ON-LINE MONITORING FOR TURBINE BYPASS SYSTEM BASED ON REAL-TIME SIMULATION

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ABSTRACT

Faults may occur in nuclear power plants, but it is difficult for operators to recognize the situation and take effective measures quickly. However, on-line monitoring may help operators to detect the abnormalities so that the safety of nuclear power plants will be improved. As Turbine Bypass System runs during transient processes, quantitative simulation model is utilized for on-line monitoring. In addition, analyzing for residual errors of simulated and corresponding measured values are done by principle component analysis. Under normal operation, the methodology allows real-time tracking to set dynamic thresholds. While a failure occurs, faults can be detected. Simulation analysis show the effectiveness and accuracy of this methodology.

Key words: Hybrid monitoring；Real-time simulation；Turbine Bypass System;

1 INTRODUCTION

Nuclear power plants are complex engineering systems which have great potential dangers. If accidents occur during the operation, they may lead to catastrophic consequences on global ecological environments. After service, safety and reliability of a NPP mainly depend on operators' operation. Unfortunately, operators may be prone to take incorrect measures due to the complexity of accidents and urgency of time. According to statistical data, human error is one of the leading factors in nuclear accidents.

Therefore, On-line monitoring methods which allow early and timely fault detection are vital for enhancing the safety of NPP. Furthermore, they provide essential information for fault diagnosis. Currently, methods of on-line monitoring mainly concentrate in two aspect. One is focus on hardware innovation to improve the existing sensors or develop new sensors so as to measure the previous unpredictable parameters. The other one puts emphasis on analyzing the relationship between existing measurements and corresponding devices to detect abnormal condition, and this paper mainly researches on software scheme.

Scholars all over the world studied on-line monitoring methods and had gained many achievements. Currently, the methods can be divided in two groups, data driven and model-based methods: For data-driven methods, the reusability and fault tolerance of these methods are much better than others. Daneshvar adopted principal component analysis to monitor the boiler system of thermal power plants. But these methods rely on data analysis that is impossible to acquire enough data in every condition. In addition, diagnosed results are hard to be explained and confirmed. Further, the parameters measured in Turbine Bypass System (GCT) are changing all the time which makes them unable to do statistical analysis, let alone to monitor the condition. Model-based methods can delve into the mechanism of equipment which are easy to be explained. William utilizes mass and energy conservation equations to warn operators when the equipment turns to abnormal conditions. But these methods highly depends on the precision of modeling. In addition, the parameters required in conservation equations may not be acquired in NPP. More importantly, NPP is a complicated non-linear system which leads to relatively high inertia, so this method is too simple and even during a steady processes the monitoring result is inaccuracy for some complicated devices, let alone to use for transients.

With the rapid development of simulation and computer technologies, a quantitative model-based method has become possible. The difference with the mass-energy conservation equations is that the proposed method lies on the mechanism simulation of devices, which can reflect dynamic behaviors of NPP. Under normal operation, the method allows real-time tracking with NPP. When a failure occurs, corresponding parameters can be compared to detect the fault.

2 ANALYSIS OF TYPICAL FAULT IN GCT

2.1 Workflow of GCT

The flow chart of GCT which includes GCTc and GCTa is shown in Fig. 2. For GCTc, two discharge pipelines are connected to main steam pipelines and vent to desuperheating and decompression device. In each pipeline that connected with condenser, a manual normally open isolation valve and a discharge control valve are utilized. In addition, GCTa that consists of three separate pipelines is utilized for discharging to atmosphere when condenser is not available.

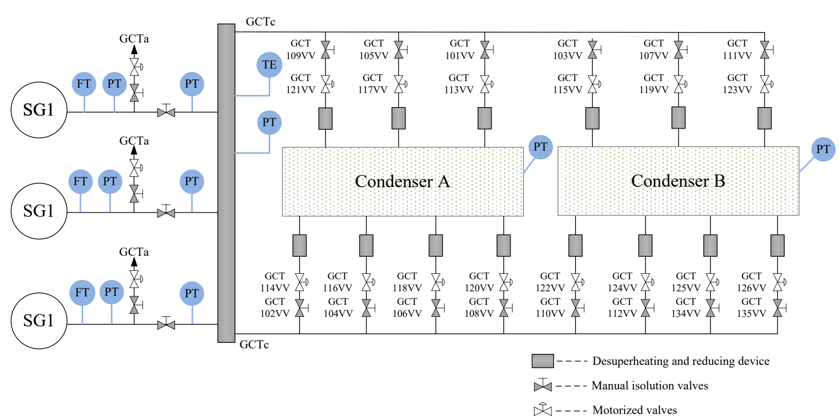

Fig 2. The flow chart of GCT

Two control modes are designed for GCT: When turbine load is less than 20%, pressure control mode based on main steam pressure is adopt; while turbine load is more than 20%, GCT is controlled by reactor coolant temperature. As shown in Fig.2, measurements are very limited which increase the difficulty for the implementation of on-line monitoring.

