Biuletyn WAT
Vol. LXVII, Nr 1, 2018

Diagnosing of a complex technical object in four-valued logic

STANISŁAW DUER[1], DARIUSZ BERNATOWICZ[2], PAWEŁ WRZESIEŃ[3], RADOSŁAW DUER[2]

[1]Koszalin University of Technology, Faculty of Mechanical Engineering,
15-17 Racławicka Str., 75-620 Koszalin, Poland, stanislaw.duer@tu.koszalin.pl
[2]Koszalin University of Technology, Faculty of Electronics and Computer Science,
2 Śniadeckich Str., 75-453 Koszalin, Poland, dariusz.bernatowicz@tu.koszalin.pl, rduer@wp.pl
[3]Vortex Energy Polska sp. z o.o., 26 Malczewskiego Str., 71-612 Szczecin, Poland,
nfo@rscgroup-online.pl

Abstract. This paper presents the essence of an investigation of a complex technical object with the use of four-valued logic. To this end, an intelligent diagnostic system (DIAG 2) is described. A special feature of this system was its capability of inferring k at $\{k = 4, 3, 2\}$, in which case the logic $\{k = 4\}$ is applied. An important part of this work was to present the theoretical foundations describing the essence of inference in the four-valued logic contemplated. It was also pointed out that the basis for classification of states in the multiple-valued logic of the diagnostic system (DIAG 2) was the permissible interval of changes in the values of diagnostic signal features. Four-valued logic testing was applied to a system of wind turbine equipment.
Keywords: technical diagnostics, diagnostic inference, multiple-valued logic, artificial intelligence
DOI: 10.5604/01.3001.0011.8018

Introduction

The organisation of facility servicing processes relies heavily on the ability to identify the states which precede a non-operational state of the facility; hence, the application of two-valued logic for this identification is insufficient [3, 6, 7-11]. Diagnostics based on three-valued logic inference was developed. The practical applications saw an increasing use of the three-valued logic developed by J. Łukaszewicz

[1, 2, 4, 7-10]. The authors of [4-7, 9] presented their research achievements, which significantly increased the value of engineering facility diagnostic solutions in terms of three-valued logic inference. The classification of states applied with three-valued logic defines operational state "2", non-operational state "0", and partially (reduced) operational state "1". The references [1, 2-13, 16-19] demonstrate that the application of this third state expands the deliverable scope of diagnostic results. This problem is particularly important for the performance of technical servicing of engineering facilities. The conclusion remains valid that this additional output of diagnostic information improves the mean time between failures.

The works [2, 9] present a novel organisational concept of a servicing system, including the control of the operating process with three-valued logic diagnostic information. The foundation of this concept is a reliable diagnostic output of state "1", reduced operationally.

The diagnostic information is output by an intelligent diagnostic system (DIAG 2), developed at the Koszalin University of Technology, Faculty of Mechanical Engineering, Department of Power Engineering. DIAG 2 works effectively with an RBF (Radial Basis Function) artificial neural network. A novel feature in this class of intelligent diagnostic systems is the capacity of diagnosing facilities with k-valued logic, which includes three-valued logic.

The experience of this team in the diagnostics of engineering systems and the conclusions of the team related to the acquisition of diagnostic information usable in the organisation and design of servicing systems are presented in [3-4]. These works detail the design of a developed intelligent system, capable of identifying the states of structural members inside different facilities.

1. Four-valued logic of states

The development of three-valued logic ($k = 3$) with states in a set of {2, 1, 0}, was significantly contributed to by the author of [2, 8]. The application of three-valued logic in the diagnostics of engineering facilities, industrial processes and manufacturing processes, has provided practical information effects. A distinctive achievement of the application of three-valued logic was the determination of the partially operational state, "1". The ability to determine the partially operational state became a foundation for the development of modern smart systems which support the organisation of servicing systems for engineering facilities [3-9]. It can be assumed that k-valued logic may provide completely new experiences in the operation of engineering facilities. The existing references do not include any work concerning k-valued logic with ($k > 3$) in technical diagnostics. The essence of inference in multiple-valued logic of diagnostic systems is shown in Fig. 1.

