EXPERIMENTAL AND EXTERNAL-PROTON-BEAM MAGNET POWER-SUPPLY SYSTEMS AT THE BEVATRON*

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Abstract

Magnet power-supply systems for both experimental and external-proton-beam (EPB) magnets used at the Bevatron are described as feedback control systems. Individual components contained in the systems are also described. The power-controlling component first used in the supplies was a three-phase magnetic amplifier. Silicon-controlled-rectifier (SCR) bridges are being used now. The requirements placed on the experimental magnet supply systems are ± 0.1% current regulation with ± 10% line-voltage perturbations occurring every pulse of the Bevatron. The EPB systems must track to at least ± 0.1% a dynamic signal closely related to the proton beam energy. The performance criteria for EPB systems involve both error coefficients and transient response.

Requirements Placed on the Systems

A general requirement placed on the experimental magnet power-supply system of the Bevatron is that the current shall be maintained to a given value within ± 0.1% over both long and short periods of time. Any perturbations in the current caused by up to 10% line perturbations shall not exceed this tolerance. To achieve this kind of long-term regulation the variation with temperature of the current monitoring device, the reference, and the amplifier must be small enough that regulation will be maintained over a temperature range of 40°C. The zener diode used in the latest supplies is the 1N939A, which has a temperature coefficient of 0.0005%/°C.

The perturbations that affect the regulation characteristics of the supplies are mainly line-voltage variations and perturbations and the change in resistance of the magnet as the temperature of the magnet changes. The magnets are all water-cooled and the water temperature generally changes about 10°C as the magnetic field comes up to operating level. This then amounts to a 4% change in resistance of the copper windings. The line-voltage perturbations are either long-term changes where the line changes up to 3% and stays at a level for a sustained period, or perturbations occurring every pulse of the Bevatron as the contactors on the main motor-generator sets are connected and the external beam supplies are pulsed. These types of perturbation act as a series of steps or impulses on the system and not only couple into the load part of the circuit but also into the controlling elements, especially into certain types of SCR firing circuits.

The EPB systems must track to at least ± 0.1% a dynamic signal closely related to the proton-beam energy. In addition to the ramp-shaped energy signal, some magnet systems require a dc bias so that the sum of the two signals generates the correct field shape for slow spills of beam. The EPB systems are subject to the same perturbations as the experimental supplies.

An additional component of current which must fall within the ± 0.1% specification is the ripple component of the current which is caused by the output being a phased-back voltage source. All supplies operating at the Bevatron are three-phase bridges, so the ripple frequency component of the current is six time the power-line frequency, or 360 cps. The closed loop around the pulse-width-controlled power supplies has a bandwidth of 120 cps, so all reduction in the magnitude of ripple going from voltage to current is done by the inductance of the magnet unless the output voltage is also filtered. The peak-to-peak 360-cps fundamental is 100% of the average output of the supply at half the rated output.

Feedback-System Design

The control systems synthesized have assumed various forms depending on the characteristics of the power supplies and the requirements to be satisfied. The systems must be analyzed for the magnet-current response to line-voltage perturbations and to variations in reference. In the early magnetic-amplifier power supplies, line-voltage response was the dominant factor because there was no intention of tracking dynamic reference signals to high accuracy in view of the slow response of the system. The EPB system requirement of tracking the beam energy exceeded the capabilities of the magnetic-amplifier supplies, so large transistor banks were added. Subsequent EPB systems have utilized the bridge SCR supplies without the addition of transistors, and all subsequent SCR systems have been designed with the requirement of dynamic tracking

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in mind.

The approach to system design after satisfying the dynamic power requirements has been to optimize the output response to both line-voltage perturbation and reference inputs. This optimization is a compromise between the best response to either one or the other input, because both the power supply and compensating elements associated with the control amplifier are between these two inputs. Minor loop feedback from the power-supply voltage output was used in the magnetic amplifier supplies but was not found necessary in the SCR supplies.

