DCS Modification Design for I&C System of Nuclear Power Plants

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Abstract: Taking the DCS modification project of I&C system in the nuclear power plant as an example, this paper introduces a solution to replace the traditional I&C system with DCS (or digitization technology) from the aspects of function optimization, power supply design, I/O channels design, HMI, cabinet layout, etc. The modified I&C system retains all the functions of the original system, and greatly improves the reliability, interactivity, scalability and convenience in maintenance of the system.

1. Introduction
In recent years, the DCS technology is applied in all nuclear power plants around the world. However, the analog circuits, relay logic and partly PLC system are still serving in the early-built plants. With the development of industrial control technology, DCS is successfully applied in many power plants and shows excellent performance in the field of instrumentation and control (I&C). Correspondingly, one of the early-built nuclear power plants has to face the following problems: the insufficiency of I&C system spare parts, complex system structure, difficulty in maintenance and high failure rates. Therefore, the upgrading modification of I&C system for the power plant is imperative. In this paper, the modification of the I&C system in KRG202AR BAY1/BAY2 is taken as example to analyze and discuss the design of the I&C system in NPPs (nuclear power plants). The performance of the modified I&C system validates the reliability and feasibility of the newly designed DCS, and thus we can draw a conclusion that DCS technology is able to substitute traditional I&C systems in NPPs.

Note: In the following passages in this paper, several exclusive concepts in nuclear power industry will be used. They are described below:

KRG202AR: a set of I&C cabinets combination consists of 7 sub-cabinets, in which BAY1 and BAY2 are modified to DCS. Similarly, KRG200AR stands for another I&C cabinet.

GST/GRV/GPV/GSS/CI/APP/PA/GRE: the names of flowing or processing systems in NPPs, which are related to the modified control system, KRG202AR.

KRG: an I&C system in NPPs.
GST027VN: an electric valve controlled by KRG202AR.
KRG732XR: a relay in KRG202AR to select the main controller of GST027VN.
KRG7**US: signal acquisition or conditioning card in I&C cabinets.
LMC: an AC power supply system in a nuclear power plant.
LCA: a DC power supply system in a nuclear power plant.

2. Problem Analyzing
KRG202AR of the nuclear power plant is a series of signal acquisition, processing and controlling
cabinets based on the early GEM80 PLC system. This type of PLC is an old product which is traced back to 1970s, and it is widely used in KRG cabinets or systems in the power plant. The cabinet integrates the power modules of GEM80 PLC, RAM cards, ladder program processing cards, I/O processing cards, analog input/output cards, logic input/output cards, etc.

KRG202AR includes 7 cabinets, BAY1~BAY7. The main functions of BAY1 and BAY2 includes: acquire the operating parameters of GST/GRV/GPV/GSS/CVI/APP/APA systems, processing the internal signals, and realizing the turbine trip protection, load shedding protection, GST027VN control and other functions. After 20 years of operation, the aging of the GEM80 PLC system is quite serious. The operation status of the cards and the number of spare parts can not support the continuous normal operation of the whole system, especially the analog cards have no spare parts and can not be purchased from the original manufacturer. Therefore, it is urgent to modify this early installed I&C system in the nuclear power plant.

3. Design and Analysis of the Modification Scheme
The DCS modification for the old I&C system is quite different from the DCS design for the new power plants. DCS modification of traditional I&C systems should be subjected to more constraints, and DCS technology should be introduced to realize the system functions on condition that the current functions are not affected. Before design, it’s necessary to clarify the scope of modification, lay out the signal interfaces of the original system in the design phase. In addition, the modification process will be limited by the existing technical conditions. At the same time, the DCS modification of the old system is usually a gradual process, the interface requirements of subsequent modification should be considered for the modified DCS.

Based on the above analysis, as to the DCS modification of KRG202AR BAY1/BAY2, the DCS software and hardware system are only considered to replace the signal acquisition, processing, logical operation and signal output functions of the original system, while the signal input and output outside the cabinet remain unchanged, and the protection control logic of the associated processing systems will also remain unchanged. This design principle should also be taken into consideration in the overall DCS modification program of the nuclear power plant.

