Piotr WASIEWICZ, Marcin LESZCZYŃSKI
Institute of Automatic Control and Robotics, Warsaw University of Technology, Warszawa, Poland

DESIGN STATION FOR FAULT TOLERANT CONTROL SYSTEMS

Keywords

Fault tolerant control (FTC), system protection, system reconfiguration, fault detection and isolation (FDI).

Abstract

The presented station prepared for the design of fault tolerant control (FTC) systems has been created in the Institute of Automatic Control and Robotics at Warsaw University of Technology. It consists of the hydraulic installation equipped with Emerson's instrumentation, DeltaV-control system and AMandD-advanced monitoring and diagnostic system. The fault tolerance of certain sensors, controllers, actuators, and process components can be achieved by the use of functional redundancy, which consists in the performance of appropriate changes in the operation manner of the faulty system. The various industrial FTC applications and new diagnostic-protection algorithms can be developed on the basis of considered station.

Introduction

Growing demands towards the quality and quantity of industrial production of many goods increases the necessity to achieve a higher reliability of particular automatic control systems. Nowadays, it is especially important with reference to the strong competition observed in all industrial branches.

Therefore, more and more effort is spent on the development of FTC systems. This means the use of functional (software, analytical) redundancy which consists in the performance of appropriate changes in the operation manner of the process and the faulty control system. It can be realised thanks to the use of the partial process model and the relations existing among the values of certain parameters and process variables.

The problems connected with the fault tolerance of automatic control systems were published a long time ago [8, 9, 10, 11, 14, 15, 17]. The functional structure of a microprocessor-based controller tolerating instrument faults has also been presented [15]. However, intensive research works in this field were done in the recent years. One can find a description of many practical applications of analytical redundancy for diagnostics and system protection [3, 4, 5, 6, 16]. Also many survey papers [1, 12, 19] and books [2, 7, 18] have been published.

To drop the process automation costs, such contemporary automatic control systems are commonly designed on the basis of PLCs (Programmable Logic Controllers) and SCADA systems (Supervisory Control And Data Acquisition), instead of applying the more expensive DCS systems (Distributed Control System). The usage of such monitoring and control units gives the opportunity to a convenient implementation of the adequate algorithms of process control, monitoring, diagnosis, and protection on the spot in the nearest place to the controlled process.

Development of FTC systems involves the integration of diagnostic, reconfiguration, and control software. Two conceptions of such integration are possible:

1. With the use of co-operation between controllers and the independent process diagnostic station. FDI tasks are performed in the supervisory station on the basis of process data acquired from controllers, and then appropriate decisions concerning the reconfiguration of control algorithms are transmitted to controllers and performed on the spot. This conception can invoke unwanted delays in the performance of protection actions.
2. On the basis of the embedded diagnostic-protection procedures integrated with the control algorithms are implemented in the controllers. This conception can significantly decrease the operation period of the unhealthy system.

The laboratory station prepared for the design of FTC systems is presented in this paper. Both the above mentioned solutions can be designed and tested on the basis of the system. The achieved results are illustrated in Fig. 1.

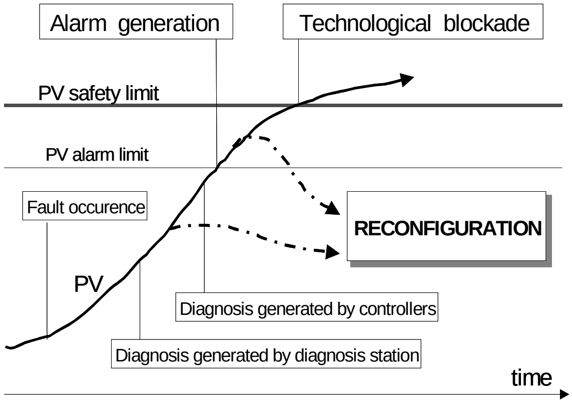

Fig. 1. A given PV chart showing differences between action of automatic blockade and FTC system in cases when a diagnosis is generated by a diagnosis station or by a controller

