Chapter

# Reliability-Oriented Design of Vehicle Electric Propulsion System Based on the Multilevel Hierarchical Reliability Model

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

## Abstract

This chapter describes a methodology of evaluation of the various sustainability indicators, such as reliability, availability, fault tolerance, and reliability-associated cost of the electric propulsion systems, based on a multilevel hierarchical reliability model (MLHRM) of the life cycles of electric vehicles. Considering that the vehicle propulsion systems are safety-critical systems, to each of their components, the strict requirements on reliability indices are imposed. The practical application of the proposed technique for reliability-oriented development of the icebreaking ship's electric propulsion system and the results of computation are presented. The opportunities of improvement of reliability and fault tolerance are investigated. The results of the study, allowing creating highly reliable electric vehicles and choosing the most appropriate traction electric drive design, are discussed.

**Keywords:** electric vehicle, reliability-oriented design, fault tolerance, electric propulsion system, multilevel hierarchical reliability model, Markov model

## 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 the electrification of the different types of vehicles: ships, planes, trains, helicopters, busses, 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 in **Figure 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 in **Figure 1**

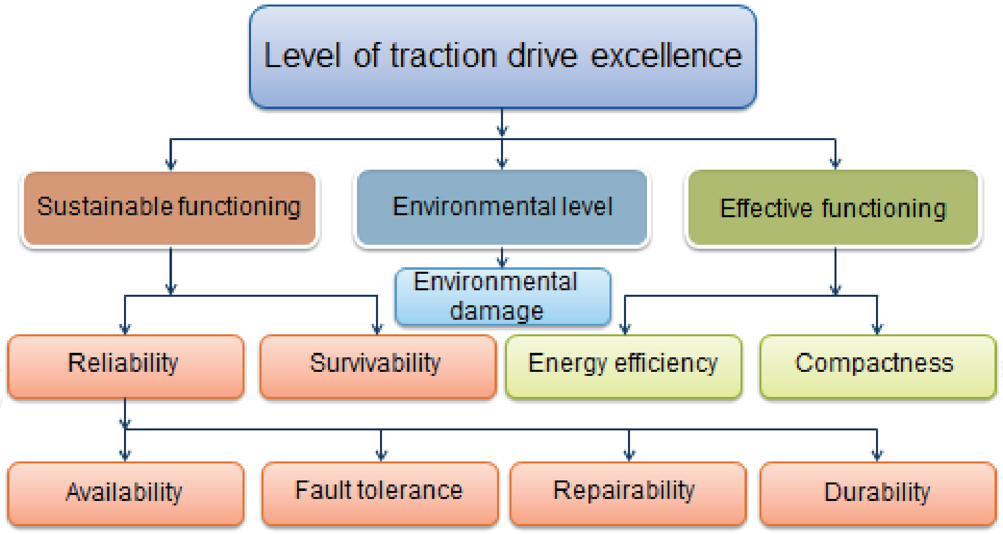


**Figure 1.**
*Structure of the traction drive level of excellence.*

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 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 (MLHRM) 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 combinations of fuzzy theory and AHP, the so-called fuzzy AHP, and analytic network process (ANP) method has been used in [3] for inter-criteria dependency 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 applications. 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) are 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 of [9], the four-level (system, subsystem, assembly, and device-component) representation of variable-speed drive systems is proposed for the analysis of reliability, availability, and maintainability. The calculations were performed analytically and step by step. Bolvashenkov et al. [10] describes the rules and properties of multilevel hierarchical representation of the vehicles' propulsion system 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]. Ref. [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 Refs. [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 effect analysis (FMEA) with weighted risk priority number (RPN), and in the second case [14], it is proposed to do this based on a multistate 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 a 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 the estimation of the 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 component 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 a 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 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 the 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.

The main advantages of the proposed methodology derive from the use of system approach principles for the development of the methodology and the bidirectional principle of the MLHRM functioning. In accordance with the principles of the system approach, the model allows to take into account the horizontal and vertical interaction of components of different levels of the MLHRM, considering the impact of the real operating conditions.

The bidirectional structure of the model functioning allows to solve the problems of reliability and fault tolerance optimization of electric vehicles, both at the stage of designing and in the stage of operation.

