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AUTOMATIC CONTROL OF THE TRIM-COIL POWER SUPPLIES AT THE BERKELEY 88-INCH CYCLOTRON*

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Abstract

The automatic-control requirements of the 88-inch cyclotron trim-coil power supplies resemble those of many industrial processes. Certain set points must be automatically realized and maintained throughout an extended experimental run. The recently installed system reduces trim-coil setup time to less than 5 min, and maintains these set points within 0.1% or less over an 8-hour period. Although the system is primarily analog, the set points for a run are programmed on an IBM card and entered into the system through a digital-to-analog interface. The system is being extended to include the many machine-parameters--such as the deflector positions and voltages--that have set points.

Introduction

The 88-inch cyclotron uses 17 trim coils, each with its own power supply. For each particle and energy that has been developed there is a set of 17 currents, known as the trim-coil solution, that is considered to give the optimum trimming field.

Presently these trim-coil currents, as well as many other machine parameters, are set manually by an operator and maintained constant by individual electronic regulators. An average of one particle or energy change occurs per 8-hour shift, and the resulting machine setup takes about 30 minutes. The system to be described is the first phase of a project to set most of the machine parameters within 5 min. Because there are always items such as television adjustment and fine tuning for beam, a realistic prediction of the time that will be needed for a complete energy or particle change is 15 to 20 min. The saving of 10 min per shift, at $200 per hour for cyclotron time, amounts to about $30 000 annually.

The design requirements and philosophy of our complete automatic control system are fully described elsewhere,[1] and are partially treated in this report.

System

Each of the trim-coil currents is controlled to about 0.2%, short term, by a regulator. The long-term (8 to 16 h) stability is within less than 1%. Figure 1 is a simplified block diagram of a typical trim-coil power supply and regulator. The system starts as a potentiometer, which determines the value of the reference. The potentiometer is adjusted manually when the current is to be set or changed. It is important to the operation of the cyclotron, and to further development of beams, that this means of direct operator control not be sacrificed. The output, which is current, is converted by the feedback loop to a voltage of the same order of magnitude as the reference. The feedback loop is either a shunt or a transductor. The difference (error) between the reference and the feedback-loop output is amplified by the regulator amplifier so as to cause the output to change until the error is reduced to zero.

A simple method of automatic control of several supplies involves setting a series of input reference levels (e.g., potentiometer settings) from a known correspondence between reference setting and output. That is, the potentiometer readings from previous experiments are just reproduced automatically for a like experiment. A serious disadvantage is that, over a long period, this correspondence changes due to aging of parts, and changes again immediately upon any replacement of parts.

A better approach is to design a single, highly precise reference that supervises the existing series of references sequentially. While a particular unit of the system is being sampled, the corresponding output current is compared with the programmed output current, which is the highly precise reference, and the result of the comparison is used to reset the individual reference as necessary. The individual references maintain the power supply outputs during the rest of the cycle.

For automatic digital control, all the existing references would either have to be redesigned so as to be operated by relays or solid-state switches, or the potentiometers could be driven by stepping motors. Then the actual currents would have to be converted from their analog form to a corresponding digital representation so that they could be compared with the supervisory reference, which is either punched tape or an IBM card.

On the other hand, analog operation, which involves working directly with voltages and currents within the automatic-control system, would require either an analog supervisory reference or a digital-to-analog conversion of a punched-tape or IBM-card supervisory reference. A

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digital supervisory reference is advantageous in providing greater information density than an analog reference, and being more usable in future computer studies.

A summary, then, of the most appealing automatic-control system for an operating cyclotron is:

1. Supervisory: the individual references are supervised sequentially so as to maintain required outputs;
2. Analog: all operations within the supervisory loop, as well as within the parameter-regulating systems, are analog--that is, all operands are voltage representations of the current involved;
3. Digital input: the supervisory reference is on either punched tape or IBM cards, with digital-to-analog conversion.

With the above description in mind, we can derive a suitable block diagram as shown in Fig. 2. In this figure the sampling period is 0.33 sec and the sampling rate is therefore 3/sec.