2.2 The Typical Accident Processes

A nuclear power plant was in 10% nuclear power so that the control mode of GCT was in pressure control. Unfortunately, malfunctions occured as follows:

（1）The level fluctuations of 1st steam generator

The water level of steam generator was under auto-control, but the fault in GCT lead to the fluctuations of water level. However, the feed water valves were all around 46% and the water level of 1st steam generator was still within control ranges.

（2）Manual control of GCTc until 1st steam generator shutdown

As operators did not know what happened, they tried to check out whether there was a fault in GCTc. Therefore, they set GCTc in manual control and lowered the discharge in pressure control mode which lead to the close of valves gradually. After 1 min, main steam pressure was higher than threshold which triggered GCTa to let out to atmosphere. However, in order to increase the reference of secondary-loop load after main steam pressure dropped, operators had to increase the output of GCTc.

Unfortunately, the water level of 1st steam generator fluctuated again so that the output of GCTc had to be lowered until shutting down. As a result, the water level of 1st steam generator continuously decreased from -0.27m to -0.5m and the loss of pressure was done by intermittent pressure relief of GCTa.

After GCTa ran, output signal of secondary-loop load mainly used for regulating level of steam generator was low. Also, level deviation in steam generator level control was utilized for modifying a closed-loop deviation, which was basically irrelevant with decreasing of level. Although the manual control for steam generator was utilized, water level of 1st still triggered the low-low threshold because of the big volume and inertia in steam generator. As a result, reactor had to shut down automatically.

2.3 Fault Analysis

By on-site inspection, the reason was a screw of position feedback device in GCT121 valve loosing as shown in Fig. 2 that lead to continuous abnormal movements, specifically, constantly switch with momently shutting down. As operator did not realize that the fluctuation of water level was caused by GCT121 valve, they continually opened and closed GCTc that aggravated fluctuations. In addition, the water level control system cannot receive feedback of secondary-loop load which caused shutting down of reactor.

Although the design for control logic of water level control in low power had defects, the root reason was that operators were not aware of the mechanism and cannot detect and locate the faults. Due to frequent fluctuations of water level, main steam pressure and other parameters, it is difficult for operators to implement correct operation. However, on-line monitoring for GCT can help operators detect the fault and compress alarms early which avoid severe accident consequences.

3 THEORY OF ON-LINE MONITORING USING MECHANISM SIMULATION

3.1 Simulation Modelling of GCT

There are mainly two simulation modeling categories. One is the graphical methods, the other one is the traditional handwork programming. The advantage of graphical modeling methods is that common elements such as pipelines and tanks are added from simulation library. As a result, GCT is modelled by only filling in the essential data for each element which means it utilizes visual elements to replace handwork programming. On the other hand, handwork programming by Fortran or C language have to compile codes step by step so that they have a heavy workload. Therefore, The SIMEXEC platform and two phase-flow simulation software JTOPMERET which is a graphical modeling method are utilized to build simulation model of GCT. SIMEXEC platform allows interaction with obtained data from NPP and developed human-machine interface universality and instantaneity. Additionally, JTOPMERET can calculate in real-time and keep great accuracy that is suitable for on-line monitoring.

