Distributed Fusion Algorithms in Embedded Network On-line Fusion System

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Abstract - In order to solve effectively the issue of remote on-line detection and fault diagnosis of hydroelectric generating units in FengMan hydropower plant, a kind integrated project of combining embedded network fusion with multi-sensor consistency information fusion algorithm and fuzzy comprehensive assessment algorithm is proposed based on distributed and embedded architecture. Multi-sensor consistency information fusion algorithm is adopted in local fusion center. Fuzzy comprehensive assessment algorithm is introduced into traditional decision fusion technology under the "soft" decision architecture. The process of fusion is composed of the comprehensive operation and the global decision through fusing the local decision of multiple sensors for obtaining the global decision of the concerned object in global fusion center. These algorithms have been successfully applied in fault detection and diagnosis of hydroelectricity digital simulation system and hydropower plant of Jilin Fengman. Tests on experimental device show that the proposed algorithms are effective and can be applied widely.

Keywords: Multi-sensor consistency information fusion, decision information fusion, fuzzy comprehensive assessment, fault diagnosis, hydroelectricity digital simulation system.

1 Introduction

FengMan hydroelectricity digital simulation system is a large-scale system in Jinlin province, which was successfully developed and industrialized by Northeastern University for three years. The simulation object is typical No.3 and No.10 units of FengMan hydropower plant. The system now runs stably in FengMan hydropower plant, it is used to locale operators training in China and hydroelectricity research. It has been appraised by Liaoning province science and technology bureau in Dec. 2001. Appraisal experts include hydroelectricity and cybernation as well as computer experts, Appraisal conclusion: first creativity in China, technique of simulation keeps ahead in China.

How to implement real-time simulation system that integrates the digital simulation system with real-time control and remote monitoring becomes a new research issue to us.

Information fusion is a new information process technology for the alliance of data obtained from multiple sources, such as sensors, database, knowledge base and so on. It aims at obtaining coherent explanation and description of the concerned object and environment, through making the most of multi-sensor resource, combining the redundant, complement information that each sensor has obtained by rationally employ each sensor and its sensor data. Information fusion is a kind of comprehensive, multiple angles, multiple layers analysis and process to the concerned object [1].

Information fusion could be classified into three levels according to the abstract level of data, namely pixel level fusion, charter level fusion and decision level fusion [2]. Decision fusion is a kind of high-level fusion process, and its result is often utilized as the basis for the system decision. Because the decision level fusion often concerns all kinds of factors, besides the data that obtained by sensors, further more the evidence of decision fusion process is often uncertain, it is very difficult to construct the accurate model that has high reliability for a certain problem. But in practical application, the decision level fusion can bring some especial benefit, such as high robustness, processing different class information, and so on, so it has been paid attention to by scientists and engineers, and become an important subject in the study of information fusion theory and application.

In this paper, a kind integrated project of combining embedded network fusion with multi-sensor consistency information fusion algorithm and fuzzy comprehensive assessment algorithm is proposed based on distributed and embedded architecture. Multi-sensor consistency information fusion algorithm is adopted in local fusion center, a new decision level fusion algorithm, which considers the fuzzy property of the decision level fusion and adopts the "soft" decision architecture of information fusion, is researched. The algorithm introduces fuzzy comprehensive assessment into decision assessment at the process of the fusion. In the practical application, these algorithms have been successfully applied in fault detection and diagnosis of hydroelectricity digital simulation system and hydropower plant of Jilin Fengman. In the analyses of factual data, the performance of these algorithms precedes that of the traditional diagnosis method.

2 Hydroelectric digital simulation system of FengMan hydropower plant based on distributed and embedded architecture

2.1 System architecture

The architecture of hydroelectricity digital simulation system of FengMan hydropower plant is shown as Fig.1.

2.2 Embedded network on-line fusion

Webit is a product which make equipment connected directly to network by Northeastern University development, it's basic idea is : a unattached, less cost, WWW server and some application are embedded in the equipment, consequently the equipment takes on unattached network intelligence. Webit is a Web server using computer chip, it is supported by special OS, compared to PC, it takes on smaller volume and cost, it is embedded in equipment easily, it makes equipment become a self-governed Web server possess of IP address. Principle frame chart of on-line detection by network is shown as Fig. 2.

