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Diagnostics of low-capacity solar power station equipment with 2- and 3-valued logic

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Abstract. The paper outlines research issues relating to 2- and 3-valued logic diagnoses developed with the diagnostic system (DIAG 2) for the equipment installed at a low-capacity solar power station. The presentation is facilitated with an overview and technical description of the functional and diagnostic model of the low-power solar power station. A model of the low-power solar power station (the tested facility, a.k.a. the test object) was developed, from which a set of basic elements and a set of diagnostic outputs were determined and developed by the number of functional elements *j* of *j*. The work also provides a short description of the smart diagnostic system (DIAG 2) used for the tests shown herein. (DIAG 2) is a proprietary work. The diagnostic program of (DIAG 2) operates by comparing a set of actual diagnostic output vectors to their master vectors. The output of the comparison are elementary divergence metrics of the diagnostic output vectors determined by a neural network. The elementary divergence metrics include differential distance metrics which serve as the inputs for (DIAG 2) to deduct the state (condition) of the basic elements of the tested facility.

Keywords: technical diagnostics, diagnostic inference, multiple-valued logic, artificial intelligence
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1. Background

Technical diagnostics is based on two-valued logic, where the value 1 denotes an operational state and the value "0" denotes a non-operational state. The purpose of two-valued logic diagnostics is to identify the non-operational state (a failure) and enable identification of the element which generates the non-operational state [1, 2-13]. The organisation of facility servicing relies heavily on the ability to identify the actual state (operational or non-operational) and the states which precede a non-operational state of a facility. Hence, the application of two-valued logic for this identification has become insufficient [1-3, 4-6, 7-13]. Diagnostics based on three-valued logic inference has been developed. The organisation of facility servicing also relies on the capacity of identifying partially (reduced) operational states, which occur directly before the non-operational state. It is why practical applications of technical diagnostics have seen an increasing use of the three-valued logic developed by J. Łukaszewicz [7]. S. Duer [4-9] developed three-valued logic diagnostics mainly by the application of RBF artificial neural networks. The diagnostic inference applied in this three-valued logic differentiates the operational state "2" and the partial (reduced) operational state "1" and the non-operational state "0". References [4-8] show that the addition of the partial (reduced) operational state expands the obtainable diagnostic data feedback. No work currently exists that explicitly and practically suggest a qualitative or quantitative difference between 3-valued logic diagnostics and 2-valued logic diagnostics.

Technical diagnostics has been efficiently developed in the recent years and sees applications for the diagnostics of technological processes and technical equipment. Diagnostic programs based on artificial neural networks and evolutionary or genetic algorithms, including ant algorithms, have seen an effective use in technical diagnostics [7, 16]. The authors hereof systematically improved the diagnostic of technical equipment with a diagnostic method which consists in an analysis of distance metrics – the outputs of a comparison between the images of diagnostic output vectors and their respective master vectors. The diagnostic method is based on artificial intelligence solutions (such as the DIAG 2 software) [4-16]. DIAG 2 is a proprietary work of a research team headed by Professor S. Duer at the Koszalin University of Technology, Faculty of Mechanical Engineering.

The paper outlines research issues relating to 2- and 3-valued logic diagnoses developed with the diagnostic system (DIAG 2) for the equipment installed at a low-capacity solar power station. Reference literature is devoid of this type of work that would explicitly present the solution to the problem. The research tool developed into (DIAG 2) provides a capability of solving the problem.

2. Functional and diagnostic structure of low-capacity solar power station equipment

The Department of Power Engineering at the Koszalin University of Technology developed a laboratory test stand for testing the processes of diagnosing low-capacity solar power station equipment. A schematic of the laboratory test stand is shown in Fig. 1.

Fig. 1. Laboratory test stand for testing the processes of diagnosing low-capacity solar power station equipment (courtesy: S. Duer)

Low-capacity solar power stations (see Fig. 1) are usually operated with electrical power storage systems formed by battery banks. The functional system of a low-capacity solar power station features the following components:

- *PV* (photovoltaic module) generator;
- battery banks;
- battery charge state controller;
- DC (direct-current) load and/or
- an inverter with an AC (alternating current) load.

