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Voltage Enhancement of the DC Power Supplies for Dynamic Current Control of LHD Superconducting Coils

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The fundamental operation of the helical-type reactor will be performed under the dc magnetic field. But in some situations such as start up of excitation, dynamic control of magnetic field will be required. Also the LHD operation requires dynamic control of magnetic field, and the output voltage of power supplies are enhanced using additional pulse power supplies for this purpose. With the pulse power supplies, the magnetic axis swing operation was realized. This configuration of the power supply is also adaptive to the fusion reactor.

Keywords: helical type reactor, dynamic current control, superconducting coil, pulse power supply

1 Introduction

The fundamental operation of the helical-type reactor will be performed under the dc magnetic field and the power supplies to excite the superconducting magnets will be optimized for the steady state excitation to minimize the loss, but in some situations such as start up of excitation, dynamic control of magnetic field will be required. For this dynamic operation, some additional power supply will be required. The LHD operation has similar situations. Its usual plasma operations are performed under the steady state magnetic field and the power supplies are optimized to the steady state operations. With the progress of the fusion plasma research, more dynamic experiments are planed and they require the dynamic control of magnetic field. For this purpose, the output voltages of power supplies are enhanced using additional pulse power supplies. This paper introduces the outline of the enhanced power supplies for the LHD superconducting coils and the test results using them.

2 Outline of the LHD power supplies

For the LHD, the superconducting coils are excited by six power supplies shown in Figure 1. To design the pulse power supplies for the LHD, the required voltages to dynamic magnetic axis control for the standard confinement are calculated. As the result, it was shown that the output voltage of the power supplies for IS and IV coils are bottle neck and we decided to boost these power supplies with construction of the additional high voltage power supplies.

Figure 2 shows the circuit diagram of the IV power supply. The steady state power supply shows the current power supply shown in Figure 2 and the pulse power supply means the additional one. As shown in figure, these two power supplies are connected in series and the both output voltages are induced to the coil. When some problem for the operation of super conducting coil is occurred, the pulse power supply must not disturb the operation of the protection circuit, so the insertion point is chosen as shown in the figure.

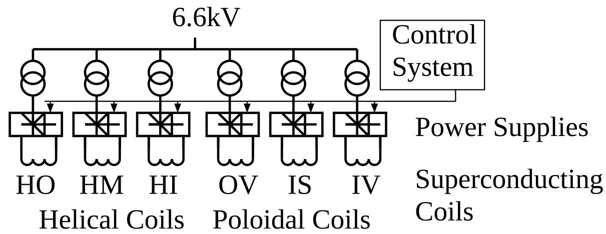

Fig. 1 Block diagram of the power supplies for LHD superconducting coils.

Table 1 shows the specifications of current power supply and additional power supply for IV coil. The output currents of steady-state power supplies are set to realize the 3 T of magnetic field at the plasma center. The output currents of pulse power supplies are decreased to reduce the construction cost.

Table 1 Specifications of the power supplies for IV coil

	current power supply	pulse power supply
Output voltage	33V	180 V
Output current	15.6kA	6.2 kA
Operating time	continuous	120 s
Duty ratio of operation	-	1/15

Because of the limitation of the operating current and

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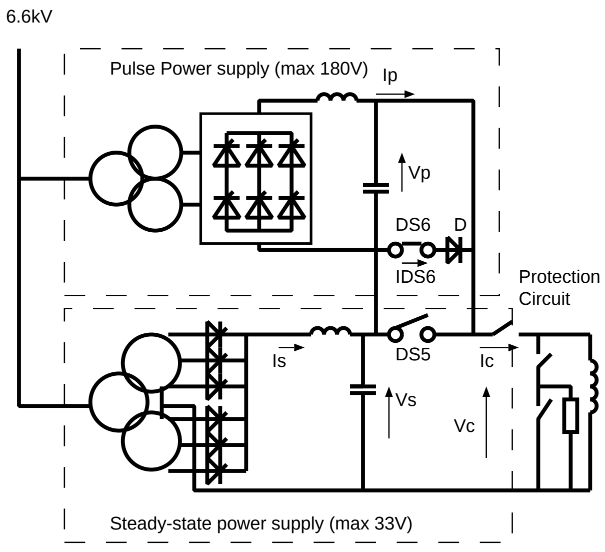


Fig. 2 Circuit diagram of the power supply for IV coil.

