Research on Control Strategy of Nuclear Island Ventilation Systems in Nuclear Power Plant

Zhou Xiao[1,2](✉), Heng Li[1,2], Li-Ming Zhang[1,2], Xin Du[1,2], and Hua-Qing Peng[1,2]

[1] State Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment, China Nuclear Power Engineering Company Ltd., Shenzhen 518172, China
xiaozhou@cgnpc.com.cn

[2] I&C Department, China Nuclear Power Engineering Company Ltd., Shenzhen 518172, China

Abstract. This paper explains the overall control strategy of nuclear island ventilation system in CPR1000 NPP (Nuclear Power Plant), and expounds the current situation of nuclear island ventilation system. It analyzes the problems to be solved and challenges to be faced. Based on the market products, this paper puts forward the new control strategy and idea. It is necessary to develop nuclear safety-class electrical heater power regulation control cabinet used for local temperature regulation control, and local control cabinet based on simple hardware or an integrated safety-class electrical heater with self-control. The safety-class local power regulation control cabinet and on-off local control cabinet were developed successfully in this study, but there are not products on the safety-class integrated electrical heater with self-control in market, which shall be developed in the future. Then, propose a control logic architecture, and introduce the control logic design idea how to implement from the equipment level to the plant level. At present, in new construction NPPs, nuclear island ventilation systems have basically realized the "system level" control level and completely realized the "sub-function level" control according to this study. Subsequently, the "system-level" and "plant-level" relationship can be sorted out to further realize "plant-level" control. More intelligent ventilation and air conditioning algorithms may be also introduced to improve the overall control level of nuclear island ventilation system in NPP.

Keywords: Nuclear Power Plant · Nuclear Island ventilation system · Control strategy

1 Introduction

Nuclear Island ventilation systems in NPPs are auxiliary systems, and have two functions, (i) Maintaining ambient conditions in the plant unit buildings that enable personal access and normal equipment operation to be ensured. (ii) Monitoring and limiting controlled air releases under normal operation or accident conditions [1]. Compared with other industries and non-radioactive factory buildings, the nuclear island ventilation system has its own uniqueness and needs to meet the functions of Nuclear Power Plant's radioactive tolerance and personnel residence [2].

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The main control functions of nuclear island ventilation systems are shown in Fig. 1. Actuators and instruments of nuclear island ventilation systems are distributed to corresponding control platforms to implement control. Some equipment is controlled in Local control cabinet, and some is controlled in DCS (Digital Control System) control platform.

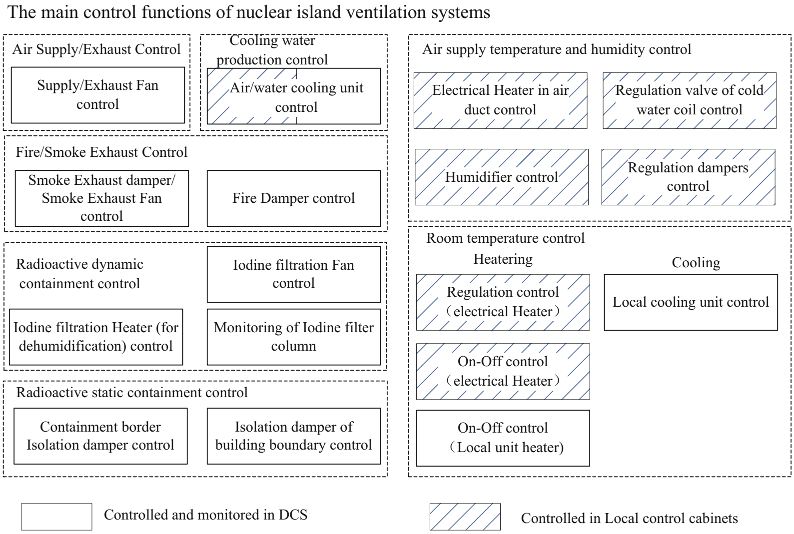


Fig. 1. Main control functions of nuclear Island ventilation systems

There are lots of equipment controlled in non-safety classification local control cabinets in CPR1000 NPPs. The logical and analog control system in local control cabinets is configured with relay units according to the control requirements, or DDC (Direct Digital Control) controller or PLC Controller is configured to implement programming control [3]. The fault status of the local control cabinet is sent to DCS. Local control cabinet adopts standardized design according to different actuators and control targets, and is divided into five standard control modes, each mode corresponding to a standardized control cabinet, as shown in Table 1. During the design, it can also be matched according to different requirements. For example, if the two functional combinations of regulation controlling of cooling and start-stopping electrical heater need to be combined, it can be realized by combining Mode B and Mode D circuits into a cabinet.