Fig. 2 shows the power system circuit diagram of a low-capacity solar power station. Fig. 2 also shows the measurement apparatus used in the tests contemplated in this work. A solar battery circuit is closed with a regulator unit. The short-circuit current of the solar power station is measured with an ammeter, ***A***, and the PV system output voltage is measured with a voltmeter connected to the solar power station's input (see Fig. 2).

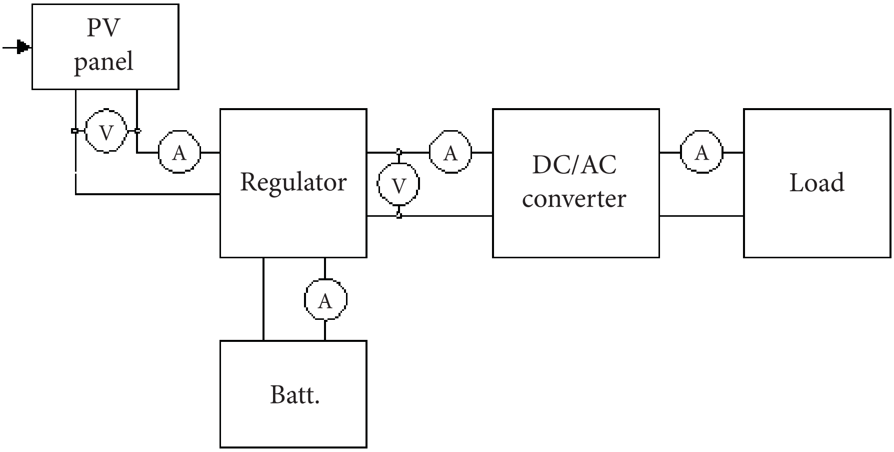


Fig. 2. Diagram of the measurement system for testing a low-capacity solar power station; PV panel: photovoltaic cell; Batt.: battery; A: ammeter; V: voltmeter

The basis of technical diagnosis of engineering equipment and objects (facilities) $\{O(e_{i,j})\}$ is diagnostic processing of the tested object [4-16]. Diagnostic processing of the tested object comprises technical and processing activities and tasks with certain analytical tasks. An effect of the activities was a functional and diagnostic diagram, the structure of the engineering facility (object), consisting of the number of *j* functional elements, and a determined set of diagnostic outputs, $\{X_{i,j}\}$ (see Fig. 3).

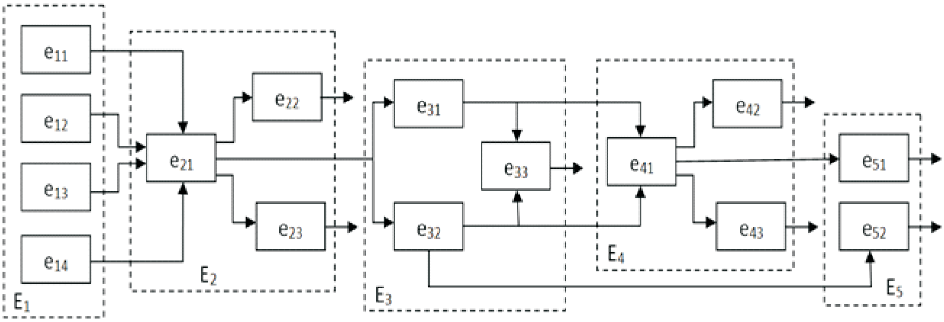


Fig. 3. Diagram of the functional and diagnostic structure of low-capacity solar power station equipment, with: E_1 — PV system; E_2 — voltage regulator system (controller module); E_3 — electrical power storage system; E_4 — DC/AC converter; E_5 — the load system

The functional units shown in the functional and diagnostic diagram in Fig. 3 were numbered, or "addressed" as follows: (E_i) i-is the sequential number of the functional unit in the object. The functional elements of each functional unit were addressed as ($e_{i,j}$), with j being the sequential number of the functional element in the functional unit i [4-16].

The set of basic elements determined from the functional and diagnostic diagram (see Fig. 3) and which develop the diagnostic outputs in the solar power supply system which was tested are shown in Tables 1 and 2.

