TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 17
Number 1
March 2023
DOI: 10.12716/1001.17.01.08

Reliability Evaluation of Electrochemical Energy Storage Systems Supplying the Ship's Main Propulsion System

P. Szewczyk & A. Łebkowski
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The paper presents the structure of hybrid and electric modern ship propulsion systems. Types and configuration of electrochemical cells for selected electric energy storage facilities on the ship were presented. The method and results of reliability analyses, such as failure mode effect analysis (FMEA), reliability block diagram (RBD) and fault tree analysis (FTA), used to estimate the probability of failure of the energy storage systems supplying the ship's main propulsion, are presented. Methods of evaluation and verification of the proposed reliability model using a laboratory model and available operational and service data are discussed. A proposal for a quantitative risk analysis of potential damage during the operation of the energy storage has been presented.

1 INTRODUCTION

Contemporary trends in technological development have been defined by the long-term policy of the European Union by legal acts, which will most likely direct the development of the sector related to electric propulsion systems supported by hydrogen sources. The development concept of the European Union aims to achieve climate neutrality by 2050. As part of the activities carried out, such strategies and regulations as the "Green Deal"" [1] or the "Fit for 55" package" [2, 3] were developed. The task of the adopted strategies is to transform the EU into an energy-efficient and highly technological climate-neutral economy [4, 5]. The above policy also includes issues related to zero- or low-emission propulsion systems of vessels.

In order to achieve the presented goals, technological solutions that would be able to meet such high environmental requirements are sought. Such activities are supported by the governments of many countries, as well as various types of organizations. An example of it is the organization ZESTAs [6], whose goal is to promote the rapid and massive implementation of Zero Emissions Ship Technology (ZEST). As part of the activities carried out, pro-ecological, pro-effective and pro-economic activities are promoted, aimed at supporting technologies related to electric drive systems, powered mainly from electrochemical energy storage and hydrogen cells. The obvious reason for this is the advantage of minimal carbon emission of electric machines, in comparison with thermal machines. Electric motors do not emit any pollutants during operation and do not require the use of oxygen from the environment. They also generate significantly lower levels of noise and vibration than internal combustion engines. The most important feature of electric machines is their much higher mechanical efficiency, exceeding 95% compared to internal combustion engines. Electric motors also have a better power-to-weight ratio, are less mechanically complex and have fewer components, and do not require many auxiliary installations to operate. In addition, due to their properties, electric motors offer more precise ways to control their speed, which translates into more efficient maneuvering of the ship. Unfortunately, in relation to heat engines, the electric drive system has one drawback, which is related to its power sources. Current green electricity sources are characterized by a much lower level of energy density (0.17-1.8 MJ/kg) compared to fossil fuels (40-47 MJ/kg). For this reason, various types of configurations are built, using diesel power generating sets, Electrochemical Energy Storage System (EESS), supercapacitors, hydrogen fuel cells, as well as hybrid systems consisting of various combinations of the above-mentioned energy sources. Hybrid solutions contribute to reducing fuel consumption and emissions. They also enable periodic elimination of exhaust fumes and flexible operation of the ship's propulsion system [7, 8].

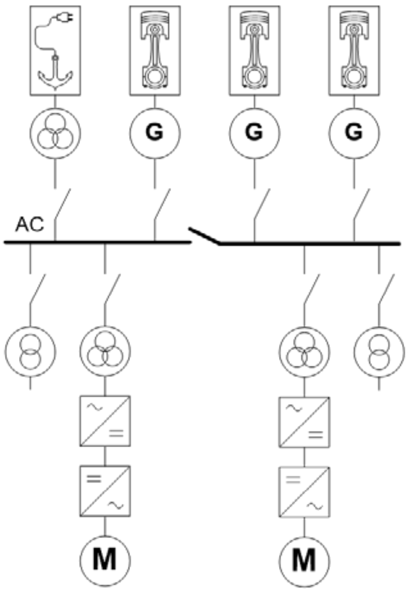


Figure 1. An exemplary configuration of a modern diesel-electric propulsion system for a ship.

Additionally, in order to minimize energy consumption, energy storage systems (ESS) can be supported by other ecological technologies, using for example: Flettner rotors [9–12], soft sails, hard sails, kite towing, suction wings, turbines, modified ship hull structures, foils, aeration systems, or optimization of transit routes [13–18]. Thanks to the applied design solutions, it is possible to reduce the demand for energy consumption, and thus reduce the emission of toxic gases at the level of 10% to approx. 60%.

Thanks to the use of EESS, it is possible to reduce the energy consumption of ship propulsion systems, both diesel-electric hybrid and purely electric. The configuration of the diesel-electric ship's power propulsion system is shown in Figure 1.