In recent years, the requirements of ventilation system design and equipment specifications have been gradually improved according to latest standards and designs. The safety classification principle of the Nuclear Island ventilation system of CPR1000 NPPs mainly followed RCC-P "Design and Construction Rules for the system design of 900 MWe Pressurized Water Reactor Nuclear Power Plant", but follow to IAEA SSG-30 in new construction NPPs today; therefore, the classification of some local control cabinets shall be raised from non-safety classification to safety classification. How to give consideration to safety and construction cost will become a research topic.

Table 1. Standard control mode table for local control in CPR1000 NPPs

No.	Standard mode	Control function	Actuator	Classification
1	Mode A	Constant temperature and humidity regulation control	Electrical heater, Regulating water valve of cooling coil, Humidifier	NC+[a]/NC
2	Mode B	Cooling (regulation control)	Cooling coil water valve regulation control	NC+[a]/NC
3	Mode C	Heating (regulation control)	Electrical heater and power regulator	NC+[a]/NC
4	Mode D	Heating (on-off control according to temperature)	Electrical heater	NC+[a]/NC
5	Mode E	Temperature regulation control (with air regulation dampers)	Electric Heater, Regulating water valve of cooling coil, air regulation dampers	NC+[a]/NC

Note a: compared with NC classification equipment, NC+ adds seismic or special environment requirements.

In order to facilitate central monitoring and management, the most of equipment is controlled by DCS. Operators can remotely control the equipment in main control room. The logical design of CPR1000 NPPs mainly implements the some “sub-functional levels” control, but not implement the “system levels” control. Nuclear island ventilation systems still have some equipment that operated be operator through the button one by one. So the control algorithm of nuclear island ventilation control system is simple and the level of automation is low in CPR1000 NPPs. With the development of the times and the automation technology, it is necessary to improve the level of control.

This paper analyzes and explains the overall control strategy of nuclear island ventilation system in Nuclear Power Plant, and expounds the current situation of nuclear island ventilation system. It analyzes the problems to be solved and challenges to be faced during the implementation process. Finally, this paper puts forward a control strategy and reference idea of nuclear island ventilation system.

2 Analyses of Industry Development and Challenges

2.1 Safety Classification Requirements Changes and Challenges

Safety classification in CPR1000 NPP is mainly determined according to RCC-P. China’s safety classification standards mainly refer to foreign standards and design concepts. As a widely used and instructive system, used in many countries, IAEA SSG-30 provides a complete set of procedures and methods for confirm the safety classification of items from safety functions. It is a set of methods based on determinism. probability theory is used as a supplementary method [4]. The whole method has strong logicality. As the third generation Nuclear Power Plant built in recent years, the French third generation European PWR (EPR) has determined its safety classification based on the European

Nuclear Power User Requirements Document (EUR). The safety classification method of EPR and the safety classification concept in EUR are similar to IAEA SSG-30. Analysis of IAEA SSG-30 standard analysis method and EPR case is helpful to identify the challenges to ventilation system caused by changes in safety classification requirements.

IAEA SSG-30 defines 3 kinds safety categories, namely, Safety category 1, Safety category 2, and Safety category 3. The classification description is summarized in Table 2.

Table 2. Relationship between functions credited in the analysis of postulated initiating events and safety categories [5]

Functions credited in the safety assessment	Severity of the consequences if the function is not performed		
	High	Medium	Low
Functions to reach a controlled state after anticipated operational occurrences	Safety category 1	Safety category 2	Safety category 3
Functions to reach a controlled state after design basis accidents	Safety category 1	Safety category 2	Safety category 3
Functions to reach and maintain a safe state	Safety category 2	Safety category 3	Safety category 3
Functions for the migration of consequences of design extension conditions	Safety category 2 or 3	Not categorized[b]	Not categorized[b]

Note b: Medium or low severity consequences are not expected to occur in the event of non-response of a dedicated function for the mitigation of design extension conditions.

Combined with the examples of CPR1000 and EPR, it is found that there are some similarities and many differences in safety classification between CPR1000 and EPR NPP. The differences are mainly reflected in design conditions, safety function classification, design and manufacturing specification classification of pressure-bearing mechanical equipment, and classification of equipment used to alleviate design expansion conditions.