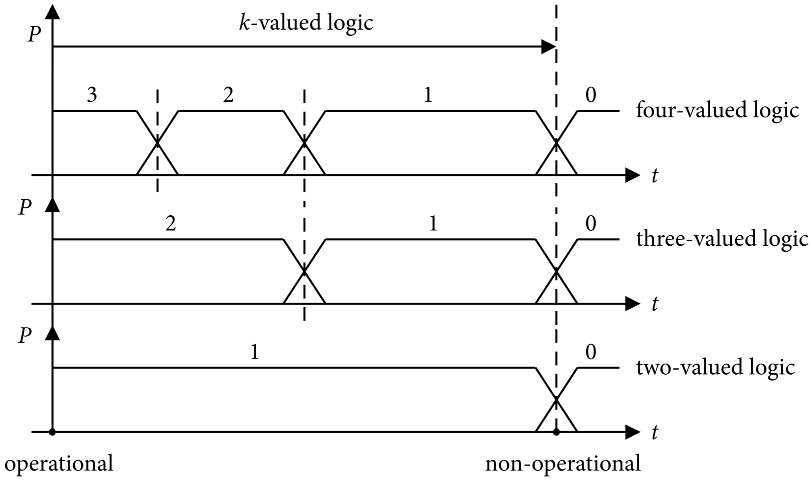

Fig. 1. Essence of inference in multiple-valued logic of diagnostic systems.

If the ***partially operational state, “1”***, is distinctive in three-valued logic (k = 3), then four-valued logic (k = 4) with states corresponding to the logical values in the set {3, 2, 1, 0} has a fourth distinctive state, ***critical operational state, “1”***. The critical operational state of four-valued logic may include the j structural features of a facility, or object, the reliability of which is insufficient at the given moment. The internal elements (structural components) in the critical operational state continue to function and are operated directly before their sudden (critical) failure. Hence, the problem of identification of critical operational state “1” in (k = 4) logic becomes extremely important in technical diagnostics.

If the nominal values of input features are provided, the output of the object will be a value which characterises the state of the object. Testing the output Y_i comprises measuring its features and comparing the measurement result to the feature of reference signal $Y_{(w),i}$. Instead of comparing the output to its reference signal, it is much easier to verify that the diagnostic outputs are within their permissible interval of changes. The change interval of the feature of the diagnostic output i with four-valued logic is shown in Fig. 2. There are three change intervals shown, as follows:

- The interval of insignificant changes in the output $(Y_i^{3'}, Y_i^{3})$, which is the object’s feature state “3”,
- The interval of significant changes in the output $(Y_i^{1'}, Y_i^{3'}) \cup (Y_i^{3}, Y_i^{1})$, which is the object’s feature state “1” or “2”,
- The interval of impermissible changes in the output $(-\infty', Y_i^{1'}) \cup (Y_i^{1}, +\infty)$, which is the object’s feature state “0”.

Not unlike three-valued logic, four-valued logic is a special case of k-valued logic (Fig. 2). Its functions and argument may assume one of the four values determined by the symbols {3, 2, 1, 0}. Introduction of a four-valued logical assessment of states

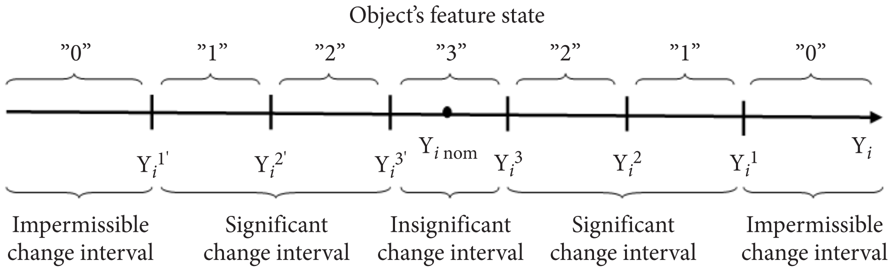

Fig. 2. Intervals of change of the feature value in the diagnostic output *i*.

to technical diagnostics should lead to a diagnostic process in which the actual state of the tested object has a status assigned from the following set [2]:

- {3} — set of operational states in which the object is fully capable of performing in accordance with its intended use, whereas a change in the value of one or more features of the output must be within the interval of insignificant changes;
- {2} — set of partially operational states in which the object is capable of limited performance, whereas a change in the value of one or more features of the output must be within the interval of significant changes;
- {1} — set of critical operational states in which the object is capable of very limited performance, whereas a change in the value of one or more features of the output must be within the interval of critical changes. This state directly precedes a failure and requires preventive measures to refurbish the object;
- {0} — set of non-operational states in which the object has lost its functioning resource and has become incapable of performance according to its intended use. In this state, a change of one or more features of the output must be within the interval of impermissible changes.

