The control system of a 2kW@20K helium refrigerator

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Abstract. The automatic control of a helium refrigerator includes three aspects, that is, one-button start and stop control, safety protection control, and cooling capacity control. The 2kW@20K helium refrigerator's control system uses the SIEMENS PLC S7-300 and its related programming and configuration software Step7 and the industrial monitoring software WinCC, to realize the dynamic control of its process, the real-time monitoring of its data, the safety interlock control, and the optimal control of its cooling capacity. This paper firstly detailed describes the control architecture of the whole system, including communication configuration and equipment introduction; and then introduces the sequence control strategy of the dynamic processes, including the start and stop control mode of the machine and the safety interlock control strategy of the machine; finally tells the precise control strategy of the machine's cooling capacity. Eventually, the whole system achieves the target of one-button starting and stopping, automatic fault protection and stable running to the target cooling capacity, and help finished the cold helium pressurization test of aerospace products.

1. Review

At present, in our aerospace field, the system-level test platform of pressurization and transport only has the capability of system tests in liquid nitrogen temperature area. It does not meet actual conditions of the cold helium pressurization system on the rocket, and also can not simulate some key characteristics, such as system's start impact, magnetic valves' temperature drop, and so on. So it is very necessary to extend the platform's test capability to liquid hydrogen temperature area. In the past, we usually used the way of soaking in liquid hydrogen to cool the helium to 20K, which could obtain the test condition of high pressure and low temperature, and then finished tests in liquid hydrogen temperature area. But hydrogen belongs to flammable and explosive medium, so tests are very difficult to be controlled, and have very high risk. It's almost impossible to test the vibration environment in this way.

After years of research, a 2kW@20K helium refrigerator has developed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. Using this helium refrigerator as a cold source to cool the high pressure helium in the pressurized tank, does not need hydrogen medium, and has much higher safety. It can also satisfy large flow experimental studies of the pressurization system, and realize the coupling of cryogenic and vibratory environment, so that better reflect the real work situation on the rocket. It enables the pressurization system to have the capability of hydrogen temperature area and high pressure system experiments, and also enhances the authenticity and coverage of the experiments.

The new aerospace products' performance test platform with 2kW@20K helium refrigerator is shown in figure 1. First, the high-pressure helium from the helium distribution station comes through the liquid nitrogen exchanger, and is cooled to be 80K. Then the 80K helium is injected into the pressurized tank to be further cooled and pressurized. Cold helium from the 20K helium refrigerator exchanges heat with the injected helium inside the pressurized tank through its shell and tube heat exchanger, then returns to the helium refrigerator after heating up. In this way, the helium in the pressurized tank is constantly cooled, pressurized and cooled again. Finally, the helium reaches the temperature of 20K and the pressure of 20MPa, and the system is kept stable by the cooling capacity of the helium refrigerator [1].

