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Review

Review Models and Methods for Determining and Predicting the Reliability of Technical Systems and Transport

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Abstract: Modern power and transportation systems are subject to high requirements for reliability and performance in performing their specified functions. At the same time, these requirements are constantly increasing with the increasing complexity of technology and the introduction of electronics and computer technology into its structure. This is fully applicable to energy and transportation infrastructure, including electric vehicles. The complexity of the systems and increasing requirements for them have led to the fact that the problem of increasing their operational reliability has acquired great importance. The article presents a review of methods and justification of ensuring a high level of reliability and serviceability of technical systems as one of the most important tasks in the creation and operation of complex systems, such as modern energy and transportation systems. It is shown that a significant reserve in solving the problem of increasing the reliability and performance of technical systems is the information on failures and malfunctions of these systems obtained from the field of operation. The methodology of collection and processing of statistical information on failures of vehicles described by different distribution laws is outlined.

Keywords: technical reliability; reliability models service life prediction; quality energy systems; electric vehicles; transportation

MSC: 65C20

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1. Introduction

An independent scientific direction reliability theory [1] originated in the United States a few years after the end of World War II, when the Americans began military operations in Korea, far from stationary bases, where it would be possible to repair or replace the failed military equipment. To address the reliability problem, the USA Institute of Radio Engineers (IRE) created the Reliability and Quality Control Section, which began to publish quarterly journals and, beginning in 1954, convened annual reliability symposiums.

In the 1960s, two books were published almost simultaneously in the USSR and the USA, which laid the theoretical foundation for reliability analysis, "Mathematical Methods in Reliability Theory" and "Mathematical Theory of Reliability".

Modern technical systems are subject to high requirements for reliability and operability in performing their assigned functions. At the same time, with the complication of technology, the introduction of electronics and computer technology in its structure, these requirements are constantly increasing [2–4]. This fully applies to technical systems and transport. The increasing complexity of systems and the increasing requirements for them have led to the fact that the problem of increasing their operational reliability has become of great importance. A technical system that does not meet the high requirements for reliability, and the level of consumer properties, has no prospects in conditions of fierce competition of similar products [5,6]. Unreliable transport cannot function effectively, because each of its failures entails significant material losses, and often leads to road accidents [7,8].

The priority importance of vehicle reliability is confirmed by statistical data showing that the cost of maintaining them in good working order is constantly growing [9,10]. Total annual losses associated with the maintenance and repair of machinery for various purposes during the period of operation exceed their original cost by several times. In order to avoid failures, it is crucial to possess knowledge about the reasons behind their occurrence and manifestation, the patterns that dictate the changes in the technical condition of the object, and the influence they exert on its overall performance [11–13].

Basically, if no violations of design and operating standards or unfavorable effects of random external factors are not taken into account, the vast majority of objects reach the limit state due to wear or fatigue failure of structural elements. In this regard, the identification of physical processes of wear and fatigue failure, the establishment of dependences of physical and mechanical properties of the surface layer of the part on the mode of its operation, environmental factors allow the controlling of these processes, to reduce their intensity [14–16].

The solution to the problem of improving the reliability of technical systems should be based on reliable information on their failures and malfunctions, actual resources, labor intensity of maintenance and repair, as well as factors affecting these indicators in real operating conditions [17]. The most objective and exhaustive information about the reliability of technical systems gives operational tests, which are carried out in typical operating conditions of enterprises. Processing and analysis of such information make it possible to evaluate the level of actual reliability of a particular model of transport, unit, assembly [18], component, identify weak points in the design, develop specific measures to improve operational reliability. Maintaining transport systems in an operable state is provided by the maintenance system, which includes a set of control, diagnostic and preventive measures, the implementation of which allows for minimizing the probability of failures in operation. An important element of this system is technical diagnostics, which provides individual information about the technical condition of the system as a whole and its individual elements. Technical diagnostics as a scientific direction is directly connected with the theory of reliability. It substantiates methods and means of periodic checks of reliability and operability of transport, assesses compliance of parameters of technical condition with their normative values, reveals the need for necessary maintenance and repair operations. Diagnosis is a qualitatively better form of control works, because it allows to determine the technical condition of complex objects without disassembly and to predict the reserve of its serviceable operation (residual life). Prediction of individual residual resource of an object allows not only to prevent its possible failures, but also to plan operation modes and preventive measures more soundly. Therefore, prediction of residual life can be considered as one of the important elements of operation and maintenance management system [19,20].

Modern industry is widely evolving in the creation of new technologies, new element bases, increasing the complexity of circuits used in production. Such a leap allows the development of more complex devices that meet many promising trends and decisions of designers and planners. Such newly created devices must meet a large number of requirements, among which we can highlight reliability [11–24]. Because of the complexity of the execution of devices and the large number of tasks performed, high reliability requirements are imposed on the hardware. In practice, enterprises use several different techniques, among which it is possible to distinguish:

- reliability tests;
- simulation modeling;
- reliability assessment based on the calculation of failure rates.

Reliability testing serves as a means to evaluate the reliability of a device under specific test conditions, and it is considered one of the methods used to obtain reliability assessments. These tests are conducted on a batch of products, from which a sample is selected for evaluation. The primary objectives of these tests include:

- reliability tests with a given sample size;
- reliability tests by single-sample and double-sample methods.

Tests by the sequential method. According to the purpose of the tests are divided into definitive and control tests. Conducting defining tests is necessary to find reliability indicators. Such as:

- average operating time to failure;
- probability of failure-free operation;
- average MTBF.

Control tests are necessary to determine whether a batch of products meets the specified reliability or not.

In addition, there are special reliability tests:

- lifetime tests;
- accelerated lifetime tests;
- tests for destruction under the influence of external factors.

The measure of the error is the confidence interval, given by the confidence limits, which can be obtained by knowing the mathematical model of the probability distribution of failures [25]. As a rule, the mathematical model is initially unknown. Therefore, test results are compared with known types of distributions. Test results are considered to be more accurate than operational results [26]. However, reliability estimation based on test results has a number of significant drawbacks: Tests are rather financially expensive and also require a lot of time. A part of the resource of products is spent during the tests. The results are not always reliable. That is why analytical methods of reliability evaluation are more often used in practice. For instance, simulation modeling. Simulation modeling is a kind of mathematical modeling. Its essence is in the analysis of a real device operation by means of an experiment imitating this device operation. Such simulation is a numerical method for calculating the characteristics of a device. Simulation modeling has its own specifics: such modeling is used in cases where it is difficult to describe the operation of a device by means of a mathematical model, that is, it is impossible to predict the result of its operation. To describe a formal model, an approximation of functional dependencies is used, and if this is not possible, then the algorithm of device operation [26]. As a rule, the stages of device operation are described in probabilistic terms. Another peculiarity of simulation modeling is that it takes into account the maintenance element of the device. The process of conducting reliability research through simulation modeling follows the following sequential steps:

The problem with this methodology is its complexity and resource consumption. That is why it is used only when it is difficult or impossible to get an analytical solution. That is why the most used method of reliability assessment in production is the calculation of failure rates.

This review aims to consider mathematical models and methods of reliability analysis of complex technical systems. The experience gained by the authors in the course of source analysis shows that there is a recognized order and composition of the stages of reliability analysis design. These are the determination of the system structure and calculation of reliability and serviceability characteristics of its elements; analysis of types and consequences of failures (most often at the level of typical replacement elements); reliability analysis at the system level, taking into account different types of redundancy, specifics of functioning, maintenance and repairs. A characteristic feature of performing design research in this area is the use of specialized reliability analysis software. Commercial level reliability analysis software (Windchill Quality Solutions 10.0, Isograph 7.0, RAM Commander 8.5), contains a standard set of modules, supporting the project analysis of systems. The techniques utilized in reliability research encompass various tools such as reliability block diagrams, fault trees/event trees, and the Markov models.

In accordance with this division, the review presents the structure of technical reliability of complex systems:

1. General studies in mathematical modeling of reliability.
2. Models for reliability analysis of redundant series-parallel and bridge systems using basic formulas of event probability theory.
3. Logical and probabilistic methods of reliability analysis.
4. Apparatuses of fault trees, event trees, including examples of fault trees for monotonic and non-monotonic systems, the use of binary decision diagrams in software implementation of fault trees and a critical review of common cause failure models.
5. Markov modeling of the reliable behavior of systems.
6. Modern apparatus of reliability analysis of complex systems, based on aggregation of logical and probabilistic reliability models, including dynamic failure trees.
7. Qualitative and quantitative analysis of failure types and consequences.

The structure of the research methods adopted in this article is presented in Figure 1.

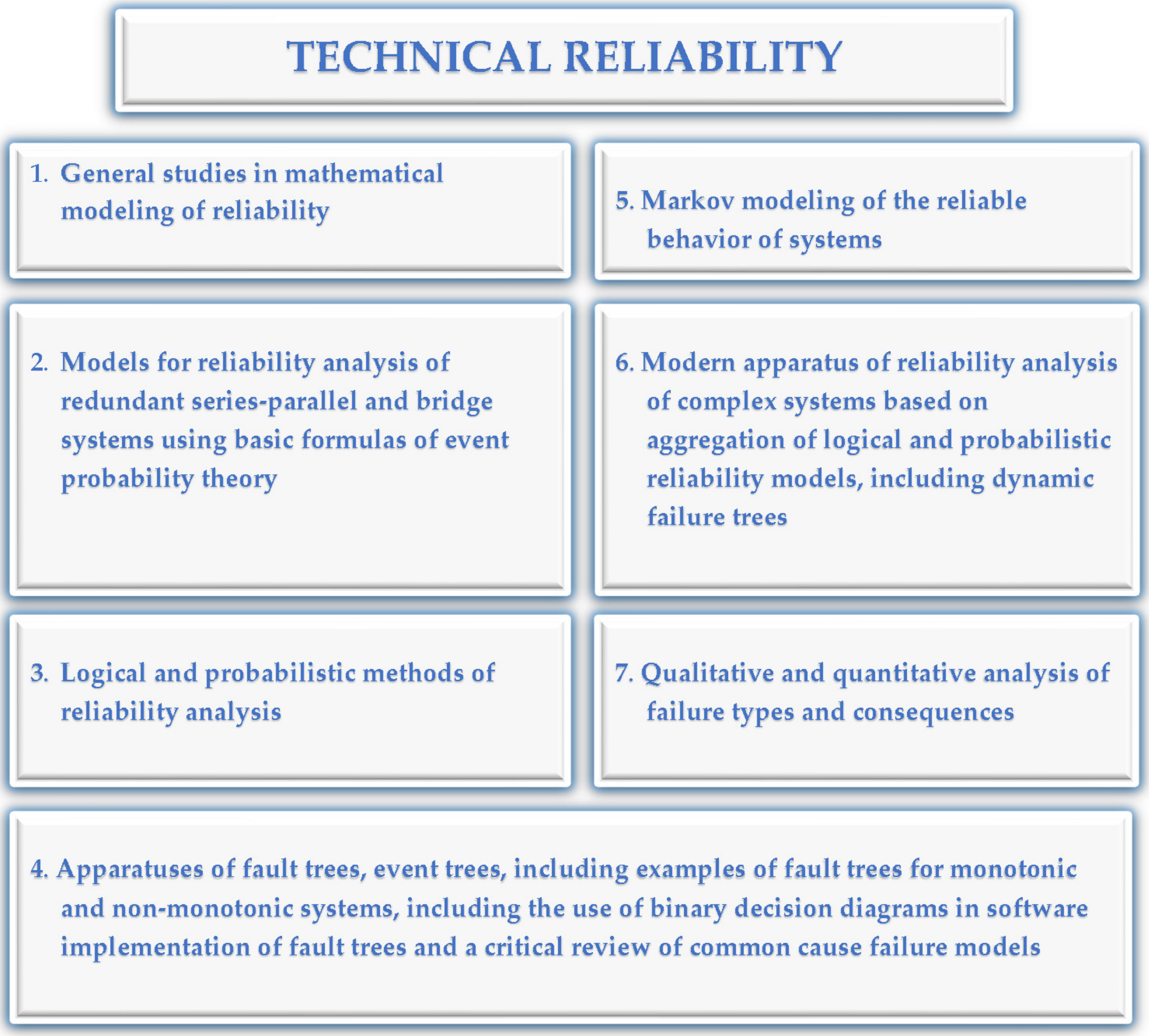

Figure 1. The structure of technical reliability research methods adopted in this article.