At present, the NC-DCS (non-safety DCS) platform Hollias-MACS6, offered by China Tech-energy Company (CTEC), has been applied in several CPR1000 NPPs. With the maturity in technology, the MACS6 platform is able to maintain technical coherence and consistency in the NC-DCS modification in the nuclear power plant. Therefore, the MACS6 platform from CTEC can be applied to the NC-DCS modification in the NPP, and firstly applied in the KRG202AR BAY1/BAY2 modification project.

3.1 System Frame Design
The system frame of KRG202AR BAY1/BAY2 before modification is shown in Figure 1:
Figure 1. The system frame before modification

The system frame after modification is shown in Figure 2. The external interface should be consistent with the original system to meet the functional requirements of the original system. The operation parameters of the processing systems are acquired for internal signal processing to generate turbine trip protection, load shedding protection, unavailability of CVI condenser, GST027VN control and other signals.

Based on the functions of the original system and the characteristics of DCS, the redundancy
structure of a single cabinet with double CPUs can be adopted in the new system, so as to improve the redundancy of CPU and reliability of the control system.

3.2 Power Supply Design

The power supply network of KRG202AR BAY1/BAY2 before modification is shown in Figure 3, including the following parts:

- **GEM80 PLC power supply**: including two ways, one is the LMC 220VAC (alternating power supply), the other one is the 24VDC converted from LCA 48VDC to feed the PLC and field instruments;

- **Inquiry power supply**: directly provided by the 48VDC system.

Schematic diagram of system power supply network before modification is shown below:

![Figure 3. Power Supply Network before modification](image)

The power supply of KRG202AR BAY1/BAY2 after modification is shown in Figure 4, including the following parts:

- **DCS power supply**: it includes two ways, one is converted from 220VAC to 24VDC, the other one is converted from 48VDC to 24VDC. After safety isolation, the two ways will supply power to DCS and field instruments together.

- **Inquiry power supply**: 48VDC offered by LCA system provides inquiry power supply directly.

![Figure 4. Power supply network after modification](image)
Comparing the original power supply network with the modified one, the power voltage of DCS is much lower than the original one. The working voltage is reduced from 220V AC to 24VDC. So it improves the safety and convenience for inspection and maintenance in the future. Furthermore, the power consumption of the new system is lower than the original one. The comparison of the power load between the two systems is shown in Table 1. Thus the whole power load of the conventional island in NPPs will be reduced when the DCS modification program accomplished. Simultaneously it will improve the reliability of the power supply system due to the characteristics of the DCS hardware.

| Power Type | Load of original system | Load of new system          |
|------------|-------------------------|----------------------------|
| 220VAC     | 250W                    | 120W+80W (Screen)          |
| 48VDC      | 150W                    | 120W                       |

### 3.3 AI Channel Design

As to KRG202AR BAY1/BAY2, there are four types of analog voltage signals from the field respectively sent to two AI acquisition units. Now the voltage signals are converted into standard current signals by the isolation and converting cards, and then acquired to DCS by the acquisition unit NM482+NM3480. Meanwhile the field standard current signals are directly acquired to DCS by NM482+NM3480 unit. The scheme of isolating and converting voltage signals and then input to DCS acquisition cards can avoid adding voltage signal acquisition cards in the cabinet, so it’s able to get high redundancy for current signal acquisition channels in the limited cabinet space. This design idea can not only ensure realizing the original functions, but also save the cabinet space on premise of improving the redundancy of acquisition points. At the same time, the signal acquisition channels via the voltage stabilizing diodes of the original system are changed to a mature technology, isolation card acquisition, which effectively improve the reliability and stability of the equipment.