### 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 **Figure 2** has six levels, which correspond

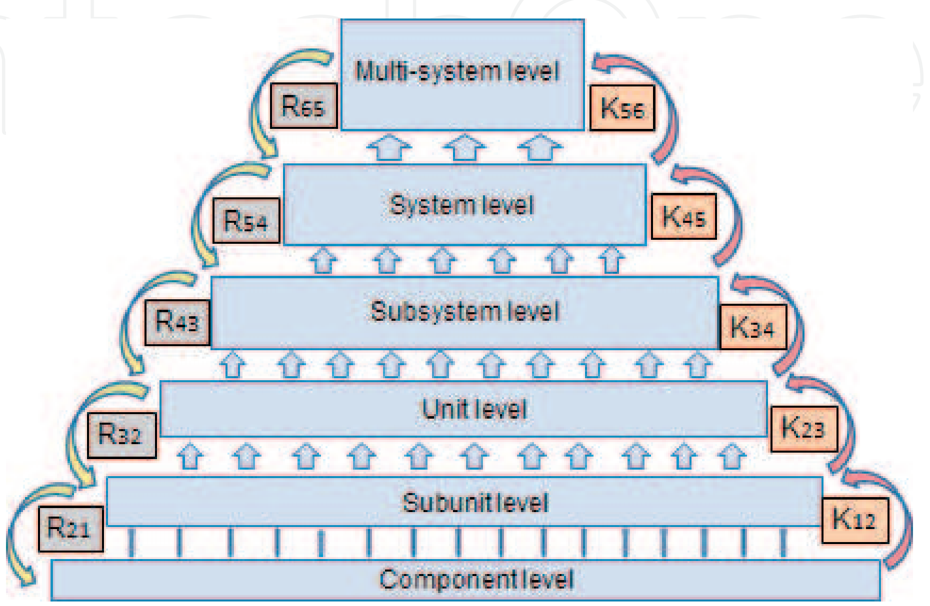


**Figure 2.**
*General structure of the MLHRM.*

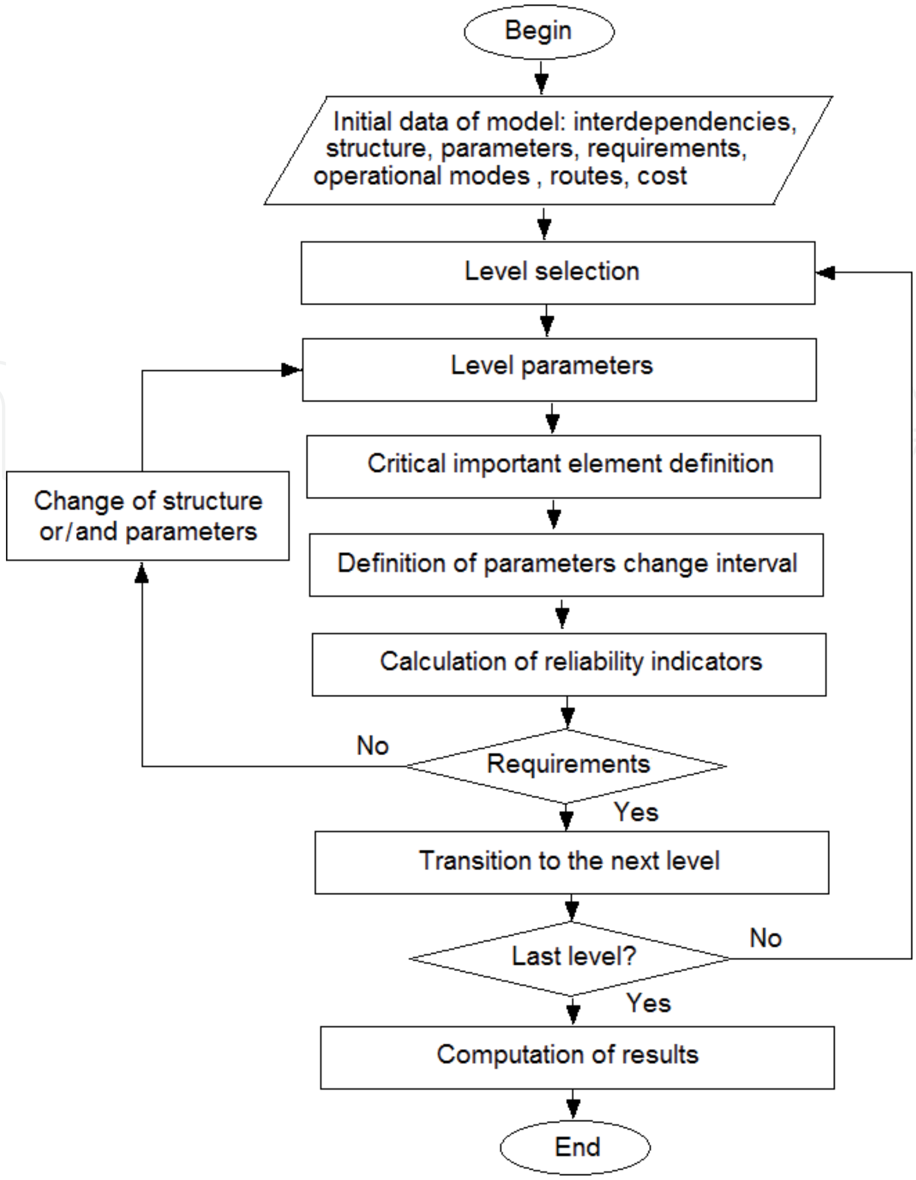


**Figure 3.**
*Algorithm for rapid analysis of the reliability characteristics of a technical system.*

to the task of analyzing and optimizing the reliability characteristics of electric vehicles, taking into account their interaction in random environment.

The coefficients $K_{12}$–$K_{56}$ determine the magnitude of the influence of the reliability of the lower level of the model on the neighboring upper level. The coefficients $R_{21}$–$R_{65}$ determine the ratio of the required values of the performance of the upper level of the model relative to the neighboring lower level.The coefficients $K_{12}$–$K_{56}$ from **Figure 3** can be defined by Eq. (1):

$$K_{n(n+1)} = \sum (Cr_{ni} \cdot P_{ni}), 1 \le n \le 6, 1 \le i \le m_n, \quad (1)$$

where $Cr_{ni}$ is the criticality value of the $i$th element of the $n$th level, $P_{ni}$ is the failure probability of $i$th element of the $n$th level, and $m_n$ is the number of elements of the $n$th level.

The coefficients $R_{21}$–$R_{65}$ can be computed by Eq. (2):

$$R_{(n+1)n} = Y_{(n+1)}/X_n, 1 \le n \le 6, \quad (2)$$

where $Y_{(n+1)}$ is the upper neighboring level performance, $X_n$ is the lower neighboring level performance, and $n$ is the number of level.

