Reliability assessment of variable speed induction motor drive with fault tree analysis

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***Abstract* — A model for assessment of the reliability, of a variable speed drive with an induction motor, is presented in the paper. The relationship between the causes of failures and their effects on the drive system has been analyzed using failure modes and effects analysis (FMEA) and fault tree analysis (FTA).**

Keywords — FMEA, FTA, induction motor, reliability indicators, variable speed drive.

I. Introduction

Maintaining the reliability of electrical systems within a given range is quite a complex task given the statistical and probabilistic nature of the reliability indicators. The difficulty of this task is conditioned, on the one hand, by the increasing requirements for maintaining reliable performance and, on the other, by the increasing complexity of modern electrical systems. These features require the calculation of the reliability of systems with a high accuracy, which requires long tests, a very good organization for collecting, processing, and analysis of information on the maintenance, repair, causes of faults and the technical condition of the facilities in operation [1].

Variable speed drive (VSD) systems with induction motors are widely used in all production systems. Therefore, ensuring and improving the reliability of electrical drive performance, while maintaining high technical and economic parameters such as power factor, efficiency, and dynamic performance, plays an important role in reducing operating costs. The reliability of the drive systems is planned in the design process, ensured during their construction, and is used-up and maintained in given limits during their operation. Reliability should be considered as a complex operation-characteristic that may include: availability, durability, maintainability, and combinations of these characteristics.

Studies show that more than 60% of the operating costs associated with a product are due to the fact that the maintenance programs implemented are reactive (not preventive or predictive) and the number of repairs is increasing over time. Therefore, solving the problem of effective maintenance procedures can lead to operational costs savings. From this, it can be concluded that in order to improve the reliability of electric drives in operation, an analysis must be made and maintenance procedures must be designed so that they are effectively related to reliability indices [2, 3].

There are a number of reliability assessment techniques that can be used to obtain the desired results: Reliability predictions, failure modes, and effects analysis (FMEA), failure tree analysis (FTA), reliability block diagrams (RBD) analysis, and Markov analysis. These techniques depend on the type of system, time, cost, and what results are needed to determine the reliability of the system.

II. Failure modes and effects analysis

FMEA is part of the inductive methods for assessing the reliability and safety of the system. This method consists of dividing the system into components in order to assess which elements can fail, how and why failures occur, and ultimately to determine the consequences of each failure. FMEA is one of the most widely used reliability assessment methods, focusing on the design and assessment of the impact that failure has on system performance and safety [4].

Failure modes and effects analysis is often one of the first steps in assessing the reliability of systems. It includes the consideration of the largest possible number of elements, units, and subsystems in order to determine the type of possible failures and the probability of their occurrence, their causes, and consequences. Analysis with the help of FMEA is performed in the following sequence: development of a block diagram of the system, identification of possible faults and the reasons for their occurrence, establishment of a procedure for detecting faults, and summarizing all the information in tabular form.

The results obtained from the conducted FMEA analysis of adjustable electric drive with induction motor are shown in Table 1. The adjustable electric drive is divided into 12 separate elements, 22 possible damages of the electric drive elements, and the reasons that cause them are considered.

FMEA analyses can be grouped into four main categories, according to the analyzed objects and the approach to performing the analysis:

- System - examines the product at the system level, in terms of the integration of its subsystems and components, their relationships and interactions with other systems, including the environment and the user. The focus is on the functions and interconnections that are unique to the system as a whole.

