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Study on VDI-2048 for Plant Efficiency Calculation

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1. Introduction

In case of the on-line performance monitoring system, the measurement uncertainty is comparatively high, comparing the special instrument for testing performance. That is because it directly uses the measured data from measuring instrument for plant operation to analyze performance. So if measured data applies to performance analysis as it is, the diagnostic results of performance are likely to be distorted. It is a representative example when main steam mass flow of a steam generator is measured lower than main feedwater mass flow of outlet, or when efficiency of low pressure turbine is analyzed excessively low or exceeds 100 percent. Therefore, we need to obtain measured data minimizing uncertainty to calculate thermal efficiency as exactly as possible. In calculating the efficiency of an Nuclear Power Plant(NPP), measurement uncertainty is the most difficult to be solved technically and data reconciliation methodology is one method of ensuring to minimize uncertainty. In this paper, the case study on previous nuclear power plants was carried out by using redundancy of measured data from measuring instrument for plant operation, so as to calculate nuclear power plant efficiency accurately.

2. Methods and Results

This section describes introduction, basic principles, and applications of VDI-2048 which was published by Germany standardization organization.

2.1. Theoretical Background

The key concept on data reconciliation methodology is to utilize the redundancy of data from all measurement points. Redundancy is classified as measurement redundancy and physical redundancy. While measurement redundancy can be obtained by installing multiple measuring instruments on one measurement point, physical redundancy indicates the physical association among measured data such as mass balance, energy balance, or correlations. This redundancy of data characterizes over-determined system. It means the condition that there are more unknowns than equations constituting modeling of process. Due to the errors which influence measurement, it is no wonder that the result from untreated measured data has low reliability. Data reconciliation methodology provides the solution to this problem, and makes reconciled data have more statistical reliability by using measured data and redundancy of data in process. There are two basic principles on data reconciliation. First, each measured data must be corrected as little as possible. Second, all the equations for calculating reconciled data must strictly reflect the uncertainty affecting the measurement. Supposing the error that influences measurement and standard deviation can be presented by a normal distribution, which has independent or certain correlation between two, this method finds out optimal values that meet constraints. The result of data reconciliation provides obviously satisfied reconciled data to constraints, confidence indicators of data from data reconciliation, relatively decreased uncertainty of reconciled data comparing to that of untreated data, Nuclear power plants belonging to Electricite de France(EdF) and many of them in Europe have the uncertainty about 0.3% on reconciled heat output from reactor. The result of data reconciliation methodology does not depend on a single measured data that has great errors, and provides better reconciled data than initial measured data. Data reconciliation methodology has rich experiences and feedback all over the world. This methodology is used to monitor heat output measurement drift from reactor in a number of nuclear power plants around the world, especially in Germany and Switzerland, and was approved by Safety Management Executive in each country.

2.2. Mathematical Algorithm

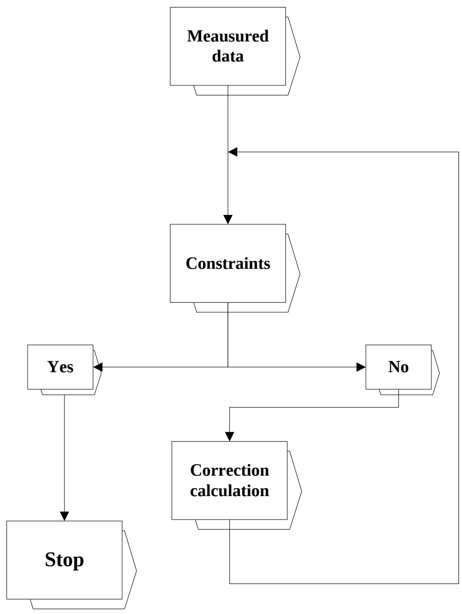

Fig. 1. Basic sequence for data reconciliation

The Fig. 1. is the algorithm of data reconciliation, provided by VDI-2048. The algorithm of data reconciliation, presented by VDI-2048, has six steps in total. The first step is to set the constraints of measured data. The second step is to check whether measured data meets the constraints or not. In the third step, if measured data meets the constraints, the calculation process should be stopped. If not, the functional matrix about measured data should be generated. The fourth step is to calculate the error square sum by using the functional matrix. The fifth step is to conduct the f-test. If the f-test is satisfied, in the final step, calculate the reconciled data and confidence interval by using correction vector and covariance matrix. If the F-test is not satisfied, generate the Functional matrix again, where the confidence interval is adjusted, and repeat the same procedures. We carried out the case study by making use of the algorithm as in Fig. 1.

