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Fault detection and diagnosis of pneumatic valve using Adaptive Neuro-Fuzzy Inference System approach

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ABSTRACT

Detection and diagnosis of faults in cement industry is of great practical significance and paramount importance for the safe operation of the plant. In this paper, the design and development of Adaptive Neuro-Fuzzy Inference System (ANFIS) based fault detection and diagnosis of pneumatic valve used in cooler water spray system in cement industry is discussed. The ANFIS model is used to detect and diagnose the occurrence of various faults in pneumatic valve used in the cooler water spray system. The training and testing data required for model development were generated at normal and faulty conditions of pneumatic valve in a real time laboratory experimental setup. The performance of the developed ANFIS model is compared with the MLFFNN (Multilayer Feed Forward Neural Network) trained by the back propagation algorithm. From the simulation results it is observed that ANFIS performed better than ANN.

1. Introduction

In cement industry there is a crucial need for checking and monitoring the equipment condition precisely since they are mostly subject to hazardous environments, such as severe shocks, vibration, heat, friction, dust, etc. The problem of detecting faults in pneumatic valve used in cooler water spray system in cement industry is strategically important because of its various implications like avoiding major plant breakdowns and catastrophes. Taking into account that a valve malfunction in many hazardous applications can cause serious consequences, the fault diagnosis of industrial servo-actuated valves is a very important task.

Many analytical based techniques [1–3] have been proposed during the past several years for fault detection of technical plants. The important aspect of this approach is the development of a model that describes the 'cause and effect' relationships between the system variables using state estimation or parameter estimation techniques. The problem with these mathematical model based techniques is that under real conditions, no accurate models of the system of interest can be obtained. In that case, the better strategy is of using knowledge-based techniques where the knowledge is derived in terms of facts and rules from the description of system structure and behaviour. Classical expert systems [4,5] were used for this purpose. The major disadvantage of this method is that binary logical decisions with Boolean operators do not reflect the gradual nature of many real world problems.

The presence of nonlinearities, e.g., stiction, and deadband in a control valve limits the control loop performance. Stiction is the most commonly found valve problem in the process industry. Reference [6] focuses on the understanding, from real-life data, of the mechanism that causes stiction and proposes a new data-driven model of stiction, which can be directly related to real valves. It also validates the simulation results generated using the proposed model with that from a physical model of the valve.

Oscillations in process control loops present a common problem. Reference [7] proposes a new algorithm to detect valve stiction for diagnosis of oscillation. Formalism for the qualitative description of input–output characteristics of a valve is also proposed for implementation of the detection algorithm. The method was evaluated on several industrial data sets. It showed excellent performance for detection of stiction.

Limit cycles caused due to valve nonlinearity such as stiction can be eliminated with proper valve maintenance. Valve maintenance is undertaken during production stops, which are scheduled once every 6 months to 3 years. The loss of energy and product quality

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during this intermediate period can be quite high. Stiction compensation algorithms can mitigate this problem to a large extent. Reference [8] two novel approaches for stiction compensation are proposed: (a) a simple two-move approach and (b) an optimization based approach much in the spirit of predictive control strategies. Both the approaches are based on a data-driven model for stiction. The merits and demerits of both these approaches are discussed. The results are illustrated using simulation case studies. The two-move approach is also validated on a liquid level system.

A significant number of control loops in process plants perform poorly due to control valve stiction. Developing a method to detect valve stiction in the early phase is imperative to avoid major disruptions to the plant operations. Nonlinear principal component analysis (NLPCA), widely known for its capability in unravelling nonlinear correlations in process data, is extended in [9] to diagnose control valve stiction problems.

Reference [10], describes a method for automatic diagnosis of stiction in control valves. The diagnosis is performed using a shape analysis of the waveform of the oscillations that appear in the process output during stick–slip motion. The procedure is automatic in the sense that no process information is assumed except the one that is already available in the controllers. The procedure can be used both online and off-line. Results from industrial tests are provided in the paper.

In [11], a nonlinear fuzzy model with transparent inner structure is used for the generation of six different symptoms in electro-pneumatic valve. The resulting symptom patterns are classified with a new self-learning classification structure based on fuzzy rules. The key advantage of fuzzy logic is that it enables the system behaviour to be described by “if–then” relations [12]. The driving force behind a fuzzy logic system is the idea that some uncertainty exists in categorizing the values of the system variables. This uncertainty present in the decision making process can be incorporated into the diagnosis system via fuzzy set theory.