In the process of upgrading the I&C systems in the early-built nuclear power plants, one of the constraints for the traditional I&C systems to carry out DCS modification is to ensure that the system functions meet the original requirements, and the performance is not lower than the original systems under the condition of limited site space. The modification solution of AI channels of KRG202AR BAY1/BAY2 shall achieve the modification goals under these constraints. This design idea can be referred to for the subsequent DCS modification of the whole I&C systems in nuclear power plants. Using DCS technology to solve these problems can also present the advantages of DCS technology.

According to the characteristics of each AI channel of the original systems, 4 AI acquisition methods are designed for KRG202AR modification:

1) One-in-one-out type for voltage signal isolation card. In the original system, one sensor signal is transformed to two voltage signals in parallel by the conditioning card. After the modification, a voltage signal isolation card is added to convert the voltage signal to current signal and sent to BAY1/BAY2 respectively. Taking the GST001MP as an example, the structure of acquisition channel before modification is shown in Figure 5:
After the modification, the circuit between the transmitter and the conditioning card remains unchanged, just connect the voltage signal isolation card to the output end of the conditioning card, and convert the signal into 4~20mA current signal, which is sent to the NM482+NM3480 acquisition units in BAY1/BAY2. This type of AI acquisition mode is shown in Figure 6:

With this solution, the voltage signal acquisition units are avoided, and the space saved can be used to install the current acquisition units, which perfectly improves the redundancy of AI points.

2) One-in-two-out type for current signal isolation card (sent to KRG and GRE cabinet respectively). In the current signal circuit of the original system, two voltage stabilizing diodes are connected in series. One diode is connected to GRE001AR at both ends; and the other one is connected to KRG202AR BAY1 at both ends, which is acquired by the current signal acquisition card. Taking GPV003MP as an example, the acquisition channel before modification is shown in Figure 7:

For this kind of signal transmission channel, the voltage stabilizing diodes can be removed, and the
original signal is sent to the current signal isolation card, and the isolation card supplies power to the transmitter. At the same time, two current signals are output, one to GRE001AR, and the other one to NM482+NM3480 acquisition unit in KRG202AR BAY1. The architecture of the modified signal channel is shown in Figure 8:

Figure 8. Typical diagram of current signal in one-in-two-out signal acquisition channel (to GRE)

In the new acquisition channel shown above, the isolation card uses 24VDC from the cabinet as power supply, and the two-wire connection method is used between the isolation card and the sensor to acquire the current signal while supplying power to the sensor. With this solution, the signal acquisition circuit of KRG/GRE cabinet is changed from the original one to a relatively independent one, which can avoid the failure of the whole circuit caused by one single equipment failure. At the same time, the stability of the isolation card with mature technology is better than that of the diodes, which can avoid the channel abnormality caused by transient current, diode temperature drift and breakdown, finally significantly improves the reliability of the system.

3) One-in-two-out type for the current signal isolation card (the original circuit with conditioning card in series). In the original GPV004/006MP signal acquisition circuit, a conditioning card and a voltage stabilizing diode are connected in series. On the one hand, the conditioning card sends the acquired signals to GPV001/002EU (display units) and KKO001AR (an I&C cabinet). On the other hand, the two ends of the diode are connected to the current signal acquisition card of KRG202AR BAY2. Taking GPV004MP as an example, the signal acquisition channel before modification is shown in Figure 9:

Figure 9. Diagram of the original GPV004MP acquisition channel

For this kind of signal transmission channel, the current signal isolation card is considered to be used for signal acquisition. At the same time, the signal is divided into two channels, one sent to the conditioning card in KRG200AR, the other one sent to NM482+NM3480 signal acquisition unit in KRG202AR BAY2. The modified signal channel is shown in Figure 10.
Figure 10. Schematic diagram of current signal in one-in-two-out acquisition channel

Similar to the previous scheme, the signal is shunted by the isolation card to realize the independence of different acquisition cabinets, which can effectively avoid the failure of the whole circuit caused by the single device failure.