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TABLE I. FMEA TABLE OF AN ADUSTABLE SPEED INDUCTION MOTOR DRIVE

Element	Fault type	Failures causes	Failure effects		Fault detection
			for the subsystem	for whole system	
E1 - Bearings and bearing housings	F1 - Misaligned bearing houses; F2 - Loss of lubrication; F3 - Incorrect coupling/loading; F4 - Cracks in the bearing houses	C1 - Deficient mounting; C2 - Large clearance bearing/bearing box; C3 - Overheating; C4 - Impure lubricant; C5 - Bad lubricant circulation; C6 - Excessive external forces; C7- Mechanical damages; C8 - Eccentricity	The moving part (Rotor) is affected	The whole system is affected	Tests during the assembly phase; Regular tests during exploitation
E2 - Stator ferromagnetic core	F5 - Insufficient core clearance; F6 - Electrical connection between adjacent laminations	C1 - Deficient mounting; C2 - Large clearance bearing/bearing box; C3 - Overheating; C9 - Aging of the insulation layers between the laminations	The entire machine is affected	The whole system is affected	Tests during the assembly phase; Regular tests during exploitation
E3 - Stator winding	F7 - Winding interruption; F8 - Inter-turn short circuit; F9-Connection interruptions	C10 - Vibrations; C11 - Frequent start-ups; C12 - Dynamic effect of the high current during start-up or plugging; C13 - Errors appearing since manufacturing stage	The entire machine is affected	The entire machine is affected	Tests during the assembly phase; Tests during the instalation phase;Regular tests during exploitation
E4 - Inslulation	F10 - Insulation electric breakdown	C1 - Deficient mounting; C11 - Frequent start-ups; C14 - High/Low temperature; C15 - High/Low humidity	High risk for serious machine damage		Tests during the assembly phase;Tests during the installation phase; Regular tests during exploitation
E5 - Rotor ferromagnetic core	F5 - Insufficient core clearance; F6 - Electrical connection between adjacent laminations	C1 - Deficient mounting; C2 - Large clearance bearing/bearing box; C3 - Overheating; C8 - Eccentricity; C9 - Aging of the insulation layers between the laminations	The moving part (Rotor) is affected	The whole system is affected	Tests during the assembly phase; Regular tests during exploitation
E6 - Rotor winding	F11 - Broken rotor bars; F12 - Craked end rings	C10 - Vibrations; C11 - Frequent start-ups; C12 - Dynamic effect of the high current during start-up or plugging; C13 - Errors appearing since manufacturing stage	The moving part (Rotor) is affected	The whole system is affected	Tests during the assembly phase; Regular tests during exploitation
E7 - Housing with mounting shoes	F13 - Housing cracks; F14 - Exceeded overall dimensions	C13 - Errors appearing since manufacturing stage; C14-Thermal shock strain; C15-Over-torque	The stator housing is affected	The system can operate with such a fault	Tests during the assembly phase; Regular tests during exploitation
E8 - Ventilation system	F15 - Blocked cooling fan; F16 - Blocked or deformed ventilation chanels; F16 - Failure of the temperature sensors (for machines with external ventilation)	C1 - Deficient mounting; C7- Mechanical damages; C10 - Vibrations; C11 - Frequent start-ups;	The entire machine is affected	The entire machine is affected	Checks in exploitation
E9 - Rectifier	F17 - Diode fault (short or open circuit)	C3 - Overheating; C16 - High supply voltage; C17 - High current	The power supply of the machine is affected	The power supply of the machine is affected	Checks in exploitation
E10 - DC - link	F18 - DC-link capacitor fault	C3 - Overheating; C16 - High supply voltage; C18 - Improper mounting; C19 – Sudden current transients due to rectifier or inverter fault	The power supply of the machine is affected	The power supply of the machine is affected	Tests during the assembly phase;Tests during the installation phase; Regular tests during exploitation
E11 - Inverter	F19 - IGBT switching failure; F20 - Gate unit supply failure	C3 - Overheating; C20 - High voltage; C17 - High current; C21 - Loss of control signal; C22 - Loss of operational power supply	The entire machine is affected	The entire machine is affected	Tests during the assembly phase;Tests during the installation phase; Regular tests during exploitation
E12 - VFD Controller	F21 - Missing feedback signal; F22 - Conrol system failure	C13 - Errors appearing since manufacturing stage; C22 - Loss of operational power supply;	High risk for serious machine damage		Tests during the assembly phase;Tests during the installation phase; Regular tests during exploitation

- Constructive - oriented entirely to the design of the developed object, this analysis is related to design issues, in order to improve the functionality and ensure reliable and safe operation of the product;
- Technological - considers the production and assembly processes, in order to optimize them to achieve the design requirements defined by the design, with minimized time, waste and material used;
- Specific - FMEA is sometimes used as an initial assessment to select a conceptual option, considering and comparing alternative design solutions or possible changes.

III. Fault Tree Analysis

Fault Tree Analysis (FTA) is a tool for causal analysis of the occurrence of certain events. These types of models are used to diagnose and evaluate the reliability of large, complex and dynamically changing technical systems. Through the fault tree, all the features of the technical system can be modeled, including structural, software and algorithmic, and human and environmental effects.