The publication presents the methods and results of reliability analyses, i.e. FMEA, RBD and FTA, used to estimate the probability of failure of EESS energy storage units used on ferries with electric propulsion. For the selected configuration of the energy storage, qualitative analyses were supported by calculations carried out for the quantitative analysis of the risk of potential damage during the operation of the energy storage.

2 CONFIGURATIONS OF SELECTED PROPULSION SYSTEMS OF SHIPS

Energy storage systems (ESS) are the main technological element on an electric ship. ESS can be built on the basis of electrochemical cells, supercapacitors, hydrogen fuel cells or mixed structures, the so-called hybrid (HESS - Hybrid Energy Storage System). Lithium-ion (Li-Ion) cells are mainly used to build the Electrochemical Energy Storage System (EESS). Depending on the chemical composition, Li-Ion cells have different parameters and cost. For example, we can distinguish the following types of cells:

– NMC (Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$), characterized by an average level of safety, average cost, low number of life cycles - approx. 1500, average energy density - approx. 220 Wh/kg);
– LFP (Lithium Iron Phosphate ($LiFePO_4$), characterized by a high level of safety, average cost, average number of life cycles - approx. 3000, average energy density approx. 120 Wh/kg);
– LTO (Lithium Titanate (Li_2TiO_3); characterized by a high level of safety, high cost, high number of life cycles - approx. 10,000, low energy density approx. 80 Wh/kg);
– LCO (Lithium Cobalt Oxide ($LiCoO_2$): characterized by a low level of safety, medium cost, low number of life cycles - approx. 1000, average energy density - approx. 200 Wh/kg);
– LMO (Lithium Manganese Oxide ($LiMn_2O_4$): characterized by an average level of safety, low cost, low number of life cycles - approx. 700, average energy density - approx. 150 Wh/kg);
– NCA (Lithium Nickel Cobalt Aluminum oxide (LiNiCoAlO2): characterized by an average level of safety, low cost, low number of life cycles - approx. 500, high energy density - approx. 260 Wh/kg) [19];
– G-NMC (Graphene / Lithium Nickel Manganese Cobalt Oxide): characterized by an average level of safety, average cost, high number of life cycles - approx. 8,000, average energy density - approx. 130 Wh/kg) [20].

Depending on the type of ship (tug boat, Ro-Ro ferry, passenger ship, off-shore ship, etc.) and due to the thermal conditioning system, NMC, G-NMC, LFP and LTO cells are most often used.

Figure 2 shows an exemplary, illustrative configuration of the electric drive system, using a combustion generating set, a hydrogen fuel cell and EESS, which can also be used as HESS.

A characteristic feature of the presented solution is usage of a DC power supply system for the ship. Thanks to this solution, it is possible to obtain greater stability of power supply and quality of electricity, as well as to obtain economic and environmental savings [21–28]. In addition, the use of a direct current system enables the reduction of: up to 20% of fuel; up to 30% of the weight and area occupied by the electrical power system; up to 40% of the mass of transmission cables; up to 85% of the volume of cable corridors. In addition, there is no need to synchronize generating sets connected to the busbars, as in the AC power system.

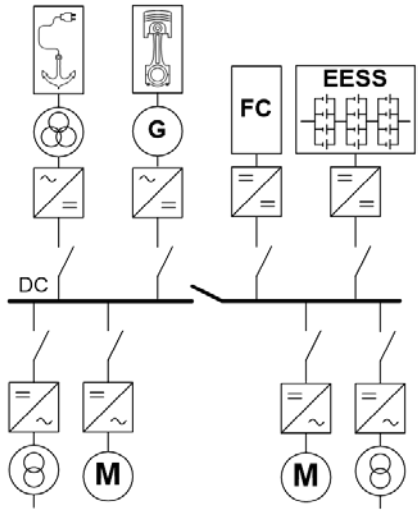


Figure 2. An exemplary configuration of the ship's electric propulsion system.

2.1 *Selected configuration of EESS*

In the electrical propulsion systems of ships, the voltage level on the main busbars can range from 400 to as high as 1,200 VDC. The capacity of the energy storage for a ship with a length of approx. 80 meters and a width of approx. 15 meters is approx. 6.6 MWh [29]. For larger Ro-Ro ferries with a length of approx. 190 m and a width of 28 m, the energy storage capacity - depending on the navigation area - may be approx. 33 MWH (360 tons), and for diesel-electric hybrid systems - approx. 23 MWh. Reliability analyzes were carried out for an energy storage consisting of 32,640 G-NMC cells with a capacity of 55 Ah, a nominal voltage of 3.65 V, with an average weight of one cell with a housing of approx. 1.5 kg (130 Wh/ kg). The configuration of the analyzed energy storage, built of 20 strings, consisting of 51 modules with 32 cells, connected in the 4s8p configuration, is shown in Figure 3.