2. Functional & diagnostic model of wind turbine equipment

The foundation of diagnostic testing of engineering facilities is the knowledge and experience of the diagnostician and the functional and diagnostic models of the facilities [2-12]. To meet the objective of this work, a diagnostic information flow in a wind turbine system was developed (Fig. 3). A functional and diagnostic diagram of the wind turbine system was also developed (Fig. 3).

This wind turbine model was the basis for the result of the functional and diagnostic analysis carried out on the wind turbine. Seven functional units of *i* were identified in the wind turbine model. Each of functional unit *i* had a subset of its functional elements *j* determined. The functional and diagnostic analysis identified

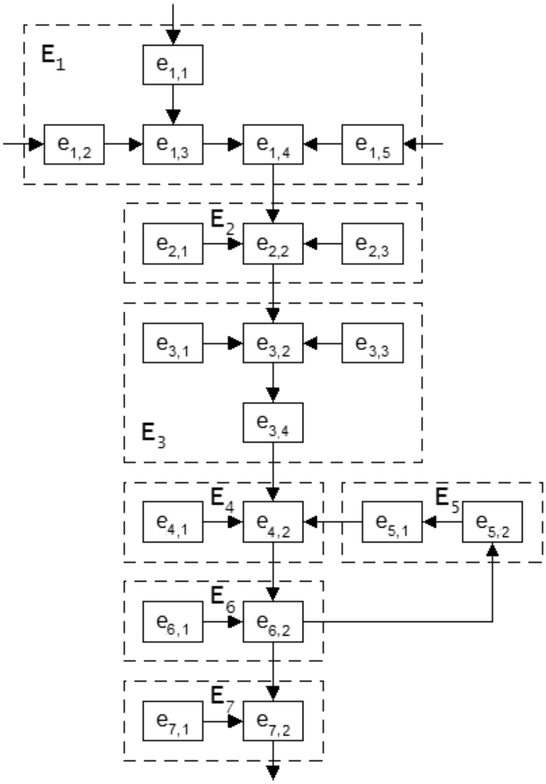

Fig. 3. Wind turbine functional and diagnostic diagram, with: E_1 — power generator drive system; E_2 — synchronous generator system; E_3 — generator field magnet system; E_4 — power controller system; E_5 — power inverter system; E_6 — voltage and current coordinate converter system, and E_7 — MV transformer system.

a set of diagnostic outputs $\{X(e_{i,j})\}$ in the wind turbine model (Fig 3). The diagnostic outputs were identified at the outputs of the *j*-th functional element. The determined set of diagnostic outputs $\{X(e_{i,j})\}$ of the wind turbine is listed in Table 1.

The basis of technical diagnosis of engineering equipment and objects (facilities) $\{O(e_{i,j})\}$ is diagnostic processing of the tested object. Diagnostic processing of the tested object comprises technical and processing activities and tasks with certain analytical tasks. A deliverable of this is a structure of the engineering facility (object) defined with a functional and diagnostic diagram, for which a set of diagnostic outputs was determined $\{X_{i,j}\}$. The functional units (modules) shown in the functional and diagnostic diagram in Fig. 3 were numbered, or 'addressed' as follows: (E_i) is the *i*-th number of the unit in the object. The functional elements of each functional unit were addressed as $(e_{i,j})$, with *j* being the number of the functional element in functional unit *i*.

Table 1

Set of the diagnostic outputs $\{X(e_{i,j})\}$ determined for the wind turbine model

Object units	Set of the diagnostic outputs $\{X(e_{i,j})\}$ determined for the wind turbine model				
E_1	$e_{1,1}$	$e_{1,2}$	$e_{1,3}$	$e_{1,4}$	$e_{1,5}$
E_2	$e_{2,1}$	$e_{2,2}$	$e_{2,3}$	$\varnothing$	$\varnothing$
E_3	$e_{3,1}$	$e_{3,2}$	$e_{3,3}$	$e_{3,4}$	$\varnothing$
E_4	$e_{4,1}$	$e_{4,2}$	$\varnothing$	$\varnothing$	$\varnothing$
E_5	$e_{5,1}$	$e_{5,2}$	$\varnothing$	$\varnothing$	$\varnothing$
E_6	$e_{6,1}$	$e_{6,2}$	$\varnothing$	$\varnothing$	$\varnothing$
E_7	$e_{7,1}$	$e_{7,2}$	$\varnothing$	$\varnothing$	$\varnothing$