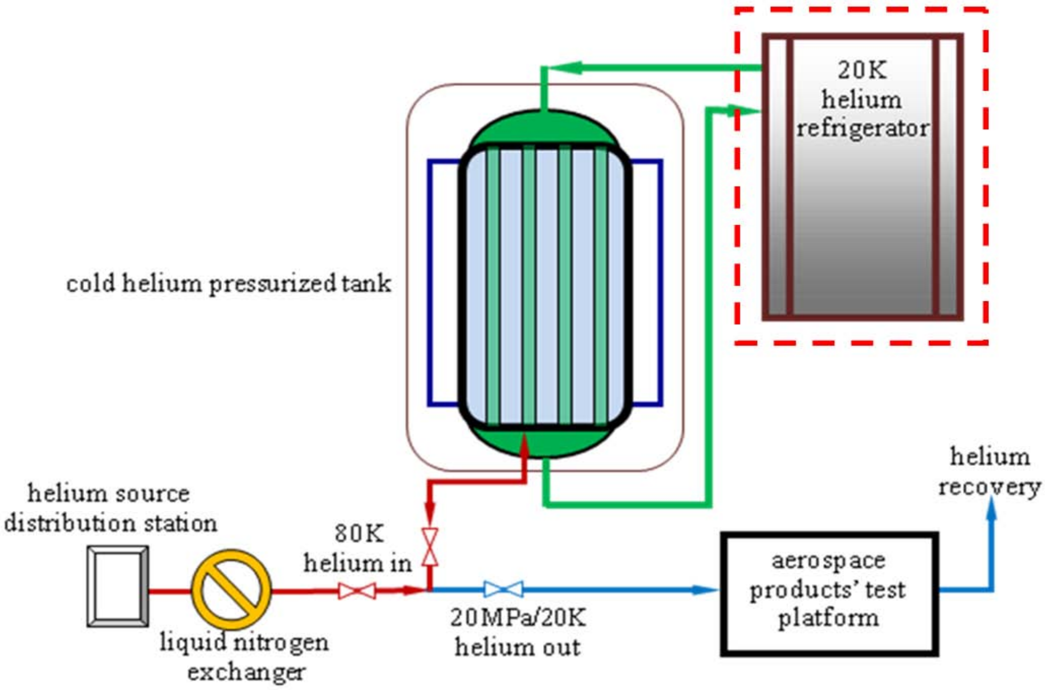

Figure 1. The principle diagram of aerospace products' test platform in liquid hydrogen temperature.

2. General introduction of the control system of 20K helium refrigerator

For a refrigerator applied in aerospace field, to realize its equipments unmanned monitored, temperature precise controlled stable and fast interlock responding to accidents to ensure the system's security is the main factors to proof its stability and reliability during its running. And all of these need to be realized by the control system. The process control system of 2kW@20K helium refrigeration uses PLC S7-300 with its matching programming and configuration software Step7, and industrial monitoring software WinCC. They are all well-known and mature international products, so it can promise the stable and reliable performance of the system, and also its low failure rate.

2.1. Structure diagram of the control system

This control system is dual-CPU redundant configured, and uses Profibus as its system bus and distributed I/O ET200M as its extension mode. The composition of the whole system is shown in figure 2.1.

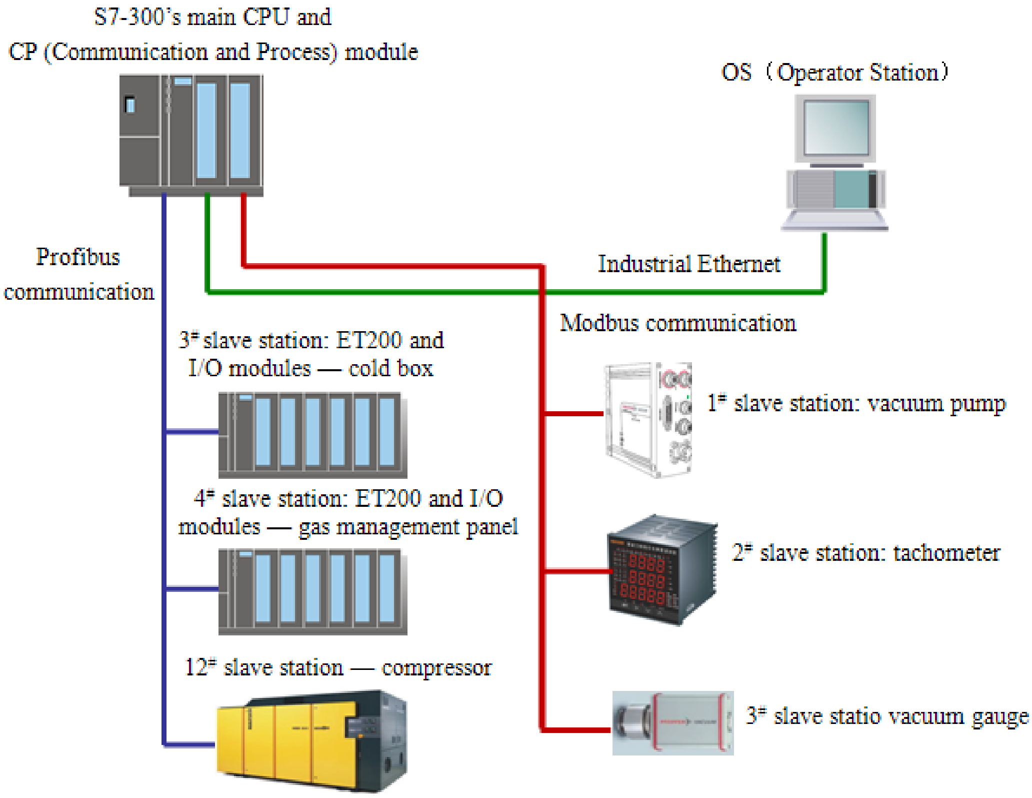

Figure 2.1. Structure diagram of 2kW@20K helium refrigerator's control system.