But the limitation of Fuzzy logic is that in general the rules and membership function are formed by the experience of the human experts. With an increasing number of variables, the possible number of rules increases exponentially, which makes it difficult for experts to define a complete rule-set for good system performance.

Artificial Neural Network based methods for fault diagnosis [13–15] has received considerable attention over the last few years. The advantage of neural network approach is their generalization capability, which lets them deal with partial or noisy inputs. The neural networks are able to handle continuous input data and the learning must be supervised in order to solve the fault detection and diagnosis problem. The multilayer perceptron network is the most common network used today. Due to their powerful non-linear function approximation and adaptive learning capabilities, neural networks have drawn great attention in the field of fault diagnosis. Ka-Veng Yuen et al. [16] have developed a practical methodology for damage detection in smart structures by the pattern matching approach using an Artificial Neural Network (ANN). They have presented a Bayesian probabilistic method to select the ANN model class with suitable complexity. In [17] probabilistic-entropy-based neural network (PENN) model is applied to solve a fire safety engineering problem. The network learns online with an incremental growth network structure and performs regression in a noisy environment.

Then [18] used a back propagation Artificial Neural Network to model a process valve actuator. The performance of the network output and actual outputs were compared. Neural networks have been used for fault detection in induction machines [19]. The implemented network is suitable for single fault detection of stand alone induction motors. However, significant increase in the scale of such a neural network is observed when multiple faults are to be detected. But the neural network approach needs lot of data to develop the network before being put to use for real-time applications. Owing to the sizeable scale and limited number of training samples, proper training of this network then becomes a very difficult task. Also, Artificial Neural Network is a black box technique and it does not give the physical insight to the process dynamics.

Adaptive Neuro-Fuzzy networks are enhanced FIS (Fuzzy Inference System) with learning, generalization and adaptivity capabilities. These networks encode the fuzzy if-then rules into a neural network-like structure and then use appropriate learning algorithms to minimize the output error based on the training/validation data sets. ANFIS stands for Adaptive Neuro-Fuzzy Inference Systems and tunes a fuzzy inference system with a back-propagation algorithm using the collection of input/output data. The ANFIS approach [20–22] uses Gaussian functions for fuzzy sets, linear functions for the rule outputs and Sugeno's inference mechanism. The parameters of the network have the mean and standard deviation [23] of the membership functions (antecedent parameters) and the coefficients of the output linear functions (consequent parameters) used for the fault diagnosis of induction motor with variable speed drive. The learning algorithm is a hybrid algorithm consisting of the gradient descent and the least-squares estimate. Using this hybrid algorithm, the rule parameters are recursively updated until acceptable error is reached. This paper presents the ANFIS approach for fault detection and diagnosis of a pneumatic valve used in cooler water spray system in cement industry.

The paper is organized as follows: in the next section, the system description for this study is outlined. Section 3 describes the fault detection in pneumatic actuator and Section 4 describes Adaptive Neuro-Fizzy Inference System (ANFIS). Section 5 demonstrates the development of ANFIS model for fault diagnosis and Section 6 describes the results and discussion and finally, in Section 7, conclusions are drawn from the work.

2. System description

In the cement industry the output of kiln is the clinker product which is of high temperature up to 1100 °C, it is necessary to reduce the temperature of the clinker by using cooler fans and the water spray system. The functions of the clinker cooler process are to maximize the heat recovery to the kiln process, minimize the ultimate clinker temperature.

The measurement of clinker temperature is done by using thermocouple sensor. The direct measurement of clinker temperature is not possible on a continuous basis. Hence the measurement of cooler vents gas temperature using thermocouple sensor is proportional to the temperature of the clinker. The description about this system is well explained in [24]. The schematic layout of the cooler water spray system setup is shown in Fig. 1. The various safety instruments used in the cooler spray system are Butter fly valve, reducer, filter, orifice plate, shut off valve, flow transmitter, block and bleed valve, globe valve, ball valve, non-return valve, pressure gauge, temperature element/transmitter, etc.

2.1. Physical structure of pneumatic valve

The internal structure of the pneumatic valve is shown in Fig. 2. The flow is set by the position of the rod, which determines the restricted flow area. The actuator sets the position of this rod. There are many types of servo-actuators: electrical motors, hydraulic cylinders, spring-and-diaphragm pneumatic servomotor, etc.

The most common type of actuator is the spring-and-diaphragm pneumatic servomotor due to its low cost. This actuator consists of a rod that has, at one end, the valve plug and, at the other end, the plate. The plate is placed inside an airtight chamber and connects to the walls of this chamber by means of a flexible diaphragm.