# Extra-Low-Voltage DC Power Supply for Large-Scale Superconducting Coil for Fusion Device



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# Extra Low Voltage Dc Power Supply for Large Scale Superconducting Coil for Fusion Device

Hirotaka Chikaraishi, *Member, IEEE,* and FFHR Group

***Abstract*—A helical type fusion reactor uses huge scale dc superconducting magnets driven up to 100 kA DC to make a steady state magnetic field to confine the fusion plasma. The required voltage to keep the current in the steady state operation is close to zero, thus a dc power supply is required whose output rating is 100 kA and 0.1 V. To realize such low voltage power supply, a converter that works under low frequency such as 0.1 Hz is applicable due to the large load inductance. Having such a low frequency and voltage operation, mechanical contacts driven by piezo devices can beneficial be used as switching devices in the converter. With this switching device, the forward voltage drop becomes lower than the semiconductor devices and the power loss in the steady state can be reduced. A conceptual design of this converter have been made confirming the operation of a piezo driven mechanical switch device in dc power supply.**

***Index Terms*—extra low voltage, dc power supply, piezo actuator**

## I. Introduction

IN the National Institute for Fusion Science (NIFS) in Japan, projects related to fusion energy are ongoing. One is the "Fusion Engineering Research Project" which is researching a helical type fusion plant is aimed to be a "Force Free Helical Reactor (FFHR)"[1][2]. Such of a large fusion plant uses a large dc superconducting magnet to generate the magnetic field confining the fusion plasma.

For example, a superconducting magnet of FFHR stores over 170 GJ of magnetic energy and its operating current will be 100 kA. These superconducting coils making up the magnet are operated in dc condition, and the required voltage to keep the current in the steady state is very low although their large current.

The existing plasma experimental devices including Large Helical Device (LHD) use dc power supplies with semiconductor switching device to control the coil current[3], but their voltage drop in the power supplies are much higher than the output voltage so the efficiency during the steady state operation becomes very low. To resolve the above situation, we have started to design an extra low voltage dc power supply that operates in cryogenic condition.

Using such large scale coils, their inductance will be large and the required voltage low. This means that the current ripple becomes low even though the converter works at low switching frequency. Recently, flux pumps which use superconducting switches have been studied for similar applications[4][5] but we have challenged by a new approach which uses mechanical switches.

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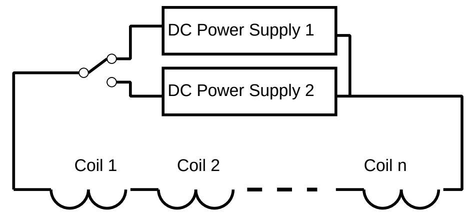
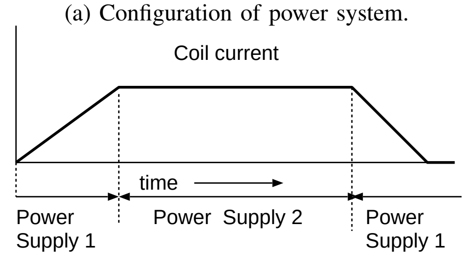



(a) Configuration of power system.




(b) Coil current and power supplies for excitation.

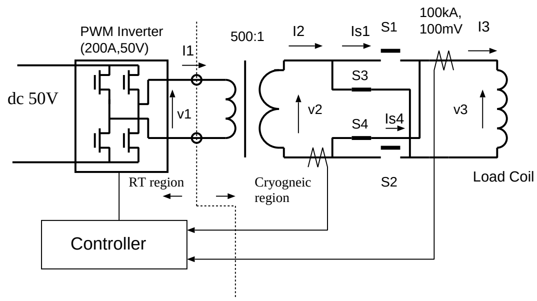
Fig. 1. Circuit Diagram of Dc Power Supply for Superconducting Coils for FFHR.

