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# A PULSED EXTRACTION MAGNET SYSTEM AT THE ZERO GRADIENT SYNCHROTRON (ZGS)*

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## Summary

Pulsed operation of six extraction magnets has saved $67,000 in FY 75. Conversion of four six-phase supplies involved some unique analog circuitry. A minicomputer operated function generator provides control of up to 20 magnet power supplies with new dI/dt data available every 4 ms. The operator control console has several options which appreciably decrease set up time and decrease operator error.

## Introduction

The ZGS extracts simultaneously into two proton lines. Each extraction line consists of four magnets which consume about 350 kW per magnet when the accelerator is operating at 12.3 GeV/c. Seven of the eight extraction magnets are laminated. Four of the eight magnets were operated dc from 60 Hz, six phase solid state supplies. Three were excited by motor-generator sets. One has been pulsed since 1972 for operational, not power saving, reasons.

We have long considered the cost saving and other advantages which would accrue from pulsed operation but other activities always had prior claim to the capital and manpower required to make conversion to pulsed operation. The energy crisis experienced by the nation and the budget crisis experienced by the ZGS made us consider this again in early 1974. We estimated that we could save 1.6 MW when operating at 12.3 GeV/c and this would result in an economy of $9,000 per month. Since this time our energy costs have changed such that we now save $15,000 per 12.3 GeV/c operating month. Even with our curtailed operating schedule, we have saved about $67,000 and 5000 MW hours in FY 75. Since the conversion project has cost only about $105,000, we have obviously made a reasonable investment.

The obvious task of purchasing pulsable power supplies for two magnets and strengthening the magnet insulation systems for pulsing were routinely carried out. Besides these jobs, two more challenging activities were presented. The first of these was the modification of the control loops of the four existing solid state supplies. These control loops were so slow that they could not turn on the current in the required time and could not track the thermally induced resistance changes during the pulse. A unique solution to this problem is described. The second challenge was really an opportunity to modify the control concept of all our extraction magnets. Seven magnets were already being pulsed with four instructions per ZGS cycle. Using a minicomputer we were able to control 20 magnets with break points as often as every 4 ms. The circuitry and programming required to adapt a minicomputer to this use is described. The operator interface which provides his access to the minicomputer and a read-out of the times and values of his instructions, and the actual magnet currents are also described.

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## Regulator Performance Goals

Our goals were to achieve output current rise times of the order of 100 ms, current regulation of better than 0.1% during the flattop and low ripple in the output current. In addition we wished to provide two adjustable regulated current levels during a ZGS pulse. One level is for extraction of beam from the ZGS at an intermediate energy and the other level is for extraction of beam at a high energy.

These goals were accomplished by rebuilding only the regulators for the four slow supplies. Modification of major components could be done only at a prohibitive cost.

## Shunt Regulator

The input to the original shunt regulator was directly connected to the voltage applied to the magnet load. This dc connection was not satisfactory for the 100 ms rise current pulse because the swings in voltage on the magnet were so large and fast that the shunt regulator transistors failed.

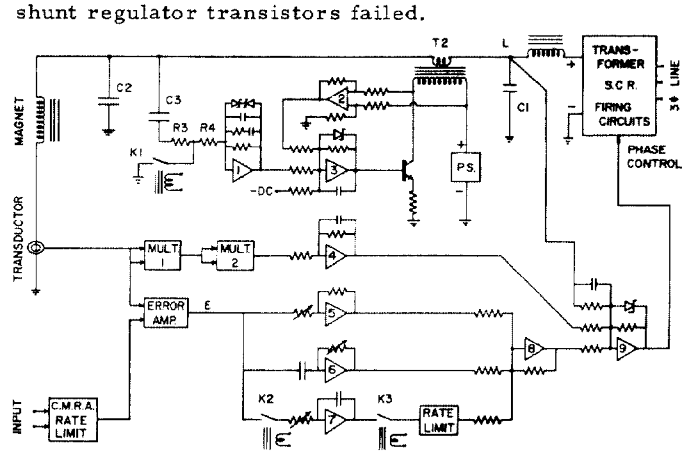


Fig. 1. Simplified Schematic of the New Regulator

The modified circuit is given in Fig. 1 in simplified schematic form. The input of amplifier 1 is coupled to the magnet voltage through the capacitor, $C_3$. In addition, the input to amplifier 1 can be grounded by the relay contact, K1.

In normal pulsed operation, the relay contact, K1, is closed until the magnet current is nearly constant. The relay contact is then opened to permit the shunt regulator to reduce the ripple. The contact is then closed before a command is given to change the magnet current.

The time constant $C_3 (R_3 + R_4)$ in Fig. 1 is chosen to pass all of the normal ripple frequencies and at the same time allows the changes in magnet voltage that are required to slowly ramp the magnet current during "flattop". The amount of ripple reduction is controlled largely by the gain of amplifier 1 at the ripple frequencies and by the turns ratio of the transformer, T2. The over-all ripple reduction is of the order of a factor of 5.

## Main Regulator

The main regulator for the dc current in the magnet is shown in the bottom part of Fig. 1. It is a proportional plus integral plus derivative type of controller but with significant additions.