Fault tree analysis is a deductive (top to bottom) method aimed at identifying causes or combinations of causes that can lead to a particular event. It is very appropriate when it is necessary to establish and demonstrate how the system will react to a particular fault or malfunction, but it cannot be used to predict all possible failures. Only one type of failure can be analyzed with one failure tree. A separate tree should be created for each possible failure type. This drawback is eliminated by compiling separate fault trees for the individual system elements and grouping them into a common model [5].

The fault tree is a systematized graphical model that uses logical elements to model a variety of combinations of failures, faults, errors, and normal events (states) leading to unwanted initial states (system failures). Using the strict and structured fault tree construction methodology allows the analyzer to model unique combinations of failures and errors that can cause the initial event to occur. However, the proper construction of the model requires in-depth knowledge of the analyzed system and the algorithm of its operation.

Many of the concepts used in constructing the fault tree are taken from graph theory. The fault tree of the adjustable electric drive, built on the basis of the conducted FMEA analysis, is shown in Fig.1. The initial event (system failure) is called the root of the fault tree. In the intermediate levels of the tree are the immediate causes (blocks, elements), which alone or in combination lead to the occurrence of the initial event and are related to the latter through logical elements. In the fault tree shown in Fig. 1, the intermediate levels correspond to the individual units and elements of the adjustable electric drive, as these units and elements are modeled by separate subsystems (sub-trees). The realization of the model through separate sub-systems allows modeling the reliability indicators both for the respective sub-system (when evaluating different constructions or topologies) and for the whole drive.

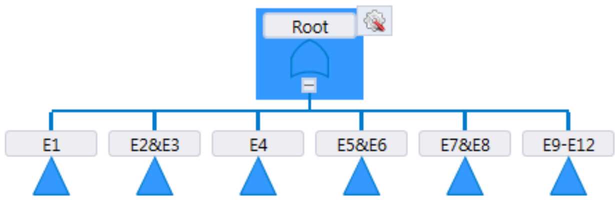

Fig. 1. Fault tree of the variable speed induction motor drive

The models of some of the subsystems in the fault tree of the adjustable speed electric drive are shown in Fig. 2, Fig. 3 and Fig. 4. The lowest level events, are called base events or failure tree leaves and correspond to the reasons for failure.

