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The Development of a Signal Validation Scheme for the Redundant Multi-Channel Measurement System

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다중채널 측정계통의 신호검증기법 개발

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Abstract

It is necessary to adopt a simple signal validation for avoiding the complexity of algorithm and verification in the design process of the instrumentation and control system in nuclear plants. This paper suggests a signal validation method developed on the basis of consistency checking for the multi-channel measurement system without any analytic process model. It includes a simplified algorithm for estimating the fixed bias error of each channel and a weighted averaging method. The weighting factor of each channel is updated according to its calculated bias error. The developed method has been tested to verify its performance through several input scenarios.

요 약

원전 계측제어계통의 설계구현에서는 알고리즘및 독립적 검토의 복잡성을 피하기 위해 되도록 간단한 신호검증방법이 일차적으로 요청된다. 본 논문은 다중채널측정 시스템의 채널간의 일치성검사를 기본으로 하여 개발된 신호검증 알고리즘을 제안한다. 이 방법은 간략화한 고정편차 추정법을 포함하며, 추정된 고정편차의 크기를 고려한 가중인자를 사용하여 가중평균을 구한다. 제시된 방법의 성능을 확인하기 위하여 가상의 다중입력 조건으로 실험하였다.

1. Introduction

There are many sensors and measurement channels installed for providing signals to the monitoring and control systems in Nuclear Power Plants (NPPs). Most of signals are obtained and processed through redundant multi-channels. If any channel is wrong with its value, operators should identify the suspected channel and change the signal source to another one[1].

Advanced NPPs of the future will use digital components mostly in the Instrumentation and Control(I&C) system. With adoption of new technology and programmable equipment, the increased performance of the I&C system can reduce the burden of operators, and it will be possible to obtain more reliable measurement value. In order to gain the reliable instrumentation signal, it is desirable to include a signal validation technique in the computerized I&C system of NPPs. The signal validation is either an algorithm or a program logic that checks the status of measured variables and determines the health of signal to produce a reliable value[2].

Various methods for failure detection and signal validation have been reported[3−7]. Many of these mathematically good feasibility and worth for appli-a reference value. These modelling approaches have mathematically good feasibilty and worth for application to various engineering fields. However, for simple design practice, they can be too complex for both engineers and designers in understanding the modelling algorithm. Furthermore, it may not be suitable when the process has an unknown failure or the inputs of the process model do not have sufficient reliability, because its model is no longer available.

Deyst et al. [6] and Ray et al. [7] announced a signal validation method for the multi-channel measurement system without the process system model. Since they introduced the parity space representation method, it has been one of the most general principles in the signal validation field. C.E (Combustion Engineering) developed a modified and simplified algorithm from the parity space approach for using in the DIAS(Descrete Indication and Alarm System)[8]. Belblidia et al[9] proposed another simple signal validation scheme which is using the degree of inconsistency calculation.

Both methods of C.E. and Belblidia are very useful for application to I&C system design of NPPs due to the ease of understanding and simplicity. However, they do not take account of the fixed deviation which can be generated by hardware drift. Ray et al. [10] expanded the parity space method to estimate the fixed error bias among several channels.

This paper suggests another simple approach for the validation of multi-redundant measured signals. This method is based on the degree of inconsistency checking method[9] and includes a simple bias estimation with the deviation vector concept. The estimated bias error is put into the weighting factor to calculate the weighted average value of the measured parameter. The algorithm is presented in section 2 and the system structure is shown in section 3 as well as test results.

2. Algorithm Development

2.1. A Measurement Model and the 1st Step Signal Validation

Several sensing channels measuring one scalar variable(e.g. temperature, pressure.) can be expressed as[2]

$$\underline{m}(k) = H \times (k) + \underline{e}(k), \tag{2.1}$$

where $\underline{m}$: $(n \times 1)$ measured signals,

H: $(n \times 1)$ scale factor or transition matrix, $[1, 1, . ,1]^T$ in general,

x: (1×1) true value of the measured variable,

$\underline{e}$: $(n \times 1)$ measurement noise vector with $E[e] = 0$, and

n: number of total channels.

