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OPTIMIZATION OF MAINTENANCE OF GENSETS USING EXPERT SYSTEMS FOR FAULT DIAGNOSIS

OPTIMIZACIJA VZDRŽEVANJA GENERATORSKIH ENOT Z UPORABO EKSPERTNEGA SISTEMA ZA DIAGNOSTICIRANJE NAPAK

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Abstract

The usage of expert systems simplifies the determination of the technological condition of the genset, i.e. the fault diagnosis. This results in the optimization of maintenance in technical workshops, which particularly comes into play in military systems in which a great number of technical resources must be maintained. The expert system is based on the "Knowledge Base", obtained by researching and collecting data from professionals who have years of experience in the maintenance of electric generators. The Knowledge Base is made to list the most common faults first; then the hypotheses are associated with a certain probability. The processing of collected information is carried out according to Bayes' method, which is based on the classical probability theory. In order to decide upon a failure happening within the context of certain facts, a calculation of true values is carried out, which will help in developing an ideal diagnostic program during further research.

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Povzetek

Uporaba ekspertnega sistema za diagnosticiranje napak v generatorskih enotah omogoča poenostavitev določitve stanja posamezne enote in morebitno diagnostiko napak. Rezultati optimizacije vzdrževanja v servisnih delavnicah so izredno pomembni v vojaških sistemih, kjer je potrebno ohranjati nenehno večje število naprav v stanju pripravljenosti. Ekspertni sistem temelji na podatkovni bazi znanj, ki je pridobljena preko zbiranja podatkov iz večjega števila opravljenih preizkusov in izkušenj strokovnjakov z večletnimi izkušnjami s področja diagnostike generatorskih enot. Predlagan ekspertni sistem pri vzdrževanju naprav izvede pregled seznama najpogostejših napak in samodejno izvede diagnostiko z določeno verjetnostjo. Obdelava zbranih podatkov poteka po Bayes-ovi metodi, ki temelji na klasični teoriji verjetnosti. Za določitev možnosti napake na podlagi zbranih dejstev se izvede izračun dejanskih vrednosti, kar omogoča nadgradnjo ekspertnega sistema z nadaljnjimi raziskavami.

1 INTRODUCTION

This paper shows the optimization of the maintenance system of gensets in technical workshops. It is particularly suitable for use in the armed forces, where a great number of mobile gensets is present. They are necessary in case of greater damage and failures in the electrical system, which may occur in the event of natural disasters and war. Therefore, their reliability and availability are vital, in both civilian and the military structures. Due to that, regular maintenance is being carried out, which requires certain financial resources. In addition to such resources, an important issue is also the involvement of specialized staff in the maintenance process. Since a large amount of resources is involved, every simplification of the maintenance procedure, as small as it may be, is essential in saving financial resources and engagement of material, technical and human resources.

In complex systems, such as gensets maintenance processes, the identification of the technical conditions of equipment is the most time consuming, i.e. fault diagnosis.

To formulate a diagnostic algorithm of the equipment states, a systematic study of the behaviour in good working condition and during a failure has been carried out. Collecting data on the failures and their indicators was derived from three key sources:

- technical documentation with the regulations on the quality of the product,
- documents about receiving resources for repair in the past five years, from which the reasons of arrival can be seen, as well as the methods carried out in order to correct the deficiencies,
- by conducting research among the employees with years of experience in the maintenance of gensets.

By consolidating the collected data, a “Knowledge base” has been formed, shown partially in Table 3. The data were processed according to Bayes' theorem, and true values were obtained, which will help in further research to develop an ideal program and special instructions for searching and removing irregularities in the assembled form. This provides a comprehensive understanding of the resources’ technical condition before dismantling and achieves the greatest effect in reducing the duration of a repair. In addition to that, the described procedures enable the determination of the scope and complexity of repair and the necessary tools, equipment and spare parts in advance.

2 GENSET MAINTENANCE PROCESS

The maintenance process is a complete series of organizational and technical measures exploits to establish the functionality of faulty resources, i.e. to repair corrupted technical features after the resources' usability has passed or after the appearance of random defects. The maintenance process consists of a series of different steps connected with the repair, manufacturing of parts, their control, storage and transport. This process also includes the development of technical documentation, planning, standardization, the supply of materials, spare tools and accessories as well as the refinement and development of technological processes and diagnostic methods, *[1]*.

Due to the large number of technical resources in military systems, methods are continuously elaborated, which contributes to the optimization of maintenance and the work productivity of technical workshops. The important point in optimization is the shortening of repair times, which can be significantly affected by the improvement of technological processes and diagnostic methods. For now, the greatest effect is achieved by an elaborated principle of repairing a set (Figure 1), in which expert systems for failure diagnosis can be applied, which significantly reduces the overall repair time.