The purpose of this review is to help create adequate reliability analysis models for the systems under study. With the help of the data presented in the review, it is possible to set the parameters of reliability analysis models correctly and to interpret the obtained results correctly.

2. Scientific Aspects of the Development of Technical Reliability Models

Leading to the scientific aspects of the development of models of technical reliability [26], according to the authors, mathematical models of reliability can be divided into two groups:

1. Structural models. They are based on logical schemes of interaction of elements included in the system, from the point of view of preserving the performance of the system as a whole. They use static information about the reliability of elements without involving information about the physical properties of the material, parts and connections, external loads and impacts, about the mechanisms of interaction between the elements. Structural models are presented in the form of block diagrams and graphs (e.g., failure trees, event trees), and initial information is presented in the form of known values of probability of failure-free operation of elements, failure rates, etc.
2. Mathematical models of reliability theory that take into account mechanical, physical and other real processes that lead to changes in the properties of the object and its components. Such are the models of mechanics, widely used in calculations of machines and structures. Force and kinematic interaction of machine elements and structures is complex. The behavior of these objects essentially depends on their interaction with the environment, and on the nature and intensity of operation processes.

To predict the behavior of parts and machine elements it is necessary to consider the processes of loading, deformation, wear, accumulation of damage and destruction under variable loads, temperature and other external influences. It is possible to estimate reliability indices of systems by a calculation-theoretical method based on physical models and static data concerning properties of materials, loads and impacts.

Mathematical modeling of most technical (objects) systems can be performed: at the micro level; macro level; meta level.

At the micro-level, the mathematical model of a technical system is a system of levels describing processes and phenomena in materials and media with specified boundary conditions. The system of equations itself is usually known (equations for loading of a thick-walled vessel), but its exact solution can be obtained only for some special cases, so the task arising in modeling is to build an approximate discrete model, at that, we have to make a number of assumptions and simplifications when modeling rather complex technical objects and proceed to modeling at the macro level.

The mathematical models at the macro level are based on component equations of individual elements and topological equations, the form of which is determined by the links between the element and the technical system. Formal methods are used to obtain topological equations: generalized, tabular, nodal, and state variables.

At the meta-level, mainly technical objects that are the subject of research of automatic control theory and objects that are the subject of mass service theory are modeled. Macro-level mathematical apparatus can be used for the first category, while event modeling techniques are used for the second category of objects.

Although mathematical models of reliability are a significant idealization of the laws of functioning of technical objects (systems), they allow in a probabilistic form to predict the behavior of objects in real conditions of functioning and to estimate many quantitative characteristics of reliability. At that, the degree of idealization is mainly determined by the requirement of simplicity of the models used. Complex reliability models may require a very large sample volume for estimating their parameters in experimental studies, as a result of which the use of such models becomes technically and economically unprofitable (meaningless). Mathematical models of element reliability used in practice are, as a rule, simple distribution laws that are expressed by elementary functions or their integrals, which represent reliability laws.

Reliability indicators are some functions of the parameters of the mathematical model. Reliability models of technical systems are also complex functional dependencies that take into account failure patterns of elements and system structure.

Thus, we can consider that the system reliability model is a mathematical model that establishes the relationship between the reliability indicators of the system, reliability characteristics of the elements, its structure and parameters of its functioning process. In addition, the failure model is a mathematical description of physical and (or) chemical processes that constitute the failure mechanism.

Models, the construction of which will reveal the processes of failure distribution and make it possible to assess the reliability of systems at the stage of design, operation, should take into account the degree of danger, that is, the possibility of comparison with the norms of reliability.

One classification of reliability models includes models for gradual and sudden failures for non-recoverable and recoverable single-use and reusable systems, i.e., two groups of reliability models are distinguished:

- reliability models that take into account gradual failures. In these models, the occurrence of various damage processes leads to a change in time of the failure parameter. Usually, it is possible to limit ourselves to 1–2 parameters. A characteristic example of gradual failures are cases of wear and aging impact on the state of operability;
- reliability models that take into account sudden failures. The reason for the occurrence of sudden failures is not related to the change in the state of systems during the period of its previous operation or storage, but depends on the level of external influences, is associated with an unfavorable combination of external factors, that is, the construction of models is associated with the operating conditions of the system, modes of operation, with the probability of extreme loads.

In the model of system reliability only those properties or characteristics of elements and only those their mutual relations in the system, which are essential from the position of reliability, are reflected. Models of system reliability are subdivided into parametric models and models in terms of element failures. Parametric models of reliability (as a rule characteristic for simple systems) are built on the representation of output characteristics in the form of function of random parameters of elements (parameters as random functions of time). The system is considered not to have failed if its output parameters are within specified limits during a given time. Models in terms of element failures are basic in the study of the reliability of complex systems. The model reflects, with a clear definition of the concept of failure for all elements of the system, the impact of failures of system elements on the reliability of the system.

After the analysis, the authors came to the conclusions that according to the principles of construction of models can be divided into:

- Analytical (for simple tasks of determining dependencies between system parameters and reliability indicators);
- statistical (in case of interaction of a large number of factors, when solving complex problems);
- combined (analytical models for parts of the problem and statistical models of the problem as a whole).
- Reliability models of elements by the degree of detailing of factors accounting are subdivided into:
- models of “load-durability” type (thermal, mechanical, electrical, radiation, etc. are considered as loads);
- models of “time distribution” type.

According to the authors, out of the set of laws of distribution of random variables developed in the probability theory, five laws are of the greatest importance for the reliability theory: exponential, normal, Weibull, Poisson and binomial. Combinations of these laws are used to describe complex multifunctional systems.

Exponential distribution (for continuous random variables). It is one of the simplest and most convenient distribution laws for analyzing the reliability of complex multi-element technical systems when evaluating their operation at small time intervals comparable to the time of task execution, and when each activation of the system is preceded by strictly regulated maintenance.

Normal distribution (Gauss law). The law occupies an exceptional place in reliability theory:

- As a means of describing random wear and aging events for small element simple systems;
- it is a limit to which other laws approach when the number of tests tends to infinity;
- independent random variables obey it, the sum of which is greater, the more accurately obeying the normal law.

Weibull distribution (for continuous random variables). The Weibull distribution was obtained experimentally. It can be used to describe the failure-free operation of objects during all three typical periods of operation: run-in, steady-state operation and aging. It is used to study the distribution of resources and service life. The Weibull distribution as a special case at $t = 1$ includes exponential, Rayleigh, and near-normal distributions.

Poisson distribution (for discrete random variables). This distribution is used in reliability theory when the occurrence of some discrete number of identical events is of interest. The occurrence of each event (failure) corresponds to some point on the time scale.

The binomial distribution is the Bernoulli distribution (for discrete random variables). It is often used to determine the probability of discrete random variables, positive and integer, such random events as the total number of failures in a sequence of n trials.

The binomial distribution is used in statistical quality control of a sample of products (not more than 10% of the entire batch) or in determining the number of failures of non-repairable products within a given time during testing. At very small values of q (failures) the binomial distribution can be replaced by the Poisson distribution ($nq < 0.2$), and at large values ($nq > 20$)—by the normal distribution, where n is the number of tests.

Thus, depending on the availability of statistical information on product failures in reliability theory, either theoretical or statistical descriptive models are used (e.g., in the form of histograms), which are built on the basis of a mathematical description of the true mechanisms, processes affecting failure. Theoretical models allow us to describe the phenomena in the whole range of its possible development and to study the behavior of the system in conditions in which experiments have not yet been set. Theoretical models, therefore, can be referred to as predictive models.

In order to make a reasonable choice of the type of theoretical distribution of MTBF, it is advisable to use statistical information on failures. The selected theoretical distribution of operating time should correspond to a certain model of the product approaching failure. Detection of such correspondence depends on the type and purpose of the investigated products.

When analyzing the algorithms of technical reliability models, the authors of the paper distinguish four basic blocks that stand on the basis of the model of technical and technological processes control on the basis of the theory of reliability of technical systems.

1. Development of models and methods of systems reliability analysis. Reliability analysis models can be categorized into two main classes: dynamic models, which account for events and failures as evolving processes over time, and static models, where the system states are determined by the operational and non-operational elements at a specific time, denoted as t. Dynamic models apply:
    - modeling of systems by Markovian, semi-Markovian processes [1,6–13];

- methods of the theory of restoration, semi-Markov and regenerating processes (mainly, asymptotic results are used either for the system as a whole or for individual redundant links) [1,6,14–17];
- statistical simulation modeling (Monte Carlo) [12,16,18–21];

In the framework of static models, reliability analysis is carried out by the following methods:

- method using basic formulas of probability theory (probability of sum and product of events, full probability formula) and combinatorics; applied mainly to series-parallel, parallel-sequential structural reliability schemes and schemes m of n [7,9,11];
- methods based on recording logical conditions, functions of interest to the researcher through the states of system elements with subsequent application of logic algebra theory (logic and probabilistic methods used in failure trees, functional integrity schemes, reliability block diagrams) [22–30]

2. Preparation of initial data for system reliability models:
   - reliability prediction, which includes calculation of element base reliability based on the physics of element failures and statistical tests [31–40];
   - prediction of maintainability, i.e., determination of average restoration times for standard maintenance and repair operations [41];
   - analysis of types, consequences and criticality of failures, in the course of which possible types of failures of elements, their frequency characteristics, the degree of influence of these failures on the system as a whole are revealed [42,43].
3. System reliability management on the basis of testing and operation [44–48]:
   - development of methods and organization of determining and control reliability tests;
   - conducting tests in order to test the proposed methods;
   - organization of accelerated reliability tests;
   - statistical analysis of the distribution functions of operating time to failure and recovery time;
   - statistical evaluation of reliability indicators based on the results of testing and operation with subsequent adjustment of design solutions;
   - justification and adjustment of terms and volumes of maintenance, number of spare parts and service personnel.
4. Automation of reliability analysis: The task of adequate modeling of reliability of complex structure systems can be solved only with the help of automation, moreover, the software for reliability analysis must include the whole set of methods of both static and dynamic models, support for fault tolerance forecasting, serviceability, analysis of failure types and consequences.

