HIGH-SPEED, HIGH-ACCURACY MAGNET POWER SUPPLY USING FET CHOPPER FOR SYNCHROTORON FACILITY

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ABSTRACT

The bending magnet power supply for the accelerator built at the NTT LSI Laboratories must be able to quickly control the current for highly inductive coils with very high accuracy during the transition from the rising slope to the flat top as well as the flat top of the current reference. To meet this requirement, we have developed a new power supply which consists of four dc power supplies, an inverter, a forcing and two high speed choppers. The high speed chopper is made up of 200 MOSFETs connected in parallel that are switched at 33 kHz. The control circuit has a fast response with a crossover frequency of 4,000 rad/sec. The test results show the deviation between the reference and the actual current is within $\pm 1\times10^{-4}$, when the current through a magnet coil which has a time constant of 3.3 seconds is increased to the rated current of 800 A at the rate of change of 660 A/sec. This paper describes the outline of the power supply and the result of its tests.

[1] SPECIFICATIONS OF BENDING MAGNET POWER SUPPLY

In the conventional power supplies for accelerator magnets, the requirements of power supplies for storage rings concern stability and ripple under constant current, and those for synchrotron rings specify reproducibility and ripple during current rising.

The bending magnet power supply for the synchrotron accelerator at the NTT LSI Laboratories, however, must satisfy the specifications for both storage and synchrotron rings. Also a high accuracy with which the new power supply must control a point of transition from the rising current to the flat current, cannot be met with the conventional accelerator magnet power supplies.

Table 1 shows specifications of the bending magnet power supply for the synchrotron accelerator built at the NTT LSI Laboratories. The technical tasks posed by these specifications can be summarized into the following four points:

(1) The required rate of change of magnet coil current is large(0.75P.U.(600 A)/0.9 sec), compared with the time constant of the magnet coil(3.3 sec).

(2) The magnet coil has high inductance and saturating characteristics.

(3) The follow-up control accuracy must be within $\pm 1\times10^{-4}$ a reference for the current range of 1.5% to 100% of the rated current.

(4) A high current accuracy is required in controlling the transition from the rising slope to the flat top of the current waveform.

As detailed in Section 3, the automatic current regulation system that satisfies the above requirements must have a fast response with an open loop gain crossover frequency of about 4,000 rad/sec. Such fast control cannot be realized by conventional thyristor rectifiers which have large dead times. The existing series regulators formed with transistors have no problem in terms of high-speed response. However, since the magnetic coil inductance is large, there is a great difference between the output voltages when the current is increasing and when it is level which increases power loss of transistors. Thus, we decided to develop a high-speed chopper circuit using MOSFETs.

Table 1 Specification of Bending Magnet Power Supply

Current Control (While 1.5%-100% of rated current)	
Current ripple	$\pm 1\times10^{-4}$
Stability	$\pm$1x10-4
Follow-up accuracy	$\pm 1\times10^{-4}$
Reproducibility	$\pm 1\times10^{-4}$
Condition of Environment	
Temperature	0-40°C
Voltage regulation	±10%
Load regulation	±10%
Magnet Coil Constant	
Inductance	972 mH
Resistance	294 mΩ
Rated current	800 A

[2] CONFIGURATION OF POWER SUPPLY FOR MAGNETS

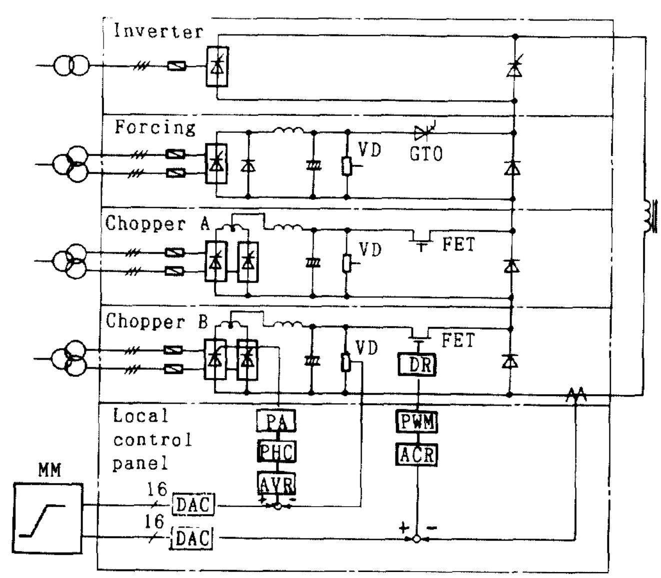
Configuration

Figure 1 shows a circuit diagram of the bending magnet power supply which consists of four power supplies--inverter circuit, forcing circuit, chopper circuit A and chopper circuit B--connected in series. Descriptions of functions and features for each circuit follow:

Inverter Circuit: The inverter circuit is a line-commutated converter which produces an output voltage of about -1,000 V and which returns the energy accumulated in the magnetic coil to the system when the power supply is stopped. When the power supply is in operation, thyristors connected in parallel with the inverter output are turned on to let the load current bypass the inverter.

