Development of the quench protection system for the CFETR CS model coil

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Abstract: The Central Solenoid (CS) model coil, which is responsible for developing and verifying the larger-scale superconducting magnet technology of China Fusion Engineering Test Reactor (CFETR), has been designed and is currently being manufactured at ASIPP. The energy storage of the CS model coil is 407MJ, so a reliable quench protection system is needed to ensure the safety of the coil when a quench occurs. This paper describes the progress of the quench protection system. The two-stage commutating current technique is used to solve the difficulties that the breaker cannot directly break the high DC current. For the key components in the circuit, the prototype of the breaker was manufactured and the performance test was carried out. The engineering design and manufacture of the discharge resistor were carried out. An experimental study of the quench protection circuit was carried out to verify the feasibility of the design. Besides, the reliability of the quench protection control system is qualitatively analyzed based on the fault tree.

1. Introduction

The Central Solenoid Model Coil (CSMC) project was initiated in 2015 to enable China to acquire the larger-scale superconducting magnet technology for China Fusion Engineering Test Reactor (CFETR) [1-2]. The CSMC is a hybrid superconducting magnet composed of Nb3Sn and NbTi coils [3-4]. The operation current of CSMC is 47.65kA and total stored energy is up to 407.6 MJ. Quenching causes local temperature rise and high voltage in a superconducting coil and therefore it is necessary to discharge the magnetic energy stored in the coil [5]. The quench protection system for CSMC is proposed and the main circuit is shown in figure 1 [6]. This paper describes the progress of the quench protection system work. For the key components in the circuit, the prototype of the breaker was manufactured and the performance test was carried out to verify the feasibility of the design. The engineering design and manufacture of the discharge resistor were carried out. Based on the fault tree, the reliability of the quench protection control system is qualitatively analyzed.
2. Main circuit components

2.1 DC rapid circuit breaker
The quench protection breaker is one of the key components in the quench protection system. Considering the reliability of the switching action and the economic cost, the DC rapid circuit breaker is selected as the quench protection breaker for CS model coil. This breaker is a mechanical switch with a rated current of 50kA and a rated voltage of 2.5kV. During operation, the main busbar and the main contacts are cooled by water, effectively increasing the current capacity and reducing the size of the breaker. The prototype of DC rapid circuit breaker is shown in figure 2. After the prototype is manufactured, its key performance tests are carried out, including thermal stability testing and breaking performance testing.

Figure 2. Prototype of DC rapid circuit breaker
The main circuit of the thermal stability experiment is shown in figure 3. The power supply can supply up to 60kA. B1 is a bypass thyristor, K1 and K2 are isolation switches, DCCT1 is a current sensor, and L is a load inductance (5mH). Before the test, the temperature measurement points were arranged in the key parts such as the moving main contact, the static contact and the busbar of the prototype. During the test, the temperature inspection instrument was used to measure and record the temperature of each measuring component of the circuit breaker. When the temperature measurement point changes less than 1K/h, it is considered that the temperature rise of the circuit breaker enters steady state. The test result was shown in figure 4. Under the rated current of 50kA, the temperature of the highest part of the contact is about 50℃, in line with national standards.
The breaking capacity is one of the most important indicators of the circuit breaker and can directly affect the reliability of the quench protection system. The main circuit of the breaking performance experiment is shown in figure 5. B1 is the bypass thyristor, DCCT is the current sensor, L is the load inductance (5mH), F is the fuse, D is the diode component, and Re is the discharge resistor (50mΩ). During the test, the circuit breaker DS is first closed, and the energy storage inductor L is charged by the power source. When the current reaches 50kA, the circuit breaker breaks. Under the arc voltage generated by the DS breaking, the breaker current is commutated to the resistor branch or the fuse branch connected in parallel, and the circuit breaker breaking process ends. The test result is shown in figure 6. The breaker was successfully disconnected under the rated current of 50kA and verified the feasibility of the secondary commutation. The maximum arc voltage of the breaker is about 1.4kV.
2.2 Discharge resistor

The discharge resistor is a key component in the quench protection unit. It will absorb the energy stored in the superconducting coil and will protect the coil from damage. According to the hot spot temperature calculation of the coil and the terminal voltage requirement, the resistance of the discharge resistor is calculated as 51.2mΩ and the corresponding discharge time constant of coil is 7s [7].