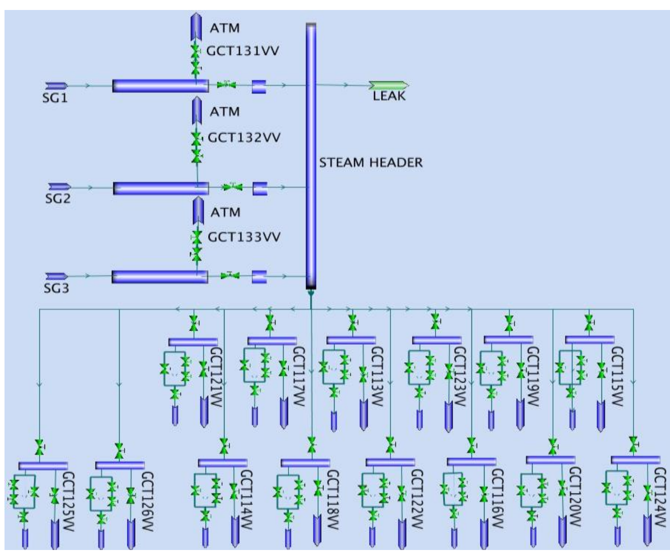

Fig 3. Node graph of GCT monitoring model

In general, the more numbers and types of sensors are, the more accuracy and detailed monitoring units will be. But the number of sensors is limited As shown in Fig. 3 is the thermal-hydraulic simulation model. According to the layout of measurements as shown in Fig. 2, the inlet and outlet pressure are chosen as calculated boundary. In addition, inlet flows of GCT are utilized as the characteristic parameters to compare with the corresponding measurements. Furthermore, Off-line debugging are done to keep trends all same with designed parameters.

3.2 Residual Analysis Based on PCA

Principal Component Analysis (PCA) utilizes the orthogonal transformation to convert a series of relevant variables to linear irrelevant variables. PCA has a great advantage in data compression and feature extraction. Therefore, PCA is utilized for residual analysis.

The array $X_{n\times m}$ is made up by residual errors of calculated values and the corresponding measurements under normal operation， where n means sample size and m means the number of residual errors. And then the array is standardized which is represented as:

$$X=\widehat{X}+E \quad (1)$$

Where， $\widehat{X}$ means ideal values of X, and E means errors of modeling. $\widehat{X}$ and E are represented as follows by PCA：

$$\widehat{X}=\hat{T}\hat{P}^T=\sum_{i=1}^{l}t_i p_i^{\,T} \quad (2)$$

$$E=\tilde{T}\tilde{P}^T=\sum_{i=l+1}^{m}t_i p_i^{\,T} \quad (3)$$

Where，l<m is the number of principle component；T and P represents score matrix and load matrix. And P is eigenvector of Xn×m's covariance matrix Σ. According to load matrix T, score matrix is：

$$\sum=P_{m\times m}D_\lambda P^T_{m\times mm},T_{n\times m}=X_{n\times m}P_{m\times m} \quad (4)$$

Where， D_λ is eigenvalue of diagonal matrix $diag\left(\lambda_1,\lambda_2,\cdots,\lambda_m\right)$.Therefore,

$$X_{n\times m}=X_{n\times m}\hat{P}_{m\times l}\hat{P}^T_{m\times l}+X_{n\times m}\tilde{P}_{m\times(m-l)}\tilde{P}^T_{m\times(m-l)}=X_{n\times m}\hat{C}_{m\times m}+X_{n\times m}\tilde{C}_{m\times m} \quad (5)$$

Further, the number of principal components is calculated based on the minimum reconstruction error variance. And u_j is the none refactoring variance of ξ_j：

$$u_j=\frac{\xi_j^T\left(I-\hat{C}\right)\Sigma(I-\hat{C})\xi_j}{\left[\xi_j^T(I-\hat{C})\xi_j\right]^2} \qquad (j=1,2,...,m) \quad (6)$$

Where，I is m×m unit matrix，ξj is fault direction of ξ, $\xi\in I_{m\times m}$. Obviously， u_j is related with $\hat{C}$, and $\hat{C}$ is closely related with the selection of main components. In order to achieve good reconstruction of each dimension, searching the number of principle components by $\underset{i}{Min}\left(\sum_{j=1}^{m} u_j\right)$ is done.

Different number of principle components are selected and then $\sum_{j=1}^{m} u_j$ is calculated respectively. Furthermore, the number of principle components related to minimum $\sum_{j=1}^{m} u_j$ is the optimal one.