2.2. Hardware， software and communication configurations

On the hardware, this control system uses one PLC main frame and three PLC slave stations ($3^{\#}$, $4^{\#}$ and $12^{\#}$ stations), two ET200 distributed I/O and I/O modules, one host computer operating station, and so on. The slave computer uses S7-300 PLC control system, and uses CPU315-2PN/DP as its central process unit. According to the requirement of I/O points, the system uses the form of two distributed I/O and Profibus (field bus) communication to extend I/O modules, which can support the extension of 16 modules at most, and makes high performance price ratio of the system. The communication between the slave computer and the operator station (host computer) is depending on Industrial Ethernet. The slave computer's main CPU integrates Industrial Ethernet interface, and supports functions such as Ethernet data communication, program download, etc. The vacuum pump, tachometer and vacuum meter in the system do not use Profibus, but use Modbus to communicate with the slave computer, through the CP communication module on the PLC main frame. This makes the system compatible with more communication modes.

On the software, the system uses Step7 V5.4 as its slave computer programming software, and WinCC V6.2 as its host computer process monitoring software. Functions of the slave computer include hardware configuration, logic programming and communication configuration. The host computer is used for configuring the system flow chart screen, parameter display screen, PID control screen, trend curve screen and alarm screen. And it can also confirm alarms, record events and print reports. It makes users operate in a friendly screen for process monitoring, operation control, data processing, and so on. And it enables operators to master the running situation of the refrigerator in time, and then can take effective controls to promise the test of aerospace products' performance more stable and reliable. The human and machine interface of the refrigeration made by the host computer is shown in figure 2.2.

