Multi-level Hierarchical Reliability Model of Technical Systems: Theory and Application

Igor Bolvashenkov, Jörg Kammermann, Ilia Frenkel and Hans-Georg Herzog

Abstract This chapter describes an assessment methodology for various sustainability indicators of technical systems, such as reliability, availability, fault tolerance, and reliability associated cost of technical safety-critical systems, based on Multi-Level Hierarchical Reliability Model (MLHRM). As an application case of the proposed methodology, the various sustainability indicators of electric vehicle propulsion systems are considered and evaluated on the different levels of the hierarchical model. Taking into account that vehicle traction drive systems are safety-critical systems, the strict requirements on reliability indices are imposed to each of their components. The practical application of the proposed technique for reliability oriented development of electric propulsion system for the search-and-rescue helicopter and icebreaker LNG tanker and the results of computation are presented. The opportunities of improvement regarding reliability and fault tolerance of such technical systems are investigated. The results of the study, allowing creating highly reliable technical systems for the specified operating conditions and choosing the most appropriate system design, are discussed in detail.

Keywords Multi-level hierarchical reliability model · Technical system · Reliability oriented design · Fault tolerance · Electric propulsion system · Markov model · Reliability associated cost

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1 Introduction

The rapid modern development of new technical systems in various areas of the industry is directly related to a significant increase in their complexity. In addition, the levels of integration of subsystems, units and components and, accordingly, their mutual effect largely increase as well. This, in turn, has a very strong impact on the reliability, fault tolerance, and maintainability of the designed technical systems. Reliability concepts can be applied to virtually any engineered system. In its broadest sense, reliability is a measure of performance.

All of the above fully applies to the traction drive of electric vehicles, the creation of which is a major challenge in the modern way to electrification of the different types of vehicles: ships, planes, trains, helicopters, buses, and cars. For transport facilities that are safety-critical systems, the issues of assessing and optimizing reliability indicators are of particular importance.

As can be seen from Fig. 1, the magnitude of the level of technical excellence of an electric traction drive is determined by three comprehensive criteria: sustainable functioning, efficient functioning, and environmental level. It follows from Fig. 1 that the maximum number of factors affects the amount of sustainable functioning criterion of the traction drive. Accordingly, the above criterion has the maximum potential to increase the value of the level of excellence of the traction electric drive and an electric vehicle as a whole. In addition, the most stringent requirements are imposed on reliability, fault tolerance, and survivability of electric vehicles, which are safety-critical systems.

In this way, reliability-oriented design of the vehicle electric propulsion system and, accordingly, all its subsystems, units, and components is a very urgent and complex task while considering their interactions. In recent years, a multilevel approach

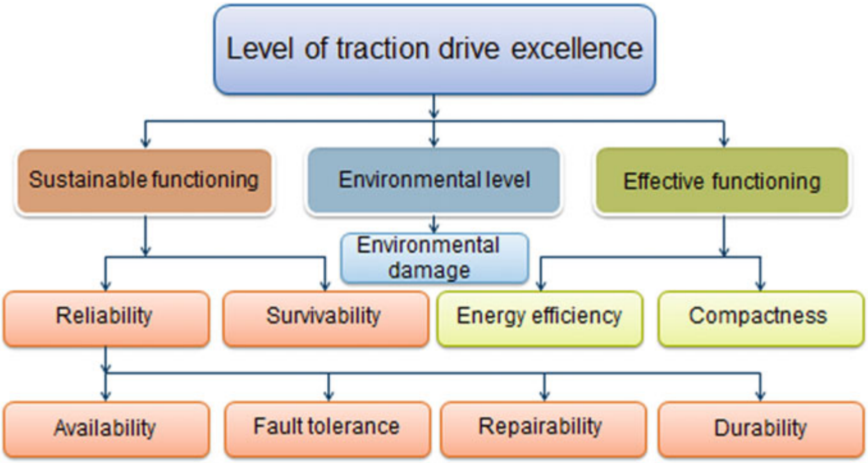


Fig. 1 Level of excellence

in the development, design, and optimization of various technical systems and their particular parameters has become quite widespread. In addition, when using a multilevel approach in most cases, the various levels are interconnected hierarchically. Depending on the complexity of the system being developed, the multilevel hierarchical reliability model may consist of a different number of levels. In the simplest case, it can consist of three levels.

Attempts to develop the methods for solving such a problem were undertaken by various research groups. The first group of scientists, whose works are presented in [1–4], uses the method of hierarchical decomposition of the technical system, better known as analytic hierarchy process (AHP). It was developed by Thomas L. Saaty in the 1970s and represents a structured technique to organize and analyze complex decisions, described in detail in [1]. This approach has significant advantages when important components of the decision are difficult to quantify or to compare, or when communication between team members is made difficult by their different specializations, terminology, or perspectives. Due to the relatively simple mathematical formula, as well as the easy data collection, AHP has been widely applied by many researchers.

The integral shortcoming of the AHP is the fact that the criteria are assumed to be completely independent, even though in real world problems, the criteria are often dependent. In [2] the AHP approach was applied in the four-level hierarchical tree to identify the main attributes and criteria that affect the level of accuracy of the models used in probabilistic risk assessment. The main disadvantage of AHP approach is the inability to consider the uncertainties of the process. In order to overcome this limitation the application of different hybrid combination of fuzzy theory and AHP, so-called called Fuzzy AHP, and analytic network process (ANP) method have been used in [3] for inter-criteria dependencies definition and in [4] for the vehicle safety analysis. It should be noted that in real life, most of the decision problems are represented by a network and not only structured as a hierarchy.

Various hierarchical stochastic models have proven to be a powerful tool for analyzing the reliability of complex technical systems for different application. The authors in [5] described a method, called the hierarchical Markov modeling (HMM), which allows to perform the predictive reliability assessment of distribution electrical system. This method can be used not only to assess the reliability of existing distribution systems, but also to estimate the reliability impact of several design improvement features.

HMM creates a primary model based on the system topology, secondary models based on integrated protection systems, and tertiary models based upon individual protection devices. Once the tertiary models have been solved, the secondary models can be solved. In turn, solving the secondary models allows the primary model to be solved and all of the customer interruption information to be computed.

An interesting approach to solving the complex problem of performance, availability, and power consumption analysis of infrastructure as a service (IaaS) clouds, based hierarchical stochastic reward nets (SRN) is presented in [6]. In order to use the resources of an IaaS cloud efficiently, several important factors such as performance, availability, and power consumption need to be considered and evaluated carefully. The estimation of these indicators is significant for cost-benefit prediction and quantification of different strategies, which can be applied to cloud management.

Possible techniques and ways to solve the problem of a multistage reliability-based design optimization (MSRBDO) based on Monte-Carlo method, and its application to aircraft conceptual design, which is described in detail in [7] and with subsequent corrections and development in [8]. In recent years, a multilevel (tiered) systematic approach has become increasingly widespread for analyzing and optimizing the various characteristics of technical systems, the theoretical foundations of which are described in detail in [9–12].

In the work [9] the four-level (system, subsystem, assembly, and device-component) representation of variable-speed drive systems is proposed for analysis of reliability, availability, and maintainability. The calculations were performed analytically and step by step. Paper [10] describes the rules and properties of multilevel hierarchical representation of the vehicles propulsion systems life cycles and the optimal types of stochastic methods and models for use at each individual level.

A new look at solving the problem of assessing various system resilience, based on the three-level (tiered) approach is proposed in [11]. Reference [12] presents a systematic four-level approach to develop the reliability design of the mechanical system—the refrigerator, which is similar to the target of this chapter, but it does not present any analytical optimization.

A significant amount of research works is related to the assessment of the reliability of particular units or component at one of the local levels of the multilevel model and the development of appropriate methods and models [13–16]. In references [13, 14], several options for assessing reliability at the component level are presented. In the first case [13], it is proposed to do this using failure mode and effects analysis (FMEA) with weighted risk priority number (RPN), and in the second case [14] it is proposed to do this based on a multi-state Markov model, which allows to consider random environmental conditions.

The hierarchical model for lithium-ion battery degradation prediction, discussed in [15], represents reliability assessment technique at the unit level of multilevel model. The three-level (system, subsystem, and component) aircraft engine model's hierarchical architecture is described in [16]. This paper concludes that in a large system, such as an aircraft engine, failure prognostics can be performed at various levels, i.e. component level, subsystem level, and system level. A similar approach for estimation of remaining useful life (RUL) for the multiple-component systems—when using the prognostics and health monitoring (PHM) technologies in modern aircraft—is proposed in papers [17, 18]. This methodology combines particular components RUL estimations into a single system level RUL estimation. This characteristic becomes more relevant when the number of components within the system increases.

2 Methodology of Multilevel Hierarchical Reliability Model

In order to solve the problem of implementing the reliability-oriented design for electric propulsion system, the authors, based on previous own research and research of other scientists, developed the methodology for creating and using the multilevel hierarchical reliability model (MLHRM) of electric vehicles' functioning. The main features, techniques, and potentials of the model are presented below.

The proposed method of reliability oriented design of vehicle electric propulsion system based on the MLHRM, allows to solve a complete set of tasks related to the full range of indicators of comprehensive reliability for the safety-critical electric traction systems, such as failure-free operation probability, fault tolerance, availability, maintainability, durability, reliability associated cost, etc.

2.1 *Structure of MLHRM*

Figure 2 shows the general view of the MLHRM structure. The number of levels of the model can vary depending on the complexity of the technical system and the tasks to be solved. The model presented in Fig. 2 has six levels, which correspond to the task of analyzing and optimizing the reliability characteristics of electric vehicles, taking into account their interaction in random environment.