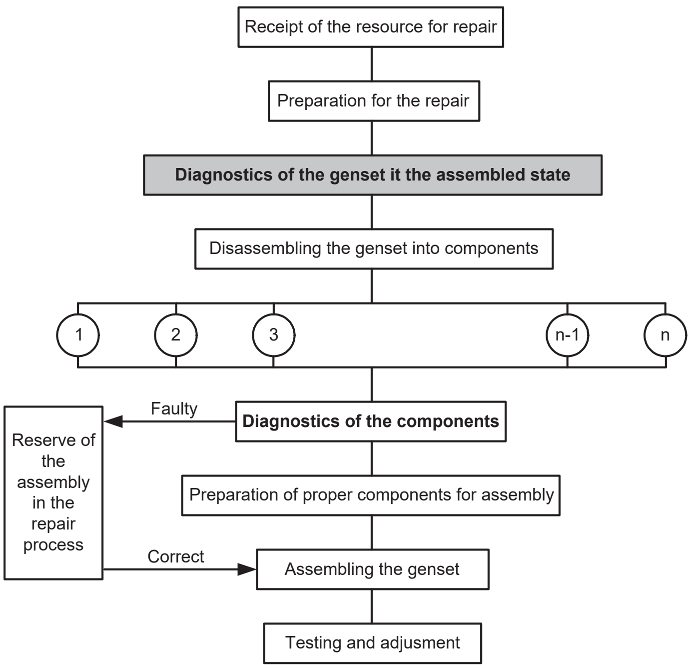

Figure 1: *Schematic of the technological process on the principle of repairing a set*

On receipt of the resource for repair, a protocol for the description of the status is made. Next, the repair and diagnostics are prepared in the assembled state, which represents a complex problem, especially in complex systems such as gensets. Their complexity lies in that they are composed of several technically different subsystems: diesel engine, synchronous generator with excitation, control protection, and connecting and other circuits. This means that for their diagnostics the criteria which mark the permissible and impermissible states of each mentioned subsystems must be known. Therefore, in order to reduce the time to detect faulty parts, it is necessary to develop an optimal program for fault diagnostic and on the basis of that program to prepare a summary of special instructions for the search for faulty parts.

The use of special instructions for troubleshooting turns random search steps into pre-planned sequences of actions. It is usually easier to locate defective parts when checkpoints are determined, which are used to check for permitted values of technical requirements.

The main tasks of diagnostics in the assembled state are:

- check of the working ability,
- identification of faulty circuits,
- determination of the circuits that need no repair.

The diagnostics in the assembled state is carried out according to the appropriate instructions for each type of genset. The data on irregularities with which the resource is sent and the data on the time and mode of exploitation help to repair diagnose the fault.

The diagnosis is carried out in a specific order, which ensures the completeness of the expected checks and excludes the repetition of certain other checks.

A properly conducted diagnostics provides a comprehensive insight into the state of the resource and enables:

- determination of the scope and complexity of the repair,
- determination of necessary tools, equipment and spare parts,
- determination of employees with certain qualifications (electricians, machinists, mechanics),
- definition of the time required for the repair.

After the diagnostics and detailed insight into the state of the resource, the disassembling continues with the next, so far mostly well elaborated step according to the schematic of the technological process from Figure 1.

3 EXPERT SYSTEM FOR DIAGNOSIS OF THE GENSET STATE

3.1 Knowledge base

The expert system for fault diagnosis is based on a reliable "Knowledge base", in which the diagnostic features are shown. These data were obtained by studying the standard and the manufacturer's technical documentation, *[2, 3, 4]*, workshop production orders from the previous five years and the implementation of surveys of employees who have years of experience in the maintenance of gensets. The expert system is designed to ensure the rapid determination of genset condition (correct, indication of failure-needed maintenance, fault-needed service). This is an additional tool that connects users and maintenance technicians. Typically, these are two technical levels and are not at the same location neither under the same management. The user (a soldier in the described case) with a basic knowledge of operation during the daily work notes "disturbances" in the work of the genset, which are categorized in the group of Easily Detectable Failures (EDF). These are linguistic variables with distinctly subjective characters; they are shown in Table 1.

