Conceptual Design of DC Power Supplies for FFHR Superconducting Magnet*)

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The force-free helical reactor (FFHR) is a helical-type fusion reactor whose design is being studied at the National Institute for Fusion Science. The FFHR will use three sets of superconducting coils to confine the plasma. It is not a fusion plasma experimental device, and the magnetic field configuration will be optimized for burning plasma. This paper introduces a conceptual design for a dc power system to excite the superconducting coils of the FFHR. In this design, the poloidal coils are divided into a main part, which generates a magnetic field for steady-state burning, and a control part, which is used in the ignition process to control the magnetic axis. The feasibility of this configuration was studied using the Large Helical Device coil parameters, and the coil voltages required to sweep the magnetic axis were calculated. It was confirmed that the axis sweep could be performed without a high output voltage from the main power supply. Finally, the power supply ratings for the FFHR were estimated from the stored magnetic energy.

Keywords: dc power supply, fusion reactor, FFHR, superconducting magnet

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1. Introduction

A force-free helical reactor (FFHR) consists of a series of helical-type fusion reactors that operate under a magnetic confinement like that of the Large Helical Device (LHD) [1,2]. A helical-type reactor is suited to steady-state operation and has the advantage that the electro-magnetic force acting on the helical coil is balanced. In particular, the overturning forces on helical coil become zero in the top and bottom positions, so a simple self-supporting structure that can provide a large space for vertical ports is required [3]. Designs for various FFHR models have been studied; the main parameters of typical models are shown in Table 1. In this table, FFHR-2 ml is a previous model suitable for a fusion power plant, and FFHR-dl is a demo fusion reactor currently under study. These reactors have three sets of dc superconducting coils that create the magnetic field that confines the plasma. These three coils are helical, inner vertical (IV), and outer vertical (OV) (Table 2). The FFHR is not an experimental fusion plasma device but a fusion power plant, and the requirements of the power system for the superconducting coils differ from those of the LHD For example, the magnetic field configuration will be optimized for steady-state plasma burning and the flexibility of the magnetic field control will be minimized. For the same reason, the power system that excites the superconducting coils must be simple and optimized for this type of operation. In the following sections, a conceptual design for the FFHR power supply is presented.

Table 1 Design parameters of a typical FFHR model.

Design parameters	FFHR-2m1	FFHR-d1
Field periods, m	10	10
Plasma major radius, R_p [m]	14.0	14.4
Plasma minor radius, a_p [m]	1.73	2.54
Magnetic field, B_0 [T]	6.2	4.7
Coil major radius, R_c [m]	14.0	14.6
Coil minor radius, a_c [m]	3.22	3.8
Electron density, $n_{e(0)}$ [$10^{19}\mathrm{m}^{-3}$]	26.7	25
Temperature [keV]	$T_i = 15.8$	$T_e = 10.5$
Fusion power, PF [GW]	1.9	3.0
Magnetic stored energy [GJ]	154	(Under estimation)

Table 2 Magnetomotive force of superconducting coils for FFHR [MA].

Coil	FFHR-2m1	FFHR-d1
Helical coil	43.26	36.67
OV coil	−22.53	−19.88
IV coil	−11.61	18.50

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Table 3 Specifications for superconducting coils in FFHR-2m1.

Coil	Current [kA]	Turn num.	Effective induct. [H]	Voltage* [kV]
Helical coils, From Ha1 to Ha8 and Hb1 to Hb8	100.1	54	2.91	7.3
OVu1, OVl1	−100.1	110	1.60	4.0
OVu2, OVl2	−100.1	115	1.67	4.2
IVu, IVl	−100.1	116	−0.17	−0.44

* With quench protection
Time constant of current decay during quench protection is 20 s.

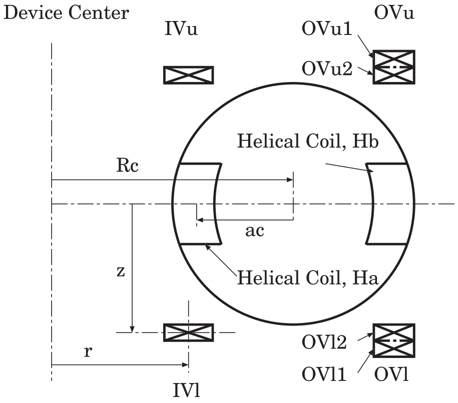
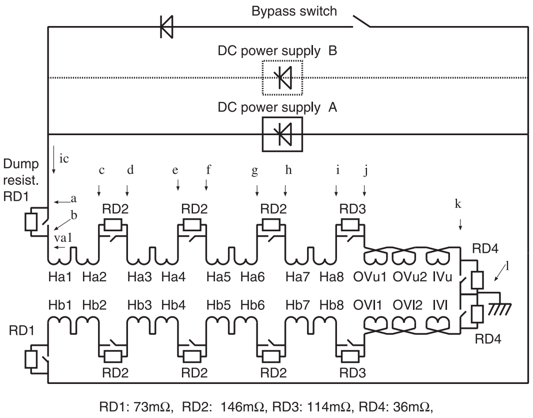
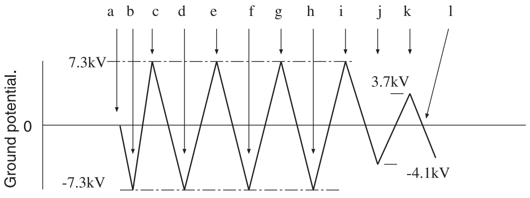


