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BEVATRON GUIDE FIELD CONTROL*

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Summary

The Bevatron guide field power supply has been under computer control for one year. This facility allows operational parameters to be programmed at operator request in order to provide the desired field profiles commensurate with the current experimental program. With a requirement of one part in fifteen thousand accuracy for resonant extraction, the digital system has been enlarged until a real-time closed-loop control function meet this specification. A one gauss window for entry into flat-zones is now maintained, while a relative flatness tolerance of ±1/2 gauss is held during the typical 2-sec. flat-zone.

This paper includes the structure of a new data-acquisition system with emphasis upon the use of a fast magnetic-core memory to gather blocks of data, as well as to hold the necessary digital threshold values to be arithmetically compared with the results of the data gathering facility. Also covered, is the implementation of the system in the detection and ultimate reduction of incipient fault conditions within the guide field power supply.

Introduction

The Bevatron Power Supply Computer Control System provides five basic features to simplify the control of magnet pulsing: (1) an input procedure that allows an operator to easily define various Bevatron pulse profiles, (2) the ability to analyze the power supply response to any pulse profile prior to pulsing the magnet, (3) a method of selecting and switching to a new operational mode, (4) the ability to analyze the power supply response to the operational mode, (5) a real-time closed-loop computer control for establishing the magnetic fields at beam spill times to an accuracy of 1 part in 15,000 gauss. (.0065%)

A versatile data acquisition system augments the power supply control feature by adding 256 channels of data access to the computer facility. To provide these features, a computer program called "BMAG"[1] is used in one of the Bevatron digital processors. The program provides a total of 17 operational functions that may be requested by teletype key command.

Pulse Profile Control

The Bevatron power supply includes two motor generator sets each with 70-ton flywheels. Figure 1 illustrates the electrical connection of these M.G. sets and their related control loops[2] The 8 high voltage rectifier cubilces that convert the ac generator output to pulsed dc magnet excitation are at the center of the diagram. The sequential and precise control of these rectifiers determines the pulse profile and accuracy of the Bevatron guide field. During a Bevatron pulse this power system converts energy stored in the rotating flywheels to stored energy in the magnetic field and finally inverts the magnetic energy back to the flywheel. Maximum voltage and current from the supply is 15,000 volts at 8400A with stored energy in the magnet peaking at 78MJ. Various pulse profiles and repetition rates can be programmed for the supply as long as the average power loss does not exceed 6MW, the capacity of the two 3600 horsepower induction motors.

The pulse profile may include combinations of mezzanine, flattop and back-porch constant current regions. (See Fig. 2) In the past, these periods have been defined as a time after a current level marker. The level was chosen by the operator by controlling a series of time delays after the current marker was reached. In the more complex profiles as many as 11 variables were adjusted to provide the proper profile. In the BMAG program, the magnet field is sampled every 0.01G during a Bevatron pulse. When a selected value of field is reached a control pulse is transmitted to the Bevatron power supply. This pulse switches the proper high voltage cubicles into either rectification or inversion depending upon the required pulse profile. Figure 2 also tabulates the cubicle switching to provide a mezzanine, flattop, back-porch pulse. A simple pulse matrix of five pulses will define the most complex profile that is considered useful at the Bevatron. The operator will enter the pulse profile data through a teletype keyboard in the sequence shown below. When pulsing on profile 5, the magnet field response would be that illustrated in Fig. 2.

```
      F ← KEYBOARD COMMAND
PROFILE = 5
FIELD   = 7     FIELD IN KILOGAUSS
TIME    = 500
FIELD   = 12
TIME    = 300   TIME IS LENGTH OF FLAT -
FIELD   = 10      ZONE IN MILLISECONDS
TIME    = 200
FIELD
```

Profile Analysis Prior to Pulsing

When a new pulse profile is requested, several operational parameters must be known. What is the motor power demand and pulse length? Is the repetition-rate too high or the pulse length too long for a full power repetition-rate? What magnet current is required? The analysis portion of the program calculates the answers to these questions prior to the selection of the profile as an operational pulse. An analysis readout of a 1.56 second 12.45kG flattop is shown below. This mode was one of the Bevatron's operational modes during October, 1970.

```
     A
PROFILE = 4
RRMAX   = 11.109  (MAX REP RATE)
MW/MOTOR   2.658 MEGAWATTS
ZONE     FIELD(KG)        TIME(MS)        AMPS

 1.        12.425          1540          5038
 2.                        1560
 3.         0.0            1799

PULSE LENGTH  4900
```

