Model-based analysis and evaluation of sensor faults in heat source system

A Motomura¹, S Miyata¹, Y Akashi¹, J Lim¹, K Tanaka², S Tanaka³ and Y Kuwahara⁴

¹School of Engineering, The University of Tokyo, Japan.
²Tokyo Electric Power Company Holdings, Inc., Japan
³TEPCO Energy Partner, Incorporated, Japan
⁴MTD Co., Ltd., Japan

E-mail: akira-motomura012@g.ecc.u-tokyo.ac.jp

Abstract. Faults cause building systems to under-perform in operation. An operation and maintenance process of building systems using fault detection and diagnosis (FDD) essentially requires evaluating the influence of faults in advance because deciding how to respond to faults is necessary to establish the strategies. However, many studies on FDD in a building’s operation have not considered these processes. Then, we focused on sensor errors as faults at ten temperature sensors and four flow sensors in a real heat source system and examined to evaluate the influence of faults. The real heat source system with two chillers and two cooling towers were used to demonstrate calculating system behavior with sensor faults, analyzing results, and evaluating the influence of sensor faults. We developed a detailed simulation model of the system covering a sensor network and combining automatic control system based on the specifications. Using this simulation, we calculated the system behavior without faults and behaviors with fourteen sensor faults in six fault severity levels. As for the annual system coefficient of performance (SCOP), the results showed that sensor faults had influence in various degree and each sensor has different features against fault severities. Some sensor faults had no effect on the system controls, but others had wide influence on controls of sub-systems and energy efficiency reduction. By considering these features of sensor faults, we evaluated the influence of each faults using the annual SCOP as an indicator. Using this method, we analyzed the influence of faults in detail and prioritized sensor faults using the indicator. It is expected that this fault evaluation method helps operation and maintenance of the system.

1. Introduction
Buildings are often considered to contain faults, and faults cause building system to under-perform in operation. In commercial buildings that have equipment are not properly managed and optimally controlled, an estimated 5% to 30% of the energy is wasted (Katipamula and Brambley 2005, Roth et al. 2005). In order to reduce such energy waste, many studies on fault detection and diagnosis (FDD) in a building’s operation have been carried out. An operation and maintenance process of building systems using FDD essentially requires evaluating the influence of faults and deciding how to respond to faults (Katipamula and Brambley 2005). However, many studies on FDD have not considered these processes. Therefore, assuming what kind of faults can occur in a building system and evaluating the
influence of the faults in advance can help an operation and maintenance of the system. Here we assumed faults in a system and evaluated the influence of them. There are too many kinds of faults which can occur in building systems to assume. A sensor fault is one of the kinds of faults in the systems and there are many studies on sensor faults in a part of building systems such as chillers and air handling units (Du and Jin 2007, Wang and Xiao 2004). However, there are few studies on sensor faults in a heat source system covering a sensor network and combining automatic control system. Therefore, we focused on faults due to sensor errors in a heat source system. First, we developed detailed simulation model of a real heat source system covering a sensor network and combining automatic control system. Based on it, we calculated faulty system behaviors, and we analyzed the behaviors evaluated the influence of the faults using the annual system coefficient of performance (SCOP) as an indicator.

2. Methods

2.1. Target system
The target building is a factory completed in 2003. A conceptual diagram of the target heat source system and the specifications of the equipment are shown in table 1 and figure 1. This system consists of centrifugal Liquid chiller, primary chilled water pump, secondary chilled water pump, condenser water pump, direct-contact cooling tower. The equipment is controlled automatically. In particular, a control of the number of chillers and secondary chilled water pumps, variable flow rate control on primary chilled water pumps, secondary chilled water pumps and condenser water pumps, condenser water bypass valve control and variable air volume control on cooling towers is performed. Actual operation data was collected by BEMS at 15-minute intervals and in this study the data of 2013 was used.

| Equipment               | Name   | Specification                                      |
|------------------------|--------|---------------------------------------------------|
| Centrifugal Liquid chiller | TR-1   | Refrigerating capacity : 1,758 kW (500 USRT)       |
|                        | TR-2   | Water flow of chiller : 3,145 L/min (15 ℃ → 7 ℃) |
|                        |        | Water flow of condenser : 5,925 L/min (32 ℃ → 37 ℃) |
|                        |        | Output : 298 kW                                    |
| Primary chilled water pump | CP-1   | Water flow : 3,145 L/min (15 ℃ → 7 ℃)             |
|                        | CP-2   | Pump head : 200 kPa                                |
|                        |        | Output : 18.5 kW                                   |
|                        |        | Caliber : 150 φ × 125 φ                            |
| Secondary chilled water pump | CP-3   | Water flow : 3,145 L/min (15 ℃ → 7 ℃)             |
|                        | CP-4   | Pump head : 400 kPa                                |
|                        | CP-5   | Output : 37 kW                                     |
|                        |        | Caliber : 150 φ × 125 φ                            |
| Condenser water pump   | CWP-1  | Water flow : 5,295 L/min (Min : 12 ℃)             |
|                        | CWP-2  | Pump head : 250 kPa                                |
|                        |        | Output : 45 kW                                     |
|                        |        | Caliber : 200 φ × 150 φ                            |
| Cooling tower          | CT-1   | Water flow : 5,295 L/min (37 ℃ → 32 ℃)             |
|                        | CT-2   | Outside air wet-bulb temperature : 27 ℃            |
|                        |        | Output : 7.5 × 2 kW                                |
2.2. Simulation model

