FMEA AND FTA ANALYSIS APPLIED TO THE STEERING SYSTEM OF LNG CARRIERS FOR THE SELECTION OF MAINTENANCE POLICIES

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Abstract. *With the discovery of new natural gas reserves in the basins of oil exploration, the need for its flowing off is indispensable. One of the alternatives for the flowing off of gas produced in gas offshore platforms are LNG carriers. This work will analyze the steering system for LNG carriers which have been used for decades for the distribution and transportation of natural gas from production points to distant markets. Depending on the location of the accident, it may bring great consequences, like serious environmental impacts, material losses and especially loss of human lives, not only the crew but also the population that is near the accident site.*
The work aims to carry out the failures analysis of steering system for LNG carriers through the development of a method based on classical systems reliability assessmen tools, such as FMEA and FTA. The failure modes of the system components are analyzed and the causes of a steering system failure are defined based on FTA analysis. For the most critical componets a maintenance policy is proposed based on RCM philosophy.

Keywords*: Steering system, Reliability, LNG carrier.*

1. INTRODUCTION

In recent years the maritime transport of LNG has increased considerably. The cause of this increase is due to demand of natural gas as an alternative energy source for electric energy generation and also for industrial use.

According to the International Maritime Organization IMO (2002), during the last 50 years, in the transport LNG, were registered 182 maritime accidents worldwide. Among them were recorded four accidents caused by failure in steering gear system of the ship. Depending on the location of the ship, the failure of steering gear system, may bring consequences, like serious environmental impacts, material losses and especially loss of human lives, not only the crew but also the population that is near to the crash site. In 1979, the LNG carrier called El Paso Howard Boyd, stranded in the York Spit Channel due to failure of a hydraulic pump of the steering gear system, causing materials losses, but not affecting human lives. In 1982, the crew of Descarte LNG carrier, lost the control of the steering gear system of the ship, and this accident did not cause neither LNG spill nor injuries in the crew. In the decade of the 80, there were registered two accidents due to failure of the steering gear system, in the ships called LNG Aries and Gadinia. These accidents did not cause environmental impacts.

The steering gear system performs a basic task in the navigation, once it is used to execute all kinds of maneuvers with the ship such as follow a planned trajectory and carry out a change of direction, avoiding possible collisions and groundings.

The work aims at carrying out the failures analysis of steering gear system of LNG carriers through the development of a method to identify the critical failure modes of its components, based on system reliability analysis tools, and to propose maintenance policies for that components based on Reliability Centered Maintenance philosophy.

2. STEERING GEAR SYSTEM

The first steering gear was designed for James Macfarlane Gray in 1866. He fitted a successful steam based steering gear in the famous ship named the "Great Eastern". A number of designs of steam powered steering gears were later developed and some of them are still in use. Nowadays the configurations have changed with new concepts developed according to international standards but continuous to meet the main objective that is steer a ship under given operational conditions.

To achieve the main objective the steering system has to present some basic requirements in order to prevent any accident at sea or when entering or leaving the port, which are valid not only for the LNG carrier but also for any kind of ship. The basic requirements are:

- Be continuously available;
- Move the rudder fastly to any position in response to the orders from the bridge during maneuvering, and to hold it in the required position;
- Have arrangements for relieving abnormal stress and returning the rudder to its required position;
- Keep the ship on course regardless of wind and waves actions.

As we can see one requirement is that the system must be continuously available when requested. This requirement will depend on its reliability and on the alternative arrangements available for supporting continuous operation of steering capability. In the Fig. 1 a typical arrangement of the steering gear system is showed.

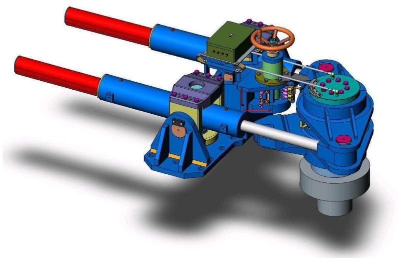

Figure 1. Steering gear system

According to SOLAS guidelines (Safety of Life at Sea), the main steering gear must be able to steer the ship at maximum ahead service speed and be capable at this speed of putting the rudder from 35º on one side to 30º on the other side in not more than 28 seconds. That performance can be achieved when the two hydraulic pumps of the system come into operation, because this maneuver need to be executed at the maximum performance. Obviously, tankers that have more than 10,000 tons gross tonnage and upwards, especially in ship that contain inflammable products, like LNG carriers, the compliance of these conditions are essentials in order to avoid dangerous consequences.