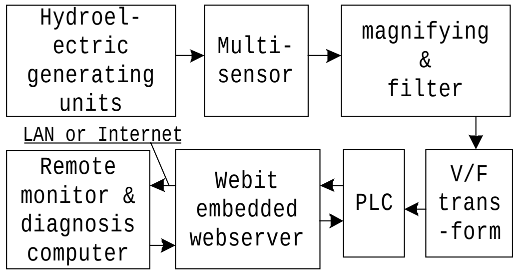

Fig. 2. Principle frame chart of network on-line detection.

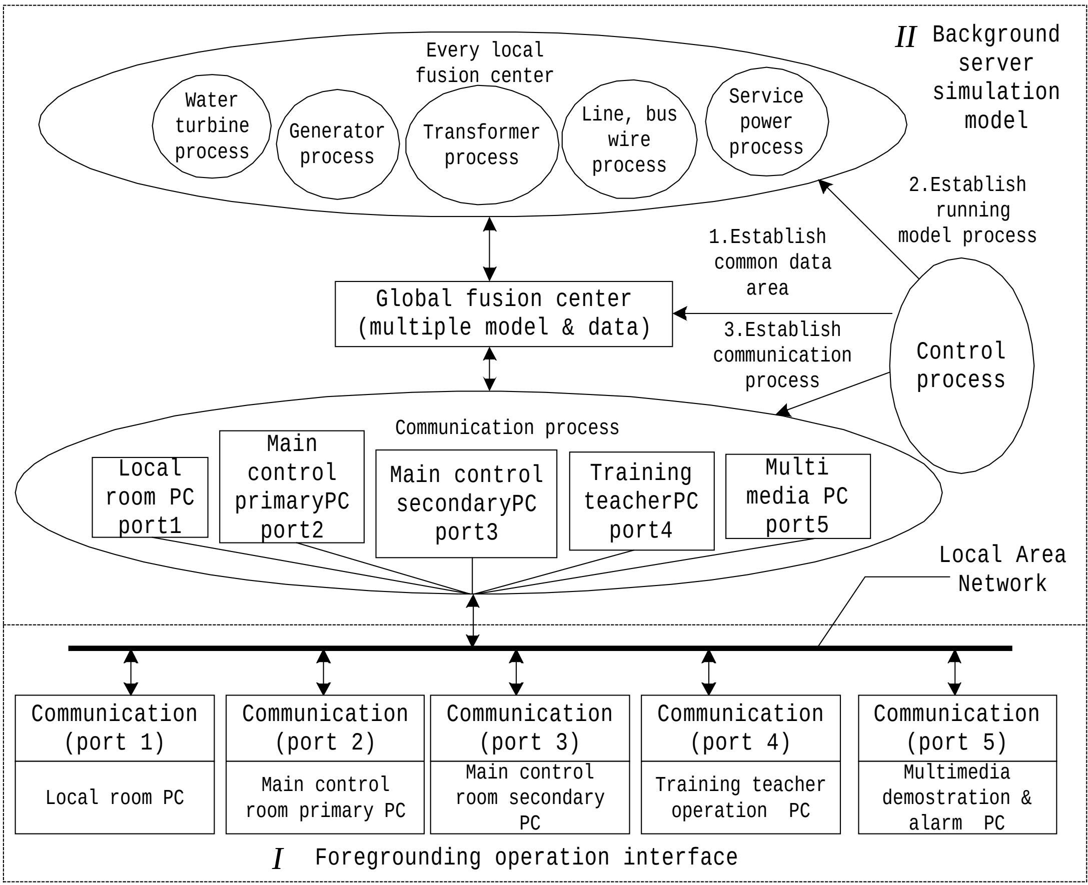

Fig. 1. Architecture of hydroelectricity digital simulation system of FengMan hydropower plant.

Hardware composing frame chart of Webit is shown as Fig. 3 and Fig. 4.

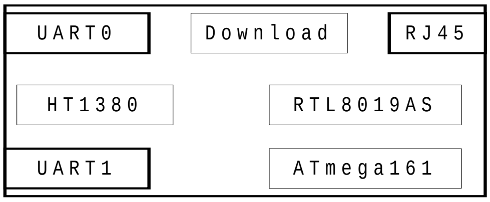

Fig. 3. Hardware makeup chart of Webit.