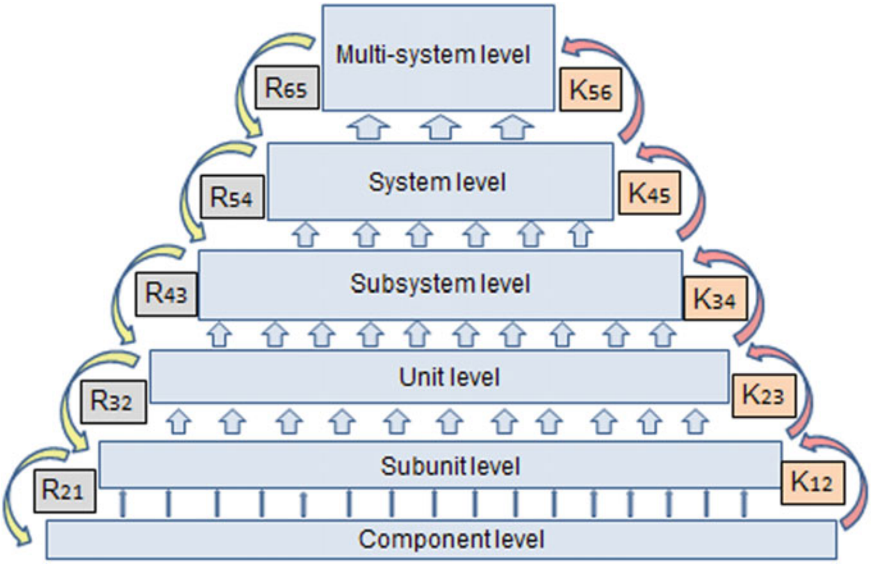


Fig. 2 General structure of MLHRM

The coefficients K12–K56 determine the magnitude of the influence of the reliability of the lower level of the model on the neighboring upper level. The coefficients R21–R65 determine the ratio of the required values of the performance of the upper level of the model relative to the neighboring lower level.

As noted above, the MLHRM shown in Fig. 2 includes six levels, namely, component level (CL), subunit level (SUL), unit level (UL), subsystem level (SSL), system level (SL), and multi-system level (MSL).

At the CL, based on statistical reliability data, analytical calculations, or using Markov models for binary-state components, reliability characteristics of element of the next level (SUL) are determined. In operational mode, component failures can lead to the degradation of the whole system performance.

Respectively, the performance rate of any component can range from fully functioning up to complete failure. The failures that lead to a decrease in the element performance are called partial failures. After partial failure, elements continue to operate at reduced performance rates, and after complete failure the elements are totally unable to perform their missions.

At the SUL the initial parameters for the analysis of reliability indicators of the red level are determined. As subunits, the independent functional parts of the next level (UL) can be considered. In turn, at the UL, an analysis and evaluation of independent functional units, which are integral parts of the next level, SSL, are carried out.

The reliability indicators calculated at the UL are the input data for the models used within the next level—the SSL. In the case of electric vehicles simulation, the SSL corresponds to the level where the assessment of the reliability characteristics of the entire electric traction drive takes place.

The basic model of the vehicle electric propulsion system at this level can be represented as stochastic model of multi-state system with the change of discrete operating load modes. Each operational load mode complies with specific power characteristics, which have to be implemented with highest probability for safety operation of the vehicle.

Thus, on the one hand, there are requirements for safe vehicle operation, which form a model of demand. On the other hand, there is the guaranteed generated electric power, which values form the model of performance. The combined performance-demand model allows to determine the characteristics of reliability, based on which it is possible to estimate the degree of fault tolerance of vehicles electric propulsion system and to optimize its values according to the project requirements.

At the SL, complex reliability indicators of electric vehicle are investigated. The input data for modeling at this level of MLHRM are the output reliability characteristics, which are obtained at the SSL. In turn, the output characteristics of SL are the input data for models of the top-level MSL.

At the MSL, the reliability associated economical characteristics of the joint operation of a multiple number of electric vehicles under real operating conditions are estimated taking into account their interaction and random environment. The problems solved at this level were not the purpose of present study and, therefore, are not considered in this chapter.

Based on the presented MLHRM, an algorithm was developed for accelerated estimation of the compliance of the propulsion system reliability indicators with the project requirements, which is shown in Fig. 3.

In accordance with the above algorithm, the main task of a simplified rapid assessment of reliability indicators is to determine the critical important components of

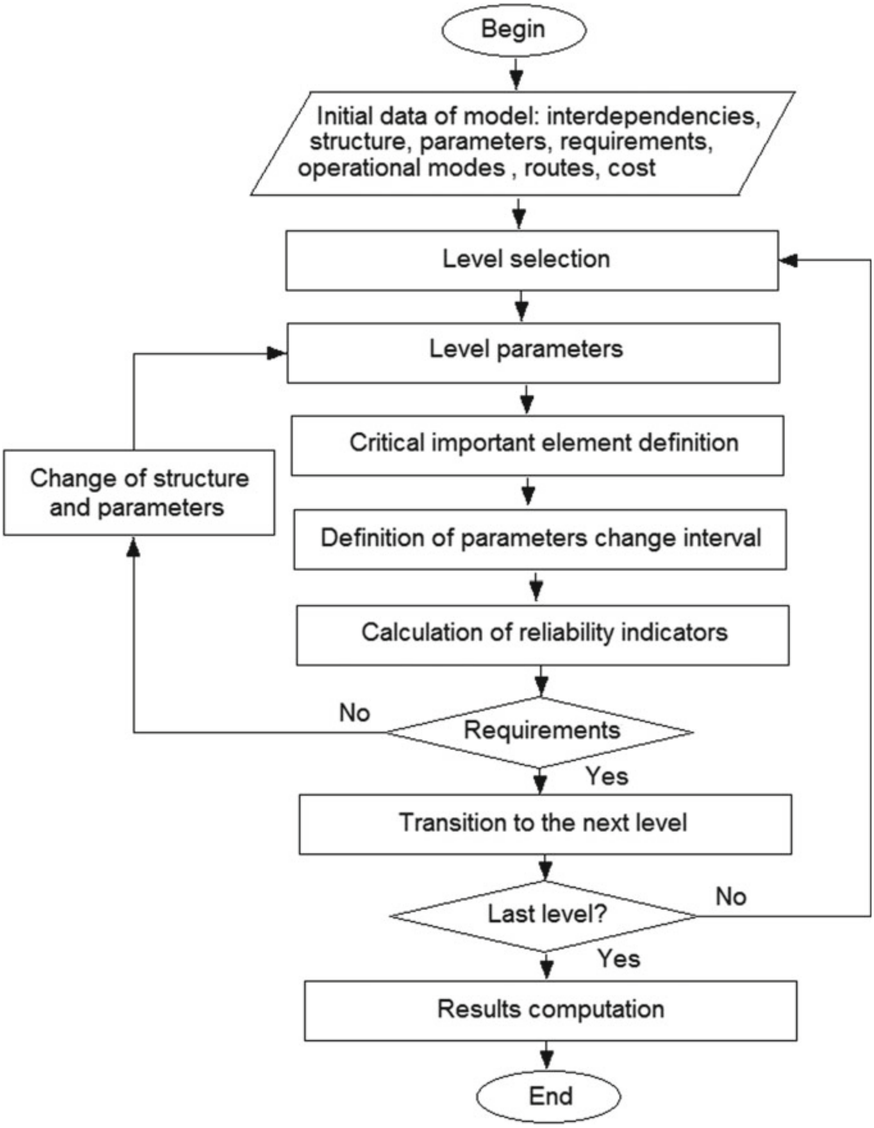


Fig. 3 Algorithm for rapid analysis of the reliability characteristics of a technical system

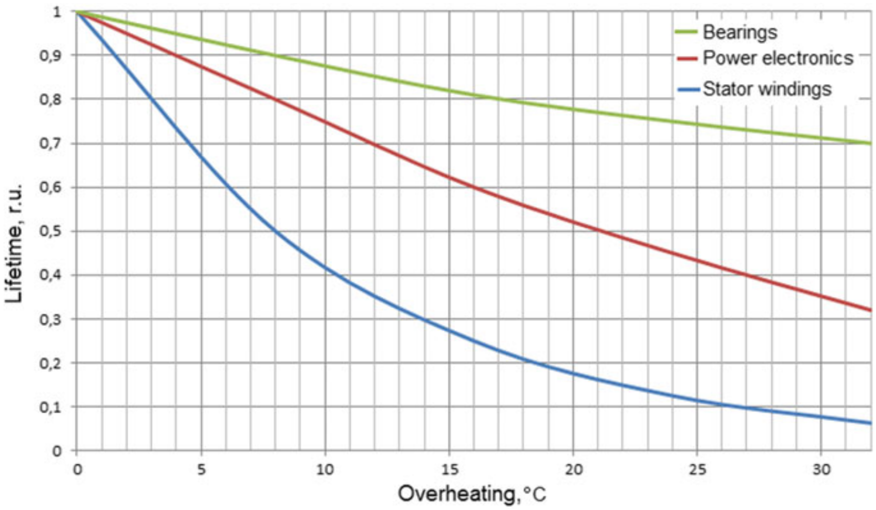


Fig. 4 Critical importance analysis of the subunits

each level of MLHRM and the degree of its influence on the reliability characteristics of the neighboring upper level.

In this case, the critical important parts of each level can be determined based on risk priority number (RPN), failure mode and effects and criticality analysis (FMECA) or based on experimental data, as shown in Fig. 4, which was previously presented in [19–21] for the main subunits of the traction electric motor: stator windings, power electronics and bearings.

From the results shown in Fig. 4, it follows that the most sensitive parts to thermal effects in various operating conditions and in terms of reliability, are the stator windings of the traction electric motor. In this case, for further investigations, the stator windings are accepted as a critical important subunit for the unit—the traction electric motor. Similarly, the critical important parts for the remaining levels of MLHRM can be defined.

2.2 *Goals, Methods and Models*

At each level of the MLHRM, specific models are used to solve specific tasks in order to achieve the corresponding goals at each level. Figure 5 graphically presents the problems associated with the reliability characteristics of electrical propulsion systems that can be solved by means of MLHRM. In addition, Fig. 5 presents the methods and models recommended in order to assess the reliability indicators of different MLHRM levels.