This simulation model was developed by combining automatic control logics based on the specifications of equipment and control with the physical models of the equipment. The calculation flow of the model is shown in Figure 2 and is performed in the order of automatic control, calculation of flow, calculation of heat, and calculation of power consumption. This model covers a sensor network of the heat source system, and whether the sensor has an error or not, the set points and the controlled variables are calculated using the measured values of the sensors in the automatic control logics. From BEMS data, five input values are used: a load flow rate, a load heat quantity, a set point of supply water temperature, an outside air dry-bulb temperature, an outside air relative humidity. The output values are 52 items such as a flow and temperature of chilled water and condenser water, a power of equipment, and so on. In this model, the calculation period is one year, and the calculation interval is one minute by performing linear interpolation on input values.

Among the parameters required for developing this model, there were several unknown parameters that could not be obtained from the specifications of equipment and control. They were such as parameters that were not measured and could be manually changed locally. In this study, we analyzed BEMS data of the system in detail beforehand and identified these parameters using only BEMS data deemed not to be affected by faults. Using this method, we calibrated this model.

**Figure 1.** Target system

**Figure 2.** The calculation flow of the simulation model
We compared the calculation results of this model with the actual measured values by BEMS data. The comparison of power of TR-1 for representative week is shown in figure 3 as an example. Although there are some biases, the developed simulation can capture the system behaviors. From the above, it was confirmed that this model has high accuracy. Therefore, we handled the calculation results of this model as the system behavior without faults (F0).

![Figure 3. Simulation result and actual measured value (Power of TR-1)](image)

### 2.3. Data generation of faulty system behavior

Based on this simulation model, we virtually produced the system behavior with faults. In this study, we focused on faults due to sensor errors and assumed faults that a certain error occurred in measured values for ten temperature sensors and four flow sensors (table 2 and table 3). In addition, we assumed six different fault severity levels for each fault. The error of sensors was set based on a manual of sensors (ABEE 2013). The error of temperature sensors was set to be a certain amount and the error of flow sensors was set to be a fixed rate of the reading value. The underlined fault severity levels in table 2 and table 3 are within the tolerance of sensors.

#### Table 2. Faults of temperature sensors

| Label | Sensor                        | Location | Fault Severity Level          |
|-------|-------------------------------|----------|------------------------------|
| Ft1   | Chilled water inlet temperature of a chiller | TR-1     |                              |
| Ft2   | Chilled water outlet temperature of a chiller | TR-1     |                              |
| Ft3   | Condenser water inlet temperature of a chiller | TR-1     | -1°C, -0.5°C, -0.1°C, +0.1°C, +0.5°C, +1°C |
| Ft4   | Condenser water outlet temperature of a chiller | TR-1     |                              |
| Ft5   | Condenser water inlet temperature of a chiller | TR-1     |                              |
| Ft6   | Condenser water outlet temperature of a chiller | TR-1     |                              |
| Ft7   | Condenser water inlet temperature of cooling towers | CT-1     |                              |
| Ft8   | Condenser water outlet temperature of cooling towers | CT-1     |                              |
| Ft9   | Condenser water inlet temperature of cooling towers | CT-1     |                              |
| Ft10  | Condenser water outlet temperature of cooling towers | CT-1     |                              |

#### Table 3. Faults of flow sensors

| Label | Sensor                        | Location | Fault Severity Level          |
|-------|-------------------------------|----------|------------------------------|
| Ft1   | Chilled water flow           | CP-1     | -10%, -5%, -1%, +1%, +5%, +10% (Read Scale) |
| Ft2   | Chilled water flow           | CP-2     |                              |
| Ft3   | Condenser water flow         | CWP-1    |                              |
| Ft4   | Condenser water flow         | CWP-2    |                              |

The underlined fault severity levels within the tolerance of sensors.
3. Results

We analyzed the characteristics of some faults in detail using this calculation result. Ft1 is a fault that causes the sensor error of chilled water inlet temperature of TR-1. When a positive error occurs in the measurement value of the sensor, the temperature difference between the chilled water inlet and outlet of the refrigerator is calculated larger (figure 4(a)). As a result, the load factor of TR-1 is also calculated higher. As the set point of the condenser water flow is determined from the load factor of the chiller, the set point of the flow of CWP-1 increases and the power of CWP-1 increases (figure 4(b)). Ft3 is a fault that causes the sensor error of chilled water outlet temperature of TR-1. A negative error in Ft3 affected the power of CWP-1 in the same way.