Isograph (England, USA), ITEM iQRAS (England, USA), RAM Commander (Israel), and Windchill Quality Solutions (Relex) (USA) are among the leading software products utilized in the realm of reliability analysis. These are integrated software tools that include various methods of analysis, implement various forms of model setting (graphs, failure trees, event trees, reliability flowcharts), contain extensive databases of initial data, have a developed graphical user interface, are exhaustively documented, have both local and network configurations, are interfaced by import-export with databases, text editors, spreadsheets, logistics software, SAPE [30,49–56].

Another set of frequently used software tools for reliability and safety analysis are ARBITR (PC ACM SZMA)—software package for automated structural simulation and calculation of reliability and safety of systems; Automated System for Reliability Calculation (ASRN-2000, 2002), implementing the standardized reliability models of radio electronic element base; ASONIKA-K—software for reliability calculation on the basis of statistical simulation methods, also containing the reliability models of radioelectronic element base;

UNIVERSAL—software for calculations of reliability and functional safety of technical devices and systems (Russia, VNII UP of the Russian Ministry of Railways).

Approaches to Ensuring Reliability and Technical Efficiency of Designed Systems

The modern period of technological development is characterized by the development and implementation of complex technical systems and complexes. Currently, fully automated technological complexes have been created and are successfully operating [26]. During the development, testing and operation of such complexes the issues of forecasting and reliability assurance acquire special importance. The importance of this problem is due to the fact that reliability in the existing concepts is defined not only as one of the basic properties of the system, characterizing its ability to perform the specified functions. Reliability behavior determines technical efficiency and safety of systems functioning.

The requirements for the reliability of complex technical systems are diverse and high. They include requirements for qualitative analysis of types and consequences of failures and fault tolerance, high requirements for reliability indicators and coefficient of performance preservation, requirements to testability indicators (completeness and depth of control, reliability of control).

There are three complementary approaches to ensuring the reliability and technical efficiency of designed systems: increasing the reliability of the element base, introducing redundancy, ensuring multi-level operation.

The first approach implies the use of highly reliable elements manufactured by modern technologies, tested and selected for a given mode of operation, protection of elements from external harmful effects (climatic, mechanical, radiation, etc.), reducing the load on the elements.

If the measures realized in the initial approach turn out to be insufficient and the reliability of the system components does not meet the required level, there is a need to use redundancy. Redundancy acts as a method of increasing the reliability of the system by introducing additional elements and functions that exceed the minimum criteria necessary for the smooth operation of the system and the achievement of its goals. In [1] five types of redundancy are distinguished: structural, temporal, informational, functional, and load redundancy. Structural redundancy is a way to improve the reliability of the object, which involves the use of redundant elements that are part of the physical structure of the object.

Another way to ensure reliability indicators (in particular, the coefficient of efficiency preservation) is to design systems with multilevel functioning in case of failures. Multilevel functioning from the point of view of reliability means that when failures occur, the system does not remain at the same, for example, 100% performance level, which is the case in redundant systems, and does not reduce the performance level to 0% (system failure), but moves to intermediate, usually discrete levels, reducing its efficiency (performance).

Delving deeper into analyzing the reliability of systems that include structural redundancy and operate at multiple levels, we can propose the concept of a reliability index, which serves as a quantitative measure of one or more properties that affect the overall reliability of an object. A reliability index quantifies the degree to which a particular object or group of objects possesses certain properties that determine their reliability. Reliability indices may be dimensioned or dimensionless. Objects studied within the framework of reliability theory can be divided into two large classes—recoverable and non-recoverable. It should be borne in mind that these concepts are relative and depend on the functions and modes of operation performed by the object. One and the same product, a computer, can be considered a non-recoverable object if it is used in the control system of a rocket on a flight to Mars, or a recoverable object if it operates locally and is used for accounting calculations. The restoration of an object means not only the repair of one or another of its parts, but also their replacement, and possibly the complete replacement of the entire object.

Therefore, reliability indicators can also be divided into two classes—reliability indicators of non-recoverable and recoverable objects.

Definitions of reliability indicators are usually presented in two forms: probabilistic and statistical. The probabilistic form is usually more convenient for a priori analytical reliability calculations. The statistical form is more convenient for the experimental study of the reliability of technical objects.

An important concept, present in many formulations of reliability indicators, is operating time. Thus, under the operation time can be understood the duration or quantity of work performed by the object, i.e., the operation time can be measured not only in units of time, but also in units of products, traveled distance, etc., as well as in units of time. For example, in one of the standards for calculating the reliability of naval equipment, the repeatability indicators have the dimension of 1/mile.

We focus on the review of articles dealing with methods and models, vehicle problems, in particular electric vehicle reliability and energy problems, which have developed strongly in the last few years. The literature review concept adopted will be useful for professionals studying the reliability design of electric vehicles. The methods and models are commented on in the context of the reviewed articles. At the same time, a detailed knowledge of the methods is only possible after reading the cited articles. Thus, the presented knowledge is derived from the application of reliability theory to the technical problems presented in the reviewed articles. I think this should be mentioned in the paper.

3. The Structure of Technical Reliability of Complex Technical Systems and Transport

3.1. General Studies in Mathematical Modeling of Reliability

In reference [35], a target function is introduced to optimize the cost of operating a microgrid that incorporates large-scale plug-in electric vehicles (PEVs) and renewable energy sources. The target function takes into account consumer profits by incorporating incentives from demand response programs. Additionally, a function is utilized to connect the vehicles to a network of PEVs integrated into the grid.

Figure 2 likely illustrates the integration of plug-in electric vehicles into the microgrid network, showcasing how they can contribute to the overall operation and reliability of the system. This integration allows for more efficient utilization of renewable energy sources and enables demand response programs to incentivize consumer participation in the grid's operation.

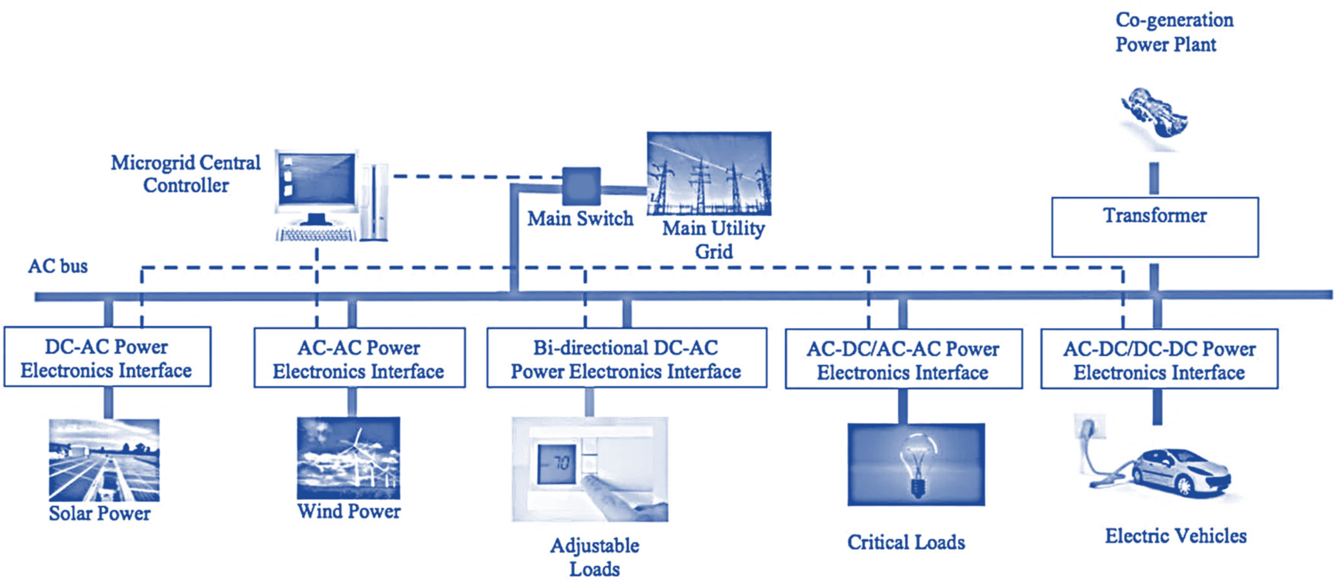

Figure 2. Schematic of the microgrid testbed.

The optimization process in this context utilizes genetic algorithms to find the best configuration for the microgrid's operation, considering both networked and isolated modes. Alongside optimization, reliability metrics are calculated to evaluate the performance of the microgrid. To validate the proposed strategy, numerical studies are conducted on a microgrid testbed.

The presence of plug-in electric vehicles (PEVs) significantly enhances the reliability of the microgrid. PEVs can supply power to the microgrid when needed, reducing the occurrence of failures and improving overall reliability.

The increasing adoption of renewable energy sources and electricity storage in the residential sector, driven by the development of new smart grid technologies (as mentioned in reference [36]), has led to a higher penetration of these technologies. The reliability of the electrification architecture, which incorporates these advancements, is analyzed to ensure its effectiveness and dependability. Figure 3 likely illustrates the analysis of the electrification architecture, providing insights into its reliability and performance.

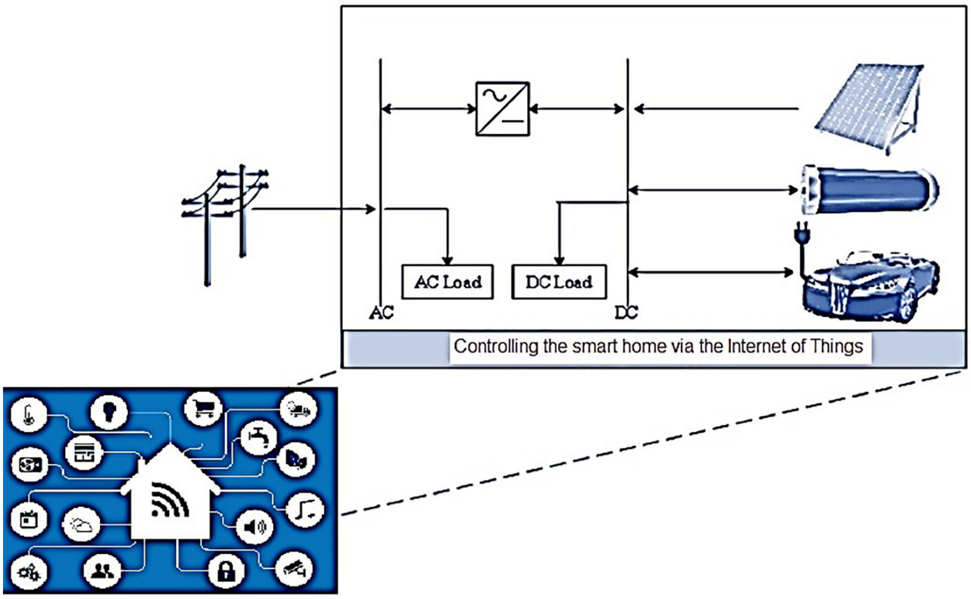

Figure 3. Hybrid smart home structure according to the second plan.