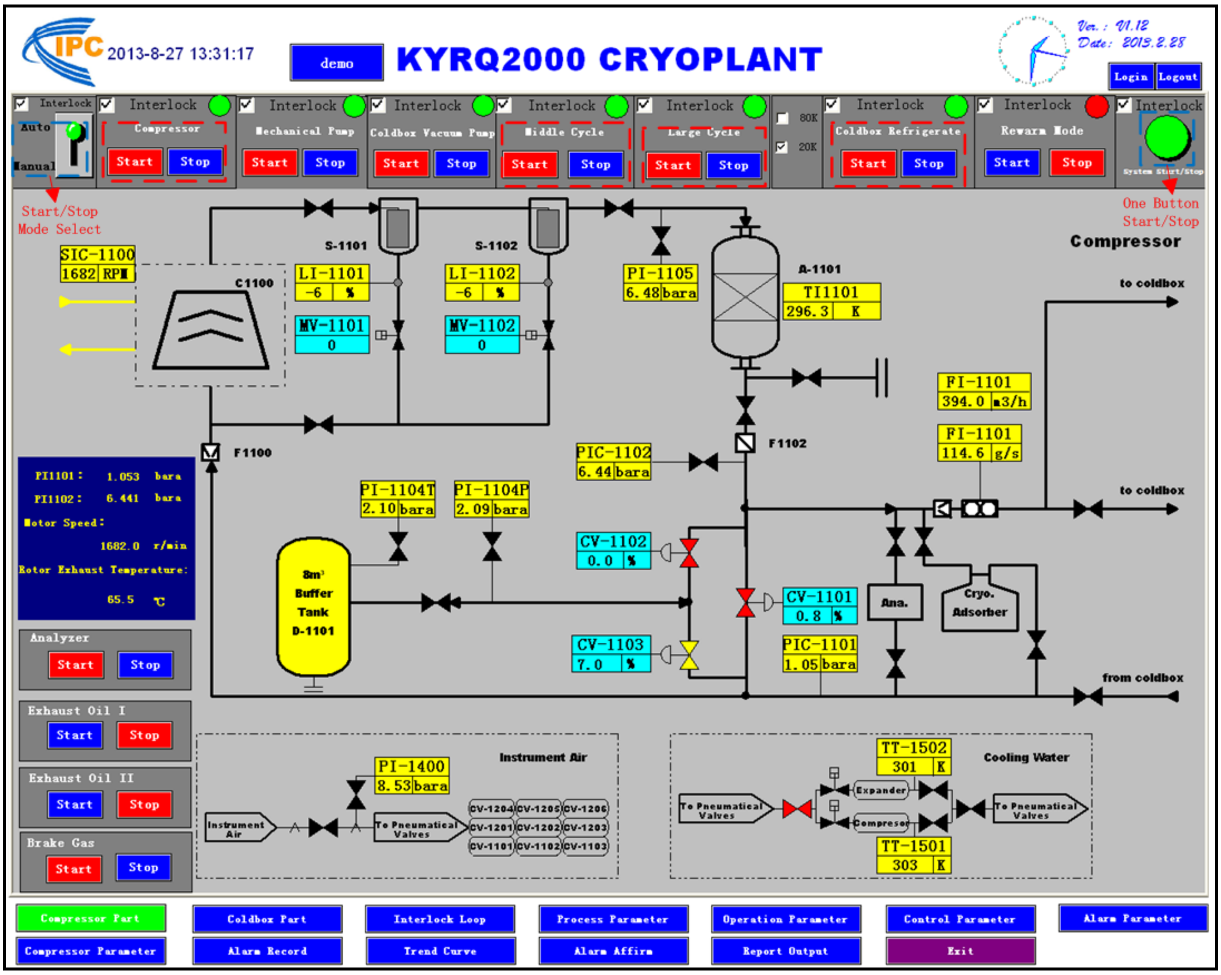

Figure 2.2. The human and machine interface of the refrigerator made by WinCC V6.2.

3. Sequence control strategy for the refrigerator's one-button start and stop and its interlock strategy of automatic fault protection

3.1. Sequence control strategy for the refrigerator's one-button start and stop

In order to meet the needs of different stages of the experiment, and also to operate the refrigerator in a better order, we divide the system into four modes, as shown in figure 3.1. The first (inside the No.1 box) is the compressor mode. In this mode, the compressor and three control valves (CV1101, CV1102, CV1103) in the gas management panel act, which makes system's high and low pressure reach to the set value and remain stable. The second (inside the No.2 box) is the middle cycle mode. In this mode, turbine's bypass valve (CV1202) and cold load's bypass valve (CV1205) act, on the base of the last mode. It feeds through the whole system (connect the cold box and room temperature part), and makes the system's high and low pressure stable. The third (inside the No.3 box) is the coldbox refrigeration mode. In this mode, turbine's control valve (CV1201) and turbine act, on the base of the last mode, meanwhile CV1202 closes, which makes system's refrigeration begin. The fourth (inside the No.4 box) is the large cycle mode. In this mode, the cold load's gas supply valve (CV1203) and gas return valve (CV1205) act, on the base of the last mode, meanwhile CV1205 closes, which supplies the interface to users.