The governing equations used the data reconciliation case study is as in the following.

Equation (1) is for setting main diagonal factor in the covariance matrix.

$$S_{X,ii} = S_{X_i}^2 = \left(\frac{V_{X_i}}{1.96}\right)^2 \tag{1}$$

Where,
$S_{X,ii}$ = Covariance matrix of the measured values
V_{X_i} = Confidence interval

Equation (2) is for setting the confidence interval.

$$S_{G_i}^2 = \left(\frac{\partial g_i}{\partial x}\right) \cdot S_X \cdot \left(\frac{\partial g_i}{\partial x}\right) \tag{2}$$

Equation (3) is also an equation for setting the confidence interval. The confidence interval of calculation result data used in VDI-2048 has 95% confidence level. The confidence level can be changed upon interest.

$$g_i(x) \pm V_{gi(x)} = g_i(x) \pm \lambda_{95\%} S_{G_i} \tag{3}$$

Where
$\lambda_{95\%}$= 95% confidence level of a normal distribution

Equation (4) is for the F-test.

$$\frac{u^2}{r} = \frac{\xi_0}{r} \le F_{r,\infty;95\%} \tag{4}$$

Where
r = Degree of freedom
$\frac{\xi_0}{r}$ = Error square sum
$F_{r,\infty;95\%}$ = 95% Quantile of the error square sum

Equation (5) is for setting the confidence indicator. In order to satisfy 95% confidence level within the given uncertainty, the calculated confidence indicator should be less than 1.96. If it exceeds 1.96, those instruments have to be checked.

$$\left|\frac{v_i}{\sqrt{\max\left(s_{v,ii}, \frac{s_{x,ii}}{10}\right)}}\right| \le 1.96 \tag{5}$$

Where
v_i = confidence interval
$s_{v,ii}$ = Covariance matrix of the correction values
$s_{x,ii}$ = Covariance matrix of the measured values

Equation (6) is to set the correction vector.

$$v = -(S_X \cdot F^T) \cdot (F \cdot S_X \cdot F^T)^{-1} \cdot f(x) \tag{6}$$

Where,
F = Funcional matrix of the auxiliary conditions
S_X = Covariance matrix of the measured values
$f(x)$ = Vector of contradictions

Equation (7) is for setting the reconciliation value.

$$\bar{x} = x + v \tag{7}$$

Where,
$\bar{x}$ = Reconciled data
x = Measured data
v = Correction vector

We would verify that Data Reconciliation could be applied to the actual nuclear power plant by using upper equations.

2.4. Case study

In the case study, data reconciliation methodology was conducted, based on the mathematical basis that is explained in Uncertainties of measurement during acceptance tests on energy conversion and power plants out of VDI-2048. The case study was performed, depending on the typical examples of data reconciliation in the actual nuclear power plants. Typical examples are as in the following.

Case I : P & T at Saturated Condition. Examples are conditions in main steam lines, turbine extraction lines, condenser shell-side, and so on.

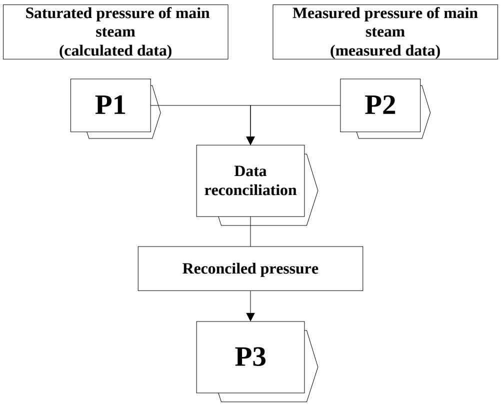

Fig. 3. Diagram for Case I

Since the main steam system of the turbine cycle of PWRs is operating in saturated conditions, many of measurements are associated with each other in terms of thermo-dynamical redundancy. However, pressure and temperature measurements are not usually consistent when they are compared after calculating saturated property, for instance, between a measured pressure and a calculated pressure using a measured temperature.