3.3 The On-line Monitoring Processes of GCT

The simulation of system safety analysis or full-scope simulator only require the similar change trends with that of NPP and do not consider transient accuracy. In addition, there is no interactive data between simulation model and NPP which means monitoring task cannot be completed. Therefore, proposed on-line monitoring of GCT is mainly made up by four modules, which contains data collection and management, monitoring models, analysis of the residuals based on PCA and human-machine interface. The flow chart of Fig. 4 shows how these four modules cooperate with each other to complete the on-line monitoring task:

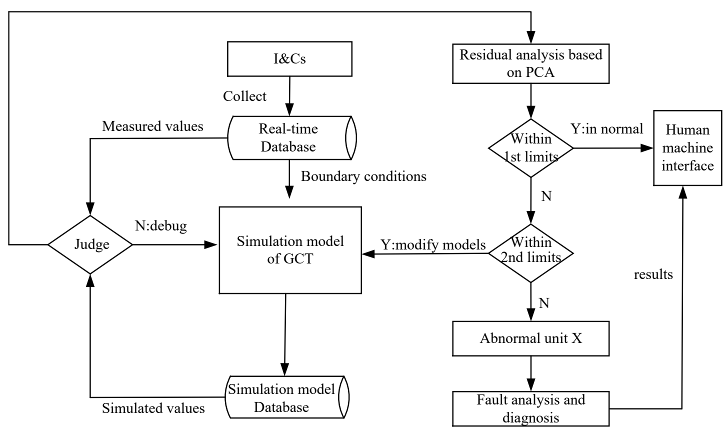

Fig 4. Flow chart of on-line monitoring processes

(1) Data acquisition and storage: all parameter which contain data of sensors, actions of instrumentation and control system (I&Cs) and operations of operators are acquired. And then they are classified and stored in real-time database.

(2) Off-line debugging of simulation model: static and dynamic debugging are done to keep trends of simulation model same with actual processes.

(3) Data initializing and updating of simulation model: Data interfaces between real-time database and simulation model are connected to transmit the status of boundaries and operation of I&Cs to simulation model. In addition, calculated and measured values are compared to check whether they are consistent with the each other. If any parameter is inconsistent, the corresponding simulation model should be regulated until the residual errors are less than 1%.

(4) Residual analysis based on PCA: When the NPP is in normal, the statistics are within the allowable range so as to continue on-line monitoring. If there are performance deterioration in any equipment, the corresponding residuals exceed one-level limits and do not vary obviously. However, if fault occurs in the monitoring unit, the residuals change significantly and also exceed two-level limits. Therefore, calculated errors can be found and alarms can be triggered.

(5) Modification of monitoring model: After performance deteriorates, the simulated system and equipment should be modified immediately until satisfying the requirements of residual analysis module.

4 SIMULATION ANALYSIS

The proposed on-line monitoring methodologies mainly focus on sudden abnormalities that arise from the change of the structure and machinery such as leakage of pipeline and misoperation of valves. Without on-line monitoring, some faults may lead to severe consequences as shown in section 2.2. Therefore, this paper utilizes the typical fault that presented in section 2 as an example to verify the accuracy and effectiveness of the proposed methodology. In addition, human-machine interface is developed by C# programming.

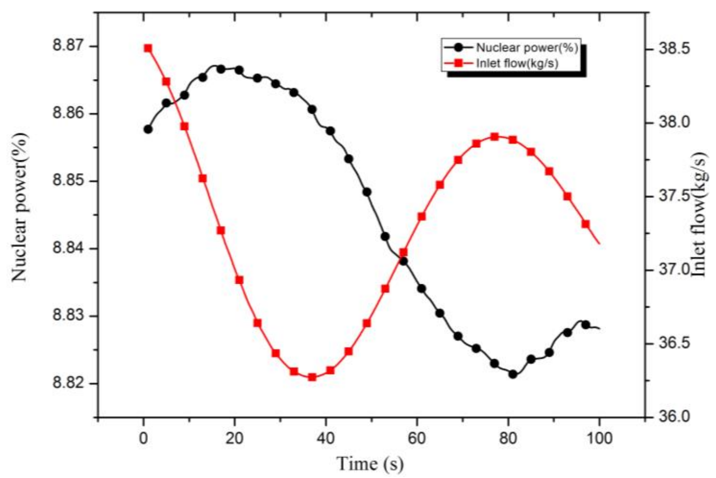

Fig 5. Nuclear power and inlet flow of GCT

900MW full scope simulator is utilized as NPP because it is impossible to do corresponding experiments for getting actual data. Starting up of reactor is done according to operation procedures, and some parameters in GCT are shown in Fig. 5 after regulating the concentration of boron to maintain nuclear power at around 10%.