1. Design station for FTC systems

The laboratory hardware and software system dedicated for the research of FTC systems has been designed and realised in the Institute of Automatic Control and Robotics at Warsaw University of Technology. The design station consists of:

- physical process model, hydraulic installation, giving the possibility to introduce many faults,
- industrial instrumentation and actuators made by Emerson (earlier Fisher Rosemount), operating in Fieldbus Foundation standard communication,
- DeltaV industrial control system (Emerson's also),
- AMandD advanced monitoring and diagnostic system (own, original solution).

The overview of the design station for FTC systems is shown in Fig. 2 and the diagram of its hydraulic installation in Fig. 3.

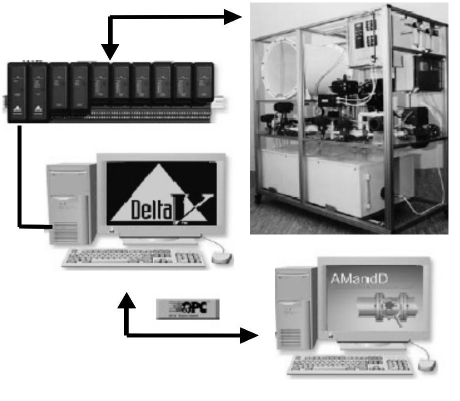

Fig. 2. The overview of the design station for FTC systems

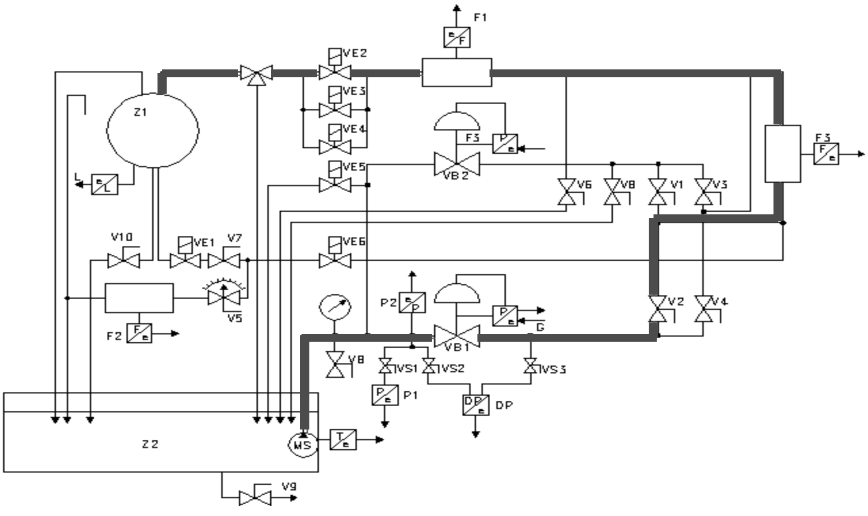

Fig. 3. The diagram of the hydraulic installation of the FTC design station (the structure for normal operation with the use of VB1 valve)

2. Advanced monitoring and diagnosis system: AMandD

The Advanced Monitoring and Diagnosis system-AMandD is the main element of the FTC system design station. It is the original software system dedicated for the diagnosis and identification of industrial processes. It has been developed within the framework of FP5 EU grant CHEM and our own activities. The system is intended for applications in the power, chemical, petrochemical, pharmaceutical, steel, food and other industries. It is also applicable for didactic purposes. System AMandD offers a wide range of the newest diagnostics and identification algorithms. Open architecture of the system gives the advantage of its easy integration with any available automatic control and monitoring system.

The following research, development and design works have been performed with the use of the AMandD system:

- development of the process modelling methods for diagnostic purposes,
- design of virtual sensors,
- development of fault detection methods,
- development of fault isolation methods,
- design of instrumentation fault tolerating systems,
- design of actuator fault tolerating systems.