In this paper, first, the outline of the dc power system for superconducting magnet of FFHR is introduced. Next, a concept of low voltage power supplies that uses mechanical contact is proposed. In this concept, mechanical contact is a key device, then a small model is made and tested.

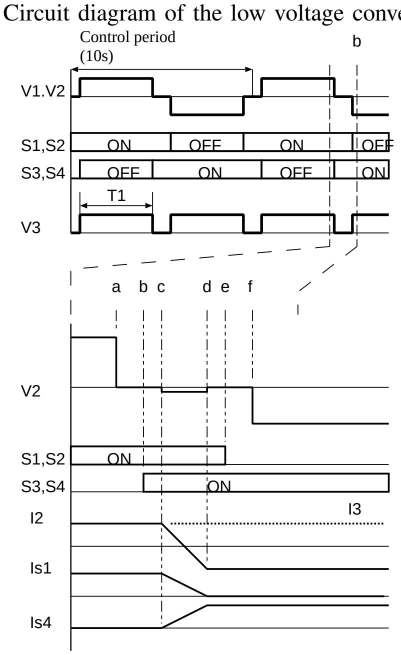
## II. Outline of a Power System for a Fusion Magnet

The FFHR has superconducting coils to create the magnetic field. For the conventional plasma test facility such as LHD, each coil is excited by a separated power supply, but this configuration requires the same amount of power supplies than coils [3]. The FFHR has many superconducting coils and using similar configuration is difficult therefore a different approach has been planned. Fig. 1 shows a configuration of the new power system. Each coil is tuned to have the same operation current and all are connected in series. With this one conventional medium voltage power supply can excite all coils when ramping up or down as shown in Fig. 1(a), and at the flat top the current can be switched to power supply 2, which is at steady state operation a low voltage power supply, as shown in Fig. 1(b).

When ramping up and ramping 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 the exciter is switched to power supply 2, which is a low voltage power supply at steady state operation, as shown in Fig. 1 (b).




(a) Circuit diagram of the low voltage converter.




(b) Operation sequence of the converter.

Fig. 2. Diagram of Low voltage Converter and its Operation Sequence.

## III. Conceptual Design of Power Supply

One of the key points for design of the converter is the operating frequency of the main circuit. This is related to selection of the switching device. The lowest switching frequency is limited by the current ripple and the size of the transformer used in the power supply. The amplitude of current ripple $I_r$ is estimated using the output voltage $V_o$, load inductance $L$ and the switching period $T$ as $V_oT/(2L)$. $L$ exceeds 10 H and $V_o$ is about 0.1 V. Because the steady state coil current is from 10 kA to 100 kA, the ripple current of 1 mA is negligible small. The previous equation gives the limit of $T$ longer than 20 s. Thus we select as a switching period 10 seconds for the conceptual design of the power supply [6]. When the switching period is this long, a mechanical contact can be use as the switching device instead of a semiconductor power device.

Fig. 2 shows conceptual circuit diagrams of the presented dc power supply and its operation sequence.

In this circuit the PWM inverter supplies rectangular voltage of 0.1 Hz and the output is connected to a superconducting transformer. The secondary winding is connected to a rectifier using mechanical contacts that are driven to synchronize with input voltage. The controller in the figure performs current feed back and synchronous rectifier operation with zero current and zero voltage (ZVZC) switching. An example of operation sequence shown in Fig. 2 (b) is as follows, The inverter outputs zero voltage (a), then SW3 closes with zero voltage (b), and the inverter outputs small voltage controlled using PWM to transfer the current from SW1 to SW3 (c). After the current of SW1 becomes zero, SW1 opens with zero current (d) and the inverter outputs a negative voltage and then the sequence is completed (f). This sequence runs within 1 second, and it demands that the turn on and turn off delay of mechanical contact are less than 50 ms.

