Study On The Reliability Improvement Of The Control Of The Main Feed Pump In The Second Circuit Of Nuclear Power Plants

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Abstract. There is a safety hazard in the interlock control logic of the second circuit electric main feed pump of the CPR1000 nuclear power unit. When the unit is operating at full power, if the speed of an operating pump suddenly drops below 3950 rpm or if the pump outlet pressure suddenly drops but does not reach the pump trip threshold, the standby pump cannot be automatically interlocked to start. If the standby pump is not started in time, it will cause the unit to overpower the first circuit or even trip the reactor. In this paper, the control strategy of the second circuit electric main feed pump is analysed and demonstrated, and after simulation tests, a feasible improvement plan is proposed, which effectively improves the control reliability of the second circuit electric main feed pump in nuclear power plants.

1. Introduction
The electric main feed pump of the second circuit of the nuclear power plant supplies feed water to the steam generator. The CPR1000 nuclear power unit is equipped with three electric main feed pumps. The unit adopts the operation mode of "two operations and one standby" during normal operation, and the control logic will automatically interlock to start the standby pump when any one of the main feed pumps trips or fails, in order to meet the design requirements of the second circuit water supply function.

During the full power operation of Unit 1 of a nuclear power plant, the No. 1 and No. 3 electric main feed pumps were operating online and the No. 2 electric main feed pump was in hot standby. No. 1 feed pump was abnormal due to the spoon tube control circuit, resulting in a sudden
drop in pump speed from 4500rpm to 760rpm and a drop in pump outlet pressure from 76.4bar.g to 31.3bar.g. However, at this time, No.2 feed pump failed to start automatically. The operator started the No. 2 feed pump in the main control room as a matter of urgency and manually reduced the power of the unit. The lowest steam generator water level during this period had dropped to -1.06m (Reactor Trip Threshold: -1.26m), with a maximum first circuit thermal power of 102.09% Pn. The reason for the sudden drop in speed of feed pump No. 1 was the failure of the spoon tube position sensor, which caused the spoon tube position to drop to 0%, resulting in a sudden reduction in the speed of this pump, while the interlock control logic of the electric feed pump was unreasonably designed and failed to interlock to start the standby pump in time when the operating pump lost its working capacity.

2. Causal analysis

Because the manufacturer of the electric main feed pump originally designed the pump to start after the normal operating speed of a minimum of 3950rpm, so for the feed pump outlet pressure low low interlock start standby pump trigger conditions added to the pump speed must be greater than 3950rpm restriction, the purpose is to characterise the operating pump outlet pressure appears abnormally low. In the event of an abnormality in the speed control circuit as described above, e.g. failure of the spoon tube equipment etc., resulting in a sudden drop in speed below 3950rpm, the logic for this interlock to start the standby pump is blocked by a speed greater than 3950rpm signal condition and the standby pump cannot be started automatically. If the operator fails to intervene in time, there is a risk of overpowering the first circuit or even reactor tripping. A logical schematic of the electric main feed pump outlet pressure low low interlock to start the standby pump is shown in Figure 1.

![Figure 1. Schematic diagram of the feed pump outlet pressure low low interlock to start the standby pump](image)

The pump outlet flow rate low-low signal in the control logic of Figure 1 lags far behind the pressure low-low signal trigger, and this logic function cannot meet the water supply requirements of the second circuit when the unit is operating at full power. According to the simulation test results, when the operating electric main feed pump loses its working capacity, the earlier the standby pump starts, the smaller the disturbance to the unit, and the interlock condition of low pump outlet flow cannot realize the system protection function in time and effectively.

3. Improvement options

3.1. Adding RS triggers to the original logic

The control logic designed by the electric main feed pump manufacturer requires the operating pump speed to be maintained above 3950 rpm. When the pump outlet pressure falls below 35 bar.g, the control logic determines that this operating pump is abnormal at this time. If the pump continues to maintain operation not only can not meet the work capacity requirements, but also will cause more damage to the pump body equipment. The control strategy is therefore designed to take the pump out of service and automatically start the standby pump. In response to a design flaw in the original design
that prohibited the interlocking of the standby pump when the pump outlet pressure was low in the event of a sudden drop in speed. An RS trigger is added to the original control logic and set to S-side priority, which resets the RS trigger output when the pump stops or the speed control is cut to manual. A logical schematic of this improved scheme is shown in Figure 2.