One of the most important parts of AMandD system is the MITforRD module dedicated to the identification of static and dynamic models of the processes. The creation of the following models is accessible at present:

- classic, linear models in the shape of transfer function in discrete time G(z). Identification is performed by means of the least squares minimisation criterion and SVD algorithm. The model order and delay times can also present subjects of identification,
- artificial neural networks (ANN) models with classic structure (multilayer neural network). The system provides a set of the various network of learning methods, for example: error back propagation, conjunctive gradients, simulated annealing, and genetic optimisation,
- fuzzy TSK models with identified structure, parameters and coefficients describing system behaviour in particular areas. The conclusion section of the fuzzy rules has a polynomial form. Identification of these models is performed by means of specialised evolution algorithm,
- polynomial models (polynomial structure identification and parameter estimation).

The above list does not cover all possible model types. The open architecture of the system results from the plug-in technology and enables the users an easy extension of the list of available models. Models are very useful for the creation of soft sensors and residual generation.

CalcPaths module of AMandD system, similar to Matlab Simulink, allows to easily configure the signal processing loops by means of static and dynamic function blocks. It may also be applied for the development of analytical models based of physical and chemical equations or for creating process simulators. The CalcPaths module also provides a set of simple algorithms supporting the creation of heuristic tests for fault detection purposes.

Methods based on analytical, neural, fuzzy and heuristic approaches making use of relations between process variables are implemented for fault detection tasks in the AMandD system. Fuzzy logic is applied for the evaluation of residuals. Parameters of fuzzy sets may be fixed manually or automatically, based on statistical processing of residuals in normal process states.

The fault isolation algorithm of the iFuzzy-FDI module of the AMandD system applies fuzzy logic for the diagnostic conclusion. The generated diagnosis indicates faults with the assigned fault certainty coefficients. An algorithm may be applied in many variants, depending on introduced settings.

Integration of AMandD with DeltaV control systems gives the possibility of the development of instrumentation and actuator FTC systems. One can implement redundant control algorithms in the control system. Decisions concerning the reconfiguration of the system structure are undertaken on the basis of the achieved diagnosis information, as shown in Fig. 4.

Two different examples of the use of AMandD system in on-line mode to perform FDI and FTC tasks are shown in Section 3.

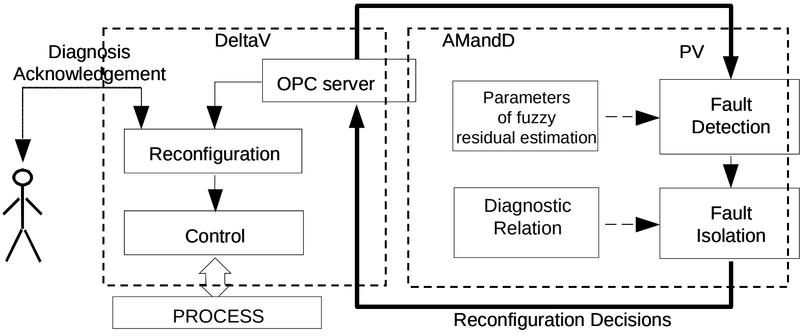

Fig. 4. The diagram of co-operation between AMandD diagnosis system and DeltaV control system

3. The on-line use of AMandD system for FTC purposes

The cascade control system of the water level has been designed and tested in order to illustrate the possibilities of FTC system creation with the use of AMandD and DeltaV software. The water level is the main control variable and the water flow is the auxiliary one. Two possibilities of sensor fault tolerance are accessible. The first one, when the value of redundant water flow is estimated by CALC function block of DeltaV system and switched on (when necessary) by AMandD system is shown in Fig. 5.