4) The current signal directly acquired type. In the original system, this kind of signal is directly acquired by the current signal acquisition card (KRG740US) in KRG202AR. In the new DCS system, NM482+NM3480 unit is also used to acquire the signal directly, and NM3480 terminal module supplies power to the transmitter. This acquisition method is widely used in NC-DCS. Taking GPV005MP as an example, the signal channel before modification is shown in Figure 11:

Figure 11. Schematic diagram of original GPV005MP signal acquisition channel

The sensor's power supply will be changed to the terminals of NM3480 module, as shown in Figure 12.

Figure 12. Schematic diagram of current signal direct acquisition channel

Due to the fact that the current limitation of NM3480 module is 30mA, lower than 150mA of the
original fuse, the channel abnormality caused by over transient current in the circuit can be effectively avoided. In nuclear power plants, it is quite common for analog signals to be directly acquired by the acquisition cards. When we upgrade the original system to DCS, there are plenty of products to choose. However, the current limitation protection, voltage level and other parameters of DCS acquisition cards should be considered in the design stage and applying process.

### 3.4 AO Channel Design

Analog signal output is also an important and widely used function in I&C system of nuclear power plants, which is used to transfer control signals, or used as display signal source, etc. When designing the DCS modification for analog output channels, the signal formats, loading capacity and adaptability of AO cards in DCS system should be considered. AO channel in KRG202AR BAY1/BAY2 is only used to control the valve GST027VN. In the new system, the AO signal is output by NM510+NM3510. The AO unit can output current signal in the range of 0~20mA, and the maximum loading impedance is 750Ω. Considering the maximum loading impedance of the current output channel of the original AO card is 500Ω, the driving ability of the new card is better than that of the original card.

### 3.5 DI Channel Design

When designing the DI channels, designers need to consider whether the field signal is active or not, and select the proper DCS acquisition modules and wiring methods according to the characteristics of the signals. The DI signals of process system acquired by KRG202AR BAY1/BAY2 are all dry contact signals of 48VDC. When designing the new DCS system, NM622A+NM3610 unit is used, and the An/Bn terminals of NM3610 module are used to connect the signal wires. The acquisition module only plays the role of on-off switch of signals, supporting the connection method of common negative wiring, and provides the inquiry voltage by LCA 48VDC. The acquisition mode is similar to the original system.

The DI signal interface after modification is shown in Figure 13.

![Figure 13. Schematic diagram of DI signal interface of New System](image_url)

Since the new DI card has optic-electric isolator and fuse, the new DI channel can effectively improve the safety and reliability of equipment under abnormal status.

### 3.6 DO Channel Design

In nuclear power plants, DO channels are usually used to send out control, alarm or other signals. When DCS technology is expected to realize the original DO functions, it is necessary to consider the output characteristics of the channel, such as whether it is active, voltage level, current limitation, and whether the loading capacity meets the requirements of the original system. NM710+NM3715 unit is used to output logical signals in the modification. NM3715 is a 16-channel tiny mechanical relay output terminal module, and its relay output terminal capacity is 250mA/48VDC (the relay contact can bear 2A current at most, while the output current is limited to 250mA).

The schematic diagram of DO signal interface circuit is shown in Figure 14:
Figure 14. Schematic diagram of DO signal interface circuit of new system

Compared with the old system, the reliability of the device is greatly improved (the original card has no optic-electric isolation module nor output terminal fuse). Considered that the output relay capacity of NM3715 module is limited, an isolation relay needs to be added when driving a high load, and different specifications of isolation relays need to be selected according to different loads.

3.7 HMI Design
The early human-machine interface (HMI) of I&C systems in NPPs usually has simple functions and limited information capacity, while the HMI based on DCS technology can significantly improve its performance. In KRG202AR, a small LCD is used as the HMI, and the information displayed is quite limited. After the modification, a 19-inch touching screen is implemented to the cabinet to display the working status of cabinet hardware, process alarms, important logic actions and other information. Compared with the original LCD, the interface is more friendly and intuitive, with richer contents and convenient operations. In addition, the subsequent maintenance and information tracking will be greatly simplified.