Difference in Design Conditions

For CPR1000 and EPR NPP, operational condition analysis is an important input for safety classification, but there are great differences in working condition list range and safety analysis between CPR1000 and EPR NPP, which will inevitably lead to different classification results [6].

Operational Condition List: EPR NPP is more comprehensive than CPR1000 NPP in considering operational conditions, and also considers accident conditions, severe accident under shutdown [6].

Safety Analysis: CPR1000 NPP only analyzes a controllable and stable state, but does not analyze a state that can stably dissipate nuclear core heat for a long time. EPR NPP analyzed the safe shutdown state of sustainable heat dissipation [6].

Difference in Safety Function Classification

The safety function classification of CPR1000 NPP can be directly determined according to the definition of RCC-P. EPR NPP put forward the concept of safety function classification, and determine safety function classification as foundation to determine the item classification, making EPR NPP's safety function classification method more logical. Safety Function classification follows the design requirements of EUR and is divided into F1A, F1B and F2 functions. The actual system or part of the system is a combination of mechanical and electrical components used to perform at least one function. For a system or equipment, multiple functions are likely to be performed. Therefore, the actual system classification in the project is to determine which classification each part of the system and equipment is [7].

Judging from the development rules and changes from CPR1000 to EPR NPP, the safety classification method is gradually refined, more comprehensive accident evaluation under all operational conditions, and more detailed safety classification method guides system design. Different safety classification methods lead to determine different safety classification, as shown in Table 3.

Combined with Table 3, it can be seen that changes in safety classification and NPP's system design have led to higher classification of air supply temperature control and room temperature control. It will mainly affect: (i) Level 1 control cabinet requirements to be raised to safety category 2, and the equipment shall follow the corresponding software and hardware design specifications. Combined with the current product situation, it will affect the current control strategy. (ii) Level 0 actuators and instruments shall meet the relevant safety classification requirements.

2.2 Automatic and Control Level Requirement Change and Challenge

The automatic and control level of CPR1000 NPP ventilation system is at the control level of some "sub-functional levels". Due to reduce the burden of operators, and operator have more energy to operate other important equipment and handle more important events, a higher level of automation in the new generation NPP shall be required. Therefore, new requirements are put forward for the control design of nuclear island ventilation system, and it is expected that at least part of the "system level" control level can be realized and the "sub-function level" control can be fully realized. See Fig. 2.

Table 3. Comparison table of safety classification of ventilation system equipment

No.	Functions	Actuator	Monitoring and control mode	Control platform	Safety classification CPR1000	Safety classification (IAEA SSG-30)	Difference of safety classification
1	Air Supply/Exhaust control	Supply/Exhaust fan	Start-stop control	DCS	1E/SR/NC	1/2/3/NC	None
2	Cooling water production control	Air/water cooling unit	Start-stop and regulation control	Local control unit + DCS	1E/SR/NC	1/2/3/NC	None
3	Fire/Smoke exhaust control	Fire damper	On-off control	DCS	NC+	2/3	The classification of equipment is determined according to different start-stop functions, and some fire dampers perform Safety category2 function [8]
		Smoke Exhaust damper/Smoke Exhaust fan	Start-stop control	DCS	NC	3/NC	Some equipment are upgraded to Safety category 3

(*continued*)

Table 3. (*continued*)

No.	Functions	Actuator	Monitoring and control mode	Control platform	Safety classification CPR1000	Safety classification (IAEA SSG-30)	Difference of safety classification
4	Radioactive dynamic containment control	Iodine filtration heater (for dehumidification)	Start-stop control	DCS	SR	2	None
		Iodine filtration Fan	Start-stop control	DCS	SR	2	None
		Iodine filter column	On-site differential pressure monitoring (for inspection and maintenance, filter replacement)	None	NC+	3	None
5	Radioactive static containment control	Containment border Isolation damper	On-off control	DCS	1E	1	None
		Isolation damper of building boundary	On-off control	DCS	SR/NC+	2/3	None
6	Air supply temperature and humidity control	Electrical Heater in air duct	Start-stop control	Local control cabinet	NC+/NC	2/NC	The classification requirements of some equipment have been improved

(*continued*)

Table 3. (*continued*)