Ft10 is a fault that causes the sensor error of condenser water outlet temperature of cooling towers. When a negative error occurs in the measurement value of the sensor, the rotation speed of the cooling tower fans which is controlled by this value decreases. This raises the actual condenser water temperature. Figure 5(a) shows the condenser water inlet and outlet temperature of TR-1 in Ft10 is measured higher than those in F0. This reduces the efficiency of the chiller and increases the power of the chiller (figure 5(b)). Although the power of the cooling towers is slightly decreased due to the reduction of the rotation speed of the cooling tower fans, the influence on the power of the chiller is larger. As a result, Ft10 greatly increases the power of the whole system.

Ff3 is a fault that causes the sensor error of condenser water flow of CWP-1. When a negative error occurs in the measurement value of the sensor, this flow is controlled by CWP-1 to coincide with a set point of the condenser water flow and actual flow becomes larger than F0. In figure 6(a), the measured condenser water flow is consistent with that of F0. As a result, the power of CWP-1 increases. Moreover, the power of the cooling towers also increases as heat processed in the cooling towers also increases (figure 6(b)). Therefore, Ff2 greatly increases the power of the entire system.
Figure 6. Effects of Ff3

4. Discussion

In order to compare and evaluate the influences of all faults together, the annual SCOP of each fault and F0 was calculated from these results. Figure 7 shows the annual SCOP change rate from F0 for each fault and each fault severity level. Sensor faults sometimes cause an improvement of the annual SCOP. The cause of these improvements is conceivable that the control of the system in F0 is not optimized or the fault has affected systems which not included in the simulation model such as the air conditioning system. Therefore, in this study, we dealt only with fault data which showed decline in annual SCOP.

Figure 7. Rate of annual SCOP change

In order to evaluate the influence of faults, we estimate influence of faults with expectations of SCOP decrease rate as equation (1).

\[
E_{Fn} = \sum_l (R_{Fn,l} \times P_{Fn,l})
\]  

(1)

where \(F_n\) is the fault label, \(l\) is the fault severity level, \(E_{Fn}\) is the expectation of SCOP decrease of \(F_n\), \(R_{Fn,l}\) is the annual SCOP decrease rate of \(F_n\) and \(l\) [%], and \(P_{Fn,l}\) is the occurrence probability of \(l\) in \(F_n\).
We assumed that an occurrence probability follows a uniform distribution in this paper: 1/7 for all faults. The calculation results are shown in table 4.

| Label | Expectations of SCOP Decrease Rate [%] |
|-------|---------------------------------------|
| Ft10  | 0.614                                 |
| Ft1   | 0.334                                 |
| Ft5   | 0.146                                 |
| Ft2   | 0.0840                                |
| Ft6   | 0.0824                                |
| Ft7   | 0.0204                                |
| Ft8   | 2.25×10^{-8}                          |
| Ft9   | 0.00                                  |

Table 4. Influence of faults

For temperature sensors, Ft10 was the highest expectation of SCOP decrease. We assessed Ft10 was the most influential fault in temperature sensor faults. In Ft9, the expectations of SCOP decrease was 0.00; it showed Ft9 had no effect on annual SCOP. Since both a positive error in Ft1 and a negative error in Ft3 had the same degree of effect on the power of CWP-1, Ft1 and Ft3 were completely equal in the expectations. In the same way, Ft2 and Ft4 had the same degree of effect on the power of CWP-2 and were completely equal in the expectations. For flow sensors, we considered that Ft3 was the most influential fault and Ft2 was the least influential fault. Condenser flow sensor faults have higher expectations than chilled water sensor faults. We assumed that this result can change taking the air conditioning system into consideration.

5. Conclusions
In this study, we calculated the behavior of the heat source system with faults due to sensor errors using a detailed simulation model and evaluated the influence of faults using expectations of the annual SCOP decrease rate as an indicator. Using this method, we analyzed the influence of faults in detail and evaluate appropriately faults. We expected that this fault evaluation helps an operation and maintenance of the system. For example, it is possible to decide the priority of repairing faults according to the influence of faults. In this research, we focused on faults of sensors and evaluated using only the annual SCOP as an indicator. Therefore, as future work, we considered that it is necessary to investigate more diversely by increasing fault types and indicators. In addition, although we assumed that a frequency of faults is uniform, it is necessary to use an appropriate frequency of faults in fault evaluation as a future work. It is also a future work to evaluate faults in cooperation with the FDD method and maintenance planning.

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