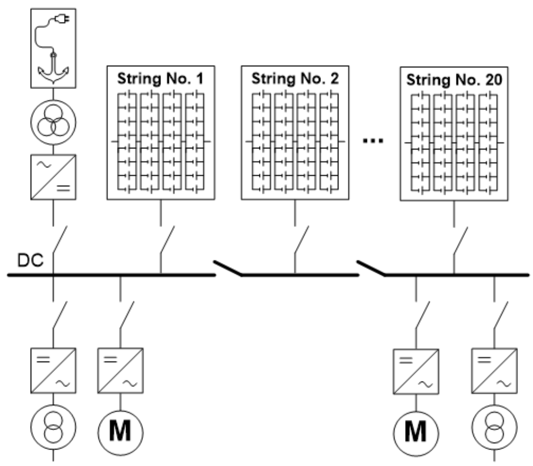


Figure 3. Configuration of the analyzed energy storage powering a ship with an electric drive.

The basic parameters of the module include: Nominal Capacity 440Ah, Nominal Energy 6.1 KWh, Max. Energy 6.42 kWh, Max. Voltage 16.4V, Nominal Voltage 14.6V, Min. Voltage 12.4V, Weight 48.2kg. The weight of a single string is approx. 2,458.2 kg, and the weight of the entire energy storage is 49,164 kg [20]. Thanks to the development of the presented configuration, redundancy for the electric propulsion system is ensured, which is a key element for the operation of the ship.

3 RELIABILITY ANALYSIS METHODS

System reliability is defined as the probability that the required system functions will perform under specified conditions for a specified period of time. Mathematically, reliability (R) is defined as:

$$R(t) = e^{-\lambda t} \tag{1}$$

where R – reliability, λ – failure rate (1/year).

The probability of ensuring failure-free operation of the system is determined by the product of the probabilities of failure of each of the analyzed system components and can be written as:

$$R_S = R_1 \cdot R_2 \cdot \ldots R_n \tag{2}$$

In order to ensure the reliability of a given product at the appropriate level, a systemic design process is important, which aims to identify design hazards and properly assess the risk of the structure. The introduction of this process is particularly important when implementing new technologies that determine the security and reliability of a given system. This process is widely discussed in the scientific literature, as well as undertaken more and more often by practitioners [29–31], which accounts for its effectiveness. The construction of a safe and reliable energy storage for the main propulsion of a ship is a major challenge in which DFR should be an important part of the construction process.

The process of designing for reliability (DFR) of a complex system (i.e. ESS) requires detailed planning already at the stage of conceptual work and defining product requirements. At this stage, in addition to the functional assumptions, other requirements should also be established, i.e.: the target working environment, failure rate, serviceability, expected service life. Determining the requirements at an early stage of R&D works allows for proper planning of analyzes and tests, which significantly shortens the product design time, ensuring that reliability requirements are met. The process of designing for reliability requires the use of many analyzes and tests, they are a requirement of applicable standards in a given industry or target region for which a given product is intended. For the discussed example of an energy storage, three methods of reliability assessment were proposed: reliability prediction analysis, FMEA and FTA. The proposed methods are a small part of the entire DFR process for the construction of an energy storage.

3.1 *Failure Mode Effect Analysis*

Failure Mode Effect Analysis (FMEA) is a popular cause and effect analysis of potential failures and assessment of the risk of their occurrence. Risk assessment consists in assigning appropriate values of the probability of a given risk (Occurrence), threats caused by their occurrence (Severity) and the degree of detection (Detection). The total risk rating of a single failure mode, defined as the Risk Priority Number (RPN), is the product of these three values. This method is used in many industries and is standardized through e.g. MIL-STD 1629, SAE J1739, etc., however, internal processes and risk assessments are used in the early design stage, based on the experience of a given organization. FMEA is a qualitative method, the main purpose of which is a systemic analysis of potential threats and which helps to assess the risk, based on predetermined criteria and weights for a specific product or product line. FMEA allows for systemic analysis of potential threats and assessment of the value for each of the categories: Severity, Occurrence and Detection. Risk scales for a given category are defined by accepted standards or internal procedures, however, in the case of a structural FMEA, it is important that they are the same in a given project or group of assessed risks. In the FMEA method, each analyzed risk is assessed by the RPN determinant (risk priority number), which consists of the product of the following weights: severity, occurrence and detection.

$$RPN = S \cdot O \cdot D \tag{3}$$

The RPN value allows to assess and assign appropriate priorities in the analyzed risk group, and then to make appropriate decisions regarding the reduction of these threats. In the case of Design FMEA (DFMEA), the RPN is a measure of design improvement in the next design iteration (risk reduction or acceptance).

