The Application of Sneak Circuit Analysis on Chemical and Volume Control System

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Abstract. In the chemical and volume control system (RCV) of nuclear power plant pipelines are very complex, there are many valve control nodes. These make the probabilistic risk of unexpected situation rather high in design and running. In order to increase the reliability and safety of the system in design and running, the sneak circuit analysis technology is applied in gas and liquid pipelines of RCV to find latent path and temporal sequence in design and running. Improvements and advices are given to avoid these latent risks in design and running.

1. Introduction
As an important auxiliary system of nuclear power plant, chemical-and-volume control system also serves as one of the systems and items related to nuclear safety. In addition to the three essential functions of volume, chemical and reactivity control, the system also undertakes important functions of auxiliary and safety. Due to many pipeline connection nodes of each functional module in the system and many associations of valve control, the operation sequence of valves and equipment under different working conditions is complicated, which leads to the high risk of sneak circuit (potential paths, timing, indications and signs) in system design and operation[1][2].

Sneak circuit always occurs all of a sudden, which is not easy to detect by conventional examination. With the increase of the complexity of the system and the number of nodes, the sneak circuits increase in series. As a very effective analysis method, analysis of sneak circuit can be used to identify all potential paths of large complex systems. Thus, it is an essential part of safety, reliability and quality assurance [3]. Due to the complexity of the system and equipment involved, a complex thermal fluid system is designed by gradations and groups. Because different designers boast different design concepts and experience, and even some of them have certain limitations on knowledge, various sneak circuits system will inevitably occur when the system being composed. Under certain conditions, these sneak circuits will perform beyond the designer’s expectation, which may affect the normal function of the system and do great harm to the system.

Through the analysis of gas-liquid pipelines of thermal fluid system, the chemical-and-volume control system for important nuclear auxiliary systems can be clarified, and the possible potential path can be confirmed, and suggestions for improvement can be given. It is of great significance to improve the safety and reliability of the system.

2. Introduction of Analysis of Sneak Circuit of Gas-Liquid Pipeline
The technology of sneak circuit not only originates from but also develops in electronic circuit.

In thermal fluid system, mass flow and heat transfer are contributed to difference in pressure and temperature respectively, which are similar to the physical principle of current flowing from high
potential to low one; various valve elements are used to control the mass flow, including stop valve, throttle valve, pressure regulating valve, safety valve, etc., which are similar to the functions of switch, diode and transistor for breaking, connecting and flow direction of current; all load elements can be showed by resistance, such as pressure vessels, water storage tanks, steam turbines, heat exchangers, etc.

Based on the similarity of the two, the mapping equivalent rules of the conversion between thermal fluid system and circuit system can be established, according to which the extracted system diagram is converted into the circuit diagram for analysis. Then, the conclusion of the sneak circuit can be obtained through the analysis technology in electric circuit.

3. Analysis of Sneak Circuit in Chemical and Volume Control System

3.1 System Description
The chemical and volume control system ensures the three necessary functions of the primary circuit, including controls of volumes, chemicals and reactivities; it is also responsible for some auxiliary and safety functions [4], including providing shaft seal water for the main coolant pump, auxiliary spray water for the pressurizer, single-phase pressure control for the primary circuit, water filling, exhaust and hydrostatic test of the primary circuit. It can also maintain the water quantity during the small break of the reactor coolant system, guarantee the reactivity control together with the boron and water supply system of the reactor, and operate the charging pump as a high-pressure safety injection pump in safety injection.

Shown in Fig. 1 is a flow diagram of the chemical and volume control system.

![Fig.1 Brief flow diagram of RCV](image)

3.2 Simplification and Conversion of System
The functions of chemical and volume control system can be achieved by a large number of function modules set in the system. Through the system flow diagram (Fig. 1) and the division of system
functions, it can be seen that the system bears more functions under different working conditions, which is easy to produce potential indication and identities of functions; many interfaces between main function modules and the outside space is large make the pipeline and the outside prone to unexpected potential paths; The switching of the nodes between the interfaces of more function modules rely on a large number of control valves to be completed, which is easy to cause the occurrence of potential timing.

The flow diagram of Fig. 1 is simplified physically and functionally for the needs of analysis. A simplified system diagram for analysis is shown in Fig. 2.

Then, based on the equivalence of converting the thermal fluid system into the circuit system, the nodes with higher pressure in the system, such as the outlet of the main system discharge circuit, the main pump shaft seal reflux, the safety injection outlet from the refueling water tank, the residual heat removal outlet, and the make-up water system interface are all taken as the “source points”, and the primary system upper flushing circuit, pressurizer auxiliary spray, main pump shaft seal and waste heat removal, safety injection removal, etc. are as “ground” to generate the circuit diagram with the original component reserved, and add nodes to form the analysis circuit diagram, as shown in Fig. 3.

![Fig.2 Simplified system diagram](image-url)
3.3 Path Search and Analysis
Based on the analysis circuit diagram after conversion in Fig. 3, all paths can be searched from high potential to low potential, and a clue list of all paths can be formed. Then, the clue list is screened to exclude irrelevant paths and form critical path, according to the constraint rules of gas-liquid pipeline and circuit conversion in the online search list. Finally, under the actual working conditions of the system, the analyzed critical paths are determined one by one to search out all potential paths, and then the prevention and improvement for the sneak circuit can be suggested.