Figure 3 is a more complete block diagram of the automatic-control system supervising channel J, a typical member of the sequence of 17 trim-coil power supplies. While channel J is being sampled, the voltage output signal from the output shunt is fed through the Input Multiplexer and Signal Conditioner to the Comparator and Motor Drive. At the same time the programmed value of channel J is fed through the Program Multiplexer, converted to a voltage, and compared in the Comparator and Motor Drive with the voltage output signal. The difference is amplified by the Motor Drive and is fed through the Output Multiplexer to change the channel J reference as required. While the other channels are being sampled, the output of power supply J is maintained constant to 0.2% by the existing channel J regulator. A provision is made in the system for printing out the program, the error, and the actual output values of the channels.

For the long-term project we will look at the beam parameters such as energy, intensity, and focus as the product of the system, and the many machine parameters, such as radio-frequency dee voltage and frequency, main magnetic field strength, trimming-field strength, and the deflector positions and voltages as the controllable inputs. Phase II will include the above-mentioned inputs in the automatic control system.

Hardware

The current ratings of the 17 trim coil power supplies range from 750 to 2500 amperes; we have both Silicon-Controlled Rectifier and Magnetic-Amplifier power supplies. A typical system's open-loop gain, including regulator amplifier, power supply, and transductor, is about 200 to 1000. This gives a maximum reduction in errors of about 0.1%. Due to amplifier drifts, however, the long-term, or daily, stability is about 1%. The signal that is fed back to be subtracted from the reference voltage is derived from a transductor whose output varies from 0 to 15 V for the range of output current. The reference is a 15-V power supply whose output is continuously variable by means of a potentiometer in the control panel. This potentiometer is driven manually with a knob and automatically with a motor. The output signals utilized in the automatic-control system are derived from switchboard metering shunts to provide better linearity.

Since the following discussion refers to multiplexers, I define the term as used within this system. Figure 4 (a) shows schematically an N-to-1 multiplexer and 4 (b) shows a 1-to-N multiplexer. The N-to-1 Multiplexer converts a parallel store of data to a time sequence of data for analysis by a single information processor. The 1-to-N multiplexer diverts a time sequence of data from a single information processor to a parallel group of devices.

The 17 shunt signals are fed into the Input Multiplexer, which consists of 17 double-pole mercury-wetted-contact relays. These relays are driven in sequence at a 3/sec rate by the multiplexer control; every other normally open contact is wired in parallel so as to provide a single two-wire output. This output is fed to the signal conditioner, which is a gain-switched, temperature-controlled differential amplifier whose gain is stable to 0.01% and whose drift is less than ± 5 μV per day. The gain is switched to provide a 10-V signal for full output current of the power supply output being measured regardless of the mV to A rating of the shunt. The output of the signal conditioner, then, is a sequence of 17 voltages proportional to the 17 trim-coil currents, and goes to the "measurement" input of the Comparator and Motor Drive.

The program originates on a single IBM card whose rows and columns are used to provide 40 channels (23 channels are for later use) of 24 bits each. Of these 24 bits, 13 bits are set point data and 11 are miscellaneous data. The card is read statically and therefore continuously.

These 17 program channels are fed to the input of the Program Multiplexer. This multiplexer consists of 17 24-pole relays, which are driven in sequence at a 3/sec rate by the multiplexer control, and whose normally open contacts are wired in parallel to provide a single 24-wire output. The output is thus a sequence of 17 24-bit binary numbers that are related to the 17 power supply set points desired.

The set point data are converted to voltages of 0 to 10 V in the Digital-to-Analog Converter, a Raytheon DAC-20 model. With 13 bits, the output voltage can be set to about one part in 8000. The miscellaneous data are used to program the readout system. The output of the D-to-A Converter, therefore, is a sequence of 17 voltages proportional to the desired 17 set points, and goes to the "Program" input of the Comparator and Motor Drive.