The instrumentation value of channel i at the sampling instance k can be represented by $m_i(k)$. Assuming that $\hat{x}(k-1)$ is the estimated value at the previous instance, the expected change during one sampling period can be defined as

$$e_{n+1}(k) = x(k). - \hat{x}(k-1). \tag{2.2}$$

The amount of $e_{n+1}(k)$ is affected by several conditions such as sampling period, plant transient mode and parameter types. In case of temperature instrumentation, it will be smaller than in other variable cases with the same conditions. For next step calculation, it is necessary to define $\hat{x}(k-1)$ as $m_{n+1}(k)$. That is

$$\begin{aligned} m_{n+1}(k) &= \hat{x}(k-1) \\ &= \hat{x}(k-1) - x(k) + x(k) \\ &= x(k) - (x(k) - \hat{x}(k-1)) \\ &= x(k) - e_{n-1}(k) \end{aligned} \tag{2.3}$$

As the first step of signal validation, the limit checking algorithm investigates each channel value and picks up the valid values which are within a certain operating range. Any value which is beyond maximum value or minimum value implies a hardware failure of its channel. Therefore, it shall be set to a faulty channel at this first step. If the number of total non-faulty channels, n′, is even, the measurement model including $m_{n+1}(k)$ value is reconstructed as the form of Eq.(2.4). If not, it does not include the estimated value at the previous instance, like Eq. (2.1). The model will be

$$\underline{m}'(k) = H'x(k) + \underline{e}'(k), \qquad (2.4)$$

where n′ : number of total passed channels,

$\underline{m}'$: $[m_1, \cdots\cdots m_n]^T$ when n′ = odd number,

or $[m_1, \cdots\cdots m_{n+1}]^T$ when n′ = even number,

$\underline{e}'$: $[e_1, \cdots e_n]^T$ when n′ = odd number,

or $[e_1, \cdots e_{n+1}]^T$ when n′ = even number,

$m_{n+1}(k) \equiv \hat{x}(k-1)$, and

H′ : scale factor or transition matrix with the demension of $(n \times 1)$ or $((n+1) \times 1)$.

The reason for including the estimated value of the previous step for the model of even number of channels is to obtain the majority when the values of all channels are distributed into two equal groups. If n′ is even, it is difficult to pick out the expected right channels by voting when a half of n′ have the values around one point and the other half have the values around another point far from the other, as shown in Fig. 1.

Fig. 1 illustrates an example where two channels are giving low values and the other two sensing channels are indicating high values far from those of the first two channels. Undoubtedly, the deviation between A group and B group is much more than error boundary. In this case, more information is needed to choose the valid group. The historical data can be used as a reference for selecting logic. An estimation based on the process model with historical data could be a base for this work. However, it requires the process model and a complex calculation. In this paper, the previous estimated parameter value, $m_{n+1}(k)$, is regarded as a sensed value of another virtual channel. Therefore, in the situation of Fig. 1, the additional information, $m_{n+1}(k)$, is referred for selecting a group between A and B.

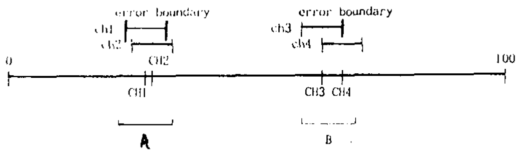


Fig. 1. A Particular Distribution of Measured Signals

2.2. Calculating the Degree of Inconsistency and the Weighted Average

With the modified measurement model of Eq.(2. 4), the degree of inconsistency [9] at time k is calculated as

$$K_i(k) = \sum_{j=1}^{L} d_{ij} \ [i, j, \neq \text{ faulty channel}], \qquad (2.5)$$

where $K_i(k)$ = degree of inconsistency of channel i,

$d_{ij}(k) = 0$ if $\{|m_i(k) - m_j(k) - (\varepsilon_i + \varepsilon_j)\} < 0$,

$d_{ij}(k) = 1$ if $\{|m_i(k) - m_j(k) - (\varepsilon_i + \varepsilon_j)\} \geq 0$,

$L = n$, if n′ is odd,

$L = n+1$, if n′ is even,

$m_i(k)$ = measured value of channel i,

ε_i = error boundary of channel i,

$m_{n+1}(k) \equiv \hat{x}(k-1)$, and

$\varepsilon_{n+1} \equiv$ max ‖ the changing amount of the measured variable during a sampling period ‖.