After the superconducting coil is quenched, it needs to release energy of more than several hundred megajoules to the discharge resistor. Therefore, under the condition of meeting the energy-shifting requirements, which material is used to design the energy-shifting resistor can be economical and meet the actual requirements, is very important for the quench protection system. The circuit process after the current is transferred to the discharge resistor is analyzed before material selection.

Assume that the allowable temperature rise of the discharge resistor is $T_0$, $\rho$ is the resistivity at 20 °C, $\alpha$ is the temperature coefficient of resistance at 20 °C, the coil energy storage $W$ is 407.6 MJ. Since the coil energy is almost completely released on the energy-shifting resistor, this process lasts for a few seconds, in which the heat dissipation of the resistor in the air can be ignored. Assuming that the energy transfer resistance is adiabatic, its temperature rise can be calculated by:

$$W = C_e m T_0$$  \hspace{1cm} (1)

Where $C_e$ is the specific heat of the resistor; $m$ is the mass of the potential resistance.

$$K_1 = C_e m = \frac{407.6 \times 10^6}{T_0}$$  \hspace{1cm} (2)

After the coil is quenched, if any one of the three quench protection breaker in series is disconnected, the current will be completely transferred to the discharge resistor, we can get

$$L \frac{di}{dt} + iR = 0$$  \hspace{1cm} (3)

Where $R = R_20[1 + \alpha(T - 20)]$, $R_20$ is resistance of the energy-shifting resistor at 20 °C, the value is 51.2mΩ. According to $dW = i^2 R dt$, then we get:

$$W = \int_0^t i^2 R dt = C_e m(T - 20)$$  \hspace{1cm} (4)

By taking the derivative of $t$ in (4), we can get:

$$C_e m \frac{dT}{dt} = i^2 R$$  \hspace{1cm} (5)
Combined with formulas (3) and (5), we can obtain

\[ L \frac{di}{dt} + C_e T \frac{dT}{dt} = 0 \quad (6) \]

After solving differential equation (6), we can get

\[ \frac{1}{2} L i^2 = -C_e mT + K_2 \quad (7) \]

The initial conditions are: \( I_0 = 47650A \), \( T = 20^\circ C \), after some conversions, we can get

\[ T = \frac{0.1795}{K_1} i^2 + \frac{K_2}{K_1} \quad (8) \]

Where \( K_2 = 407.6 \times 10^6 + 20K_1 \)

Suppose \( K_3 = \frac{K_2}{K_1} \), \( K_4 = \frac{0.1795 R_20}{K_1} \), \( K_5 = R_20 (1 - 20\alpha + K_3 \alpha) \) and combined with formulas (3) and (8), obtain

\[ L \frac{di}{dt} - K_4 i^3 + K_5 i = 0 \quad (9) \]

After solving differential equation (9), we can get the expression of the current of the discharge resistor during the process of energy transfer

\[ i = \sqrt{\frac{K_5 K_6}{K_4 K_6 - e^{2K_5 t/L}}} \quad (10) \]

Where \( K_6 = \frac{I_0^2}{K_4 i^2 - K_5} \)

The expression of the temperature of the discharge resistor as a function of time is

\[ T = -\frac{0.1795}{K_1} \times \frac{K_5 K_6}{K_4 K_6 - e^{2K_5 t/L}} + K_3 \quad (11) \]

The expression of the voltage of the discharge resistor is

\[ U = R i = 0.0512 (1 - 20\alpha + \alpha T) i \quad (12) \]

We calculated the performance parameters of the cast iron material, aluminum material, iron-chromium-aluminum material (1Cr13Al14) and stainless steel material (SUS304L), which are selected as the discharge resistors, respectively, into the above relevant formulas.

**Table 1. Parameters of each discharge resistor material**

| Material            | Resistivity@20°C $\rho(\Omega \cdot mm^2/m)$ | Resistance temperature coefficient $\alpha(10^{-6}/°C)$ | Specific heat $C_e(J/Kg \cdot °C)$ | Allowable temperature rise $T_0(°C)$ | Weight (Kg) |
|---------------------|---------------------------------------------|---------------------------------------------------|-----------------------------------|-------------------------------------|-------------|
| cast iron           | 0.85                                        | 1000                                              | 470                               | 200                                 | 4336        |
| aluminum            | 0.029                                       | 4000                                              | 920                               | 200                                 | 2215        |
| iron-chromium-aluminum | 1.26                                        | 150                                               | 491                               | 200                                 | 4151        |
| stainless steel     | 0.675                                       | 1800                                              | 500                               | 200                                 | 4076        |
Figure 7. Curve of electrical parameters over time during resistance energy transfer of each material: a) current versus time curve; b) voltage versus time curve; c) temperature versus time curve