In the Comparator and Motor Drive, the "measurement" signal and the "Program" signal are subtracted, and the difference (or error) is amplified to drive the motor-driven potentiometers in the trim coil power supply reference. There are actually two parallel amplifiers in this block; a low-gain amplifier is active over most of the 0.33-sec period of each measurement to provide the coarse adjustment for the motor-driven potentiometers, and a high-gain amplifier is active over a 0.03-sec period of each measurement for the fine adjustment. The outputs of the two amplifiers are added and followed by a stage of power amplification. Each amplifier input is controlled by a mercury-wetted-contact relay which keeps the input grounded until all the current-carrying relays in the following stages have switched. The mercury relays are then opened for 0.25 sec for the low-gain amplifier and 0.03 sec for the high-gain amplifier. The output of each amplifier is limited to ± 10 V. Figure 5 shows the different forms of the output voltage for a given motor-potentiometer drive. The pulse lengths were derived by consideration of the maximum setup time desired, and of the curves of angular displacement of the motor-potentiometers versus both pulse length and pulse height.

The output of the Comparator and Motor Drive is a sequence of 17 error voltages with waveforms as in Fig. 5. This output is fed to the input of the output Multiplexer. This multiplexer consists of 17 four-pole relays, which are driven in sequence at a 3/sec rate by the Multiplexer Control. Its input is the normally open contacts wired in parallel, with the swingers providing the 17 outputs. The 17 outputs go to the 17 trim-coil power-supply reference motor-potentiometer motor leads.

The Multiplexer Control is a telephone-type stepping relay, driven by a multivibrator, which distributes power to the various multiplexer relays.

The monitoring equipment includes short-circuit tests to check dc level drifts, standard voltage checks for gain drifts, and printout of "measurement," "program," and "error" signals.

A computer program has been written to convert the 17 trim coil currents desired for a particular solution to a single punched IMB card for direct insertion into the automatic control system.

Acknowledgments

P. F. Pellissier, Engineering group leader, provided guidance through many discussions and made several contributions to the system concept. M. J. Renkes coordinated the many efforts involved.

Footnote and Reference

*Work sponsored by the U. S. Atomic Energy Commission.

1. David R. Struthers, Automatic-Control-System Design for the Berkeley 88-Inch Cyclotron, UCRL-16210, June 1965.

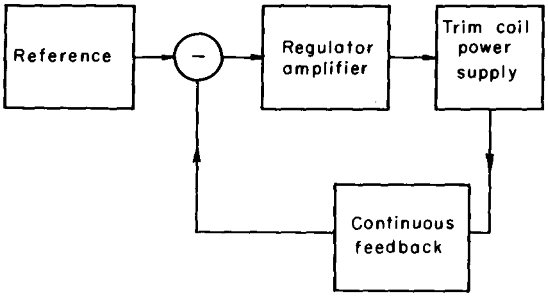


Fig. 1. Typical trim-coil power-supply regulating system.

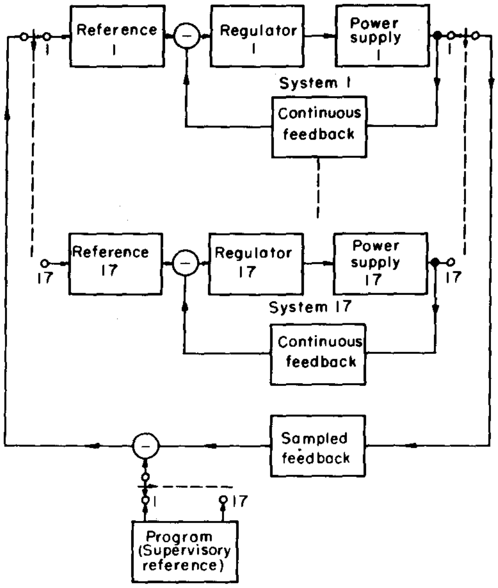


Fig. 2. Supervisory control block diagram.