One of the main objectives of the FMEA is to identify and assess the risk of failure (failure mode). In the analyzed sample energy storage, a study of failure modes for basic elements was carried out. The table presents the results of the analysis in a shortened form.

The result of the analysis indicates that the highest risk is a failure of BMS management system. The probability of such an event is estimated to be medium (5), but the importance of failure mode for the entire system is high (9), and its detection before the failure is low (9). Therefore, in this example, the RPN parameter, which defines the total estimated risk, is rated at 405. The cause of this mode is a failure of the electronics responsible for controlling and managing the batteries or software. The next highest rated risk at the RPN=245 level is a short circuit of the battery cell, the probability of such an event being medium (5), the threat to the system (7), and the detection at (5). Increasing the internal resistance of the cell to a level causing an open circuit is a relatively low risk (3), its importance is medium (5), and its detectability is limited due to its easy serviceability (7). The most frequently observed problem in the operation of battery cells is an underestimated change in capacity. This may be the result of technology, improper operation or the quality of the cells. The probability in the analysis was assessed at (7), medium importance (5) due to redundancy ensuring energy reserve, and detection at (7). The analysis also presents the risk for the battery module assembly, damage to the internal electrical connections of individual batteries at the level of RPN=225, and the mechanical assembly at the level of RPN=105.

Assigning numerical parameter values for potential failures on design stage is often subjective and should not be used as a benchmark for comparing products from other manufacturers. The described example of the FMEA analysis allows for the identification and classification of failure modes, which may result in changes in the structure, appropriate planning of tests or the introduction of preventive service actions.

The FMEA analysis is a good example of systemic risk analysis. However, the presented example shows that this method is not a universal way of assessment and additionally, the conditions of use, environment, etc. must be taken into account. Therefore, the risk tables must reflect the target working environment, operator and carrier conditions, and the costs of a potential failure. In case range is important, the capacity change parameter will have a different RPN than when speed is more important, etc.

3.2 *Reliability prediction and modeling*

Reliability prediction is one of the methods used in the Design for Reliability (DFR) process. It is a method that allows a detailed analysis of the structure of the system, consisting of many components, properly cooperating with each other. Failure Rate (FR) data used in reliability prediction can come from the following sources: observations of similar systems, observed field data, laboratory tests ALT (accelerated life test) or from published standards, e.g. SR322, MIL-HDBK217, FIDES or 217Plus. The RBD method is used to model dependencies between subsystems and components. The reliability block diagram (RBD) is a graphical representation of the dependence of the functional states of the analyzed system in terms of the reliability risk of its components. The analysis is used to identify and allocate potential reliability issues and their impact on the overall system reliability. The advantage of the RBD method is the possibility to carry out a quantitative risk analysis in systems with redundant subsystems "k out of N".

Table 1. FMEA selected results

Subsystem	Failure Mode	Failure Cause	Occurrence O	Severity S	Detection D	RPN
BMS	Control failure	Major electronics failure	5	9	9	405
Battery cell	Short	Overload	5	7	7	245
	Open	Overload	3	5	7	105
	Limited capacity	Degradation, wear out	7	5	5	175
Battery pack	Electrical connections	Vibration, shock, manufacturing issues	5	9	5	225
	Mechanical assembly	Design issues, overload, improper installation	3	5	7	105

In the analysis, the model of Li-Ion cell was used according to the FIDES standard, the parameters used are described in Table 2, details of the model in the standard [32, 33].

Table 2. Parameters of the Li-Ion battery cell model

Parameter	Symbol	Value
Failure Rete of battery	λ0-battery	0,21
Activation Energy (eV)	Activation Energy (eV)	0,40
Thermal stress	Thermal stress	0,85
Component quality	λ_{Cst}	0,14
Mechanical stress	Υ_{Mech}	0,01
Thermal stress	$\Upsilon_{Thermal}$	0,85
Weibull shape factor	β	5,0

Table 3. ESS parameters in reliability prediction analysis

Parameter	Symbol	Nominal value	Minimum value
No of cells		26 112	
No of strings		20	
No of modules		1120	
Nominal ESS Voltage	V	744,6	632,6
Nominal ESS Capacity	Ah	14 892	12 648
Nominal ESS Energy	kWh	11 088	7 998

Based on the assumptions made for the single cell model, the reliability value R(t) for individual energy storage modules was estimated, and are presented in Table 4.