It can be seen from the current curve in the figure 7 that the current of the aluminum resistor with the largest temperature coefficient of resistance has the fastest current drop, that is, the discharge is the fastest, followed by the stainless steel material. That is the smaller the temperature coefficient of resistance, the slower the material can move. It can be seen from the voltage curve that the aluminum resistance with the highest temperature coefficient of resistance shows a small voltage overshoot,
so the temperature coefficient of resistance of the selected material should not be too large. Comprehensive consideration and analysis, stainless steel materials can better meet the above requirements, so we choose stainless steel as the material of the discharge resistor. The engineering design parameters of the discharge resistor of the quench protection system are summarized in Table 2.

Table 2. The engineering design parameters of the discharge resistor

| Item                        | Parameter       |
|-----------------------------|-----------------|
| resistance(mΩ)              | 51.2            |
| Max voltage(V)              | 2500            |
| Max energy(MJ)              | 407.6           |
| weight(Kg)                  | 4076            |
| Highest temperature rise (℃) | 200             |
| Qualified hot spot temperature condition I2t (A^2t) | 7.947×10^9 |

The figure 8 shows a partially completed discharge resistor array. The discharge resistor is composed of a plurality of stainless steel tubes of equal length and cross-sectional area. The resistance values of all the series are 51.2mΩ. Each stainless steel tube can be adjusted by external joints and slip ring to change the resistance. Under this structure, the stray inductance of the discharge resistor can be effectively reduced by a reasonable connection method, which facilitates the commutation process of the quench protection system.

Figure 8. The picture of discharge resistor array  
Figure 9. The photo of fuse

2.3 Fuse
As a key component in the loop, the fuse can reduce the arc-extinguishing burden of the breaker during the energy transfer process of the coil, and generate a high pulse voltage, forcing the coil current to be transferred to the parallel-connected discharge resistor branch. We made the fuse with an equal section melt. The fuse consists of a melt, an epoxy cylinder and quartz sand. Quartz sand has a strong current limiting and arc extinguishing capability, which can absorb part of the inductor energy storage [8]. The length of fuse melt is 17 cm and cross-sectional area is 24 mm2 (t_b=20 ms) based on the previous analysis.

According to the parameter calculation and structural design of the fuse, the
manufacture of the fuse is completed, and figure 9 is the picture of the fuse. The outer yellow part is an epoxy barrel with quartz sand for arc extinction. When the secondary commutation process of the quench unit is completed, the fuse will be blown, and the new melt and the cooled quartz sand need to be replaced to prepare for the next operation of the quench protection unit.

3. Quench protection control system
The quench protection control system consists of a software and hardware protection system. The two protection systems are independent of each other and redundant with each other to ensure fast and reliable control of the closing and opening of the quench protection breaker after the coil has a quench.

Since the reliability of the quench protection control system will directly affect the operation safety of the magnet, the fault tree is used to qualitatively analyze the system to find out the key factors affecting the reliability of the system, and propose measures to improve the system reliability [9]. The control circuit of the hardware control system is shown in figure 10.

Figure 10. The control circuit of hardware control system
Firstly, it is determined that the top event \( T \) is “the quench protection unit cannot operate”, and then the top event is analyzed, and all the causes of the top event are listed as intermediate events, including the \( M_1—DS1 \) cannot operate; \( M_2—DS2 \) cannot operate; the \( M_3—DS3 \) cannot operate. Detailed analysis is performed for each intermediate event, and the decomposition results are shown in Table 3. Based on the above analysis, the fault tree of the hardware control system is shown in figure 11:
Table 3. Decomposition results of events