The degree of inconsistency, K_i, is a kind of voting logic based on the cross comparison. It can be any value from 0 to n. If the value of K_i of a channel is the largest among all channels, it means that the channel is suspected to be the faulty channel. Therefore, it should be removed from next calculation. The removing procedure is continued until the degree of inconsistency of all remaining channels are zero. This process forms the second faulty channel detection step.

The remaining channels are expected to have normal function. However, it is possible for any faulty channel to be disturbed by noise so that it comes up to the normal value in certain instances. Therefore, this detection algorithm reassigns a faulty channel to a normal channel only if it passes the detection test more than three times. This checking process is the third detection step.

After completion of the detection procedure, calculation of the estimated valid value of the measured parameter should be done. The estimated mean value can be obtained by the weighted averaging method. $|\varepsilon_i - \hat{c}_i|$ was selected for the weighting factor of each channel. c_i means the fixed error(bias) of channel i. It is described in detail in section 2.3. The greater the fixed error, the less weighting is applied. The estimating equation has resulted into:

$$\hat{x}(k) = \frac{\sum_{i=1}^{n} m_i(k) * |\varepsilon_i - \hat{c}_i(k-1)|}{\sum_{i=1}^{n} |\varepsilon_i - \hat{c}_i(k-1)|} \quad [i \neq \text{faulty channel}]. \quad (2.6)$$

In certain situations, all channels could be set to be faulty in Eq.(2.5). For example, if all deviations between two channels are larger than error boundary, neither channel can pass the entire detection procedure. In this case, the estimated output value is expected to be the weighted average among channels that have passed through the former detection step. If some channels have passed the first and second step but cannot pass the third step, the valid value is supposed to be the weighted average among those that passed through the 1st and 2nd step detection.

This situation occurs every time that this software begins at power-on. Any channel cannot pass at the third step, because they do not have any passed experience for more than three sampling times.

2.3. Detection of the Fixed Error(bias)

When a measurement system has n sensing channels for one scalar variable, its measured value at time k could be modelled including bias errors, as following[10]

$$\underline{m}(k) = [H + \Delta H(k)]\, x(k) + \underline{b}(k) + \underline{e}(k), \quad (2.7)$$

where ΔH: scale factor error,
$\underline{b}$: bias error.

In Eq.(2.7), the true value, x, can be replaced by $\hat{x}$ in aproximation. Therefore, the equation becomes as

$$\underline{m}(k) \simeq [H + \Delta H(k)]\, \hat{x}(x) + \underline{b}(k) + \underline{e}(k). \quad (2.8)$$

Here, the deviation vector, $\underline{d}(k)$, is defined as

$$\underline{d}(k) \equiv \underline{m}(k) - H\,\hat{x}(k) = \Delta H(k)\,\hat{x}(k) + \underline{b}(k) + \underline{e}(k) = \underline{c}(k) + \underline{e}(k), \quad (2.9)$$

where $\underline{c}(k) \equiv \Delta H(k)\,\hat{x}(k) + \underline{b}(k)$. (2.10)

If the total bias $\underline{c}(k)$ is estimated, it can be applied to change the weighting factor in Eq.(2.6).

In general, it is difficult to define the dynamics of $\underline{c}(k)$ accurately. If the noise error $\underline{e}(k)$ is random with zero mean value and its probability density is the same at each channel, $\underline{c}(k)$ can be calculated by a simple digital filter[11] as

$$\hat{\underline{c}}(k) = \alpha \underline{d}(k) + (1-\alpha)\, \hat{\underline{c}}(k-1), \quad (2.11)$$

where α = Coefficient of filter (0~1.0).

If both the dynamics of $\underline{c}(k)$ and $\underline{e}(k)$ are defined precisely with time variant function, the $\underline{c}(k)$ can be calculated by another filter technique, for example, Kalman filter, Wiener filter, etc.

The dynamics of drift in the measurement system is different according to hardware and sensors. But, in most cases it varies very slowly. Therefore, α, the filter coefficient, will be selected as a small value. The estimated bias value obtained in Eq.(2.11) is feedbacked to the weighting factor for estimating the parameter value. in Eq.(2.6).