TABLE 1

Object internal structure

Object units	Object basic elements, $\{e_{i,j}\}$			
E	e_1	e_2	e_3	e_4
E_1	$e_{1.1}$	$e_{1.2}$	$e_{1.3}$	$e_{1.4}$
E_2	$e_{2.1}$	$e_{2.2}$	$e_{2.3}$	$\varnothing$
E_3	$e_{3.1}$	$e_{3.2}$	$e_{3.3}$	$\varnothing$
E_4	$e_{4.1}$	$e_{4.2}$	$e_{4.3}$	$\varnothing$
E_5	$e_{5.1}$	$e_{5.2}$	$\varnothing$	$\varnothing$

with: $e_{1.1}$ — PV module no. 1; $e_{1.2}$ — PV module no. 2; $e_{1.3}$ — PV module no. 3; $e_{1.4}$ — PV module no. 4; $e_{2.1}$ — voltage regulator (controller module); $e_{2.2}$ — voltage measurement system; $e_{2.3}$ — current measurement system; $e_{3.1}$ — battery no. 1; $e_{3.2}$ — battery no. 2; $e_{3.3}$ — current measurement system; $e_{4.1}$ — inverter (PWM unit); $e_{4.2}$ — voltage measurement system; $e_{4.3}$ — current measurement system; $e_{5.1}$ — load no. 1; $e_{5.2}$ — load no. 2

It was assumed that the basic element (module) identified in the engineering object structure diagram was an object element (module) with an indivisible structure and which generated its own output signal. Each such output signal is a diagnostic signal. If an element generates more than one diagnostic output, a single generic diagnostic output should be determined which best reflects the performance (including the diagnostic and reliability characteristics) of the element j. Table 2 lists the set of the diagnostic outputs j of j determined from the solar power supply system, or the object.

The values of the diagnostic outputs and their respective masters, listed in Tables 3 and 4, were measured to diagnose the tested solar power supply system with DIAG 2.

TABLE 2

Set of basic elements and their respective diagnostic outputs in the solar power supply system

Object units		Object basic elements		Diagnostic outputs in elements j
Symbol	Unit name	Symbol	Object element name	
E_1	PV system	$e_{1.1}$	PV module no. 1	$X(e_{1.1})$
		$e_{1.2}$	PV module no. 2	$X(e_{1.2})$
		$e_{1.3}$	PV module no. 3	$X(e_{1.3})$
		$e_{1.4}$	PV module no. 4	$X(e_{1.4})$
E_2	voltage regulator (controller unit) system	$e_{2.1}$	voltage regulator (controller unit)	$X(e_{2.1})$
		$e_{2.2}$	voltage measurement system	$X(e_{2.2})$
		$e_{2.3}$	current measurement system	$X(e_{2.3})$
E_3	electric power storage system	$e_{3.1}$	battery no. 1	$X(e_{3.1})$
		$e_{3.2}$	battery no. 2	$X(e_{3.2})$
		$e_{3.3}$	current measurement system	$X(e_{3.3})$
E_4	DC/AC converter	$e_{4.1}$	inverter (PWM unit)	$X(e_{4.1})$
		$e_{4.2}$	voltage measurement system	$X(e_{4.2})$
		$e_{4.3}$	current measurement system	$X(e_{4.3})$
E_5	load system	$e_{5.1}$	load no. 1	$X(e_{5.1})$
		$e_{5.2}$	load no. 1	$X(e_{5.2})$

TABLE 3

Table of the test object diagnostic output masters

Object units	Values of the diagnostic output masters, $\{X_{(w)}(e_{i,j})\}$ of the test object			
E_i	e_1	e_2	e_3	e_4
E_1	11.7 to 12.4	11.7 to 12.4	11.7 to 12.4	11.7 to 12.4
E_2	11.7 to 12.4	11.7 to 12.4	1 to 4	$\varnothing$
E_3	11.7 to 12.4	11.7 to 12.4	0.5 to 4	$\varnothing$
E_4	220 to 235	220 to 235	0.5 to 10	$\varnothing$
E_5	220 to 235	11.7 to 12.4	$\varnothing$	$\varnothing$

TABLE 4

Table of the test object diagnostic outputs (examples)

Object units	Values of the diagnostic output masters, $\{X_{(w)}(e_{i,j})\}$ of the test object			
E_i	e_1	e_2	e_3	e_4
E_1	11.7	12.4	12.4	11.7.
E_2	12.4	11.7	3.5	$\varnothing$
E_3	11.7	12.4	4.	$\varnothing$
E_4	226	230	7.	$\varnothing$
E_5	228	12.4	$\varnothing$	$\varnothing$

3. Diagnostics of low-capacity solar power station equipment with 2- and 3-valued logic

The functional units of the test object were shown in (DIAG 2) as "units", and the basic components were shown in the same as "elements". The subassemblies are tertiary elements which are "intermediate elements" and enable bidirectional transformation of the hierarchical form of the test object into an internal matrix structure shown in Fig. 4 and 5.