The coefficients $R_{21}$–$R_{65}$ are used to calculate the required indicators of various levels of the MLHRM within the design of electric vehicles with the specified reliability and fault tolerance parameters.

The coefficients $K_{12}$–$K_{56}$ are used to improve the reliability indicators of various levels of the model during the operational time of the electric vehicles.

As noted above, the MLHRM shown in **Figure 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 the 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, the 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 vehicle 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 multistate 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 the vehicle's 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 the 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 the present study and, therefore, are not considered in this chapter.Based on the presented MLHRM, an algorithm was developed for the accelerated estimation of the compliance of the propulsion system reliability indicators with the project requirements, which is shown in **Figure 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 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 **Figure 4**, which was previously presented in [19–21] for the main subunits of the traction electric motor: stator windings, power electronics, and bearings.

Depending on the task to be solved and the level of the model, the probability of failure-free operation, availability, degree of fault tolerance, etc. can be considered as indicators of reliability of the components.

In order to meet the requirements of the project on reliability and fault tolerance of electric vehicles, it may be necessary to change the reliability parameters of the components and/or the structure of the electric propulsion system.

The intervals of possible changes in the reliability parameters (failure rate, repair rate) of the propulsive system elements are determined preliminarily based on statistical data on the reliability of each element, given, for example, in the reference literature.

From the results shown in **Figure 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 the MLHRM. In addition, **Figure 5** presents the methods and models recommended in order to assess the reliability indicators of 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