Fig. 1 Coil arrangement of FFHR-2m1.



(a) Circuit diagram



(b) Ground potential of coil terminals in quench protection.

Fig. 2 Circuit diagram of FFHR-2m1 superconducting excitation.

2. Design Concept for Power System for FFHR Superconducting Coils

2.1 Power system for FFHR-2m1

To elucidate the concept, the power system for FFHR-2 ml is presented first. The following conditions and requirements apply to the dc power supply:

1. The magnetic field is only steady state, and dynamic control of, for example, the magnetic axis shift is not required.
2. The coils should be excited during one night.
3. With quench protection, the ground potentials of the coil terminals are less than 8 kV.

Under these conditions, the following power system with a low-voltage dc power was designed.

First, the operating currents of the superconducting coils, which are shown in Fig. 1, were set to the same value, with the turn numbers of the coils selected as shown in Table 3. Each helical coil was divided into eight blocks, and the OV coils were divided into two blocks to reduce the induced voltage. With this setting, all the coils can be connected in series and be excited by a single dc power supply, as indicated I in Fig. 2 (a) by a solid line.

In this configuration, the same current flows through all the coils, so the effective inductance, which is related to the induced voltage, becomes the sum of the self and mutual inductances of the coil. The effective inductance and voltages for each coil are shown in Table 3.

The dump resistors were connected in series and distributed so as to reduce the ground potential, as shown in Fig. 2 (b). The switches connected to the dump resistors in parallel are opening switches that operate when quench is detected. Operational failure of these switches results in a higher ground potential of the superconducting coils; therefore, redundancy is necessary, for example, by connecting two switches in series.

In this configuration, every coil operates with the same current and the electro-magnetic forces on the helical coil are always balanced. Simultaneously, it is easier to control the current because there is no need to consider the magnetic coupling between coils.

A standby power supply, shown in Fig. 2 as “Power supply B” and indicated by dashed lines, is used as a backup to increase the system’s reliability. If a certain problem is detected in “Power supply A”, the current is transferred to B according to the following procedure:

1. The bypass switch is turned on, and power supply A is shut down. Then, the coil current is transferred to the bypass switch.
2. Power supply B starts operating and generates a small positive voltage. Then, the coil current is transferred from the bypass switch to power supply B. Next, the bypass switch opens, and the exchange of power supplies is completed.

The technique for current transfer between a mechanical switch and a thyristor rectifier has already been developed and used in the LHD [4].

2.2 Power system for FFHR-d1 demo reactor

After the design study of FFHR-2m1, the focus changed to the FFHR-d1 demo reactor. The power system concept for FFHR-d1 is inherited from FFHR-2m1, but the following requirement must be added. When the fusion plasma is heated, the plasma axis moves as the heating progresses and this movement must be canceled by controlling the magnetic field.

To control the magnetic axis, the following two-coil set system is considered.

Main coil set This set is used to create the basic magnetic field for operation. The axis of the magnetic field is optimized for steady-state plasma burning.

Control coil set This coil set generates a vertical field and is used to shift the magnetic axis while the plasma heating process proceeds toward ignition.

A feasibility study of this system requires the detailed parameters of the coils, but they have not yet been determined for FFHR-dl. Therefore, we use the parameters of the LHD, whose magnetic field configuration is similar to that of FFHR-dl.

3. Feasibility Study for Two-Coil Set System Using LHD Parameters

The LHD has three sets of poloidal coils [4] but the magnetic field configuration is similar to that of FFHR-d1, so the results can be applied to FFHR-d1 with slight modifications.

Figure 3 shows the coil configuration and Fig. 4 shows the power system for excitation when a two-coil system is applied to the LHD. The control coils for the vertical field are placed on the main poloidal coils. For the helical coils, it is difficult to place additional coils because of their complex form; therefore, we will not use control coils.