3. Design of Signal Validation System

3.1. Structure of Validation Scheme

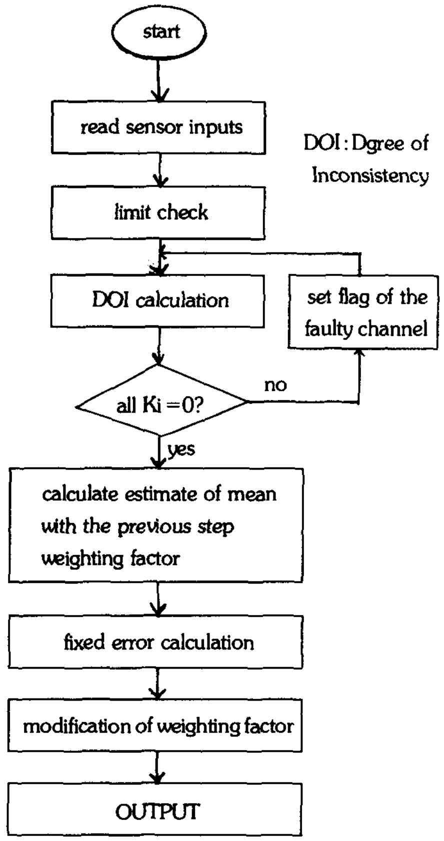


Fig. 2. Flowchart of Validation Scheme

The faulty channel detection algorithm and fixed error estimation method were incorporated into a signal validation system. The block diagram is shown in Fig. 2.

It consists of several software blocks, and their functions are as follows.

1) **Signal Acquisition**: The measured data from sensor/transmitter are converted to digital values and calculated into the appropriate engineering units. Also, the limit checking process is performed. Any channel having overranged value is set faulty for removing from the next step calculation.
2) **Inconsistency checking**: The degree of inconsistency, K, is calculated and any faulty channel with maximum inconsistency degree is separated from normal functioning channels.
3) **True value estimation**: All channels having passed successfully the limit checking and inconsistency checking step more than three times are put into the true value estimation stage. This is done by weighted averaging method.
4) **Fixed error calculation**: The fixed error is calculated by the simple digital filter in Eq.(2.11). The filter coefficient can be varied according to the type of measured parameter and sampling period and tuned by simulation or experiments.
5) **Modification of weighting factor**: The calculated fixed error should be applied to compensate the weighting factor of estimation as in Eq.(2.6).

3.2. Simulation

The developed signal validation method was tested on a personal computer with various input scenarios for four redundant channels. The input signals were generated with random noise and fixed deviations. In order to examine the performance, several situations and trends were taken into the simulation.

Fig. 3 illustrates the simulation results when two channels have failures at different times. The thick line is the validated value and others are input signals. Fig. 4 shows the case where two channels have failed at the same time. Even when the third channel also has failed after two channels, the algorithm kept tracing the remained channel in operating range as shown in Fig. 5. Fig. 6 indicates the response to the step transient inputs.

The developed algorithm has the characteristic approaching a specific value on a same input distribution, even if it has different initial values, as shown in Fig. 7. Therefore, it can be concluded that the estimation value of this signal validation method is partially independent from initial fixed error values although it takes account of the fixed errors.