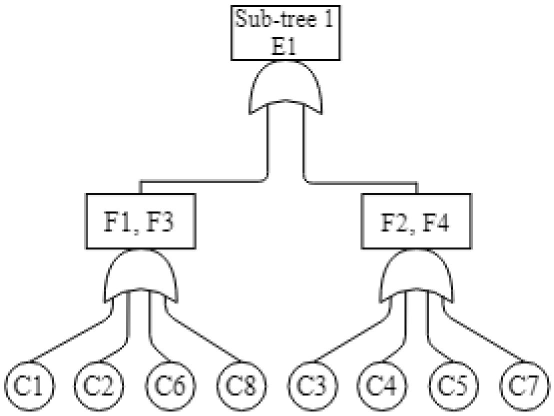

Fig. 2. Sub-tree Bearings and bearing housings

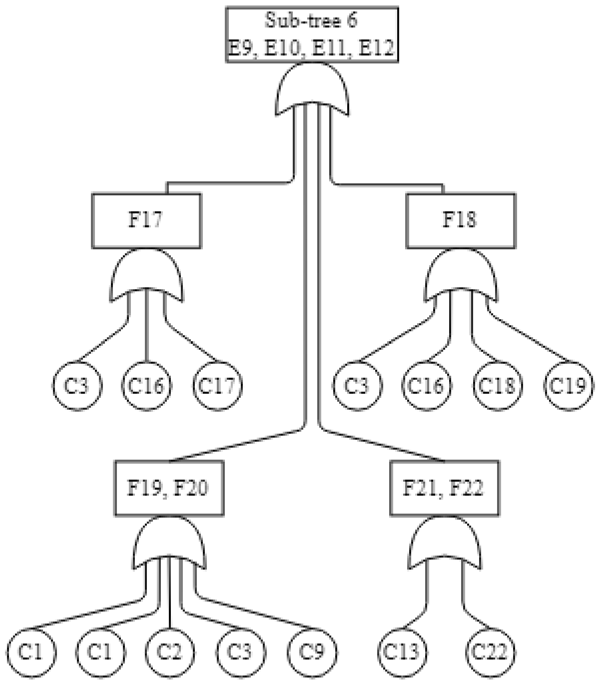

Fig. 3. Sub-tree Variable frequency drive

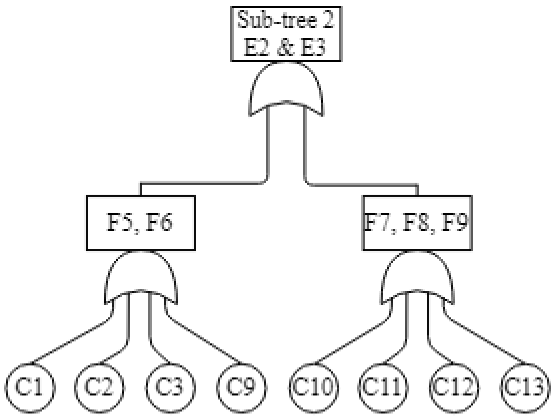

Fig. 4. Sub-tree stator windings and magnetic core

The graphical model is transformed into a mathematical model in order to calculate the values of the reliability indicators of the system. The graphical (mathematical) model developed in this way allows obtaining the time distributions of the probabilities of failure and failure-free operation, as well as indicators such as the expected number of failures, system downtime, and the intensity of conditional and unconditional failures.

The fault tree of the adjustable electric drive is modeled by using the TopEvent FTA software product. This software allows setting different models of change the probability of failure of an element caused by a specific reason (Fig. 5). This feature allows the modeling of the change in the reliability indicators to be performed on the basis of theoretical distributions of the probability of failure, operational data or a combination of both types of input data.

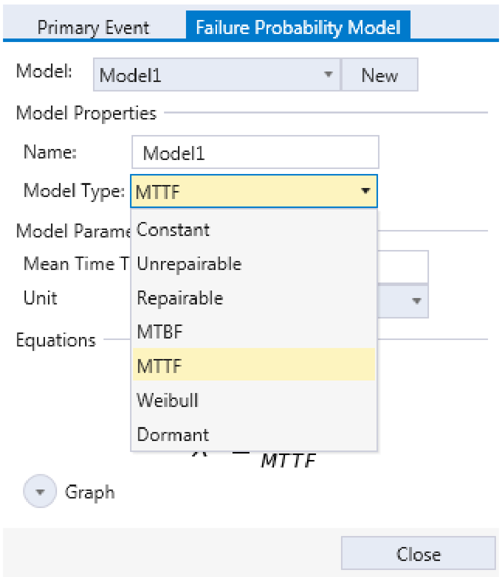

Fig. 5. Failure probability modelling functions

In order to achieve high accuracy in predicting the reliability indicators, a combination of methods is used to determine the probabilities of failure or failure-free operation of the components of the system that have the greatest impact on the overall reliability. The probabilities of failure or failure-free operation are estimated on the basis of the design and operating parameters of the elements of the electric drive.

A. Bearings

The reasons leading to the failure of bearings are various in their physical nature and the degree of their influence on the reliability characteristics of the bearing. The probability of bearing fault for a given operating time *t* is subject to Weibull's distribution law:

$$P(t) = e^{\left(-\frac{t}{6{,}84 L_h}\right)^{1{,}17}}, \qquad (1)$$

where: $L_h = \frac{(C/Q_b)^k}{60n} 10^6$ is the 90% service life of the bearing;

C – dynamic loading capacity of the bearing;

Q_b – equivalent dynamic loading of the bearing;

k – coefficient depending on the bearing type $k=3$ for ball bearings and $k=3{,}333$ for roller bearings;

n – rotation speed.

The dynamic load Q_b depends on the radial and axial forces acting on the motor shaft and is calculated according to the diagram shown in Fig. 6.

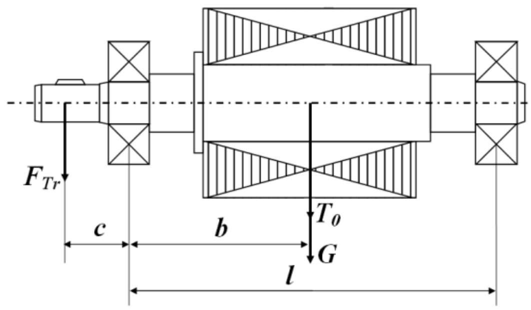

Fig. 6. Bearing dynamic load scheme

The maximum radial load on the bearing is determined by the formula:

$$R = \frac{(G + T_0)b}{l} + k_0 F_{Tr}, \qquad (2)$$

where: G is the weight of the rotor;

T_0 – force caused by the one-sided attraction of the rotor;

F_{Tr} – radial force in the transmission system;

$k_0 = c/l$ for the drive end of the shaft $k_0 = (c+l)/l$ for the non-drive end of the shaft [6].