Simulation model of GCT is established by JTOPMERET and debugged off-line according to the parameters in Fig. 5. Further, measurements mentioned above are transmitted to real-time database. And then, the simulation models are connected with the corresponding real-time parameters. After that, admittances that reflect the relation between pressure and flow of adjacent pipelines are regulated until the corresponding errors are within thresholds. In consequence, on-line monitoring interface during normal operation is shown in Fig. 6.

Operators can check measurements and corresponding simulated values, and the status of GCT is shown in top resident interface.

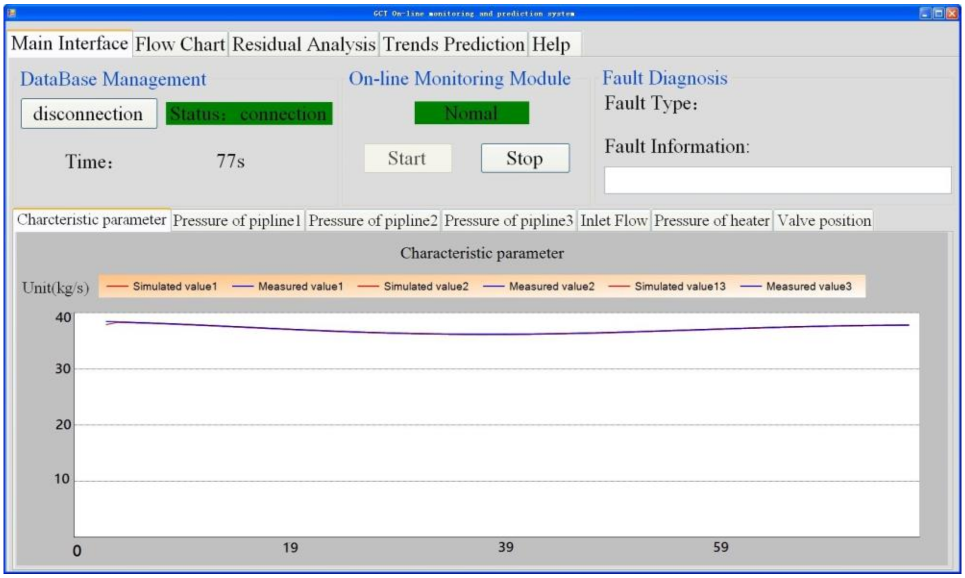

Fig 6. Human-machine interface of on-line monitoring in normal operation

After NPP maintaining in 10% nuclear power, this paper assumes that mechanical fault of position feedback device in GCT121 valve is inserted in random in 150s. So, the control system of GCT is normal but the GCT121 valve cannot follow. In order to simulate the phenomenon of the typical fault in 900MW simulator, GCT121 valve is constantly opened for 10s and then shut down for 2s as shown in the blue line of Fig. 7.

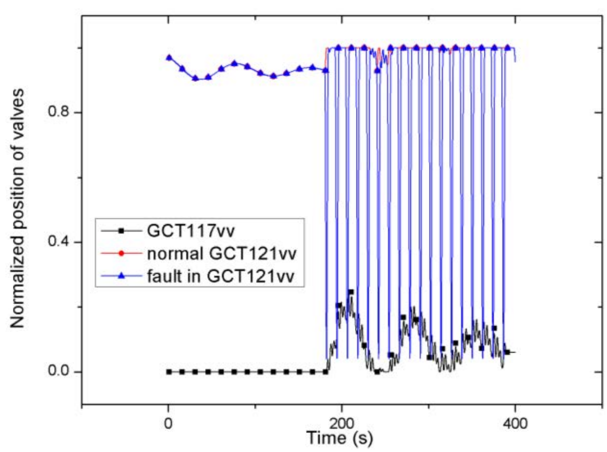

Fig 7. The change trends of valves

After the fault occurs, on-line updating of simulation model by acquiring control logic from I&Cs and boundaries are done continually. As there is no malfunction in simulation model, the simulated inlet flow would be different with the corresponding measurements. The monitoring results are shown in Fig. 8 and the residual analysis based on PCA is displayed in the active region. Clearly, T2 and SPE statistics of residual errors exceed two-level threshold.

Therefore, a malfunction occurs in this unit and alarms are triggered. In addition, the fault can also be detected by the change trends of inlet flow of GCT as shown in Fig. 9.