All international standards that govern the functionality of the steering gear are based on the regulations of SOLAS 74. To meet these requirements, the LNG carriers must have a main and an auxiliary steering gear, arranged in such a way that the failure of one does not turn the other inoperative. The auxiliary steering gear has to perform its function after a single failure in the piping system or in one of the power units in the main steering gear, in order to avoid the lose of the vessel direction especially in situations that represent a high risk like during navigation in areas where it could happen a crash with another ship.

According to Smith (1983) when the ship is navigating in open water, it is normally necessary the use of only one power unit and the auxiliary unit would be in a standby mode. On the other hand when ship is entering, leaving or maneuvering in harbor areas probably the situation change and the auxiliary unit is requested to come into operation providing a higher rate of rudder movement and a faster rate of turn. Figure 2 shows the hydraulic system of the steering gear system that includes the power units that pressurize the oil, the control units and finally the actuator units.

This paper will focus the study on the hydraulic system that composes the steering gear once its failure can cause a catastrophic failure including ship collision.

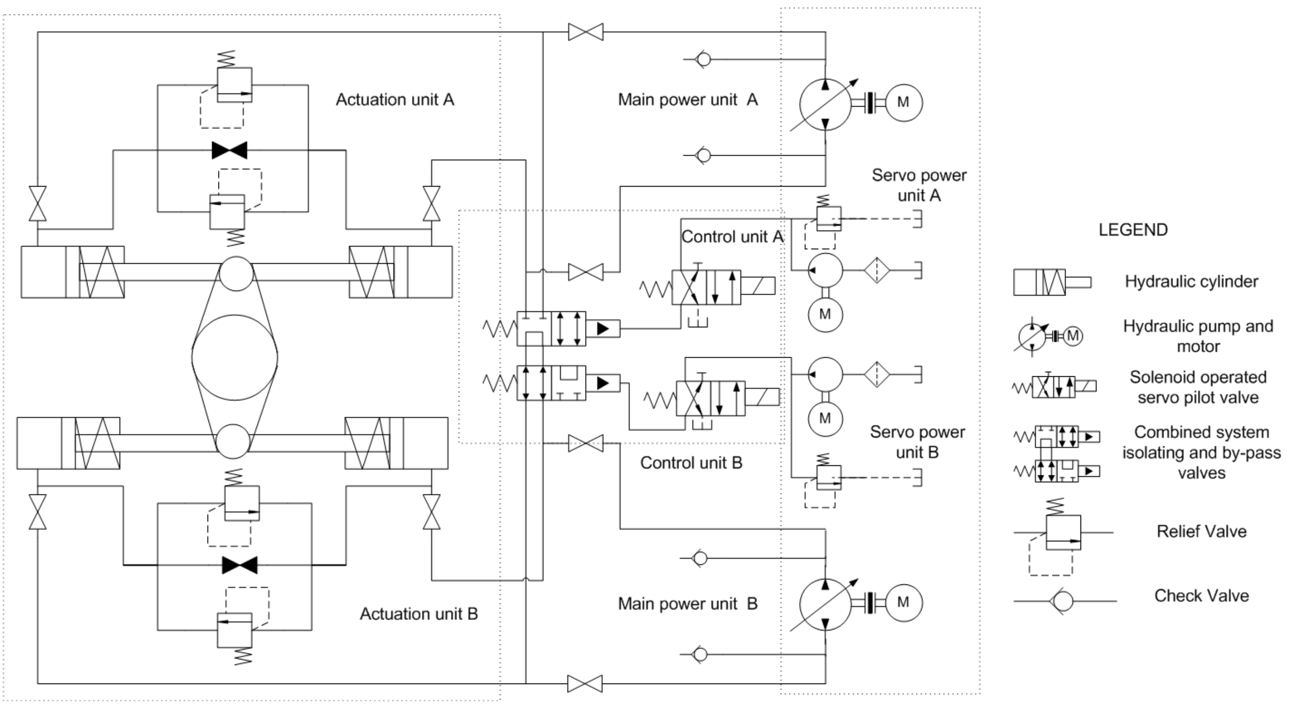

Figure 2. Hydraulic diagram of the steering gear system

3. METHOD

The first step consists in carring out a study of the hydraulic unit of the steering gear system.

The second step involves the elaboration of the functional description (identifying the functions of each of the components of the system) and elaboration of the functional tree (graphical representation of the functional relations of the components).