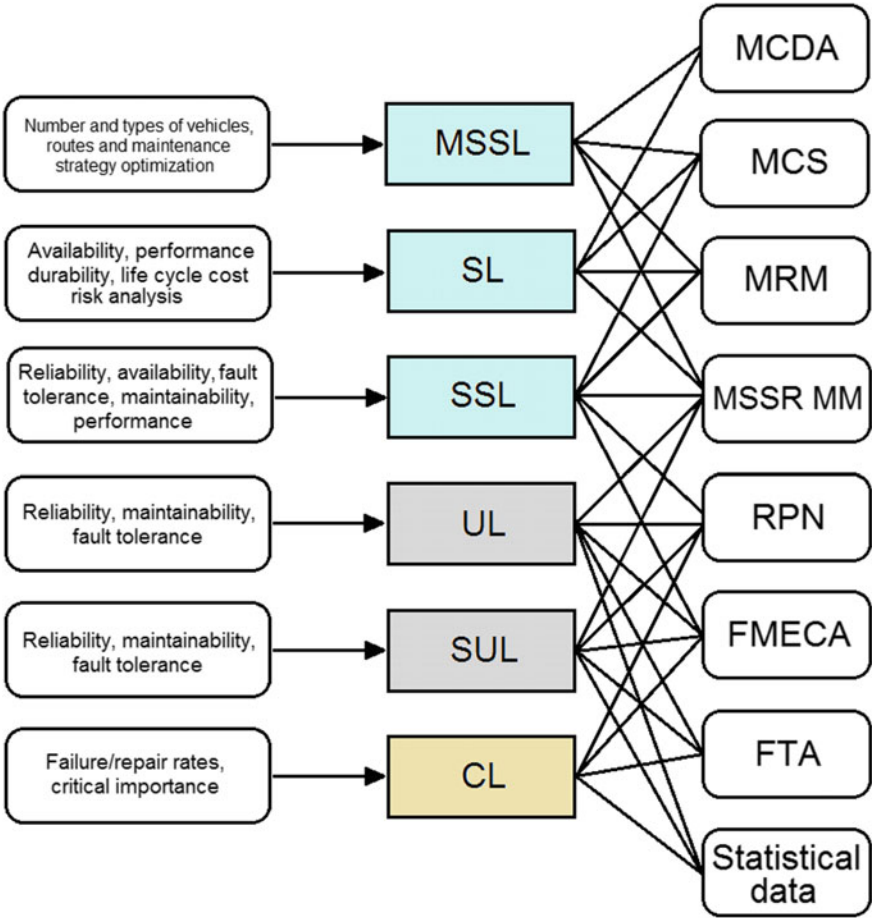


Fig. 5 Tasks and methods of their solutions for different MLHRM levels

Below, a detailed description of the tasks and methods for their solution, applied to each level of MLHRM is given.

2.2.1 Component Level

The main tasks that are solved at the CL are the collection, analysis, and structuring of statistical data on the reliability of all components that affect the reliability of the neighboring top level of the MLHRM. It also identifies the critical important components and their degree of influence on the reliability features of the next level—the SUL. Possible methods for achieving these goals are fault tree analysis (FTA), failure mode and effects analysis (FMEA), FMECA, and RPN. Several examples of the reliability characteristics analysis of electric propulsion systems at CL of MLHRM are described in [21–23].

2.2.2 Subunit Level

As subunits, this chapter examines individual, relatively independent parts of units having a specific functional orientation. At the subunit level, based on the data obtained in the previous component level, it is advisable to determine the characteristics of reliability, maintainability, and fault tolerance of the subunit groups, forming the corresponding elements of the next level—the UL. The recommended methods for analyzing and evaluating the above reliability characteristics are FTA, FMEA, FMECA, and RPN using experimental failure and repair statistics. If there are blocks that are not binary, but multi-state elements (elements with degraded states), the multi-state system reliability Markov models (MSSR MM), described in details in [20, 23, 24], can be applied for the computation.

2.2.3 Unit Level

At the UL, the tasks of computation and optimization of reliability, maintainability, and fault tolerance of autonomous functional parts (units), within the propulsion system of electric vehicles, are solved. Taking into account that the units are elements with several degraded states, that is, multi-state systems, it is advisable to use MSSR MM for their research. In addition, by means of MSSR MM, one can take into account the actual load modes of the units, regarding overloads capacity and the aging processes. The transition probabilities for MSSR MM can be calculated by means of the degree of fault tolerance (DOFT) [24] using statistical operational data or can be determined at the design stage based on the requirements to the safety and sustainable vehicle operations. In order to determine the critical important elements of the UL for further optimization, RPN, FMECA, FTA, and experimental test methods can be used.

2.2.4 Subsystem Level

At the SSL the problems of determining and optimizing the reliability characteristics of operational availability, maintainability, fault tolerance, redundancy (functional and structural), and performance of entire electric propulsion system should be solved. In order to build the corresponding combined stochastic model of the electric vehicle propulsion system including electric energy source, the concept of balanced relationship between demand (required power) and performance (available power) have been applied.

Hence, the model of the electric propulsion system operation can be represented as a MSSR MM with the change of discrete operating modes: start (takeoff), acceleration (climb), constant speed (cruise), deceleration (reduction of altitude), and stop (landing). Along with MSSR MM, Markov reward models (MRM) and Monte-Carlo simulation (MCS) can be widely apply.

2.2.5 System Level

At this level, the most preferred are the various stochastic models of the electric vehicle's lifecycle, which allow to assess the reliability indices of repairable systems by optimizing maintenance strategies according to intensity of the scheduled and unscheduled repairs, the use of functional systems of monitoring, forecasting reliability, and diagnostics. These may be MSSR MM, MRM, MCS and multi-criteria decision analysis (MCDA).

A definition of current and forecasted values of reliability indices, performed considering the external and internal operation conditions of the vehicle, as well as taking into account the availability (or non-availability) of structural or functional redundancy. Thus, the study and optimization task of the so-called reliability associated costs (RAC) estimation, based on MRM, is most interesting and promised [20].

In order to build such a model, the process of the vehicles operations can be represented by a chain of the lifecycles: operational, non-operational, working, standing, etc. The data on duration of each cycle are obtained based on the analysis of statistical operational data of a particular type of vehicle on certain routes and areas.

3 Application Cases

As application examples of the proposed MLHRM methodology for assessing and optimizing the reliability characteristics of electric traction drives, the electric propulsion systems of a search-and-rescue (SAR) helicopter and an icebreaker liquefied natural gas (LNG) Arctic tanker are considered.

The selected objects of investigation differ significantly in almost all operational vehicle indicators, such as operational conditions, the values of nominal performance, the possibility of repairs during operation, etc. The main purpose of the selection of such objects is to show the universality of the proposed model and methodology for various types of electric vehicles.

3.1 Electrical Helicopter

Functionally, the MLHRM of the electrical helicopter is presented in Fig. 6. As a basic conventional prototype for the design and development of the full electric propulsion system, the Airbus helicopter EC135 currently being in operation has been considered. The traction system of the EC135 has two gas turbine engines. Accordingly the turbines Turbomeca Arrius-2B2 or Pratt and Whitney PW206B2 are installed as gas turbine engines on the EC135.

In consideration of statistics from the German automobile club (ADAC), every SAR helicopter in Germany is operated by a daily average of 8–10 h, i.e., the average ratio of operational time in one year is 0.33–0.42. Thus, in the further simulation an annual flight of the helicopter assumed to be equal to 3000 h. Table 1 shows the weight and dimensions of a traditional traction drive of the EC135 with two turbines.

Generally, the propulsion system of the electrical helicopter consists of a various units, such as electric energy source (EES), power electronics (PE), control unit (CU), and traction electric motor (EM), as is shown in Fig. 7. In addition to the units indicated in Fig. 7, the electrical propulsion system of the helicopter includes switchboard (SWB), sensors (SENS) and other blocks, that affect its reliability.

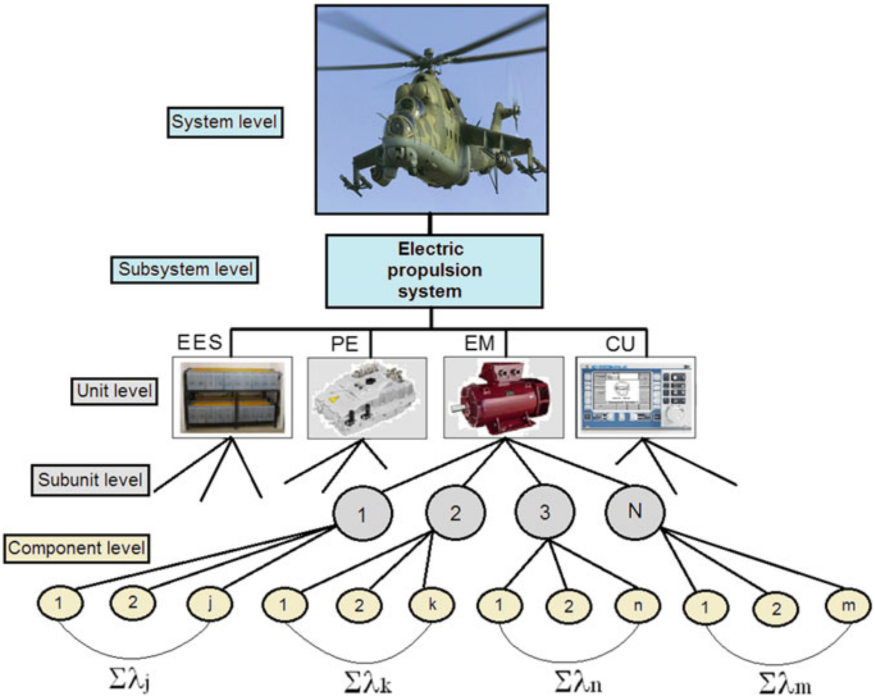


Fig. 6 MLHRM structure of helicopter with electric propulsion

Table 1 Technical data of EC135 traction drive

Component	Weight (kg)	Volume (l)
Two turbine engines	228	330
Fuel tank	650	737
Total	878	1067