Table 4. Reliability prediction of individual ESS components.

ESS Component	R(t)	Failure Rate 1/y
String 4s	0,999706	0,000147
Moduł 4s8p	0,997651	0,001176
Sting 51s	0,885426	0,060843
ESS	0,087556	1,218088

Reliability of a single module consisting of 4 battery cells is R(t) = 0.999706. The reliability values of the remaining modules presented in Table 3 assume a series connection in the reliability block diagram. In this configuration, failure of a single block affects the performance of the entire system. The lack of redundancy is the worst-case scenario in this case and indicates the limit value for R(t) = 0.087556. It shows the impact of damage to a single string, consisting of 4 cells, on the failure of the entire energy storage. In fact, the developed RBD model allows for a detailed analysis of the occurrence of individual failures in a system with redundant subsystems.

The analysis assumed that the necessary condition to fulfill the assumed mission is to ensure the minimum parameters of the energy storage specified in the specification. Nominal parameters were adopted as the initial state, and the difference between these parameters determines the acceptable risk of damage, ensuring operation in accordance with the assumptions (fail-free operation). Nominal and minimum values are shown in Table 3. To ensure minimum voltage and energy storage capacity, it is acceptable to disable 4 of the 20 strings in this energy storage example. In this configuration, the storage capacity is 11,913Ah, the voltage is 144V and the energy is 8,871 kWh. The developed RBD model assumes the possibility of redundancy and calculates the probability of completing a given mission - ensuring the minimum capacity and voltage of the energy storage, with various damage variants. The model uses the “k out of n” equation for redundancy calculations in the form:

$$m\ out\ of\ n = \sum_{k=m}^{n} \frac{n!}{k!\,(n-k)!} (e^{-\lambda t})^{k} \times (1 - e^{-\lambda t})^{(n-k)} \quad (4)$$

where m is the number of fail-safe modules needed to complete the mission, n is the total number of modules in the system, and λ is the failure rate.

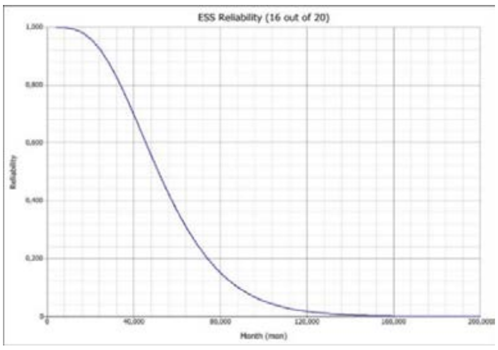
Table 5. Dependence of system reliability on string 51 redundancy consisting of 51 modules

Configuration k-out-of-n	R(t)	Failure Rate 1/y
20 out of 20	0,0875556	1,218088
19 out of 20	0,314151	0,834944
18 out of 20	0,592703	0,515722
17 out of 20	0,808970	0,277477
16 out of 20	0,927905	0,12569

The analysis shows that the reliability of the energy storage, assuming that there are 4 redundant strings in the system, is R(t) = 0.927905, and the failure rate is 0.125690/year.

The developed model allows for the analysis of the risk of failure at each level of the listed modules and the impact on the failure rate of the entire ESS.

The performed reliability prediction analysis indicates the reliability of the entire energy storage at the level of R(t) = 0.927905 and failure rate FR = 0.12569/yr. This means that the availability (availability) of the energy storage in the first 24 months is at the level of 93%. The mean time between failures (MTBF) is 8 years. The graphs in Fig. 4 show an estimated decline in reliability after approximately 24 months and a median lifetime of approximately 4.5 years. Fig. 5 shows the failure rate increase over a time.