Table 1: *Example of linguistic variables that describe the group of Easily Detectable Failures with distinctly subjective character*

The engine can't start or has difficulties starting
The engine stops a short time after the start
Low engine performance
Low oil pressure
The engine rotational speed drops fast
The engine overheats
The engine throws out thick black smoke
Low generator voltage idling at nominal speed
The generator produces no voltage
The main circuit breaker can't be turned on
Checking the static frequency characteristics - doesn't fulfil the conditions

Based on the detection of disorders from the EDF group, the overseer Expert System focuses further procedures toward maintenance technicians, who represent a higher level of technical knowledge of the genset (a technician in the Repair Institute in the described case). In this process, linguistic variables that describe disorders categorized in group of Hard Detectable Failures (HDF) shown in Table 2 and associated probability of failure from the knowledge base of an expert system have been used.

The importance of resolving the problems of large logistics systems with the use of expert systems that conventional linguistic variables (shown in Tables 1 and Tables 2) convert into digital data should be emphasized. This enables the use of software tools for conducting the control, monitoring and planning of logistics in systems that spatially and hierarchically belong to different sub-systems of management. The general objective is to improve the management of the overall system (military systems in the described case).

Table 2: *Example of linguistic variables that describe a group of Hard Detectable Failures without subjective character*

Damaged fuel supply pipeline
Corroded or loosened connections on the battery
Discharged battery
Fault on the electric starter
Dirty fuel refining system
Dirty air refining system
Faulty injectors
Lack of oil in the motor
Dirty oil refining system
Faulty oil pump
Rotational speed regulator fault
Low engine compression
Loose contact on the voltage regulator
The generator is demagnetized
Faulty mode selector

In the Knowledge Base partially shown in Table 3, the most common faults are shown first, then the hypotheses are associated with a certain probability. The table is just a segment of the Knowledge Base, which will be further expanded during future research.

Table 3: *Knowledge Base with entered fault probabilities*

	Hypothesis p(H)		EASILY DETECTABLE FAILURES											
			The engine can't start or has difficulties starting	The engine stops a short time after the start	Low engine performance	Low oil pressure	The engine rotational speed drops fast	The engine overheats	The engine throws out black smoke	Low generator voltage idling at nominal speed	The generator produces no voltage	The main circuit breaker can't be turned on	Checking the static frequency characteristics - doesn't fulfil the conditions	Checking the static voltage characteristics -doesn't fulfil the conditions
HARD DETECTABLE FAILURES	Damaged fuel supply pipeline	YES	0.9	0.3	0.95		0.6	0.1					0.8	0.6
	p(H1)=0.2	NO	0.2	0.6	0.1		0.5	0.9					0.2	0.4
	Corroded or loosened connections	YES	0.7											
	on the battery p(H2)=0.05	NO	0.4											
	Discharged battery	YES	0.8											
	p(H3)=0.1	NO	0.2											
	Fault on the electric starter	YES	0.9											
	p(H4)=0.005	NO	0.2											
	Dirty fuel refining system	YES	0.6	0.9	0.99		0.8	0.1	0.1				0.8	0.6
	p(H5)=0.1	NO	0.5	0.2	0.05		0.3	0.95	0.95				0.2	0.4
	Dirty air refining system	YES	0.2	0.1	0.8		0.7	0.6	0.95					0.5
	p(H6)=0.1	NO	0.8	0.9	0.2		0.4	0.5	0.1					0.4
	Faulty injectors	YES	0.9	0.2	0.8		0.6	0.9	0.9				0.6	0.6
	p(H7)=0.05	NO	0.1	0.9	0.3		0.5	0.2	0.1				0.4	0.4
	Lack of oil in the motor	YES	0.05	0.9	0.1	0.99	0.6	0.95						
	p(H8)=0.01	NO	0.9	0.2	0.95	0.01	0.5	0.05						
	Dirty oil refining system	YES				0.95		0.4						
	p(H9)=0.05	NO				0.1		0.7						
	Faulty oil pump	YES				0.99		0.85						
	p(H10)=0.01	NO				0.05		0.2						
	Rotational speed regulator fault	YES	0.6	0.5	0.7		0.99	0.6	0.7				0.99	0.6
	p(H11)=0.1	NO	0.4	0.6	0.4		0.05	0.5	0.4				0.1	0.4
	Low engine compression	YES	0.9	0.1	0.9	0.8	0.7	0.95	0.7				0.9	0.6
	p(H12)=0.2	NO	0.2	0.9	0.2	0.2	0.4	0.1	0.3				0.1	0.4
	Loose contact on the voltage regulator	YES								0.9	0.7		0.6	0.9
	p (H13) = 0.01	NO								0.1	0.3		0.4	0.1
	The generator is demagnetised	YES									0.85			
	p(H14)=0.2	NO									0.2			
	Faulty mode selector	YES												
	p(H15)=0.05	NO												