The constraint in the first case study is as in the following Fig. 3.

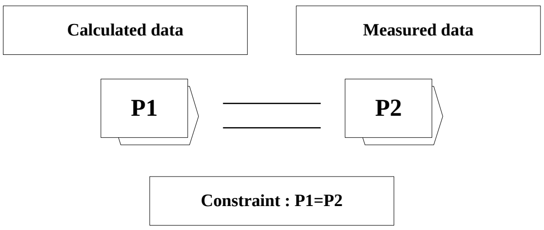

Fig. 3. Constraint for Case I (Thermo-dynamical redundancy)

We demonstrated the algorithm for Case I using typical data of main steam conditions. The resulting data reconciliation of main steam pressure, which is satisfying the constraint, is as in the following Table I.

Table I : Result of data reconciliation of Case I

P(bar)&T(℃)	Measured data	Calculated data	Reconciled data
pressure	70.00 ± 3.5		68.01 ± 2.73
Sat. temperature		280 ± 14	
Sat. pressure	64.91 ± 4.4		68.01 ± 2.73

The constraint in the first case study is that the measured main steam pressure and the saturated pressure at measured main steam temperature must be same. We presumed the measured main steam pressure and temperature, according to the condition in the actual nuclear power plants. The measured pressure is 70 bar and temperature is 280 ℃. The saturated pressure at 280 ℃ is calculated as 64.91 bar, taking advantage of the steam table. When the measured pressure 70 bar and the saturated pressure 64.91 bar are applied to the data reconciliation methodology, we can obtain the reconciled data 68.01 bar. This method resulted in the reconciled data with minimized uncertainty.

Case II : P & T at Common head. Examples are feedwater heater common head, pump common head, and so on.

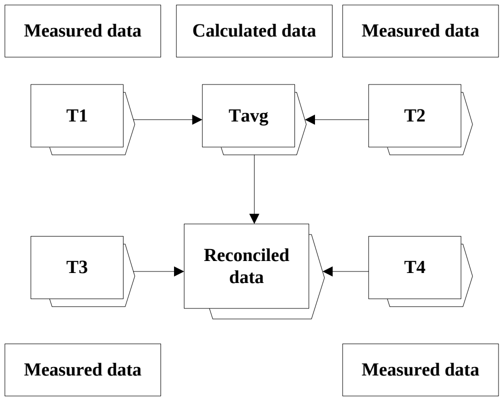

Fig. 4. Diagram for Case II

The second case is to calculate the reconciled data satisfying the constraint by measurement redundancy. Turbine cycle of NPPs has usually multiple trains due to reliability concerns. The multiple trains can have a common head to downstream. In this case, Case II can typically occur. For example, the constraint is that the average value of T1 and T2, and that of T3 and T4 must be same in Figure 4. This constraint is usually not satisfied in actual plants.

The constraint in the first case study is as in the following Fig. 5.

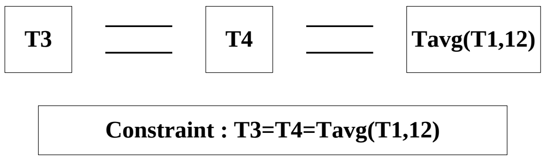

Fig. 5. Constraint for Case II (measurement redundancy)

Table II: Result of data reconciliation of Case II

T(℃,)	Measured data	Calculated data	Reconciled data
Tavg(T1,T2)		222.5 ± 2.23	215.59 ± 1.25
T3	215 ± 2.15		215.59 ± 1.25
T4	210 ± 2.10		215.59 ± 1.25

Table II shows the reconciled data satisfying the constraint. We supposed that the average value of T1 and T2 is 222.5 ℃, that of T3 is 215.00 ℃, and that of T4 is 210.00 ℃, suitable for the feedwater condition in an NPP. As a result, this method draws a conclusion that the reconciled data is 215.59 ℃ and the confidence interval is ± 1.25. Whereas the measured data is not satisfied with the constraint

T3=T4=Tavg(T1,T2), the reconciled one is satisfied according to Table II.