3.8 Design of Cabinet Layout
The layout and installation space of the original I&C cabinet in NPPs is another significant constraint for DCS modification. In design phase, the environmental factors such as field space and original cabinet layout should be fully considered to ensure that the newly designed DCS cabinet can meet the installation requirements on field. If necessary, non-standard equipment may be designed and manufactured according to site requirements. There are cabinets on both sides of KRG202AR BAY1/BAY2, so it is necessary to customize the new cabinets on basis of the original cabinet size to ensure that the two cabinets after modification can be installed on site according to the installation and layout of the original cabinets. At the same time, in order to meet the needs of the internal equipment layout of DCS cabinets, the cages inside the newly designed cabinet shall be also customized, as a result its size and number of card slots are different from the standard rack.

3.9 Logic Functions Optimization Design
Due to the technical distinguish between the old system and DCS, it is necessary to optimize and modify the internal signal processing and control logic of the cabinet, but the protection and control functions of the original system should not be changed.

In the original KRG202AR, the main control unit of GST027VN is equipped with 24-hour automatic switching logic. In view of the dual CPUs redundancy design in two cabinets of the new system, the reliability of the system is high enough, so it is not necessary to switch the main control
unit every 24 hours. At the same time, considering that the CPU load will be increased when the control unit is automatically switched every 24 hours, the new system is allowed to cancel the 24-hour automatic switching logic of GST027VN controller. Instead, the new switching logic based on dual CPUs’ fault signal is designed.

The monitoring of CPU status of the original KRG202AR is realized by WATCHDOG (built-in status monitoring relay in GEM80 PLC), while the new DCS platform has no WATCHDOG module. In order to realize the system state monitoring function, the CPU heartbeat signal is used in design. The working principle of heartbeat signal is as follows: in normal state, CPU of BAY1 generates continuous pulse signal (heartbeat signal), which is sent to BAY2 through a DO point and received by a DI point of BAY2. If the heartbeat signal is continuously sent and received, it means that BAY1 is working normally, and there is no need to switch the main control unit of GST027VN; if the heartbeat signal stops or the voltage level remains constant, it means that the dual CPUs of BAY1 are both in fault. Then BAY2 sends signals to control KRG732XR to switch the main control unit of GST027VN to BAY2. On the contrary, BAY2 also sends heartbeat signal to BAY1 at the same time. Because the heartbeat signal is a continuous pulse, considering the limited life of the mechanical relays in NM3715 module, the output terminal module NM3716 with solid state relays is used to output the heartbeat signal.

The working principle of heartbeat signal in DCS is shown in Figure 15:

![Figure 15. Working principle of heartbeat signal in DCS System](image)

This optimization scheme makes full use of the advantages of high redundancy and reliability of DCS hardware, reducing unnecessary logic actions and CPU loads, improving the reliability of GST027VN control channel, and further improves the safety level of the plant. It is of great significance in nuclear power plants to reasonably optimize the processing and control logic on the basis of the characteristics and advantages of DCS platform during the design of DCS for traditional I&C systems to ensure the system functions and improve the safety and reliability of the systems.

4. Conclusion
The DCS modification of KRG202AR BAY1/BAY2 is based on the existing mature platform and
technology. At the same time, it is the first project of DCS modification program of the whole power plant, which means the pilot significance of demonstration. As far as the nuclear power plant is concerned, DCS modification not only upgrades the hardware and software, but also updates the technical concepts. This improvement changes the original point-to-point acquisition and control mode to the centralized processing and display, distributed acquisition and execution mode with computer as the core. Due to the characteristics of the distributed control mode, the new DCS will greatly simplify the architecture of the field measurement and control systems, and effectively solve the problems of spare parts insufficiency, aging equipment and high failure rates faced by the present system. At the same time, it will bring convenience for outage or daily inspection and maintenance, which is of great significance to improve the safety and economy of the NPP.

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