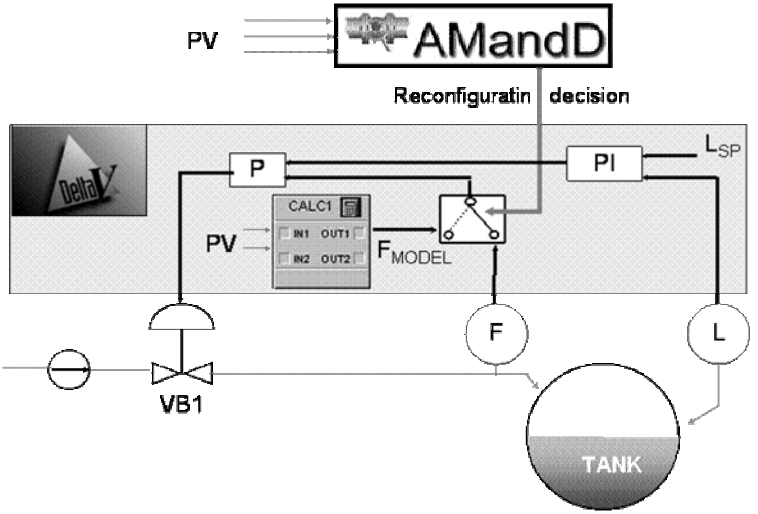

Fig. 5. FTC system tolerating fault of F water flow with the use of functional redundancy designed inside of the controller

The algorithms for the water level cascade control system have been prepared in DeltaV-FBD language. The FTC feature has been achieved due to the use of CALC function blocks estimating the values of the redundant process variable. As an example, the algorithm of the main control loop of the system is shown in Fig. 6. The achieved results are illustrated in Fig. 7.

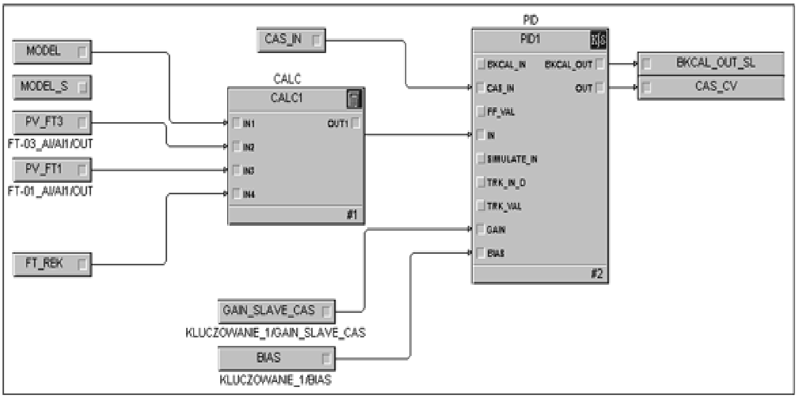

Fig. 6. The control programme designed in FBD language for the main control loop of the water level cascade controls the system shown in Fig. 5

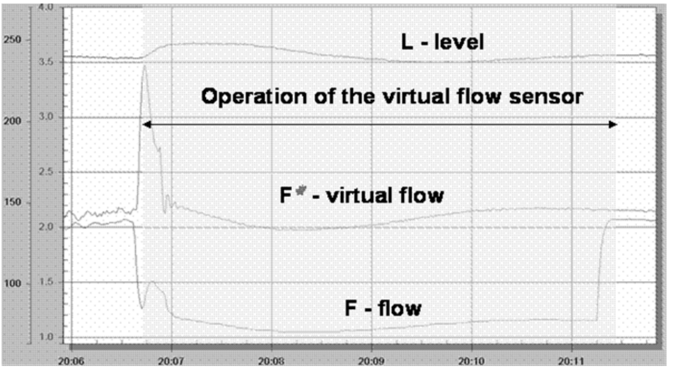

Fig. 7. An example of the results achieved with the use of analytical redundancy-flow value estimated by CALC function block of DeltaV system

The second fault tolerance possibility lies in the fact that the value estimation, as well as switching on (when necessary) of the redundant variable are both performed outside of the controller, by AMandD system. The case for the water level cascade control system is shown in Fig. 8.