Figure 2. Schematic diagram of improvement option 1 - adding RS trigger logic

After the electric main feed pump has been started and is running normally, the pump has been locked out of normal operation by means of an RS trigger, so that if the pump speed suddenly drops below 3950rpm, the pump outlet pressure low low condition can be triggered to automatically interlock the standby feed pump, eliminating the logic flaw in the original design of the speed threshold signal blocking the feed pump outlet pressure low low interlock to start the standby pump.

3.2. New logic for direct interlocking of standby pump start for low operating pump outlet pressure
While the above modification to add RS triggers to the original logic solves the control logic deficiencies in the original design, the low low threshold of feed pump outlet pressure (less than 35 bar.g) in the original design does not guarantee the design requirement to provide a reliable water supply to the steam generator when the unit is operating at full power. Simulation tests were carried out on a simulator. When the unit is running at full power and the outlet pressure of one feed pump is below 73 bar.g, there is a continuous drop in the water level of the steam generator, and if the operator does not start the standby pump in time, there is still a potential risk of overpowering the first circuit. Therefore, based on the results of the simulation tests, an adapted set of standby pump logic was added to the control logic of each electric main feed pump to improve the reliability of the electric feed pump supply to the steam generator. A logical schematic of this improved scheme is shown in Figure 3.
When the electrical power of the unit is greater than 55%, the electric feed pump is running and the speed control mode is automatic, the deviation between the speed setting and the measured value is greater than 250 rpm and the pump outlet pressure is lower than 73 bar.g, the standby feed pump is started directly, while the pump is still maintained in continuous operation. All three electric main feed pumps are in operation at this time and the simulator has shown that this mode of operation does not cause any disturbance to the unit. This improved solution allows earlier determination of whether the capacity of the second circuit electric main feed pump to supply water to the steam generator meets the design requirements, and has no impact on the operation of the unit by starting the standby pump earlier in the event of abnormal system parameters. Because the low threshold pump outlet pressure (73 bar.g) in the new logic was verified to be very close to the value of the pump during normal operation during simulation tests, the logic causes an increased probability of false start of the standby pump. However, in line with the conservative design strategy for nuclear power units, this solution is conducive to ensuring that the electric main feed pumps maintain the design requirements for the second circuit water supply capacity, and can effectively prevent the first circuit from operating at excessive power due to the second circuit water supply not meeting the requirements.

According to the results of the simulator, the instantaneous 7% drop in the scoop tube at different power levels of the unit corresponds to a drop in pump speed of about 250 rpm, and the impact on the feedwater regulation and steam generator water level is within the control range. No reactor tripping occurs at any power levels of the unit. If the momentary fall of the spoon tube is greater than 7%, the steam generator water level will not be adjusted to a stable state if the operator does not intervene or does not intervene in time, and there is an eventual risk of the reactor tripping. The maximum deviation between the actual speed and the set value during normal operation of the electric feed pump is about 81 rpm. The set value and the actual speed deviation threshold are therefore selected in such a way that a margin of 2 times is added to this operational experience to avoid false triggering of the signal during normal operation.

Under normal operating conditions, the steam generator inlet pressure is about 66 bar.g. The electric feed pump outlet pressure should be selected at a lower threshold than the steam generator inlet pressure in order to guarantee the steam generator water supply requirements. According to the results of the simulator verification, the steam generator water level could not be regulated to a steady state when the scoop tube was suddenly closed by 14% opening (corresponding to a drop in pump speed of about 450 rpm) without the intervention of the operator, and there is an eventual risk of the reactor tripping. As a result, a low threshold for pump outlet pressure can be selected by reference to the pressure value corresponding to a sudden drop in electric feed pump speed of approximately 450 rpm at full power of the unit. A corresponding pressure value of approximately 72 bar.g for a full