As the typical magnet time constants are not long enough to satisfy the dominant pole requirements determined by the open-loop gain characteristics of the system, a pole-zero combination is inserted in the loop, with the zero occurring in the vicinity of the magnet pole. This compensation is usually inserted by minor loop feedback; it occurs in the SCR system around the amplifier along with lead network compensation if the power supply has a filter on the output voltage. The dynamics of the closed-loop response are determined by root-locus construction, with closed-loop poles normally 60 deg from the imaginary axis.

The linear part of the system is basically a two-pole configuration with the dominant pole and the high-frequency-amplifier pole determining the closed-loop response. However, the nonlinear part of the system--either the magnetic amplifier or SCR power supply--really determines the high-frequency characteristics. The closest analytical approach to the SCR supply system found in the literature is that of pulse-width modulated systems, the difference being that the SCR supplies work from a sine-wave power source rather than dc. The magnetic amplifier is additionally complicated by the feedback that exists internally from the output to the input of the self-saturating type. This feedback effectively introduces a time constant in addition to a time delay.

The SCR-system loop has been treated as a linear sampled-data system with a 2.67-msec (360-cps) sampling rate. The loop is designed so that the loop gain is unity at one-third the sampling frequency or 120 cps, which gives an adequate phase margin. The magnetic-amplifier system loops must be additionally compensated for the added pole contributed by the magnetic amplifier.

The response of the system to line-voltage perturbations is determined not only by the closed-loop complex-pole positions, but also by the zero at the location of the dominant open-loop pole introduced as compensation at the amplifier. This zero occurs because the dominant pole is in feedback for line-voltage perturbations.

It is convenient to define the errors in tracking a ramp function at the reference as the position error and the velocity error. The position error is the error signal required to achieve the required range of output current under steady-state conditions. In following a ramp, the position error is therefore also a ramp equal to the output current divided by the forward gain, $e_p = (I\ \text{magnet})/G_{dc} = K_1 t/K_p$, where K_p is defined as the position-error constant, and K_1 is the slope of the ramp. By making the forward gain high enough, one can make the position error negligibly small compared to the velocity error in the external-beam systems.

The velocity error is constant during a ramp and equal in magnitude to $e_v = K_1/K_v$, where the velocity error constant K_v is defined by $1/K_v = \sum_{j=1}^{n} (1/p_j) - \sum_{j=1}^{m} (1/z_j)$, where p_z are the closed-loop poles, and z_j the closed-loop zeros of the system. This expression shows that for a system with dominant left-half plane poles, the wider the bandwidth the greater the velocity constant and the lower the velocity error. Truxal describes pole-zero configurations for achieving an infinite velocity constant,[1] but unfortunately the transient response is generally adversely affected by using these configurations. The external-beam systems must follow the beam energy into "flat-top" operation and therefore need fast transient response and good steady-state ramp characteristics so that a minimum amount of recovery time is necessary when entering and leaving the flat-top part of a pulse.

In EPB systems the position error has been reduced well below the velocity error by running as high a dc-loop gain as allowed by the transient response to line-voltage perturbations. As the dc gain is increased, the introduced dominant pole must occur at proportionately lower frequencies. Because this dominant-pole position becomes zero in the closed-loop current response to voltage perturbations, the magnitude of transient overshoots also increases. In EPB systems the position constant, K_p, is between 5000 and 10 000, while the velocity constant, K_v, is between 1000 and 2000.

The magnetic-amplifier supply systems and the combination magnetic-amplifier-transistor EPB systems are described elsewhere,[2] and will not be described in this paper. The SCR systems have superseded the magnetic-amplifier units in all EPB and experimental applications.

