Polish J. Environ. Stud. Vol. 15, No. 4b (2006), 18-26

Selected Measures and Models of the Safety of Offshore Vessel Marine Power Plants

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Abstract

Using a vessel supporting the exploration of the sea bottom (offshore vessel), these authors present some measures of the safety of the marine power plant understood as its property of being resistant to the occurrence of dangerous situations. Two safety states have been pointed out: one in which safety unreliability occurs, and the other in which safety unreliability does not occur. The following safety measures have been formulated: safety reliability R_B, being the system (power plant) resistance to its operational errors, resulting in a risk to the system, to systems co-operating with it, the environment and human life; safety unreliability Q_B, which is the system (power plant) susceptability to its operational errrors, the consequences of which constitute a risk to the safety; the probability of power plant failure that causes an interruption in or incomplete operation of the power plant (functional unreliability Q_Z). An attempt is made to assign certain safety models to power plant systems and their selected parts and pieces of equipment.

Keywords: technical system, dynamic positioning, safety operation, safety measure, safety model, offshore vessel, functional reliability, safety reliability

Introduction

At present the concept of safety is used in reference to items which, if fail, create an actual risk to human life or health. It also refers to those technical objects the failure of which causes various economical losses due to interruptions in operation and necessary repairs. All kinds of marine vessels belong to this group of technical objects. The most frequent definition of safety found in the literature on the subject more or less reads: *safety of an item is its ability to function without faults that may lead to its destruction.* This definition of safety refers to those faults that are equivalent with the destruction of a technical object or directly lead to its destruction (in the probabilistic sense). Therefore, the concept of safety has been broadened in comparison with the one previously used, connected with a hazard created by a technical object failure to its user's life.

Depending on the adopted definition of object safety and on the type of technical object, various measures of safety can be applied. Some of these measures are presented herein and refer mainly to the operation of a marine power plant. Nowadays, probabilistic methods are increasingly used in the theory of safety. One characteristic feature of these methods is that they use a number of various safety measures derived from various probabilistic measures. The concepts of safety and reliability are strictly connected with each other, and so are safety and reliability measures.

A schematic diagram of the electric and diesel power system of the vessel that this work focuses on with is shown in Fig. 1. The analysis covers the following components of the system: main electric power plant (4 x *Detroit Diesel 149 – ABB HSG 500 MDE* – 1370 kVA/1800 rev/min and 2 x *Detroit Diesel 149 – ABB HSG 500 MG4* – 1620 kVA/1800 rev/min), auxiliary electric power plant (3 x *Detroit Diesel V71 Turbo – 600 kVA/1760 rev/min)*, auxiliary electric propulsion (2 x *Ulstein TMC92 – 1470 kW*) and bow thrusters (3 x *Ulstein 375 TV* – 1100 kW).

