Internal Energy Dump for Superconducting Magnet Protection of the LHD-Type Fusion Reactor FFHR

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The superconducting magnet systems of LHD-type reactors have large magnetic energies of over 100 GJ. When a quench occurs, this magnetic energy must be absorbed quickly with a resistor. A conventional energy dump with an external resistor generates a high terminal voltage, which may cause a serious dielectric breakdown. This paper presents the internal energy dump concept for quench protection of the LHD-type reactor FFHR. In an internal energy dump, a shorted secondary circuit acts as a heater and induces a normal transition of the whole coil. Most of the magnetic energy can be absorbed inside the coil while the temperature of the coil rises. In the case of the FFHR, the temperature rises up to 200 K. We designed and analyzed a secondary circuit using a copper winding. The designed circuit can reduce the terminal voltage by a factor of ten and induce a normal transition of the adjacent superconductor within 1 s. The results show that the internal energy dump concept is appropriate for design of superconducting magnets for fusion reactors.

Keywords: fusion reactor, heliotron reactor, large helical device, superconducting magnet, quench protection, magnetic energy, internal energy dump

1. Inroduction

Heliotron power reactors have competitive advantages for steady-state operation due to the fact that they employ currentless plasma. These advantages have been demonstrated by the Large Helical Device (LHD) with a superconducting magnet system since the start of experiments in 1998 [1]. Engineering and physics results from studies of the LHD confirm that LHD-type heliotron reactors are well suited for steady-state power plants. Based on the outputs from the LHD, we have performed design studies of LHD-type demonstration reactors (the FFHR series). The detailed design of the blanket, operating scenario, superconducting magnet, coil-supporting structure and maintenance procedures has been published previously [2, 3]. In the design studies, we applied realistic technologies that are expected to be developed in the near future.

Heliotron power reactors also have an important advantage in the superconducting magnet design. Superconductors do not generate heat loss due to a changing magnetic field, known as ac loss. Therefore, large cooling capability is not required, in contrast to Tokamak reactors. We therefore propose an indirect cooling method, which is commonly used in accelerator magnets, as an alternative to pool cooling and forced-flow cooling [4, 5]. The use of indirect cooling allows a simple coil structure to be used.

An important issue for the design of superconducting magnets is the dumping of magnetic energy when a quench occurs. A heliotron reactor magnet consists of continuous windings with large diameter. Therefore, the magnet has large magnetic energy of over 100 GJ. Because an unexpected quench may cause burn-out of a superconductor, a protection system must be developed to reduce the coil current rapidly and to dump the magnetic energy. The conventional protection system has an external resistor near a power supply, which absorbs most of the magnetic energy. This method is called the external energy dump. When employing an external energy dump in large magnets, there are two important engineering issues. First, high voltages over 10 kV are applied across a coil, which may cause a dielectric breakdown. Second, the external resistor must have a large mass of heat-absorbing material. When using water as heat-absorbing material, a large amount of water must be heated and evaporated. To absorb a magnetic energy of 100 GJ, 40,000 kg of water is required.

To resolve the issues of the external energy dump, we have investigated an internal energy dump concept [6, 7]. In this concept, the magnetic energy is absorbed into the coil using the normal resistance of the superconductor. When a quench occurs, an embedded heater induces the normal transition of the whole of the superconductor. A

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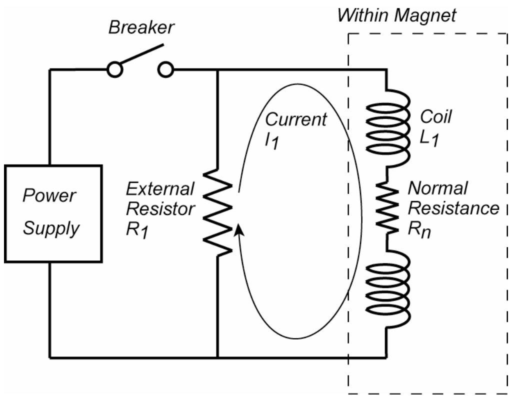

Fig. 1 Quench protection circuit with an external resistor.