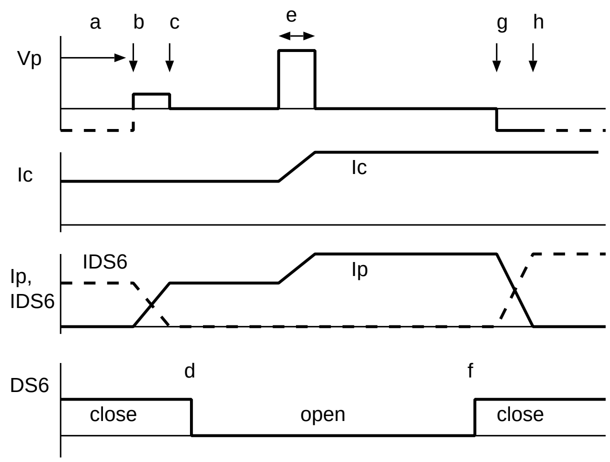


Fig. 3 Sequence of connection and disconnection of the pulse power supply.

time of the pulse power supply, two bypass switches are connected as shown in Figure 2. In the figure DS5 is a large current but slow operation switch and DS6 is medium current but quick operation switch. For the high magnetic field operation, which requires the higher current than 6.2kA, the DS5 is closed and the coil is excited by the steady state power supply only.

For the low magnetic field operation using pulse power supply, the DS5 is opened. In this situation, for the steady state operation, DS6 is turned on; the coil is excited by the DC power supply and the pulse power supply standby for operation. When the high voltage is required, DS 6 is turned off quickly then the pulse power supply is inserted in series and the coil current flows through the pulse power supply.

3 Connection and disconnection sequence of pulse power supply

The connection and disconnection of pulse power supply must be performed under the condition, that the coil current are flowing, without serge voltage occurred by the operation. Also any rush current in the circuit must be avoided in the sequence. Especially DS6 makes parallel circuit to the output of the pulse power supply, so additional diode D is inserted in series with DS 6 to block the shirt circuit current.

The insertion sequence of the pulse power supply is shown in Figure 3. The sequence runs as follows;

a Before the pulse operation, the DS 6 is close and the pulse power supply generate negative voltage. In this situation, the coil current I_c flows through DS6.

b When the signal to start of pulse operation is triggered, the pulse power supply generate the positive voltage, then I_c to pulse power supply from DS 6 and the current flowing DS 6 I_{sw} decrease to zero. [c] At this time, a reverse voltage for the series diode D is induced and D cut off. With this diode, short circuit current flowing DS 6 is blocked.

d When I_{sw} becomes zero, DS 6 turned off and the pulse power supply output voltage is controlled to zero immediate.

After the connection sequence, the output voltage V_c can be swing to control I_c with high ramp rate. The current swing is finished, the pulse power supply returns to zero voltage state. The time delay to connect the pulse power supply is less than 1 s and is enough short for the plasma experiment.

The disconnection sequence is simpler as follows;

f DS 6 is closed and the pulse power supply turns to the regeneration mode. The coil current transfers to DS6 from the pulse power supply.

g When Ip becomes zero, the pulse power supply stop automatically and all coil current flows through DS6 again. [h]

Even though the power supplies are in the sequence of connection and disconnection, the coil current must be regulated with current controller described in the next section. This regulation is performed by the steady state power supplies, which works in this sequence.

4 Current control

The coil current control must be performed with seamless even if the pulse power supply is inserted or not. For this reason the control system is modified. Figure 4 shows the block diagram and inside of the dashed line is additional part. The current regulator receive the current reference I_c* and the actual current I_c, which is measured by the current

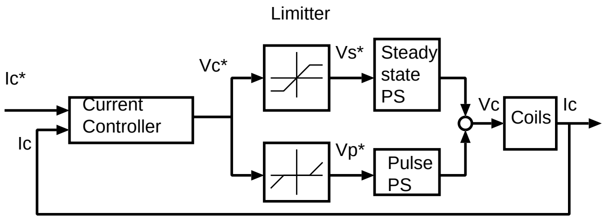


Fig. 4 Block diagram of the current controller.