Entering the Active Profile

When the computer-operator team has determined that the requested profile is valid and within the pulsing capabilities of the power supply, the profile may be selected for pulsing. As many as ten independent profiles may be stored simultaneously. Paper tape entry

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* This work performed under the auspices of the Atomic Energy Commission.

and recording, supplements the magnetic disc overlay capacity. The technique of profile change is shown below.

```
B
PROFILE = 4     "B AND 4 ARE THE
RRMAX    = 11.109  OPERATOR ENTRIES"
****TIME****   13.414
PROFILE   4.    IN USE
```

Active Profile Analysis

When the Bevatron is pulsing, BMAG program offers an analysis of the power supply and magnet response to the computer controlled excitation. Of immediate interest to the operator is the actual value of field obtained at the start of a flat-zone. This value is determined by turn-off sequences initiated by the control pulses. The program is written to read and record field values 10-msec into the flat zones. Upon command the computer will correct for the difference between the profile entry value and the actual value if such field accuracy is required.

In addition to field values, the change in speed of the 124 ton rotating shafts of the two motor generators are monitored. This reading is made to insure that centrifugal forces are within specifications. No pulsing modes are allowed that demand speed ranges of more than 70 rpm per pulse.

Guide Field Stability

Stability of the 120 MVA Bevatron Power Supply can be measured by recording pulse-to-pulse changes of operating parameters. The use of the EPB Septum Channel and resonant extraction techniques has reinforced the demand for pulse-to-pulse repeatability.

The teletype printout below shows instanteous operating parameters at start of pulse (#2), start of flattop (#8), and at end of flattop (#1).

```
X
PROFILE     10
PULSE FIELD ERROR AMPS DI/Z TIME SPEED DS/Z
  2.   .000  .000                   878
  8. 12.558 -.001 5140 5140 1590   848 -30
  1. 12.826  .266 5339  199 1760   841 -36
SHALL I CORRECT ? N
```

This printout describes a typical flattop pulse at the Bevatron. The flattop start is programmed for 12,559G and increases 200A during the 1760msec of flattop. The rate of change of field is approximately 9 G/msec. Therefore, a one gauss maximum error demands that the rectifier cubicles switch into the flattop mode in less than 110μsec after the field indicator pulse. Direct field measurements with a resolution required for maintaining stability and flatness to 0.0065% are time-consuming at best. A real-time continuously updated, digital integrator has been implemented to provide the necessary resolution. Windings within the useful area of the guide-field provide a voltage-source (Fig. 3) whose magnitude and polarity is directly proportional to the rate of change of flux contained within the area of the windings. This voltage is converted to a pulse train by means of a voltage to frequency converter. The repetition rate of the pulse train is directly proportional to the instantaneous voltage induced in the windings. The information from the converter is in the form of UP/DOWN pulses corresponding to a 0.01G change in the main magnetic field. These pulses are accumulated in scalers to give the instantaneous field. The gauss scaler now becomes the new standard for energy identification. Sixteen 1kG markers are distributed through the Bevatron, replacing the current marker system. All processors have access to the field scaler by way of direct memory access. The processor puts out data corresponding to the desired field resolved to centigauss. This value is compared with the value in the field scaler using a high speed comparator. If the field is increasing the greater-than signal is used to produce a command pulse and an interrupt is sent back to the processor to inform it the field has been reached. If the field is decreasing, the less-than line is used.

A 10MHz clock is used for timing throughout the Bevatron. This clock is used to time the length of the flat zones. This feature is combined with the field-compare so the data the processor puts out signifies both magnitude and time/field mode. Just prior to starting a new pulse, the residual field is measured, and this value is pre-set into the field scaler to give the field value an absolute quantity.

Changes in the speed range of the motor generator sets during successive Bevatron pulses will cause shifts in the flattop start field. This is due to the fact that although the magnitude of the guide field can be compared to 0.01G, the recitifier cubicles must be switched into the flattop mode at descrete 3-phase rates, which are a function of shaft rotational rate. Load variations and changes in the 12,000 volt motor feeder line are major causes of shift in the speed range. Any long term drift in the Kramer motor control[3], the synchronizing control loops[2] or the firing angle control circuitry will cause long term instability in the power supply. To minimize these instabilities, the BMAG program utilizes subroutines to monitor and update control references. One typical sub-routine programs the magnet voltage to insure optimum time relationship between the field marker and rectifier control pulses. A second subroutine controls the rectifiers to insure that the field slope during the flattop also meets the 1G error limit. Additional subroutines program the Kramer motor control reference for power balance of the two machines as well as compensating for 12kV line changes.