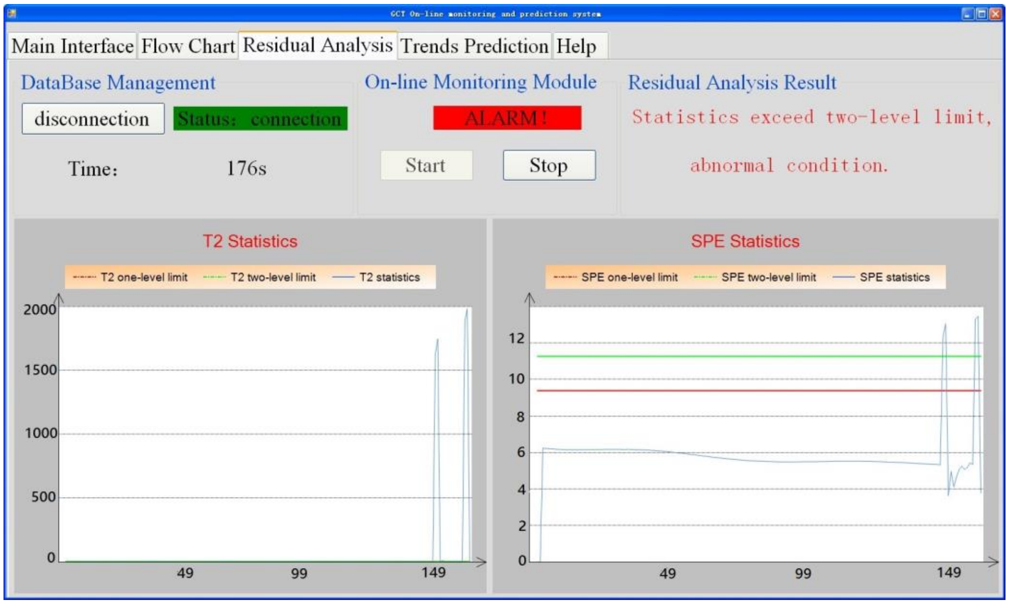

Fig 8. Human-machine interface after the fault

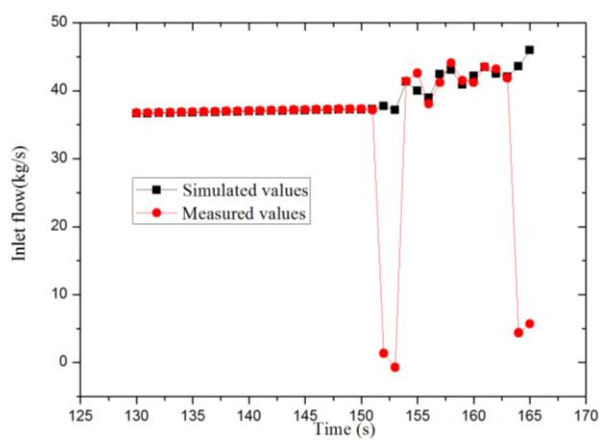

Fig 9. Inlet flow of GCT

Obviously, the on-line monitoring of GCT based on real-time simulation can help operators to detect faults but cannot diagnose faults due to the limited number of measurements. In order to prevent similar accidents, some suggestions are provided on the basis of on-line monitoring:

1. In Hardware scheme, thorough reformation of these type valves should be done. Otherwise, installation of flow measurements in the branch of GCT is necessary in order to satisfy the demands of fault diagnosis;

2. In Software scheme, according to the design of control logic, the number of running branches in GCTc influenced by production of steam is limited. In this simulation analysis, there are only three branches working during the whole processes. Therefore, each branch is isolated one by one in order to observe the fluctuations of steam flow and parameters in steam

generator. And in this case, fluctuations of these parameters disappear after shutting down the branch which contains GCT121 valve. As a result, faults occur in this branch.

5 CONCLUSIONS

The on-line monitoring for Turbine Bypass System are implemented by combining real-time simulation with PCA. Malfunctions in GCT can be monitored and detected in time. Additionally, the diagnosis of faults can be further done by combining with this method. As a result, Simulation analysis shows the merits of this monitoring methodology, as follows:

(1) The traditional data-driven and model-based methods are useless for the monitoring of transient processes.

(2) The PCA-based residual analysis is utilized to ensure the accuracy of real-time simulation.

(3) The operation procedure and control logic of GCT in emergency can be improved and suggested.

In conclusion, the proposed methodologies are benefit for operators especially during transient monitoring processes. Further, the safety and reliability of NPP will be improved.

6 ACKNOWLEDGMENTS

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