can be found in (Silva, 2017) - Appendix E.

Quantitative Analysis

For the quantitative analysis of the fault tree, the reliability data of the basic events, such as failure rate, average failure time, repair time, etc., are fundamental. As in the previous analyzes, the modeling performed considered the constant failure rate provided by the OREDA database.

The graphical representation of the fault tree is present in Figure 2 and was generated for the analysis period corresponding to 26.508h. In this Figure, the probability of failure of the top event is indicated to the right side of the logic gate OR by the number 1. As well as each of the events that contribute to the event that are represented beside logic gate with the indication of their respective probability of failure. The resulting probabilities allow to affirm that the communication failure event is the one that is most likely to lead to the top event (38.19%), followed by the undersea electronic fault (32.87%) and the failure of the activation of the hydraulic functions 16.49%).

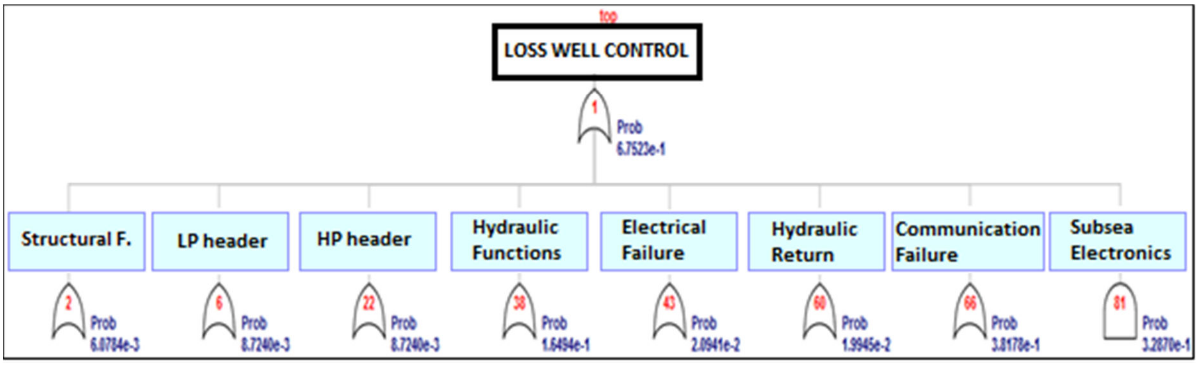

Fig. 2 - Fault Tree - Loss Well Control.

The probability of failure was calculated for a period slightly longer than three years (26,508 h). Figure 3 summarizes the result of the analysis in this period, with the abscissa axis being in the unit of hours on a logarithmic scale to maintain the best visual layout of the curve. In this Figure, it is possible to identify that the probabilities of failure for the period of 7,400 h and 26,508 h are, respectively, 17.35% and 67.52%. In other words, the reliability in the highlights is 82.65% and 32.48%.

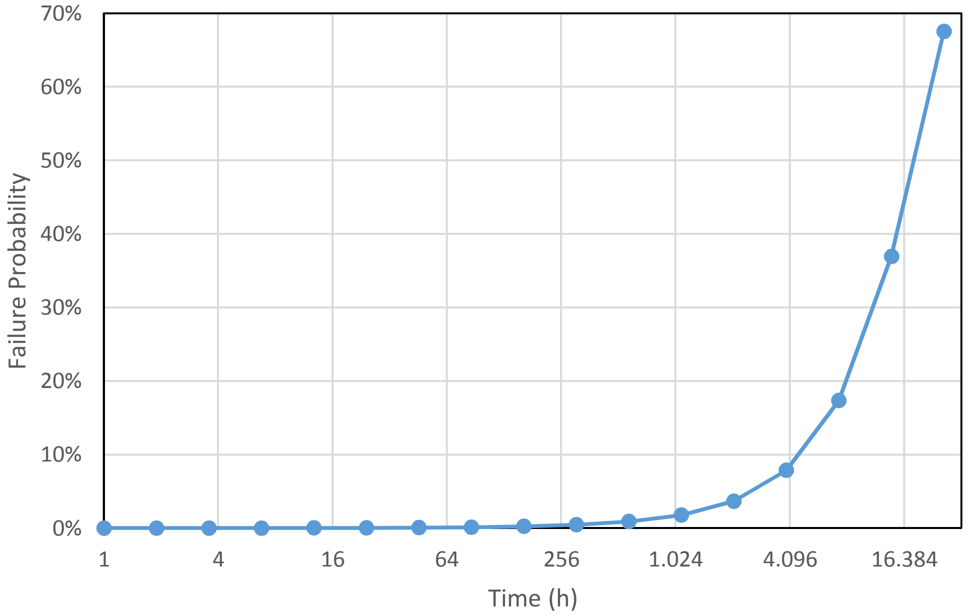

Fig. 3 - Failure probability.

Another interesting aspect observed in Figure 3 is that in the first 1.100h, considering that the system was properly installed, tested and commissioned, the probability of failure at the end of this period is 1.78%. From that point, the failure probability grows faster.

Qualitative Analysis

The qualitative evaluation of the fault tree was performed through the identification of the minimum cut sets), which consists of determining the minimum groups of basic events necessary to cause or lead to the top event. That is, the minimum cut set can be verified by simulating the scenario where all components that integrate the cut set are not operative, the rest are and the system remains inoperative. In this condition, if an element of the cut set return to operate the system also returns.

In the simulation, made in R software, resulted in sixty minimum cut sets that are listed in Appendix D (Silva, 2017). There are thirteen of first order, forty-one of second order, four of third order and two of fourth order. The order indicates the number of elements (basic events) that compound the cut set. No sets with order higher than four were identified.

