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Quench detection and protection system design and analysis of the 7 T superconducting magnet *

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Abstract A NbTi 7 T superconducting magnet with a 338 mm bore system was rebuilt and the first experiment was carried out in Jan. 2009. The balancing-bridge method used for the quench detection system is analyzed and an improvement of the principle of balancing-bridge conformation is given. The inductances of the coils are calculated to estimate the proportion of the bridge arms. The appropriate parameters are selected for the balancing-bridge.

Key words quench detection, quench protection, balancing-bridge

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1 Introduction

One set of the superconducting conductor test system was donated to the Institute of Plasma Physics of the Chinese Academy of Science (ASIPP) by the French Atomic Energy Commission (CEA) in 2002. The system mainly consists of 4 coaxial superconducting coils with 338 mm bore [1], operating with superfluid helium at 1.8 K and atmospheric pressure. The maximal magnetic field is 10 T. The configuration of the magnet is shown in Ref. [2]. The main parameters of the magnet are shown in Table 1.

Table 1. Main parameters of the magnet.

item	technical parameters
bore	338 mm
height	600 mm
central field	10 T(1.9 K), 7 T(4.2 K)
operating current	1340 A(1.9 K), 1000 A(4.2 K)
conductor	NbTi-Cu-CuNi
operating temperature	1.8 K superfluid
	helium or 4.2 K helium

To develop the cable-in-conduit conductor (CICC) technology for the International Thermonuclear Experimental Reactor (ITER), the magnet system was rebuilt in ASIPP [3]. New subsystems such as the helium cycling and power supply were set up. The low-temperature transmission pipelines, diagnosis system, quench detection and protection system were designed. The first objective was to run the magnet up to 1000 A at 4.2 K stably.

In this paper the balancing-bridge quench detection method and quench protection system are described.

2 Quench detection

2.1 Quench detection method

During operation, a tremendous energy is stored in the superconducting coils. This energy should be removed from the coils as soon as quench occurrs, otherwise partial overheating will destroy the conductor or the insulation between the neighboring layers of the coils [4]. Methods of quench detection normally used include the following indicators: temperature, pressure, ultrasonic, mass flow, voltage, etc. Because of its obvious meaning and rapid response, the voltage detection method is used widely [5].

For the superconducting coils which work stably, a balancing-bridge is adapted for the quench detection. A quench detection and protection circuit of a superconducting magnet is shown in Fig. 1.

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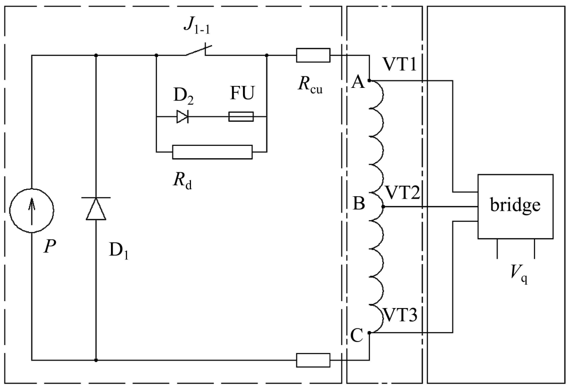

Fig. 1. Quench detection and protection circuit. The dashed border shows the power supply and quench protection system, the point line border shows the superconducting coils and the solid line border shows the quench detection system.

2.2 Analysis of the balancing-bridge

The simulation circuit of the balancing-bridge is shown in Fig. 2. This circuit is formed by two current loops, marked as Loop 1 and Loop 2.