The third step is the development of Failure Tree Analysis (FTA) in order to define the most critical components for steering gear system operation.

The next step is the development of the Failure Mode and Effects Analysis (FMEA) for each critical component. The goal of FMEA is to identify, concisely, the failure modes and failure mechanism of interest supporting future decisions regarding the selection of maintenance practices to minimize the occurrence of those failure modes.

For the most critical components the most appropriate maintenance policies are selected, through the application of decision diagrams for selection of maintenance practices recommended by RCM. This maintenance policy philosophy is focused on the use of predictive or preventive maintenance tasks that aim at reducing the occurrence of unexpected failures during the component's normal operation. In Fig. 3 a flowchart is used to illustrate the method main steps.

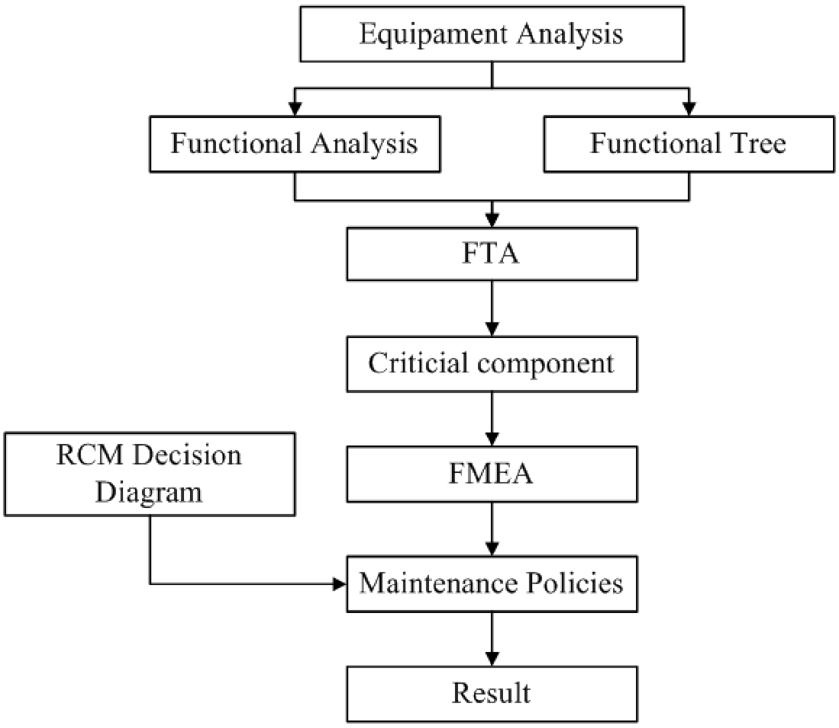

Figure 3. Flowchart representing the method main steps.

4. APPLICATION

4.1. Functional Tree

The functional tree is a tool that facilitates the understanding of the system, which is essential for a proper analysis of reliability. It's development is important to define the behavior and interactions between the system components in order to identify a failure that can interrupt the main function of the system.

In the functional tree the relations between different levels of the system are represented starting with the main function of the system and detailing how the system perform this function. The functional tree has a vertical orientation as the How-Why. Starting from a function of the system, the question How is asked to determine which subsystem contributes to that function and Why that contribution is important. Figure 4 represents the construction of a functional tree for the steering gear system.