Due to space constraints, not all the path description and analysis results are listed in this article. Some crucial results of path search and analysis are listed in Table 1.

| No.  | Path | Path Analysis |
|------|------|--------------|
| [01] | 0-088VP-003RF-16-15-21-001PO-24-073VP-25 | After filtration, the shaft seal water is recovered by the top-up pump. Design function. |
| [02] | 0-088VP-003RF-16-003PO-17-18-050VP-19 | After filtering, the shaft seal water returns to the primary circuit. Design function. |
| [03] | 0-088VP-003RF-16-003PO-17-18-227VP-20 | After filtering, the shaft seal water goes to the auxiliary spray of the pressurizer. Non-design features. |
| [04] | 0-088VP-003RF-16-003PO-17-22-23 | After filtration, the shaft seal water goes to the safety injection system. Non-design features. |
| [05] | 0-088VP-003RF-16-15-21-002PO-22-17-18-227VP-20 | After filtering, the shaft seal water goes to the auxiliary spray of the pressurizer. Non-design features. |
| No. | Path | Path Analysis |
|-----|------|---------------|
| [06] | 0-088VP-003RF-16-15-21-002PO-22-23 | After filtration, the shaft seal water goes to the safety injection system. Non-design features. |
| [07] | 1-257VP-021RF-259VP-26 | Excessive drain water from the primary circuit enters the drainage system. Design function. |
| [08] | 1-257VP-021RF-259VP-27-088VP-003RF-16-15-21-001PO-24-073VP-25 | Excessive drain water from the primary circuit merges with the shaft seal water, and after filtering, returns to the shaft seal. Design function. |
| [09] | 1-257VP-021RF-259VP-27-088VP-003RF-16-003PO-17-18-050VP-19 | Excessive drain water from the primary circuit returns to the primary circuit system. Non-design features. |
| [10] | 2-003VP-001EX-010VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-030VP-14-002BA-033VP-15-16-003PO-17-18-19 | After passing through the lowering circuit for temperature and pressure reduction, the lowering water flow enters the purification circuit and is stored in the volume control box. When necessary, it is pressurized by the upper charge pump and returned to the first circuit. Design function. |
| [11] | 2-003VP-001EX-010VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-030VP-14-002BA-033VP-15-16-003PO-17-18-227VP-20 | After the cooling water flows down through the cooling circuit, it enters the purification circuit and is stored in the volume control box. When the main pump is powered off or malfunctions, the valve is manually opened to perform auxiliary spraying. Design function. |
| [12] | 2-003VP-001EX-010VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-030VP-14-002BA-033VP-15-16-003PO-17-22-23 | After cooling and depressurization, the discharged water goes to the safety injection system. Non-design function. |
| [13] | 2-003VP-001EX-010VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-030VP-14-002BA-033VP-15-21-001PO-24-073VP-25 | After cooling and depressurization, the discharged water goes to the main pump shaft seal. Non-design function. |
| [14] | 2-003VP-001EX-010VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-12 | After cooling and depressurization, the discharged water goes to the residual heat removal system. Non-design function. |
| [15] | 3-310VP-6-002RF-017VP-001DE-7-03DE-8-026VP-002FI-10-11-12 | When the reactor refueling or repair cold stop, the residual heat removal system returns directly after discharged residual heat removal circuit flows purification process. Design function. |
| [16] | 3-310VP-6-002RF-017VP-10-11-12 | The residual heat removal lower discharge flow is directly returned to the residual heat removal system without processed by purification circuit. Non-design features. |
| [17] | 4-154VP-14-002BA-033VP-15-16-003PO-17-18-050VP-19 | Primary circuit replenishment. Design function. |
| [18] | 4-154VP-14-002BA-033VP-15-16-003PO-17-18-227VP-20 | Make-up water enters the auxiliary spray of the pressurizer. Non-design features. |
| No. | Path | Path Analysis |
|-----|------|---------------|
| [19] | 5-21-002PO-22-23 | Pump water in the refueling water tank and go to the safety injection system. Non-design features. |
| [20] | 5-21-002PO-22-24-073VP-25 | Pump water in the refueling water tank and go to the main pump shaft seal. Non-design features. |

3.4 Conclusion of Analysis of Sneak Circuit

Through the analysis of the critical path, it can be seen that sneak circuits definitely occur in the chemical and volume control system. The triggering of the potential path of the system is mainly caused by the potential sequence and indication, such as Path [11]. This function is to provide auxiliary spray water through the manual isolation valve 227vp when the main pump is powered off or breaks down or the pressurizer loses the main spray function. Meanwhile, the 050vp isolation valve needs to be closed. The function cannot be implemented successfully without exact sequence, proper operation and clear indications of valves.

The result owns to the functions chemical and volume control system modules switched by means of a large number of control valves. To achieve this requires that the control switching must ensure the correct and timely operation sequence without any errors in the identification of key valves and in the operation process.

As a result, in order to prevent the occurrence and the triggering of sneak circuit, the possible abnormal flow can be prevented by setting one-way valve between the functional modules; by formulating a strict operation procedures for valve control and strict personnel operation in accordance with the operation flow instructions; by adding clear operation instructions to the control of key valve of the system. By doing so, the safety and reliability of the system can be guaranteed.

4. Conclusion

The system safety and reliability call for stringent specification due to the complexity of nuclear power plant system and high degree of automation control. As an effective analysis method, sneak circuit analysis technology can be used to identify all potential paths of large and complex systems. Thus, it is a very important part of safety, reliability and quality assurance. With the continuous advancement of nuclear power plant localization process, the mode in China has changed from thorough technology introduction to independent development. It is of great significance and economic value to improve the security and reliability of system design through the employment of analysis technology of sneak circuit.

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