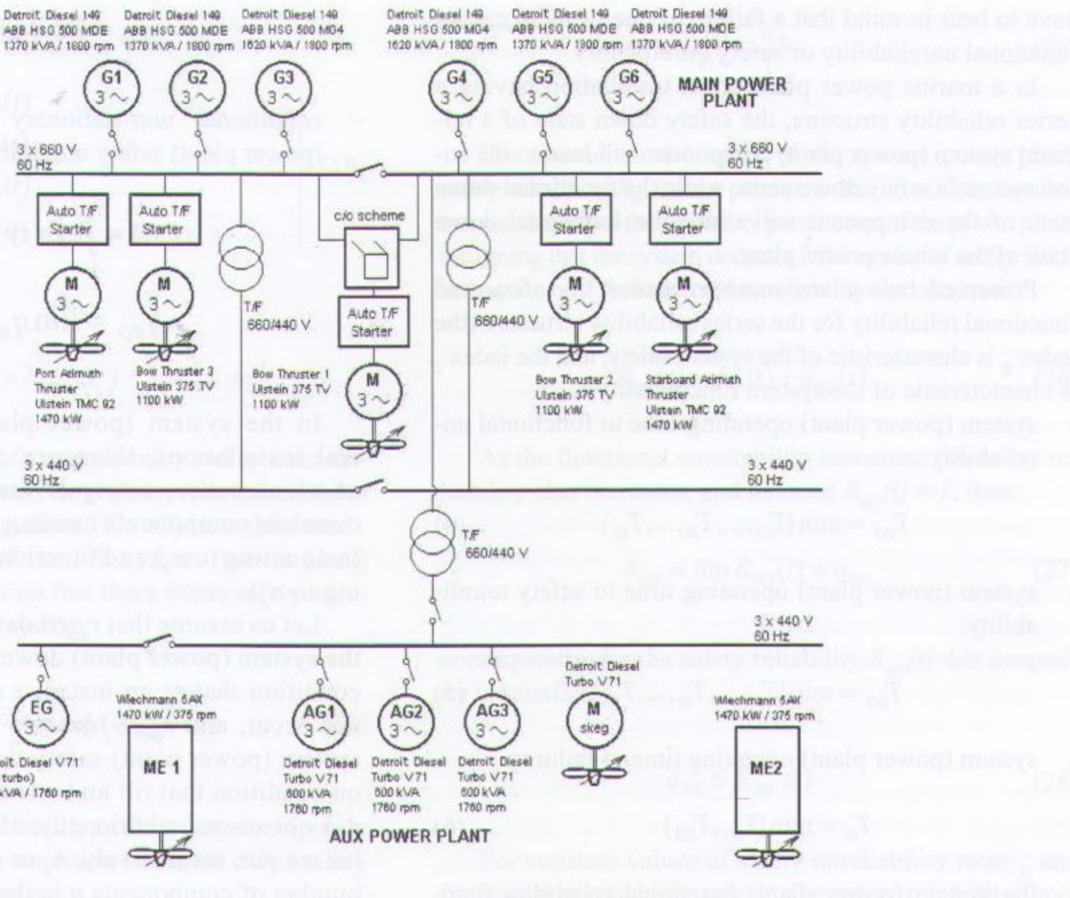

Fig. 1. A schematic diagram of an electric-diesel power plant of a multi-purpose offshore vessel.

The Concept of Marine Power Plant Safety

The concept of ship's power plant safety is to be understood as its property that can be described as the resistance to the occurrence of hazardous situations. Two safety states have been distinguished:- one in which safety unreliability occurs, and the other, in which safety unreliability does not occur. The safety unreliability of a marine power plant is its susceptibility to the occurrence of hazardous situations. The relevant safety measures can be as follows [1]: safety reliability R_B, resistance of the system (power plant) to errors in its operation posing a threat to the system, co-operating systems, the environment and human life; safety unreliability Q_B, the susceptibility of the system (power plant) to its operational errors, the effects of which may threaten the safety. There is an obvious relationship between the above measures of the power plant safety:

$$R_B + Q_B = 1 \tag{1}$$

Another basic safety measure, apart from the ones presented above, is the probability of power plant failure that causes an interruption of or incomplete operation of the power plant. This measure is sometimes referred to as functional unreliability Q_Z [2]. If events causing the safety unreliability Q_B or functional unreliability Q_Z exclude each other, then the total unreliability Q of the power plant is the sum of the measures Q_B and Q_Z:

$$Q = Q_B + Q_Z \tag{2}$$

that is:

$$R_B = 1 - Q + Q_Z \tag{3}$$

and the measures R_B, Q_B and Q_Z are characterized by conditional probabilities.

General risks occurring in the operation of a power plant are as follows: risk to the safety, *i.e.* a condition of the power plant in which certain failures may bring about secondary failures or other undesired processes that accompany failures; a risk to the safety of objects co-operating with the power plant, *i.e.* such state of the power plant, in which its failure may directly or indirectly endanger the safety of equipment and components co-operating with the power plant; a risk to the environmental safety, *i.e.* such state of the power plant, in which its failure may cause a direct or indirect risk to the environment of the human being; a risk to human life, *i.e.* such state of the power plant, in which a failure of its components may cause a serious injury to human body or loss of life.

Selected Measures of Safety Reliability and Up State of the Marine Power Plant

Considering the structure of the entire power plant or any of its installations consisting of n components, we have to bear in mind that a failure of one of them causes functional unreliability or safety unreliability.

In a marine power plant or its installation having a series reliability structure, the safety down state of a relevant system (power plant) component will lead to the entire system's safety down state, while the functional down state of the component will cause the functional down state of the whole power plant.