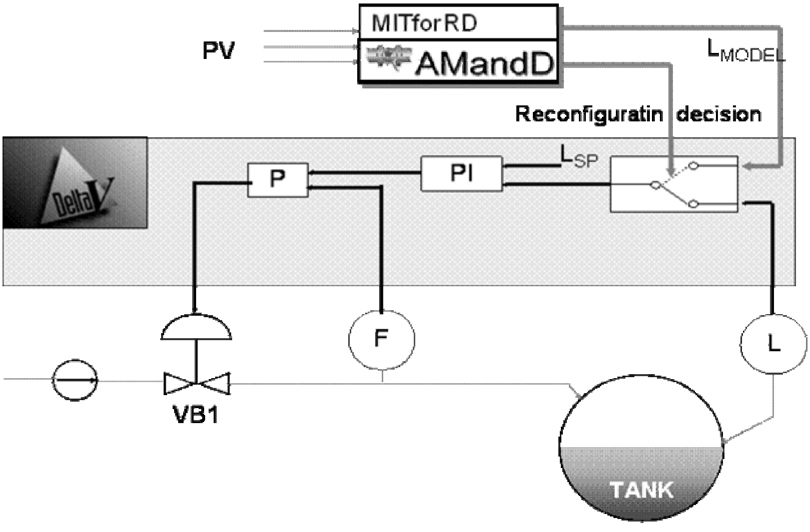

Fig. 8. FTC system tolerating fault of L water level with the use of functional redundancy performed by AMandD system, outside of the controller

The achieved results connected with FTC system presented in Fig. 8, are shown in Fig. 9.

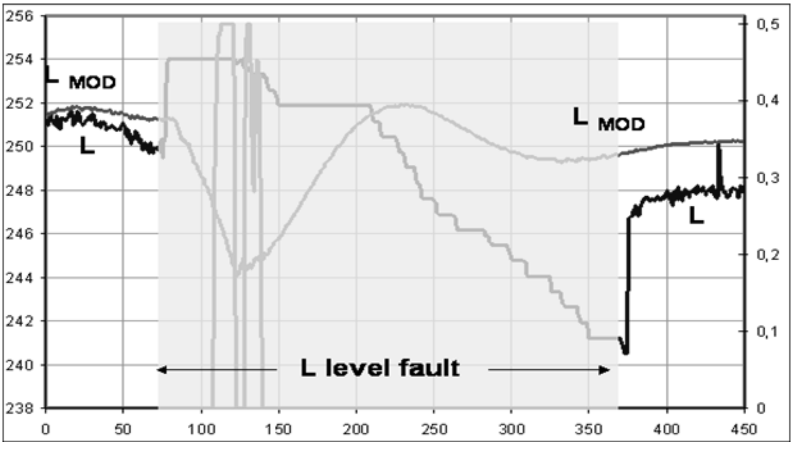

Fig. 9. The chart illustrating the tolerance of L level sensor fault is the main control variable of the level control, cascade system (Fig. 8). The fault has been introduced at 73rd sec, and the earliest diagnoses occurred at 108th sec. Switching on the software redundancy (L level estimated by AMandD system) took place at 122nd sec.

Apart from analytical redundancy described above it is also possible to use the hardware redundancy of the flow sensor (F1 and F3). The achieved results are shown in Fig. 10.