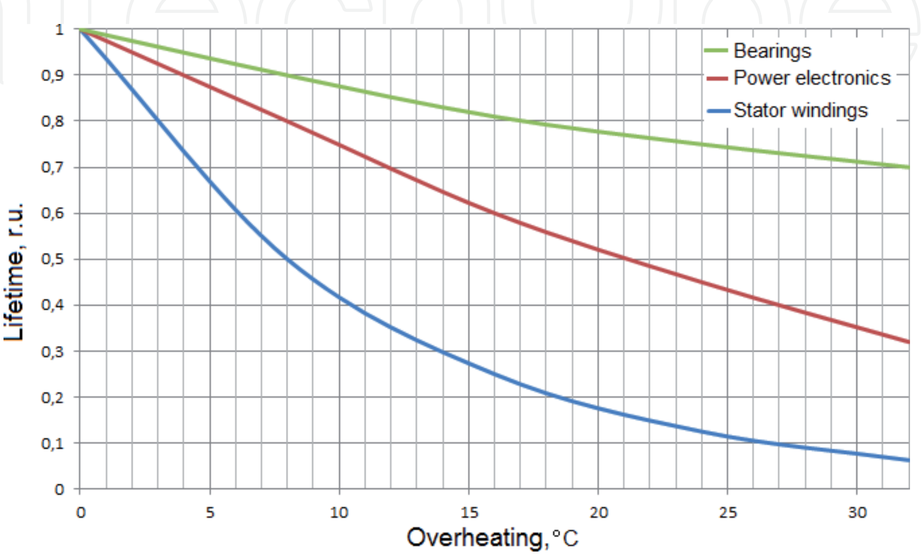


**Figure 4.**
*Critical importance analysis of the subunits [19].*

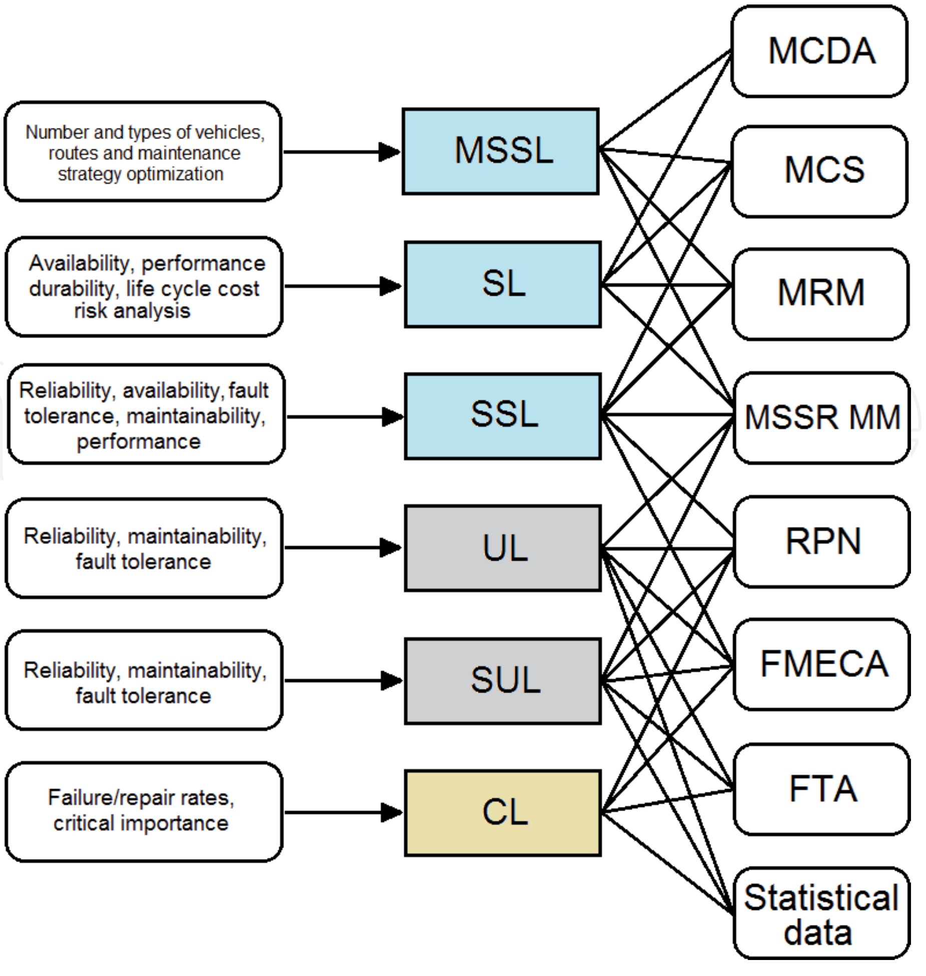


**Figure 5.**
*Tasks and methods of their solutions for different MLHRM levels.*

important components and their degree of influence on the reliability features of the next level—the SUL. The 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 characteristic analysis of electric propulsion systems at CL of the 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 multistate elements (elements with degraded states), the multistate system reliability Markov models (MSSR MM), described in detail 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, multistate 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) has 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 the intensity of the scheduled and unscheduled repairs, and the use of functional systems of monitoring, forecasting reliability, and diagnostics. These may be MSSR MM, MRM, MCS, and multicriteria decision analysis (MCDA). A definition of current and forecasted values of reliability indices are carried out, considering the external and internal operation conditions of the vehicle, as well as taking into account the 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 vehicle operations can be represented by a chain of the lifecycles: operational, nonoperational, working, standing, etc. The data on the 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 case

As an application example of the proposed MLHRM methodology for assessing and optimizing the reliability characteristics of electric traction drives, the propulsion system of icebreaking cargo ship is considered. Functionally, the MLHRM is presented in **Figure 6**. The new Arctic liquefied natural gas (LNG) tanker "Christophe de Margerie," built in 2017 by Daewoo Shipbuilding & Marine Engineering in South Korea, was selected as the research object to investigate the 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].

Reliability indicators of lower levels have been calculated based on statistical data (failure rates, repair rates, etc.), and well-known analytical methods are not included to this chapter, however, are fully presented in [25]. This chapter concentrates on the upper levels, which are more complicated and interesting considering the overall electric vehicle reliability.

As a MSL of the MLHRM in this case, the joint operation of several ships in a caravan with icebreakers, the joint operation of the whole fleet to deliver the similar type of cargo in corresponding directions, the operation of the shipping company, etc. can be considered.

In **Figure 6**, the following notation is used: EES, electric energy source; EC, electric converter; EM, electric motor; CU, control unit; and $\lambda_j$, $\lambda_k$, $\lambda_n$, and $\lambda_m$, 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 the 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 the MLHRM, **Figure 7** shows the most 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 MW, which supply electric energy to a two-section main switchboard.