Transductors

The transductor is an interesting device that can have a bandwidth from dc to megacycles with only magnetic coupling between the signal winding and output winding of two or more reactors (see Fig. 1). These reactors combined with an ac source, load resistor, and appropriate diodes make up the circuit. The essential idea is that with two cores and a current source in the signal winding (in our case, a bus carrying magnet current through the center of the core) the circuit is arranged so that one or the other of the two cores will always be in an unsaturated state. Having one or the other core unsaturated means there is always magnetic coupling between windings and therefore bandwidth from dc to whatever frequency the distributed inductance and capacitance determine. The transductor is like 'an infinite B-H loop core' in capacity to absorb volt-seconds. Always having coupling from input to output is exactly the opposite in principle from the operation of the magnetic amplifier. The magnetic amplifier transmits information from input to output only because the reset done on the core by the input during one period determines when the core saturates the next period and therefore the output level. There is never direct coupling in the magnetic amplifier as in the transductor, but rather at least one period of delay usually accompanied by a time constant before the output responds to a change in the input. The confusion regarding the frequency capabilities of the transductor can be eliminated if the fundamentally different mode of operation compared to that of magnetic amplifiers is understood. On the transductor the current source determines the current flowing in the control winding, whereas in a magnetic amplifier the control currents are functions of the core-exciting current requirements and the voltages present. Any saturable reactor or magnetic amplifier goes into a transductor mode of operation when driven from a current source. Different features are associated with the various circuits, however. An additional circuit which performs only in the current-driven mode of operation has been invented here at the Laboratory by Windsor.[3] In the circuit shown in Fig. 1 the two upper cores are the basic transductor. The third core provides coupling with the primary while the current is reversing each cycle in the upper two cores. The fourth core filters out the magnetizing-current square wave (at 120 cps) while maintaining coupling with the primary.

Silicon-Controlled Rectifier Power Supplies

A block diagram of the SCR power-supply system used in both experimental and EPB applications is shown in Fig. 2. The magnet current signal from the transductor is compared with the reference and the error amplified and compensated by a differential amplifier. The amplifier drives the SCR firing circuit which controls the output of the power supply. In some applications the power-supply output must be filtered to reduce the magnet-current ripple to less than 0.1%. There are twenty-one 105-kW SCR supplies rated 75V, 1400 A dc, and eight 196-kW supplies rated at 140 V, 1400 A in operation at the Bevatron. One of the 196-kW supplies is shown in Fig. 3. There are now 13 SCR supplies in the EPB system beyond the four magnetic-amplifier transistor units.

The firing circuits must be synchronized with the phase voltage of each particular SCR in the circuit. The commonly employed mode of control is a dc signal combined with the appropriately phased sinusoidal voltage which fires the SCR at the appropriate time in the cycle.

The firing circuit we have employed utilizes a ramp wave shape rather than a sine wave. The circuit is shown in Fig. 4. The phase voltage is converted to a ramp across capacitors C3 and C4 by first converting the voltage into a square wave of current with a full-wave-bridge—choke arrangement. The diodes across C3 and C4 provide the necessary current return path to prevent the capacitors charging in the wrong sense during their reset half cycle. The choke—capacitor arrangement provides essentially complete isolation for the ac line voltage. This isolation means that none of the line-voltage perturbations caused by many switching-type supplies loading the line come through into the firing circuits. Silicon controlled rectifiers 2 and 3 fire on alternate half cycles when the appropriate capacitor voltage exceeds the control amplifier voltage. A capacitor (C1 or C2) then discharges into a pulse transformer, which in turn fires the power SCR's (SCR 1 or 4) of that phase.

Because the firing circuit compares the voltage buildup across a capacitor with the output of an amplifier, any noise present in the amplified signal can cause jitter in the firing angle. If the amplifier could perform only as a low-pass network with no gain at the 360-cps current ripple frequency and beyond there would be no problems. To design the overall system with the maximum possible bandwidth, however, requires that the amplifier contribute very little phase lag at frequencies below a few kilocycles per second. The phase shift due to the pole-zero compensation has returned to a minimum at lower frequencies, and the lead network to compensate for the filter on the power-supply output contributes gain and leading phase. The system must be arranged so that the gain at high frequencies from the magnet current to the output of the amplifier is not too great. Otherwise the amplifier output saturates on the amplified ripple current signal or causes jitter in the firing circuit. In the existing SCR system the ripple component in the output of the amplifier is one or two volts out of the 25-V range.

These regulators have the same operating controls that were provided on the magnetic amplifier regulators, i.e., current control, remote voltage control, and local voltage control. When operating in remote and local voltage control, the loop is closed around the amplifier itself and the compensation on the first collector stage is accordingly readjusted to stabilize the feedback loop. The voltage control biases the main power supply by controlling the firing point with either the local potentiometer or the remote helipot. The other adjustment on the regulator is a variable resistor in feedback which determines the high-frequency gain of the device. The value of this feedback resistor depends on the inductance of the magnet that a given supply is operating, which varies from 22 to 2500 kΩ for magnet inductances that vary from 1 to 590 mH.