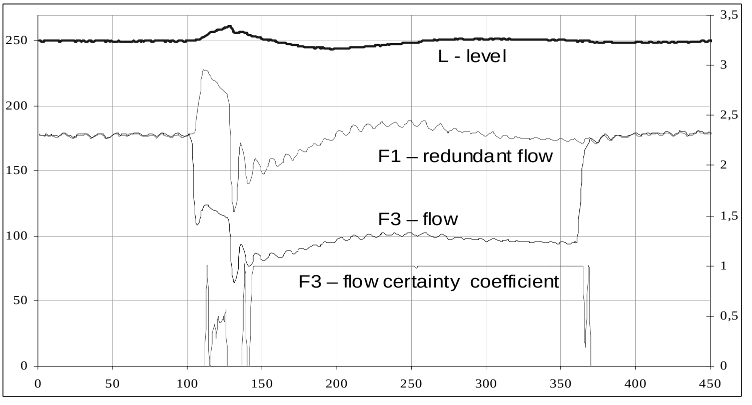

Fig. 10. The chart illustrating the fault tolerance of F3 flow sensor which is an auxiliary control variable of the level cascade control system. The fault has been introduced at 102nd sec, and the earliest diagnoses occurred at 112th sec. Switching on the hardware redundancy (F1 flow) took place at 124th sec.

4. The tolerance of actuator faults

In multidimensional systems that have many actuators, there is sometimes a possibility of alternative system operation without the use of all actuators with some healthy actuators. Some technological installations are equipped with many pumps or segments of pipeline that are different in diameter and have their own control valves. They are used for so-called “rough-exact” process control.

The presented FTC design station gives the possibility to introduce the artificial actuator faults. Faults can be introduced either by forcing improper pressures in chambers of pneumatic valve servomotors or by insertion of the positioner faults. In the reported research an additional supply of servomotors from external air pressure sources has been made. The results achieved during the VB1 valve fault simulation, detection and toleration processes are shown in Fig. 11. Switching off the faulty VB1 valve and switching on the healthy VB2 valve was the undertaken protection action. The reconfigured structure of the hydraulic installation of the design station is shown in Fig. 12.

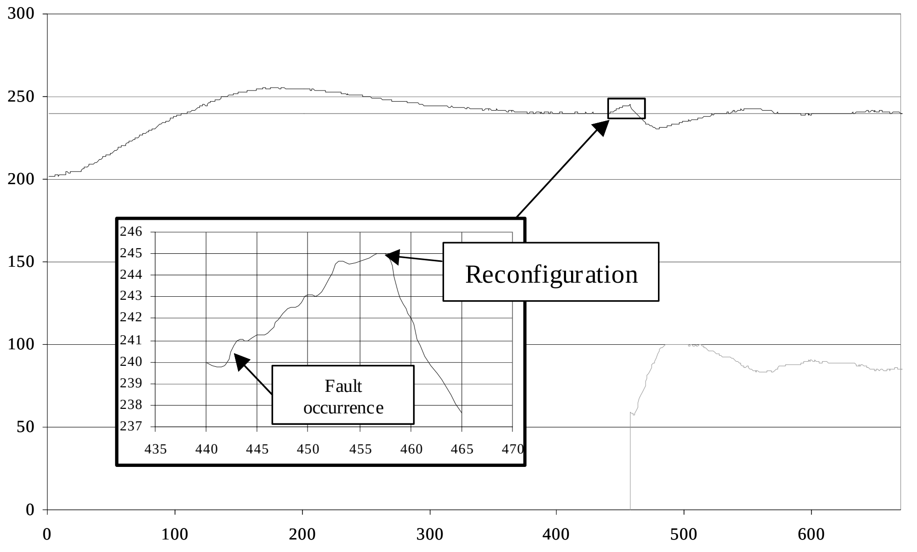

Fig. 11. The chart illustrating an actuator fault tolerance. The simulated VB1 valve fault has been isolated by the diagnostic system AMandD after 16 sec from the moment of fault introducing. Switching off the faulty VB1 valve and switching on the healthy VB2 valve was the performed protection action