The diagnostic status of the test object was determined in (DIAG 2) by testing the set of vectorized diagnostic outputs and comparing them to their respective master vectors [2-13]. The classification stage during the diagnostic process provided a determination of a defined state of each basic element of the tested engineering object. The classification of the states of the functional units of the test object itself was determined with classification rules and depended on the value of logic (i.e. the number of states) (see Fig. 4 and 5).

The process of state classification in (DIAG 2) was carried out by opening the "Classification" pane from the tool bar. The "Classification" pane featured configuration and result options, including state tables (maps of states). The configuration allowed setting the type of state logic, the classification interval range, the options of visual output in the state tables, and the BRF artificial neural network parameters. The adopted test object states in multiple-valued logic were determined in the Polish Standards for reliability and servicing quality [4, 15] (Fig. 4 and 5).

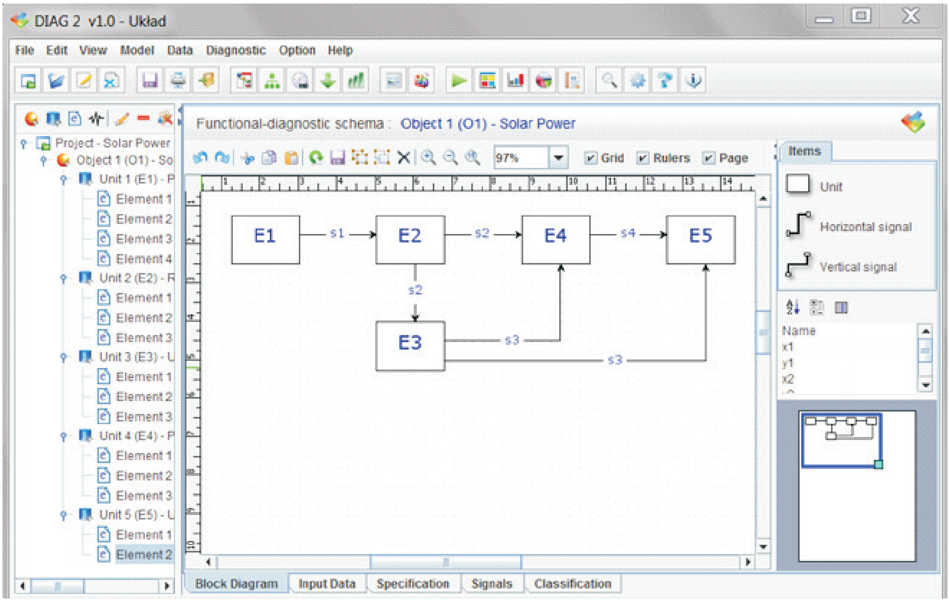
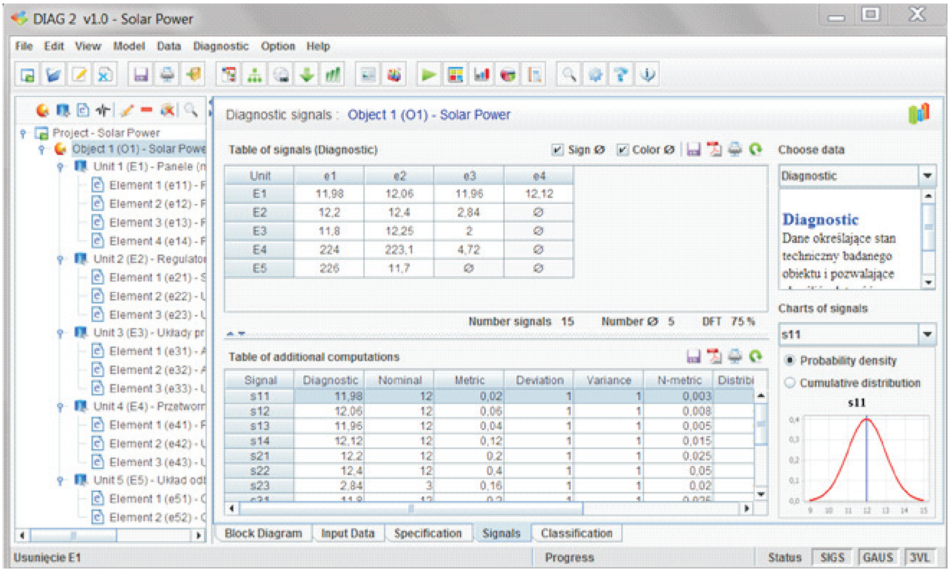