with: $e_{1,1}$ — turbine shaft stabilizer unit, $e_{1,2}$ — main gear, $e_{1,3}$ — gear temperature control system, $e_{1,4}$ — coupling, $e_{1,5}$ — generator brake, $e_{2,1}$ — synchronous generator, $e_{2,2}$ — generator temperature control system, $e_{2,3}$ — main gear brake systems, $e_{3,1}$ — field magnet coil, $e_{3,2}$ — excitation voltage control system, $e_{3,3}$ — matching system, $e_{3,4}$ — excitation current control system, $e_{4,1}$ — inverter PWM unit, $e_{4,2}$ — generator power control, $e_{5,1}$ — controller rectifier, $e_{5,2}$ — inverter, $e_{6,1}$ — U_A, U_B and U_C 3-phase voltage coordinate converter unit, $e_{6,2}$ — I_A, I_B and I_C 3-phase current coordinate converter unit, $e_{7,1}$ — MV transformer temperature control system, and $e_{7,2}$ — MV transformer unit.

3. DIAG 2 computer diagnostic program with four-valued logic inference

Application of DIAG 2 in technical diagnostics requires preparation of the input diagnostic information from a complete functional and diagnostic analysis. Only the basic elements of an object, i.e. the modules in the functional and diagnostic model of the object, must be addressed as $(e_{i,j})$, with: j as the number of the functional element in a functional unit (module), and i as the number of the functional unit of the object.

The input data can be supplied to DIAG 2 manually with a keyboard, or automatically with the outputs of a test system (test card). DIAG 2 was developed to enable adjustments of the dimensions of the tested object's structure, including modification of the number of functional units, or modification of the number of basic elements (modules) of the functional unit.

The results are shown in Figs. 4 and 5. The results of the diagnostic process carried out with DIAG 2, an intelligent diagnostic system, can be output in different and convenient graphical formats. The basis of the diagnostic information output from DIAG 2 is the State Table of the tested object, as shown in Fig 4. The finished information can be output into other graphical forms of visualisation, including charts, histograms, and reports. A combination of specific output presentation forms enables a more thorough analysis, or a more efficient comparison of the finished diagnostic information outputs for different k-values of the logic applied to evaluate the states.

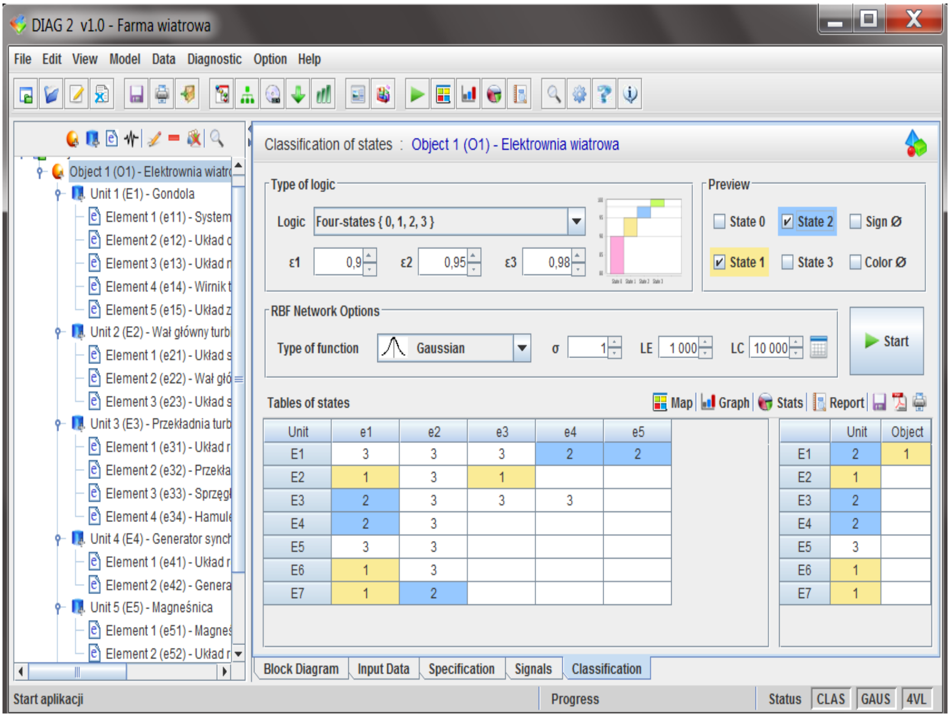

Fig. 4. Output form in DIAG 2, showing the wind turbine Equipment Table, with: {3} — set of operational states; {2} — set of partially operational states; {1} — set of critical operational states, and {0} — set of non-operational states.