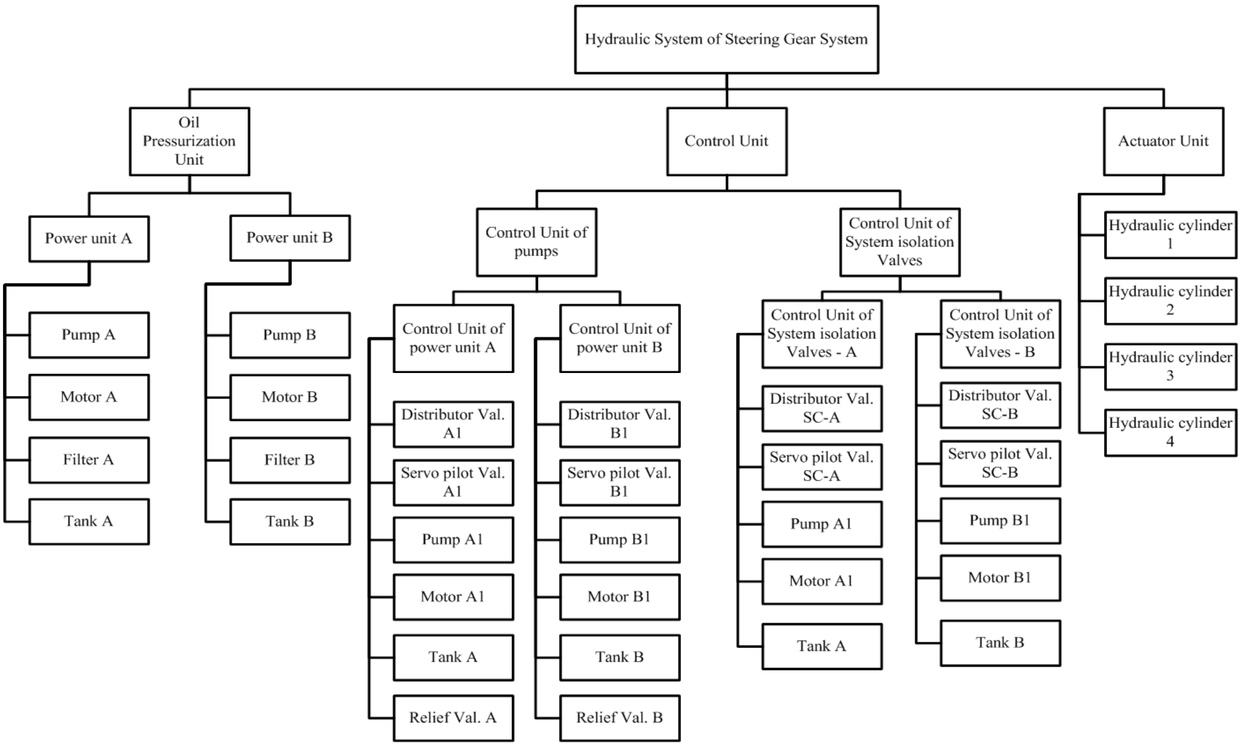

Figure 4. Funtional Tree of the hydraulic system in the steering gear system

4.2. Failure Tree Analysis

According to Kececioglu (1991), the Fault Tree Analysis (FTA) is a reliable and secure technique, which is applied to complex and dynamic systems, aiming at determining the causes of an undesirable event called the "top event". The fault tree uses a logical structure in form of ramifications with symbols of Boolean algebra. The tree logical expression must be developed to obtain the cut-sets that allow the evaluation of the probability occurrence of the top event. This reliability analysis tool is based on a deductive analysis, where the success of the application depends much on the knowledge of the system operation.

The FTA is widely used in the aerospace field, electronic, and nuclear industry. This technique was originally developed in 1961 by H. A. Watson at Bell Telephone Laboratories for evaluating the reliability in the missile launching safety control system.