Forcing Circuit: When current is raised this circuit is activated to apply high voltage to the coil so that, despite a large inductance in the magnetic coil, the current can quickly be increased. The output voltage is adjustable up to 1,000 V. After a specified current is established, GTOs are turned off and the load current bypasses the forcing circuit through diodes.

Chopper Circuit A, B: The chopper circuits A and B



MM :Memory module
AVR:Automatic voltage regulator
PHC:Phase controller
ACR:Automatic current regulator
PWM:Pulse width modulator
DAC:DA converter
DR :Driver
PA :Pulse amplifir
VD :Voltage divider

Fig.1 Circuit diagram of bending magnet power supply

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constitute a major part of the bending magnet power supply and control the coil current by regulating the pulse width of the choppers. The chopper circuits A and B are identical in performance and structure but are shifted in the switching phase by 180° to improve ripple characteristics and operation speed.

[3] DESIGN AND ANALYSIS OF CONTROL SYSTEM

Basic Considerations for Control System Design

The control system is designed with the following three considerations:

(1) Steady state deviation should be reduced.
(2) Good follow-up control must be maintained.
(3) The system as a whole should be made a first order system to ensure stability.

Since the load is a coil that forms a system of first order lag, a proportional and integral control is used to meet requirements (1) and (3). The requirement (2) will be discussed in the next section.

Examination of Follow-Up Control

Examination by Bode Diagram: If we let "a" stand for the current rise speed and "Kv" for the gain of a one-loop transfer function of a system at the angular frequency $\omega=1$, then the steady-state velocity deviation input is given by

$$\varepsilon = a/Kv$$

Substituting $\varepsilon = 1\times10^{-4}$ and

$a = 0.75\text{P.U.}(600\text{ A})/0.9\text{sec} = 0.833$, we obtain

$$Kv = a/\varepsilon = 0.833/1\times10^{-4} = 8330 \text{ (78 dB)}$$

What percentage of the above gain must be accounted for by a gain of the control circuit at an electronic circuit level was checked by using a Bode diagram. In drawing the Bode diagram, the circuit diagram of Figure 1 was rewritten into a block diagram as shown in Figure 2.

In Figure 2, the chopper consists of power supplies connected in series, each with the control input signal of 10 V and the output of 170 V, so that its gain is 34 times. The chopping frequency is 33 kHz and there are two phases; thus the dead time of 15 μs is used. DCCT produces 10 V output for 800 A. It has a second order filter with a cutoff frequency of 5 kHz to prevent external noise from entering the control system. The integration time of the ACR amplifier is matched with the time constant (3.3 seconds) of the load coil to prevent the system from oscillating. The forcing power supply connects to the automatic current regulation system at point A as an open loop, so its explanation is omitted. The Bode diagram with the proportional gain of the ACR amplifier of Figure 2 set at 10,000 times is shown in Figure 3. In Figure 3, the gain for $\omega = 1$ is 73 dB, 5 dB smaller than the 78 dB that was obtained earlier.

Analysis of Control System Using EMTP

An approximate value of the gain required for the control circuit at the electronic circuit level was determined from the Bode diagram. Then, we performed analysis using the EMTP (Electro Magnetic Transient Program) to check the response of the system including the forcing power supply. We also checked whether the transition can be made smoothly from acceleration mode to storage mode. The EMTP is one of the most widely used transient analysis programs developed by BPA (Bonneville Power Administration).

The chopper was simulated as a continuously variable dc power supply because of the computation intervals. The load was simulated by reactor and resistor. Of the voltage required to establish the load current, the inductive component Ldi/dt is supplied from the forcing power supply and the resistive component R× i is supplied from the chopper.

Figure 4 shows the results of simulation. In Figure 4, the initial charge of the forcing power supply is started at t=0 and, at t=0.25sec, the GTOs of the forcing power supply are turned on and at the same time the chopper power supply is started to raise the current. From t=1.15 sec to 1.45 sec, the voltage reference for the forcing power supply is linearly reduced. The rate of change of the current reference is gradually reduced from t=1.15 sec.