The digital facility, of which the guide-field control is a part, includes a disc-oriented mass-storage capability. This feature provides a "multi-processor" structure from the standpoint of data-swapping. The processor controlling the guide-field has the additional responsibility of generating the functions to be performed by the numerous pole-face windings within the useful beam aperture of the main magnet. A 32-channel serial control data transmission and current-monitoring system is operated at a 1kHz rate, with the software of BMAG calculating the time-variable values required to implement the trapezoidal functions at injection and the set-point dc levels required for flattop beam spill.

Data Acquisition

The first employment of a new concept in data-acquisition techniques is in a multi-channel system recently installed in the main power supply for the Bevatron (Fig. 4). Typical ignitron tube anode currents are 2000 amperes and each high-voltage cubicle includes tube "pairs", designed to conduct in parallel and thus share normal conduction currents. It is understandable that an unusual or spurious operation of this system can result in improper sharing of current paths, and in fact, can result in catastrophic tube failure due to inordinately high anode currents. Ignitrons require proper phasing of grid waveforms as well as ignitor currents as referenced to the anode voltage waveform. A failure in either of these control signals can prevent one tube of a pair firing, thus creating excessive anode currents in its partner.

One of the prime purposes of data-acquisition is to determine the state of a series of parameters. This means a quantitative treatment, but one which borders upon the qualitative to the extent that "Threshold crossing" is actually of paramount concern. The unique treatment offered by this new system is to provide all threshold values and required response functions in a block of peripheral memory. This reference data is successively brought into a digital comparator, into which is also fed the results of the analog-to-digital conversion. At this earliest possible time, threshold crossing is detected and simple resultant responses are initiated. Responses such as interruption of succeeding firing pulses or phasing-back of firing angles are examples. Other responses are simply to flag the occurrence or to interrupt a digital processor, which can then examine the contents of the peripheral memory, which contains the results of several previous cycle of acquisition. This method of detection is as close to real-time as the repetition-rate of parameter acquisition allows.

Forty-eight tubes under surveillance and 4 parameters per tube results in a total of 192 channels of analog multiplexing. It is desirable to retain a record of previous data for each of the parameters, in order to properly diagnose causes of failures and to provide a histogram of fault growth. Therefore, after comparison of the threshold with the converted parameter value, the value is inserted into its respective location in a block of the peripheral memory. Upon completion of one cycle of 192 channels, the block address is advanced to a new block and thus 10 earlier values of each parameter are always available, each collected at successively later periods of time, to allow reconstruction of the history of each tube in the system for several cycles prior to detection of the impending fault condition.

With the rectifier system, operating at a nominal frequency of 60Hz, a tube's conduction period is 6 msec. It is desirable to sample the magnitude of the 192 parameters as many times as possible during one conduction cycle. It was determined that ten blocks of core could be filled with data and comparisons performed, if the total acquisition cycle duration was 400μsec. It is this requirement that establishes an individual sequence duration of 2μsec. In this period of time, a parameter must be addressed, multiplexer settled, analog to digital conversion accomplished, digital comparison made and parameter magnitude written into memory. It is also necessary that the digital threshold value be read out of core during this same interval, prior to the comparison interval. During the time that a parameter is being written into memory, the analog multiplexer can be allowed to seek the address of the next parameter to be accessed. Other time-sharing is accomplished by reading and re-writing the threshold value from core during the same interval utilized by the ADC to convert the analog value and provide the digital results to the comparator. These considerations established the operating characteristics required of the modular devices employed. System resolution requirements of 0.1% allow use of a 10-bit successive approximation converter with a conversion rate of 100nsec per bit. In order to accomplish the tasks required within the 2μsec allowed, a core memory module with 900nsec full cycle time is included. The unit utilized is a 16-bit, 4K word model. The parameter magnitude data occupies 10-bits of each word. The additional bits are utilized as flag bits, counter for incrementing to keep track of the number of unusual occurrences, or as a code, occupying the most significant 6-bits of the threshold reference words in memory. This code indicates the course of action to be taken dependent upon the results of the threshold comparison. It provides the flexibility needed to handle signed parameters and to allow inversion of the normal threshold action when the fault condition is a decrease in magnitude.