The fault tree for the hydraulic system was built according to the following procedure. First, a top event was defined and the other events in the fault tree were identified stepwise by a deductive method. In this method, a cause for a particular event is based on a literature survey, or expert knowledge, and defined as the event on the next hierarchical level. Then the cause of that event is analyzed, and this procedure is repeated until the basic events, listed in the lowest hierarchical level of the tree, are identified. On the tree, all events are correlated with a Boolean logic operator AND gate or an OR gate. The AND gate represents the union of the events combined by the gate. It means that an event occurs when all the input events in the next hierarchical level combined by the gate occur. The OR gate represents the intersection of the events combined by the gate, meaning that an event occurs when one or more of the events in the next hierarchical level combined by the gate occur. The fault tree was constructed for the hydraulic system failure considering that the ship is navigating in open water. The tree is shown in Fig. 5.

For the present analysis the failure is the event that causes the impossibility of turning the rudder to maneuver the ship.

After the construction of the Fault Tree the next step is carry out the qualitative analysis. This analysis shows the specific combinations (intersections) of the basic events that are sufficient to cause the occurrence of the top event.

For the qualitative analysis of Fault Tree 68 minimal cut sets with two basic events was obtained, and 64 minimal cut sets with three basic events were identified.

The next step is the fault tree quantitative analysis. The failure rate of the components was obtained from Offshore Reliability Data OREDA (2002) and from Nonelectronic Parts Reliability Data (1995). Table 1 shows the components failure rates considered in the fault tree numerical analysis.

The probability of occurrence of the top event was calculated for a period of 12 days (288 hours), assumed as the arrange period of navigation of the LNG carrier in open waters during one trip. The reliability of the Steering System is

0,9986 under this condition, that represent a high reliability once that system is composed by a main and auxiliary hydraulic system. The last one is considered a "stand-by" system which increases the system reliability.

Table 1. Hydraulic System Components: Failure rates and failure probability calculated for 12 days of continuous operation.

Component	Failure rate (failure/hour)	Failure Probability (288 hours)	Reference
Pump A	5.40E-05	0.01606949	NPRD
Motor A	6.88E-06	0.00206187	NPRD
Filter A	1.19E-07	0.0000357	OREDA
Tank A	2.76E-08	0.00000828	OREDA
Pump B	5.40E-05	0.01606949	NPRD
Motor B	6.88E-06	0.00206187	NPRD
Filter B	1.19E-07	0.0000357	OREDA
Tank B	2.76E-08	0.00000828	OREDA
Pump A1	9.56E-06	0.00286389	NPRD
Motor A1	6.88E-06	0.00206187	NPRD
Distributor Valve A1	2.21E-05	0.00660807	NPRD
Servo Pilot Valve A1	2.24E-05	0.00669747	NPRD
Distributor Valve SC-A	2.21E-05	0.00660807	NPRD
Servo Pilot Valve SC-A	2.24E-05	0.00669747	NPRD
Pump B1	9.56E-06	0.00286389	NPRD
Motor B1	6.88E-06	0.00206187	NPRD
Distributor Valve B1	2.21E-05	0.00660807	NPRD
Servo Pilot Valve B1	2.24E-05	0.00669747	NPRD
Distributor Valve SC-B	2.21E-05	0.00660807	NPRD
Servo Pilot Valve SC-B	2.24E-05	0.00669747	NPRD
Hydraulic Cylinder 1	8.00E-09	0.0000024	NPRD
Hydraulic Cylinder 2	8.00E-09	0.0000024	NPRD
Hydraulic Cylinder 3	8.00E-09	0.0000024	NPRD
Hydraulic Cylinder 4	8.00E-09	0.0000024	NPRD

In order to select the critical components of the steering gear hydraulic system it is necessary to apply the item importance concept that is defined as the ratio of the probability sum of the minimal cut sets including a particular basic event (item) to the sum of the probabilities of all minimal cut sets. The most critical components obtained from the analysis are showed in the Tab. 2. According to the Tab. 2 the most critical components are the Pump A and Pump B. The pumps (variable delivery axial piston) have a high contribution degree regarding to occurrence of the top event.

Table 2. The most critical components of the steering gear and their item importance.