All components of the regulator, transductor power supply, and firing circuits are packaged in a printed-circuit-board bin (see Fig. 5). The transductor power supply and the ± dc supplies are together in one enlarged circuit-board package, the amplifier and compensation circuitry are mounted on a second printed-circuit-board package, and the three firing circuit boards occupy the remainder of the bin. The pulse transformers which take the signals to the large SCR's are mounted adjacent to the power SCR's to eliminate the possibility of feeding-back the high powered dc connections of the power supply into the printed-circuit-board bin.

To distribute the firing pulses from the pulse transformer to the various sets of three parallel SCR's, a distribution board is used for each group of SCR's. A resistor-capacitor combination in each gate is used to enhance the signal-to-noise ratio. A diode must be placed in each lead returning from the cathode to avoid shorting out the current-balancing reactors in the cathodes. In the group of 21 supplies recently put into operation, a few SCR's out of the 378 total misfired on the noise signal caused by an adjacent-phase SCR firing. The problem could be eliminated by placing a silicon diode in series with the gate lead, as most pickup occurs in the loop formed by the common-cathode firing connection through the current-balancing reactors to the main common-cathode point. This problem could also be avoided by firing each SCR from a separate pulse-transformer secondary.

A separate chassis is provided in each power supply to allow the supplies to be paralleled. One of the two supplies is arbitrarily designated the master supply, and the firing pulses from the firing circuits in this supply are fed to the SCR pulse transformers in both units. The amplifier of this master supply senses a transductor signal which is the parallel combination with both the master and slave units. Because the transductor is a current transformer, this arrangement can be regarded as the paralleling of two current transformers across half of the transductor resistance that is normally used in the circuit. The interconnections between the two supplies are accomplished through one bundle of cables.

The firing pulses rather than the amplified error signal at the output of the amplifier are used to transmit firing information because the noise adjacent to the supplies has a high content of pulses. Because of the limited bandwidth of the amplifier, these pulses would appear on top of the error signal, where small changes cause large variations in the time of firing. By transmitting a relatively large firing pulse (12 V), the signal-to-noise ratio is far better and can be improved additionally by adding a diode at each SCR gate.

A filter is required on the output of the experimental SCR supplies as they are planned to be used predominately with the Brookhaven laminated quadrupoles, some of which have an inductance as low as 1 mH compared to a resistance of 0.024Ω for a filter factor of 100 at 360 cps. As the additional reduction in ripple current required is only approximately 10 times, the filter used is an LCR combination shown in the Fig. 6.

The corner frequency of this network is 36 cps, and it behaves essentially as a single time constant to give a 10-to-1 reduction of the 360-cps ripple without the corresponding power loss of an RC. An additional advantage of this LCR over an LC network for just ten times filtering is the relative ease of compensation in the feedback network around the amplifier. The transfer function of the filter is $E_0/E_i = (S+\omega_0)/\omega_0(S^2+\omega_0 S+\omega_0^2)$, where $\omega_0 = 2\pi(36 \text{ cps})$. A lead network from 36 to 360 cps is adequate compensation for this network and is incorporated in the feedback network around the amplifier. The dc gain of the system varies from 2000 to 10 000, depending on the magnet resistance, and the closing frequency is approximately 120 cps. The velocity constant, K_v is approximately 1000.

Acknowledgments

Acknowledgment is due members of the Bevatron Electronics Engineering staff who have contributed to this program in addition to their other responsibilities. Alfred Windsor has brought the transductor to fruition as a useful high-performance device, Pierre Pellissier contributed in the specification of the SCR supplies and the mechanical design of the transistor banks, Thomas Sibary developed the firing circuit, and Henry Lancaster contributed to the analysis of the system.

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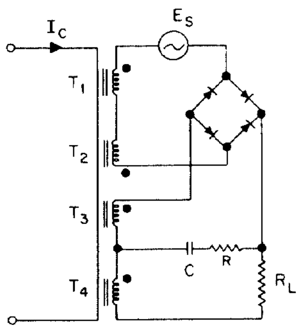

Fig. 1. Transductor. Series-connected saturable-reactor circuit with cores added for filtering.