Presented below are some measures of safety and functional reliability for the series reliability structure (the index $_B$ is characteristic of the system safety, and the index $_Z$ is characteristic of the system functionality):

- system (power plant) operating time to functional unreliability:

$$T_{ZO} = \min\{T_{Z1},...,T_{Zi},...,T_{Zn}\} \quad (4)$$

- system (power plant) operating time to safety unreliability:

$$T_{BO} = \min\{T_{B1},...,T_{Bi},...,T_{Bn}\} \quad (5)$$

- system (power plant) operating time to failure:

$$T_O = \min\{T_{BO}, T_{ZO}\} \quad (6)$$

- the system (power plant) functional reliability function:

$$R_{ZO}(t) = \prod_{i=1}^{n} R_{Zi}(t) \quad (7)$$

- the system (power plant) safety reliability function:

$$R_{BO}(t) = \prod_{i=1}^{n} R_{Bi}(t) \quad (8)$$

- the system (power plant) reliability function:

$$R_O(t) = R_{ZO}(t)\cdot R_{BO}(t) \quad (9)$$

- failure rate function referring to failures causing the system (power plant) functional down state:

$$\lambda_{ZO}(t) = \sum_{i=1}^{n} \lambda_{Zi}(t) \quad (10)$$

- failure rate function referring to failures causing safety down state:

$$\lambda_{BO}(t) = \sum_{i=1}^{n} \lambda_{Bi}(t) \quad (11)$$

- function of the system (power plant) failure rate:

$$\lambda_O(t) = \lambda_{ZO}(t) + \lambda_{BO}(t) \quad (12)$$

- conditional non-stationary and stationary system (power plant) functional unreliability functions:

$$q_{ZO}(t) = \int_0^t \lambda_{ZO}(\tau)\cdot R_O(\tau)d\tau \quad (13)$$

$$q_{ZO} = \lim_{t\to\infty} q_{ZO}(t) \quad (14)$$

- conditional non-stationary and stationary system (power plant) safety unreliability functions:

$$q_{BO}(t) = \int_0^t \lambda_{BO}(\tau)\cdot R_O(\tau)d\tau \quad (15)$$

$$q_{BO} = \lim_{t\to\infty} q_{BO}(t) \quad (16)$$

In the system (power plant), consisting of several installations, there are components, the failure of which causes safety or functional down states, or there are components causing only safety down states (amounting to n_B) and functional down states (amounting to n_Z).

Let us assume that $r_{ZO}(t)$ denotes the probability that the system (power plant) down states does not occur on condition that at an instant t safety unreliability does not occur, and $r_{BO}(t)$ denotes the probability that the system (power plant) safety down state does not occur on condition that till an instant t functional down state did not occur; additionally, if in the previous formulas we put, respectively, n_B or n_Z instead of the general number of components n in the system, we obtain three cases described by the systems of Kolmogorov equations:

- for the determination of safety reliability measures:

$$\left.\begin{array}{l} \dot{r}_{BO}(t) = -\lambda_{BO}(t)\cdot r_{BO}(t) \\ \dot{q}_{BO}(t) = \lambda_{Bi}(t)\cdot r_{BO}(t) \\ r_{BO}(0) = 1 \\ q_{Bi}(0) = 0 \end{array}\right\} \quad (17)$$

where:

$$\lambda_{BO}(t) = \sum_{i=1}^{n_B} \lambda_{Bi}(t),\ i = 1, 2, ..., n_B;$$

- for the determination of up state reliability measures:

$$\left.\begin{array}{l} \dot{r}_{ZO}(t) = -\lambda_{ZO}(t)\cdot r_{ZO}(t) \\ \dot{q}_{ZO}(t) = \lambda_{Zi}(t)\cdot r_{ZO}(t) \\ r_{ZO}(0) = 1 \\ q_{Zi}(0) = 0 \end{array}\right\} \quad (18)$$

where:

$$\lambda_{ZO}(t) = \sum_{i=1}^{n_Z} \lambda_{Zi}(t),\ i = 1, 2, ..., n_Z;$$

for a general case:

$$\left.\begin{array}{l} \dot{R}_O(t) = -\lambda_O(t)\cdot R_O(t) \\ \dot{q}_{ZOi}(t) = \lambda_{Zi}(t)\cdot R_O(t) \\ \dot{q}_{BOj}(t) = \lambda_{Bj}(t)\cdot R_O(t) \\ R_O(0)=1; \qquad q_{ZOi}(0)=q_{BOj}=0 \end{array}\right\} \quad (19)$$

where:

$$\lambda_O(t) = \lambda_{BO}(t) = \lambda_{ZO}(t),\ j=1,\ i,\dots,\ n_B$$

For constant rates of safety unreliability and up state reliability of power plant system components, selected measures obtained by solving the equations (17 - 19) have this form:

- safety unreliability of the i-th system (power plant) component, on condition that there exists safety unreliability of the whole system:

$$q_{Bi}(t) = \frac{\lambda_{Bi}}{\lambda_{BO}}\cdot\left[1-\exp(-\lambda_{BO}\cdot t)\right] \quad (20)$$

- stationary safety unreliability of the i-th system (power plant) component, on condition that there exists safety unreliability of the system:

$$q_{Bi} = \frac{\lambda_{Bi}}{\lambda_{BO}} \quad (21)$$

- safety unreliability of the system (power plant), on condition that the power plant system is in down state:

$$q_{BO}(t) = \frac{\lambda_{BO}}{\lambda_O}\cdot\left[1-\exp(-\lambda_O\cdot t)\right] \quad (22)$$

- stationary safety unreliability of the system (power plant), on condition that the power plant system is in dawn state:

$$q_{BO} = \frac{\lambda_{BO}}{\lambda_O} \quad (23)$$

- safety unreliability of the i-th system (power plant) component, on condition that the power plant system is down state:

$$q_{BOi}(t) = \frac{\lambda_{Bi}}{\lambda_O}\cdot\left[1-\exp(-\lambda_O\cdot t)\right] \quad (24)$$

- stationary safety unreliability of the i-th power plant system component, on condition that the power plant system is damaged:

$$q_{BOi} = \frac{\lambda_{Bi}}{\lambda_O} \quad (25)$$

The unconditional function of the system (power plant) safety reliability $R_{BO}(t)$ is a parameter that in a more detailed manner describes the reliability parameters of the power plant, informing that the system does not fail in terms of safety if it is in up state or if its functional unreliability has occurred:

$$R_{BO}(t) = R_O(t) + q_{ZO}(t) \quad (26)$$

As the functional unreliability increases, the safety reliability also increases, and because $R_{BO}(t) = 1$, then:

$$R_{BO} = \lim_{t\to\infty} R_{BO}(t) = q_{ZO} \quad (27)$$

consequently, for the safety reliability $R_{BO}(t)$ this inequality is satisfied:

$$q_{ZO} \le R_{BO} \le 1 \quad (28)$$

For constant values of safety unreliability rates $_{Bi}$ and functional unreliability rates $_{Zi}$, the safety reliability function $R_{BO}(t)$ can have this form:

$$R_{BO}(t) = R_O(t) + [1-R_O(t)]\cdot q_{ZO} = R_{BO}(t)\cdot q_{BO} + q_{ZO} \quad (29)$$

Taking into account:

$$Q_O(t) = q_{BO}(t) + q_{ZO}(t) \quad (30)$$

and putting it into the relationship (26) we obtain the following unconditional function of the system (power plant) safety:

$$R_{BO} = 1 - q_{BO}(t) \quad (31),$$

The above measures of safety and functional reliability can be used for searching for a component that causes safety unreliability, by putting the conditional probabilities q_{Bi}; $i = 1, 2, \dots, n_B$ in the decreasing order:

$$q_{B1} \ge q_{B2} \ge \dots \ge q_{Bi} \ge \dots \ge q_{Bn_B} \quad (32)$$

or searching for a component that causes functional unreliability, also by putting the conditional probabilities q_{Zi}; $i = 1, 2, \dots, n_Z$ in the decreasing order:

$$q_{Z1} \ge q_{Z2} \ge \dots \ge q_{Zi} \ge \dots \ge q_{Zn_Z} \quad (33)$$

The majority of equipment pieces included in particular installations of marine power plants are renewable components, either by repairs or replacement.

Models of Marine Power Plant Safety

There are three basic models of the safety of non-renewable power plant components:

- series model, in which two kinds of failures may occur, leading to safety unreliability in one case, and functional unreliability in the other;
- parallel model, in which failures cause functional unreliability, and a damaged element after some time passes from the state of functional unreliability to the state of safety unreliability (the element has some time surplus relative to safety unreliability);
- series-parallel model, in which failures immediately cause safety unreliability or functional unreliability or there occur failures that first cause functional unreliability, then safety unreliability.

The above models correspond, among others, to the following power plant systems: series model is represented by systems in which a failure, *e.g.* short circuit, causes safety unreliability, while a failure such as interruption causes functional unreliability (this refers particularly to electric circuits of the power plant); parallel model corresponds to cooling systems of the power plant, in which a failure in the first stage causes functional unreliability, and after an extended period of operation affected by that failure the cooled machines can be destroyed, *i.e.* safety unreliability is the case; series-parallel model corresponds to systems in which a basic element or elements are made redundant by additional components; in case a basic element fails, the power plant can continue operation with other basic or standby components running, although this, in time, may lead to safety unreliability.