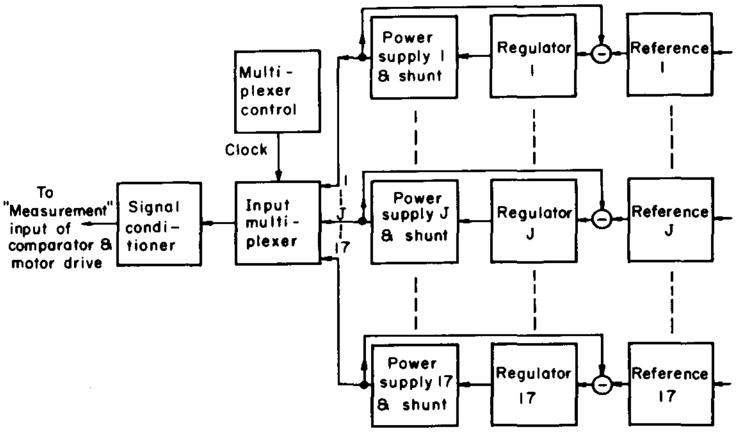


Fig. 3a. Measurement.

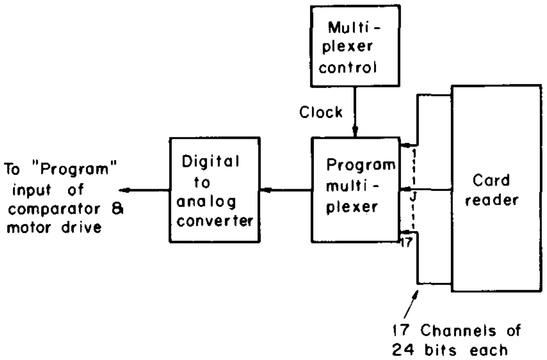


Fig. 3b. Program.

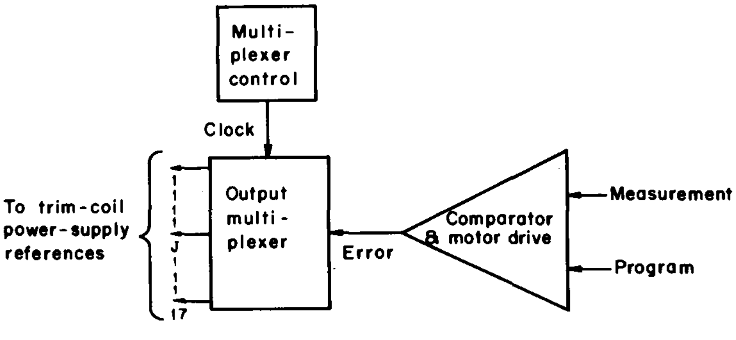
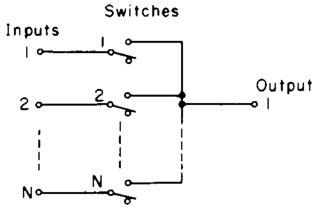
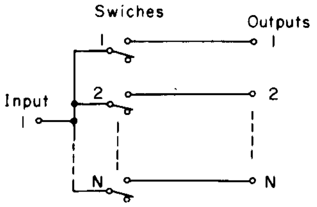


Fig. 3c. Reference correction.



(a) N to 1



(b) 1 to N

Fig. 4. Simplified multiplexers.

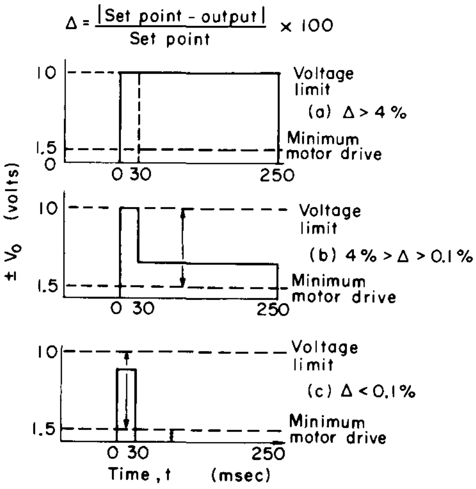


Fig. 5. Output voltage forms.

DISCUSSION

WEGNER: What is the estimated cost of the system including the engineering?

STRUTHERS: The cost so far has been $675 per channel, for the 17 channels. The estimated cost, by the time we complete the 40 channels, will be about $20,000.