No.	Functions	Actuator	Monitoring and control mode	Control platform	Safety classification CPR1000	Safety classification (IAEA SSG-30)	Difference of safety classification
			Power regulation control		NC+/NC	2/NC	
		Regulation valve of cold water coil	Regulation control	Local control cabinet	NC+/NC	2/NC	
		Regulation damper	Regulation control	Local control cabinet	NC+/NC	2/NC	
		Humidifier	Start-stop and regulation control	Local control cabinet	NC+/NC	3/NC	None
7	Room temperature control	Local electrical Heater	Start-stop control	Local control cabinet	NC+/NC	2/NC	The classification requirements of some equipment have been improved
			Power regulation		NC+/NC	2/NC	
		Local unit heater (with fan)	Start-stop control	DCS	NC+/NC	2/NC	
		Local cooling unit	Start-stop control	DCS	1E/SR/NC	1/2/3/NC	None

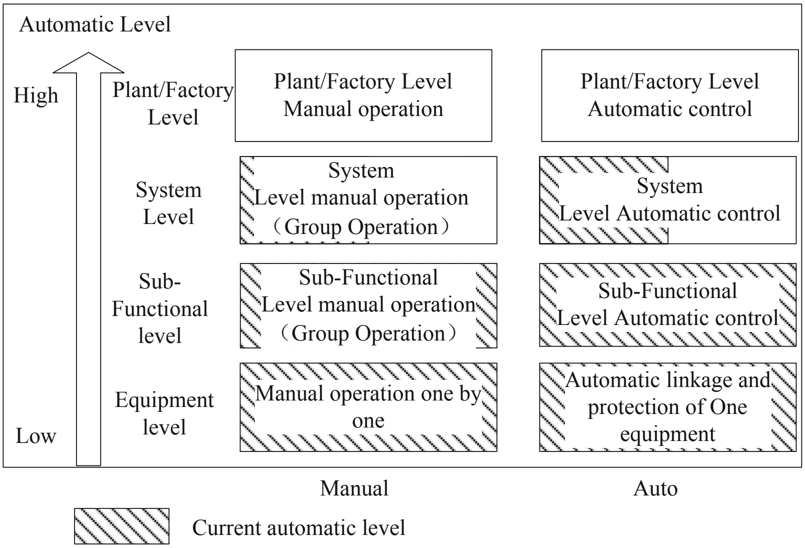


Fig. 2. Desired automatic and control level

3 Control Strategy and Development Ideas of Nuclear Island Ventilation Systems

Based on challenges faced by nuclear island ventilation system, the following solutions or ideas are put forward for reference.

3.1 Control Strategy Face to the Challenge of Safety Classification

The safety classification of air supply temperature and humidity regulation control and room temperature control is improved to category 2 has great influence on the control strategy. At present, there are few safety classification controllers with mature application experience, mainly DCS products or some customized control components. Therefore, the control strategy is proposed for the following two conditions.

Regulation Control
The actuators and instruments of Level 0 select safety-level equipment. Combined with the current market situation, an optimization scheme type 1 is proposed for the equipment upgraded to safety-level, as shown in Fig. 3.

(i) The regulating water valves/air dampers are changed from intelligent type to non-intelligent type, and the safety-class electric regulation valves/air dampers are selected, and the valves/dampers needs to be controlled by the safety-class switchgear.
(ii) Safety-class local power control cabinet needs to be developed. The cabinet mainly includes power regulators. At present, there are few power regulators that have

passed safety-class certification on the market and need to be customized for development.

(iii) The control and regulation control of electrical heater and valves are implemented by safety-class DCS. It solves the selection problem of safety-class local control cabinet, and operators in MCR (Main Control Room) can obtain more information and monitor remotely more equipment.