Fig. 4. Resultant form DIAG 2 for the "Structure" module

The resultant form of the operation of (DIAG 2), which monitored the operating state of the solar power station system, is shown in Fig. 7. The diagnostic information generated by (DIAG 2) was expressed with 3-valued logic. The information depicted in Fig. 4 as "Structure" of the test object is a multi-level internal structure, comprising a structure of the functional units *i* of *i*, or a selected structure of the elements *j* of *j* within the functional units *i* of *i*.



Unit	e1	e2	e3	e4
E1	11,98	12,06	11,96	12,12
E2	12,2	12,4	2,84	∅
E3	11,8	12,25	2	∅
E4	224	223,1	4,72	∅
E5	226	11,7	∅	∅

Number signals 15 Number ∅ 5 DFT 75 %

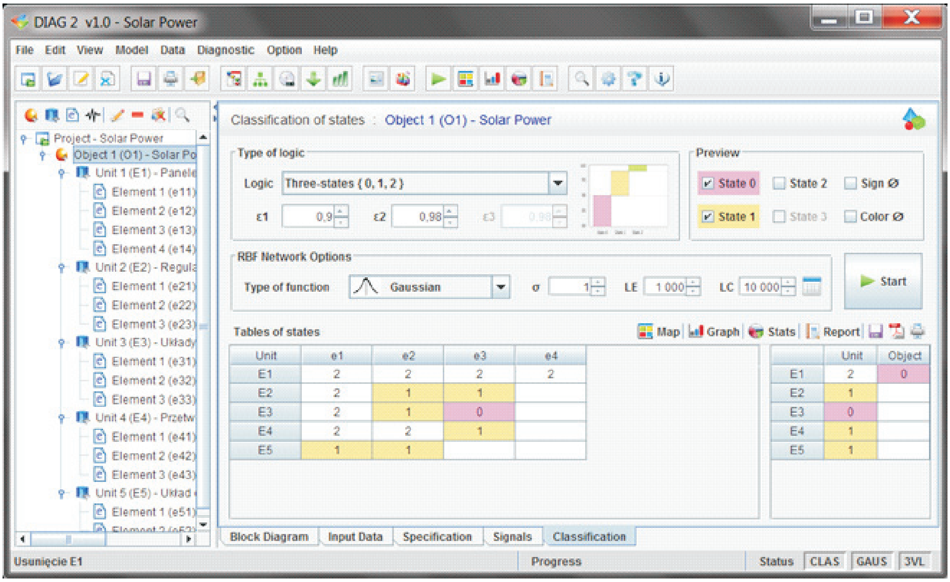
Diagnostic
Dane określające stan techniczny badanego obiektu i pozwalające

Signal	Diagnostic	Nominal	Metric	Deviation	Variance	N-metric	Distribi
s11	11,98	12	0,02	1	1	0,003	
s12	12,06	12	0,06	1	1	0,008	
s13	11,96	12	0,04	1	1	0,005	
s14	12,12	12	0,12	1	1	0,015	
s21	12,2	12	0,2	1	1	0,025	
s22	12,4	12	0,4	1	1	0,05	
s23	2,84	3	0,16	1	1	0,02	

Fig. 5. Engineering object classification pane of the "Output Values" module

Fig. 6 shows the resultant (and final) form of the diagnostic information with 3-valued logic. The final form of the diagnostic information output for the states of the tested object, the internal structure of which featured 15 basic elements *j* (modules), located in the functional units *i* of *i*. The primary level of the diagnostic information depicted in Fig. 6 for the test object is "Table of basic element states" shown as the values of the states from the set {2, 1, 0}. The secondary and tertiary level of the diagnostic information of the test object could serve to present the states of the functional units *i* of *i*, or the state of the test object.