The net result of these considerations is a peripheral memory bank synchronized to the conduction periods of mercury ignitrons, address keyed to sequence through significant parameters as they become properly oriented in real-time (Fig. 4). Rapid cycling through a number of parameters during each repetition cycle with occasional side-trips to acquire static data with no real-time significance, allows a histogram of data by successively inserting each block of data point in adjacent blocks of peripheral memory. This is continued over 10 blocks of data and provides a rotating list of blocks each with data from the current cycle and 9 previous cycles.

Analog data has predominated in this discussion so far. The system also includes provisions for status monitoring for safety and control chains. This provides a software capability for alterations of chains, since all chain points are collected and assembled in parallel words of 10-bits each and then presented to a digital multiplexer. The output is scanned occasionally in place of the analog converter output. The threshold words used to compare against the digital status words allows simple logical decisions to be made dependent upon the status of the collected chain data.

Low slewing rates are required of the many conditioning amplifiers in the system. Low-cost integrated circuit operational amplifiers are utilized in differential mode at the inputs. Silicon-gate semiconductor analog switches with internal chip address decoding simplify logic and switch drivers. Because of the fast transient response required by the buffer amplifier between the multiplexer and ADC, an ultra-fast-settling operational amplifier was selected.

Communication with the memory has been established through both keyboard and digital processor direct-memory-access channel.

Conclusion

A new technique in pulse programming, data monitorong and error detection has been outlined as it exists in the Bevatron Power supply at the Lawrence Radiation Laboratory at Berkeley. Its essence is represented by its rapid-data-acquisition, real-time threshold detection and fast response in field corrections.

Work is continuing in the areas of automatic reference setting visual display techniques and computer surveillance of additional parameters with special emphasis on reduction of magnet field ripple.

References.

1. Robert Belshe, Robert Frias, "BMAG-Bevatron Magnet Pulser Control Program", UCID Report 3425, Lawrence Radiation Laboratory, Berkeley, Feb. 1970.

2. Bevatron Operations and Development, Power Supply Reconnection, UCRL Report 18864, Lawrence Radiation Laboratory, Berkeley, July - September 1968.

3. Robert Frias, Bevatron Operations and Development, The Bevatron Kramer Motor Control, UCRL Report 16554, Lawrence Radiation Laboratory, Berkeley, July - September 1965.

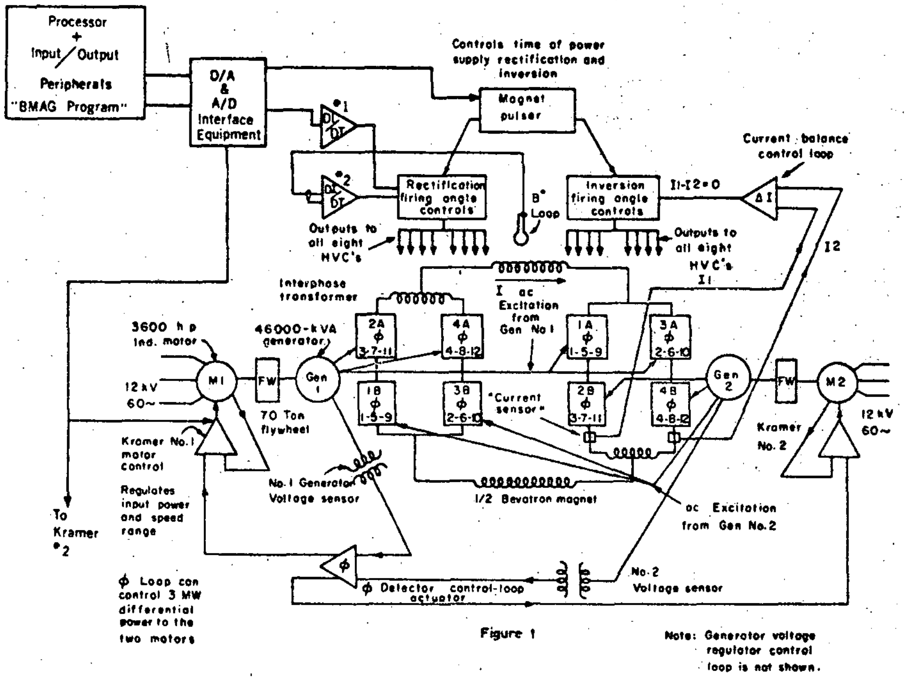


Figure 1

Note: Generator voltage regulator control loop is not shown.