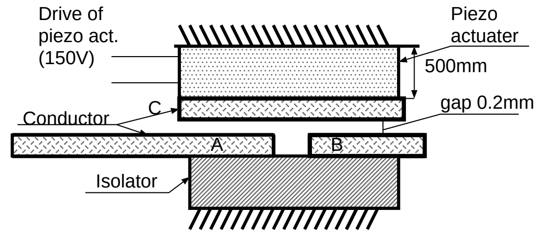



Fig. 3. Mechanical Switch using Piezoelectric Device.

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

To realize this configuration, a transformer whose size and weight may be large because of the low operation frequency and a mechanical contact must be designed. In the following subsection, each term is discussed.

### A. Low Frequency Transformer

In this power supply, the size of the transformer may become a challenge. We estimate the size under the condition that the second voltage $V_2$ is 0.1 V and the turn number $N_2$ is 4. The required magnetic flux $\Psi = V_2T/N_2$ becomes 0.12 Wb. Then the cross section of the core becomes 0.06 $m^2$ and the core size becomes approximately 0.25 m * 0.6 m *0.6 m when the maximum magnetic flux density $B_{max}$ of iron core is $\pm$ 1.0 T. This size is not so large and reasonable as a component of the power supply.

### B. Switching Device

The switching device is also a key component of the power converter. For this power supply, the mechanical contact is considered as a switching device. Because the secondary voltage is as low as 0.1 V, the narrow gap between conductors such as 0.2 mm, is acceptable. To drive the conductor switch, a piezoelectric actuator is suitable due to the required tiny stroke, its quick response, can generate an adequate high pressure, and has a low driving current. Furthermore, the piezoelectric device is already applied as a micro actuator in the cryogenic condition, and it has been proofed of cryogenic operation.

The stroke of the piezoelectric device is about 0.1 % of its length when the mechanical stress is zero. When it loads pressure, the piezoelectric device shortens by mechanical stress, thus more length is necessary. We consider the deformation caused by stress to be 60 % and selection the length of piezoelectric device to be 500 mm. In this switch, it is not necessary to control the position of the conductor. Then the piezoelectric device can be driven by a simple rectangle signal when the switch is closed, and this means that the configuration of its driver can be simple.

The concept of the piezo-driven contact is shown in Fig. 3. Two conductors A and B are put on an isolated plane, and a movement C is put on the piezo actuator. When the piezo actuator is driven, the contact C is pushed down and it bridges the gap between A and B.

### *C. Main Specifications of Low Voltage Converter*

With the above considerations, the main specifications of presented low voltage power supply are shown in Table I.

TABLE I
SPECIFICATION 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-section 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 | |
| Drive of switch | Piezoelectric electrical driver |
| Driving voltage | 150 V |
| Length | 500 mm |

## IV. EXPERIMENTS OF PIEZO DRIVEN CONTACT

The key device of this power supply is a piezo-driven conductor. Therefore a small demo device has been made to confirm its operation at room temperature. The specifications of the piezo device used in the model are shown in Table II. This piezo actuator has a stroke of 93 $\mu$m, but in no load condition. To induce pressure to the conductor switch, the gap will be set at about half of the no load stroke. With this situation, the stroke is about 40 $\mu$m and the pressure will be 550 N. The moving conductor part that is labeled C in the figure has a square shape of 20 mm * 20 mm with center hole of 5 mm, this gives an effective surface area of 380 $mm^2$. Thus, the contact pressure at rated voltage will be about 1.4 MPa.