B. *Inter-turn insulation*

In most cases, failures of general-purpose induction motors occur due to damage to the windings, which are distributed as follows: damage to the inter-turn insulation 73%, damage to the ground wall insulation - 10%, damage to the main insulation between phases - 17%. It follows that the reliability of the windings of induction motors is determined mainly by the reliability of the inter-turn insulation. The considered method of calculation allows estimating the probability of failure-free operation of the inter-turn insulation for a period of time during which there is no intensive aging of the insulation, i.e. for the period during which no defects appear due to the influence of operational factors. For asynchronous motors operating in rated modes, this time period is 10 000 hours. The probability of trouble-free operation of the inter-turn insulation is obtained on the basis of the design characteristics of the winding - wire diameter, average winding length, number of turns in one stator channel, etc. The reliability (probability of failure-free operation) of the inter-turn insulation can be determined by the dependence:

$$R(t) = P(t) = [1 - q(U_{mv})]^N , \qquad (3)$$

where: $q(U_{mv})$ is the probability of a breakdown in a single section of the inter-turn insulation over a period of time t_{est};

t_{est} - time period for which the estimation is made;

U_{mv} - maximum value of the phase voltage, taking into account the occurring switching overvoltages;

N – number of single sections of the inter-turn insulation in the winding (number of per phase) [7].

C. *Ground wall and phase to phase insulation*

The main criterion for the performance of the insulation is the breakdown voltage U_{br}. However, the determination of the breakdown voltage value is related to the destruction of the insulation, so it is necessary to use such performance criteria that can be measured without damaging the electrical insulation. Such criteria include active insulation resistance, insulation capacity, dissipation factor, amplitude and frequency of pulse-acoustic emissions, and others. During operation, the insulation often works in harsh environmental conditions. Insulation degradation occurs as a result of heating, mechanical stress (vibration, pressure, shock, etc.), the influence of moisture, aggressive environments, and other factors. Of these factors, the temperature has the most serious influence due to the thermal aging of the insulation. To assess the influence of temperature on the service life of the insulation, the formula can be used.

$$T = T_0 . 2^{\frac{\Theta}{\Delta\Theta}} , \qquad (4)$$

where: T_0 is conditional service life of the bearing Θ=0°C and ΔΘ=8°C;

Θ - operating temperature of the motor;

ΔΘ – absolute value of temperature rise that causes reduction of the service life by 50% [8].

The value of the absolute temperature rise ΔΘ depends on the thermal class of the insulation. The values of ΔΘ for the most widely used insulation thermal classes are given in Table 2.

TABLE II. DEPENDENCE OF ΔΘ ON THE INSULATION TEMPERATURE CLASS

Insulation temperature class	A	E	B	F	H	C
Maximum operating temperature Θ	105	120	130	150	180	>180
Temperature rise ΔΘ	8	9,14	9,9	11,8	13,7	-

Chemically active substances such as acids, bases, and their solutions have an adverse on the insulation. The oils and vapors of solvents that fall on the insulation lead to its intense degradation. The influence of temperature, humidity, and aggressive environments on the service life of the insulation is assessed by empirical dependence:

$$T = Ae^{\frac{B}{Q}} C^{-m} \eta^{-n} , \qquad (5)$$

where: A is a coefficient depending on the physical and chemical properties off the insulation material;

C – concentration of chemically active substances;

η – relative humidity;

B, Q and m, n are empirical coefficients.

D. *Variable frequency converter*

Quantitative assessment of the reliability of power electronic converters is essential in determining the possibilities for coordination of a given design of the converter with certain specifications. This assessment also serves as a criterion for comparing different topologies, control strategies, and components used in power electronic converters. All analyzes of the reliability of electronic converters include some form of a model of the object, which can be at the component level or at the system level. The system-level reliability model provides a clear picture of functional relationships and provides a framework for developing quantitative assessments of system reliability. The mean time to failure MTTF is the most often used indicator for assessment of the reliability of frequency converters. It can be determined on the basis of the failure rates of the individual components, using the dependence:

$$MTTF_{FC} = \frac{1}{6\lambda_D + \lambda_C + 6\lambda_T} , \qquad (6)$$

where: λ_D, λ_C and λ_T are the failure rates of the diodes (rectifier), capacitors (intermediate DC-link), and IGBT transistors (inverter).