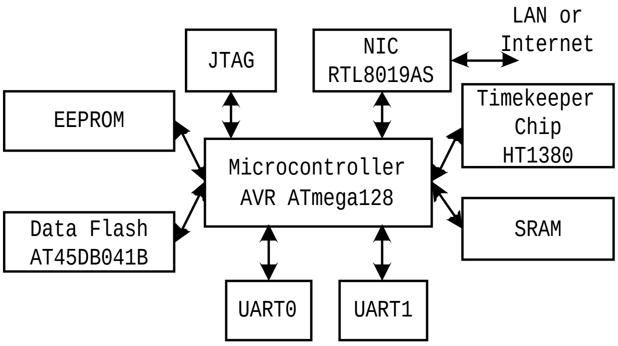

Fig. 4. Hardware makeup chart of Webit inside.

Main composing component is as follows: microcontroller-ATmega161, network card control chip-RTL8019AS, clock chip-HT1380, two universal serial port-UART0 and UART1, a RJ45 network interface and software download port-Download.

3 Multi-sensor consistency information fusion algorithm in local fusion center

Multi-sensor consistency information can eliminate data of existing biggish error and can obtain information of biggish support degree, moreover, algorithm is simple [4].

This paper adopts believable distance to compare measured data of sensors for verifying consistency of sensor measure [5]. Suppose measure model of sensors is described by Gauss probability density function:

$$p_i(x) = \frac{1}{\sqrt{2\pi}\sigma_i}\exp[-\frac{1}{2\sigma_i^2}(x - x_i)]^2 \quad (1)$$

x_i is measure value of sensor i of Eqs. (1); σ_i^2 is corresponding variance.

Probability distance d_{ij} and d_{ji} are defined as consistency verifying of sensor i and sensor j.

$$d_{ij} = 2\left|\int_{x_i}^{x_j} p_i(x \mid x_i)\, p_i(x_i)\, dx\right|$$

$$d_{ji} = 2\left|\int_{x_j}^{x_i} p_j(x \mid x_j)\, p_j(x_j)\, dx\right| \quad (2)$$

$p_i(x \mid x_i)$ and $p_j(x \mid x_j)$ are corresponding condition probability.

Probability distance of each sensor can be described by distance matrix D when n sensors measure one object character synchronously:

$$D = \begin{bmatrix} d_{11} & d_{12}\cdots & d_{1n} \\ d_{21} & d_{22}\cdots & d_{2n} \\ \vdots & \vdots & \vdots \\ d_{n1} & d_{n2}\cdots & d_{nn} \end{bmatrix}_{n\times n} \quad (3)$$

Distance matrix describes consistency degree of each sensor. Relation matrix-R of each sensor can be defined based on Distance matrix-D:

$$R = \begin{bmatrix} r_{11} & r_{12}\cdots & r_{1n} \\ r_{21} & r_{22}\cdots & r_{2n} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2}\cdots & r_{nn} \end{bmatrix}_{n\times n} \quad (4)$$

In Eqs. (4), r_{ij} is determined by probability Threshold - ε:

$$r_{ij} = \begin{cases} 1 & d_{ij} <= \varepsilon \\ 0 & d_{ij} > \varepsilon \end{cases}$$

Relation matrix R can be expressed expediently using oriented graph. Oriented graph adopt the sensors that are in use as nodes, if $r_{ij}=1$, well then an arrowhead is drawn from node i to node j. The whole oriented graph will express the intuitionistic all the inter-sensors in use. Together exist three kinds relation for sensor i and sensor j, (1) rij=rji=0, indicates that sensor i and sensor j is unattached each other; (2) $r_{ij}=1$, $r_{ji}=0$ indicates that sensor i and sensor j is sustaining infirmly; (3) $r_{ij}=r_{ji}=1$, indicates that sensor i and sensor j is sustaining strongly. Therefore, the most sensors connecting group can be confirmed, more exact estimation value can be obtained by fusing inner sensor data. Sensors that are unattached with the most sensors connecting group are eliminated, Sensors that infirm sustaining with the most sensors connecting group are doubted to have errors and should be carried through as follows: if possible, it can obtain compensation; if impossible, it can't be considered.

We can combine these measure data of sensors by adopting all kinds of effective fusion algorithms after confirming the most sensors connecting group, so that measured object is estimated roundly and congruously.