TABLE II
SPECIFICATION OF PIEZO ACTUATOR

| Model | PZA 12-6 (Matsusada precision) |
|---|---|
| Case diameter | 12 mm |
| Case length | 112 mm |
| Stroke with no load | 90 $\mu$m |
| Output | 1000 N |
| Drive voltage | 0 - 150 V |

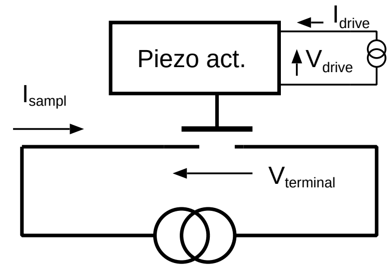
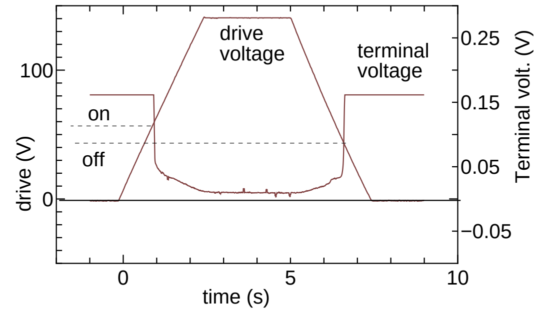
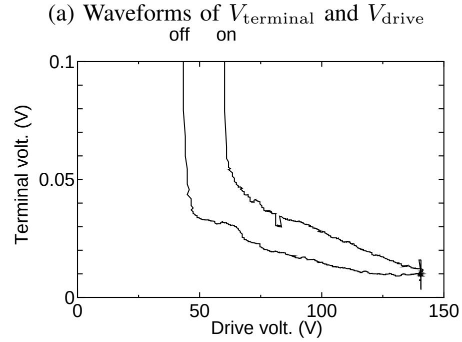



Fig. 4. Experimental Setup for Steady State Test.




(a) Waveforms of $V_{\rm terminal}$ and $V_{\rm drive}$




(b) Plots of $V_{\rm terminal}$ vs $V_{\rm drive}$

Fig. 5. Drive Voltage and Terminal Voltage of Steady State Test.

### *A. Steady state operation test*

First, we made a steady state experiment to measure the turn on and turn off voltage. Fig. 4 shows an experiment setup. In these experiments, the piezo actuator is driven with constant current source which is set to 2 A, and charge and discharge with constant current of 2 mA. The main terminal is connected to a current source and the terminal voltage drop is measured and the result is shown in Fig. 5. The piezo device works as a capacitor with the equivalent model. Then the drive voltage will ramp up and ramp down with constant rates decided by its capacitance and drive current. The ramp up and ramp down rate of the drive voltage are about 56 V/s, then the equivalent capacitance is estimated at 28 $\mu$F, that is three times larger than the specification. Fig. 5(a) shows that the conductor turns on at 60 V of drive voltage, and the voltage drop and the contact resistance decrease according to the increase of drive voltage. Finally, the terminal voltage drop and the contact resistance reaches to 11 mV and 5.5 m$\Omega$, respectively. This forward voltage drop is about 10 % of the converter output voltage and more low resistance is desirable for a switching device. When the drive voltage starts to ramp down, the contact resistance

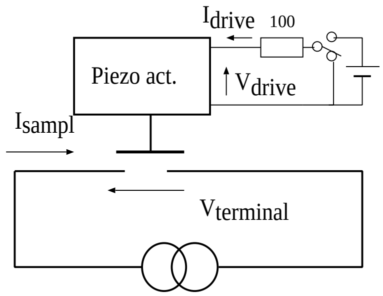
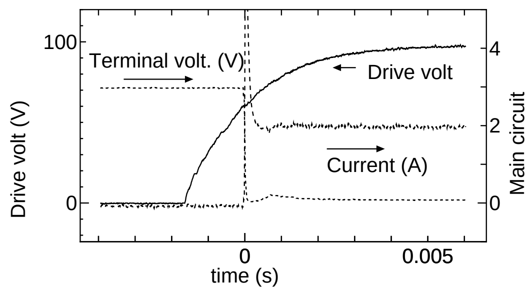
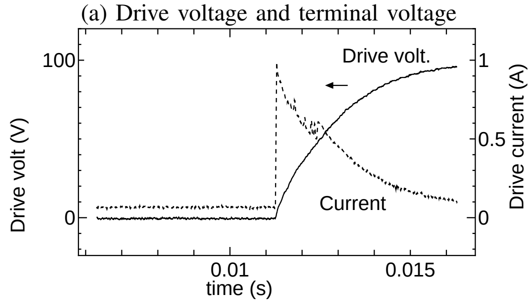



Fig. 6. Experiment Setup for Response.