Critical Components	Item importance
Pump A	0.4414
Pump B	0.4414
Servo Pilot Valve A1	0.1840
Servo Pilot Valve B1	0.1840
Distributor Valve A1	0.1815
Distributor Valve B1	0.1815
Pump A1	0.0775
Pump B1	0.0775
Motor A	0.0569
Motor B	0.0569

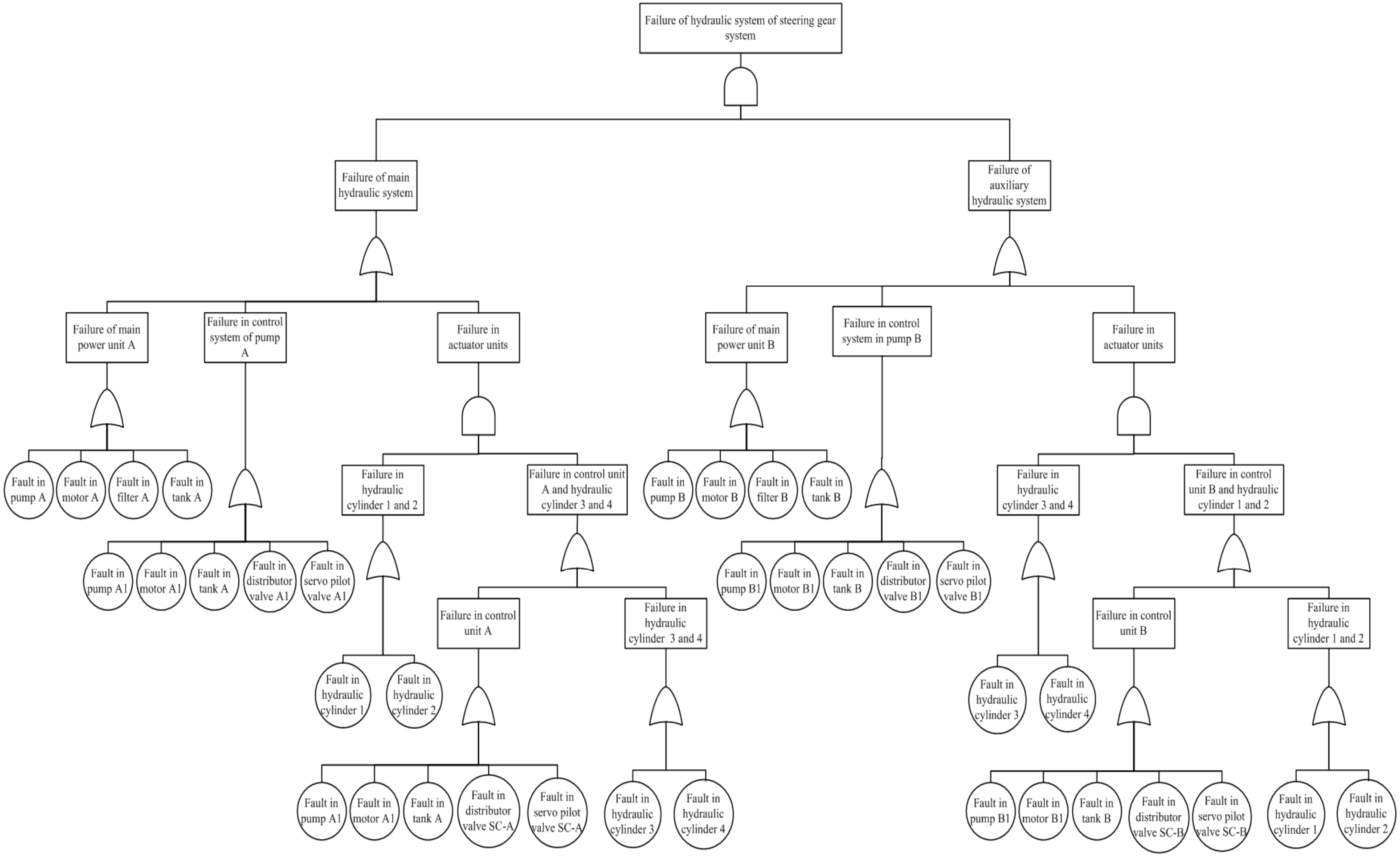

Figure 5. Fault Tree Analysis for hydraulic unit of the steering gear system operating in open water.