Because the distributing of inspected device parameter(e.g.,temperture,voltage and so on) takes on non-well-proportioned characteristic, so we adopt multi-sensor for inspecting of each kind device parameter. Aim at the characteristic of hydroelectric generating units, four same sensors of each kind device are adopted, these sensors are placed in different positions, so sensors of each kinds device make up of four sensors groups.

Measure result of gas sensor of equal precision takes on normal distribution characteristic, therefore the information fusion of device parameters measure can adopt the fusion algorithms of integrating arithmetic average and batch estimation.

Detailed method is as follows: firstly we educe consistency measure data by above consistency information fusion method for collected measure data list of four sensors setting at different places in the device inspecting, afterwards these data are compartmentalized two groups according to the principle that if two sensors border upon place, then they are located in different groups, batch estimation algorithm is adopted to averages of two groups measured data, fusion value- $\hat{C}^+$ is estimated that approaches better true value of device parameters, consequently exact measure results of device parameters are obtained, uncertainty is eliminated further in process of measuring.

Supposed No.1 group consistency measure data are : C_{11}, C_{1m} m<=2 ;

Supposed No.2 group consistency measure data are : C_{21}, C_{2n} n<=2.

Arithmetic average of the two groups measured data is respectively:

$$\overline{C}_{(1)} = \frac{1}{m}\sum_{p=1}^{m} C_{1p} \tag{5}$$

$$\overline{C}_{(2)} = \frac{1}{n}\sum_{q=1}^{n} C_{2q} \tag{6}$$

Corresponding standard error are respectively:

$$\hat{\sigma}_{(1)} = \sqrt{\frac{1}{m-1}\sum_{p=1}^{m}(C_{1p} - \overline{C}_{(1)})^2} \tag{7}$$

$$\hat{\sigma}_{(2)} = \sqrt{\frac{1}{n-1}\sum_{q=1}^{n}(C_{2q} - \overline{C}_{(2)})^2} \tag{8}$$

Measure results of No. 1 and No.2 group are considered synchronously, gas concentration fusion value - $\hat{C}^+$ and variance- $\hat{\sigma}^+$ can be educed respectively after estimation group by group according to batch estimate theory:

$$\hat{\sigma}^+ = \frac{\hat{\sigma}^2{}_{(1)}\hat{\sigma}^2{}_{(2)}}{\hat{\sigma}^2{}_{(1)} + \hat{\sigma}^2{}_{(2)}} \tag{9}$$

$$\hat{C}^+ = \frac{\hat{\sigma}^2{}_{(2)}}{\hat{\sigma}^2(1) + \hat{\sigma}^2{}_{(2)}}\overline{C}_{(1)} + \frac{\hat{\sigma}^2{}_{(1)}}{\hat{\sigma}^2(1) + \hat{\sigma}^2{}_{(2)}}\overline{C}_{(2)} \tag{10}$$

Eqs. (10) is device parameter value of data fusion based on multi-sensor parameters estimate.

4 Model of fuzzy comprehensive assessment

Comprehensive assessment method is one of the important methods and tools in the decision and analysis. Fuzzy comprehensive assessment is comprehensive assessment method to the object and phenomena that is influenced by multiple factors using fuzzy set theory [3][6]. The method has been successfully applied into the industry process, evaluating of product, supervise of quality and so on.

In the process of fuzzy comprehensive assessment, it is denoted that (U, V, R) is assessment model of fuzzy comprehensive assessment, and the Factor Set U consists of all elements which relates to the assessment, it can be represented as $U = \{u_1, u_2, \cdots, u_m\}$, In general, every factor u_i has its different weight a_i. The weight set ***A*** is a fuzzy set, which is represented by a fuzzy vector, $A = (a_1, a_2, \cdots, a_m)$, where a_i is the value of the membership function of the factor u_i relating ***A***, that is, it represents the degree of every factor in the comprehensive assessment. In general, it satisfies:

$$\sum_{i=1}^{m} a_i = 1 \qquad a_i > 0 \tag{11}$$

The set V is the Assessment Set, which is the set that consists of the assessment degree of the object. It can be represented by $V = \{v_1, v_2, \cdots, v_n\}$, where v_i is the assessment degree for this assessment.

The matrix $R = (r_{ij})_{m\times n}$ is a fuzzy mapping from ***U*** to ***V***, where r_{ij} express the possibility degree of j[th] assessment when condistering the i^th^ factor, that is the membership degree of from u_i to v_j.