The proposed framework is designed as a mixed integer linear programming problem (MILP) that not only takes into account the costs associated with investment and operation but also assesses the reliability of each structure across different DC load ratios. Additionally, it thoroughly investigates the optimal sizing of renewable energy sources and their impact on electric vehicle demand, considering the varying prices of photovoltaic and battery packs. To evaluate the effectiveness of this approach in determining system reliability, numerical simulations are conducted.

Metropolitan cities have a multitude of parking lots (PLs), each capable of accommodating hundreds of cars. Integrating PLs into the grid offers numerous technical and economic advantages, especially with advancements in battery storage systems and the increasing use of electric vehicles [37]. This study focuses on examining the influence of electric vehicle PLs on the reliability of the distribution system.

The reliability performance of the distribution feeder is assessed using a recently proposed PL storage capacity model that incorporates data on load and component failures specific to the distribution feeder (Figure 4). The objective of this study is to quantify the expected benefits of interactive PL and distribution system operation. The paper presents an analysis of the impact of PL ASC (Advanced Storage Capacity) on the reliability of the distribution feeder during instances of outages or equipment failures.

In the event of a power failure or feeder component failures, the transmission line is utilized as a backup power source for the network. The simulation results demonstrate that by employing the transmission line in a standby operation, the reliability of the feeder and load points can be enhanced by up to 26% and 44%, respectively.

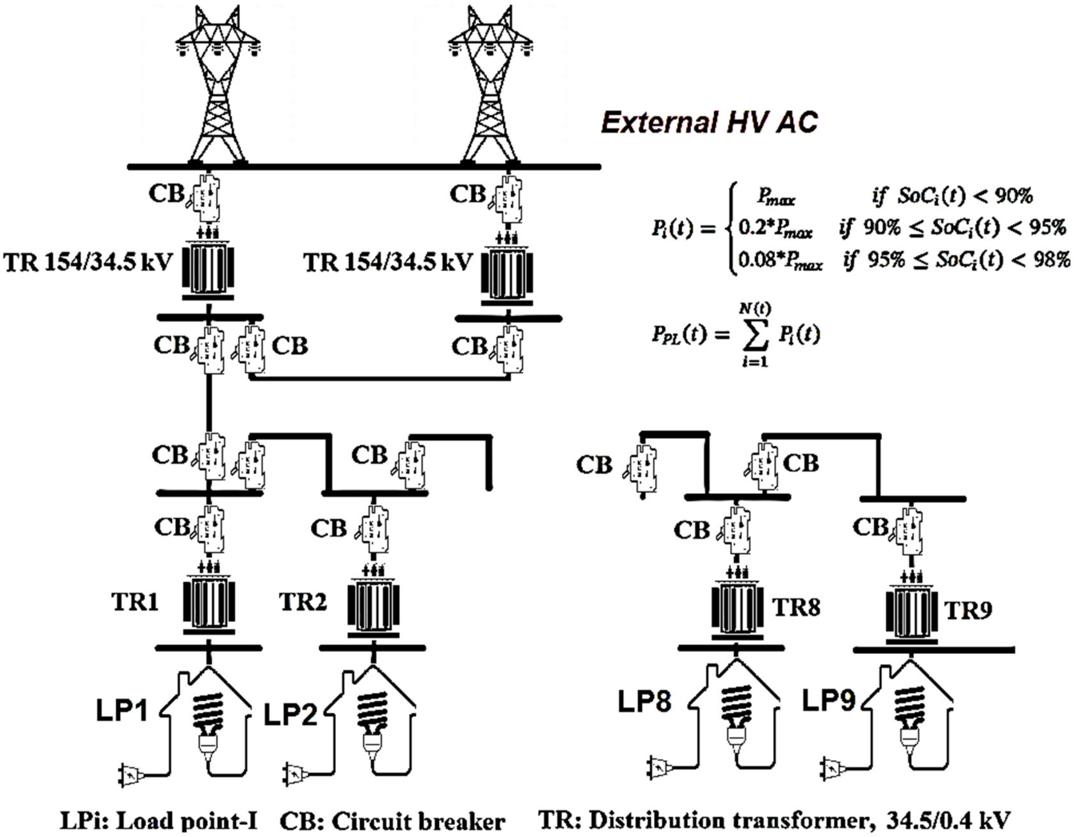

Figure 4. Distribution feeder where the PL is supplied.

In [38], a two-objective robust path finding algorithm is proposed for managing Battery Electric Vehicle (BEV) routes in a road network where uncertainties exist in travel time and energy consumption. The algorithm aims to simultaneously maximize two targets: the probability of arriving on time within the travel time budget (referred to as TTR), and the probability of completing the trip without depleting a given energy budget (referred to as ECR). A two-target stochastic optimization model is formulated to address these objectives, as depicted in Figure 5.

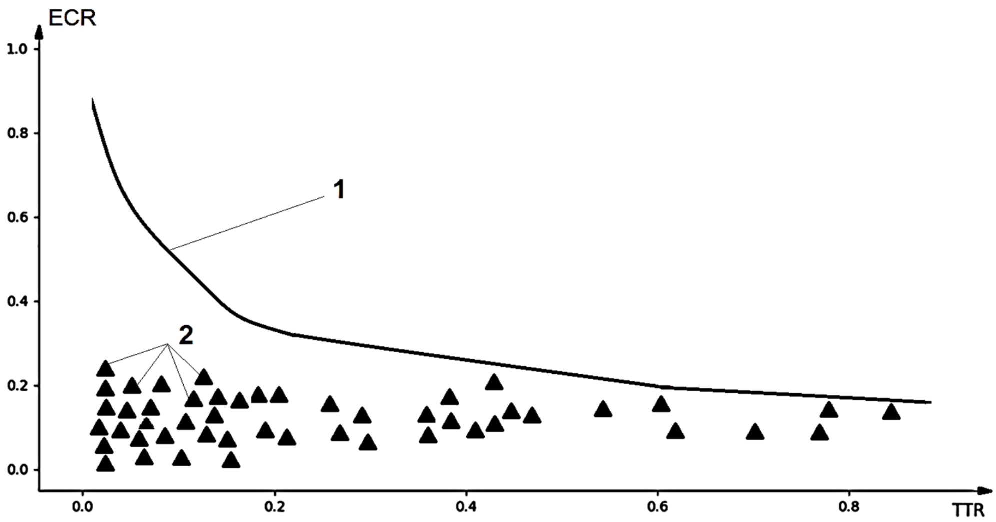

Figure 5. Solution space for both travel time reliability and energy consumption reliability objectives: 1—non-dominated paths; 2—k most reliable paths for the TTR objective.

In the publication [39], an infrastructure is introduced that enables the charging of electric vehicles while incorporating features such as smart charging, vehicle-to-grid connectivity, and local generation. The paper also presents a method for assessing the size, operation, and reliability of four distinct DC microgrid configurations. These configurations involve various components such as photovoltaic stations, power plants, and energy storage, with the specific choice of the converter and connection playing a crucial role. Figure 6 illustrates the infrastructure and its components as described in the paper.

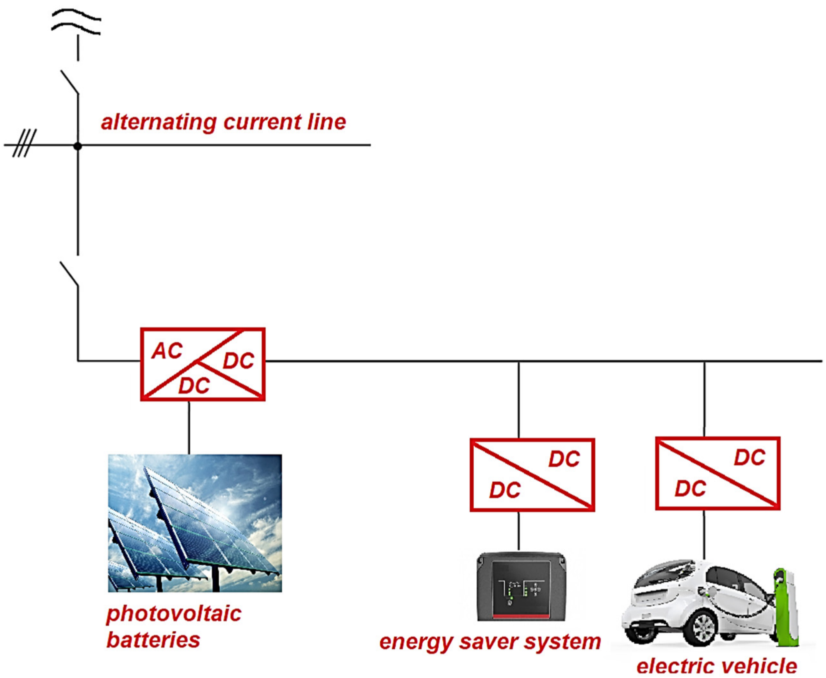

Figure 6. Solution space for both travel time reliability and energy consumption reliability objectives.

The paper [40] introduces a model for evaluating the reliability of a photovoltaic charging station. To capture the correlation between the output power of PV modules and the charging load of electric vehicles, a hybrid copula function is constructed. An example is provided to demonstrate the application of the model in assessing the reliability of the PV charging station.

In the article [41], the focus is on the reliability of asynchronous traction motor windings used in urban electric transport. The characteristic curve of stator failure probability is presented, along with experimental data on failure rates. These findings can be utilized in both the design phase of asynchronous traction motors and during operation to optimize preventive maintenance strategies. Figure 7 illustrates the relevant information discussed in the article.

The reliability analysis of an asynchronous traction motor (ATM) suggests that it is crucial to ensure that the failure rate approaches zero in the design and operation of ATMs. With a Poisson flow of failures, it can be assumed that the probability of uninterrupted operation (no-failure operation) will be approximately 0.98.

In reference [42], a model is presented for aggregating the charging load from electric vehicles in a parking lot, taking into account factors such as electric vehicle traffic patterns, usage, and charging requirements while considering element reliability. The electric vehicle charging load is combined with the system load to assess the reliability of the overall power system.

To estimate the reliability score, a DC load flow analysis with linear programming is performed, incorporating a minimum load constraint objective function. This analysis provides the load loss probability (LOLP) as a measure of reliability. The model's validity is demonstrated using shopping center parking lots as case studies.