The presented safety models are described with Kolmogorov equations, after solving the systems of equations for the particular models:

- series model:

$$\left.\begin{aligned}
&R_s(t) = \exp\left\{-\left[\int_0^t \lambda_B(\tau)d\tau + \int_0^t \lambda_Z(\tau)d\tau\right]\right\}\\
&R_Z(t) = R_s(t) + Q_Z(t) = 1 - Q_B(t)\\
&Q(t) = Q_B(t) + Q_Z(t)\\
&Q_B(t) = \int_0^t \lambda_B(\tau)\cdot R_s(\tau)d\tau\\
&Q_Z(t) = \int_0^t \lambda_Z(\tau)\cdot R_s(\tau)d\tau
\end{aligned}\right\} \quad (34)$$

- parallel model:

$$\left.\begin{aligned}
&R_r(t) = \exp\left[-\int_0^t \lambda_Z(\tau)d\tau\right]\\
&R_B(t) = R_r(t) + Q_Z(t) = 1 - Q_B(t)\\
&Q_Z(t) = \exp\left[-\int_0^t \lambda_{ZB}(\tau)d\tau\right]\cdot\left\{\int_0^t \lambda_Z(\tau)\cdot\right.\\
&\left.\cdot R_r(\tau)\cdot\exp\left[\int_0^t \lambda_{ZB}(\Theta)d\Theta\right]d\tau\right\}\\
&Q_B(t) = \int_0^t \lambda_{ZB}(\tau)\cdot Q_Z(\tau)d\tau
\end{aligned}\right\} \quad (35)$$

- series-parallel model:

$$\left.\begin{aligned}
&R_{sr}(t) = \exp\left\{-\int_0^t [\lambda_{Z1}(\tau) + \lambda_{Z2}(\tau) + \lambda_{B1}(\tau)]d\tau\right\}\\
&Q_{Z1}(t) = \int_0^t \lambda_{Z1}(\tau)\cdot R_{sr}(\tau)d\tau\\
&Q_{B1}(t) = \int_0^t \lambda_{B1}(\tau)\cdot R_{sr}(\tau)d\tau\\
&Q_{Z2}(t) = \exp\left[-\int_0^t \lambda_{ZB}(\tau)d\tau\right]\cdot\left\{\int_0^t \lambda_{Z2}(\tau)\cdot R_{sr}(\tau)\cdot\right.\\
&\left.\cdot\exp\left[\int_t^t \lambda_{ZB}(\Theta)d\Theta\right]d\tau\right\}\\
&R_B(t) = R_{sr}(t) + Q_{Z1}(t) + Q_{Z2}(t)\\
&Q_{B2}(t) = \int_0^t \lambda_{ZB}(\tau)\cdot Q_{Z2}(\tau)d\tau\\
&Q_B(t) = Q_{B1}(t) + Q_{B2}(t)\\
&Q_Z(t) = Q_{Z1}(t) + Q_{Z2}(t)
\end{aligned}\right\} \quad (36)$$

where:

$R_s(t)$, $R_{sr}(t)$, $R_r(t)$ - system (power plant) reliability; $Q_Z(t)$ - functional unreliability; $Q_B(t)$ - safety unreliability; $Q_{Z1}(t)$ - functional unreliability of a system (power plant) component without time surplus; $Q_{Z2}(t)$ - functional unreliability of a system (power plant) component with time surplus; $Q_{B1}(t)$ - safety unreliability of a system (power plant) component without time surplus; $Q_{B2}(t)$ - safety unreliability of a system (power plant) component with time surplus; $\lambda_{B1}(t)$ – safety unreliability rate of a non-redundant system (power plant) component; $\lambda_Z(t)$ – up state failure rate; $\lambda_{Z1}(t)$ – up state failure rate for a non-redundant system (power plant) component; $\lambda_{Z2}(t)$ – up state failure rate for a redundant system (power plant) component; $\lambda_{ZB}(t)$ – safety failure rate for a redundant system (power plant) component on condition that its functional unreliability occurs.