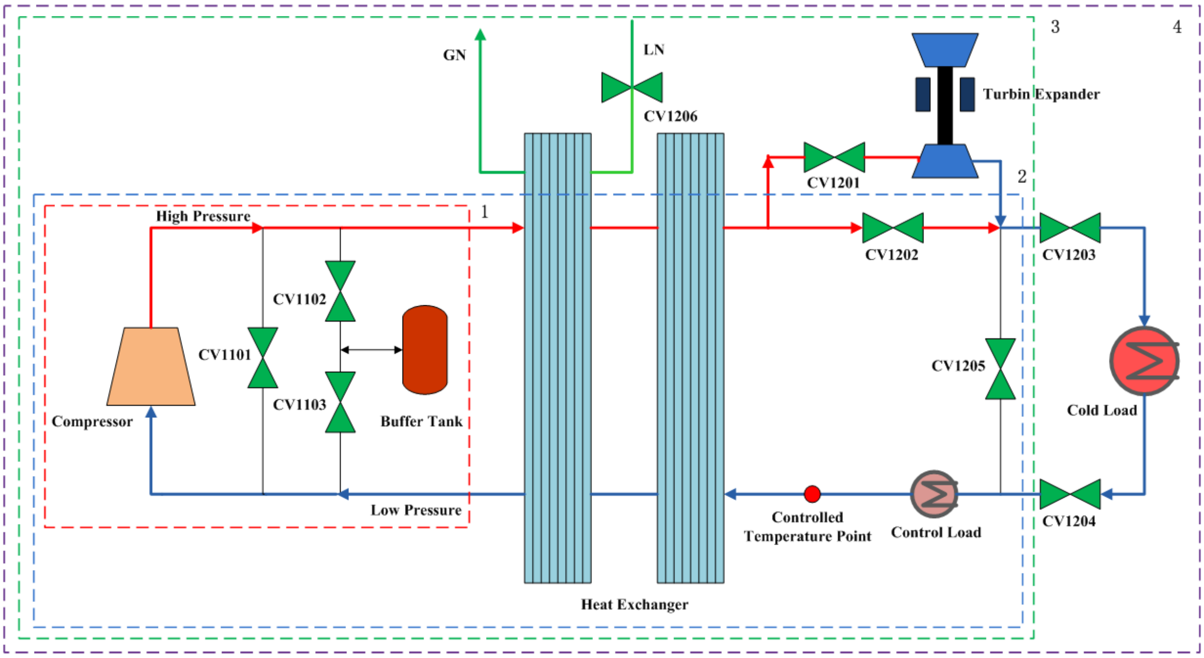

Figure 3.1. Brief flow chart of the whole refrigerator.

We have two alternative modes to start and stop the refrigerator, that is auto mode and manual mode, as shown in figure 2.2. In “manual" mode, all the parts (inside dashed boxes) can be manual started and stopped independently through their own “start” and “stop” button. In "auto" mode, the entire system can be started and stopped automatically just through one button — “system start and stop” button (except some peripheral devices, such as mechanical pump, vacuum pump, analyzer, instrument gas, cooling water unit, etc), and need not any other operations. The refrigerator’s automatical start order is: compressor→middle cycle→clodbox refrigeration→large cycle; while its automatical stop order is: clodbox refrigeration→large cycle→middle cycle→compressor.

3.2. Fault protection interlock strategy of the refrigerator

In order to ensure the safe operation of the whole refrigeration system, it is necessary to establish interlock protection for its key components and vulnerable parts. Once the refrigerator has any abnormalities, it can realize "soft landing" and ensure the safety of persons and equipments. This control system has established comprehensive and effective interlock protection measures. According to the experiences of similar equipments at home and abroad and also the needs of users, we divide system’s interlocks into three categories, as shown in figure 3.2. When each type of interlock faults occurs, the system will respond different equipment responses in its need. This can fully ensure the safety of the system, and realize the safety guarantee of the unmanned operation. In system’s “manual” mode, we can input or cutoff each mode and equipment interlock independently anytime we need. And in system’s “auto” mode, all the mode and equipment interlocks is automatically input or cutoff in a certain order, which realizes one-button start and stop of the system.