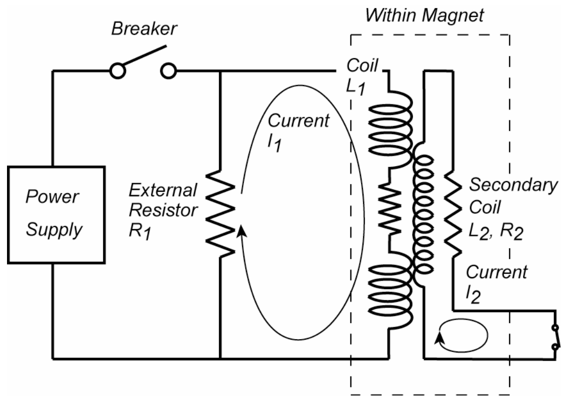

Fig. 2 Quench protection circuit with a secondary circuit.

conventional resistive heater needs a power supply, and hence we employ a shorted secondary circuit as a heater. The current of the secondary circuit is induced by the decay of the coil current. The secondary circuit, therefore, does not need a power supply. In this paper, we demonstrate the applicability of the internal energy dump as a protection system for the FFHR. The design of the secondary circuit is presented and its performance is investigated.

2. Comparison between External and Internal Energy Dumps

Figure 1 shows a typical quench protection system with an external resistor. When a quench is detected, the breaker is opened. The current then shifts from the power supply to the external resistor. The resistance of the resistor R_1 is usually much higher than that of the superconductor in the normal state R_n. The coil current I_1 decays with a time constant τ of L_1/R_1 while the resistor absorbs the magnetic energy. The maximum terminal voltage is I_0R_1, where I_0 is the initial current. The maximum voltage V_m can be rewritten as:

$$V_m = \frac{2E}{I_0\tau} \quad (1)$$

where E is the stored magnetic energy of the coil. The maximum voltage is proportional to the energy. Note that the coil current must be increased to reduce the voltage. For the FFHR with the coil current of 100 kA, the decay time constant should be less than 18 s to avoid burn-out of the superconductor [5]. The maximum terminal voltage then reaches 60 kV, which is much higher than the designed voltage for typical superconducting magnets. To reduce the voltage, the coil must be divided into several subdivisions.

In an internal energy dump, the resistance R_n is higher than R_1 because the whole of the superconductor become normal. Therefore, the decay time constant is assumed to be L_1/R_n. The maximum terminal voltage can be reduced because R_1 can be determined independently of the quench protection. Therefore, the coil current can potentially be reduced. In addition, the external resistor does not require a large amount of heat-absorbing material as most of the heat is absorbed by the coil itself.

3. Temperature Rise of the FFHR Magnet during an Internal Energy Dump

The internal energy dump causes a uniform temperature rise of the whole coil. Here we investigate whether the magnetic energy can be absorbed into the coil. The balance equation between the magnetic energy E and the heat capacity of the coil can be written as:

$$E = \sum_i V_i \int_{T_0}^{T_m} C_i(T)dT \quad (2)$$

where i is the material number, V_i is the volume of each material, and $C_i(T)$ is the specific heat per unit volume. T_0 and T_m are the initial and maximum temperatures. We applied this equation to the helical coil of the reactor design FFHR2m1. The coil structure is presented in detail in a previous paper [5]. The materials include superconductors, insulators, and cooling panels. The maximum temperature T_m was calculated to be 210 K for a magnetic energy of one helical coil of 66 GJ, which is within acceptable levels, indicating that the internal energy dump can be successfully applied.

