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Keywords

«Nuclear fusion », «DC power supply », «ZCZVS converters »

Abstract

A helical-type fusion facility uses a large-scale superconducting DC magnet. To maintain the coil current of this magnet during steady-state operation, a large output current supplied by a very-low-voltage power supply is necessary. For this purpose, a DC power supply using a mechanical contact as a switching device was designed, and a small model of the contact was tested.

Introduction

A helical-type fusion plant or fusion plasma experimental facility uses a large-scale DC superconducting magnet to confine the fusion plasma. For example, the Large Helical Device (LHD), which is operated at the National Institute for Fusion Science (NIFS), uses a DC superconducting magnet set with a stored energy of about 1 GJ, and the Force-Free Helical Reactor (FFHR)[2], which is under design at the NIFS, will use a 170-GJ-class DC superconducting magnet.

The main parameters of the magnet are listed in Table I. For the superconducting magnet of FFHR, its operating current will be 100 kA. This superconducting magnet is operated under DC conditions and the voltage required to maintain the coil current in the steady state is very low, even though the current is large. For example, the coil voltage of the helical coil of the LHD is about 10 mV in the steady state, even though the operating current is greater than 10 kA. For the FFHR, the terminal voltage in the steady state is estimated as about 100 mV, as in Table I.

Table I: Required DC power supplies for the superconducting magnets of fusion facilities.

Coil	FFHR	Helical coil of LHD	OV coil of LHD
Operating current	100 kA	10 kA	24 kA
Inductance	25 H	3 H	1.2 H
Voltage drop during steady-state operation	(<0.1 V)	<10 mV	<10 mV

In the existing plasma experimental devices including the LHD, we use DC power supplies with semiconductor switching devices to control the coil current, but the voltage drops are much higher than the output voltage; thus the efficiency during the steady-state operation becomes almost zero. To resolve the above situation, we have begun to design an extra low voltage DC power supply that operates under cryogenic condition[4]. For such large-scale coils, the inductance will be large, and the required voltage is low. Then, the current ripple will become sufficiently low when the converter operates at a low

switching frequency. For this low-frequency power supply, we present a power supply using mechanical contact driven by a piezoelectric actuator, and a small test device was built and tested [5]. With these experiments, it is confirmed that the piezoelectric-actuator-driven mechanical contact has a sufficient switching speed for a rectifier, but the contact resistance is too high. After this experiment, we modified the configuration of the piezoelectric-actuator-driven contact, constructed a small main circuit module that uses two or four contacts, and tested the basic characteristics of the contacts.

In this paper, the outline of the power supply for fusion plant is introduced. Next, a configuration and outline of the proposed low-voltage power supply is presented. Finally, a test device for the piezoelectric-actuator-driven contact and its test results are introduced.

1 Outline of the DC power supply for a fusion plant

The FFHR consists of a series of helical-type fusion reactors that operate under magnetic confinement, similar to those of the LHD [2]. A helical-type reactor is suited for steady-state operation and has the advantage that the electromagnetic force acting on the helical coil is balanced. The FFHR has superconducting coils for creating a magnetic field.

For a conventional plasma test facility such as the LHD, each coil is excited by a separate power supply. For example, LHD has six coils, which are denoted as HO, HM, HI, OV, IS, and IV, and they are excited with six DC power supplies, as shown in Fig. 1. This configuration requires the same number of power supplies as coils [3], but this has the advantage that each coil current can be controlled independently.

Fig. 1: DC power supplies for exciting the superconducting coils of the LHD

However, this configuration has following disadvantages. Every coil requires large-sized current leads to connect the superconducting coils and power supplies. If one of the power supplies fails, the balance of magneto-motive forces generated by the coils is broken, causing an unbalanced electromagnetic force in the FFHR superconducting magnet.

In contrast, DC power system for the FFHR has another concept, described as follows. 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 burning plasma, and the flexibility of the magnetic field control will be minimized. Moreover, the power system that excites the superconducting coils should be simple and optimized. At the same time, the FFHR has many superconducting coils, and the use of a similar configuration is difficult. Therefore, a different approach has been planned.

Figure 2 shows the configuration of the new power system. Each coil is tuned to have the same operation current, and all coils are connected in series. When we ramp up and ramp down the coil current, power supply 1, which is medium-voltage power supply with conventional configuration, is used. At the flat top of the coil current profile in Fig. 2(b), the exciter is switched to power supply 2, which is a low-voltage power supply during steady-state operation. For power supply 2, we are planning to apply a power supply using piezoelectric-actuator-driven mechanical switches.