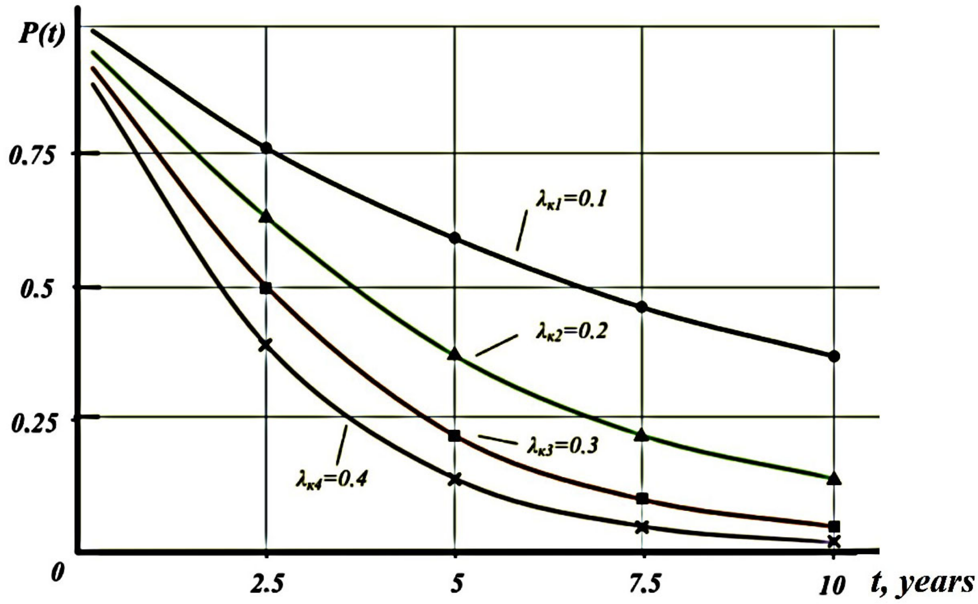

Figure 7. Reliability characteristics of the ATM stator slot insulation for various failure rates.

The results indicate that uncontrolled charging of electric vehicles can lead to a LOLP of 2.3% during peak hours, exceeding the allowable LOLP threshold of 1%. Therefore, it is recommended to regulate or limit the load imposed on parking lots equipped with electric vehicle chargers to maintain the reliability of the energy system.

The paper [43] centers around the reliability of power electronic systems utilized in electric vehicles (EVs) and hybrid electric vehicles (HEVs). It presents the reliability requirements and challenges associated with power electronics in EV/HEV applications. Additionally, it introduces advancements in power electronic components that address reliability issues and contribute to the overall system's reliability. The paper also discusses a reliability-oriented design methodology, offering examples such as the electric vehicle on-board charger and the transmission inverter. Lastly, it explores the potential for investigating the reliability of power electronics in EVs/HEVs from an external perspective.

In article [44], the evaluation of durability and reliability, critical aspects of electric/hybrid electric vehicles (EV/HEV), is discussed. In such applications, resolvers are commonly employed as position and speed sensors. The paper delves into the development and analysis of a novel multi-turn resolver designed to resolve the aforementioned issues. The proposed resolver features a single stator core and a single rotor core, thereby enhancing the overall system's reliability.

Maximizing the life cycle of modern electric vehicles and their components is a prominent area of research [45]. With the increasing demands of the automotive industry, electric vehicle traction inverters must operate under high semiconductor transition temperatures and endure severe thermal cycles. Ensuring the reliability of the power converter under these extreme operating conditions without significantly compromising drive performance poses challenges. In this context, the paper proposes a new online thermal management algorithm based on the TCT pulse frequency controller. This algorithm effectively maintains the semiconductor transition temperature below excessive levels.

In article [46], the requirements for electric vehicle (EV) powertrains, including power density, switching frequency, and cost, are becoming more stringent, necessitating high reliability to maximize the vehicle's life cycle. Incorporating a thermal management strategy is advantageous because most power inverter failure mechanisms are associated with excessive semiconductor junction temperatures. The paper introduces a new thermal management strategy that intelligently adjusts the switching frequency to keep the semiconductor transition temperature sufficiently low, thereby extending the electric vehicle's life cycle.

The paper [47] discusses the concept of utilizing electric vehicle batteries to assist the main power grid in storing energy from intermittent sources, which is considered a significant tool for increasing the adoption of green energy. Since battery degradation is influenced by various factors, it is essential to examine the impact of different grid applications on batteries. The study focuses on evaluating the reliability of the battery charging system. Interestingly, the cells that did not undergo any frequency adjustments demonstrated the highest level of reliability.

3.2. Models for Reliability Analysis of Redundant Series-Parallel and Bridge Systems Using Basic Formulas of Event Probability Theory

The reliability assessment of a composite DC converter presented in paper [48] utilizes a ride-cycle based approach. This involves considering probabilistic operational changes at different points in the drive cycle and analyzing the system in three states: switching, throughput, and shutdown of the composite system modules, excluding combined modes.

The study examines the hypothesis using the drive cycles US06, HWFET, and UDDS. The results indicate that with the proposed installation of 48 components, the composite system can achieve a reliability rating of least 20% higher than the conventional Mean Time to Failure (MTTF) evaluation method.

Furthermore, the paper explores the relationship between the number of components and reliability. By implementing active redundancy with load sharing and varying the number of components from 36 to 78, the MTTF can be further increased by 21% due to the additional 12 components.

The authors conclude that when designing conventional converters, trade-offs must be considered between reliability and other design parameters such as cost, efficiency, and power density.

The authors of article [49] address the challenge of enhancing the reliability of complex hybrid powertrains. Their article focuses on improving the efficiency, compactness, and reliability of hybrid powertrains, which are crucial goals for developers in this field. To achieve this, the authors propose linking reduced-structure inverters with Brushless Doubly-Fed Machines (BDCMs). Initially, they analyze the six operating sequences and associated switching of a three-phase BDCM powered by a Front-End Sourced Inverter (FSI) and Tail-End Sourced Inverter (TSI). This analysis is then extended to a six-phase BDCM powered by FSI and TSI, facilitated by a suitable star motor phase connection. The authors enhance the system's reliability by utilizing control techniques that avoid peak modes of operation, resulting in improved overall equipment reliability.

In a similar vein, the authors in reference [50] adopt a comparable approach. They aim to reduce operational failures by simulating the operation of a multilayer ceramic capacitor (MLCC) device using ANSYS Maxwell 3D software. Based on the simulation results, they determine optimal modes of operation that prevent overheating, thereby increasing the device's reliability.

Reference [51] introduces a hybrid two-level programming approach to enhance system reliability by optimally integrating Plug-in Hybrid Electric Vehicle (PHEV) and Renewable Distributed Generation (RDG) vehicle charging stations (VCS) simultaneously. The authors employ a method based on the hybrid Nelder-Meade cuckoo search algorithm (HNM-CS) to minimize Energy Not Supplied (ENS), resulting in reduced power losses and increased voltage magnitude within the system. They consider standard IEEE 33 bus and Tamil Nadu (TN) 84 real-time bus distribution systems with various RDGs such as photovoltaic and fuel cell systems. The operating costs of PHEV scheduling in VCS are also analyzed for a 24-h scenario. The proposed electricity-based scheduling approach mitigates the disruptive effect of uncontrolled PHEV scheduling during peak hours, and the HNM-CS optimization algorithm enables simultaneous optimization of VCS and RDG sizes based on reliability criteria. The study demonstrates a 74.67% improvement in ENS through the integration of RDG units. Moreover, selected renewable sources provide continuous support for grid demand, and the total grid operating costs are minimized using RDG units and an optimal charging strategy for each PHEV.

To evaluate the impact of electric vehicles on power system reliability, reference [52] considers a comprehensive charging infrastructure analysis. They consider all possible charging locations and define charging infrastructures, then assess the reliability impact of each infrastructure using commonly used metrics: Load Loss Expectancy (LOLE) and Loss of Energy Expectancy (LOEE). The study also analyzes the impact of mixed charging infrastructure portfolios, including cases with an equal share of all charging infrastructure and cases based on consumer preferences. The analysis is conducted using the Roy Billinton Test System, a well-known reliability testing system, with different levels of electric vehicle penetration considered in each case. The results indicate that fast charging stations have a more significant impact on reliability. Additionally, mixed charger portfolios are found to have a lower impact on reliability, even when including a fair share of fast charging stations.

3.3. Logical and Probabilistic Methods of Reliability Analysis

Logical and probabilistic methods in reliability analysis assume the reader's familiarity with logical and probabilistic methods in reliability analysis. In this section, we abbreviate the methods and the main conclusions of their authors to various energy-engineering problems, mainly electric vehicles, their power supply systems and communication infrastructure. These interesting applied issues mostly do not bring something new to reliability theory or new theoretical concepts, but consider practical problems that are solved by reliability theory and its elements. These articles are linked by the term "reliability", which evolves and can be defined differently depending on the context.

In [53], researchers aimed to develop an innovative analytical model that considers the precise PHEV model to assess the reliability and adequacy of smart grids. They introduced a new framework that determines the optimal number of PHEV states, ensuring both speed and accuracy in reliability calculations. Monte Carlo simulation (MCS) was employed to validate the proposed method for estimating the reliability of smart networks using the developed analytical PHEV model. The study investigated the influence of various stochastic parameters on the estimation of PHEV adequacy, including factors such as distance traveled, departure time, and arrival time.

To achieve the desired accuracy and computational efficiency, the presented method incorporated a reconciliation of PHEV performance probabilities. The developed method underwent validation by comparing the obtained test results with the ISS results. The introduced method had a mere 2.28% inaccuracy in EENS due to approximations, which confirmed the sufficient accuracy of the proposed framework. Furthermore, the proposed method was compared to other existing analytical approaches for reliability estimation. The test results demonstrated that the proposed method outperformed other existing analytical methods in terms of EENS calculations, while its performance in assessing system well-being was similar to other available analytical methods. Various sensitivity analyses were conducted to understand how the number of discretized states of PHEV parameters affected the accuracy of the proposed analytical method under different charging scenarios. It was concluded that in fast charging scenarios, reducing the number of discretized states for parameters such as DD (distance traveled), AT (departure time), and DT (arrival time) decreased the error in EENS. The test results also highlighted the importance of accurately modeling DD compared to AT and DT.

To achieve balanced reliability [54] in both the power grid and electric vehicle trips, an optimal method for scheduling charging stations in interconnected electric vehicle networks was proposed. To address the challenge of scheduling charging stations for large electric vehicles, a reliability-oriented multicriteria model for connected network scheduling was introduced. The reliability of the interconnected network was estimated using a method based on quasi-sequential Monte Carlo simulation.

In this study, a new reliability-oriented multi-objective optimal scheduling model was proposed for the problem of scheduling charging stations. The model was solved by implementing an optimal scheduling scheme from a set of candidate nodes. Additionally, a correlation analysis was performed to ensure the efficient solution of the proposed model for large-scale electric grids with complex traffic inputs. A test case was presented and simulated to verify the feasibility and effectiveness of the proposed method.

The study highlights the impact of implementing an electric vehicle charging and discharging management strategy on the reliability of the electric grid and transportation network. It suggests that as the State of Charge (SOC) threshold increases, the reliability index of the transportation network, represented by ETE, decreases rapidly, while the reliability index of the electric network, represented by LOEE, increases significantly. The study also demonstrates that an optimal scheduling scheme can effectively coordinate the increasing penetration of electric vehicles. By employing two schemes of newly built or expanded charging stations, LOEE experiences a slight decrease, and ETE demonstrates a significant reduction effect. Additionally, the proposed correlation analysis method improves the speed of solving the optimal scheduling problem, leading to a reduction in the average time required for optimization calculations.