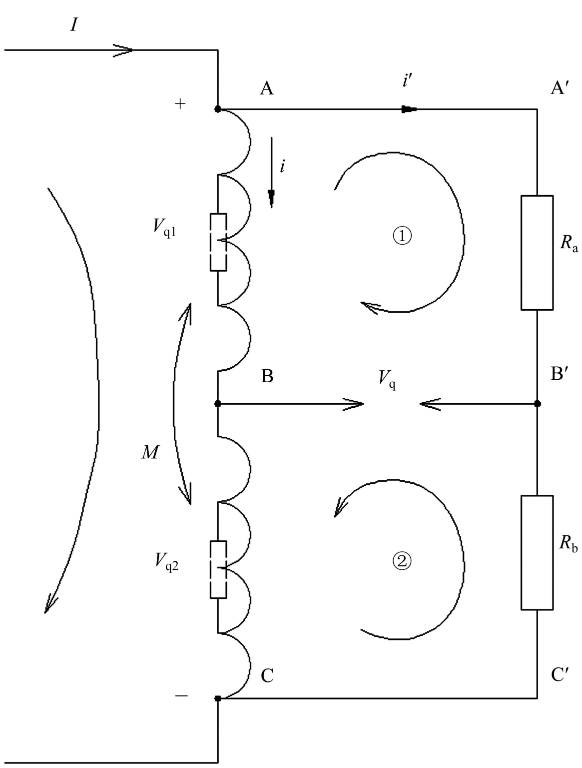

Fig. 2. Simulation circuit of the balancing-bridge. The balancing-bridge consists of two parts of the coil and balancing resistances. The mutual inductance of the two parts of the coil is M. The normal zone voltages are V_{q1} and V_{q2} when partial quenching occurs in each part of the coil.

The inductance of the magnet has a constant value L. And we divide the coil into two parts, which are L_{AB} and L_{BC}. When ramping up the magnet field, the induced voltage of the magnet is: $U = L\frac{di}{dt}$.

To insure the output of the balancing-bridge be 0 before the magnet quench, i.e. $V_q = 0$, we obtain:

$$(L_{AB}+M)\frac{di}{dt}/(L_{BC}+M)\frac{di}{dt} = \frac{R_a i'}{R_b i'} . \quad (1)$$

Simplifying Eq. (1), we have:

$$(L_{AB}+M)/(L_{BC}+M) = R_a/R_b . \quad (2)$$

Before starting the experiment, the balancing-bridge should be adjusted to satisfy Eq. (2). Then the balancing-bridge can be used as a quench detection circuit.

V_{q1} and V_{q2} are defined as the normal zone voltages after the coil quenched. Three cases are analyzed as follows.

1) Quenching occurs in Loop 1, i.e. $V_{q1} \neq 0$, $V_{q2} = 0$, then in circuit ① (see Fig. 2):

$$V_q = V_{q1} + (L_{AB}+M)\frac{di}{dt} - \frac{R_a}{R_a+R_b}U_{A'C'} . \quad (3)$$

In circuit ②:

$$V_q = -(L_{BC}+M)\frac{di}{dt} + \frac{R_b}{R_a+R_b}U_{A'C'} . \quad (4)$$

The voltage of the magnet is:

$$U_{A'C'} = U_{AC} = (L_{AB}+L_{BC}+2M)\frac{di}{dt} + V_{q1} . \quad (5)$$

Combined with Eq. (2), we obtain:

$$V_q = \frac{R_b}{R_a+R_b}V_{q1} . \quad (6)$$

2) Quenching occurs in Loop 2, i.e. $V_{q1} = 0$, $V_{q2} \neq 0$, and reasoning as above we have:

$$V_q = -\frac{R_a}{R_a+R_b}V_{q2} . \quad (7)$$

3) Quenching occurs in both Loop1 and Loop2, i.e. $V_{q1} \neq 0$, $V_{q2} \neq 0$, then:

$$U_{A'C'} = U_{AC} = (L_{AB}+L_{BC}+2M)\frac{di}{dt} + V_{q1} + V_{q2} . \quad (8)$$

Combined with Eqs. (2), (3) and (4), we have:

$$V_q = \frac{R_b}{R_a+R_b}V_{q1} - \frac{R_a}{R_a+R_b}V_{q2} . \quad (9)$$

2.3 Principle of the balancing-bridge conformation

Generally, the point B (see Fig. 2) is connected to the center of the coil, then:

$$(L_{AB}+M)/(L_{BC}+M) = R_a/R_b = 1 . \quad (10)$$

From Eqs. (6) and (7), one easily recognizes that the absolute value of V_q is half of V_{q1} or V_{q2}. V_{th} is defined as the threshold quenching voltage of the superconducting magnet, and we can obtain a quite simple criterion:

$$V_q = \pm\frac{1}{2}V_{th} \ . \tag{11}$$

Eq. (11) means that if $V_q > V_{th}$, the quench protection system will work.