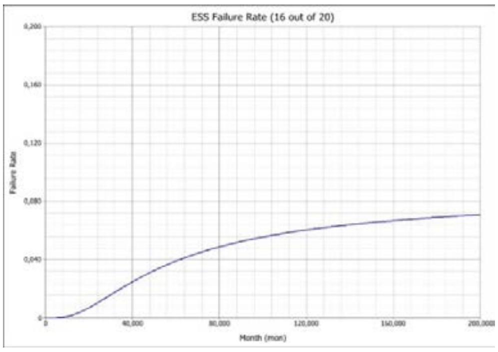


Figure 4. Reliability and failure rate in configuration 16-out-of-20

The worst configuration in terms of system reliability is the one that requires full functionality of the energy storage and ensuring the nominal parameters of the energy storage, i.e. the minimum voltage of 744V and the capacity of 18,892 Ah. In this case, a 20-out-of-20 configuration is required, i.e. no string redundancy. Figure 5 shows the reliability R(t) over time and the failure rate, which is constant over time in the absence of redundancy. The reliability graph shows a significant drop since the start of commissioning. The reliability of such a system is R(t) = 0.087556, failure rate FR = 1.28088/yr, MTBF is less than one year (0.82 years). The results of the analysis are very low and indicate the limit values considered in the model as the worst-case scenario, in which failure-free operation of all components included in the energy storage is required, i.e. at least 32,640 batteries, 1,020 BMS modules and additional modules supporting system management (21 pcs.). This is an example of how reliability prediction analysis allows risk assessment and appropriate design planning to optimize and minimize risk. Due to the very large number of components included in the energy storage, the structure of the system should be planned in such a way as to protect against the implementation of a high-risk scenario of system failure, in this case devoid of redundancy.

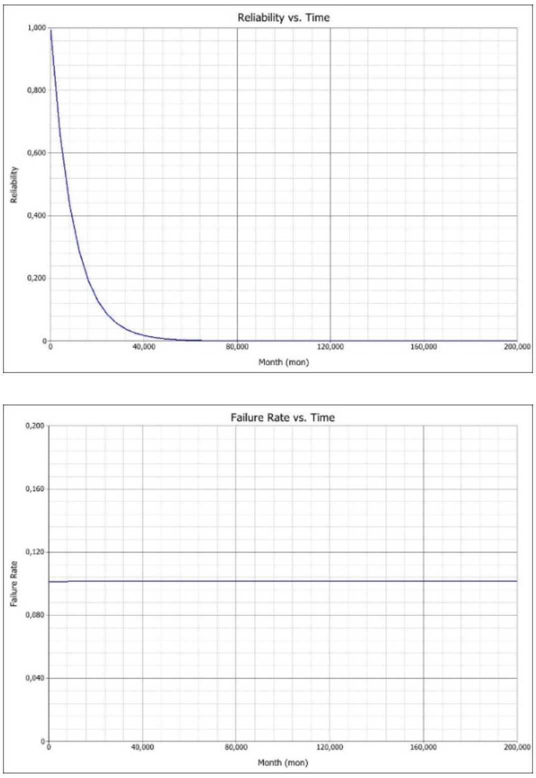


Figure 5. Reliability and failure rate in configuration 20-out-of-20

3.3 *Fault Tree Analysis*

Fault Tree Analysis (FTA) is a qualitative risk analysis method used in the DFR process to identify and evaluate the severity of a failure in a system. The FTA model presents a graphical relationship of events in the form of a logical tree that shows the relationships of factors affecting the risk of failure. Using this method, the dependencies of factors affecting potential failures are analyzed and it is often a complement to the FMEA analysis, in which the causes and effects of potential failures are analyzed in detail. FTA allows you to visually demonstrate the relationship between them, which is particularly important when assessing the reliability of power supply systems and assessing risk in energy storage [34].

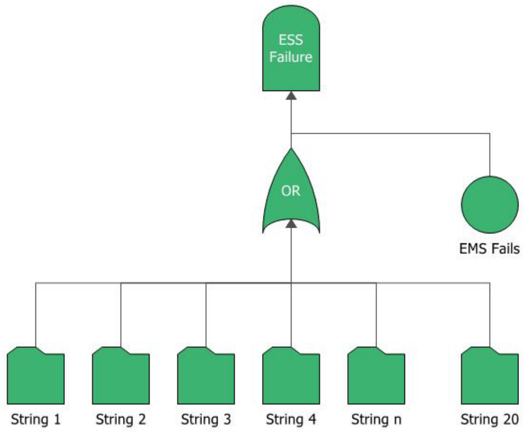


Figure 6. Simplified FTA model of ESS

Figure 5 shows a fragment of the FTA Logical Tree for the energy storage. The analysis graphically shows the dependencies of the impact of individual system failures on the total inability to perform the assumed function, i.e. the inability to provide the minimum voltage of 632 V and the capacity of 12,648 Ah, which is provided by a minimum of 16 efficient branches out of 20 in the system.

4 CONCLUSIONS

The presented methods of assessing the reliability of the ESS are part of the analyzes used in the process of design for reliability. Performing a reliability assessment at an early stage of product development helps reduce the risk of faulty design. The described methods significantly help to properly define and evaluate reliability requirements.