In the paper referenced as [55], a comprehensive view of PEC (Power Electronics Converter) reliability modeling is presented, considering the dependence of two simultaneous failure processes: gradual wear and sudden vibration deterioration. A new model for PEC reliability is proposed, accurately accounting for the dependencies between these simultaneous failure processes. The study reveals that both the gradual-sudden deterioration dependence and the sudden-sudden deterioration dependence play crucial roles in accurately estimating Uncertainty Loss of Effectiveness (ULE) for PEC. The results demonstrate a 37.2% difference in the ULE estimate when considering these reciprocal dependencies compared to not considering them. Although the study focuses on modeling and evaluating the reliability of a DC boost converter in a hybrid electric vehicle, the proposed analytics, results, and conclusions are applicable in a general context.

Reliability assessment, as discussed in reference [56], is essential for the lifetime, design, maintenance, and service of electrical systems, particularly lithium-ion batteries. The results indicate that high discharge current and high and low temperatures are key factors influencing battery reliability. Among various degradation conditions, high discharge current at standard temperature and low temperature according to the standby test protocol are identified as adequate conditions for decreasing battery reliability during its lifespan. Furthermore, a probability distribution is introduced in the reliability assessment map to describe more reliable regeneration performance throughout the battery's life, specifically for applications in railroad and other electrical transportation systems.

The integration of electric vehicle (EV) mobility into smart grids can have a significant impact on the reliability of the grid and the reliability of EV charging services. The charging load of EVs is characterized by uncertainty and flexibility, which can strain the distribution network, especially when there is a high penetration of distributed generation (DG) in the smart grids.

To improve the reliability of the network, several improvements in the operation of EV charging services are proposed. First, a comprehensive system of reliability indices is introduced, including two new indices specifically designed to quantify the reliability of EV charging services. These indices provide a measure of the dependability and performance of the charging infrastructure.

Additionally, a spatio-temporal charging model is proposed, taking into account traffic constraints and user willingness to charge. This model considers the combined transport and network structure and analyzes the impact of various operational factors on reliability.

The study also discusses the reliability of the electricity system and the reliability of EV charging services associated with the integration of distributed generation [57]. A coupled transportation grid system is used to demonstrate the effectiveness and feasibility of the proposed method.

Numerical results from the study analyze the effect of different factors on reliability, such as the level of EV penetration, trip circuit characteristics, electric vehicle battery capacity, DG installation location, and DG capacity. The findings suggest that the reliability of the system reaches its maximum level when the ratio of EV mobility (EM) power to DG capacity is 3:1.

Overall, the proposed method and studies aim to enhance the reliability of the network and ensure the efficient and dependable operation of EV charging services in the context of smart grids and distributed generation integration.

Traditionally, ensuring the reliable operation of electrical machines has relied on the use of safety factors [58]. However, this approach often results in the need to redesign the machines. In recent years, there has been a growing recognition of the need for a paradigm shift towards failure physics methodologies that strike a balance between optimal performance and the required reliability metrics.

In this context, a proposed methodology has been developed to address the reliability of low-voltage (LV) electrical machines. The methodology outlines critical implementation steps and incorporates preliminary Accelerated Thermal Aging (ATA) tests. These tests were conducted to establish a single-voltage thermal life model based on the Miner-Arrhenius law. The constructed lifetime model can be customized to a predetermined percentile and is applicable to electrical machines operating in variable modes. The methodology's applicability and feasibility have been demonstrated through a detailed discussion of an automotive case study.

Although the study focused on a specific magnetic wire, the basic steps provided can be used to develop a lifetime model for other enameled wires. It's important to note that the single-voltage lifetime model discussed in this study represents only the initial step towards implementing the Physics of Failure (PoF) methodology in electrical machines. As a future direction, researchers plan to develop lifetime models for multiple loads to enhance the accuracy of lifetime predictions.

The paper [59] explores the impact of dynamic charging mode on the reliability of the power distribution system in electric buses. The researchers first establish a dynamic charging model based on the bus's driving scheme. They then analyze the reliability of the distribution system with the dynamic charging mode using sequential Monte Carlo simulation. The simulation results, based on the IEEE RBTS Bus-6 system, demonstrate that dynamic charging can mitigate peak charging load and reduce the overall load on the power system.

The study finds that the dynamic charging mode causes less degradation in power distribution system reliability compared to the non-dynamic charging mode. Specifically, the example considered shows a 1.0% increase in EENS (Expected Energy Not Supplied) for dynamic charging compared to a 1.4% increase for non-dynamic charging. These findings suggest that building electrified roads to meet the demand for electric vehicle charging is feasible from a reliability analysis perspective. Dynamic electric vehicle charging on electrified roads is seen as a promising approach, and the paper can serve as a guide for future engineering practices.

In another study mentioned [60], Reliability-Based Design Optimization (RBDO) is successfully applied to the design of the SAEV (Shared Autonomous Electric Vehicle) system, considering uncertainties. The researchers implement real city road links using nodes and segments, reflecting real-time traffic conditions. The objective is to develop an SAEV system design that ensures targeted customer wait time reliability by applying RBDO.

The RBDO results consider various wait times and target reliability constraints and demonstrate how fleet size, battery design, and CS (Charging Station) design interact with each other. Optimal values are determined to minimize costs while meeting the target reliability. The following observations are made based on the optimal plans and results:

1. Increasing the target reliability of the RBDO design significantly increases the total cost.
2. In both DO (Deterministic Optimization) and RBDO designs, fleet size tends to increase as waiting time constraints decrease. A CS design that distributes chargers over a large area is preferable.

3. There is a tradeoff between battery capacity and fleet size. Battery capacity is determined by cost, range, CS waiting time, and fleet size, all of which affect fleet performance.
4. RBDO does not aim to minimize CS waiting time but rather designs the CS to prevent the degradation of customer waiting time reliability.
5. By reducing customer wait times during peak hours, RBDO effectively reduces customer inconvenience.
6. RBDO design ensures the reliability of customer waiting time.

Overall, these studies contribute valuable insights into the impact of dynamic charging mode on power distribution system reliability in electric buses and the application of RBDO in the design of SAEV systems. They provide guidance for future research on dynamic charging of other electric vehicle types and explore the additional potential of Vehicle-to-Grid (V2G) technology in improving power distribution system reliability.

In paper [61], a demand response-based method with a reliability constraint is proposed to maximize the allowable penetration rate of electric vehicles (EVs) into power grid buses. The increasing number of EVs can potentially reduce the reliability of power systems, but this paper presents a method to construct load profiles of EVs on power system buses. The method considers drivers' behavior and preferences for charging locations, times, and periods. A mathematical model is developed to calculate the number of I/C (interruptible/curtailable) loads, considering incentives, penalties, and demand-price elasticities. The developed model incorporates EV load requirements with existing system loads on each bus, effectively integrating EVs into demand response programs. The results demonstrate that disaster recovery programs based on I/C loads can significantly compensate for the negative impact of EV penetration on system reliability.

In papers [62,63], the reliability of the electric vehicle power distribution network is improved through optimal station location. The paper proposes a functional approach to determine the optimal Fast Charging Station (FCS) location using the East Delta Network (EDN). The study recommends integrating distributed solar generators (SDGs) at selected distribution grid locations to reduce the load on the FCS and make the system self-sufficient and reliable.

Additionally, the same paper [63] analyzes the reliability of the distribution system considering the placement of Charging Stations (CSs) and CSs with Renewable Distributed Generation (RDG) integration in the distribution network. The work explores various power management strategies that incorporate electric vehicles into the network and utilize CS "car-home" functions to enhance the performance and reliability of the distribution system.

These studies emphasize the importance of considering reliability in the design and integration of power electronic systems, EVs, and charging infrastructure. By implementing appropriate methodologies and strategies, the reliability of power systems can be improved, allowing for the effective and efficient integration of EVs into the grid.

3.4. Failure Tree Apparatuses, Event Trees, including Examples of Fault Tree Construction for Monotonic and Non-Monotonic Systems, including the Use of Binary Decision Diagrams in Software Implementation of Fault Trees and a Critical Review of Common Cause Failure Models

The review of methods described in this section is reduced to summaries of the reviewed articles. A binary decision diagram (BDD or its Shannon cofactor tree) is an effective way to represent a switching function. It is a data structure used to represent a Boolean function and can be represented as a compressed form of sets or relations. Thus, a binary decision diagram is a rooted, directed acyclic graph. The nonterminal nodes in such a graph are called decision nodes; each decision node is labeled with a logical variable and has two child nodes, called junior child nodes and senior child nodes.

The common cause failure analysis is explained as follows. To account for multiple failures in a group of identical elements, special models called common cause failures (CCF) models were developed. The impetus for the development of these models was the failure statistics, which confirm the non-zero probability of simultaneous failure of several identical elements of the system [64,65]. The causes of multiple failures are:

- design and construction errors;
- violation of manufacturing and assembly technology;
- errors during maintenance and adjustment;
- unfavorable environmental influences.

Calculations considering common causes of failures consist of two components:

1. Calculation of probabilistic characteristics of multiples of element failures.
2. Inclusion of the calculated probabilistic characteristics of multiple failures into the system-wide reliability model. characteristics of multiple failures.

In [64], the reliability of the motor controller in an electric vehicle and its components during its lifetime is investigated. The results of the analysis show that not only individual vulnerable components of the motor controller, but also the motor controller as a whole is subject to degradation over time. These results are of great importance for the design and maintenance of reliable electrical systems. It is important to examine reliability issues in the motor controller in more detail when evaluating the reliability of the entire motor to obtain a more accurate reliability index. Factors such as the structure, type, and characteristics of the motor controller components can also affect reliability.

The electric drive system is a key component of electric vehicles. Its reliability has a direct impact on the widespread adoption of such vehicles [65]. Due to the peculiarities of the operating environment and difficult operating conditions, the reliability of the motor plays a special role. Research was conducted using permanent magnet synchronous motors to identify failure types and factors affecting reliability. A failure tree model was created and weaknesses such as winding insulation, bearings and permanent magnets were analyzed, taking into account the environment and motor design. Then, a motor reliability model was developed using a hybrid intelligent al-rhythm based on stochastic modeling and neural network using MATLAB. The conducted studies showed the effectiveness of the model and algorithm. It was confirmed that the hybrid intelligent algorithm can be used to evaluate the reliability of an electric vehicle engine, and the feasibility of the proposed method was verified.

A new approach to the diagnostics of induction motors has been developed by the authors [66]. This approach is aimed at improving the reliability of electric vehicles. This approach allows us to accurately detect the occurrence of inter-turn shorts in the stator winding of an induction motor at an early stage of their occurrence. The approach works even when there are only a small number of shorted turns (96% detection accuracy). In the case of motor damage, the approach accurately determines the extent of damage by dividing it into two classes. The first class includes light damage (1–10 shorted turns). The second class characterizes significant damage (>10 shorted turns). The classification algorithm is based on the selection of the steady-state current from any phase. On this basis, the asynchronous motor can be monitored continuously. There is no interruption of the process and no shutdown of the device. The performance of this approach is about 2600 objects per second. The practical realization of this approach is possible using a medium-class personal computer. The low requirement for computing resources makes it possible to use them in systems of diagnostics of large technological processes. At the same time the accuracy of damage degree determination is at the level of 70–90%. This is lower than the accuracy of classification between the state of no damage and the occurrence of a short circuit. Increasing the accuracy of determining the degree of damage to the induction motor can be achieved. Ways to improve the accuracy are achieved by changing the feature extraction method. In addition, it can be done by using multilayer neural networks with prediction.