First attempts at operation without relays K2 and K3 and without the rate limiters revealed serious limitations. The first of these limitations was a maximum rate of rise of voltage on the magnet. If this rate was too high, the charging currents for the filter capacitor $C_1$ were so large as to cause capacitor failure. This trouble was eliminated by adding the rate limiters shown in Fig. 1.

A second limitation was that the allowable gains for the amplifiers 5, 6 and 7 were too low to achieve the desired performance in the pulsed mode. The maximum gains for stable operation are controlled by the characteristics (time constants) of the L, $C_1$ filter and of the magnet.

Relays K3 and K2 were added to the output and input of the integrator amplifier 7. This pair of relays, when operated with the proper timing, makes possible pulsed operation with a greatly reduced error on flattop. The operating sequence is as follows: Relay K3 is closed at the same time that the input command is changed from zero to the desired value (step change). The magnet voltage and current increase to a value approximating the steady state. At this time relay K2 is closed and the integrator begins to correct the error signal to zero. Near the end of the current "flattop", relay K2 is opened to put the integrator in "hold". Then Relay K3 is opened at the same time that the input command is returned to zero. At the start of the second cycle the output of the integrator amplifier 7 is much nearer to the correct value (for no error). During the second cycle, the relay sequences are the same as for the first thus further reducing the error in magnet current. Three or four ZGS cycles are required before the regulator adjusts the "flattop" current to be within 0.1% of the command.

Operation of the extraction magnet at a second set of current levels during a single ZGS cycle is accomplished by using a second integrator similar to amplifier 7 in Fig. 1. A second set of relays similar to K2 and K3 is also required.

## Magnet Warmup Compensation

The application of 350 kW of power to the extraction magnets causes the copper to warm up and the magnet resistance to change during the current pulse. This change in resistance requires a change in magnet voltage to maintain the current constant during "flattop". This is no problem during dc operation since the temperature quickly comes to equilibrium in a few seconds. In our case the integrator action of amplifier 7 in Fig. 1 and the permissible gain of amplifier 5 do not keep the current within the 0.1% desired limit.

Measurements at dc and at many current levels showed that the increase in magnet voltage over that required for "cold" magnet coils varied as the fourth power of the magnet current. Measurements of the dynamic characteristics showed that the warmup time constant for a particular magnet was about 0.75 seconds. This is undoubtedly a function of cooling water flow rate and of water circuit length.

The correction circuit for warmup uses the two transconductance type multipliers shown in the left middle part of Fig. 1 to form the fourth power of the current. This signal is sent through a time constant amplifier 4 and then added to the input amplifier 9. With this circuit, the error during "flattop" can be held to within 0.1% of the desired absolute value at all current levels.

## Operator Interface

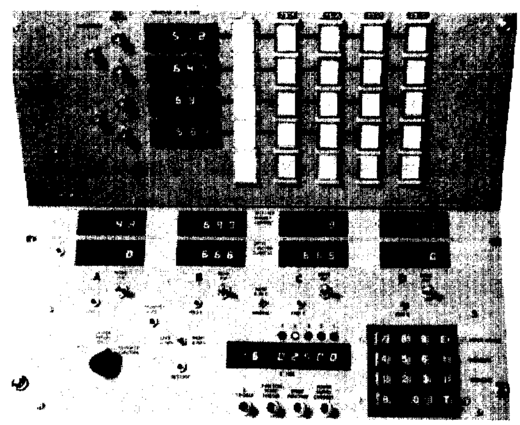

Fig. 2. The Minicomputer Control Console

Fig. 2 shows the control console. The digital keyboard and associated readout provides an adjustable time reference which is synched to a ZGS cycle clock. For description purposes, this pulse is called the "E" pulse. It is the fast positive going pulse in Fig. 3.

The upper chassis provides both a readout and selection function. Magnets can be selected in groups of four for readout sampled at time E. Analog current signals and current difference signals are also available here. This facilitates study of magnet ripple and sequence problems. Selection for minicomputer control is done on this panel also.

Fig. 3 shows a typical extraction magnet current waveform of a "front porch" and "flattop" operation. Below it is the power supply reference voltage which is generated by the minicomputer-directed function generator. A permissive signal to start this function comes from the ZGS cycle clock. Note the sharp negative spikes on the reference waveform. These spikes are not part of the command sent to the power supply but are to inform the operator of the present location of his control points. The basic wave shape generated is a trapezoid. That is, straight line segments (command voltage linearly increasing with time) are drawn by the system between the four points A, B, C and D. Looking at Fig. 2, the A, B, C and D control switches set the time location of the control points and switches B and C also control the slopes of the line segments by vertical movement of points B and C. Complex waveforms may be generated by "stacking" several trapezoids on each other and offsetting their start times. The start of a new three-line segment group may occur as often as every 4 ms. When applied to a magnet power supply, this permits adjustments of the dI/dt of the magnet every 4 ms. When the trapezoids are stacked, nothing in the memory earlier in time than time A nor later than time D is altered. However, the three new slopes between A, B, C and D are added to whatever was in the memory in the time interval between A and D.