2 Power supply using piezo-electric-actuator driven mechanical switch

One of the key points for the design of the converter is the operating frequency of the main circuit. Because the load inductance exceeds 10 H and the DC source voltage is 0.1 V, the ripple current becomes less than 1 mA when we operate the rectifier at 0.1 Hz. This ripple current is negligibly small compared with the operating current of 100 kA. With this low switching frequency, a mechanical contact can be used as the switching device instead of a semiconductor power device.

Figure 3 shows a conceptual circuit diagram of the proposed DC power supply. In this circuit, a PWM inverter generates rectangular voltage with a frequency of 0.1 Hz that is supplied to a superconducting transformer. The induced voltage is stepped down to 0.1 V by this transformer, and its secondary winding is connected to a rectifier using mechanical contacts that are driven to synchronize with the input voltage.

Fig. 2: Circuit diagram of the DC power supply for the superconducting coils for the FFHR.

Fig. 3: Diagram and operation pattern of the half-bridge configuration of the low-voltage DC power supply.

The operation frequency of this transformer is very low compared with the usual one. In this case, the size of the transformer may become the bottleneck. When we assume that the second voltage V_2 is 0.1 V and the number of turns N_2 is 4, the required change in the magnetic flux $\Delta\Psi = V_2 T / N_2$ becomes 0.13 Wb. If the maximum magnetic flux density B_{max} of the iron core is ± 1.0 T then the cross section of the core becomes 0.06 m², and the core size becomes approximately 0.3 m $\times$ 0.6 m $\times$ 0.6 m, which is sufficiently small.

To regulate the load current I_3 , the pulse width T_1 is controlled, and the average output voltage V_3 is controlled.

In the previous work, we conducted research based on the full-bridge configuration[4, 5], but the half-bridge configuration has the advantage that the number of the series switches is one, which is advantageous from the viewpoint of the voltage drop at the switch; however, the voltage applied to the opened switch is doubled. When we use a mechanical conductor as a switching device, the applied voltage does not matter because its gap has a sufficient standing voltage compared with the operating voltage. For the superconducting transformer, we change the configuration of the main circuit to a half bridge.

This configuration has the following advantages.

- The driving inverter works for a small current; thus, the power loss in the inverter becomes small.
- The transmission current to the cryogenic area becomes small; thus, the current lead becomes small.
- After attaching a superconducting cable to the winding of the transformer and connecting cables, the power loss in the main circuit decreases.
- The output voltage is controlled with primary voltage V_1 using the driving inverter; thus, it is not necessary to perform the PWM operation in the synchronous rectifier.

This power supply is loaded with a large inductance and overlapping switching is necessary to maintain the current path, as shown in Fig. 3(b). When both switches are closed, a current loop exists as shown in Fig. 4(a) and a control sequence for suppressing the excessive loop current and current reverse at the switch are presented. The commutation process shown in Fig. 4(b). The steps are as follows.

a: The driving inverter output voltage goes to zero.

Fig. 4: Loop current in the main circuit and commutation control of the rectifier.

- b:** S2 closes with zero voltage.
- c:** The driving inverter generates a small negative voltage, and the load current is transferred to S2.
- d:** When the current flowing through S1 becomes zero, the driving inverter output voltage returns to zero.
- e:** S1 is opened at zero current.
- f:** The driving inverter generates a negative voltage.

Table II: Specifications of the extra-low-voltage DC power supply.

Output current	100 kA
Output voltage	0.1 V
Inductance of load	25 H
Driving inverter	
Voltage and current	200 A, 50 V
Capacity	10 kVA
Transformer	
Primary winding	200 A, 2000 turns
Secondary winding	100 kA 4 turns
Cross-sectional area of the core	0.13 m ²
Size	0.3 m × 0.6 m × 0.6 m
Weight	approx. 1.6 t
Switching device	mechanical contact driven by piezoelectric electrical driver
Driving voltage	150 V

2 Main specifications

With the above considerations, the main specifications of the proposed low-voltage power supply are summarized in Table II.

3 Experiments with the piezoelectric-actuator-driven device

The piezoelectric-actuator-driven contact and main circuit module are the important components. Therefore, a small demonstration device has been fabricated to confirm its operation at room temperature.