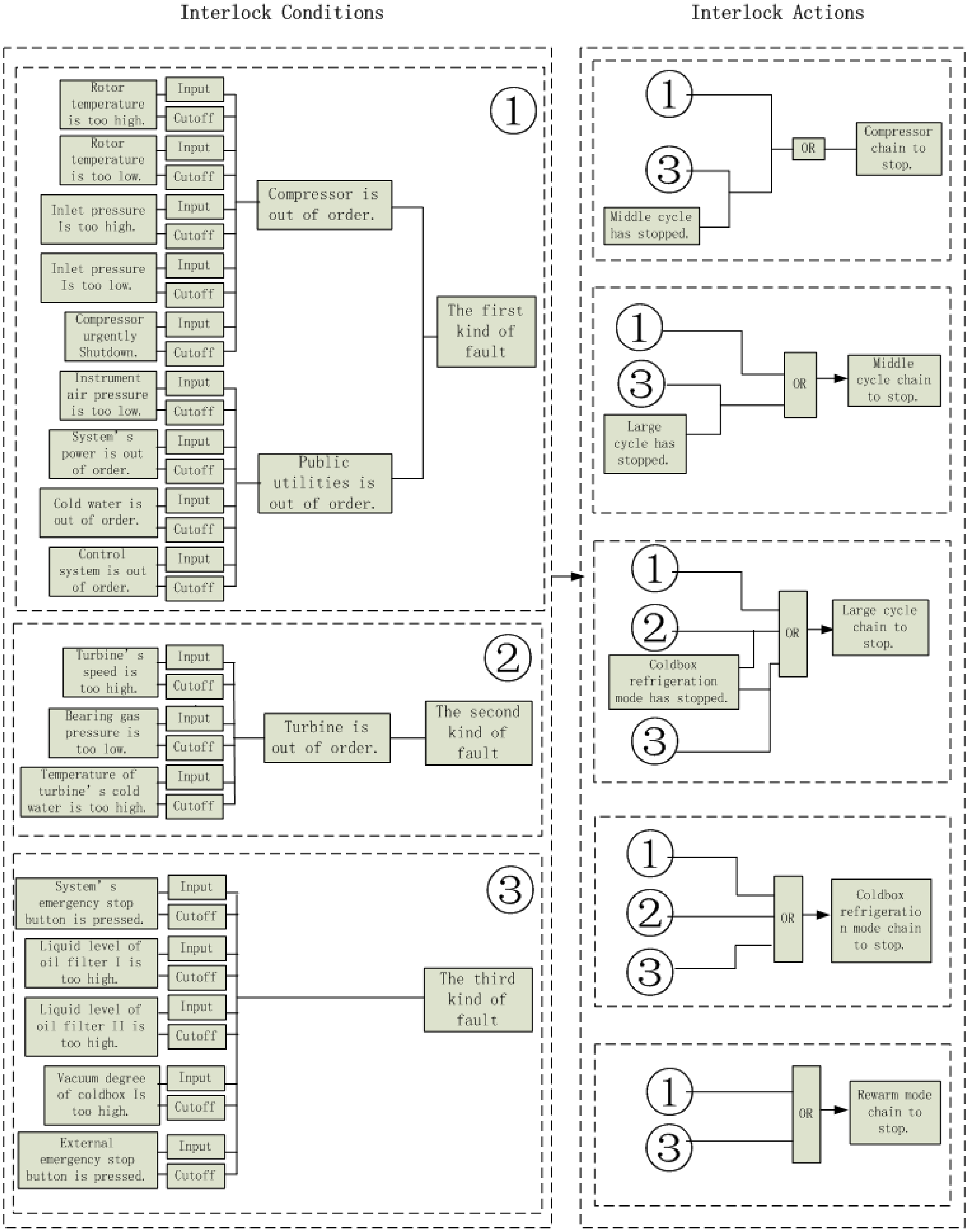

Figure 3.2. Fault protection interlock strategy of the refrigerator.

4. Temperature precise control strategy of the refrigerator

From our system design goal, when the cold load changes, the controlled temperature should be adjusted stable in a range rapidly. The permissible range of temperature change is ±0.5K, and while the cold load reaches to 2kW, the stable temperature should not be over 20K.

To achieve the goal, temperature adjustments are divided into three levels: when temperature fluctuation is around ±0.3K, the control load is operated, with its maximum heating capacity 10% of system's refrigeration capacity; when temperature fluctuation is beyond to the temperature region, between ±0.3K and ±3K, the temperature adjustment system would start adjusting the speed of the turbine expander. When the temperature fluctuation is beyond ±3K, the control system would start adjusting the large fluctuation of low pressure. The first level adjusts temperature by the PID control loop of the control load, which would change the heating capacity of the control load to compensate temperature changes; and the second level adjusts temperature by the PID control loop of the control valve before the turbine expander, which would control the mass flow of refrigeration material, and then change the speed of the turbine expander as well as system's refrigeration capacity; and the third level adjusts temperature by large fluctuation of the low pressuree, which possibly causes two reactions: when the pressure is too low, it induces the interlock protection to stop the whole refrigerator; conversely, it induces the frequency jump protection of the compressor [2].

Keeping the high pressure and low pressure stable is the necessary condition of compressor unit's normal operation, which is archived by the PID control loops of valves in the gas management panel and the compressor. Compensation gas valve and exhaust valve are used for high pressure adjustment, while bypass valve and compressor are used for low pressure adjustment.

Step7 V5.4 integrates some digital PID controllers, such as SFB41/FB41 (CONT_C), SFB42/FB42 (CONT_S), and SFB43/FB43 (PULSEGEN). All the control loops of the 2kW@20K refrigerator use the FB41 (CONT_C) block. FB41 controller uses a position-type PID control algorithm. The calculation principle of its output control variable is as follows:

$$u(n) = K_{\mathrm{P}}\left\{e(n) + \frac{T}{T_{\mathrm{I}}}\sum_{i=0}^{n} e(i) + \frac{T_{\mathrm{D}}}{T}[e(n) - e(n-1)]\right\} + M \tag{1}$$

In equation (1), $e(n)$ is the deviation; M is the integral initial value; K_{P} is the proportional coefficient; T_{I} is the integral time constant; T_{D} is the differential time constant; and T is the sampling time.

The structure principle of PID control loops in 2kW@20K system is shown in figure 4. Inside figure 4, the small box encloses the part performed by digital PID controllers, and the big box encloses the part performed by S7-300 PLC. When the controlled object deviates from its set point, the PID controller will calculate a movement using equation (1) to cause actuator acting for adjusting the controlled object close to its set point value [3].