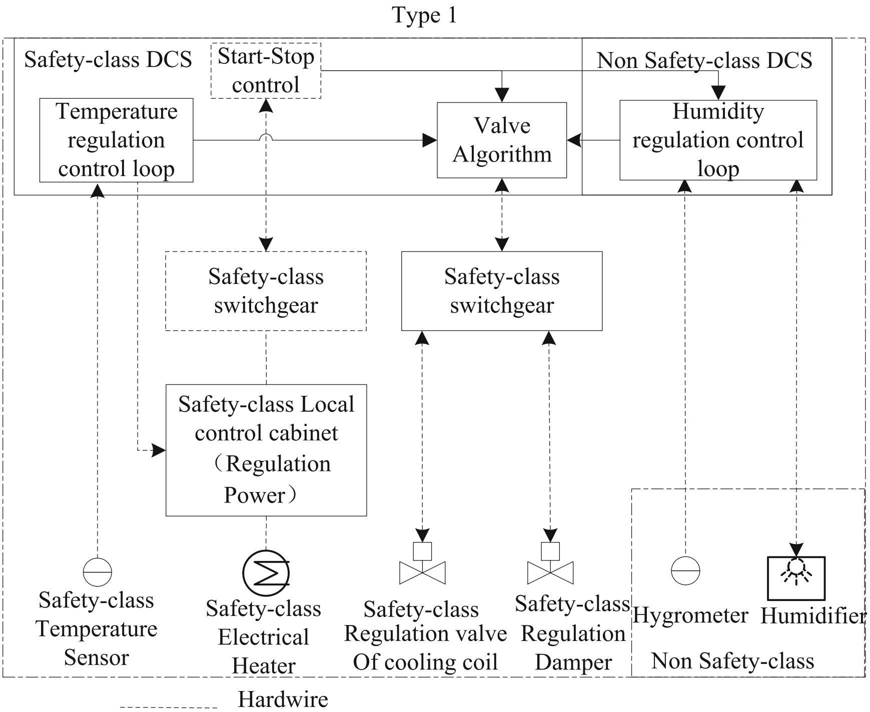


Fig. 3. Type 1 control strategy diagram

On-Off Control

For the safety classification of some on-off control electrical Heaters are improved, two design control strategies are proposed for reference for this part of equipment, as shown in Fig. 4.

Type 2a: Design and manufacture safety-class control cabinet based on simple Hardware or safety-class relay unit to implement control. Heater and local control cabinet belong to independent and different equipment.

Type 2b: Develop and manufacture safety-class integrated electrical heater with temperature switcher and control circuit. type 4b may be cheaper than type 4a, but there are not safety-class products on the market at present, which can be developed according to the actual needs of the project.

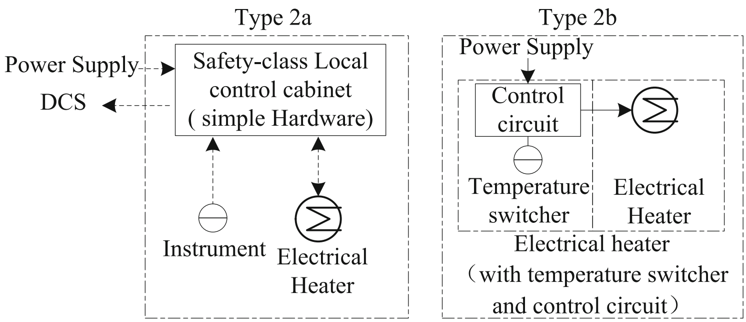


Fig. 4. Type 2a and type 2b local control strategy diagram

3.2 Ideas for Improving the Automation Level

According to the operation and maintenance requirements of NPP, the automation level of the NPP will be improved. The "system level" control level will be realized, and the "sub-function level" control will be fully realized. The following methods can be adopted to improve the control level. See Fig. 5 for the control block diagram.

(i) Sorting out the equipment-level control logic to form their own component control Logic.
(ii) Sorting out the sub-function control requirements, then forming each sub-function control logic and forming a sub-function group control algorithm. The control algorithm of the sub-function is connected to the corresponding equipment-level control logic.
(iii) Sorting out the relationship between each sub-function and system operation, and designing system-level logic based on operating conditions.
(iv) According to the functions performed by each system in plant and the operation requirements of plant, group or sequential control logic of the plant/factory level is designed and connected to group control of the system level to control each system.

4 Implementation Results

Facing the problem of upgrading the safety of the local control cabinet, we newly developed safety-class local power control cabinet (Regulation Power) for type 1 control Strategy. See Fig. 6. This control cabinet can supply power to the heater and adjust the power supply, and can receive external 4–20 mA regulation commands and output the