Fig. 4 shows diagnostic information with four-valued logic. The final form of the diagnostic information output for the states of the tested object, the internal structure of which featured 20 basic *j* elements (modules), located in the *i*-th functional unit. A study of Fig. 5 revealed that the basic elements in the subset $\{e_{1,1}; e_{1,2}; e_{1,3}; e_{2,2}; e_{3,2}; e_{3,3}; e_{3,4}; e_{4,2}; e_{4,2}; e_{5,1}; e_{5,2}; e_{6,2}\}$ were in operational state “3”. The percentage share of the basic *j* elements in the operational state in the *i*-th functional unit of the objects was 55%.

The set of states of the object’s basic elements was also shown in Fig. 5 as a bar chart of the states and their percentage shares.

The basic elements in the subset $\{e_{1,4}; e_{1,5}; e_{3,1}; e_{4,1}; e_{7,2}\}$ were in partially operational state “2”. The percentage share of these partially non-operational *j* elements in the tested object’s structure was 25% (Fig. 5). The remaining tested subset of basic elements $\{e_{2,1}; e_{2,3}; e_{6,1}; e_{7,1}\}$ were in critical operational state “1”.

The percentage share of these critical operational *j* elements in the tested object’s structure was 20%. The tested object featured no basic elements in non-operational state “0” (Fig. 5).

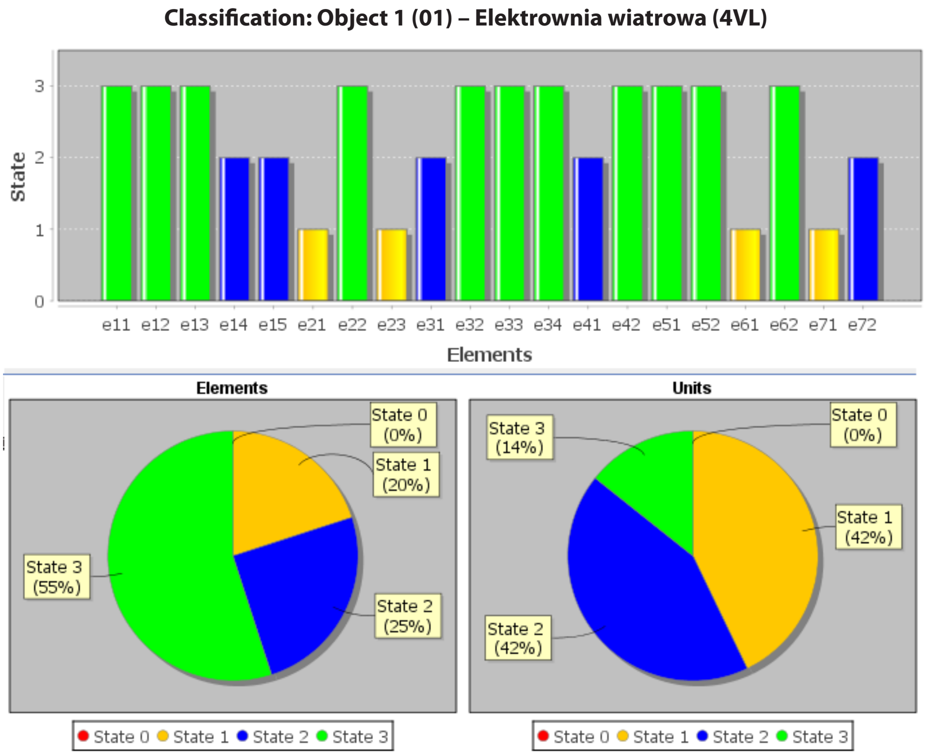

Fig. 5. Final form of the diagnostic information output in DIAG 2, shown on a bar chart and a pie chart.