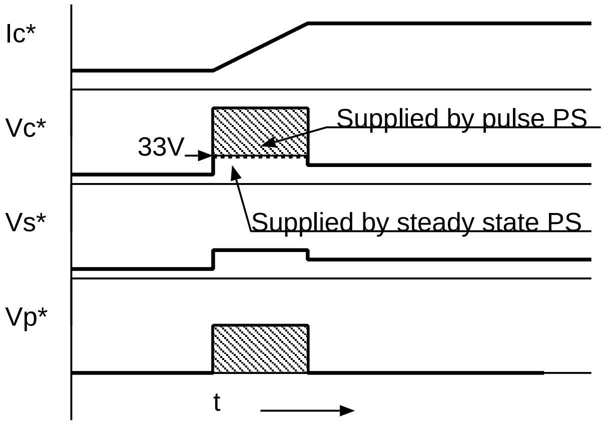


Fig. 5 Simplified drawing of the waveforms of voltage references

sensor set in the steady state power supply, and calculate the necessary voltage V_c*. In the steady state operation, V_c* is fit in 33 V, which is upper limit of the steady state power supply, and it is transferred to the steady state power supply as it reference V_s*. In the pulse operation, V_c* may reach to 218 V, which is sum of the output voltages of the steady state power supply and pulse power supply. When the V_c* over the limit of steady state power supply, the excess part limited by the limiter and generates V_s* At the same time, the excess part is picked up as a voltage reference for pulse power supply V_p*. A simplified drawing of waveforms is shown in Figure 5. With this configuration, two voltage references, which are V_s* and V_p* are generate without any switching of the control system.

5 Excitation test operation result

With the pulse power supply, some test operations were performed. Figure 6, 7 and 8 show some of the operation results.

Figure 6 shows the current and voltage waveforms when DS6 was just turn off and on. With this operation test, it is confirmed that the insertion and disconnection of pulse power supplies are done without large turbulence. When the pulse power supplies are inserted, the output voltage references of then are kept zero, but some voltage

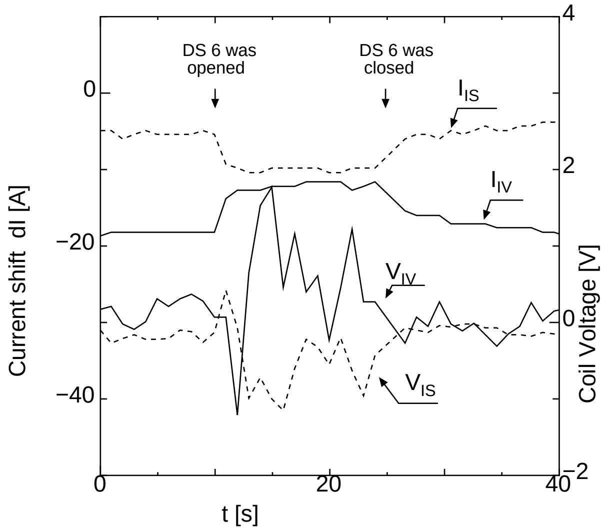
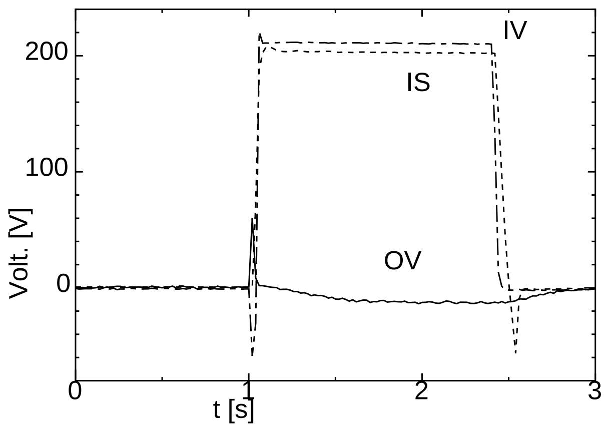
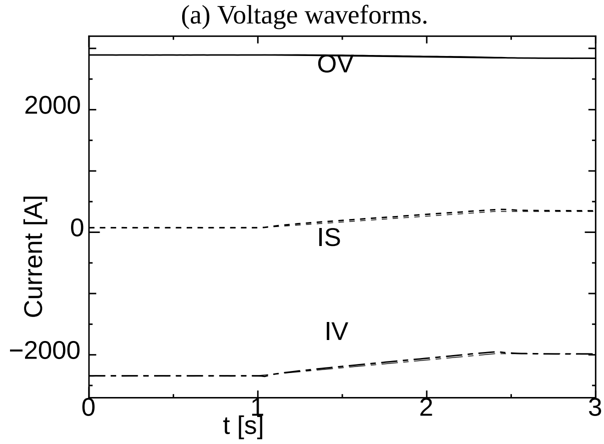