Table 4 shows the coil currents of the LHD when the magnetic axis R_p is assumed to be 3.55 m for steady-state operation, and $R_p = 3.6$ m is used for start-up. The currents at $R_p = 3.6$ m were separated into a main coil component, proportional to the values for $R = 3.55$ m, and a control coil component, obtained by subtracting the main coil current from the total current, as shown in Table 5. To connect these coils in series, the turn numbers were adjusted to produce the same coil current. After adjusting the turn number, the coil parameters attain the value as that shown in Table 6. In this table, the turn numbers are not integers, but we considered them as integers because this is only a feasibility study. Negative turn numbers indicate that the coil must be reversed, as shown in Fig. 4. With these turn numbers, each element in the inductance matrix was transferred with the following relation,

$$L'_{i,j} = \frac{n'_i n'_j}{n_i n_j} L_{i,j}, \tag{1}$$

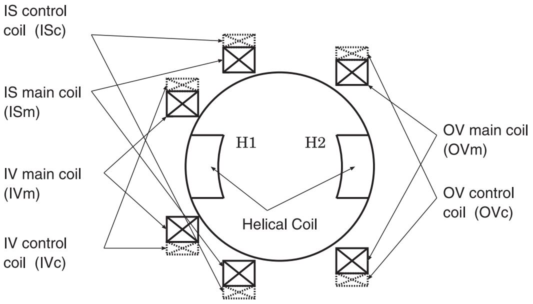


Fig. 3 Assumed coil arrangement of LHD.

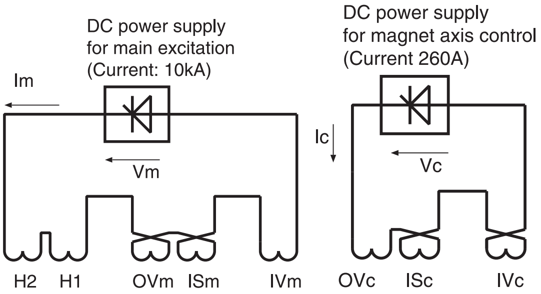


Fig. 4 Main and control coil excitation for LHD.

Table 4 Operating points of LHD superconducting coils.

	H1, H2	OV	IS	IV
Turn number	450	144	208	240
Current [A] ($R_p = 3.55$ m)	9,861	−16, 358	−2, 183	10,875
Current [A] ($R_p = 3.60$ m)	10,000	−16, 333	−2, 733	10,271

Table 5 Current values of main and control coil sets for the LHD. ($B = 2.75$ T, $R = 3.60$ m).

	H1, H2	OV	IS	IV
Turn number	450	144	208	240
Total current [A]	10,000	−16, 333	−2733	10,271
Main coil set [A]	10,000	−16, 589	−2, 213	11,028
Control coil set [A]	-	255.6	−5192	820.3

where L and L' denote the original and converted inductances of the LHD [5], and n and n' denote the original and adjusted turn numbers, respectively. The total inductance for the series-connected circuit was calculated as the sum of all the inductances, as shown in Table 7.

The required coil voltage can be calculated using the following equation:

$$[V] * T = [L][dI], \tag{2}$$

where, $[V]$ is the terminal voltage vector, $[L]$ is the inductance matrix shown in Table 7, $[dI]$ is the differential current between $R = 3.55$ m and 3.6 m, and T is the sweep time, respectively. The result of the calculation is shown in Table 8. For case 1 in this table, the magnetic field is maintained at 2.75 T at the magnetic axis. In this case,

Table 6 Coil parameters after turn number adjustment.

	H1, H2	OV	IS	IV
Main coil set				
Turn numbers of the main coil	450	−233.88	−46.05	264.7
Current at $R = 3.55$ m	9,861 A	←	←	←
Current at $R = 3.60$ m	10,000 A	←	←	←
Control coil set				
Turn number	-	144	−422.6	−918.8
Current at $R = 3.60$ m	-	255.6 A	←	←

Table 7 Inductance matrix of series connected LHD coil.

	Main coil	Control coil
Main coils	11.29 H	−5.81 H
Control coil	−5.75 H	14.04 H

Table 8 Terminal volt-second for the axis shift.