The systems of Kolmogorov's differential equations, describing the above safety models, are as follows:

- series model:

$$\left.\begin{aligned} &\dot{R}(t) = -\left[\lambda_B(t) + \lambda_Z(t)\right]\cdot R(t) = -\lambda(t)\cdot R(t) \\ &\dot{Q}_B(t) = \lambda_B(t)\cdot R(t) \\ &\dot{Q}_Z = \lambda_Z(t)\cdot R(t) \\ &R(0) = 1 \\ &Q_B(0) = Q_Z(0) = 0 \end{aligned}\right\} \quad (37)$$

- parallel model:

$$\left.\begin{aligned} &\dot{R}(t) = -\lambda_Z(t)\cdot R(t) \\ &\dot{Q}_Z(t) = \lambda_Z(t)\cdot R(t) - \lambda_{ZB}(t)\cdot Q_Z(t) \\ &\dot{Q}_B(t) = \lambda_{ZB}(t)\cdot Q_Z(t) \\ &R(0) = 1 \\ &Q_Z(0) = Q_B(0) = 0 \end{aligned}\right\} \quad (38)$$

- series-parallel model:

$$\left.\begin{aligned} &\dot{R}(t) = -\left[\lambda_{Z1}(t) + \lambda_{Z2}(t) + \lambda_{B1}(t)\right]\cdot R(t) = \\ &\qquad = -\lambda(t)\cdot R(t) \\ &\dot{Q}_{B1}(t) = \lambda_{B1}(t)\cdot R(t) \\ &\dot{Q}_{Z1}(t) = \lambda_{Z1}(t)\cdot R(t) \\ &\dot{Q}_{Z2}(t) = -\lambda_{ZB}(t)\cdot Q_{Z2}(t) + \lambda_{Z2}(t)\cdot R(t) \\ &\dot{Q}_{ZB}(t) = \lambda_{ZB}(t)\cdot Q_{Z2}(t) \\ &R(0) = 1 \\ &Q_{Z1}(0) = Q_{B1}(0) = Q_{Z2}(0) = Q_{ZB}(0) = 0 \end{aligned}\right\} \quad (39)$$

The power plant illustrated in Fig. 1 has been used to describe applications of the presented measures and models for selected faults in the system of dynamic positioning of the specific offshore vessel.

Decomposition of a Dynamic Positioning System

Among the most important subsystems of the offshore vessel's dynamic positioning (DP) system are the systems of electric power generation and distribution, propulsion (thrusters), reference sensors, control and emergency power supply. The subsystems of electric power generation and propulsion are jointly examined here as electric-diesel power plant [3].

Given below are examples of functional faults in DP subsystems and possible consequences (affecting the safety of ship and crew), occuring on a multi-purpose offshore vessel [4]. Particular cases causing functional unreliability and safety unreliability accompanied by increased consequences of specific faults affecting the operation of the dynamic positioning system are presented in Tables 1, 2 and 3. Table 1 includes various those faults in the basic DP subsystems of a class DPS-3 ship that cause functional down state.

Table 2 includes selected faults in the most important subsystems of a DPS-3 class ship, which cause functional down state that may lead to safety down state in certain environmental conditions.

Table 3, in turn, presents some faults in the major subsystems of a class DPS-3 ship, that lead to safety down state or to such functional down state that soon leads to safety down state.

Summary

Like most technical systems, the marine power plant is human-machine system. Reliable operation and the safety of the environment of such a complex system as the marine power plant is largely depends on its maintenance and handling. In order to estimate the reliability of a technical system we have to consider technical failures of the system as well as possible errors made by the power plant personnel. These errors, causing various, sometimes severe consequences of the system (power plant) safety unreliability, should be classified and taken into account in various reliability measures.

This article proposes some safety models of technical systems that can have various applications, *e.g.* in an analysis of operational safety and reliability of the power plant or its supersystems or subsystems. Some faults in ship's subsystems have been specified, and their classification based on possible consequences (created hazards). The examples are based on the power plant of a class 3 DP ship, intended for operations performed by divers. The division of faults is dependent on possible occurrence of functional unreliability only (negligible significance), functional unreliability followed by safety unreliability (minor significance) and functional unreliability equivalent to safety unreliability (which is of major importance).