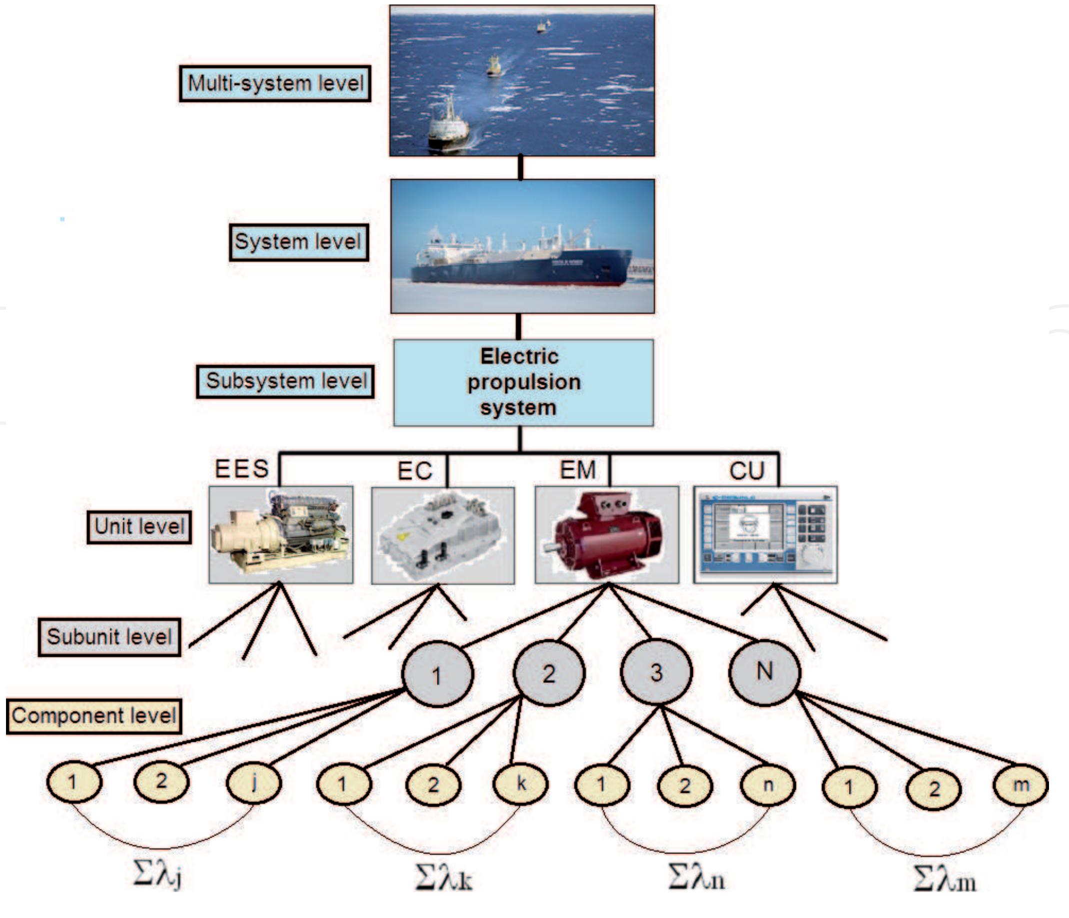


**Figure 6.**
*MLHRM structure of icebreaking cargo ship with electric propulsion.*

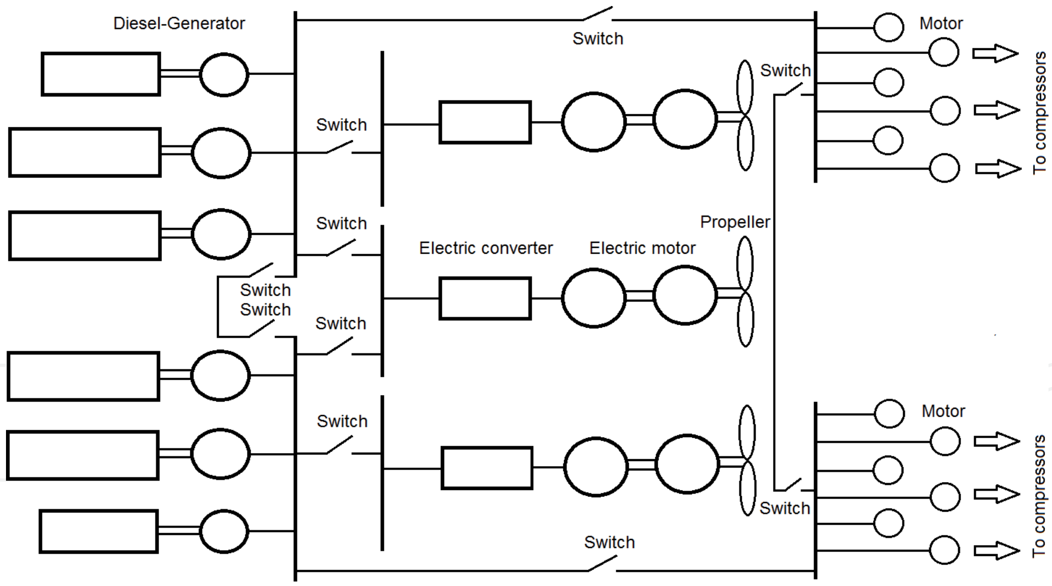


**Figure 7.**
*Structure of the whole power system [25].*

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 of the cargo. 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.

### 3.1 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 **Figure 8**.

Considering the above data in **Figure 8**, generally the reliability of electric motor $\lambda_{EM}$ can be determined by the formula:

$$\lambda_{EM}(t) = \Sigma\lambda_{Si}(t) + \Sigma\lambda_{Rj}(t) + \Sigma\lambda_{Bk}(t), \tag{3}$$

where $\lambda_{Si}$, $\lambda_{Rj}$, and $\lambda_{Bk}$ are the failure rates of parts of all parts of the 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 **Figure 9**.

Based on the above data in **Figure 9**, generally the failure rate of an electric power converter $\lambda_{EI}$ can be estimated considering the reliability values of its components by the equation:

$$\lambda_{EC}(t) = \Sigma\lambda_{Ti}(t) + \Sigma\lambda_{Dj}(t) + \Sigma\lambda_{Ck}(t) + \Sigma\lambda_{Bn}(t), \quad (4)$$

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

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 performed using components and materials with higher reliability values and based on 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.