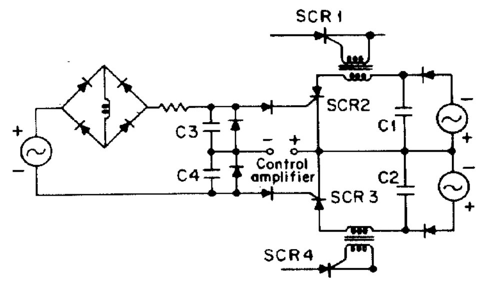

Fig. 4. Firing circuit used in SCR power supplies.

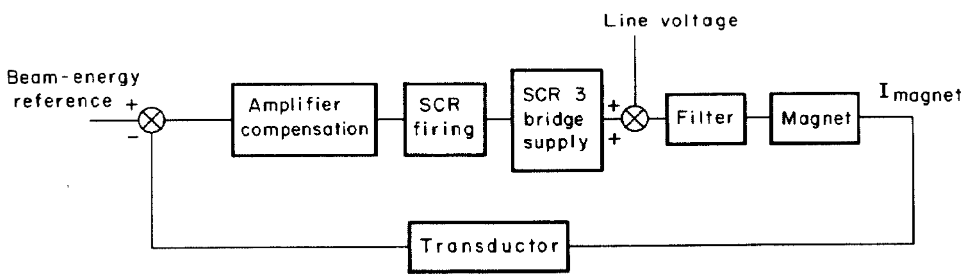

Fig. 2. Block diagram of the SCR power-supply system.

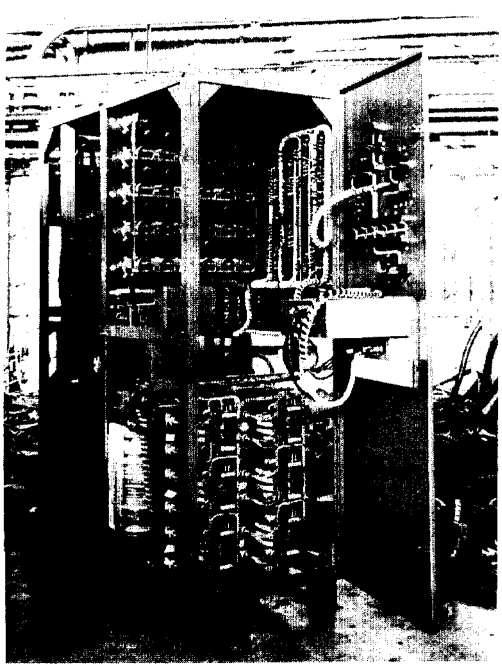

Fig. 3. The 196-kW SCR power supply.

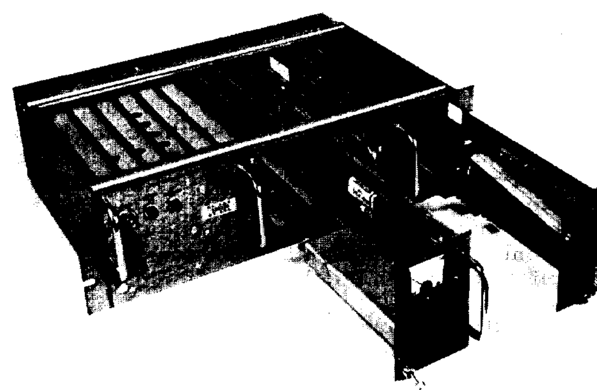

Fig. 5. Control bin for SCR power-supply system.

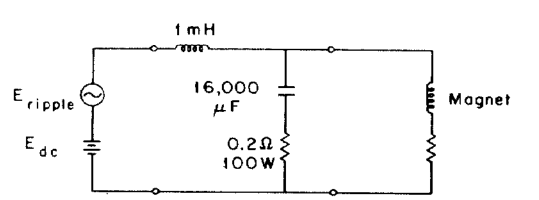

Fig. 6. LCR filter network.