Case III: P & W under user-defined correlation

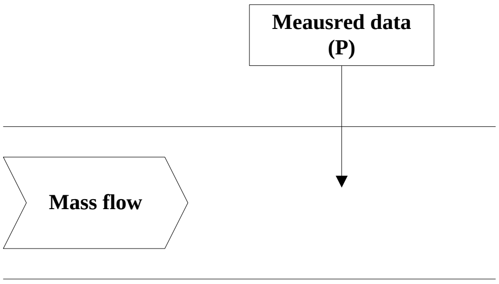

Figure 6. Diagram for Case III (measurement redundancy)

Equation (8) is governing equation of Case III.

$$\mathrm{P} = 0.0125w^2 + 0.25w + 0.5 \quad (8)$$

Where,
w = Mass flow
P = Pressure

We supposed that measured pressure and mass flow at same point can be defined as equation (8). The third case study is to calculate the reconciled data satisfying the constraint by physical redundancy. The constraint in the third case study is as in the following Fig. 7.

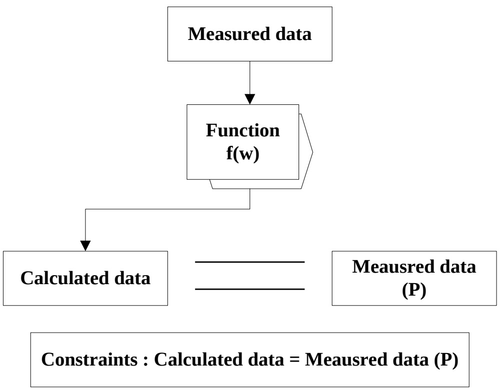

Fig. 7. Constraint in the second case study

The constraint in the third case study is that calculated data by equation (8) and measured data (P) must be same. The table III shows us the reconciled data satisfying the constraint.

Table III: Result of data reconciliation of Case III

P (bar)&W (kg/s)	**Measured data**	**Reconciled data**
Pressure	50.00 ± 5.00	44.38 ± 2.22
Mass flow	50.00 ± 0.50	50.08 ± 2.50
Calculated data	44.25 ± 0.15	44.38 ± 0.15

As a result, this method draws a conclusion that the reconciled data are 44.38 ± 0.15 and 44.38 ± 2.22 Whereas the measured data is not satisfied with the constraint calculated data=measured data (P), the reconciled one is satisfied according to Table III.

3. Conclusions

As explain above, we performed the case study on data reconciliation methodology by using measurement redundancy and physical redundancy. The former comes up because of installing multiple measuring instruments for plant operation, and the latter is acquired based on the physical association like the first law of thermodynamics (the law of conservation of mass and energy). Through this case study, we got the reconciled data, which satisfies the constraint and minimizes data uncertainty measured in the nuclear power plant secondary system at the same time. The expected effects from data reconciliation methodology provided in VDI-2048, are considered totally four. First, this method can contribute to monitoring on-line efficiency in the operating nuclear power plant. Second, it can also improve the reliability of calculated results, minimizing the measurement uncertainty. Third, it can lead to reduce the operation and maintenance costs of nuclear power plants through high reliability of the calculation results. Lastly, it can be widely applied not only to nuclear power plants industry, but to big-sized plants industry, such as hydroelectric power plant or thermoelectric power plant and process industry across the board.

REFERENCES

[1] Verein Deutscher Ingenieure, Uncenrtainties of measurement during acceptance tests on energy-conversion and power plants Fundamentals, pp. 1-88, 2000.