Figure 4(a) shows the voltage reference and output voltage of the forcing power supply. At t=1.15 sec when the reference begins to drop, the output also begins to

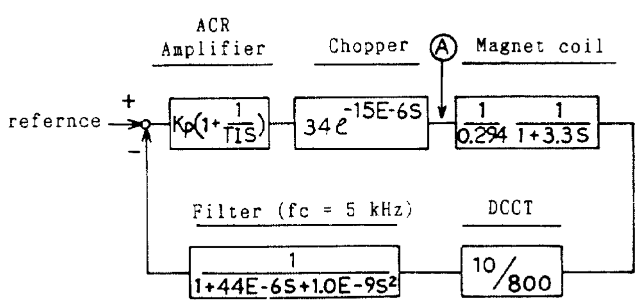


Fig.2 Block diagram of ACR of bending magnet power supply

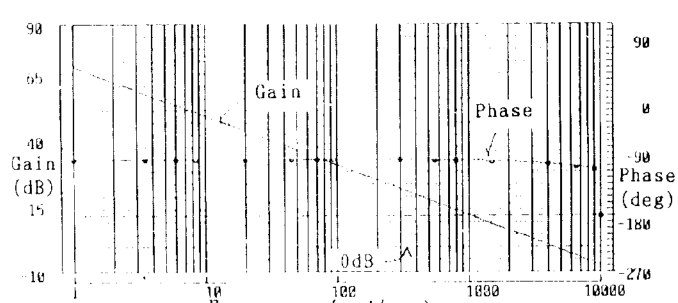
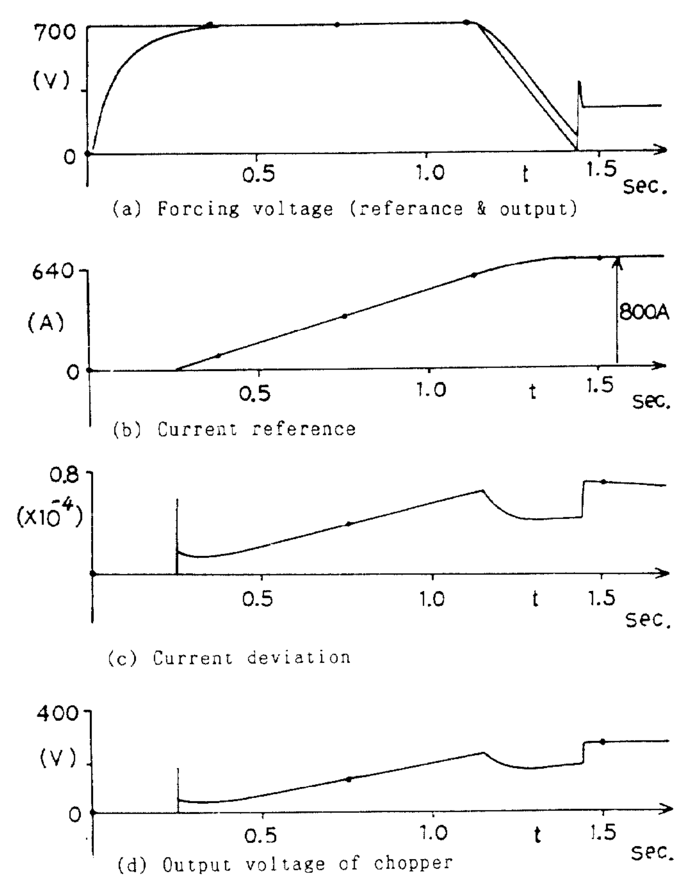


Fig.3 Bode diagram of ACR of bending magnet power supply



(a) Forcing voltage (referance & output)

(b) Current reference

(c) Current deviation

(d) Output voltage of chopper

Fig.4 Simulation waveform

decrease with some delay. Figure 4(b) shows the current reference.

The current deviation is shown in Figure 4(c) and its magnitude is within the range of $\pm 1\times10^{-4}$. As the current reference increases, the current deviation also increases. This is because an increased current results in an increase in the resistive component drop. The reason why deviation decreases in the time range from t=1.15 sec when the forcing voltage begins to fall to t=1.45 sec is that the voltage supplied from the chopper is reduced by an amount corresponding to the delay of fall of the forcing power supply. When at t=1.45 the forcing power supply is separated, the resistive component drop is compensated for by the chopper voltage alone. As a result, the deviation increases again.

Figure 4(d) shows the output voltage of the chopper. The chopper output voltage is almost the same in waveform as the current deviation of Figure 4(c). This is because the integration time is as long as 3.3 seconds rendering the integration term ineffective during the transient state, so that the chopper output voltage is practically the current deviation multiplied by the proportional gain. For the constant current, however, the integration term becomes effective, making the current deviation zero.

The EMTP analysis including the forcing power supply found that the proportional gain necessary for the automatic current regulation system is about 10,000 times.

Other Features of Control System

Adoption of Memory Module Preprogram Control: A 16-bit memory module with a 10 kHz clock was used taking into account the following requirements: that the current reference must have high accuracy, that there must be flexibility in changing the excitation pattern, and that a desired pattern must be able to be generated to smoothly change the current reference during transition from the rising slope to the flat top of the current waveform.