The developed reliability prediction model allows for a quantitative risk analysis of individual modules, the impact of their failure rate on the overall reliability of the systems and the risk of failure of each of them. Due to the complexity and high number of components that are included in the structure of the energy storage (33,682 analyzed components), the use of redundancy allows for a significant improvement in reliability from 9% in a configuration without redundancy to 93% assuming 16-out-of-20 redundancy. The model allows for the optimization of the structure in terms of the risk of failure in relation to other important parameters, i.e. cost, total weight, power, paid operation time (COPEX vs. OPEX), etc. The analysis also allows for the appropriate planning of preventive service actions, planning warehouse stocks, determining the cost-effective operation time, etc. Reliability prediction analysis is mainly used to assess the technology used, construction and quality of components and subassemblies used in the construction of a given energy storage. The risk of failure in each of the energy storage subsystems is quantitatively estimated on the basis of data for the model of basic components, i.e. the battery cell or BMS. This model allows to indicate the possibility of reducing the risk through the selection of components or the use of redundant solutions.

FMEA analysis identification of risk, its effects and causes of occurrence, and then classification and assessment in relation to other risks. It allows to qualitatively determine the importance of individual emergency modes and determine their importance for the failure rate of the energy storage. FTA allows for the analysis of dependencies between events causing a potential failure risk.

REFERENCES

[1] European Commission, The European Green Deal: COM(2019) 640 final. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=PL (accessed: Feb. 17 2023.513Z).

[2] European Commission, Fit for 55. [Online]. Available: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (accessed: Feb. 17 2023.045Z).

[3] European Commission, Timeline - European Green Deal and Fit for 55. [Online]. Available: https://www.consilium.europa.eu/en/policies/green-deal/timeline-european-green-deal-and-fit-for-55/ (accessed: Feb. 17 2023.128Z).

[4] Przybyłowski Adam, "Sustainable Transport Planning & Development in the EU at the Example of the Polish Coastal Region Pomorskie," TRANSNAV-INTERNATIONAL JOURNAL ON MARINE NAVIGATION AND SAFETY OF SEA TRANSPORTATION, eISSN:2083-6481.

[5] P. Przybyłowski, A. Przybyłowski, and A. Kałaska, "Utility Method as an Instrument of the Quality of Life Assessment Using the Examples of Selected European Cities," Energies, vol. 14, no. 10, p. 2770, 2021, doi: 10.3390/en14102770.

[6] ZESTAs, ZESTAs. [Online]. Available: https://zestas.org/ (accessed: Feb. 17 2023.620Z).

[7] Ulstein Group, Battery powered hybrid solutions for ships | Fuel systems - Ulstein. [Online]. Available: https://ulstein.com/solutions/hybrid-power (accessed: Feb. 17 2023.287Z).

[8] ABB Marine, Energy Storage System. [Online]. Available: https://new.abb.com/marine/systems-and-solutions/electric-solutions/energy-storage (accessed: Feb. 17 2023.311Z).

[9] T. Abramowicz-Gerigk and Z. Burciu, "Application of Ship Motion Simulation in Reliability Assessment of Ship Entrance into the Port," TransNav, vol. 10, no. 4, pp. 613–617, 2016, doi: 10.12716/1001.10.04.10.

[10] T. Abramowicz-Gerigk and Z. Burciu, "Design and Operational Innovations in Adapting the Existing Merchant River Fleet to Cost-Effective Shipping," Polish Maritime Research, vol. 26, no. 4, pp. 157–164, 2019, doi: 10.2478/pomr-2019-0078.

[11] T. Abramowicz-Gerigk, Z. Burciu, and L. Hapke, "Innovative Project of Propellers and Thrusters Jet Loads during Ship Berthing Monitoring System," TransNav, vol. 13, no. 4, pp. 861–865, 2019, doi: 10.12716/1001.13.04.20.

[12] Z. Burciu, T. Abramowicz-Gerigk, W. Przybyl, I. Plebankiewicz, and A. Januszko, "The Impact of the Improved Search Object Detection on the SAR Action Success Probability in Maritime Transport," Sensors (Basel, Switzerland), vol. 20, no. 14, 2020, doi: 10.3390/s20143962.

[13] K. Kula and M. Tomera, "Control System of Training Ship Keeping the Desired Path Consisting of Straight-lines and Circular Arcs," TransNav, vol. 11, no. 4, pp. 711–719, 2017, doi: 10.12716/1001.11.04.19.

[14] K. S. Kula, "Automatic Control of Ship Motion Conducting Search in Open Waters," Polish Maritime Research, vol. 27, no. 4, pp. 157–169, 2020, doi: 10.2478/pomr-2020-0076.

[15] J. Lisowski and M. Mohamed-Seghir, "Comparison of Computational Intelligence Methods Based on Fuzzy Sets and Game Theory in the Synthesis of Safe Ship Control Based on Information from a Radar ARPA System," Remote Sensing, vol. 11, no. 1, p. 82, 2019, doi: 10.3390/rs11010082.