4.3. Failure Modes and Effects Analysis

The Failure Modes and Effects Analysis (FMEA) is a tool that is used to analyze the reliability of any system. The method aims at identifying the failure modes of the components and defining the possible effects caused into the system when a failure mode occurs. The FMEA is mainly applied in design process machinery, motor cars, mechanical and electronic components. The main goal is to identify and then to limit or to avoid a given operational risk within a design.

According to Leveson (1995) the FMEA is a deductive technique that consist on failure identification in each component, its causes and consequences on the equipment and on the whole system. This technique has the occurrence of a failure as a start event and traces a path from the botton to the up. The result is a group of states (where a state is a group of conditions) that represents the effects of the initial event. This technique analyzes each component separately in comparison with the FTA that makes the analysis of failure combinations that lead to the top event, usually a hazardous condition for the system operation.

According to Kothamasu (2007) the first step in the FMEA is to identify the failure modes of the components, considering all possible modes of operation. For each failure mode, its effects are registered and documented in a table, like Tab. 3. Table 3 is composed by five columns. In the first column the component name is registered; the next column is used to describe the all functions of the component. In the third column, all possible failure modes for the component are detailed. The fourth column lists the possible causes of each of the failure modes and finally are shown the effects of each failure mode in the system.

The FMEA analysis was performed for the pumps that are the most critical components of the system, as shown in Tab. 3. The most common types of failure of variable delivery axial piston pump are contamination and cavitation according to Cowley (1992). The failure modes for the component were developed according to manufacturer´s information and other failure analysis available in the open literature.

Table 3. Failure Modes and Effects Analysis of the variable delivery axial piston pump.

Component	Function	Failure Mode	Failure Causes	Failure Effects
Axial piston pump	Deliver the hydraulic fluid with a particular flow and constant pressure	Pump provides abnormal or unstable flow	Presence of air in the fluid	Absence or slow movement of the hydraulic cylinder (possible stop of steering gear system)
			Very high viscosity of the fluid	
			Cavitation	
			Excessive internal leakage	
			The suction strainer being too small or too dirty	
			Wrong installation of the pump	
		External leakage	Excessive pressure within the pump	
			High temperature of the fluid	Insufficient pressure in the hydraulic cylinders
			Wear on port plate and barrel faces	Incorrect speed of the cylinders hydraulic
			Wear on seal	

4.4. Maintenance policies

Based on the results of the FMEA analysis, the RCM concepts can be used to recommend maintenance tasks to the most critical components selected from the FTA analysis which are the pumps. The failure of those components can cause severe degradation in the steering gear system´s performance, including the possible loss of the LNG carrier control causing severe consequence.

The objective of implementing the suitable maintenance policies is to increase the availability of the system and to reduce the maintenance costs.

The RCM philosophy the main objective is to avoid corrective maintenance tasks though the use of predictive and preventive maintenance policies. Moreover, most of the components of the steering gear system can be assisted with predictive maintenance tasks (monitoring system), and other components are assisted with preventive maintenance tasks.

For the critical component (pumps) the RCM decision diagrams are applied and, through specific and clear questions, maintenance policies are selected focusing mainly on the safety and environmental consequences (S), operational consequences (O), non-operational consequences (N) and hidden failure consequences (H) . Table 4 shows the application of RCM decision diagram for the variable delivery axial piston pump.

Product of the analysis of the FMEA´s tables, the majority of the failures in the steering hydraulic system can be avoid by maintaining cleanliness in hydraulic circuits, paying attention to manufacturer's recommendations and following the maintenance polices adopted by the ship owner. For this reason it is important to carry out oil analysis in order to determine the properties like the viscosity, particle contamination and the presence of water in the fluid. Those tests will allow us to identify the quality and the state of the oil.