3. 2 Bayes' theorem implementation

The processing of collected information is carried out according to Bayes' method, which is based on the classical probability theory. With the help of the conditional probability, the probability of an event "y" is determined; if it is known that the event "x" has occurred. Event "x" is considered a fact that is easily obtained, whereas "y" represents the probability of the state of the genset, i.e. the probability of a certain failure which needs to be defined. This probability is called “conditional probability”: $p(y|x)$.

$$p(y\,|\,x) = \frac{p(x \wedge y)}{p(x)} \tag{3.1}$$

If two events are independent, then:

$$p(x\,|\,y) = p(x) \tag{3.2}$$

$$p(y\,|\,x) = p(y) \tag{3.3}$$

According to the definition, the revolution, i.e. probability of the event “x” under the condition that “y” has occurred is:

$$p(x\,|\,y) = \frac{p(y \wedge x)}{p(y)} \tag{3.4}$$

$$From(1.3) \Rightarrow p(y \wedge x) = p(x\,|\,y)p(y) \tag{3.5}$$

Because of the commutativity:

$$p(x \wedge y) = p(x\,|\,y)p(y) \tag{3.6}$$

Including (1.6) in (1.1), we obtain the simplest form of Bayes' theorem:

$$p(y\,|\,x) = \frac{p(x\,|\,y)p(y)}{p(x)} \tag{3.7}$$

By expanding the members of the conditional probability, we get Bayes' theorem *[5]*:

$$p(y\,|\,x) = \frac{p(x\,|\,y)p(y)}{p(x\,|\,y)p(y) + p(x\,|\!\sim y)p(\sim y)} \tag{3.8}$$

From Bayes' theorem, we obtain the Bayesian method in production systems:

If “x” is true, the conclusion is “y” with the probability “p”.

With the help of Bayes' theorem, we can conclude the probability of “x”.

By interpreting this theorem with the formula (1.7):

- y of the theorem marks an evidence or a fact→E
- x of the theorem marks a hypothesis →H

$$p(H\,|\,E) = \frac{p(E\,\big|\,H)p(H)}{p(E)} \tag{3.9}$$

$$p(H\,|\,E) = \frac{p(E\,|\,H)p(H)}{p(E\,|\,H)p(H) + p(E\,|\!\sim H)p(\sim H)} \tag{3.10}$$

In order to decide upon the failure happening with certain facts, a calculation of real values is carried out, as it is elaborated in *[6]*, Chapter 7. For the purposes of determination of correct failure probabilities series of data were collected.

3. 3 Example case

In order to clarify functioning of the Bayes theorem, the implementation into Expert Systems for fault diagnosis procedures for one common event is presented.

Using genset for the energy supply of sensitive communications equipment requires frequency control of power supply by using built-in indicators' frequencies or portable devices for measuring frequencies. The user (soldier on the ground) noted that the frequency of power supply is outside the permitted areas: EDF → Checking the static frequency characteristics does not fulfil the conditions.

Based on that, the user logs in report into Expert System, which in addition to the description of failure also records the time, date, location of failure, and characteristics of genset (previously classified information in knowledge base).

- Case: Checking the static frequency characteristics – does not fulfil the conditions

Expert System based on knowledge base information of probability (Table 3 – shaded row and column) conduct following calculation:

$$p(H_5) = p(\text{dirty fuel refining system}) = 0.1 \qquad p(\overline{H}_5) = 0.9$$

$$p(E \mid H_5) = (\text{the test of the static frequency characteristics doesn't fulfil the conditions} \mid \text{dirty fuel refining system}) = 0.8$$

$$p(E \mid \overline{H_5}) = p(\text{the test of the static frequency characteristics doesn't fulfil the conditions} \mid \text{not dirty fuel refining system}) = 0.2$$

$$p(E) = p(\text{the test of the static frequency characteristics doesn't fulfil the conditions}) = p(E \mid H_5) \cdot p(H_5) + p(E \mid \overline{H_5}) \cdot p(\overline{H_5}) = 0.8 \cdot 0.1 + 0.2 \cdot 0.9 = \underline{0.26}$$

$$p(H_5 \mid E) = p(\text{dirty fuel refining system} \mid \text{if it is obvious that the test of the static frequency characteristic doesn't fulfil the conditions}) = \frac{p(E \mid H_5) \cdot p(H_5)}{p(E)} = \frac{0.8 \cdot 0.1}{0.26} = \underline{\underline{0.30769}}$$

$$p(H_5 \mid \overline{E}) = p(\text{dirty fuel refining system with the fact that it fulfils the static frequency characteristics}) = \frac{p(\overline{E} \mid H_5) \cdot p(H_5)}{p(\overline{E})} = \frac{(1-0.8) \cdot 0.1}{1-0.26} = \underline{\underline{0.02703}}$$

Comparing $p(H_5 \mid E)$ and $p(H_5)$ yields the following conclusion:

The fact that the test of the static frequency characteristics does not fulfil the conditions increases the probability of a dirty fuel refining system by approximately 3.1 times.