The pulse width of the chopper can only be changed in the range of 10% to 90% because of the constraints of MOSFET switching time. When it is necessary to lower the chopper output voltage as in the low current zone, the input voltage to chopper must be reduced. Further, since the coil has a saturation characteristic that will vary inductance, the forcing voltage reference must also be varied. Under these situations, we decided to use memory modules also for voltage references for the forcing circuit and for the thyristor converter of the chopper circuits A and B. In this method the voltages as determined from the current reference and coil characteristics are programmed (preprogram control). Writing of data into the memory modules is done by minicomputer.

[4] DEVELOPMENT OF HIGH FREQUENCY CHOPPER CIRCUIT

Configuration of FET Chopper Circuit

Major specifications for each chopper circuit are described.

(1) Output voltage and current: 170 V-800 A
(2) Chopper device : MOSFET, MG15G1AN1 (450 V-15 A, Toshiba)-200 parallel
(3) Chopper frequency : 33 kHz

The chopper circuit consists of 10 FET panels, each made up of 20 MOSFETs. Figure 5 shows details of the FET panel. Twenty MOSFETs and associated circuits are mounted on the water-cooled panel, with each MOSFET attached with a fuse for overcurrent protection. A CR snubber circuit is provided between the drain and source of each MOSFET to suppress overvoltage during switching. A gate drive circuit provides for every 20 MOSFETs and supplies gate signals to individual elements through resistors.

Our test results indiate that the current imbalance factor between panels is within $\pm$10%.

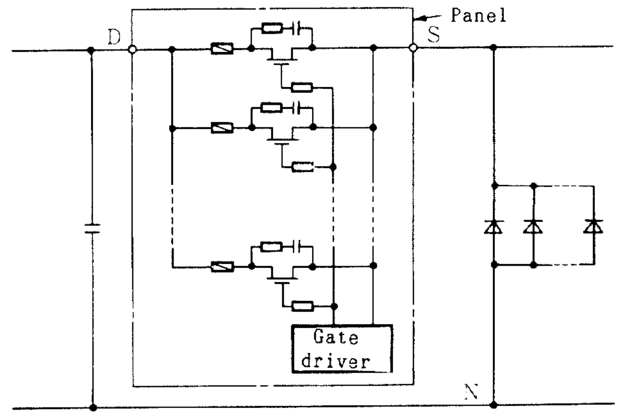


Fig.5 Circuit diagram of FET panel

[5] Results of Test

Figure 6 shows the results of a test performed on the bending magnet power supply. In the test, current was quickly raised to about 1 P.U. (=800 A) in 1.5 seconds and thereafter kept constant at that value. Up to 0.8 P.U. the rate of increase di/dt was kept constant and from 0.8 P.U. to 1 P.U. it was moderated or smoothed.

The forcing voltage was slowly reduced because the required voltage decreases due to saturation of the load coil and smoothing of the rate of change di/dt. As to the current deviation measurement, a difference between the current reference and the output current is amplified 1,000 times by an amplifier with low drift and low offset. The requirement that the follow-up performance and ripples should be within $\pm 1\times10^{-4}$ is satisfied in the range of 1.5% to 100% of the rating.

[6] CONCLUSION

A power supply for the bending magnets, the most important among the accelerator power supplies, has been described. This power supply required many stringent performance characteristics such as high speed, high accuracy, and stability. These requirements have been met by employing new technologies, such as series-connected dc voltage source configuration, high-speed choppers with many parallel MOSFETs, a preprogram control and a high-gain, wide-band amplifier.

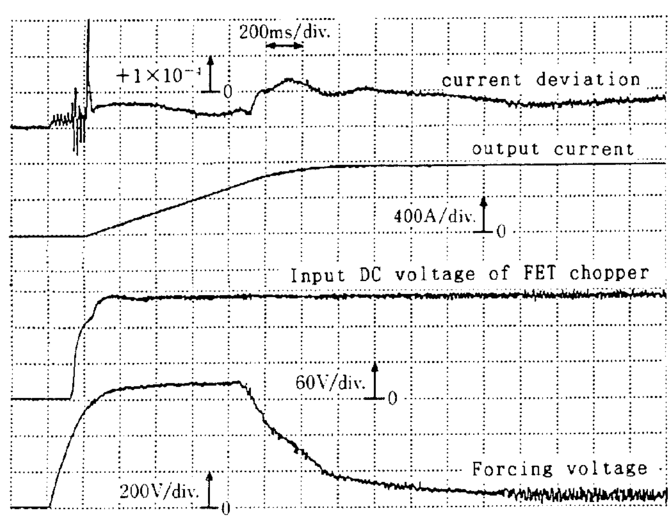


Fig.6 Waveform of bending magnet power supply