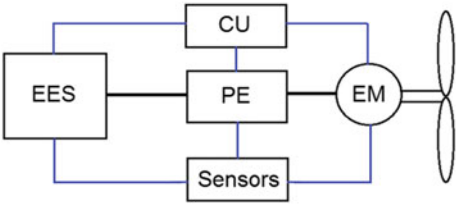


Fig. 7 Structure of the helicopter's electric traction drive

3.2 *Icebreaker LNG Tanker with Electric Propulsion*

In general, the MLHRM of the icebreaker tanker is presented in Fig. 8. The new Arctic LNG tanker "Christophe de Margerie", built in 2017 by Daewoo Shipbuilding &

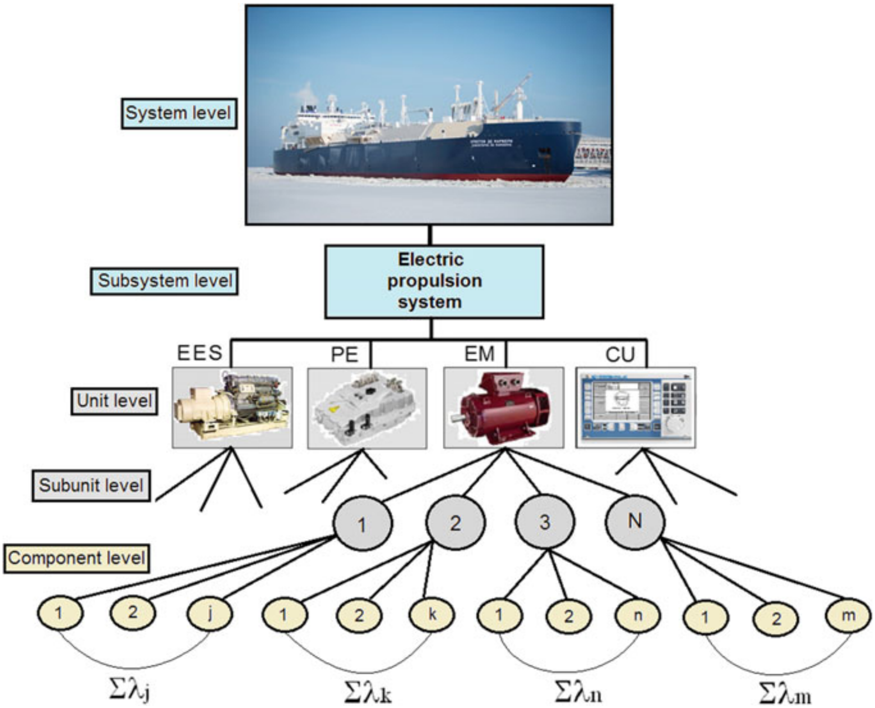


Fig. 8 MLHRM structure of icebreaking cargo ship with electric propulsion

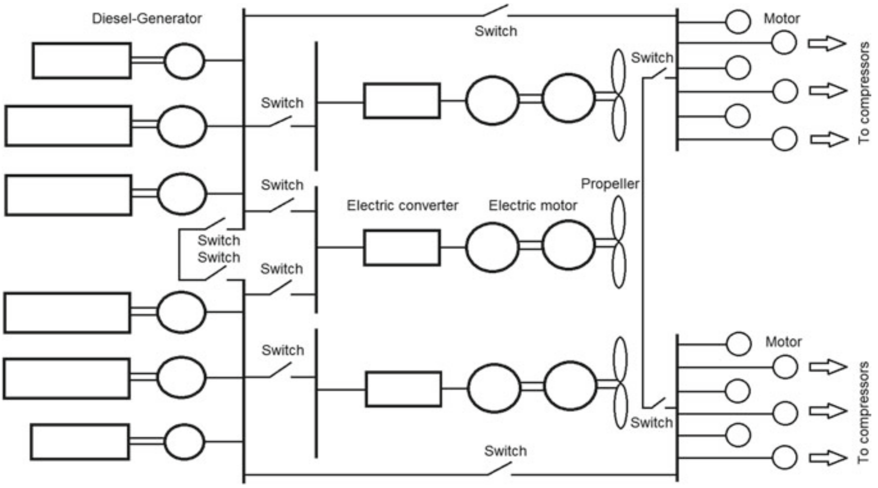


Fig. 9 Structure of the whole power system of LNG tanker

Marine Engineering in South Korea, was selected as the research object to investigate reliability features of the overall electric propulsion system. The characteristics of the LNG tanker "Christophe de Margerie", as well as its propulsion system, are described in detail in [25].

In Fig. 8, the following notation is used: EES—electric energy source, PE—power electronics, EM—electric motor, CU—control unit, λ_j, λ_k, λ_n, λ_m—failures rates of various components.

The main goal of the ship's propulsion system is to ensure the safe and efficient transportation of cargo and/or passengers. Based on the stated main goal, the functions that should be performed at each level of MLHRM are analyzed. Below is a detailed description of each model level applied to the ship's electrical propulsion system. For a more complete understanding of the essence of the multilevel structure of MLHRM, Fig. 9 shows the simplified diagram of the fully integrated power system of the icebreaker LNG tanker.

The entire ship's power system can be conventionally represented as three subsystems: the electric energy source system (EES), the ship's electric propulsion system (EPS), and the subsystem of the ship's consumers of electric energy (EEC). The first subsystem includes six diesel-generators with a total power of 62,000 kW, which supply electric energy to a two-section main switchboard. The electric propulsion subsystem consists of three electric traction drives, including electric converters and three two-section electric traction motors, located in steering gondolas of the Azipod system. The ship's consumer subsystem provides general ship needs, as well as the critical important consumer, namely the gas liquefaction and storage system (LSS), consisting of 12 powerful motor-compressors.

When transporting LNG, specifically stringent requirements are imposed on the whole power system of the tanker in terms of safe and sustainable operation. On the one hand, in the heavy ice conditions of the Arctic, it is necessary to ensure the maximum possible power on all three propellers of the vessel, and on the other hand, in the same time, it is necessary to ensure uninterrupted functioning of the LSS for the safety and keeping the cargo—liquefied gas. This feature should be unconditionally observed during the simulation on SL and MSL. It should be noted that this requirement extends over 50% of the operating time of LNG tanker.

3.3 Component Level and Subunit Level

At the component level, based on available failure statistics [21–23] and the above methods of analytical reliability calculation (FTA, FMEA, RPN, etc.) the total failure rates of all components, of which the subunits are composed, can be analyzed and estimated. For EM, as the part of UL, the subunits are a stator with windings, a rotor with magnets, a bearing, and others, as shown in Fig. 10.

Considering the above data of Fig. 10, generally reliability of electric motor λ_{EM} can be determined by the formula:

$$\lambda_{EM}(t) = \Sigma\lambda_{Si}(t) + \Sigma\lambda_{Rj}(t) + \Sigma\lambda_{Bk}(t), \quad (1)$$

where λ_{Si}, λ_{Rj} and λ_{Bk} are the failure rates of parts of the all parts of electrical machine, respectively of stator, rotor and bearing.

For EC, as the part of UL, the subunits are the semiconductors, printed circuit boards (PCB), capacitors, and others, as shown in Fig. 11.

Based on the above data of Fig. 11, generally the failure rate of an electric power converter λ_{EI} can be estimated considering the reliability values of its components by the equation:

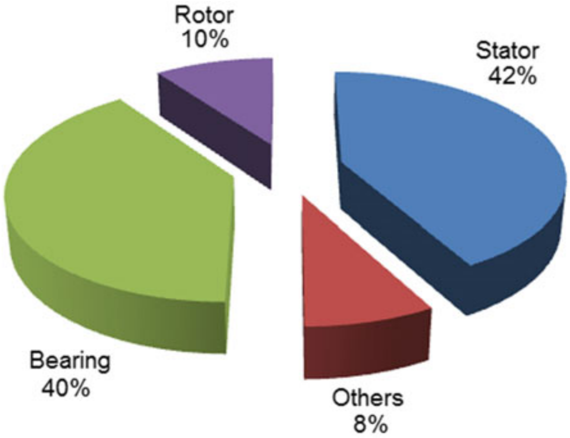
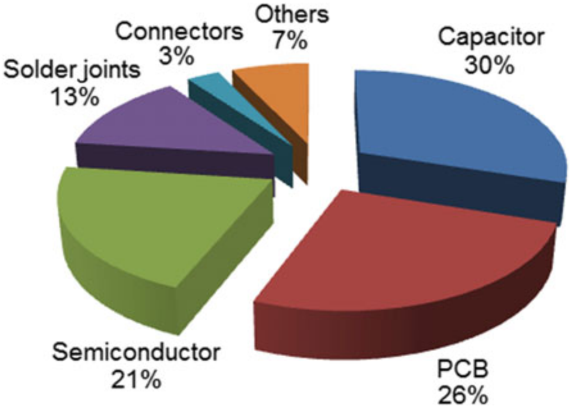


Fig. 10 Failures statistics of traction electric motor

Fig. 11 Failures statistics of electric converter



$$\lambda_{EC}(t) = \Sigma\lambda_{Ti}(t) + \Sigma\lambda_{Dj}(t) + \Sigma\lambda_{Ck}(t) + \Sigma\lambda_{Bn}(t), \tag{2}$$

where λ_{Ti}, λ_{Dj}, λ_{Ck} and λ_{Bn} are the failure rates of the all components of electric inverter, respectively of transistor, diode, capacitor, and printed circuit board.

The similar calculations are performed for all other subunits of the SUL, which are taken into consideration. Based on the results of the calculation, the sensitivity of changing the values of the reliability indicators at the subunit relatively to the change of the components' failure rates is determined. The obtained results are used further in the models at UL and SSL.

Increased reliability features on the CL can be obtained while using components and materials with higher reliability values and by various methods of critical components redundancy. In order to achieve the required performance characteristics of the SUL, as shown in [21], it is necessary to optimize the type of stator windings, permanent magnets, bearings, semiconductors, etc. In addition, redundancy of critical important parts of subunits can be used.