Due to a limited space of this work, the safety models and measures presented refer only to the series structure of power plant equipment items. These models and measures can be adjusted to be used for the modeling of safety of renewable power plant items. The work [5] presents the following models of renewable items:

- series model with non-renewable state of safety unreliability. In practice, it is the most common model of item safety. The item function unreliability occurs at the rate $\lambda_Z(t) = \lambda Z$, and the renewal at the rate $\mu_B(t)$. After safety unreliability occurs, the item is not subject to renewal. A cataleptic failure of each piece of equipment or its installation is an example of such state;
- series model with renewable safety and up states. When safety unreliability occurs in an item is renewed at the rate $\mu_B(t)$, and when functional unreliability occurs, it is renewed at the rate $\mu_Z(t)$;
- parallel model with renewable state of functional unreliability. After functional unreliability occurs, the item is renewed at the rate $\mu_Z(t)$. An example of this is

Table 1. Events of minor significance for the operation of a DP system operation.

Electric power generation – main electric power plants		
Loss of one generator set – mechanical/electrical failure		high probability – 1 failure / 1 year
Fuel oil system	Failure of fuel oil system of one engine	high probability – 1 failure / 1 year
Lubricating oil system	Failure of a lube oil system of one engine	high probability – 1 failure / 1 year
Sea water cooling system	Failure of one sea water pump	mean probability – 1 failure /(1 ÷ 10) years
Compressed air system	failure of both air compressors in main electric power plants	mean probability – 1 failure /(1 ÷ 10) years
Electric power generation – auxiliary power plant		
Fresh water cooling system	Drop in the pressure of a medium in the cooling system of auxiliary generator sets	mean probability – 1 failure /(1 ÷ 10) years
Electric power distribution		
440 V AC	failure of the emergency 440 V switchboard	mean probability – 1 failure /(1 ÷ 10) years
220 V AC	failure of the 220 V distribution panel, port side	mean probability – 1 failure /(1 ÷ 10) years
	failure of the 220 V distribution panel, starboard side	mean probability – 1 failure /(1 ÷ 10) years
24 V DC	failure of the 24V DC distribution for the deck workshop	low probability – 1 failure /(10 ÷ 100) years
Thrusters		
Bow tunnel thrusters and azimuth thrusters	Failure in 24 V DC supply for the control system	low probability – 1 failure /(10 ÷ 100) years
	Loss of the signal for propeller pitch control	low probability – 1 failure /(10 ÷ 100) years
	Loss of the feedback signal of propeller pitch or azimuthal position	low probability – 1 failure /(10 ÷ 100) years
	Failure of feedback circuit for DP system computer	low probability – 1 failure /(10 ÷ 100) years
Main propellers (two Wiechman 5 AX engines)	failure of engine control system	low probability – 1 failure /(10 ÷ 100) years
	Loss of signal for preset revolutions and propeller pitch	low probability – 1 failure /(10 ÷ 100) years
Stern tunnel thruster (*skeg*)	Failure of the propulsion engine (main engine)	high probability – 1 failure / 1 year
	Loss of signals of preset values and feedbacks for the revolutions per minute and propeller pitch	low probability – 1 failure /(10 ÷ 100) years

Table 2. Events of minor significance for for a DP system.

Electric power generation – main electric power plants		
Sea water cooling system	Drop in the pressure of the medium in the sea water cooling system	mean probability – 1 failure /(1 ÷ 10) years
Compressed air system	Low starting air pressure in one electric power plant	mean probability – 1 failure /(1 ÷ 10) years
Electric power generation – auxiliary power plant		
failure of one generator set due to a failure of a mechanical or electric subsystem		high probability – 1 failure / 1 year (Lambda 504.81 /1mln working hours)
Lubricating oil system	Drop in lube oil pressure	high probability – 1 failure / 1 year
Electric power distribution		
220 V AC	failure of 220Vswitchboard	mean probability – 1 failure /(1 ÷ 10) years
	failure of 220 V switchboard	mean Probability – 1 failure /(1 ÷ 10) years
24 V DC	failure of the 24V DC distribution for the navigatiing bridge	mean probability – 1 failure /(10 ÷ 100) years
Thrusters		
Bow tunnel thrusters and azimuth thrusters	Failure of a hydraulic pump	mean probability – 1 failure /(1 ÷ 10) years
	Failure of 24V DC supply for the control system	low probability – 1 failure /(10 ÷ 100) years
Main propellers (two Wiechman 5 AX engines)	failure of a main propulsion engine	mean probability – 1 failure /(1 ÷ 10) years

Table 3. Events of major significance for the functioning of a DP system, making it necessary to stop the DP system operation till the fault is removed.