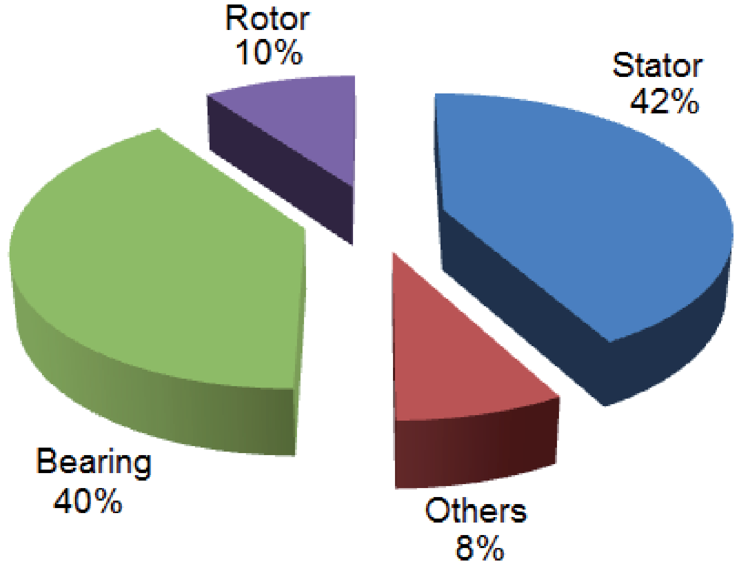


**Figure 8.**
*Failures statistics of traction electric motor [21].*

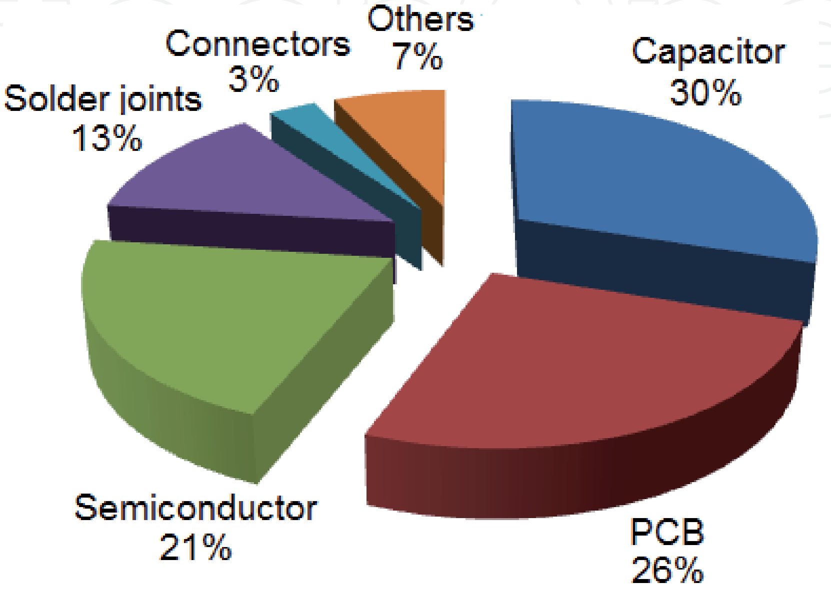


**Figure 9.**
*Failures statistics of electric converter [21].*

### 3.2 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 system presented in **Figure 6**, 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 multiphase 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 of [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.

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 20% cells redundancy. Additionally, in order to improve the fault tolerance of the electric power converter in failure cases, it is proposed to use a multilevel cascaded converter topology. The reliability characteristics of all units, taking into account the specific load conditions and aging processes, are advisable to be computed by means of the MSSR MM, as shown in [20, 21, 23, 24].

### 3.3 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 the 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 for the safety and fault tolerance, can be achieved on 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 the ice conditions, on the SSL, it is necessary to provide the multi-motor electric drives with multiphase electric motors, whose features are discussed in [27, 29].

The most comprehensive investigation of reliability indicators at the SSL is advised to be carried 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 Lz-transform method, described in detail in [20], which drastically simplified the solution of multiple differential equations.

### 3.4 System level

At the SL, the operation of the ship with electric propulsion subsystem as a whole system is considered. 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, the propulsion system of gondola type with two screws, the optimization of the maintenance and repair strategy of the power system of the tanker during navigation, predictive reliability monitoring, and a 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 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 **Figure 10** and they are:

- Loading and unloading of LNG at the terminal. Each of these two modes usually takes about 24 h. The 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 of 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 **Figure 11**.

As a result of calculating the comprehensive reliability indices of each functional block, indicated in **Figure 11**, based on the Lz-transform method [25, 29] to solve the system of differential equations of MSSR MM, a schedule of operational availability of the power system of LNG tanker for different demands was constructed, which is presented in **Figure 12**.

The graph in **Figure 12** demonstrates the ability of the tanker's power system to ensure sustainable functioning under the conditions of various operational