In the process of fuzzy comprehensive assessment , let $A=(a_1,a_2,\cdots,a_m)$ be the fuzzy set on the Factor Set U , in which a_i is the weight of u_i , $B=(b_1,b_2,\cdots,b_n)$ is the fuzzy set on the assessment set V, the comprehensive assessment can be represent as follows:

$$B = A \circ R = \{b_1, b_2, \cdots, b_n\} \qquad (12)$$

In Eqs. (12) the operator $\circ$ is often defined as the assessment arithmetic operator ($\wedge^*, \vee^*$), so Eqs. (12) can be written as :

$$\forall b_i \in B,\ \ b_i = (a_1 \wedge^* r_{i1}) \vee^* (a_2 \wedge^* r_{i2}) \vee^* \cdots \vee^* (a_m \wedge^* r_{in}) \qquad (13)$$

In general, the assessment arithmetic operator can be defined as common matrix operation (multiplication and addition) or zadeh fuzzy operation (min and max) and so on according to the practical application.

Following the comprehensive process, the synthetic evaluation of $\{b_1,b_2,\ldots,b_n\}$ a defuzzification process of making a fuzzy quantity to a precise quantity, the method, such as max membership principle, centroid method, weighted average method etc, can be adopted. In general, max-membership principle is also known as the height method, which is limited to peaked output. The centroid method is also called the center area or gravity center, it is the most prevalent and physically appealing of all the defuzzification methods. Weighted average method is only valid for symmetrical output membership functions, but it is simple and convenient. In practical application, the exact method of synthetic evaluation is usually depends on the application.

5 The decision level information fusion algorithm based on the fuzzy comprehensive assessment

5.1 The architecture of the “Soft” decision information fusion

The objects of decision information fusion is usually the local decisions of the sensors, that is, the process of decision information fusion is that of global decision under the basis of local decisions of the multiple sensors. The method or architecture of the decision information fusion is usually classified into either the “hard” decision or the “soft” decision according to the results of local decision of the sensor [1]. In the “hard” decision, the local decision of the sensor is usually the problem of binary hypothesis test , the result of hypothesis test is either zero or one according to the threshold level. So the local decision of the sensor that is directly sent to the fusion center is either zero or one. In the “soft” decision, the whole region of sensor decision is usually divided into multiple regions, and the result of the sensor includes not only the region of decision but also the possibility value belonging to the region, so the information that is sent to the fusion center in “soft” decision is the possibility of each hypothesis.

In the process of “hard” decision, the sensor couldn’t provide any information tha is lower or higher than the threshold level, so the information that is lower or higher than the threshold level is losed in the process of fusion at the fusion center. Compared with the process of “hard” decision, the process of the “soft” decision provide not only the region of decision, but also the possibility of the region. In the fusion center, the object including the region and the possibility of the region can be utilized for the process of the fusion. The architecture of the the process of the “soft” decision under the fuzzy comprehensive assessment is shown as Fig.5.