3.4 Unit Level

At this level of the MLHRM, the tasks of providing reliable performance of all functional elements, which form the subsystem of the electrical propulsion systems presented in Figs. 6 and 8, are solved. The detailed descriptions of the use of various techniques to improve the reliability and fault tolerance of electric energy sources, traction electric motors, electric converters, and control units at this MLHRM level are given in [19, 20, 23, 26].

The correct choice of the type of electric machine, the methodology of which is presented in [21], has a significant impact on the reliability indicators of an electric propulsion system. Based on the completed studies, it was proposed to use a synchronous motor with permanent magnets as the most promising one in terms of reliability and fault tolerance.

One of the most effective methods to improve the reliability and fault tolerance of traction electric motors is the use of a multi-phase motor topology with concentrated windings and galvanically uncoupled phases, described in [19, 26]. A significant influence on the characteristics of fault tolerance and overload capacity of the traction electric motor is provided by the parameters and the location of the permanent magnets on the rotor. In the work [21], it is shown that the most preferable design is the permanent magnet synchronous motor with internal v-shaped arrangement of permanent magnets on the rotor.

3.4.1 The Choice of the Phase Number of Traction Electric Motors

In order to select the suitable number of phases of the traction electric motor in accordance with the requirements on reliability and fault tolerance, it is advisable to represent the multiphase traction electric motor in the form illustrated in Fig. 12.

A multiphase electric motor means a motor with more than 3 phases. A critical electric motor failure in this chapter means the loss of one or several phases of an electric motor with a corresponding decrease of its performance—the shaft power.

Each electric motor, which has more than three phases, has a certain level of fault tolerance, i.e. is able to function in degraded states after one or more phase failures. The state space diagram of MSSR MM for the fault tolerance estimation is presented in Fig. 13.

The results of calculations, presented in Fig. 14, showed that the 9-phase electrical machine meets the requirements of the project on the fault tolerance for the propulsion system, which is equal to one FIT. In this regard, a further increase in the number of motor phases for the considered application case is inexpedient.

3.4.2 The Choice of Power Electronics

As a converter of electrical energy for the study, a multilevel inverter was chosen which has important advantages from the point of view of fault tolerance in comparison with the conventional one. At the same time, for the given parameters of the electric propulsion system, a 17-level cascaded H-bridge inverter (CHB) is defined as the most promising topology of a multilevel inverter. One submodule of CHB is presented in Fig. 15.

Results of calculations, presented in Fig. 16, shown that to the requirements of the project on the fault tolerance for electric propulsion system satisfy the 7- and 9-phase topologies.

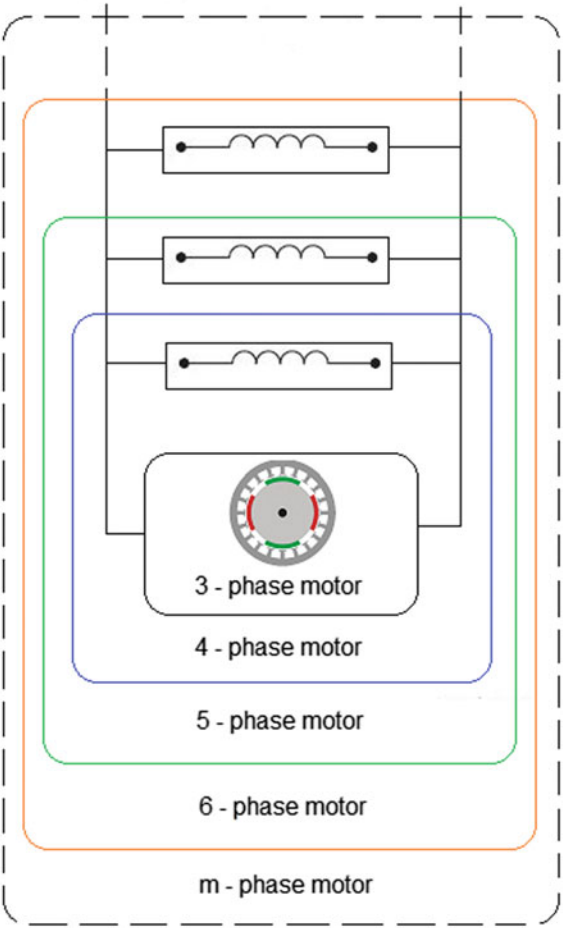


Fig. 12 Structural model of multiphase electric motor

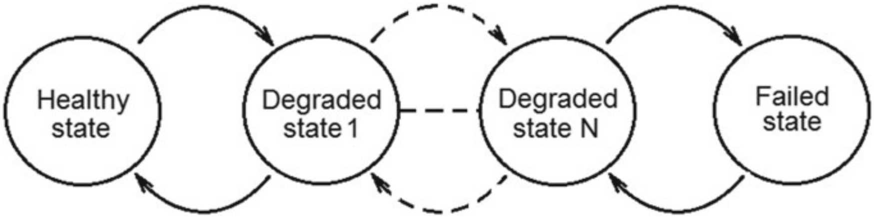


Fig. 13 State space diagram of MSSR MM for the fault tolerance estimation

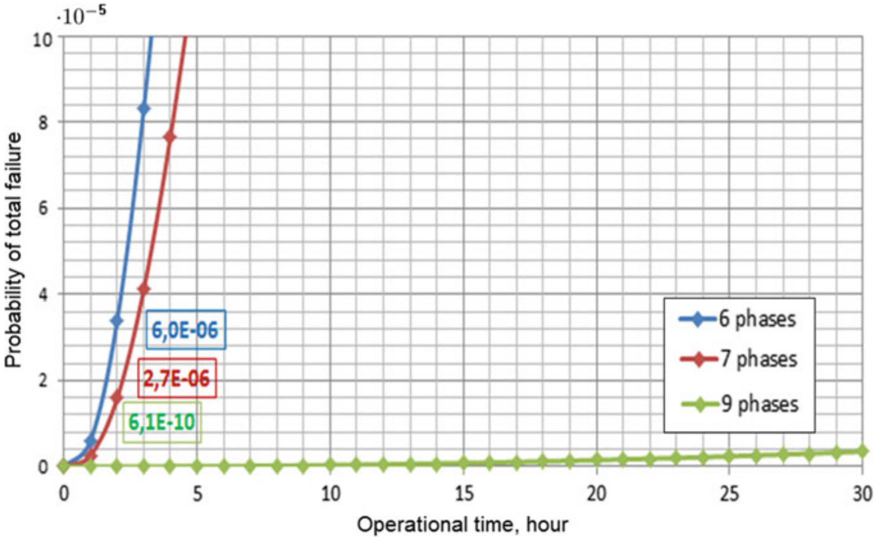


Fig. 14 Probability of total failure of the traction electric motor

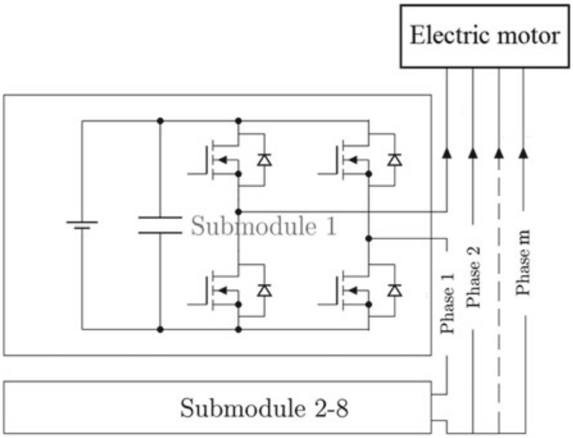


Fig. 15 17-level cascaded H-bridge inverter

3.4.3 The Choice of EM-PE Connection Topology

For the choice of the best topology of connecting 9-phase EM and PE, three well-known topologies were considered, presented in Fig. 17.

They are:

- the 3 × 3-phase system with three star connections (17a),
- the 1 × 9-phase system with one star connection (17b),

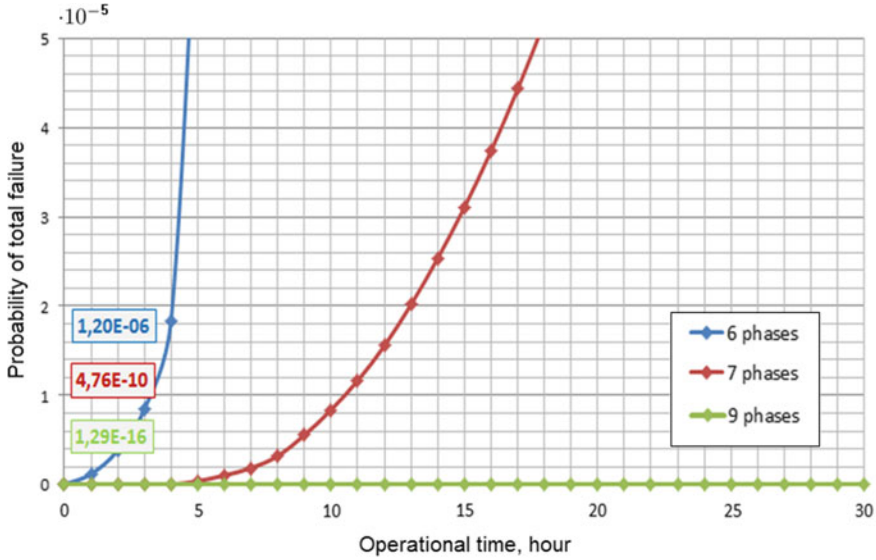


Fig. 16 Probability of total failure of one phase including the multilevel inverter

- the system with 9 galvanically separated phases (17c).

The results of the calculations, presented in Fig. 18, have shown that a modular topology of 9-phase electrical machine with galvanically uncoupled phases and a 17-level CHB inverter satisfies the requirements of the project on the fault tolerance for the propulsion system.