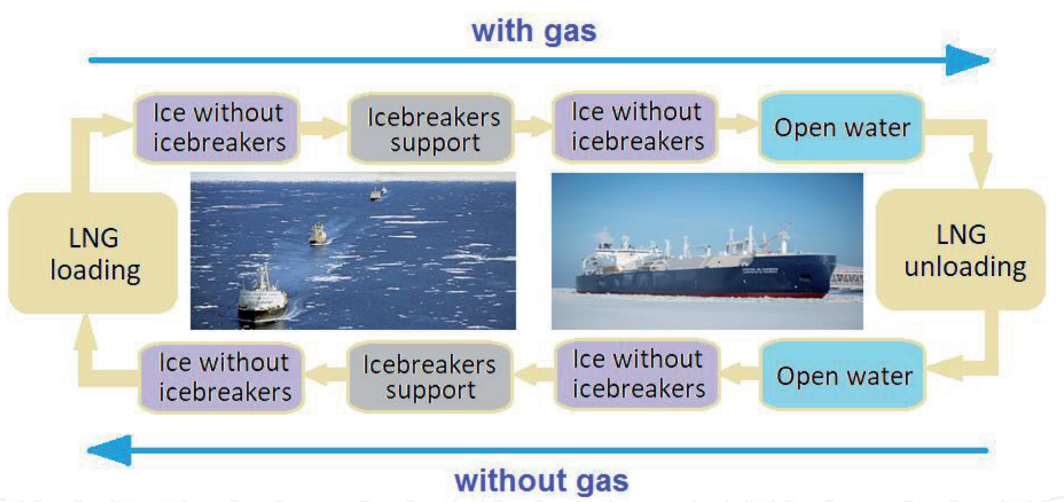


**Figure 10.**
*Operational modes of icebreaker LNG tanker.*

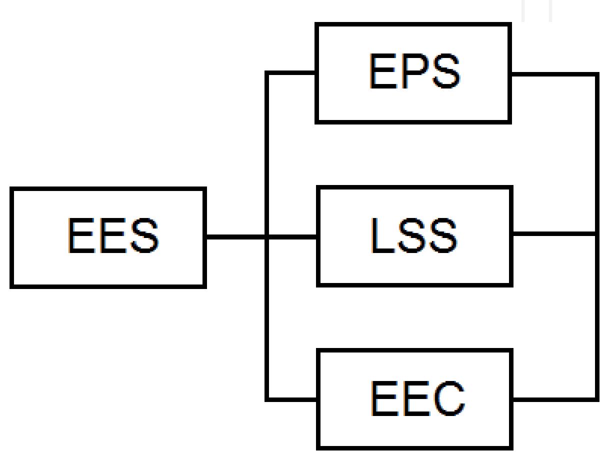


**Figure 11.**
*Structure of the hybrid-electric power system of LNG tanker.*

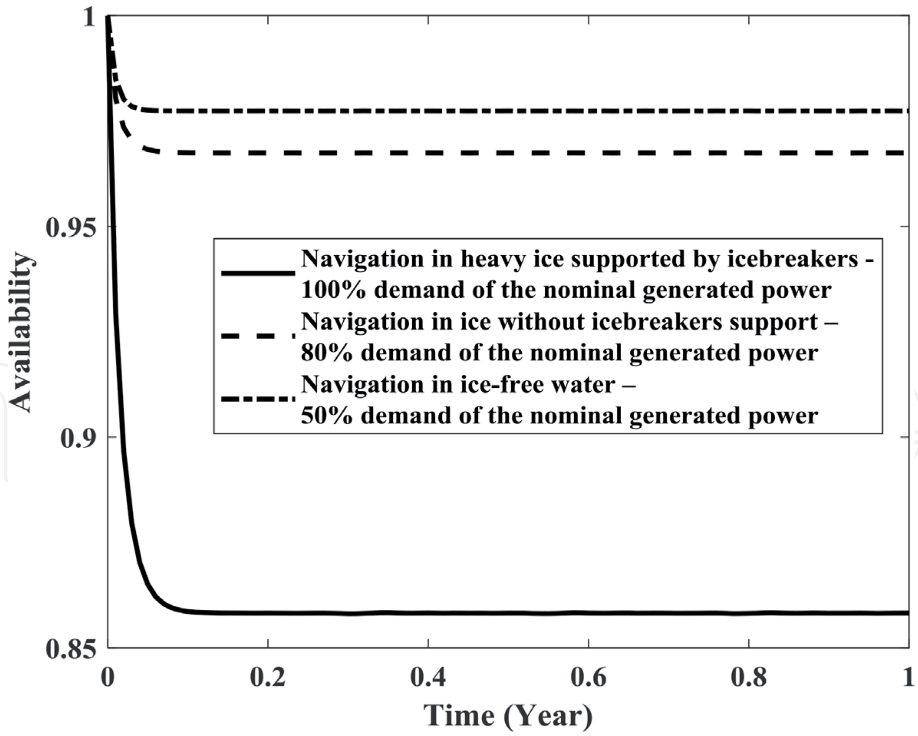


**Figure 12.**
*Operational availability of the power system of LNG tanker for different demands [25].*

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 in **Figure 12**, the Arctic LNG tanker has high operational availability for the maximum levels of demand. Its value is equal to 85.82%. This indicates that such multi-drive propulsion system is closely related to the conditions of ice navigation.

## 4. Conclusions

The chapter proposed MLHRM and methodology of its application will allow to realize the comprehensive analysis an estimation of comprehensive reliability characteristics of the vehicle electric propulsion systems at the design stage. This 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 the 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 a whole, it is possible to use systems of diagnostics, fault detection, monitoring, fault prediction, varying degrees of redundancy of elements, and various maintenance strategies.

As the application case, the new Arctic LNG tanker "Christophe de Margerie" is used to assess the value of the operational availability of the integrated electric power system during the summer-autumn period along the Northern Sea Route. The results of the research showed that regarding the sustainable operation during

Arctic navigation of the icebreaking LNG tanker, the electric propulsion system has a significant potential to improve operational availability, technical performance, and consequently economic efficiency.

For 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.

## Author details

Igor Bolvashenkov[1]*, Jörg Kammermann[1], Ilia Frenkel[2] and Hans-Georg Herzog[1]

1 Institute of Energy Conversion Technology, Technical University of Munich (TUM), Munich, Germany

2 Center for Reliability and Risk Management, SCE, Beer Sheva, Israel

*Address all correspondence to: igor.bolvashenkov@tum.de

## References


[1] Bani-Mustafa T, Pedroni N, Zio E, Vasseur D, Beaudouin FA. Hierarchical tree-based decision making approach for assessing the trustworthiness of risk assessment models. In: Proceedings of the International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA'17); 24th–28th September 2017; Pittsburgh, PA. 2017. pp. 314-323

[2] Saaty TL. Decision making with the analytic hierarchy process. International Journal of Services Sciences (IJSSci), Inderscience Publishers. 2008;**1**(1):83-98

[3] Ziemba P. Inter-criteria dependencies-based decision support in the sustainable wind energy management. Energies. 2019;**12**:749

[4] Ganji SRS, Rassafi AA, Kordani AA. Vehicle safety analysis based on a hybrid approach integrating DEMATEL, ANP and ER. KSCE Journal of Civil Engineering. 2018;**22**(11):4580-4592

[5] Brown RE, Gupta S, Christie RD, Venkata SS, Fletcher R. Distribution system reliability assessment using hierarchical Markov modeling. IEEE Transactions on Power Delivery. 1996;**11**(4):1929-1934

[6] Ataie E, Entezari-Maleki R, Rashidi L, Trivedi KS, Ardagna D, Movaghar A. Hierarchical stochastic models for performance, availability, and power consumption analysis of IaaS clouds. IEEE Transactions on Cloud Computing. 2019;**7**(4):1-18

[7] Nam T, Mavris DN. Multistage reliability-based design optimization and application to aircraft conceptual design. Journal of Aircraft, Georgia Institute of Technology, Atlanta, Georgia. 2018;**55**(5):1-15

[8] Paulson EJ, Starkey RP. Development of a multistage reliability-based design optimization method. Journal of Mechanical Design. 2013;**136**(1):1-8

[9] Wikström P, Terens LA, Kobi H. Reliability, availability, and maintainability of high-power variable-speed drive systems. IEEE Transactions on Industry Applications. 2000;**36**(1):231-241