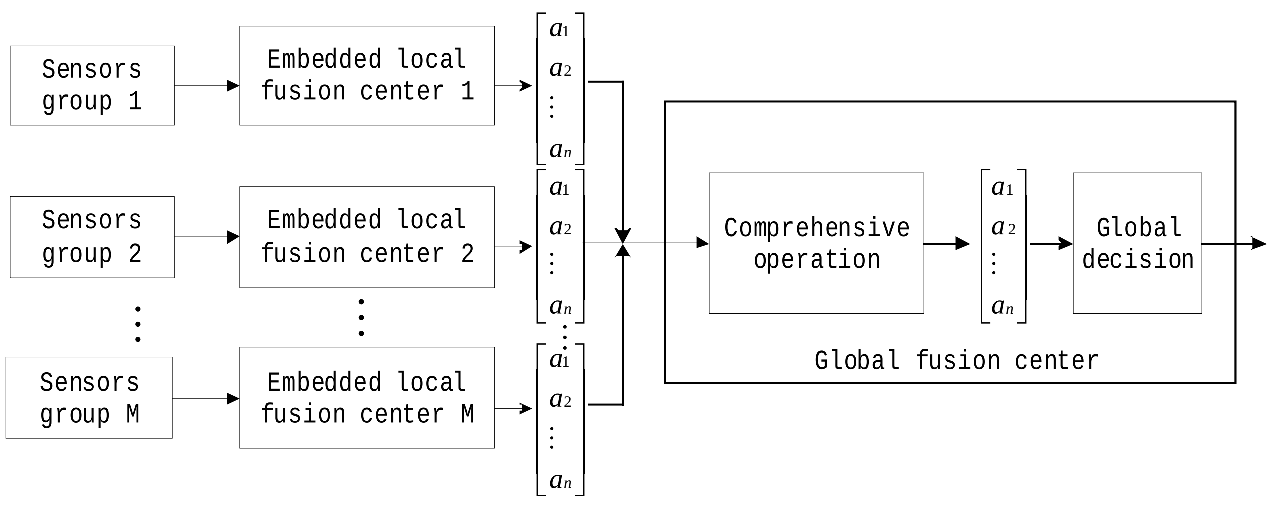

Fig.5. Architecture of the “soft” decision fusion under the fuzzy comprehensive assessment.

5.2 The description of the algorithm

From the Fig.5, the algorithm of decision level information fusion based on the fuzzy comprehensive assessment adopted the architecture of the "soft" decision. In the algorithm, we consider an information fusion system consisted of M sensors groups that observe the same phenomenon to different components in complex equipment(e.g. ,the temperture value of hydroelectric generating units in different components). Each sensors groups makes its local decision based on its observation, the local decision that include the decision region and its possibility value is sent to the global fusion center by embedded Webit, the global decision based on the local decisions of M sensors groups obtained at the local fusion center. The local fusion centers adopt multi-sensor consistency information fusion algorithm according to Section 3.

It is denoted that the set D_L is the local decision set, that is $D_L=\{D_{L1},D_{L2},...D_{LM}\}$, the result of the local fusion center is classified into *N* regions, is called as the assessment set Y, that is$Y=\{y_1,y_2,...y_N\}$. In the process of the "soft" decision of each local decision , the result of each local decision is the value of possibility on the assessment *Y*, for the i^th^ local decision, the result of local decision can be described as the vector $r_i=(r_{i1},r_{i2},\cdots,r_{in})$, through the process of normalization, the input of the fusion center for the i^th^ local decision is the vector $\overline{r_i}=\left(\overline{r_{i1}},\overline{r_{i2}},\cdots,\overline{r_{in}}\right)$.For the $\forall D_{Li}\in D_L$, the vector $\overline{r_i}$ consist of the $m\times n$ matrix *R*, that is called as the Fusion Matix of the fusion center, can be descibed as follows :

$$R=\begin{bmatrix}\overline{r_{11}} & \overline{r_{12}} & \cdots & \overline{r_{1n}}\\ \overline{r_{21}} & \overline{r_{22}} & \cdots & \overline{r_{2n}}\\ \vdots & \vdots & \vdots & \vdots\\ \overline{r_{m1}} & \overline{r_{m2}} & \cdots & \overline{r_{mn}}\end{bmatrix} \qquad (14)$$

For each local decision in the fusion system, the effect of each local decision is always different, it is denoted that *A* is the local decision vector of weight power, it is a fuzzy set on the local decision set D_L, and described as the normalized fuzzy vector $A^{'}=(a_1,a_2,\cdots,a_M)$ and $a_i=\mu(a_i)$, i=1,2,…,*M*.

In the comprehensive operation of the algorithm, the comprehensive result of the local decision weight vector and the fusion matix is the fuzzy set of the assessement set. The result can be descibed as follows:

$$B=A\circ R=\{b_1,b_2,\cdots,b_n\} \qquad (15)$$

For the comprehensive opterator, the algorithm adopted the comprehensive operator ($\wedge^*,\vee^*$) in the fuzzy comprehensive assessment.

In the process of the global decision at the global fusion center, the input is the vector $\{b_1,b_2,b_n\}$ result from the comprehensive operation, in this research, the max membership principle is adopted, that is if $\exists i\in\{1,2,\cdots,m\}$, satisfy $b_i=\max\{b_1,b_2,\ldots,b_m\}$, so the result of global decision is b_i.