Two types of the piezoelectric-actuator-driven switches are shown in Fig. 5. In a previous paper[5], we selected a double contact model, which is shown in Fig. 5(a) because it does not need a flexible

conductor and appears to be suitable for cryogenic applications. However it has the disadvantage that two contacts are connected in series and control of the two gaps is difficult. Therefore, we use the simpler configuration shown in Fig. 5(b) in the next step.

Fig. 5: Configurations of piezoelectric-actuator-driven contacts.

(a) Photograph of the contact module.

(b) Close-up photograph of the mechanical contacts.

Fig. 6: Photographs of the tested module for the piezoelectric-actuator-driven contacts.

Photographs of the test module are shown in Fig. 6. The half-bridge rectifier needs only two switches, but we built four piezoelectric-actuator-driven contacts in one module because it will be used for the full-bridge circuit after the experiments with the half-bridge. The specifications of the piezoelectric actuator used in the model are listed in Table III.

3 Steady state operation test

First, we performed steady-state experiments to measure the turn-on and turn-off voltages for each switch. Figure 7 shows the experimental setup. In these experiments, the piezoelectric actuator is driven with a current source and is charged and discharged with a constant current of 2 mA. The piezoelectric actuator works as a capacitor with the equivalent model. Then, the drive voltage is ramped up and down with constant rates determined by its capacitance and the drive current. Figure 8(b) shows that contact D turns on at 51 V and turns off at 37 V.

This piezoelectric actuator has a stroke of $132 \mu\text{m}$ at a drive voltage of 150V under no-load conditions, and its maximum force is 1 kN. The gap length between contacts is estimated from the turn-on and turn-off voltages as $33\text{--}45 \mu\text{m}$. To induce force to the conductor switch, the gap will be set at about half of the no-load stroke of the driving voltage of 100 V. In this situation, the stroke is about $40 \mu\text{m}$, and the force

Table III: Specifications of the piezoelectric-actuator

Model	PZA 12-6 (Matsusada precision)
Case diameter	12 mm
Case length	122 mm
Stroke with no load	132 μm
Output	1000 N
Drive voltage	0–150V

Fig. 7: Experimental setup for steady state operation test.

will be 550 N. The moving conductor has an effective surface area of 26 mm². Thus, the contact force and pressure at the rated voltage will be about 371 N and 14 MPa, respectively .

Fig. 8: Drive voltage and terminal voltage during steady-state operation.

For the tested contacts, the excitation is more than doubled. The curves for the voltage drop versus the drive voltages are shown in Fig. 8. The turn-on and turn-off voltages and the on-state resistance are different for each switch, but scattering is small, as shown in Fig. 8(b).

3 Dynamic characteristics

Next, the turn-on and turn-off delay times are measured with the test circuit shown in Fig. 9. A series resistor is inserted into the drive circuit in order to limit the driving current and the movement of the contact. In a previous study[5], we used 100 Ω as a series resistor, but the movement of the conductor was too fast and it impacted the counter electrode forcibly, Thus, we increase the series resistor to 2.2 k Ω for soft operation.

Figure 10 shows the turn-on characteristics with the given test circuit. The drive voltage rises with a time constant of 25 ms, which agrees with the time constant calculated with the estimated capacitance and series resistance. The time delay for turn on is estimated to be 25 ms in Fig. 10. Figure 11 shows turn-off characteristics. The turn-off characteristics also show a delay time of 35 ms.

Each of the measured turn-on and turn-off delays is sufficiently shorter than the required operation delay of the contacts for the presented operation sequence.

Fig. 9: Experiment setup for the response test.

(a) Waveform of the drive voltage.

(b) Waveforms of the terminal voltage and current.

Fig. 10: Drive and terminal voltages at turn on.

(a) Waveform of the drive voltage.

(b) Waveforms of the terminal voltage and current.

Fig. 11: Drive and terminal voltages and terminal current at turn off.

4 Summary

We conceptual design o a DC power supply that has a large output current at a very low voltage using piezoelectric-actuator-driven contacts. The power supply operates with a very low switching frequency such as 0.1 Hz. A small test module of piezoelectric-actuator-driven switch was produced and a basic test was performed. We are fabricating a test converter with this module and are planning an operational test at room temperature.

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