[10] Bolvashenkov I, Kammermann J, Herzog H-G. Research on reliability and fault tolerance of multi-phase traction electric motors based on Markov models for multi-state systems. In: Proceedings of 23rd International IEEE Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM); 22th–24th June 2016; Anacapri, Italy. pp. 1-6

[11] Linkov I, Fox-Lent C, Read L, et al. Tiered approach to resilience assessment. Journal Risk Analysis. USA. 2018;**38**(4):1-9. DOI: 10.1111/risa.12991

[12] Woo S, O'Neal DL. Reliability design and case study of mechanical system like a hinge kit system in refrigerator subjected to repetitive stresses. Engineering Failure Analysis. 2019;**99**:319-329

[13] Xiao N, Huang N-Z, Li Y, He L, Jin T. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. Engineering Failure Analysis. 2011;**18**:1162-1170

[14] Ding Y, Lin Y, Peng R, Zuo MJ. Approximate reliability evaluation of large-scale multistate series-parallel systems. IEEE Transactions on Reliability. 2019;**68**(2):1-15

[15] Xuy X, Liz Z, Chen N. A hierarchical model for lithium-ion battery degradation prediction. IEEE Transactions on Reliability. 2016;**65**(1):310-325

[16] Abbas M, Vachtsevanos GJA. System-level approach to fault progression analysis in complex engineering systems. In: Proceedings of Annual Conference of the Prognostics and Health Management Society; September 27-October 1 2009; San Diego, CA. 2009. pp. 1-7

[17] Gomes JPP, Rodrigues LR, Galvão RKH, Yoneyama T. System level RUL estimation for multiple-component systems. In: Proceedings of Annual Conference of the Prognostics and Health Management Society; 14th–17th October 2013; New Orleans, LA, USA. 2013. pp. 1-9

[18] Rodrigues LR. Remaining useful life prediction for multiple-component systems based on a system-level performance indicator. IEEE/ASME Transactions on Mechatronics. 2018;**23**(1):1-10

[19] Bolvashenkov I, Kammermann J, Willerich S, Herzog H-G. Comparative study of reliability and fault tolerance of multi-phase permanent magnet synchronous motors for safety-critical drive trains. In: Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'16); 4th–6th May; Madrid, Spain. 2016. pp. 1-6

[20] Bolvashenkov I, Herzog H-G, Frenkel I, Khvatskin L, Lisnianski A. Safety-Critical Electrical Drives: Topologies, Reliability, Performance. Switzerland: Springer; 2018

[21] Bolvashenkov I, Kammermann J, Willerich S, Herzog H-G. Comparative study for the optimal choice of electric traction motors for a helicopter drive train. In: Proceedings of the 10th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES'15); 27th Sept.–3rd Oct. 2015; Dubrovnik, Croatia. 2015. pp. 1-15

[22] Kammermann J, Bolvashenkov I, Herzog H-G. Reliability of induction machines: Statistics, tendencies, and perspectives. In: Proceedings of 26th IEEE International Symposium on Industrial Electronics (ISIE); 19th–21th June 2017; Edinburgh, UK. 2017. pp. 1843-1847

[23] Bolvashenkov I, Frenkel I, Kammermann J, Herzog HG. Comparison of the battery energy storage and fuel cell energy source for the safety-critical drives considering reliability and fault tolerance. In: Proceedings of IEEE International Conference on Information and Digital Technologies (IDT); 5th–7th July 2017; Žilina, Slovakia. pp. 63-70

[24] Bolvashenkov I, Kammermann J, Herzog H-G. Methodology for determining the transition probabilities for multi-state system markov models of fault tolerant electric vehicles. In: Proceedings of the Asian IEEE Conference on Energy, Power and Transportation Electrification; 25th–27th October 2016; Singapore. pp. 1-6

[25] Bolvashenkov I, Kammermann J, Herzog HG, Frenkel I. Operational availability and performance analysis of the multi-drive multi-motor electric propulsion system of an icebreaker gas tanker for arctic. In: Proceedings of IEEE 14th International Conference on Ecological Vehicles and Renewable Energies (EVER'19); 8th–10th Mai 2019; Monaco. 2019. pp. 1-6

[26] Bolvashenkov I, Kammermann J, Herzog H-G, Frenkel I, Ikar E, Khvatskin L. Investigation of reliability and fault tolerance of multiphase traction electric motor supplied with multi power source based on Lz-transform. In: Proceedings of IEEE International Conference on System Reliability and Safety (ICSRS'17); 20th–22th December 2017; Milano, Italy. 2017. pp. 303-309

[27] Bolvashenkov I, Herzog H-G. Use of stochastic models for operational efficiency analysis of multi power source traction drives. In: Proceedings of the Second IEEE International Symposium on Stochastic Models in Reliability Engineering, Life Science and Operations Management, (SMRLO); 15th–18th February 2016; Beer Sheva, Israel. pp. 124-130

[28] Frenkel I, Bolvashenkov I, Herzog H-G, Khvatskin L. Operational Sustainability Assessment of Multi Power Source Traction Drive. Mathematics Applied to Engineering. London, UK: Elsevier; 2017. pp. 191-203

[29] Bolvashenkov I, Kammermann J, Herzog H-G, Frenkel I. Fault tolerance assessment of multi-motor electrical drives with multi-phase traction motors based on LZ-transform. In: Proceedings of IEEE 14th International Conference on Ecological Vehicles and Renewable Energies (EVER'19); 8th–10th Mai 2019; Monaco. 2019. pp. 1-6