Bevatron Power Supply and Control System XBL 712 6266

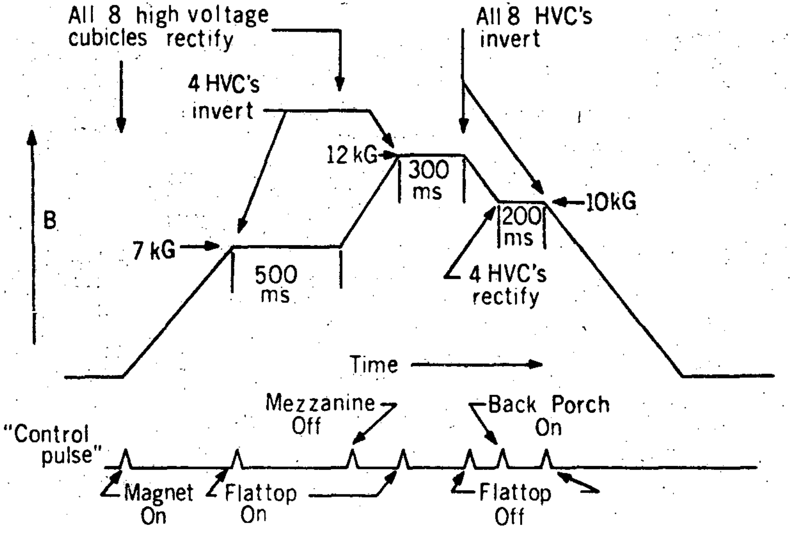
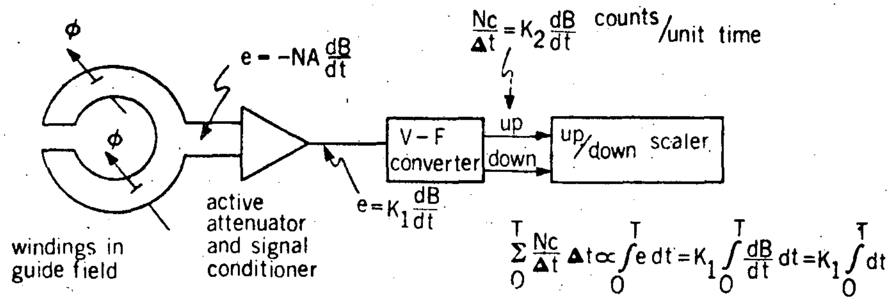


Figure 2

A Bevatron Pulse Profile

XBL 712 6267



therefor

$$N_{total}\Big|_{t=T} = KB_T$$

Figure 3 Digital Integrated Field Value

XBL 712 6268

where K is selected to scale counts to centigauss.

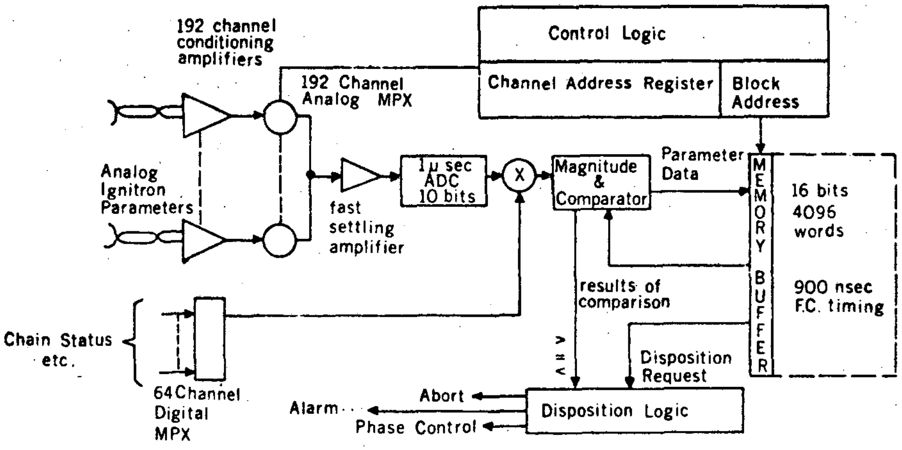


Figure 4 Ultra-fast Data Acquisition XBL 712 6271

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