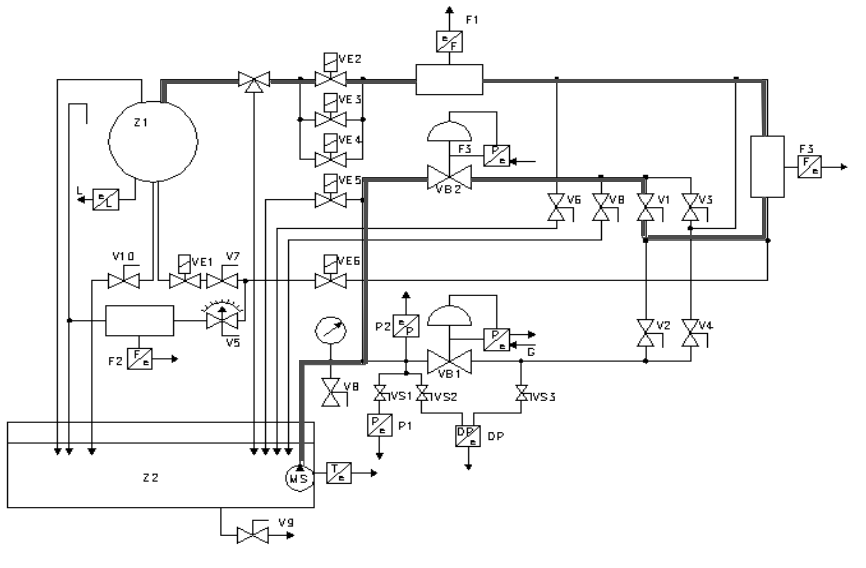

Fig. 12. The diagram of hydraulic installation after the switch on of the reduntant VB2 valve (the case of VB1 valve fault occurrence)

This is an example of functional redundancy existing in many technological processes which enables the faults of some technological components to be tolerated.

Conclusions

The described engineering station destined for the design of FTC systems is successfully used for both research and didactic purposes. From practical point of view an unconstrained possibility of distribution of fault detection, fault isolation and fault toleration tasks between controllers and supervision diagnostic stations is an especially valuable advantage of the laboratory system.

The various industrial FTC applications and new diagnostic-protection algorithms can be developed on the basis of the considered station. An example of FTC system designed for the condensation power turbine according to the methods presented in this paper has been also described [13].

It is stressed that a system reconfiguration in many cases can be performed before the end of fault isolation phase; because, in different functional states, not only a single one but a few devices (which are healthy but no more useful in the new situation) can be eliminated from the operation [10, 11, 14]. However, more precisely fault isolation results are advisable for system renewal purposes.

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References

1. Blanke M., Frei Ch., Kraus F., Patton R., Staroświecki M.: What is fault-tolerant control? In: IFAC Symposium on Fault Detection, Supervision and Safety for Technical Process-SAFEPROCESS’2000, Budapest, Hungary, June 14-16, 2000, Vol. 1, p. 40-51.
2. Blanke M., Kinnaert M., Lunze J., Staroświecki M.: Diagnosis and Fault-Tolerant Control. Springer-Verlag. 2004.
3. Bonivento C., Isidori A., Marconi L., Paoli A.: Implicit fault tolerant control: application to induction motors. Automatica, 2004, vol. 40, p. 355-371.
4. Candau J., de Miguel L.J., Ruiz J.G.: Controller reconfiguration system using parity equations and fuzzy logic. In: IFAC Symposium on Fault

Detection, Supervision and Safety for Technical Process-SAFEPROCESS’1997, Hull, UK, Vol. 2, p. 1258-1263.