Table 4 shows the true values for the other cases when the test of the static frequency characteristics does not fulfil the conditions.

This means, by reading Table 4 and comparing the values to those in Table 3, we can, in addition to the abovementioned case, conclude the following:

The fact that the test of the static frequency characteristics does not fulfil the conditions increases the probability:

- of a damaged fuel supply pipeline by 2.5 times,
- of faulty injectors by 1.5 times,
- of a rotational speed regulator fault by 5.2 times,
- of a low engine compression by 3.5 times,
- of a loose contact on the voltage regulator by 1.5 times.

The same procedure must be used to treat the easily observable facts mentioned in Table 1 (and in the first row of Table 3). The given results are, after quick and easy processing by a computer, the foundation for developing an ideal diagnostic programs.

From Table 3 and the presented example case, it is evident that the static calculation checking the frequency characteristics is not associated with all failures listed in Table 2 (and in the left column of Table 3). This is consistent with the fact that, for example, failure of the starter has no effect on the stability of the frequency of the generator power supply.

Some failures have higher and some lower correlation with Easily Detectable Failures, which are listed in Table 1 (first line in Table 3). For example: checking static voltage characteristics is not associated with failure of the starter, whether associated with dirty fuel (because at nominal loads it can lead to instability of diesel engine operation) or the major collapse of genset drive rotational speed. This directly, to a large extent, affects the characteristics of genset frequency, and to a small extent, affects the stability of voltage, as shown in Table 3. The data were confirmed during measurements implemented at genset inspection, *[4].* It was determined that a voltage regulator retains a constant voltage to a certain degree of rotational speed collapse, but voltage deviation does noticeably occur at higher and faster changes in rotational speed.

Table 4: *Calculation of true values for all cases when the test of the static frequency characteristics doesn't fulfil the conditions*

Checking the static frequency characteristics - doesn't fulfil the conditions								
p(H)		p(E | H)	p(E |~H)	p(~H)	p(E)	p(H | E)	p(H |~E)	p(H | E)/p(H)
$p(H_1)$=	0.200	0.800	0.200	0.800	0.320	0.500	0.059	2.50
$p(H_2)$=	0.050			0.950	0.000		0.050	
$p(H_3)$=	0.100			0.900	0.000		0.100	
$p(H_4)$=	0.010			0.995	0.000		0.005	
$p(H_5)$=	0.100	0.800	0.200	0.900	0.260	0.308	0.027	3.10
$p(H_6)$=	0.100			0.900	0.000		0.100	
$p(H_7)$=	0.050	0.600	0.400	0.950	0.410	0.073	0.034	1.50
$p(H_8)$=	0.010			0.990	0.000		0.010	
$p(H_9)$=	0.050			0.950	0.000		0.050	
$p(H_{10})$=	0.010			0.990	0.000		0.010	
$p(H_{11})$=	0.100	0.990	0.100	0.900	0.189	0.524	0.001	5.20
$p(H_{12})$=	0.200	0.900	0.100	0.800	0.260	0.692	0.027	3.50
$p(H_{13})$=	0.010	0.600	0.400	0.990	0.402	0.015	0.007	1.50
$p(H_{14})$=	0.200			0.800	0.000		0.200	
$p(H_{15})$=	0.050			0.950	0.000		0.050	

4 CONCLUSION

Due to the large number of technical resources in military systems, methods are continuously elaborated, which contributes to the optimization of maintenance. The greatest effect is achieved by the principle of repairing a set, for which the failure diagnosis in the assembled state has a significant role. Therefore, the study of the behaviour of gensets in different states and the development of a Knowledge Base have begun, in which the hypotheses are associated with a certain probability.

With the help of Bayes' theorem true values were calculated, used together with certain facts, to correct the probabilities listed in the Knowledge Base.

The Knowledge Base, containing the elaborated Bayes' theorem and the gathered true values, is the basis for the continuation of the research and development of ideal diagnostic programs and special instructions for diagnosing and troubleshooting.

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