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Diagnosis of feedwater heater performance degradation using fuzzy inference system

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ABSTRACT

Power generation facilities cannot avoid performance degradation caused by severe operating conditions such as high temperature and high pressure, as well as the aging of facilities. Since the performance degradation of facilities can inflict economic on power generation plants, a systematic method is required to accurately diagnose the conditions of the facilities.

This paper introduces the fuzzy inference system, which applies fuzzy theory in order to diagnose performance degradation in feedwater heaters among power generation facilities. The reason for selecting only feedwater heaters as the object of analysis is that it plays an important role in the performance degradation of power generation plants, which have recently been reported with failures. In addition, feedwater heaters have the advantage of using many data types that can be used in fuzzy inference because of low measurement limits compared to other facilities. Fuzzy inference systems consists of fuzzy sets and rules with linguistic variables based on expert knowledge, experience and simulation results to efficiently handle various uncertainties of the target facility. We proposed a method for establishing a more elaborate system. According to the experimental results, inference can be made with consideration on uncertainties by quantifying the target based on fuzzy theory. Based on this study, implementation of a fuzzy inference system for diagnosis of feedwater heater performance degradation is expected to contribute to the efficient management of power generation plants.

1. Introduction

Performance degradation refers to a phenomenon in which a device fails to exhibit its intended performance. Power generation facilities, such as Nuclear Power Plants (NPPs), operated under severe conditions of high temperature and high pressure for long periods cannot avoid performance degradation. In fact, such issues have been frequently reported with the recent aging of facilities. As the performance degradation of facilities lead to economic, it is necessary to maintain and repair facilities based on accurate diagnosis before such serious conditions occur.

A feedwater heater is a device that preheats water supplied to a steam generator to maintain appropriate temperature conditions, and has the advantages of improving the cycle efficiency, minimizing the thermal stress of the steam generator, and preventing the reduction of life. When performance degradation occurs in such a facility, the heat transfer capacity of the feedwater channel is reduced to directly affect generation efficiency.

Through the past research, we developed a methodology using a regression model (Jee, Heo, Jang, & Lee, 2011) and a methodology using diagnosis tables (Kim & Heo, 2012) to diagnose the thermal performance degradation in feedwater heaters. The methodology using the regression model is a numerical analysis method that expresses the performance degradation of the facility and the performance degradation caused by surrounding facilities as mathematical formulae and computes the results through matrix calculations corresponding to the number of facilities. Reliability of this methodology was reduced when noise occurred in the data measured at the actual site, and there was difficulty in uniform application of the methodology to power generation plants operating under different conditions. The methodology using diagnosis tables is widely used at the actual sites because it can make an inference about the type of performance degradation present based on fluctuation of the data. Nonetheless, this methodology cannot make an inference about the severity of performance degradation that is found. The purpose of this study is to apply fuzzy logic as a method to make up for the shortcomings of these prior stud-

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ies (Kothamasu & Huang, 2007; Wang & Hu, 2006; Wang & Elhag, 2008).

The body of this paper introduces a simulation of the performance degradation using simulation software, preparation of a diagnosis table using data obtained from the simulation, and a diagnosis using a fuzzy inference system.

There are different types of fuzzy inference methods, and the Mamdani fuzzy inference method is the most widely used method of direct inference. The advantage of the Mamdani fuzzy inference method using an If-Then rule is that it first determines whether an appropriate control input value of the user belongs to the membership function using 'If' and then converts the value into a number by calculating the degree to which the value belongs to the fuzzy set using 'Then'. This inference method can make use of qualitative advantages of the methodology using a diagnosis table because it prioritizes fluctuation of the variables. Further, because it is a simple operation, the instability of the numerical analysis used in the regression model can be improved. Detailed inference and operation processes will be introduced in the following section (Abraham, 2005).

In this paper, the feedwater heaters of NPPs were selected as the objects of study. When performance degradation occurs in a feedwater heater, its measurement values fluctuate. Here, while degradation of thermal performance identically occurs on the macroscopic level, internal phenomena differ in each case and show different trends in the fluctuation of the variables. This study intends to make an inference about the type and degree of performance degradation using the fluctuation of measurement values (Guimara & Lapa, 2007). First of all, the limited condition described below is taken into account for simplification of the design of the performance degradation detection system. 1) Among the diverse performance degradations that may occur in a feedwater heater, five representative single performance degradation phenomena are used, including excessive increase in drain water level due to malfunctioning of the drain valve or from other causes, reduced pressure of the heater shell due to alien substances, clogging of the tube, phenomenon in which the feedwater does not pass by the heating part due to a defect in the pass partition plate, and leakage in the feedwater tube. 2) Double performance degradation phenomena assume cases in which two of the phenomena mentioned above overlap. An assumption was made that performance degradation phenomena occur sequentially instead of simultaneously. Therefore, triple performance degradation is not considered, as it is possible to detect it before the overlapping of three phenomena (Hadjimichael, 2009).