4. Quench Protection with a Secondary Circuit

Figure 2 shows a quench protection circuit with a secondary circuit. The secondary circuit is a normal coil that is closely coupled to the superconducting coil. When the current of the superconducting coil starts to decay as the breaker is opened, the current shifts from the superconducting circuit to the secondary circuit. The

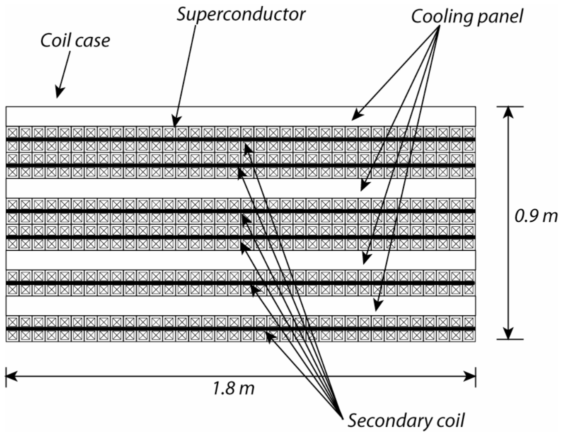

Fig. 3 Cross-sectional structure of the helical coil and arrangement of the secondary coils.

normal secondary circuit then heats the adjacent superconductor by Joule heating. Finally, the secondary circuit causes the whole of the superconducting coil to become normal. This process is referred to as quench back [6, 7]. This concept can induce a normal region more reliably than a resistive heater. The switch in the secondary circuit is closed only during a quench. A current shift during an excitation of the magnet is inhibited by opening the switch.

5. Quench Protection Circuit for the FFHR

Figure 3 shows the structure of the helical coil of the FFHR and the arrangement of the secondary coil [5]. The superconductor is wound by a layer winding method (36 turns/layer, 12 layers). Four cooling panels with cooling channels are embedded in the coil. The superconductor is cooled indirectly by the cooling panels. The secondary coils consist of copper wires and are arranged between sets of two superconductor layers. There are thus six layers of secondary coil. We determine the thickness of each layer to be 0.5 mm.

The shift of current from the primary circuit I_1 to the secondary circuit I_2 can be obtained by the following circuit equations:

$$L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} + I_1(R_1 + R_n) = 0$$
$$L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} + I_2 R_2 = 0 \qquad (3)$$

where L_2 is the inductance of the secondary circuit, M is the mutual inductance between the two circuits, and R_2 is the resistance of the secondary coil. Note that the resistance of the normal zone R_n and the resistance of the secondary coil R_2 depend on temperature. The temperature rise of the superconducting coil can be estimated from the heat balance equation:

$$C_1(T)\frac{dT}{dt} = \lambda \rho_1(T) J_1^{\,2}(T) \qquad (4)$$

where C_1 is the average specific heat per unit volume in the coil, λ is the ratio of coil volume to copper volume, ρ_1 is the resistivity of copper, and J_1 is the overall current density. In addition, the temperature of the secondary coil can be obtained by

$$C_2(T)\frac{dT}{dt} = \rho_2(T) J_2^{\,2}(T) \qquad (5)$$

where C_2 is the specific heat per unit volume of copper, ρ_2 is the resistivity of copper, and J_2 is the current density. Even though the heat transfer between the superconducting and secondary coils is neglected, the calculations can be the first step in investigating the performance of the secondary circuit.

By solving Eqs. (3) and (5), we find that the temperature rise is independent of the turn number of the secondary coil if the thickness of the coil is fixed. Therefore, the cross-section of the wire and the turn number need not be considered further. The self inductance of the secondary coil also affects the temperature rise, which increases with increasing inductance. The inductance must then be adjusted to half the inductance of an ideal close winding to avoid a burn-out of the secondary coil itself. This adjustment of inductance is technically possible using a non-inductive winding method.