[16] J. Lisowski, "The Sensitivity of State Differential Game Vessel Traffic Model," Polish Maritime Research, vol. 23, no. 2, pp. 14–18, 2016, doi: 10.1515/pomr-2016-0015.

[17] J. Lisowski, "Comparison of Dynamic Games in Application to Safe Ship Control," Polish Maritime Research, vol. 21, no. 3, pp. 3–12, 2014, doi: 10.2478/pomr-2014-0024.

[18] A. Przybyłowski, "Sustainable urban mobility planning: Gdynia city case study," EiP, vol. 17, no. 2, p. 195, 2018, doi: 10.12775/EiP.2018.014.

[19] Battery University, Types of Lithium-Ion Batteries. [Online]. Available: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion (accessed: Feb. 17 2023.210Z).

[20] "LECLANCHE-plaquette-G-NMC-KMWEB," [Online]. Available: https://www.leclanche.com/wp-content/uploads/2020/10/LECLANCHE-plaquette-G-NMC-KMWEB.pdf

[21] K. Kim, K. Park, G. Roh, and K. Chun, "DC-grid system for ships: a study of benefits and technical considerations," Journal of International Maritime Safety, Environmental Affairs, and Shipping, vol. 2, no. 1, pp. 1–12, 2018, doi: 10.1080/25725084.2018.1490239.

[22] L. Piechowski, A. Muc, and J. Iwaszkiewicz, "The Precise Temperature Measurement System with Compensation of Measuring Cable Influence," Energies, vol. 14, no. 24, p. 8214, 2021, doi: 10.3390/en14248214.

[23] A. Muc, J. Iwaszkiewiczki, P. Mysiak, and L. Piechowski, "System zasilania falowników wielopoziomowych wykorzystujący wielopulsowe prostowniki z dławikami sprzężonymi magnetycznie," ELECTROTECHNICAL REVIEW, Volume: 97, Issue: 2, no. 2, pp. 72–76, 2021, doi: 10.15199/48.2021.02.18.

[24] M. T. Hartman, "Selected elements of comparison analyse of multilevel voltage inverters," PRZEGLAD ELEKTROTECHNICZNY, Volume: 84, Issue: 4, pp. 1–3, 2008.

[25] M. T. Hartman, "Orthogonality of functions describing electric power quantities in Budeanu's concept," PRZEGLAD ELEKTROTECHNICZNY, Volume 87, Issue 1, Page: 14-18, 2011.

[26] M. T. Hartman and D. Wojciechowski, "Emanuel's method versus Iliovici's method for reactive power compensation in passive-active power conditioning scheme," in 2013 International Conference-Workshop Compatibility And Power Electronics, Ljubljana, Slovenia, Jun. 2013 - Jun. 2013, pp. 92–96.

[27] P. Stawczyk and S. Karys, "Three-phase one-branch controlled bridge rectifier for permanent magnet AC synchronous generator," in 2016 10th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Bydgoszcz, Poland, Jun. 2016 - Jul. 2016, pp. 450–454.

[28] S. Karys, Ed., Selection of Resonant Circuit Elements for the ARCP Inverter. 2009 10TH INTERNATIONAL CONFERENCE ON ELECTRICAL POWER QUALITY AND UTILISATION (EPQU 2009): IEEE345 E 47TH ST, NEW YORK, NY 10017 USA, 2009.

[29] Adamantios Mettas, Design for Reliability: Overview of the Process and Applicable Techniques, 2010. [Online]. Available: https://www.researchgate.net/publication/279484301_Design_for_Reliability_Overview_of_the_Process_and_Applicable_Techniques
[30] Understanding Design for Reliability (DfR) in Chip Making Processes | Synopsys Cloud. [Online]. Available: https://www.synopsys.com/cloud/insights/design-for-reliability.html (accessed: Feb. 27 2023).
[31] Design for Reliability: Overview of the Process and Applicable Techniques - ReliaSoft. [Online]. Available: https://www.reliasoft.com/resources/resource-center/design-for-reliability-overview-of-the-process-and-applicable-techniques (accessed: Feb. 27 2023).
[32] AIRBUS France - Eurocopter, FIDES guide 2009 Edition A September 2010: Reliability Methodology for Electronic Systems.
[33] A methodology for components reliability | FIDES. [Online]. Available: https://www.fides-reliability.org/ (accessed: Feb. 24 2023).
[34] S. Hajeforosh, Z. Nazir, and M. Bollen, “Reliability Aspects of Battery Energy Storage in the Power Grid,” in 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), The Hague, Netherlands, Oct. 2020 - Oct. 2020, pp. 121–125.