The issue of reliability of electric vehicles, especially motor controllers is extremely important, as shown by the work of previous authors [66]. It is known that power electronic components of the controller are less reliable than mechanical components of other parts of the electric car. In addition, the failure of the motor controller can cause dangerous accidents on the road. To assess the reliability of the motor controller, a failure tree analysis was performed to evaluate the reliability of the motor controller over time, which showed that its performance will gradually deteriorate [67]. The most vulnerable modules of the controller are the control module and driver module, and the most vulnerable components are the printed circuit boards. As the life of the electric vehicle increases, the reliability of the motor controller will decrease due to labeling problems. By investigating the main weaknesses of motor controllers, the authors [67] showed possible ways to improve the reliability of such a system.

3.5. Markovian Modeling of the Reliable Behavior of Systems

In the article [68], the authors conducted a study of lithium-ion batteries. They write that these batteries are the most commonly used energy storage device in electric vehicles. Due to the mass application, reliability issues for such batteries are extremely important. That said, predicting and verifying the reliability of BMS remains a challenge. The authors conduct an accelerated BMS degradation test and develop a semi-parametric framework for reliability prediction. The authors propose a semi-parametric prediction scheme for BMS reliability prediction. Since the parameter increments are dependent, a second-order Markov process is used to describe the degradation process and then obtain a nonparametric lifetime distribution for each voltage level. To describe the degradation process and obtain a nonparametric lifetime distribution at each voltage level. Since nonparametric distributions are difficult to extrapolate and since nonparametric distributions are difficult to extrapolate and to obtain reliable information as a function of utilization level, they are approximated by parametric distributions whose validity is tested by hypothesis testing. An acceleration model is used to describe the effect of covariance to describe the effect of covariance on the lifetime distributions. In this way, the reliability of the BMS can be assessed by obtaining an interval estimate and bootstrap sampling method.

Different models for reliability assessment are utilized. A similarity based methodology is proposed to compare these models. The validation of the proposed method is done using the BMS dataset obtained under real life conditions. The authors establish a comprehensive semi-parametric model to estimate the reliability of BMS and show that it gives an improvement of 39.23%. The comparison of the developed model is with another similar model.

The paper [69] states that the change of business model from traditional orientation in using charging stations gives a positive result. The traditional model is producer-oriented. If the orientation changes to the consumer, the product-service system becomes more relevant. In this paper, such a system is based on the use of charging stations for electric vehicles and their service stations. Based on the optimization model of reliability design, an attempt to maximize profit is made. The model includes two types of services, fast charging and slow charging. The model also includes the possibility of transferring customers between different types of services. This model is oriented to work with real services. Probabilistic indicators related to reliability are derived from it by applying a Markov process with continuous time. The balance between the number of loading stacks and spare parts inventory can be achieved by solving a joint optimization model. For the developed model, the paper solves a real problem using real data.

The paper [70] discusses how Electric vehicle technology has been developing rapidly in recent years. However, reliability, availability, and maintainability (RAM) issues still limit the large-scale commercial use of these vehicles. This paper proposes a metodic to analyze the RAM of an electric vehicle using quantitative data. By applying the Markov model, a mathematical model was developed. The developed model considers the reliability of all the important electric vehicle components including battery, motor, drive, controllers, charging unit and energy management unit. The study shows that increasing the recovery rate of the components can increase the durability of the vehicle. The paper also investigates the impact of charging stations on the availability of electric vehicles, and it clearly demonstrates how the reliability of grid power supply affects the performance of an electric vehicle. The presented concepts can stimulate further research on the reliability of electric vehicle design and maintenance.

In [71], it is pointed out that in order to construct a drive cycle reliability test of an electric vehicle drive system correlated with user load, a fragment of conditions is extracted from load data of 300 real users with a mileage of 3.54 million kilometers and characteristic parameters with predominant failure load of the electric drive system are constructed. Using K-means analysis and cluster analysis, the operating segments of the electric drive system under different conditions were categorized into five typical groups. Using the damage accumulation model, the damage that can occur under different conditions was analyzed and the optimal damage in- intensity models were determined for each group. The segments with the highest strength were selected to create test driving cycles to evaluate reliability. The Monte Carlo method and Markov probability matrix were used to create a pseudo-random spectrum of test loads to validate the electric vehicle drive system.

In [72] it is noted that the rapid growth in the use of electric vehicles can lead to reliability problems and increased demand for electricity in the power system. This is especially true for the reliability of distribution networks. The approach in this paper is to use a probabilistic approach to assess the impact of electric vehicles on electricity distribution systems. A two-level stochastic model for estimating the charging demand of electric vehicles is proposed, including an electric vehicle traffic model and a charging demand model. A dynamic hidden Markov model is used to capture the movement of electric vehicles. The electric vehicle traffic patterns and charging demand are modeled using the sequential Monte Carlo simulation method considering distance, charging station type and driver class. The proposed method is used to conduct reliability studies on a test system and the results of the analysis are presented. This reliability evaluation method is used to determine the impact of electric vehicles on the reliability of the distribution system. The method uses a two-level model to represent the charging demand of electric vehicles and their movement. The proposed approach is validated using Monte Carlo simulation, which allowed the calculation of several reliability metrics. The study showed that electric vehicle penetration and driving distance affect the reliability of the electricity distribution system. Increasing the number of electric vehicles with higher battery capacity also negatively affects the system reliability indices.

In paper [73] we can see that the Integration of large-scale cluster electric vehicles (EVs) and their spatial-temporal transfer randomness are likely to affect the safety and economic operation of the distribution network. This paper investigates the spatial-temporal distribution prediction of EVs' charging load and then evaluates the reliability of the distribution network penetrated with large-scale cluster EVs. To effectively predict the charging load, trip chain technology, the Monte Carlo method, and the Markov decision process (MDP) theory are employed. Moreover, a spatial-temporal transfer model of EVs is established, and based on this, an EV energy consumption model and a charging load prediction model are constructed with consideration of temperature, traffic conditions and EV owner's subjective willingness in different scenarios. With the application of sequential Monte Carlo method, the paper further evaluates distribution network reliability in various charging scenarios. In the evaluation, indices including per unit value (PUV), fast voltage stability index (FVSI), loss of load probability (LOLP), system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and expected energy not supplied (EENS) are incorporated. To validate the proposed prediction model and evaluation method, a series of numerical simulations are conducted on the basis of taking the traffic-distribution system of a typical city as an example. The result demonstrates that the proposed spatial-temporal transfer model is more practical in charging load prediction than the popularly used Dijkstra's shortest path algorithm. Moreover, high temperature, congestion and the increment of EV penetration rate will further weaken distribution network reliability.

3.6. Modern Apparatus for Reliability Analysis of Complex Systems, Based on Aggregation of Logical and Probabilistic Reliability Models, including Dynamic Failure Trees

The paper [74] describes a new method for optimizing the reliability of lithium-ion batteries in electric vehicles. This method is based on modeling the relationships between physical processes and using response surface methodology. Within this method, models of electrochemical thermohydrodynamics, stochastic degradation and operation with different states have been developed. To reduce the number of model tests, the Box-Behnken design method with response surface methodology is used. Then, the redundancy scheme and layout of the battery pack are optimized followed by sensitivity analysis of the design parameters. The results show that a large distance between the battery packs contributes to the system's reliability. By using the optimal cross-layout redundancy scheme with optimal parameters, the number of utilization cycles can be increased from 1989 to 2933 while achieving 90% system reliability. The overall optimization of redundancy and layout is important for extending the lifetime and improving the reliability of battery packs.

The paper [75] presents research results that confirm that electric vehicles are an effective way to reduce pollution from transportation. The popularity of electric vehicles has led to the emergence of charging stations for them. However, it is necessary to consider the negative impact of these stations on the electric grid. In this paper, the impact of charging stations on the standard power system is investigated based on load analysis. Charging of electric vehicles requires additional electricity from the grid, which leads to power losses. Distributed generation (DG) is proposed to compensate for these losses. In this paper, type 2 DG is used to compensate for the power losses. Also, a hybrid algorithm called HGWOPSO, which determines the optimal placement of charging stations and DGs, has been used to reduce the losses. The hybrid algorithm was validated on IEEE-33 and IEEE-69 bus systems. The accuracy of the method has been tested against other methods such as GWO and PSO. The number of charging loads for electric vehicles has been limited considering voltage and current and DGs have been added to the network to reduce losses. It is easy for engineers to select the number of DGs by analyzing the power difference between the additional load power of the charging stations and the total system power. In the IEEE-33 bus system, two WGs have shown performance improvement, while in the IEEE-69 bus system, four WGs are required. Although the addition of DGs reduces the power loss and improves the voltage profile, the impact of each additional DG is found to be negligible. In addition, a reliability analysis is performed to determine the impact of charging stations and DGs on the functionality of the distribution system. All reliability metrics are investigated in different scenarios.

This paper [76] investigates different approaches to reducing the overall production range and maximum temperature considering temperature constraints and optimize the MTTF at system level by comparing automotive applications with different types of ECUs. In addition to temperature-aware mathematical programming, we also develop efficient strategies to reduce peak temperature and quickly estimate mean uptime. We also utilized a genetic algorithm for task matching to improve the lifetime reliability of automotive systems. Our experimental results confirm the importance of misinformation for improving the reliability of automotive systems and the effectiveness of our proposed approach.

In a review [77], degradation conditions of Li-ion batteries were considered in a test case to demonstrate an understanding of the reliability of these batteries in terms of discharge rate and ambient temperature. The results showed that the reliability of Li-ion batteries at low temperatures and high discharge rates is lower than in other conditions. When the ambient temperature decreases and the discharge rate increases, the reliability of batteries deteriorates. It was also found that the capacity and power attenuation increases at 10 °C and 4 °C, respectively, more when compared to other conditions.

Researchers in [78] consider the benefits of using a battery storage system (BSS) to improve the reliability of the distribution grid. The authors created a model considering BSS characteristics to estimate the consumption of electric vehicles and their ability to serve as a backup energy source during grid failures. A method based on quantifying the impact of BSSs on distribution system reliability was then developed. For this purpose, simulations were used to account for uncertainties associated with the behavior of electric vehicle owners to improve the accuracy of the results. The study showed that the absence of a V2G (electric vehicle to grid) function increases the load on the distribution network and reduces its reliability during outages. However, by using BSS with V2G function as a backup power source in emergency situations, the power shortage can be reduced and the reliability of the power supply can be improved.

In [79], a new method for monitoring the state of broadband devices based on real-time switch operating parameters is proposed. The authors analyzed the thermal, magnetic and electrical properties of the power module to improve the switching temperature estimation process. The obtained switching temperature was used as the main indicator of power module failure in the real-time evaluation platform. To solve the problem posed in this paper, the authors developed a model platform using the proposed methodology using a 2010 Toyota Prius as a case study. This method provides accurate and complete monitoring of the power modules in the EV PE system, which are the most frequent source of failures.