Electric power generation – main electric power plants		
failure of one main electric power plant – mechanical/electrical failure		mean probability – 1 failure /(1 ÷ 10) years
failure of both main electric power plants – combination of mechanical/ electrical failures due to incorrect maintenance		Very low probability – 1 failure/100 years
Fuel oil system	no fuel supply to engines in one electric power plant	mean probability – 1 failure /(1 ÷ 10) years
Main fresh water cooling system	Drop in the pressure of the medium in the fresh water cooling system	low probability – 1 failure /(10 ÷ 100) years
Power plant supervision system – electronic speed governors	failure of speed regulation of one diesel engine of the main electric power plant	mean probability – 1 failure /(1 ÷ 10) years
	Failure of 24V DC supply for speed governors in one electric power plant	low probability – 1 failure /(10 ÷ 100) years
Electric power generation – auxiliary electric power plant		
Failure of power supply for one group of receivers from the auxiliary power plant		mean probability – 1 failure /(1 ÷ 10) years
Fuel oil system	incapability of fuel supply from tanks in the auxiliary power plant	low probability – 1 failure /(10 ÷ 100) years
Sea water cooling system	drop in sea water pressure	mean probability – 1 failure /(1 ÷ 10) years
Electric power distribution		
660 V AC	failure of main switchboard, port side	low probability – 1failure /(10 ÷ 100) years
	failure of main switchboard, starboard side	low probability – 1 failure /(10 ÷ 100) years
440 V AC	failure of the auxiliary 440V switchboard, port side	low probability – 1 failure /(10 ÷ 100) years
	failure of the auxiliary 440V switchboard, starboard side	low probability – 1 failure /(10 ÷ 100) years
	failure of the auxiliary 440V switchboard, aft	low probability – 1 failure /(1 ÷ 10) years
24 V DC	failure of 24 V DC supply, port side	low probability – 1 failure /(10 ÷ 100) years
	failure of 24 V DC supply, starboard	low probability – 1 failure /(10 ÷ 100) years
	failure of 24 V DC supply, aft	low probability – 1 failure /(10 ÷ 100) years
Thrusters		
failure of one azimuth thruster and two bow thrusters		low probability – 1 failure /(10 ÷ 100) years
bow tunnel thrusters and azimuth thrusters	malfunction of one DP system propeller	mean probability – 1 failure /(1 ÷ 10) years
	failure of 660V supply	mean probability – 1 failure /(1 ÷ 10) years
Emergency power supply		
UPS units	UPS 1, UPS 2, UPS 3, UPS 4 – failure of the inverter, short circuit	low probability – 1 failure /(10 ÷ 100) years
System of reference sensors		
Reference sensors	Taut wire system Hydroacoustic system (HPR) Radar system (Artemis) Syled Micro GPS Gyrocompass Vertical reference sensor (VRS) Anemometer	Various probabilities and consequences depending on a subsystem and performed offshore operations
DP system supervision		
System of dynamic positioning control	basic system – *e.g.* Simrad ADP 703	low probability – 1 failure /(10 ÷ 100) years
	standby system – *e.g.* Simrad ADP 701	low probability – 1 failure /(10 ÷ 100) years

the elimination of overheating of an item during overhaul work in the engine room; afterwards, if further overhaul activities are neglected, safety unreliability may occur;

- parallel model with renewable state of safety unreliability. The item is subject to renewal only after safety unreliability occurs at the rate $\mu_B(t)$. For instance, an electrical piece of equipment is destroyed after long overloading that poses a risk of fire. The replacement of the piece of equipment (renewal) results in the elimination of the hazard to safety.;
- parallel model with renewable states of safety unreliability and functional unreliability. After functional unreliability first occurs, the item is renewed at the rate $\mu_Z(t)$; later, when safety unreliability has occurred, it is subject to renewal at the rate $\mu_B(t)$. The above mentioned piece of electrical equipment can also be taken as an example. Although it was overhauled and brought to up state, after a considerably long time between overhauls – safety unreliability occurs and the piece of equipment is completely renewed (replaced).

Most offshore vessel operations, such as diving, drilling, drilling rig work etc. create substantial hazards to life and health of personnel and passengers on board as well as a possibility of the destruction of costly technical objects. In extreme cases an environmental disaster may occur. Consequently, vessels participating in seabed exploration are subject to the supervision and assessment of the safety of their operations with the use of such methods as FMEA. Therefore, it seems useful to extend this kind of analysis with quantitative safety measures (such as those herein presented), particularly for events that may have severe consequences and those that may occur with high probability.

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