	Control coil current	Volt-sec of coils	
		Main	Control
Case 1 $B = 2.75$ T	255.8 A	73 Vs	2,792 Vs
Case 2 $B = 2.748$ T	255.4 A	−0.1 Vs	2,825 Vs

some voltage is necessary for driving the main power supply when the magnetic axis is swept. It is approximately 1/40 of the voltage supplied by the control power and can be supplied by the main power. If the magnetic field is decreased by approximately 0.1%, the main coil voltage can be almost zero, as shown in case 2. In this second case, the main power does not charge the coil system even though it supplies current to the coils. This result demonstrates that a small adjustment in magnetic field or coil position can reduce the voltage required by the main power supply if the required voltage is not sufficiently small when this configuration is applied to FFHR-dl.

4. Operation Scenario and Power Supplies for FFHR-d1

The magnetically stored energy of FFHR-dl has not yet been calculated, but it is presumed to be approximately 200 times larger than that of an LHD designed from FFHR-2ml's parameters. The stored energy E is obtained as

$$E = \frac{1}{2}[i]^t[L][i], \qquad (3)$$

where $[i]$ and $[i]^t$ are the current vector and its transpose, respectively. If the operating current of the FFHR-dl coils is set to 100 kA, which is 10 times greater than that of the LHD, the inductance becomes 2 times greater than that of the LHD, as shown in Table 9.

Table 9 Estimated coil parameters for FFHR-d1.

	Current	Inductance	
		Main coil	Control coil
Main coil	100 kA	22.4 H	−11.6 H
Control coil	2.6 kA	−11.6 H	28.1 H

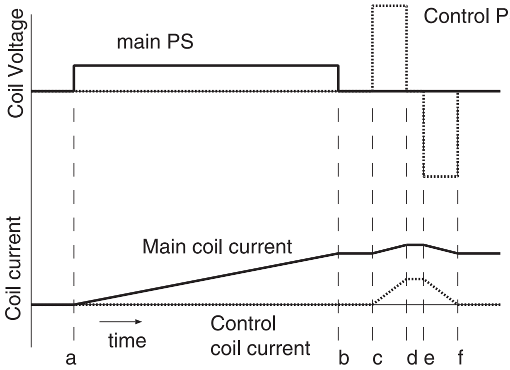


Fig. 5 Voltage and current waveforms when FFHR superconducting coils are excited.

Table 10 Main specification of power supply for FFHR.

	Current	Voltage	Capacity
Main coil	100 kA	80 V	8 MVA
Control coil	2.6 kA	16 V	40 kVA

Figure 5 shows an excitation scenario of the FFHR-d1 superconducting coils. In each part, the coils and the dc power supplies act as follows:

a-b The main coil set is excited. During this period, the control coil set is opened. This period lasts about 8 h.

c-d The magnetic axis shifts to the starting point. In the FFHR, this period is assumed to last for approximately 1 h.

e-f This period is the ignition state. Here the magnetic axis returns to the steady-state operating point as plasma heating progresses.

With the estimated inductance matrix and current sweep rate obtained from Fig. 5, the required output voltage and capacity of each power supply for FFHR-d1 are calculated as shown in Table 10. The output voltage of the main power supply became low enough during the long excitation time, and the output voltage of the control power supply was also low. The inductance can be varied according to the detailed design of the superconducting coils, which changes the voltage required by the power supply, but the essential situation does not change because the parameters of the FFHR-d1 magnetic field are based on those of the LHD. The required extent of axis shift in the ignition stage may also change, but the calculated voltage shown in Table 10 is low enough, and the increase in the output voltage for controlling the power supply is acceptable.

5. Summary

In this paper, the power systems for the FFHR superconducting coil are presented. A simple excitation system in which all the coils are connected in series and excited by a single power supply was designed for FFHR-2 ml, which requires only steady-state excitation. The system was expanded to use two coil groups, the main and control coil sets for FFHR-dl, which require the magnetic axis to shift. In the expanded system, the control set is used only during fusion plasma ignition, and it is stopped during steady-state operation. The detailed FFHR-dl parameters are not yet fixed; therefore, the required voltages for the magnetic axis shift were calculated using the LHD coil parameters. The results showed that the shift operation can be performed with zero voltage with respect to the main power supply. These results were applied to FFHR-dl, and the ratings of the power supplies were estimated. The results confirmed that the voltage required by the main power supply to control the axis is still low, although the stored energy in FFHR-dl is 200 times larger than that in the LHD.

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[1] A. Sagara *et al.*, Fusion Eng. Des. **83**, 1690 (2008).
[2] A. Sagara *et al.*, to be published in Fusion Sci. Technol.
[3] S. Imagawa *et al.*, Nucl. Fusion **49**, 076017 (2009).
[4] H. Chikaraishi, Fusion Sci. Technol. **58**, 586 (2010).
[5] H. Chikaraishi *et al.*, IEEE Trans. Appl. Supercond. **12**, 1374 (2002).