If quenching occurs simultaneously in each half of the coil and $V_{q1} = V_{q2}$, or quenching occurs from point B and spreads simultaneously, then Eqs. (9) and (10) lead to $V_q = 0$. In this case V_q cannot indicate the quenching. So, an accessory balancing-bridge should be added to avoid the dead region of quench detection. For example, 1/3 of the coil could be selected to constitute another bridge.

According to the analysis above, we come to the conclusion on the principle of balancing-bridge conformation:

1) The center of the coil is selected to constitute one balancing-bridge with the simple criterion Eq. (11).

2) Another appropriate point of the coil is selected to constitute a further balancing-bridge in order to avoid a dead region of quench detection.

A sketch of the balancing-bridge conformation circuit is shown in Fig. 3.

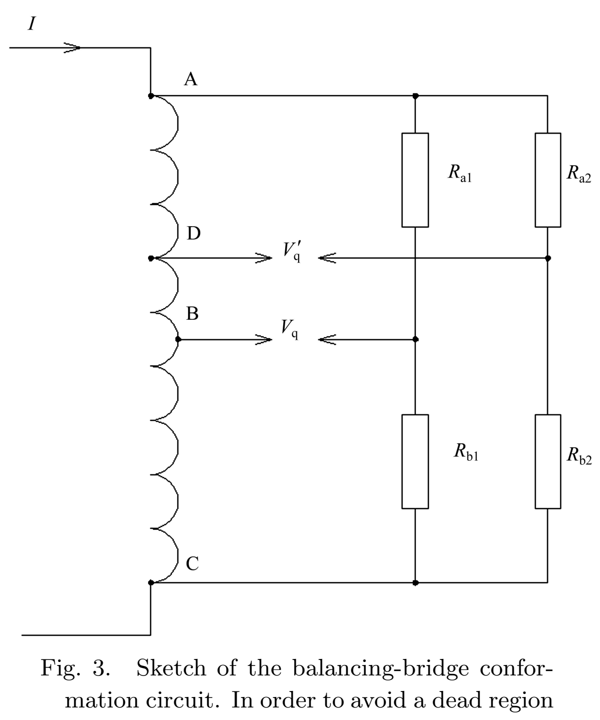

Fig. 3. Sketch of the balancing-bridge conformation circuit. In order to avoid a dead region of quench detection, the second balancing-bridge was constituted using another appropriate point of the coils.

3 Inductance calculation

The actual balancing-bridge quench detection circuit for the magnet is shown in Fig. 4. After calculation, we selected the point between coil3 and coil4 to constitute the main balancing-bridge.

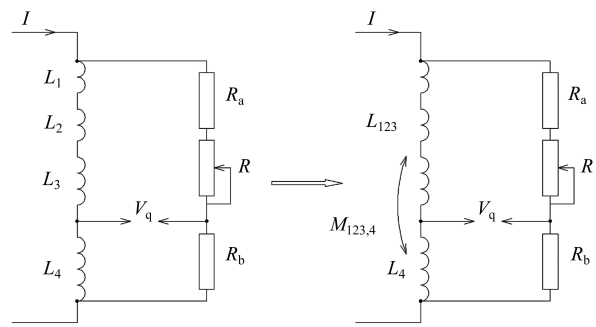

Fig. 4. Actual balancing-bridge quench detection circuit and equivalent circuit for the magnet.

As described in section 2.2, before starting the experiment, the balancing-bridge needs to be adjusted to let $V_q = 0$. From Eq. (2), one has to calculate the inductances of the coils to estimate the value of the two resistance bridge arms.

Because the configuration of the magnet is quite complex, we calculate the self inductances and mutual inductances of the coils by using the Finite Element Analysis software ANSYS. The model is shown in Fig. 5. and the results of the calculation are shown in Table 2. According to the real dimension of the coils we established the Finite Element Model of the coils.