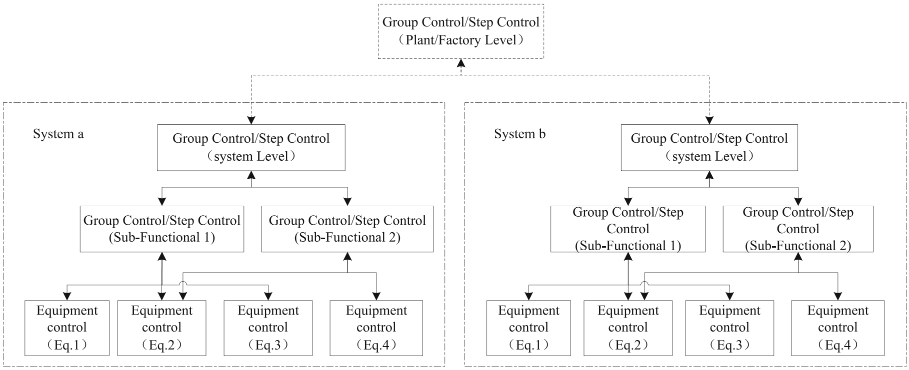
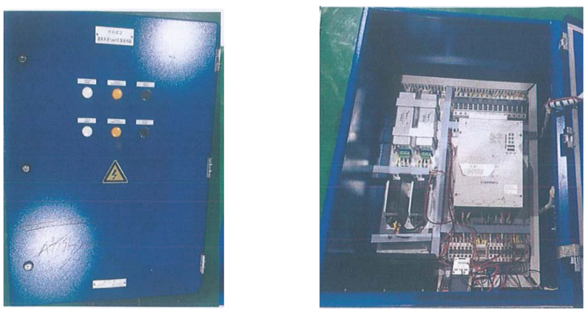


Fig. 5. System-level and plant-level automation control block diagram

fault status of control cabinet. This control cabinet has passed the safety-class equipment qualification tests and meets the K3 equipment qualification requirements of RCC-E. In order to implement the type 2 control strategy, a nuclear-level local control cabinet that meets the type 2a control strategy was newly developed, has passed K3 qualification tests, and adopts a relay circuit to achieve on/off control. The above two types of equipment have been promoted in new construction nuclear power plants. See Fig. 7.

The type 2b solution is more integrated than type 2a. If implemented, the number of equipment will be further reduced, but safety-class electric heaters with controllers need to be further developed, which is currently not implemented in the project.



(a) Front (b) Internal

Fig. 6. Diagram of type 1 local power control cabinet

In the new construction nuclear power plant, the system-level and sub-function level group control of the nuclear island ventilation system are designed. The example is shown in Fig. 8. The operator can realize the system-level and sub-functional level control through the group buttons, and realize equipment-level equipment individual or group management through the group mode button. After adopting the method of improving the automation level, the operator's operation and control level is ultimately greatly improved.

(a) Front (b) Internal

Fig. 7. Diagram of type 2a local control cabinet

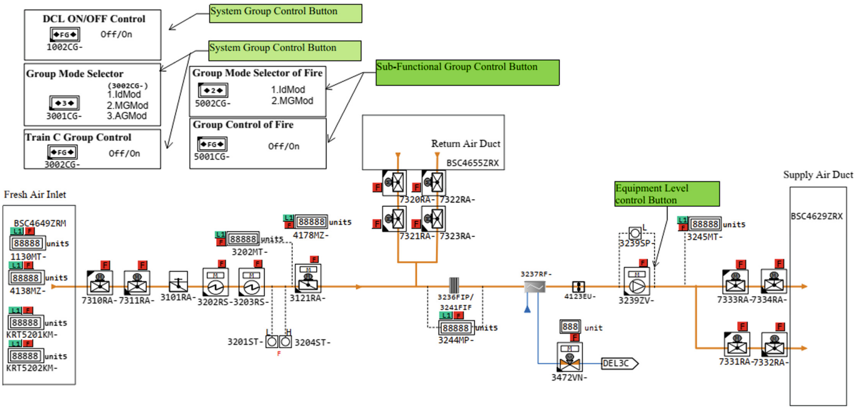


Fig. 8. The example of system group control

5 Conclusion

This paper expounds the current design of nuclear island ventilation system. The safety and automation level of ventilation system have higher requirements with the development of the industry. and new requirements and challenges are faced.

Facing the challenges of safety classification enhancement, it is necessary to develop nuclear safety-class electrical heater power regulation control cabinet used for local temperature regulation control, and local control cabinet based on simple hardware or an integrated safety-class electrical heater with self-control. The safety-class local control cabinet of type 1 and type 2a were developed successfully in this study and used in new construction NPPs, but there are not safety-class products of type 2b in market, which can be developed in the future. The products of type 2b can be widely applied to northern NPP, which may reduce the project implementation cost.

Facing the challenges of automation level improvement, propose a control logic architecture, and introduce the control logic design idea how to implement from the equipment level to the plant level. At present, in the new construction NPPs, nuclear island ventilation systems have basically realized the "system level" control level and completely realized the "sub-function level" control according to this study. Subsequently, the "system-level" and "plant-level" relationship can be sorted out to further realize "plant-level" control. More intelligent ventilation and air conditioning algorithms may be also introduced to improve the overall control level of nuclear island ventilation system in NPP.

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