A distinctive feature of the FTA method is the ability to determine the coefficients of the so-called importance factors of the component, which classifies the components in terms of their impact on system reliability [9].

The importance factor (marginal importance factor) of the i-th component of the system at time t can be determined by the formula:

$$I^B(i|t) = \frac{\partial h(p(t))}{\partial p_i(t)}, \qquad (6)$$

where: $h(p(t))$ is the reliability function (fault-free operation probability);

$p_i(t)$ - the function of the reliability of the i-th component.

The diagnostic importance factor (DIF) of the individual elements is the part of the probability of failure (unreliability), which includes the failure of the i-th element of the system. The diagnostic importance factor is defined as:

$$DIF_i(t) = \frac{q_i(t).Q(t)\big|_{q_i(t)=1}}{Q(t)}, \qquad (7)$$

where: $q_i(t)$ is the failure probability of the i-th component of the system;

$Q(t)$ and $Q(t)\big|_{q_i(t)=1}$ are the generalized probability of system failure and the probability of system failure at $q_i(t)=1$.

The result for the probability of failure obtained during the simulation with the software product for a time period of evaluation $t_{est} = 10000h$ is shown in Fig.7.

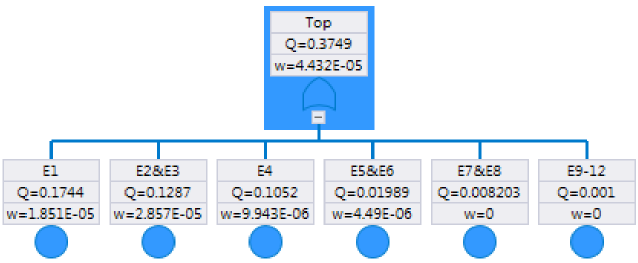

Fig. 7. Results for the unavailability of the of the variable speed induction motor drive

The results for the other reliability indicators of the adjustable speed electric drive obtained in the simulation are shown in Table 3.

TABLE III. RESULTS FOR RELIABILITY INDICATORS OF THE VARIABLE SPEED INDUCTION MOTOR DRIVE

Unavailability	0,374908
Availability	0,625092
Average Unavailability	0,174044
Unreliability	0,369107
Reliability	0,630893
Unconditional Failure Intensity. Units [1/hour]	4,43E-05
Average Unconditional Failure Intensity. Units [1/hour]	3,66E-05
Conditional Failure Intensity. Units [1/hour]	7,09E-05
Average Conditional Failure Intensity. Units [1/hour]	4,61E-05
Expected Number of Failures	11,365713
Total Down Time [hours]	1340,44
Probability of Failure on Demand (PFD)	0,374908
Average Probability of Failure on Demand (PFD Avg)	0,174044
Probability of Failure per Hour (PFH)	4,43E-05
Average Probability of Failure per Hour (PFH Avg)	3,66E-05

Table 4 presents the results for the reliability indicators of the individual elements, the degree of contribution of the elements to the overall reduction in reliability, and the importance factors of the elements.

TABLE IV. RESULTS FOR RELIABILITY INDICATORS OF THE INDIVIDUAL ELEMENTS

Minimal cut set	**E1**	**E2&E3**	**E4**	**E5&E6**	**E7&E8**	**E9-12**
Unavailability	0,17441	0,12868	0,10516	0,01989	0,0082	0,08328
Contribution	0,33565	0,24764	0,20237	0,03827	0,01578	0,16027
Marginal importance factor	0,69479	0,65832	0,64101	0,58525	0,57835	0,62571
Critical importance factor	0,28421	0,19868	0,15809	0,0273	0,01112	0,12221
Risk reduction worth	1,39705	1,24794	1,18778	1,02807	1,01120	1,13923
Diagnostics importance factor	0,40906	0,30179	0,24663	0,04664	0,01923	0,19532

CONCLUSION

The obtained model for reliability assessment of the variable speed drive allows obtaining the reliability indicators for the system and its individual elements and their change over time. The model has high flexibility in the way of presenting the input data settings (failure probabilities, meantime between failures, etc).

The results obtained from determining the importance factor of the components and the diagnostic factor of the individual elements can be used in the design of the built-in diagnostic systems and in the development of an optimal program of the diagnostic process.

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