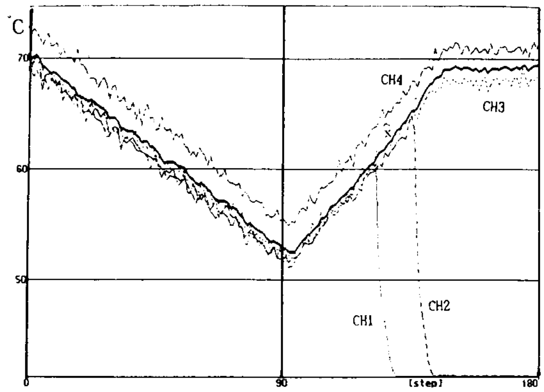


Fig. 3. Simulation Result with Two Channels Failed Sequentially

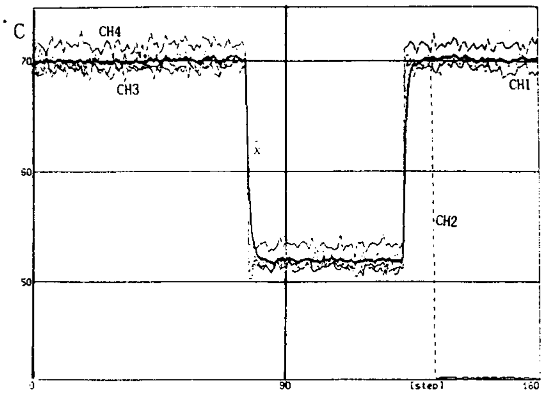


Fig. 6 Output Response to Step Change

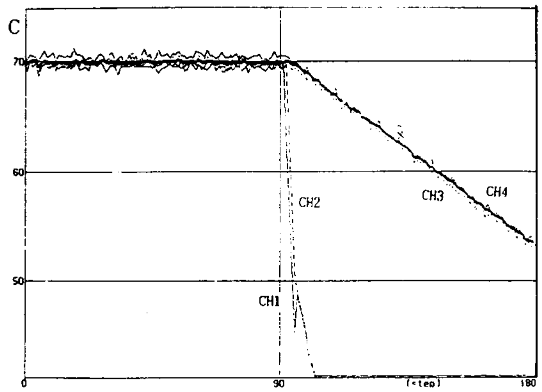
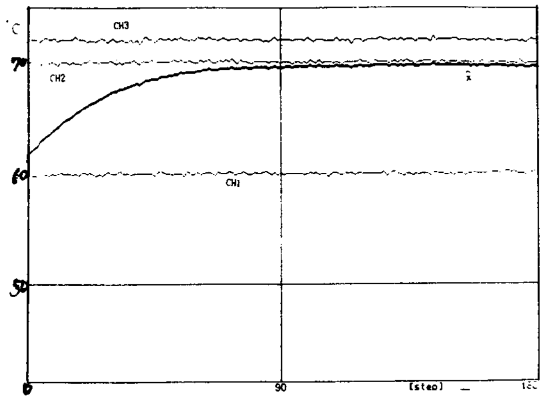


Fig. 4. Simulation Result with Two Channels Failed Simultaneously



($\hat{x}(0)$=61, C1(0)=−1.0, C2=9.0, C3=11.0)

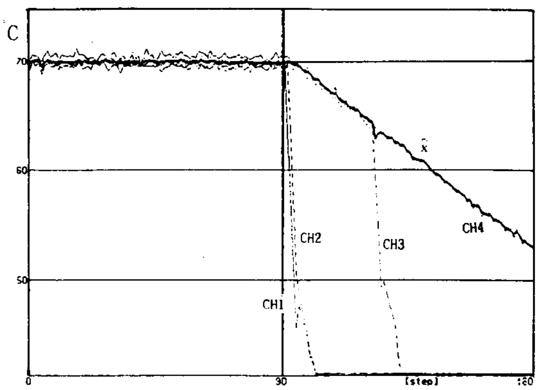
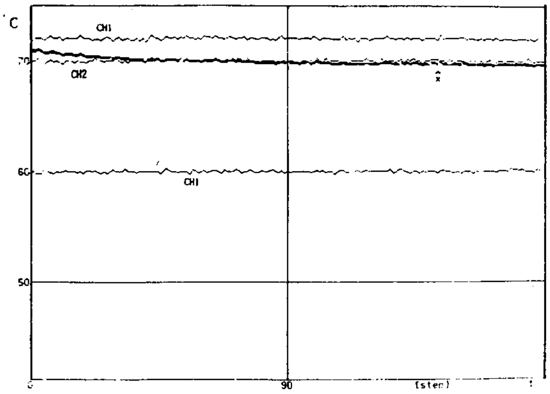


Fig. 5 Simulation Result with Three Channels Failed



($\hat{x}(0)$=71, C1(0)=−11, C2=−1.0, C3=1.0)

Fig. 7 Output Responses to Different Initial Values

4. Conclusion

This developed signal validation uses a simple consistency checking and estimates the true value using weighting factor. Also, a simple digital filter calculates the fixed errors of each channel and each fixed error is applied to an element of weighting factor. As channel bias error increases, the weighting value of the channel decreases.

The output value is roughly independent from initial fixed errors. Therefore, it gets to have tolerance to the faulty initial values. After defining general dynamic behavior of measurement variable, error boundary of each channel and interfaces to the applied system, the above signal validation method can be used in the data acquisition section of control system and sensor fault detection section of the fault diagnostic system in NPPs. Also it can be incorporated into a digital indicating system for representing reliable data to the control room so that operators could be helped for making decisions of plant status.

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