![Figure 3. Schematic diagram of the logic of improvement option 2 - new pump with low outlet pressure directly interlocked to start the standby pump](image-url)
power speed drop of approximately 450 rpm with reference to the historical curve. Meanwhile, during the normal operation of the unit, the pressure at the outlet of the operating pump basically fluctuates between 74 and 77 bar.g. A search of historical data from the production site over the last two years did not yield any data below 74 bar.g for the time being. Combining the above three points, from the perspective of facilitating the safe and stable operation of the unit, a low threshold of pump outlet pressure of 73 bar.g was chosen to achieve the function of timely start of the standby pump on the basis of reducing the risk of false start during daily operation as far as possible, increasing the time margin for emergency intervention by the operator and thus reducing the probability of over powering or stopping the reactor in the first circuit of the unit.

Taking a nuclear power plant as an example, information on the speed of the electric feed pump and the pump outlet pressure during unit operation is shown in Table 1. Simulating the process of rapid speed reduction of the operating pump, the first of the new logic's judgement conditions is triggered by a signal that the deviation between the speed setting value and the measured value is greater than 250 rpm, followed quickly by a signal that the pump outlet pressure is below 73 bar.g., and the standby pump is immediately and automatically interlocked. The reliability of the electric main feed pump interlock control logic can be improved.

Table 1. Pump speed and outlet pressure information during operation of a nuclear power plant

| Unit | Load (MW) | Pump speed (rpm) | Pump outlet pressure (bar.g) |
|------|-----------|------------------|-----------------------------|
| 1    | 1090      | 4520             | 76.2                        |
|      | -         | 4270 (Reduced by approx. 250) | 75.1                       |
|      | -         | 4070 (Reduced by approx. 450) | 71-73                      |
| 2    | 1089      | 4560             | 76                          |
|      | -         | 4310 (Reduced by approx. 250) | 75.1                       |
|      | -         | 4110 (Reduced by approx. 450) | 71-72                      |

(Note: The above data is taken from the historical data of a unit operating in 2020, all are rough readings and are for reference only)

The impact of this new logic on the operation of the system is analysed in terms of the different operating conditions of the pumping units. The pumpsets can be summarised in the following five operating conditions: normal operating conditions, start-up conditions, shutdown conditions, special operating conditions and interlock protection conditions.

1) Normal operating conditions: Under this condition, the electrical power of the unit is greater than 55% of full power, the system is stable, the electric main feedwater pump is cast to automatically track the speed setting value given by the main feedwater flow control system, the maximum deviation between the setting value and the actual value during speed adjustment is about 81 rpm and the outlet pressure of the pump can be maintained above 75 bar.g, no statistics have been found for the time being that the outlet pressure is lower than 73 bar.g. The probability that the conditions for large speed deviations are met at the same time is very small, so the probability that the judgement logic will be triggered incorrectly is also small. If the conditions of low pump outlet pressure and large speed deviation are met at the same time due to irresistible factors such as system equipment failure causing disturbances in the feedwater regulation, then the standby feedwater pump in hot standby condition will be automatically interlocked and activated. In this case, the operator should pay attention to the operating parameters of the unit and, at the same time, manually adjust the speed or stop the standby feed pump that has been started in accordance with the actual situation on site to prevent the situation from deteriorating.

2) Start-up condition: This condition is divided into cold start, hot start and automatic start modes. The automatic start mode is introduced under the protection interlock condition. In the cold start
condition, the pump is out of service and speed control is manual, requiring the operator to manually start each pump. During the manual start, the speed control can only be switched to automatic when the main steam isolation valve is open and the differential pressure signal between the two circuits is stable. The new logic cannot be triggered because the pump unit speed control is in manual mode, so the improved solution has no effect on system operation under this condition. In the hot start condition, the operator starts the standby pump manually, the start process is similar to the cold start process, the standby pump is stable before the pump set speed is allowed to cut automatically, following the speed set value given by the regulator, the new control logic in this condition has no effect on the system operation.