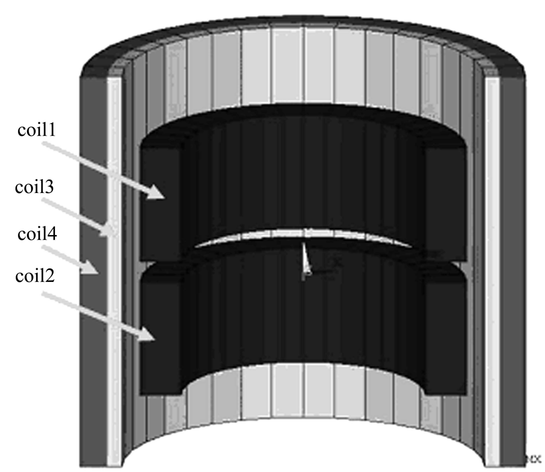

Fig. 5. Model for the inductances calculation.

The equivalent inductances are calculated as follows:

$$L_{123} = L_1+L_2+L_3+2(M_{12}+M_{13}+M_{23}) = 8.54\times10^{-1}(\mathrm{H}) , \quad (12)$$

$$L_{1234} = L_1+L_2+L_3+L_4+2(M_{12}+M_{13}+M_{14}+M_{23}+M_{24}+M_{34}) = 5.88(\mathrm{H}) , \quad (13)$$

$$M_{123,4} = M_{14}+M_{24}+M_{34} = 1.24987(\mathrm{H}) . \quad (14)$$

Combining Eqs. (2), (12), (13) and (14), according Fig. 5 we obtain:

$$r_\mathrm{R} = (L_{123}+M_{123,4})/(L_4+M_{123,4}) = (R_\mathrm{a}+R)/R_\mathrm{b} = 0.5576 . \quad (15)$$

The parameters calculated from Eq. (15) are shown in Table 3.

Table 2. Self inductances and mutual inductances of the coils (H).

coils	1	2	3	4
1	6.72×10^{2}			
2	2.10×10^{-2}	6.72×10^{-2}		
3	8.61×10^{-2}	8.61×10^{-2}	3.33×10^{-1}	
4	2.09×10^{-1}	2.09×10^{-1}	8.32×10^{-1}	2.52

Table 3. Parameters of the resistance bridge arms.

R_a/kΩ	R_b/kΩ	R/kΩ	$r_{\mathrm{R,min}}$	$r_{\mathrm{R,max}}$
10	20	2	0.5	0.6

4 Test results

The balancing-bridge uses the voltage taps connected to the coils directly. During the experiment, especially when the coils are quenched, the balancing-bridge will be under high-voltage. To protect the equipments behind the balancing-bridge, the quench detection signal must be insulated.

In order to verify the efficiency of the quench detection system before formal experiment, we ramped up the current to a small value. Then an electrical heater was installed near the first layer of the coil and was used to induce a simulated quench. Fig. 6 shows the current and quench detection voltages.

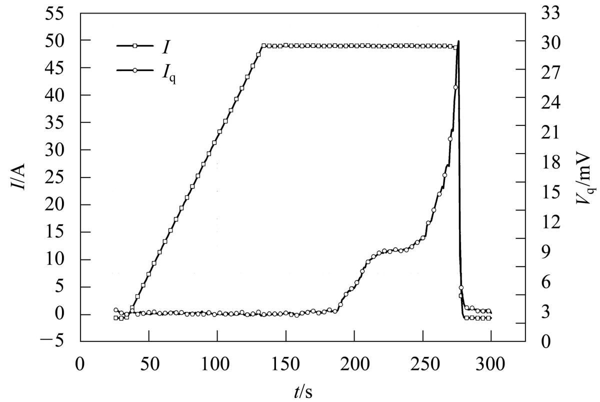

Fig. 6. Current and quench detection voltages for a simulated quench caused by an electrical heater installed near the first layer of the coil.

5 Conclusions

After long distance transportation and being unused for nearly 6 years, the superconducting magnet system was tested for the first time in ASIPP. The excitation current reached to 985 A with 0.7 A/s ramping up rate. The central magnetic field of the magnet is 6.96 T and stored energy of the magnet is about 2.85 MJ.

The experiment indicated that the superconducting magnet system is still in good status and all accessory sub-systems work well.

After detailed calculations, we selected the appropriate parameters of the balancing-bridge. During the experiment the magnet did not quench and the output of the balancing-bridge remained at $V_\mathrm{q}=0$.

The analysis results of the balancing-bridge can be used to provide references to similar applications of quench detection.

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