The most critical elements identified from this type of analysis are the cut sets that present the least amount of elements. For example, a cut set of one element means that if that component fails the whole system will be inoperative. However, given the number of sets, they were ordered in descending order relative to their relative probability of occurrence. Table 1 shows the fourteen cut sets that represent, proportionally, 94.73% of the failure probabilities of all the sets found. Thus, the remaining forty-six sets account for 5.27%.

Table 1 - Cut sets probability.

Cut sets	**PFD**	**1-PFD**	**Relative Failure Contribution**	**Sum**
E20,E37	0,2776	0,7224	23,05%	23,05%
E19	0,1441	0,8559	11,97%	35,01%
E8	0,1054	0,8946	8,74%	43,76%
E27,E44	0,0768	0,9232	6,37%	50,13%
E26,E44	0,0755	0,9245	6,27%	56,40%
E27,E43	0,0755	0,9245	6,27%	62,67%
E26,E43	0,0742	0,9258	6,16%	68,83%
E25,E44	0,0521	0,9479	4,33%	73,16%
E27,E42	0,0521	0,9479	4,33%	77,49%
E10	0,0516	0,9484	4,29%	81,77%
E25,E43	0,0512	0,9488	4,25%	86,03%
E26,E42	0,0512	0,9488	4,25%	90,28%
E25,E42	0,0354	0,9646	2,94%	93,22%
E13,E36	0,0182	0,9818	1,51%	94,73%

Thus, the basic events and their combinations listed in the Cut set column in Table 1 are the most likely failures to occur and indicate the critical points of the subsea control system when loss well control is considered as top event. The relative weight column informs how much the probability of that cut set represents in the whole cut sets found in the analysis. The total column (sum) indicates the sum of the percentages of the minimum sets.

The set {E20, E37}, which has the largest relative weight, contains the failures related to the topside control system, MCS A and MCS B, respectively. The event E19, second line in Table 1, is still related to topside system and models the sum of spurious operation failure rates, erroneous controller output and unknown faults. Event E8 indicates the hydraulic leakage faults to the internal or external medium of the DCVs that perform the twenty control functions of the SCM. The six subsequent sets are associated to failure events on the subsea electronics (E27 and E44 - failure of the SCM flowmeter sensors, E26 and E43 - failure of SCM pressure sensors, E25 and E42 - failure of the SEMs).

CONCLUSION

This research contributed to the application of reliability engineering in the subsea equipment industry applied in offshore production of oil and gas, specifically in subsea control systems. A subsea control system has been described, in terms of its functionality, in order to facilitate the understanding of the study. In addition, it was presented the main equipments that compound the subsea systems of petroleum production.

In the development of this research, a functional analysis of the control system was performed to define the function to be modelled by the fault tree analysis technique in R software and the failure rate data source was OREDA handbook.

The fault tree reliability study found a 32.48% probability that the system will be operational after 26,500h. Failures that have the greatest influence on the probability leading to top event are communication failure (38.19%), followed by subsea electronic fault (32.87%) and failure in hydraulic functions (16.49%). These probabilities were calculated for 26,500h mission time.

In the qualitative analysis, sixty cut sets were found. Fourteen of them are responsible for 94.73% of the probabilities of all sets found. The basic events present in the most representative cut sets are related to failure in topside control system (MCS A and MCS B), spurious operation failures and erroneous output of the controller.

The limitation of the study was the failure rate data for electrical and electronic equipment. These data are not in component level, as for mechanical and hydraulic components. Future work could study other topologies for the system in order to minimize influence of the components and critical failure. Another suggestion would be to propose new technologies to replace equipments and components currently used.

REFERENCES

[1] Čepin, M. (2011). Fault Tree Analysis. In M. Čepin, Assessment of Power System Reliability (pp. 61-87). London: Springer London. https://doi.org/10.1007/978-0-85729-688-7_5.

[2] Dash, I. (2012). Provision of Reliability Data for New Technology Equipment in Subsea Production Systems. Norwegian University of Science and Technology, Trondheim. Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2:629238.

[3] Kiran, D. R. (2017). Reliability Engineering. In Total Quality Management (pp. 391-404). Elsevier. https://doi.org/10.1016/B978-0-12-811035-5.00027-1.

[4] Lin, J., Yuan, Y., & Zhang, M. (2014). Improved FTA Methodology and Application to Subsea Pipeline Reliability Design. PLoS ONE, 9(3), e93042. https://doi.org/10.1371/journal.pone.0093042.

[5] Oreda (Ed.). (2015). Offshore and onshore reliability data handbook. Volume 2: Subsea equipment (6th edition). Norway: OREDA Participants.

[6] Petrobras. (2016, September 20). Plano Estratégico e Plano de Negócios e Gestão 2017-2021.

[7] R Core Team. (2017). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/.

[8] Silkworth, D. J. (2017). FaultTree: Fault Trees for Risk and Reliability Analysis (Version R package version 0.2.8/r71). Retrieved from https://www.R-project.org/projects/ftree/.

[9] Silva, A. H. M. (2017). Análise de confiabilidade de um sistema de controle de poços submarinos de petróleo. Instituto Federal Fluminense, Campos dos Goytacazes. Retrieved from http://www.saeg.iff.edu.br/.

[10] Torell, W., & Avelar, V. (2004). Tempo Médio entre Falhas: Explicação e Padrões. W. Kingston, Rhode Island: American Power Conversion. Retrieved from http://xa.yimg.com /kq/groups/16643321/1021633048/name/wp_apc_mtbf.pdf.