6 Experiment analysis

In the hydroelectricity digital simulation system of Jilin FengMan, the generator system is the important component of the system, its working condition has great influence to the stabilization of the whole system, so fault detection and diagnosis is necessary to the generator. As far as it goes in the detection system in the hydroelectricity system, the method of fault detection and diagnosis usually adopts the sensor-threshold level method, that is, in the system of fault detection and diagnosis, primary parameter of the equipment is supervised by a group sensors, the data is sent to the detection center. In the detection center, threshold level of the parameter is set in advance, when the data that is gathered exceed the threshold level, touch off the corresponding fault alarm. So the sensitivity of the whole detection system is dependent upon the threshold level. But in the pratical application, the threshold level is set artificially. If the value of the threshold level is too high, it is possible to fail to report the alarm, otherwise if the value is too lower, it is possible to cause the system alarm when the equipment is in order.

Aimed to the disadvantage of the tradtional detection and diagnosis system, the information fusion technology can be applied into fault detection and diagnosis system. In the practical diagnosis system, multiple sensors have been embedded into the equipment, and gathered the current data of circumstance. At the fusion center, redundant and complemented data have been made full use of, so precise estimation about equipment status can be achieved, belief quantity of diagnosis system can be enhanced, and fuzzy level of status is decreased. So the application of information fusion improves detection performance by making full use of resource of multiple sensors [7]. In the simulation system, we have applied the new information fusion algorithms into the temperature fault detection and diagnosis of the generator.

In this diagnosis system, three embedded temperature sensors groups have been embedded into different components of the generator (stator winding, stator iron, rotor) , and the temperature of equipment has been periodically gathered [8]. The local decision set can be defined as $D_L=\{D_{L1},D_{L2},D_{L3}\}$. It has been found in the practical application of the system that the reason of temperature alarm of the generator can be classified into the fault of cycle water equipment, cooling water equipment and misplay of operator, etc. So the assessment set can be defined as $Y=\{y_1,y_2,y_3,y_4,y_5\}$={circulation water valve shutdown by error, low pressure of circulation, cooling water valve shutdown by error, cooling water pump lose pressure and backup pump not switched, other undefined reason} in the temperature fault diagnosis system.

The effect of the three sensors groups is different in the diagnosis system because of its position, precision and so on, so in the practical application, the weight power vector has been alloted according to the experience, that is,

$$A=(a_1,a_2,,a_3) = (0.4400,0.2300,0.3300) \qquad (16)$$

The three embedded sensors groups gather the data and make its local decision, the local decision that is the value of the possibility of the fault has been sent to the global fusion center, the process of the diagnosis in the fusion center is as follows: the local decision of the sensors groups have been normalized firstly, the results of normalization of each sensors groups constitute the fusion matrix. Secondly, comprehensive operation is made between the sensor weight power vector and the matrix of decision. At last, global decision about the fault is made according to the result of comprehensive operation under the max membership principle.

For example, in the process of diagnosis the local decision of the sensors groups that have been normalized is described as Table 1.

Table 1 : Experiment data of the diagnosis system.

Local decision	O_1	O_2	O_3	O_4	O_5
D_{L1}	0.3800	0.2200	0.0000	0.4000	0.0000
D_{L2}	0.2812	0.4386	0.0000	0.2802	0.0000
D_{L3}	0.1350	0.3338	0.0000	0.5312	0.0000

In this research, the comprehensive operation of the fusion center adoptes the fuzzy set conjunction and disjunction operation, that is max-min operator, so the result of the comprehensive operation is as follows:

$$B = (0.3800,0.3300,0.0000, 0.4000,0.0000)$$

After the normalization the $\overline{B}$ can be obtained.

$$\overline{B} = (0.3423,0.2973,0.0000,0.3604,0.0000)$$

In the global decision, according to the max membership principle, the decision about the fault is made as 'the cooling water pump lose pressure and backup pump not switched', the diagnosis conclusion accord with the locale fact in hydropower plant.

7 Conclusions

- Many experiments have showed that multi-sensor consistency information fusion algorithm and distributed decision information fusion algorithm are effective and can be applied widely, the performance of these algorithms precede that of the traditional diagnosis methods.
- These algorithms have been successfully applied in fault detection and diagnosis of hydroelectric generating units of hydroelectricity digital simulation system and hydropower plant of FengMan. Remote on-line detection and fault diagnosis are implemented by adopting less cost embedded web server-Webit substitute industry control PC based on network. This system takes on preferable application foreground.

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