2. Mamdani fuzzy inference method

A fuzzy inference system (FIS) is based on fuzzy set theory, fuzzy rules, and fuzzy reasoning. It is widely applied to automatic control, robotics, pattern recognition, time series prediction, and fault diagnosis (Guillaume, 2001).

Fuzzy inference based on fuzzy reasoning is more similar to human thinking and natural language compared to existing reasoning systems, and it can be effectively used to describe approximate and uncertain phenomena in the real world. The core part of an FIS consists of a diagnostic rule with a series of linguistic forms, which includes fuzzy association. The inference result is generated by a fuzzy compositional rule. In the end, FIS performs the shifts the role of the inference rule created by experts based on inference knowledge into the role of machine. In general, FISs show outstanding results compared to existing systems when the system cannot be interpreted by existing quantitative methods due to complexity or if the obtained information is qualitative, inaccurate and uncertain. Zadeh (1965), who defined fuzzy logic, presents the 'principle of incongruity' as the reason for these results. This principle states that when a system has a certain degree of complexity, it becomes impossible to provide an accurate and meaningful description of the behavior of the system using a quantitative method. In this case, a qualitative method that sacrifices quantitative relationships is a desirable and useful model.

The authors paid attention to the strengths of the Mamdani model rather than the strengths of the TSK (Takagi–Sugeno–Kang) model, which is quick and effective in terms of calculation. Mamdani model can return output values that can intuitively express expertise, which helps operators of power plants to understand the state of a feedwater heater intuitively.

2.1. Fuzzy sets

Fuzzy sets expand an existing set using the concept of fuzzy logic, and each element has a degree to which it belongs to the set (degree of membership). Here, the degree of membership is expressed as a real number between 0 and 1, where the case in which an element completely belongs to the set is 1 and the case in which it does not belong to the set is 0. This can be expressed using Eq. (1):

$$A = \{(x, \mu_A(x)) | x \in X\},\ \ 0 \le \mu_A(x) \le 1. \tag{1}$$

$\mu_A(x)$ is referred to as the membership function (MF) of the fuzzy set A, and the membership function plays the role of the corresponding elements of the universal set X for each value of the membership function.

The fuzzy set A can be briefly expressed as below; specifically, it is expressed as Eq. (2) if the elements of the universal set □ are continuous and as Eq. (3) if they are discontinuous.

$$A = \int \mu_A(x)/x, \tag{2}$$

$$A = \sum_{x_i \in X} \mu_A(x_i)/x_i. \tag{3}$$

2.2. Fuzzy rules

Knowledge base of the fuzzy inference system consists of a database and a rule. A fuzzy rule is expressed as a linguistic rule in the form of 'If-Then'. This rule has the fuzzy conditional statements as shown in Eqs. (4)–(6) below.

$$R_1 : If\ x\ is\ A_1\ and\ y\ is\ B_1\ then\ z\ is\ C_1, \tag{4}$$

$$R_2 : If\ x\ is\ A_2\ and\ y\ is\ B_2\ then\ z\ is\ C_2, \tag{5}$$

$$R_n : If\ x\ is\ A_n\ and\ y\ is\ B_n\ then\ z\ is\ C_n, \tag{6}$$

Here, x, y and z represent state variables and inference input variables of the system used as the input information of the inference system, and A_i, B_i and C_i refer to the fuzzy values (fuzzy sets) of x, y and z defined for the universal sets U, V and W, respectively. In addition, individual conditional statements can be represented by fuzzy relations called R_i, and they are gathered to form a set of rules (Liu, Yang, Wang, Sii, & Wang, 2004; Takagi & Sugeno, 1985).

2.3. Fuzzy inference process

The inference process of the fuzzy system used in this study is as shown in Figs. 1 and 2. For convenience in calculation and indication, triangular and trapezoidal fuzzy membership functions were used.

Fig. 1 shows fuzzy sets and fuzzy rules for the inference. The first two fuzzy sets correspond to the input part of the variables.