As a predictive maintenance task it is recommended to install differential pressure gauges, in order to identify changes in the differential pressure that can be used as an indicator of the presence of solid particles in the filter.

The key to minimize electric motor problem is the use of scheduled routine inspection, including bearing cleaning and lubrication tasks. The thermography technique can be used to check the operational condition and a vibration monitoring system can be used to identify mechanical unbalance (incorrect assembly, bent shaft, poorly balanced rotor, loosen parts on the rotor or bearing wear) and electrical unbalance, indicating an electrical failure such as an open stator or rotor winding.

Table 4. Maintenance policies for the variable delivery axial piston pump.

	System				Steering Gear						
	Sub-system				Variable delivery axial piston pump						
Failure Modes	Consequence evaluation				H1 S1 O1 N1	H2 S2 O1 N2	H3 S3 O3 N3	Default Action			Proposed Task
	H	S	E	O				H4	H5	S4	
Pump provides abnormal or unstable flow	N	S	S	S	x	x					**Preventive maintenance tasks**
											1. Clean the internal components (during the machinery overhaul)
											2. Clean the suction pipelines (during the machinery overhaul)
											Predictive maintenance tasks
											1. Vibration analysis (every month)
											2. Oil analysis (every 2 months)
											3. Ultrasonic test (every 3 months)
External leakage	N	S	S	S	x	x					**Preventive maintenance tasks**
											1. Periodic inspections (every day)
											2. Seal inspections (during the machinery overhaul)
											Predictive maintenance tasks
											1. Vibration analysis (every month)
											2. Monitoring the operational pressure (during the periodic inspection)

The daily inspection tasks should try to find any trace of leakage of hydraulic oil, enabling a corrective action that will prevent further problems in the steering gear hydraulic system. Performing that preventive action daily would minimize the occurrence of large leakages that will reduce the system performance also, as a preventive task, the hydraulic oil must be changed according to the manufacturer recommendation, typically every 200 operational hours, to avoid oil contamination.

In order to evaluate the improvement in the hydraulic system reliability associated with the improvement in the pump failure rate, in Tab. 5 are presented the results of numerical simulation that indicate the system reliability as a function of the percentage of improvement of the pumps failure rate. That improvement must be associated with maintenance policy changes.

Table 5. Improvement in the system reliability decreasing the pump's failure rate.

Improvement (%)	Failure rate (failure/hour)	System reliability
0	0.016069486	0.9987
10	0.014474226	0.9988
15	0.012316523	0.9989
20	0.009865414	0.9991
25	0.007408223	0.9992
30	0.005191537	0.9993
35	0.003377572	0.9994
40	0.002027914	0.9995

5. CONCLUSION

The proposed method seems to be suitable to analyze the steering gear hydraulic system. This method can be used for complex system, and it will permit to select critical components, and to propose maintenance policies for them.

For complex systems like the steering gear hydraulic system in LNG carriers, the application of the FTA allowed the identification of critical components. From the survey of the main failure modes, causes and consequences in the FMEA analysis it is possible to obtain useful information for the development of maintenance policies.

The FMEA analysis provides bases for development of maintenance procedures (preventive maintenance) and even for a monitoring system (predictive maintenance).

According to the Tab. 2 the most critical component is the variable delivery axial piston pump. For this reason, the regulations of SOLAS require that the ship have a main and an auxiliary power units. For this component it is important to follow correctly the maintenance task recommended for the manufacturers and others proposed in this paper.

Is important to taking into consideration the time to perform maintenance tasks proposed because these actions can improving the reliability of the pump and obviously improving the reliability of the steering gear system.

These maintenance tasks have the objective for improving the failure rate of the pump and in consequence increasing the system´s reliability.

Finally, the reliability of the system is calculated considering 12 days that represent the average time during the navigation period from the terminal of liquefaction where the LNG is charging until the arrive at the terminal for discharge the LNG. The value of the reliability is 0,9986 which is a acceptable considering that the steering gear hydraulic system is one of the essential systems required for the successful and safe operation of the LNG carriers. That value can be improved with the use of suitable maintenance tasks associated with RCM philosophy.

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