A study of Fig. 6 revealed that the basic elements in the subset $\{e_{1.1}; e_{1.2}; e_{1.3}; e_{1.4}; e_{2.1}; e_{3.1}; e_{4.1}; e_{4.2}\}$ were in the operational state "2". The percentage share of the operational elements in the tested object's structure was 54%. The remaining tested subset of basic elements $\{e_{2.2}; e_{2.3}; e_{3.2}; e_{4.3}; e_{5.1}; e_{5.2}\}$ were in the partial (reduced) operational state "1". The percentage share of the partially operational elements *j* of *j* in the tested object's structure was 40%. Only one basic element $\{e_{3.3}\}$ has the non-operational state "0". The percentage share of the non-operational element in the tested object's structure was 6%.



Classification of states : Object 1 (O1) - Solar Power

Type of logic

Logic: Three-states { 0, 1, 2 }

ε1: 0,9 ε2: 0,98 ε3: 0,98

Preview

☑ State 0 ☐ State 2 ☐ Sign Ø

☑ State 1 ☐ State 3 ☐ Color Ø

RBF Network Options

Type of function: Gaussian σ: 1 LE: 1 000 LC: 10 000

Tables of states

Unit	e1	e2	e3	e4
E1	2	2	2	2
E2	2	1	1	
E3	2	1	0	
E4	2	2	1	
E5	1	1		

	Unit	Object
E1	2	0
E2	1	
E3	0	
E4	1	
E5	1	

Usunięcie E1 Progress Status CLAS GAUS 3VL

Fig. 6. Resultant form of DIAG 2, "Table of basic element states" in the diagnostic process of the solar power station equipment with 3-valued logic, with: {2} — operational state; {1} — partial (reduced) operational state; {0} — non-operational state

Based on the information derived from the diagnostic process of the test object, the application of engineering object models with 3-valued logic in the diagnostic process could demonstrate that 3-valued diagnostic is more feasible as a tool for applying the information in the organisation of technical servicing. The interpretation (identification) of the partial operational state enables application of an operational-state-based servicing (reconditioning) organisation strategy for engineering facilities (objects). The effectiveness of 3-valued logic and its applications in technical servicing are exhaustively described in [4-8].

4. Conclusion

3-valued logic, unlike 2-valued logic diagnostics, is unique in that its functions and arguments can assume one of three values, each denoted by the symbols from the set {0, 1, 2}. The addition of another reliability (technical) state by 3-valued logic to characterise an engineering object (facility) increases the value of diagnostic information provided to the testing personnel. The additional partial (reduced) operational state helps determine time to a pre-failure state in an engineering facility with better accuracy. The identification of a partial (reduced) operational state provides a more precise determination of the time at which the engineering facility will enter a state which is the most frequent cause for maladjustment, detuning, derating and reduced performance, all of which can be trouble-shot with reconditioning servicing. The identification of one of the partial (reduced) or critical states in the interval of time before failure should prompt the decision to recondition the tested engineering facility.

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REFERENCES

[1] Będkowski L., Dąbrowski T., *Podstawy eksploatacji cz. 2*, Wyd. WAT, Warszawa, 2006, p. 187.

[2] Będkowski L., *Elementy ogólnej teorii diagnostyki technicznej*, Wyd. WAT, Warszawa, 1981.

[3] Duer S., Duer R., Mazuru S., *Determination of the expert knowledge base on the basis of a functional and diagnostic analysis of a technical object*. 18th Edition, International Conference of Nonconventional Technologies, ICNcT 2016, Chisinau, Republic of Moldova, 30.06 - 1.07.2016. Nonconventional Technologies Review, 2016 Romanian Association of Nonconventional Technologies, Romanian, June, 6/2016, vol. 20, nr 2, 2016, 23-29.