3) Out of service conditions: There are two types of out of service conditions. The first is a normal stop, where the operating operator manually reduces the speed slowly to about 3950rpm and then stops the feed pump; the second is an emergency stop, where the pump set, whether in manual or automatic state, directly presses the trip button to stop the feed pump. During the first type of shutdown, the operator first cuts the speed control to manual for slow speed reduction; this signal blocks the new standby pump interlock start logic and has no abnormal effect on the operating and standby pumps that have not yet been shut down. The second emergency pump stop, the electric feed pump original design control protection logic function when a pump trips, automatically start the standby pump, for the tripped pump because its shutdown signal arrives, will block the logic of the new standby pump, no abnormal impact on the operating pump and standby pump.

4) Special operating conditions: Here the main reference is to low power and extended operating conditions of the unit. When the electric power of the unit is lower than 55% of full power operation, such as the electric feed pump has abnormal speed and other failure modes, the logic is not effective, the operator needs to pay attention to the system operating parameters in real time, if found that the pump outlet pressure or flow parameters abnormal affect the steam generator water supply, promptly manually start the backup pump to maintain water supply requirements, and after the system is stable, can manually stop the faulty pump. Under extended operation conditions, with the delay of extended operation time, the overall operating parameter curve of the unit will gradually decrease and adjust, and the operating pump outlet pressure will be lower than 73 bar.g. At this time, the triggering of the standby pump logic is only determined by a single condition of speed deviation, and the failure of the speed signal will lead to the failure of the logic, which requires more attention from the operator.

5) Protection interlocking condition: This condition refers to the original design in which the running pump protection trips and interlocks the standby pump to start automatically, and the new logic part of this renovation, when the running pump meets the trigger conditions to interlock the standby pump.

For the part of the original design where the protection trips to activate the standby pump:

When an operating pump fault signal or a protection trip signal (low flow rate, high bearing temperature, etc.) arrives, it triggers the logic to start the standby pump or to trip the pump and start the standby pump. During the start-up of the standby pump, its speed control is in the automatic state, after the standby pump starts running, the speed rises rapidly following the speed setting value, the pressure rises gradually from 4.1 bar.g, the condition of large deviation between speed setting value and actual speed (duration about 10s) and the condition of low pump outlet pressure (below 73 bar.g duration about 12s) are met, the first delay of 5 seconds will trigger the standby. The new control logic for the pump is added, but since the first 5 seconds of delay after the tripped pump stops will exit the hot standby state and the faulty pump will be blocked by the fault signal to allow the start condition, neither the tripped pump nor the faulty pump will be triggered again during this process. The simulator simulates the operating conditions of the ECP manually tripping the operating pump, the standby pump interlock starts successfully and no abnormalities are seen during the period.

For the retrofitting of the new control logic linking the standby pump section:

During the unit's operation, when the operating pump's speed drops due to a spoon tube failure or other factors, the pump outlet pressure drops below 73 bar.g and the condition of large speed deviation is met, the standby pump logic is triggered. During the start-up of the backup pump, there is a risk that
the start-up logic will be triggered again, but as the feed pump with abnormal output is not yet out of service, this joint start-up signal has no effect on it, and the operator can stop the faulty pump manually once the regulation has stabilised. If the start of the standby pump fails, the operator should carry out another manual start, keeping an eye on the water level of the unit's steam generator and the thermal power of the first circuit and, if necessary, immediately reducing the load on the unit.

4. Conclusion
Both of these improvements have been implemented at different nuclear power plant sites and no similar abnormal conditions affecting the operation of the electric feed pumps have been encountered and no other abnormalities have been reported from the site. By investigating the operation of electric main feed pumps in different nuclear power units, there are deviations in the outlet pressure of the feed pumps during normal operation, and the low threshold value of the pump outlet pressure in improvement option 2 is very close to the pressure value of the pumps during normal operation. Therefore, if it is necessary to apply improvement option 2 to the site, it is necessary to verify the fluctuation range of the normal value of the outlet pressure of each electric feed pump after the last few rounds of overhaul and to reduce the number of false starts of the standby pump as much as possible.

The reliable operation of the second circuit electric feed pump in nuclear power plants directly affects the status of the unit, and it is of great significance to ensure the safe operation of nuclear power units by continuously optimising the control logic of the electric feed pump, eliminating all kinds of safety hazards in the original design and improving the operational reliability of the equipment. The threshold signal will not only protect the pump equipment from damage, but also meet the abnormal conditions of the unit to make a timely and correct response.

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