3.4.4 The Choice of Electric Energy Sources

The methods to analyze and improve the reliability of the electrical energy source and of the electric converter are discussed in [23, 27]. In order to meet the design requirements for reliability and fault tolerance as shown in [23], as electric energy sources it is advisable to apply the energy storage, with a matrix topology of battery or fuel cells with more than 22% battery cells' and more than 20% fuel cells' redundancy. The reliability characteristics of all units, taking into account the specific operational load conditions and aging processes, are advisable to be computed by means of the MSSR MM, as shown in [20, 21, 23, 24].

Considering the strict requirements on the level of fault tolerance of the helicopter's electric traction drive, it is advisable to use reconfigurable matrix topology of EES, shown in Fig. 19, which have higher reliability and fault tolerance indices than a conventional option.

Figure 20 presents the states-transitions diagram of the Markov model of EES consisting of NxM battery cells.

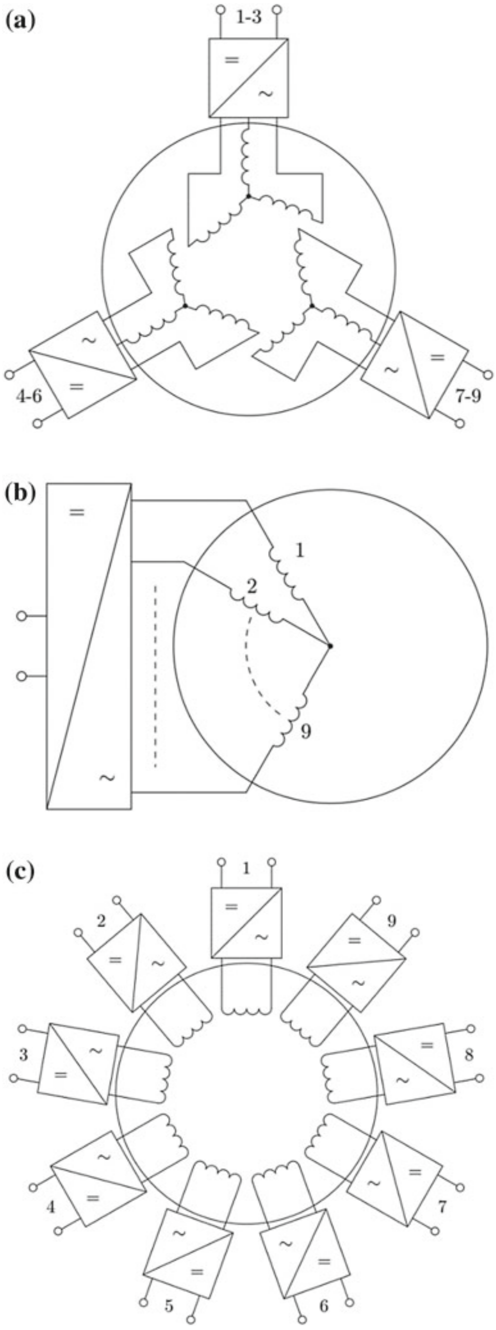


Fig. 17 Possible topologies of connecting EM and PE

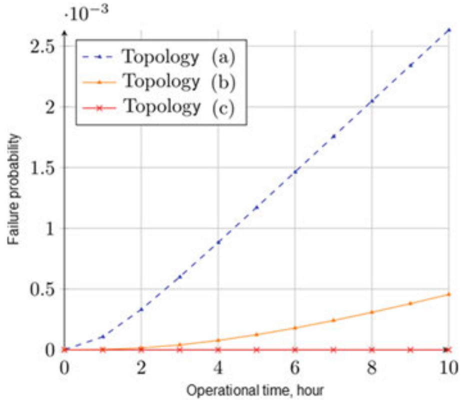


Fig. 18 Probabilities of total failure for different EM-PE topologies

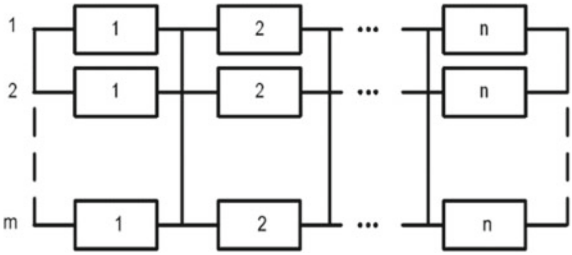


Fig. 19 Reconfigurable matrix topology of EES

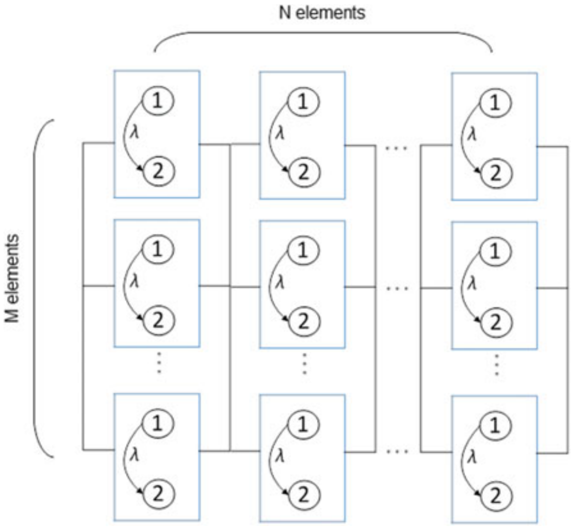


Fig. 20 Reliability block diagram

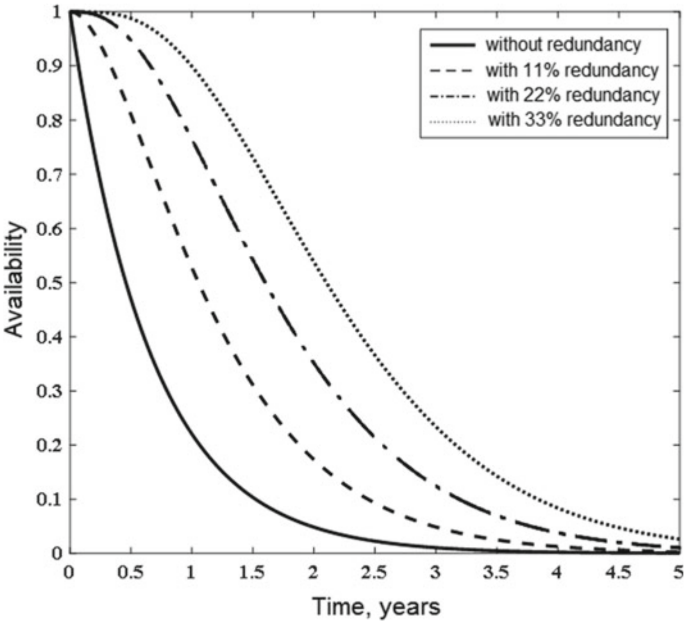


Fig. 21 Operational availability of EES based on Samsung cells

As it was mentioned, each battery cell is a device with two states of performance: a fully operational state with a nominal capacity and a total failure corresponding to a capacity of 0. According to the Markov method and the reliability block diagram (Fig. 20), the following system of differential equations has been constructed:

$$\begin{cases} \frac{dp_{i1}(t)}{dt} = -\lambda p_{i1}(t), \\ \frac{dp_{i2}(t)}{dt} = \lambda p_{i2}(t). \end{cases}$$

Initial conditions are: $p_{i1}(0) = 1,\ p_{i2}(0) = 0$.

Based on L_Z-transform method, the reliability function was calculated for the nominal load level, shown in Fig. 21.

3.5 Subsystem Level

At this level, the entire spectrum of technical tasks, which are related to the most important subsystem of an electric vehicle, is solved. The results of solving these problems will allow at higher levels to determine the financial equivalent of an important indicator of the level of excellence of an electric propulsion system—the sustainable functioning.

Such tasks include analysis and optimization of reliability, operational availability, fault tolerance, maintenance strategies, reliability associated cost, and performance of the propulsion system.

When analyzing the reliability characteristics at the SSL, it is necessary to take into account the operational load modes, the mutual influence between the units, the aging processes, the frequency, and the duration of maintenance and repairs, as well as the influence of structural and functional redundancy of the entire subsystem or its particular parts.

The required degree of redundancy of the electric propulsion system of the icebreaker LNG tanker, depending on the requirements on safety and fault tolerance, can be achieved at the SSL by using multi power electric energy sources (MPEES) consisting of six diesel generator sets. The questions of features and the analysis of the reliability characteristics of MPEES are described in detail in [27, 28].

High survivability and fault tolerance of the electric propulsion system of LNG tanker are especially important in the extremely difficult ice conditions of the Arctic. In order to ensure the safe and sustainable navigation in ice conditions, on the SSL, it is necessary to provide the multi-motor electric drives with multi-phase electric motors, whose features are discussed in [27, 29].

The most comprehensive investigation of reliability indicators at the SSL is advisable to carry out by means of MSSR MM, MRM and MCS. Moreover, taking into account the high complexity of Markov models with a high number of states for the entire electric power system, it is proposed to perform the calculations using the new powerful L_z-transform method, described in detail in [20], which drastically simplified the solution of multiple differential equations.

3.5.1 Choice of the Number of Motors with Different Number of Phases

Performance of the whole propulsion system, i.e. shaft power, is 540 kW. In order to analyze the reliability features of electrical propulsion system of helicopter and to select the best one, four options of the traction drive topology were compared. The compared variants differ in the number of electrical machines and the number of phases of each motor. The structures of helicopter's electric traction drives are shown in Fig. 22 and are as follows:

- Six 3-phase motors, each generate 1/6 of total power;
- Three 6-phase motors, each generate 1/3 of the total power;
- Two 9-phase motors, each generate 1/2 of the total power;
- One 18-phase motors, which generate the total power.

Considering that the considered structures and their component parts (multiphase motors) of the traction drive are a multistate system, it is advisable to use L_z-transform method for their particular research, described in [20, 26, 28].