A key issue for this protection method is whether we can increase the initial decay time constant of the superconducting coil (L_1/R_1) and reduce the maximum terminal voltage (I_0R_1). We analyzed quench protection for a time constant of 200 s, about ten times larger than the maximum time constant for external energy dump protection of 18 s. Figure 4 shows the calculations of the current shift and the temperature rise of the secondary coil before quench back. In this calculation, the resistance of the superconducting coil R_n is zero. The currents are normalized by the initial current of the superconducting coil and the turn number. The results show that the temperature of the secondary coil increases to about 35 K within 1 s. This temperature rise can certainly induce a normal transition of an adjacent superconductor because the critical temperature in a magnetic field of 13 T is about 10 K in the case of a Nb_3Sn superconductor.

We next analyzed the temperature rise of the coils after quench back. Figure 5 shows the calculations of the current shift and the temperature rise. The quench back is assumed to occur with a time delay of 1 s from the start of the energy dump. After the quench back, the resistance R_n is calculated using the normal resistance of the whole superconducting coil. The current of the superconducting

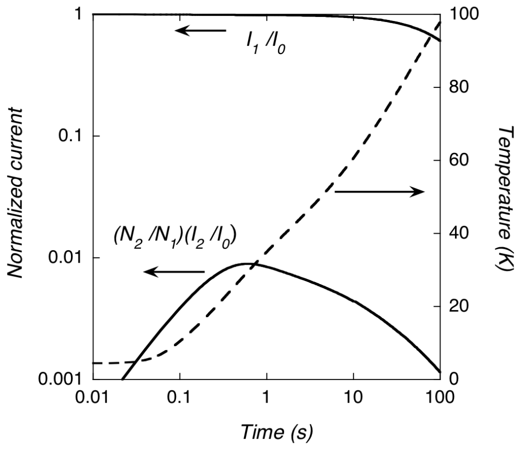

Fig. 4 Current shift (solid lines) and temperature rise (broken line) of the secondary coil before quench back. The currents are normalized by the initial current of the superconducting coil I_0 and the turn numbers. N_1 and N_2 are the turn numbers of the superconducting and the secondary coils, respectively.

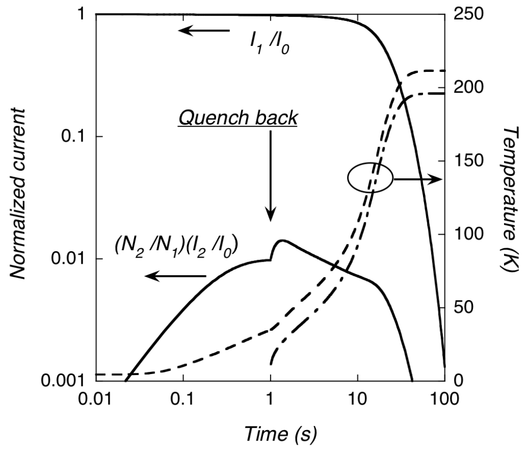

Fig. 5 Current shift (solid lines) and temperature rise of the superconducting and secondary coils during the energy dump. Quench back occurs with a time delay of 1 s. The dashed and the broken lines represent the temperatures of the superconducting and secondary coils.

coil decays rapidly with increasing temperature because the resistance of the coil increases with increasing temperature. The maximum temperatures of both the superconducting and secondary coils are about 200 K. The results demonstrate that the designed circuit can protect the coil safely even though the initial decay time constant increases by a factor of ten. The circuit also reduces the terminal voltage.

6. Conclusions

An internal energy dump concept has been demonstrated by applying it to the LHD-type fusion reactor FFHR. The analysis confirmed that the coil of the FFHR can be protected from a quench using an internal energy dump. The magnetic energy can be absorbed into the superconducting coil while the coil temperature increases to about 200 K. Quench back, which is necessary for the internal energy dump, can be induced using a shorted secondary coil consisting of copper wires. The maximum terminal voltage can be reduced by a factor of ten compared with the conventional external energy dump. The results demonstrate that the internal energy dump can be a key technology for large superconducting magnets for fusion reactors.

Acknowledgements

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