| Event Number | Intermediate events | Basic events |
|--------------|---------------------|--------------|
| M1           | DS1 not receive quench signal (M11) | Transmission failure (X1) |
|              |                     | Conversion failure (X2) |
|              | ZJ1 Relay failure (M12) | ZJ1 Contact failure (X3) |
|              |                     | ZJ1 Coil failure (X4) |
|              | TQ1 failure (M13) | TQ1 Internal fault (X5) |
|              | DS1 Node failure (X7) | TQ1 pick-up fault (X6) |
|              | Control power supply failure (X8) | - |
| M2           | DS2 not receive quench signal (M21) | Transmission failure (X1) |
|              | SJ1 Relay failure (M22) | Conversion failure (X2) |
|              |                     | SJ1 Contact failure (X11) |
|              |                     | SJ1 Coil failure (X12) |
|              | ZJ2 Relay failure (M23) | ZJ2 Contact failure (X13) |
|              |                     | ZJ2 Coil failure (X14) |
|              | TQ2 failure (M24) | TQ2 Internal fault (X15) |
|              | DS2 Node failure (X9) | TQ2 pick-up fault (X16) |
|              | Control power supply failure (X8) | - |
| M3           | DS3 not receive quench signal (M31) | Transmission failure (X1) |
|              | SJ2 Relay failure (M32) | Conversion failure (X2) |
|              |                     | SJ2 Contact failure (X17) |
|              |                     | SJ2 Coil failure (X18) |
|              | ZJ3 Relay failure (M33) | ZJ3 Contact failure (X19) |
|              |                     | ZJ3 Coil failure (X20) |
|              | TQ3 failure (M34) | TQ3 Internal fault (X21) |
|              | DS3 Node failure (X10) | TQ3 pick-up fault (X22) |
|              | Control power supply failure (X8) | - |

Qualitative analysis of the fault tree is to find all the minimum cut sets for the fault tree, and then find the key points that affect the reliability of the system.

Based on the fault tree, the process of solving the minimum cut set of the system using the downlink method is shown in Table 4. The rightmost column in the table is all the minimum cut sets calculated by the Boolean algebra formula [10], totaling 723, of which the first-order minimum cut set is 3, the second-order minimum cut set is 60, and the third-order minimum cut set is 660.
In the basic event of the minimum cut set in the fault tree, the lower the order, the greater the impact on the system fault [11]. In the case of the same order, the bottom event that occurs in different minimum cut sets will have an impact on the system. According to the minimum cut set of the hardware electronic circuit protection system, the key points of the system are X1, X2 and X8.

For these key points, the following measures can be proposed for the hardware protection system:
(1) The transmission of the quench signal requires multiple transmission lines, and the signal conversion must have multiple nodes connected in parallel.
(2) The control power supply should use two different types of high-reliability power sources, such as DC battery power and AC UPS.
(3) The relay should use products with low failure rate and high reliability, and there is redundancy.
(4) The maintenance and inspection of equipment should be strengthened to identify and eliminate existing reliability problems.

**Figure 11.** The fault tree of the hardware control system
### Table 4. The process of solving the minimum cut set of the system

| Step 1   | Step 2   | Step 3       | Step 4       | Step 5       | Step 6   | Step 7   |
|----------|----------|--------------|--------------|--------------|----------|----------|
| M1M2M3   |          | X1M2M3       | X1M21M3      | X1M3        | X1M31    | X1X2     |
|          |          | X1M2M3       | X1M21M3      | X1M3        | X1M32    | X1X17    |
|          |          | X1M2M3       | X1M21M3      | X1M3        | X1M33    | X1X18    |
|          |          | X1M2M3       | X1M21M3      | X1M3        | X1M34    | X1X19    |
|          |          | X1M2M3       | X1M21M3      | X1M3        |          | X1X20    |
| M1M2M3   |          | X1M2M3       | X1M21M3      | X1M3        | X1M34    | X1X21    |
|          |          | X1M2M3       | X1M21M3      | X1M3        | X1M34    | X1X22    |
|          |          | X1X8M3       | X1X9M3       | X1X8M3      | X1X8     | X1X10    |
|          |          | X1X2M3       | X1X2M3       | X1X2M3      |          |          |
|          |          | X1M2M3       | X1M2M3       | X1M2M3      |          |          |
| M1M2M3   |          | X1M2M3       | X1M2M3       | X1M2M3      |          |          |
|          |          | X1M2M3       | X1M2M3       | X1M2M3      | X1X8M3   | X1X9M3   |
| M1M2M3   |          | X1M2M3       | X1M2M3       | X1M2M3      | X1X8M3   | X1X9M3   |

### 4. Conclusion

The CS model coil of CFETR has a huge stored energy and need a reliable quench protection system against quench. The design of the quench protection system is introduced in the paper. For the main components in circuit, the DC rapid circuit breaker is developed and tested to verify that the breaker has good thermal stability and breaking performance. The engineering design and manufacture of the discharge resistor are also completed. Besides, the reliability of the hardware control system of quench protection system is qualitatively analyzed based on fault tree. The QP system will be, in principle, ready for operation around 2020.
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