4. Conclusion

Introduction of an additional logical state to characterize engineering or other facilities expands the available output of diagnostic information. This allows a better definition of operating strategies. This also improves the determination of aggravation probability of operating conditions due to maladjustment, non-optimal conditions, or de-rating of performance parameters. All these factors can be rectified with simple in-process tasks, such as adjustments. Identification of a partially operational or critical operational state should prompt a decision to carry out an in-operation refurbishment of the engineering facility.

This paper was funded under Statutory Research Project no. 504.02.12 of the Faculty of Mechanical Engineering at the Koszalin University of Technology.

Received November 30, 2017. Revised December 11, 2017.

Paper translated into English and verified by company SKRIVANEK sp. z o.o., 22 Solec Street, 00-410 Warsaw, Poland.

REFERENCES

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

[2] Duer S., *Inteligentny system wspomagający proces odnawiania cech eksploatacyjnych w złożonych obiektach technicznych*, Wydawnictwo Uczelniane Politechniki Koszalińskiej, Koszalin, 2012, s. 242.

[3] Duer S., *Artificial neural network in the control process of object's states basis for organization of a servicing system of a technical objects*, Neural Computing & Applications, vol. 21, no. 1, 2012, pp. 153-160.

[4] Duer S., *Applications of an artificial intelligence for servicing of a technical object, Neural Computing* & *Applications*, vol. 22, no. 5, 2013, pp. 955-968.

[5] Duer S., Zajkowski K., Płocha I., Duer R., *Training of an artificial neural network in the diagnostic system of a technical object*, Neural Computing & Applications, vol. 22, no. 7, 2013, pp. 1581-1590.

[6] Duer S., Zajkowski K., Wrzesień P., Duer R., *Diagnostyka użytkowania urządzeń elektrowni wiatrowej*, Logistyka, nr 3, 2015, s. 1140-1148.

[7] Duer S., Wrzesień P., Duer R., *Projekt systemu ekspertowego wspomagającego użytkowanie elektrowni wiatrowej*, Logistyka, Nr 3, 2015, s. 1116-1124.

[8] Duer S., Zajkowski K., Duer R., *Zastosowanie logiki 4-wartościowej w procesie wnioskowania w systemach diagnostycznych*, Biuletyn Wojskowej Akademii Technicznej, vol. 65, nr 2, 2016, s. 41-52.

[9] Duer S., Duer S., Mazuru S., *Determination of the expert knowledge base on the basis of a functional and diagnostic analysis of a technical object*, Nonconventional Technologies Review, Romanian, June, 2016, pp. 23-29.

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

[11] 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.

[12] 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.

[13] Dhillon B.S., *Applied Reliability and Quality, Fundamentals, Methods and Procedures*, Springer–Verlag, London Limited, 2007, p. 186.

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

[15] 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.

[16] Kosiński R., *Sztuczne sieci neuronowe, dynamika i chaos*, WNT, Warszawa, 2004.

[17] Klausmeier R., Using artificial intelligence in vehicle diagnostic systems, „SAE Techn. Pap. Ser, no 961124.", 1986, pp. 1-7.

[18] Świątnicki Z., Wantoch-Rekowski R., *Systemy ekspertowe*, WAT, Warszawa, 1995.

[19] Waterman D., *A guide to export systems*, Addison–Wesley Publishing Company, 1986.

S. DUER, D. BERNATOWICZ, P. WRZESIEŃ, R. DUER

Diagnozowanie złożonego obiektu technicznego w logice 4-wartościowej

Streszczenie. W artykule zaprezentowano istotę badania stanu złożonego obiektu technicznego w logice 4-wartościowej. W tym celu zaprezentowano inteligentny system diagnostyczny (DIAG 2). Cechą szczególną tego systemu jest możliwość wnioskowania w *k*-tej logice przy {$k = 4, 3, 2$}, w tym przypadku zastosowano logikę {$k = 4$}. Ważną częścią tego opracowania jest przedstawienie w nim podstaw teoretycznych opisujących istotę wnioskowania w badanych logikach 4-wartościowych. Wskazano także, że podstawą klasyfikowania stanów w logikach wielowartościowych w systemie diagnostycznym (DIAG 2) jest zinterpretowany dopuszczalny przedział zmian wartości cech sygnałów diagnostycznych. Badaniu stanu w logice 4-wartościowej poddano system urządzeń elektrowni wiatrowej.

Słowa kluczowe: diagnostyka techniczna, wnioskowanie diagnostyczne, logiki wielowartościowe, sztuczna inteligencja
DOI: 10.5604/01.3001.0011.8018