According to L_z-transform method, any j-component can have k_j different states, corresponding to different performances g_{ji}, represented by the set $\mathbf{g}_j = \left\{g_{j1}, \ldots, g_{jk_j}\right\}$, $j = \{1, \ldots, n\}$; $i = \left\{1, 2, \ldots, k_j\right\}$. The performance

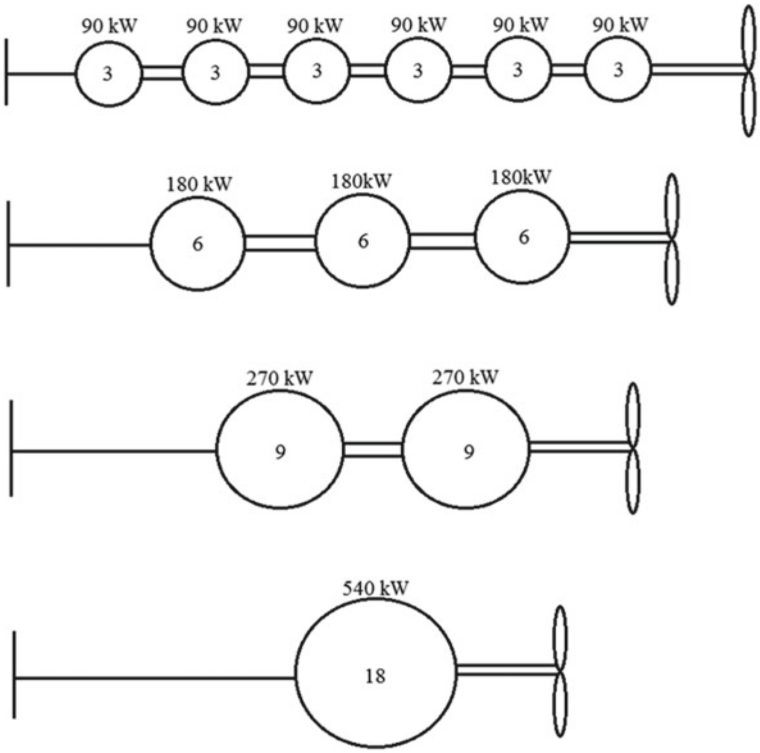


Fig. 22 Structures of various topologies of helicopter's electric drive

stochastic processes $G_j(t) \in \mathbf{g}_j$ and the system structure function $G(t) = f(G_1(t), \ldots, G_n(t))$, that produces the stochastic process corresponding to the output performance of the entire multi-state system, fully define the MSSR MM.

In this chapter, as an example of calculation, an electric drive scheme with three 6-phase traction electric motors is considered. The system's element, the 6-phase motor, has four states: fully working state with a performance of 180 kW, partial failure states with performances of 150 and 120 kW and full failure. The state-space diagram is presented in Fig. 23.

Using MATLAB® for numerical solution of the system of differential equations, it is possible to obtain the probabilities $p_1^{M_6}(t),\ p_2^{M_6}(t),\ p_3^{M_6}(t),\ p_4^{M_6}(t)$. Therefore, for such a system's element the output performance stochastic processes can be obtained as follows:

$$\begin{cases} \mathbf{g}^{M_6} = \left\{g_1^{M_6},\ g_2^{M_6},\ g_3^{M_6},\ g_4^{M_6}\right\} = \{180,\ 150,\ 120,\ 0\}, \\ \mathbf{p}^{M_6}(t) = \left\{p_1^{M_6}(t),\ p_2^{M_6}(t),\ p_3^{M_6}(t),\ p_4^{M_6}(t)\right\}. \end{cases}$$

Sets $\mathbf{g}^{M_6}$, $\mathbf{p}^{M_6}(t)$ define L_z-transforms for 6-phase motor as follows:

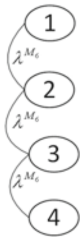


Fig. 23 State space diagram of 6-phase motor

$$\begin{aligned} L_z\left\{g^{M_6}(t)\right\} &= p_1^{M_6}(t)z^{g_1^{M6}} + p_2^{M_6}(t)z^{g_2^{M6}} + p_3^{M_6}(t)z^{g_3^{M6}} + p_4^{M_6}(t)z^{g_4^{M6}} \\ &= p_1^{M_6}(t)z^{180} + p_2^{M_6}(t)z^{150} + p_3^{M_6}(t)z^{120} + p_4^{M_6}(t)z^{0}. \end{aligned} \tag{3}$$

Multi-state model for the multi-motor electric traction drive may be presented as connected in parallel three 6-phase electric motors, shown in Fig. 24.

Therefore, the whole system L_z-transform is as follows:

$$L_z\left\{G^{SysM_6}(t)\right\} = \Omega_{f_{par}}\left(L_z\left\{g^{M_6}(t)\right\}, L_z\left\{g^{M_6}(t)\right\}, L_z\left\{g^{M_6}(t)\right\}\right) \tag{4}$$

Using the composition operator $\Omega_{f_{par}}$, the L_z-transform $L_z\left\{G^{SysM_6}(t)\right\}$ of the in-parallel-connected three identical 6-phase motors, can be obtained.

Table 2 presents the failure rates for the electric motors shown in Fig. 22.

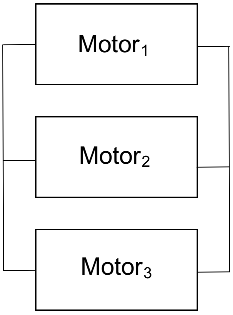


Fig. 24 Reliability block diagram of multi-motor drive with three 6-phase electric motors

Table 2 Failure rates of each element

	Failure rates (year^{-1})
3-phase motor	0.09
6-phase motor	0.15
9-phase motor	0.21
18-phase motor	0.33

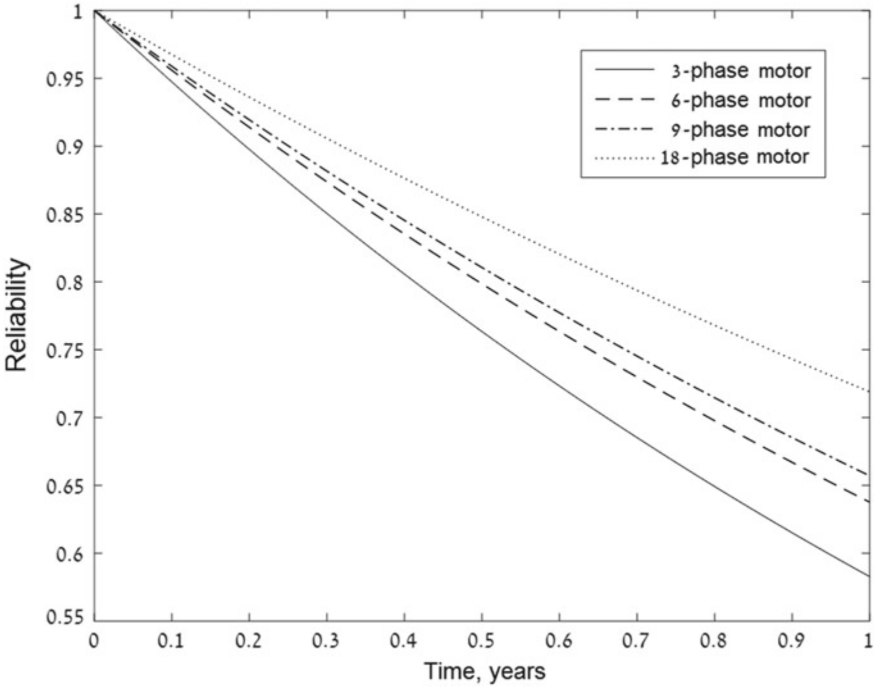


Fig. 25 Probability of the failure free operation for 100% load level

The obtained results of reliability calculation for the 100% load mode are shown in Fig. 25.

Such topologies allow to realize the required value of the performance and as a consequence, the high survivability of the helicopter (or other electric vehicles) with the possible occurrence of critical failures of the electric propulsion system.

3.5.2 The Model of the Whole Electric Propulsion System of the Helicopter

The resulting state space diagram of the MSSR MM of electric propulsion system of the helicopter, taking into account the impact of the human factor (HF), is shown in Fig. 26.

In Fig. 26 the blue state 0 of the graph corresponds to a full failure-free operation of all traction drive components. States 1–15 correspond to the partial failures of the elements of propulsion system with the partial loss of their functionality. The red state 16 represents the total failed electric traction drive and the inability of the helicopter to realize a safe flight.

Figure 27 presents the results of simulation on the Markov model, based on the state space diagram of Fig. 26.

Fig. 26 State space diagram of helicopters' electric propulsion system

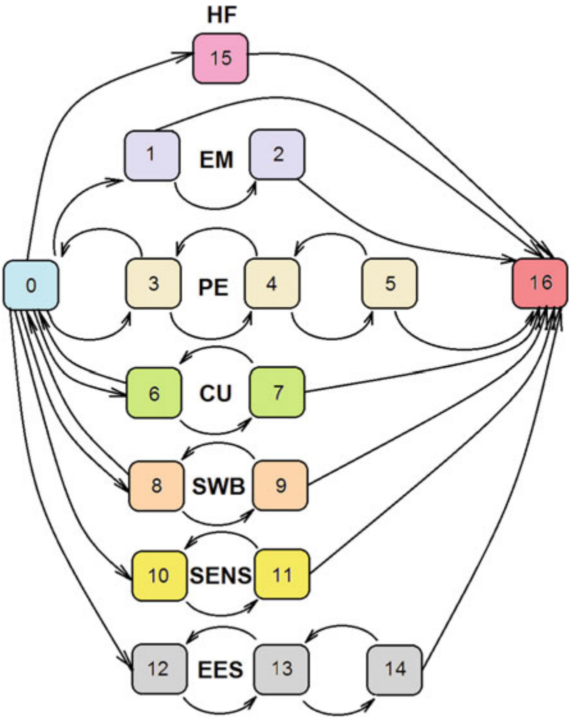
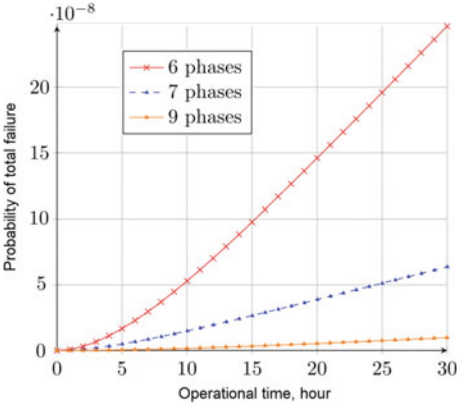


Fig. 27 Probability of total failure of electric propulsion system



For the considered topology of the helicopter's electric traction drive, which includes a multiphase traction motor, electric multilevel inverter, and 100% redundancy of SWB, SENS, and CU, the best option in terms of design requirements on the fault tolerance is the topology with a 9-phase electric motor, the 17-level CHB inverter and matrix topology of EES with partial redundancy.