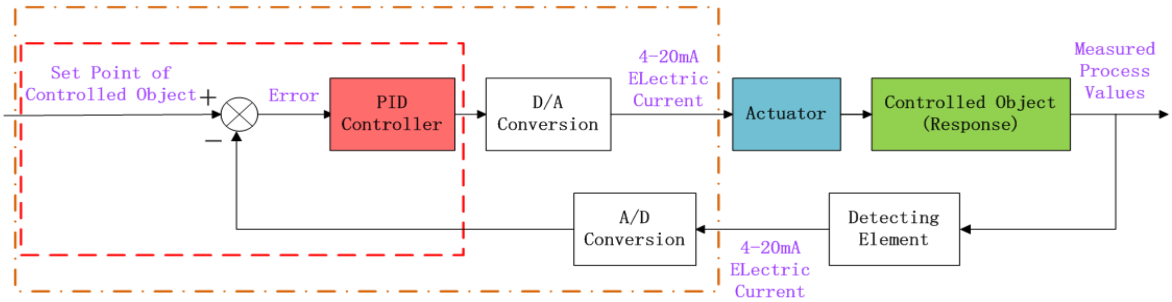

Figure 4. The structure principle of PID control loops in 2kW@20K refrigerator.

In 2kW@20K refrigerator， we use six PID control loops in total. Each loop's actuator and controlled object and also its PID coefficients are listed in table 1.

Table 1. PID control loops and coefficients of 2kW@20K refrigerator.

Controlled Object	Actuator	K_P	T_I	T_D
High pressure	Compensation gas valve (CV1102)	-82	190	0
	Exhaust valve (CV1103)	5.3	180	0
Low pressure	Bypass valve(CV1101)	55	180	0
	Compressor	-52	180	0
Turbine expander speed	Control Valve(CV1201)	2.6	200	0
Controlled Temperature	Control load	1.1	650	0

5. The test result of cold helium pressurization by 2kW/ 20K helium refrigerator

The helium refrigerator has run at the cooling capacity of 2kW@19.7±0.3K for 9 days itself [2]. And we also have used this refrigerator to help finished the cold helium pressurization experiment, which reaches the required test condition of 20MPa@20K. The refrigerator system in test site is shown in figure 5.1, and the result of the pressurization process is shown in figure 5.2.

Figure 5.1. The 2kW/20K helium refrigerator in test site.

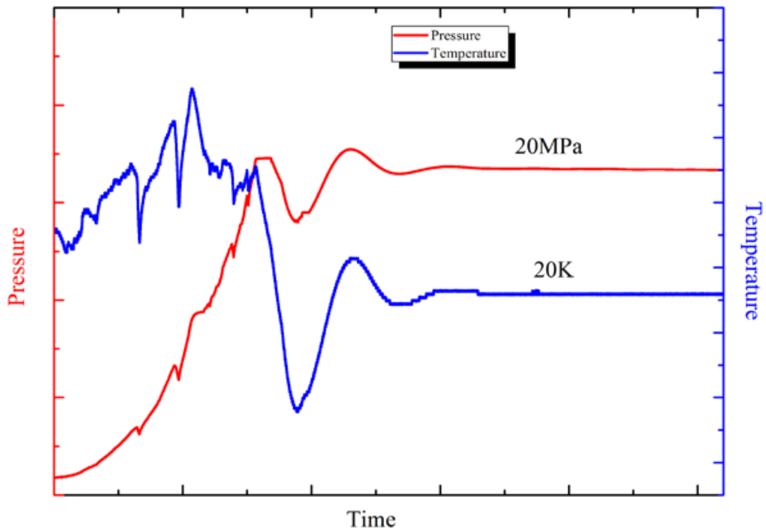

Figure 5.2. The result of cold helium pressurization by 2kW/ 20K helium refrigerator.

When the temperature of the refrigerator is about 23K, the cold helium begins to be injected. Front batches are injected rapidly, and because the cold load of the helium is less than 2kW, so between injection gaps, the temperature drops. As helium pressure close to the target value, the injection speed slows. And finally, the whole system is kept stable by the cooling capacity of the helium refrigerator. The helium inside the tank is kept stable at 20MPa@20K with temperature's change inside ±0.3K, which meets the test requirement well.

References

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