[4] Duer S., Zajkowski K., Duer R, Wrzesień P., Bernatowicz D., *Ekspertowa baza wiedzy wspomagająca diagnozowanie urządzeń farmy wiatrowej*, Wydawnictwo Uczelniane Politechniki Koszalińskiej. Koszalin, 2017, p. 163.

[5] Duer S., Wrzesień P., Duer R., *Creating of structure of facts for the knowledge base of an expert system for wind power plant's equipment diagnosis*, EEMS 2017, E3S Web of Conferences 19, 01029 (2017). DOI: 10.1051/e3sconf/20171901038.

[6] Duer R., Duer S., *Badanie diagnostyki urządzeń elektrowni słonecznej w logice 2- i 3-wartościowej*, Biuletyn Wojskowej Akademii Technicznej, 66, 2, 2017, pp. 67-79, DOI: 10.5604/01.3001.0009.9485.

[7] Duer S., *Wnioskowanie diagnostyczne o stanie obiektu technicznego w logice k-wartościowej*, Biuletyn Wojskowej Akademii Technicznej, 66, 1, 2017, pp. 115-126, DOI: 10.5604/01.3001.0009.9488.

[8] Duer S., Bernatowicz D., *The computer diagnostic program (DIAG 2) for identifying states of complex technical objects*, EEMS 2017, E3S Web of Conferences 19, 01029 (2017). DOI: 10.1051/e3sconf/20171901029.

[9] Dhillon B.S., *Applied Reliability and Quality*, *Fundamentals, Methods and Procedures*, Springer – Verlag London Limited, 2006, p. 186.

[10] Flasiński M., *Wstęp do sztucznej inteligencji*, Wyd. PWN, Warsaw, 2011, p. 331.

[11] Hojjat A., Shih – Lin Hung, *Machine learning, neural networks, genetic algorithms and fuzzy systems*, John Wiley and Sons, Inc, 1995.

[12] Instrukcja obsługi siłowni wiatrowej Nordex klasy K08 gamma.

[13] Madan M. Gupta, Liang Jin and Noriyasu H.: *Static and Dynamic Neural Networks, From Fundamentals to Advanced Theory*, John Wiley End Sons, Inc. 2003, p. 718.

[14] OSOWSKI S., *Sieci neuronowe*, Wyd. Politechniki Warszawskiej, Warsaw, 1996, p. 241.

[15] Pokorádi L., Duer S., *Investigation of maintenance process with Markov matrix*, Proceedings of the 4th International Scientific Conference On Advances In Mechanical Engineering. 13-15 October 2016, Debrecen, Hungary, pp. 402-407.

[16] Rosiński A., *Reliability analysis of the electronic protection systems with mixed – three branches reliability structure*, Reliability, Risk and Safety. Theory and Applications, [ed:] R. Bris, C. Guedes Soares & S. Martorell. CRC Press/Balkema, London, UK, vol. 3, 2010.

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Diagnostyka urządzeń elektrowni słonecznej małej mocy

Streszczenie. W artykule zaprezentowano problematykę badania wypracowanych diagnoz w logice 2- i 3-wartościowej przez system diagnostyczny (DIAG 2) dla urządzeń elektrowni słonecznej. W tym celu przedstawiono i opisano model funkcjonalno-diagnostyczny urządzeń elektrowni słonecznej. Na podstawie opracowanego modelu badanego obiektu wyznaczono zbiór elementów podstawowych oraz zbiór sygnałów diagnostycznych, które są wypracowane przez j-te elementy funkcjonalne obiektu. Przestawiono także krótki opis wykorzystywanego w badaniu inteligentnego systemu diagnostycznego (DIAG 2). System (DIAG 2) jest autorskim opracowaniem. Program diagnostyczny w systemie (DIAG 2) pracuje na zasadzie porównaniu zbioru wektorów sygnałów diagnostycznych z ich wektorami wzorcami. W wyniku porównania sygnałów wyznaczane są przez sieć neuronową elementarne metryki rozbieżności wektorów sygnałów diagnostycznych. Na podstawie metryk odległości różnicowej następuje wnioskowanie systemu co do rozpoznania stanu elementów podstawowych obiektu.

Słowa kluczowe: diagnostyka techniczna, wnioskowanie diagnostyczne, logiki wielowartościowe, sztuczna inteligencja
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