5. Chen, W., Jiang J.: Fault-tolerant control against stuck actuator faults. IEEE Proceedings on Control Theory and Applications, 2005, p. 138–146.
6. Massoumnia M.A., Van der Velde W.E.: Generating parity relation for detecting and identifying control system component failures. Journal of Guidance, Control and Dynamics, 1988, nr 11, p. 60-65.
7. Korbicz J., Kościelny J.M., Kowalczuk Z. K., Cholewa W.: Fault Diagnosis. Springer-Verlag 2004.
8. Kościelny J.M, Ostasz A., Wasiewicz P.: Fault Detection Based Fuzzy Neural Networks–Application to Sugar Factory Evaporator. 4th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Process-SAFEPROCESS’2000, Budapest, Hungary, June 14-16, 2000, Vol. 1. p. 337-342.
9. Kościelny J.M., Wasiewicz P.: Problems of Fault Protection of Technologic Processes and Automatic Control Systems. International Workshop on Advanced Approaches in Industrial Control Systems, Prague, 1993, p. 62-67.
10. Kościelny J.M., Wasiewicz P.: The Sensitivity of Diagnostic Systems to the set of Measuring Signals. The 3rd IEEE Conference on Control Application. Glasgow, 1994, p. 1145-1150.
11. Kościelny J.M., Wasiewicz P.: Fault Diagnosis and Protection in Industrial Control Systems. Engineering Simulation, special issue “Engineering Diagnostics” 1996, vol. 13, p. 889-904.
12. Patton R..J.: Fault-tolerant control: The 1997 situation. IFAC Symposium on Fault Detection Supervision and Safety for Technical Processes SAFEPROCESS’1997, Hull, UK, 1997 Vol. 2, p. 1033-1055.
13. Pawlak M., Wasiewicz P., Kościelny J.M.: Condensation power turbine control system tolerating instrumentation faults. 1st Workshop on Networked Control Systems and Fault Tolerant control NeCST’05, Ajaccio, France, October 6-7, 2005, p. 231-235.
14. Wasiewicz P.: Methodology of development of computerized control system tolerating some internal faults. Dissertation, Warsaw University of Technology, 1983, p. 1-159.
15. Wasiewicz P.: Functional structure of a microprocessor based controller tolerating failures in measuring circuits. IFAC Workshop on Instrumentation Systems for Safeguarding and Control, The Hague, The Netherlands, 1986, p. 67-72.
16. Won-Kee Son, Oh-Kyu Kwon, Lee M.E.: Fault-tolerant model based predictive control with application to boiler systems. IFAC Symposium on Fault Detection Supervision and Safety for Technical Processes SAFEPROCESS’1997, Kingston Upon Hull, 1997, Vol. 2, p. 1240-1245.

17. Yang Y., Lu Y.Z.: Sensor fault tolerant control and its application. IFAC Symposium on Fault Detection Supervision and Safety for Technical Processes-SAFEPROCESS’1991, Baden-Baden, 1991 Vol. 1, p. 55-60.
18. Zhang Y.: Active Fault Tolerant Control Systems. Springer-Verlag. 2003.
19. Zhang Y., Jiang J.: Bibliographical review on reconfigurable fault-tolerant control systems. IFAC SAFEPROCESS’2003, Washington DC, U.S.A. 2003, p. 265–276.

Reviewer:
Krzysztof LATAWIEC

Stanowisko projektowania systemów sterowania tolerujących uszkodzenia

Słowa kluczowe

Sterowanie tolerujące uszkodzenia (FTC), zabezpieczenia systemu, rekonfiguracja systemu, detekcja i lokalizacja uszkodzeń (FDI).

Streszczenie

Zaprezentowano stanowisko do projektowania systemów sterowania tolerujących uszkodzenia (FTC) opracowane i zrealizowane w Instytucie Automatyki i Robotyki Politechniki Warszawskiej. Składa się ono z instalacji hydraulicznej wyposażonej w oprzyrządowanie firmy Emerson, system sterowania DeltaV oraz zaawansowany system monitorowania i diagnostyki procesów AMandD. Tolerowanie uszkodzeń urządzeń pomiarowych i wykonawczych oraz elementtów instalacji technologicznej jest osiągane poprzez zastosowanie redundancji funkcjonalnej polegającej na dokonywaniu odpowiednich zmian w sposobie działania uszkodzonego systemu. Stanowisko umożliwia przygotowywanie przemysłowych aplikacji systemów FTC oraz opracowywanie nowych algorytmów diagnostyczno-zabezpieczających.