(a) Drive voltage and terminal voltage




(b) Drive current.

Fig. 7. Drive and Terminal Voltage and Drive Current at Turn On.

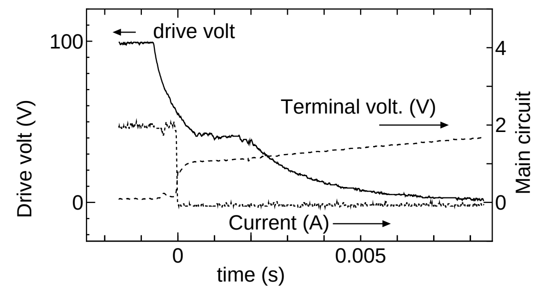
does not increase, and has hysteresis, as shown in the figure. Then, the pressure decreases according to the decrease of drive voltage and the contact resistance increases, and it reaches to 50 m$\Omega$ at 43 V of drive voltage. After that, the contact is opened and the turn off voltage is 42.5 V. From this turn on and turn off voltage, the effective gap of model is estimated as 25-36 $\mu$m and pressure at 140 V of driving voltage is about 0.7-0.9 MPa.

During the ramp up sequence, the driving voltage of the switch and its low contact resistance are not sufficiently fulfilled. Using a smaller moving conductor C will make a higher pressure at the turn on state thereby lowering the contact resistance.

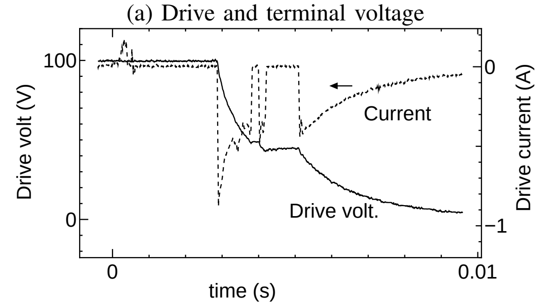
### *B. Dynamic characteristics*

Next, the turn on and turn off delay and driven current are measured with the test circuit shown in Fig. 6. The drive voltage is controlled with mechanical relay. A series resister is inserted to the drive circuit to limit the driving current.

Fig. 7 shows turn on characteristics with the given test circuit. The drive voltage rises with a time constant of 2.4




(a) Drive and terminal voltage




(b) Drive current

Fig. 8. Drive and Terminal Voltage and Drive Current at Turn Off.

ms and it agrees with the time constant calculated with the estimated capacitance and series resistor. The time delay of turn on is estimated to 2 ms in this figure. The drive current reaches 1 A and decays with time constant of its drive circuit.

Fig. 8 shows the waveforms of drive voltage, terminal voltage, and drive current at turn off. Because of the bounce of mechanical relay, the drive circuit is opened and current becomes zero during 38 ms $< t <$ 50 ms. The turn off delay is estimated less than 1 ms with this figure.

Each of the measured turn on and turn off delay is sufficient shorter than the maximum operation delay of the contacts for the presented operation sequence.

## V. Conclusion

A conceptual design of a large output current and extra low voltage dc power supply is made to excite the huge dc superconducting coil in steady state. Because of the large inductance of the load, extra low switching frequency such as 0.1 Hz is adequate from the view point of the current ripple. Based on this point, we proposed a conceptual design of a low voltage power supply that uses mechanical contacts as the switching device. Result shows that the size of transformer falls into the reasonable size even though it has to work under the very low frequency. Also, the mechanical contact driven by the piezoelectric movement is presented as a switching component and tested using a small model. The results show that the piezo driven contact has short on and off delay and these delays are sufficiently short for the presented power supply.

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