This paper [80] presents a new method for load modeling of electric vehicles with different penetration levels. It evaluates the importance of the interconnected power system by considering the outage factors of generators, transmission lines and transformers. Different charging strategies including opportunistic and controlled charging with or without grid (V2G) are also utilized. The proposed method has been validated based on IEEE RTS-79. The results show that the probability of load loss increases during peak demand, and the probability of load loss is higher for plug-in hybrid electric vehicles than for all-electric vehicles due to their higher consumption. These results also confirm that the reliability issues associated with the integration of electric vehicles can be mitigated by controlled charging and the use of bi-directional chargers to perform the V2G process, which can provide additional energy during peak demand, improving grid reliability.

The reliability of smart grid operation is extremely important. Various stochastic modeling methods have been proposed by various authors to ensure it. The Monte Carlo simulation (MCS) method has been mainly used in their development. A smaller number of authors have rushed to use and develop generalized analytical methods to solve this problem. The authors of [81] have developed a new generalized analytical methodology for assessing the reliability of smart grids. In their approach, they combine integrates two matrices. These are the segment state matrix and the topology state matrix. Based on this approach, welfare criteria and reliability indices are defined.

The study [82] describes the process of field data collection from different electric vehicles. Data registration and preprocessing methods as well as legal and privacy issues are presented. The requirements for the collected data are outlined. In addition, the developed database is explained and the registered vehicles are listed. The concept of reliability analysis based on the collected real field data is presented. Finally, the objectives of this research endeavor are outlined. In future studies, additional field data will be collected and the database will be expanded. The collected data will be used as the basis for multiple analyses from the perspective of different occupations. As part of these analyses, reliability, safety and sustainability will be assessed.

Integration of digital actuator development methods into the process of developing industrial tools is an urgent task. Such a task is addressed in [83] using the developed processes and methods. For hardware development, a system was created that collected all PDP steps and all components used in this process. This linked system is applied in the development of external software. This approach allows the creation of virtual development tools for all markets. The focus is on controlling the collection of data related to data management. Using BigData and AI methods, the managed data is analyzed, correlations are found, for example in field distribution. These methods and processes provide new opportunities in test reliability planning. Special attention is paid to the high reliability of the mechanical components and the entire system over the required service life.

The problem of optimizing the charging/discharging of electric vehicles and the location of transmission lines to improve the reliability of the distribution system is addressed in [84]. Various factors related to electric vehicles were studied and modeled. These factors included the number of electric vehicles, distance and time of daily trips, charging/discharging time, and travel speed of these electric vehicles. The solution to the problem was formulated as an optimization problem using mixed-integer nonlinear programming to achieve maximum reliability, minimum losses, and voltage regulation in the distribution system. The optimal solution was found using the PSO method. The results of the study determined the optimal location of transmission lines and the optimal charging/discharging time and rate, which helped to maximize reliability, reduce losses and regulate voltage in the distribution system.

In recent years, attention has been focused on clean energy sources such as fuel cells and lithium-ion batteries. Their main use is in transportation and for electrification of populated areas [85]. With the increasing use of these energy sources, it is important to study their behavior, reliability and safety. The paper [85] focuses on the reliability and safety of lithium-ion battery components. The paper proposes a model to evaluate the reliability of battery performance. This model is based on the concept of maintenance to improve the reliability and safety of the battery. It can predict possible problems when the battery is used in electric vehicles or airplanes. The results show that the electrolyte (ES3) is the most unreliable and requires the highest safety measures. Thus, the electrolyte (ES3) should have the highest priority in terms of reliability and safety. This model has the advantage of being able to account for inaccurate information when evaluating the reliability and safety issues of a Li-ion battery.

3.7. Qualitative and Quantitative Analysis of Failure Types and Consequences

The paper [86] indicates that we will see the expansion of electric vehicles in the near future. A thorough analysis of system reliability with electric vehicle charging schemes and their impact on the distribution network will greatly help in the planning and development of supporting infrastructure, mainly electric vehicle charging stations (EVCS). System reliability varies with failure rate, number of outages per year, average downtime, etc. Reliability indices are generally categorized into consumer-based indices and energy-based indices.

According to [87], the use of lithium-ion batteries (LIBs) in electric vehicles (EVs) is becoming more and more common because of their advantages. Among their most important advantages are light weight, high energy and power density. However, uncertainty in the ability to produce the right volume of Li-ion battery cells leads to increased failure rates and heterogeneity in quality. In turn, this yields a decrease in battery capacity and life. In this study, Design of Experiments (DOE) planning methods and robust design optimization approaches were applied. The approaches used are reliability based (RBRDO). First, the design factors affecting energy and power density were selected by sensitivity analysis using DOE. Then, RBRDO was performed to maximize power density while simultaneously reducing failure rates and heterogeneities between cells. To confirm the superiority of RBRDO in reliability and robustness, the results obtained were compared with values obtained using traditional deterministic design optimization (DDO) and reliability-based design optimization (RBDO). RBRDO increased the average energy density by 33.5% compared to the initial values and reduced the failure rate by 98.9% by improving reliability compared to DDO.

The work on inverter reliability evaluation was carried out by the authors of [88]. A short model was developed by them. This model predicts the reliability of the inverter for the thermal network. It is designed to optimize the thermal management and thereby reduce power losses. It allows for accurate temperature monitoring due to the accurate accounting of transients. The temperature difference on different layers of the power module is evaluated. The developed reliability model made it possible to determine the operating modes leading to inverter damage.

In the article [89] a reliability control model for gas pedal and brake pedals of an electric car was created. The model was developed using the Matlab/Simulink platform in accordance with Formula Student Racing rules. These rules deal with the functionality and safety requirements of the power system. In this model, the accelerator pedal voltage signals are filtered. The filtered signals are tested using an amplitude limiting module and a consistency module. The reliability control strategy of the gas pedal and brake pedals of an electric racing car is investigated. The simulation results show that the filtering model can effectively reduce the noise in the signal, make it smoother and improve the control accuracy. The amplitude limit verification model and consistency verification model effectively detect anomalies in sensor signals. The gas pedal and brake pedal validation model prevents the situation where both pedals are pressed at the same time. In this case, the power can be immediately cut off. After processing the two accelerator pedal voltage signals, the pedal position can be accurately determined. Thus, the model meets the requirements of reliability control.

The paper [90] discusses power components and modules. Components that play an important role in ensuring the reliability of the electric vehicle power supply are considered. It should be taken into account that the electric vehicle power supply system is complex and includes not only battery cells and modules. It consists of many other components. Failure of these components can lead to system failures. Thus, battery reliability should be evaluated based on the entire power system and not only on the reliability of individual battery components. The study conducted in this paper begins by predicting the failure rates of all major components. In the next step, the reliability of the entire battery system is evaluated. The results show that the reliability of the entire battery system is significantly lower than the reliability of individual components including battery modules. The system as a whole degrades faster over time compared to the degradation of individual components. An interesting fact is that the battery management system (BMS) controller is less reliable than the battery modules in the battery system under consideration.

Researchers [91] consider the use of jet propulsion motors (SRM). Their work considers the application of SRM in electric vehicles, and electric airplanes. In order to control the SRM effectively, current sensors are required for each phase winding. Failure of any of these sensors can reduce the performance of the system. The paper investigates the behavior of the system when the minimum current sensor of the SRM drive fails and proposes a control methodology. The developed methodology aims to circumvent this failure without adding additional sensors. A scheme is proposed to diagnose the failure of current sensors based on analyzing the current values. The values for analysis are obtained from phase and DC current sensors.

4. Discussion

Discussing the reviewed publications, we can conclude that the theory of reliability both in the short and long term will remain the main tool for studying the quality of complex technical systems and processes, applied methods of calculation and development of norms for design, calculation and operation of mechanical systems [92]. This theory is at the intersection of mechanics and a number of sections of applied mathematics and computer science: mathematical statistics, decision-making theory, and technical diagnostics [93].

These disciplines belong to the fundamental scientific fields. Methodological issues of machine reliability theory and design can also be referred to as fundamental scientific problems [94–96].

Along with the traditional directions of the reliability theory of machines and structures, such as statistical analysis of loads, impacts and mechanical properties of materials, justification of the selection of design loads and their combinations, methodology of assignment of safety factors, etc., the theory of reliability of machines and structures will be developed in the near future. In the near future, new directions will be developed. Among them: the methodology of reliability and residual (safe) service life assessment of a technical object for making decisions on its further operation.

Other new directions include methods of reliability prediction by calculation schemes maximally close to real objects. For example, with extensive use of statistical computational experiment; methods of computational assessment of the safety of objects in relation to rare natural and anthropogenic impacts; consideration of the human factor in calculations of the reliability of structures; methodology of designing technical objects that are resistant to human errors.

The new directions will remain the most promising in scientific terms, and their importance for practice will increase.

One of the main directions of reliability theory development in the future will be a deeper mutual penetration of reliability concepts into mechanics (including elasticity theory, plasticity theory, etc.).

At the same time, modern methods of mechanics will find wider application in solving reliability problems.

Among the new sections of mechanics one of the leading places belongs to fracture mechanics. Cracks and crack-like defects are almost inevitable in any large-size structure.

The requirement of the absence of such cracks is excessively burdensome and often simply unfeasible. The task of fracture mechanics is to indicate ways of selecting materials and forms of structures that satisfy a reasonable compromise between the requirements of economy and the requirements of high safety and reliability. Significant achievements in the field of fracture mechanics have made it possible to develop methods for assessing the crack resistance of structural materials, to outline ways of creating structures with increased survivability in the presence of cracks.

5. Conclusions

The article presents a review of articles that use methods and substantiation of ensuring a high level of reliability and serviceability of technical systems as one of the most important tasks of creating and operating complex systems, including transportation systems. This task can be solved only by implementing a set of interrelated measures at all stages of their design, manufacturing and operation. An increase in the reliability level of technical systems is achieved by various methods (redundancy of elements, rational choice of materials of friction pairs, provision of normal conditions of their operation, introduction of new strengthening technologies, etc.). The decision on the expediency of these or those technical measures should be taken according to the criterion of minimum costs for their implementation and subsequent costs for maintaining the performance of products in operation. This article analyzes the importance of the studies of the authors of the cited works in the development of the application of models and methods of the theory of reliability, the issues of determining the quality, the main properties of reliability, performance, reliability and limit states of systems. The classification of vehicle failures, quantitative indicators for assessing reliability, durability, maintainability and serviceability, as well as indicators for a comprehensive assessment of reliability are given. The reviewed articles, on the basis of which this review was made, allowing the authors of these articles to define the engineering and physical foundations of reliability, to establish the main causes of loss of performance of machines (metal fatigue, residual deformations, aging, corrosion, wear and tear). Taking into account that the main cause of failures is wear and tear, the manual pays sufficient attention to its physical essence and factors affecting the wear resistance of products. In these articles, it is specified that a significant reserve in solving the problem of improving the reliability and serviceability of technical systems is information about failures and malfunctions of these systems obtained from the field of operation. The order of collection and processing of statistical information about failures of vehicles described by different distribution laws is stated.

Thus, we can say that today there are a large number of methodologies for calculating reliability. Each of them is applicable to different cases. However, practice shows that the main one is the method of reliability estimation by calculation of failure rates.

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