Fig. 6 Voltage and current waveforms when DS6 is turned off and on.



(a) Voltage waveforms.



(b) Current waveforms.

Fig. 7 Waveforms when the dynamic current control is performed.

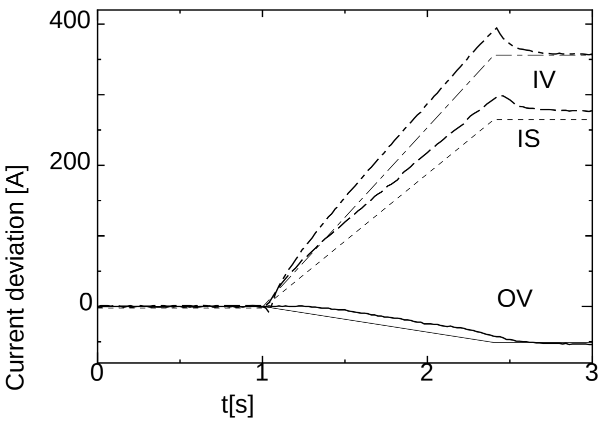


Fig. 8 Current change when the dynamic current control is performed.

turbulences are occurred and coil currents shift about 5A. These current shifts are relatively small for the operation current, but it should be smaller.

Figure 7 show the waveforms when the coil currents are swept using pulse power supplies. At $t = 1$, the current sweep starts and $t = 2.5$ the sweep finished. The coil voltages are ramp up and down quickly, and the voltage waveforms of IS and IV coils became rectangular as shown in Figure 7 (a). At the ramp up and down, the overshoot and the under shoot is observed for IV and IS voltage but it does not affect the current control.

The coil currents are swept smoothly as shown in Figure 7 (b). The detail of current change is shown in Figure 8. In these figures, the thin lines mean the coil current references and the thick lines are actual coil currents. In the figure, there are offset between the reference and actual current for IV and IS coils when currents ramp up. The offset is about 40 A and it causes the overshoot at the end of ramp up. These current offsets are caused by the reaction of the induced current flowing in the plasma or strictures such as coil can or supporting shell of the LHD. The current path in them works as resistive components connected in parallel to the coil equivalently. The effective resistance is about 5 ohms and the time constant is about 0.2 s. The feedback time constant of the controller is about 10 s and is not enough to compensate the reaction. Except this current overshoot, there is not other turbulence such as ringing and it is confirmed that the seamless control for current regulation is confirmed. With this test, it was certificated that the dynamic current control using pulse power supplies are performed without problem.

6 Conclusion

For the LHD plasma experiments, the high voltage power supplies and the control system for them were constructed to make the dynamic coil current control. In the system, it is necessary to connect or disconnect the pulse power supply without stop the system. For this purpose, a new sequence is designed and installed. Also the seamless current control using two power supplies is required and built. The operation tests using LHD coils are performed and it is confirmed that the dynamic connection sequence for the pulse power supply works as designed and the seamless current control has enough performance. The new power system is now works as powerful equipment for the dynamic plasma experiments. The proposed configuration, which uses two power supplies connected in series, is also considered in the design activity of the helical-type reactor.

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