Based on such MSSR MM the reliability characteristics of electric helicopter can be estimated and improved in accordance with the design requirements.

3.6 System Level

At the SL, the operation of the ship with electric propulsion subsystem as a whole system is considered, since this application is more informative at the SL compared to the helicopter. The operational conditions include several uncertainties and many random parameters. This fact has a significant influence on the comprehensive reliability characteristics of the Artic ship.

The objective function of the icebreaker LNG tanker is the safely, sustainable, and efficient shipping in the specified Arctic operating conditions. In accordance with this, the main objectives are to increase the carrying capacity of the tanker and to minimize the total operating costs and damages. The reliability characteristics of the icebreaker LNG tanker influence the values of both components of the objective function of the ship. In order to solve these problems, it is advisable to use MCS and MCDA, considering the random environment of the Arctic navigation conditions and the number of uncertainties, along with MSSR MM and MRM.

In this way, at the SL, it is recommendable to determine all reliability indicators of the whole tanker. Based on such reliability indices, the total cost can be calculated, which is needed to maintain sustainably the required level of performance during the operation of the tanker in real ice operating conditions. These are the operational availability, performance, deficiency of performance, maintainability, reliability associated cost, damages from unreliability, life cycle cost, risk probability, etc.

In order to improve the reliability and fault tolerance of the electric propulsion system and the LNG tanker as a whole, at this level, it is possible to use several autonomous electric drives with their own screws, to use the propulsion system of the gondola type with two screws, to optimize the maintenance and repair strategies of the power system of the tanker during navigation, and to use predictive reliability monitoring and a reliability control system of the ship electrical propulsion system.

In order to build the model of the LNG tanker life cycle at the SL, the process of the icebreaker LNG tanker operations is represented by a chain of the different operating modes. During the operation cycle depending on conditions of navigation, it is possible to distinguish four basic operating modes of an icebreaker LNG tanker. Each of them corresponds to a certain required number and power of the main engines. These operating modes are shown in Fig. 28 and defined as follows:

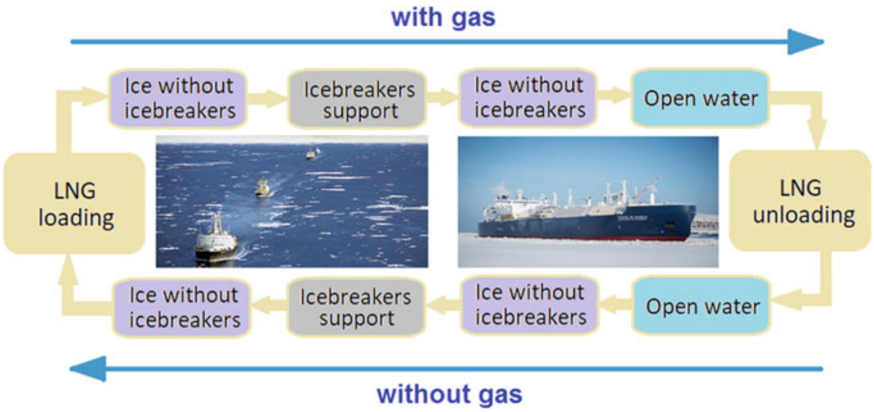


Fig. 28 Operational modes of icebreaker LNG tanker

- Loading and unloading of LNG at the terminal. Each of these two modes usually takes about 24 h. Sustainability of the loading and unloading process is determined by the reliability of onshore and ship gas liquefying and pumping systems.
- Navigation of a ship in ice-free water. The operation in this mode depends on the required velocity and needs the greater part of the operational time 50–80% of the nominal generated power.
- Autonomous movement in the ice without icebreaker support. The navigation in this mode depends on ice conditions and a wide power range from 50% up to 100% of the nominal power can be used.
- Navigation of a ship in heavy ice supported by icebreakers. In order to realize sustainable joint operation with icebreakers in this mode, electric propulsion system needs 80–100% of the nominal generated power.

Considering the abovementioned features of operational modes of the icebreaker LNG tanker propulsion system, three demand levels were chosen for calculation: 100, 80, and 50% of the main traction electric motors power.

For an accurate assessment of operational availability and performance of the electric propulsion system, it has been proposed to estimate the values separately for each of the above modes, followed by calculating the total impact on the value of the ship's operating speed and, accordingly, the amount of cargo transported per unit of time.

In order to analyze the reliability indicators at the system level of the MLHRM, the icebreaker LNG tanker power system—based on the decomposition principle—is presented in the form of four blocks: the electric energy source system (EES), the ship's electric propulsion system (EPS), the subsystem of the ship's consumers of electric energy (EEC) and LNG liquefaction and storage system (LSS). The simplified structure of the whole LNG tanker power system is shown in Fig. 29.

As a result of calculating the comprehensive reliability indices of each functional block, indicated in Fig. 29, based on the L_z-transform method to solve the system

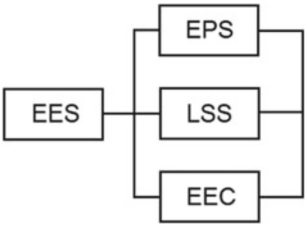


Fig. 29 Structure of the hybrid-electric power system of LNG tanker

of differential equations of MSSR MM, a schedule of operational availability of the power system of LNG tanker for different demands was simulated, which is presented in Fig. 30.

The graph of Fig. 28 demonstrates the ability of the tanker's power system to ensure sustainable functioning under the conditions of various operational demands. For this, the process of operating a fully loaded tanker during LNG delivery from the Sabetta terminal on the Russian Yamal Peninsula to the Chinese port of Shanghai was modeled. As can be seen from Fig. 28, the Arctic LNG tanker has high operational availability for the maximum levels of demand. Its value is equal to 85.82%. This

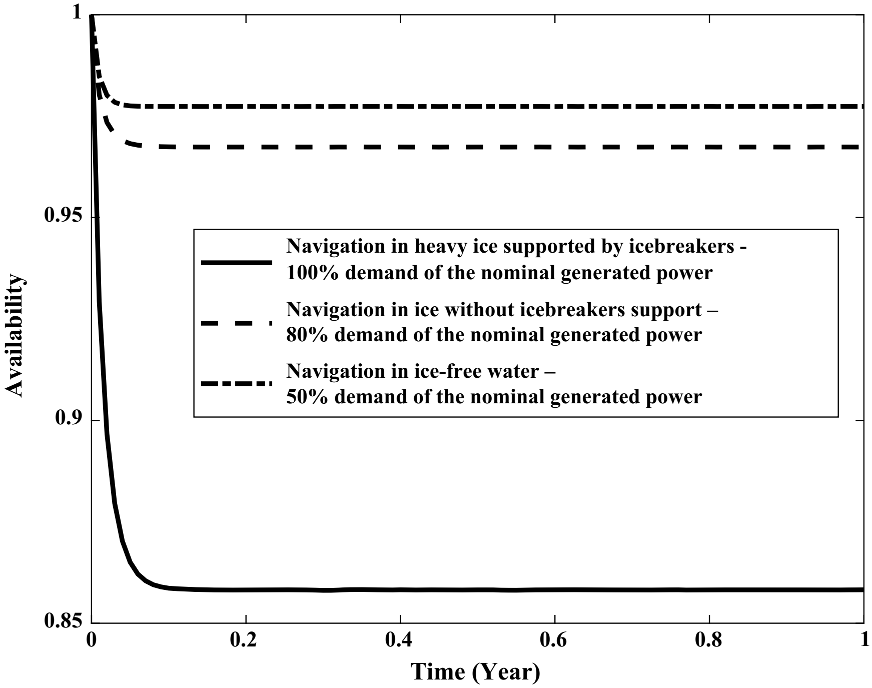


Fig. 30 Operational availability of the power system of LNG tanker for different demands

indicates that such multi-drive propulsion system closely related to the conditions of ice navigation.

4 Conclusions

It can be concluded that MLHRM and methodology of its application will allow to realize the overall analysis and estimation of comprehensive reliability characteristics of the vehicle electric propulsion systems at the design stage. It means to implement the so-called reliability oriented design of the traction electric drives. The suggested MLHRM of the vehicle's life cycle allows for each level to solve specific technical and technical-economical optimization tasks, such as optimization of the design of the electric machine, number of phases, number of electric motors, degree of fault tolerance, level of redundancy, maintenance strategy, topologies of electric converters, and electric energy sources.

The MLHRM approach allows to provide a quantitative comparative analysis of methods for improving the comprehensive reliability of the vehicle electric propulsion systems at each MLHRM level. In other words, in order to quantify the impact on the integrated reliability of the electric propulsion system and vehicle as whole, it is possible to use systems of diagnostics, fault detection, monitoring, fault prediction, varying degrees of redundancy of elements, and various maintenance strategies.

Two different application cases, namely, electric propulsion system for SAR helicopter and diesel-electric propulsion system of icebreaker Arctic LNG tanker, testify to the universality of the proposed MLHRM and appropriate methodology, as well as the possibility of its application for various technical systems.

In further studies, it is advisable to estimate the value of the reliability associated costs, as well as life cycle costs of Arctic LNG tanker for different operational routes by using different maintenance strategies, considering the gradual deterioration of the ship's icebreaking capacity during ice navigation.

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