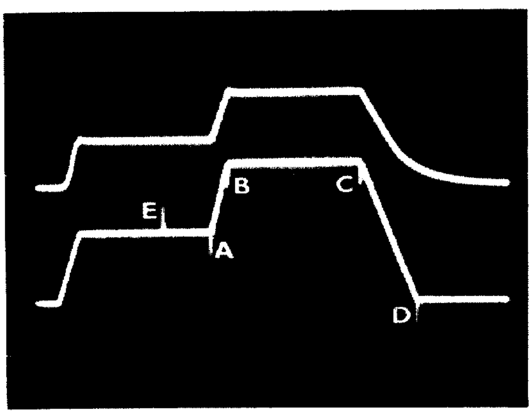


Fig. 3. Typical Command and Current Waveform

The readouts above the control switches provide data as to the value of the reference command and the value of the resultant current. These data are sampled at the control point times. The lower set of four readouts normally displays the expected currents. The numbers are continually refreshed so that the operator does not have to wait for the next ZGS pulse to see the effect of a control switch change. At the operator's option, this same set of readouts may be made to show the time, in ms, of the present set of control points. Zero time for this measurement is the ZGS permissive. The four readouts just above display the value of magnet current at the four control points. These values are often different than the reference command due to power supply dynamics.

The rotary switch on the lower left allows the operator to move the control points or even build a function on the display without modifying any magnet current. The unit is programmed to store, as "original", the operating function in the memory when a magnet is selected. Return to that original function is possible by pushing the "Restore" button.

## Special Features

One intuitively understands that an infinite variety of wave shapes is available with this technique. One does not instinctively realize that generating several complex functions that must have certain relationships between each other proves time consuming and error prone. A number of special features have been added to make frequently repeated operations easier.

One such feature allows the minicomputer to automatically move the control points to four selected E times. Thus, a function can be rapidly indexed to the ZGS operating cycle. A related feature allows transfer of these same control points to other magnets.

Two other important beam steering features are available. A "Gang B to C" feature allows movement of control point B while control point C automatically follows it maintaining both its time and amplitude relationships to B. A second feature is particularly useful when beam steering during a front porch operation such as Fig. 3. Two sets of control points A, B, C and D and A', B', C' and D' are remembered; thus, the operator can rapidly change from adjusting beam steering on the porch to beam steering on the flattop with just one switch actuation.

## The Minicomputer System

The choice of a software-based control system and a totally digital function generation scheme was based on the inherent advantages of these methods. First, once a certain complexity is reached, a software-based system has a much better complexity vs cost ratio. Second, once the system is finished, the capacity and complexity can easily and economically be increased. Third, with its crystal-controlled time base and numerically determined scale factors and point-to-point slopes, the digital function generator is highly stable.

## System Organization

Fig. 4 is a functional block diagram of the minicomputer - based function generator system. The computer used is a Data General NOVA 1210 with 8 K of memory and no special features. The computer is shown broken into two function blocks; namely, the CPU/program memory and the function generator control arrays. The reason is that the function generators access their data arrays via the direct memory access (DMA) data channel without the "knowledge" or control of the program operating elsewhere in memory. The program can then confine itself to servicing the control panel and responding to operating requests and merely maintain the many functions as numeric arrays in memory. The control panel communication link is by the more conventional program-controlled I-O.

The program maintains for each function a different numeric relationship between the requested current and the command voltage depending on the scale factor of the power supply so that all function generators can be identical. The panel readouts are always provided with normalized information in amps (which would result from the applied command voltage).

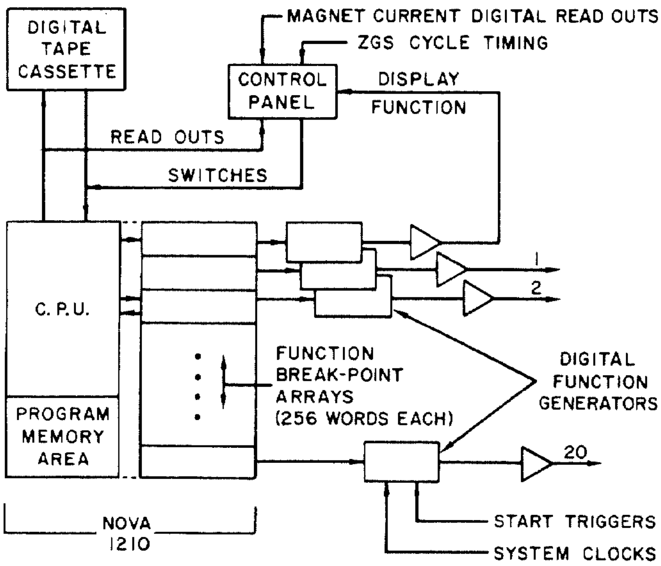


Fig. 4. Functional Block Diagram of Minicomputer-Based Function Generator System

Several power supply control systems require remote relay actuation as described above to control their regulator mode. These actuations must be in synchronism with the command waveform and are controlled through the use of extra bits in the function control array.

The computer is provided with a digital tape cassette system for the purpose of preparing and loading programs. This same device is also used to store for future use a copy of the complete extraction magnet function configuration.

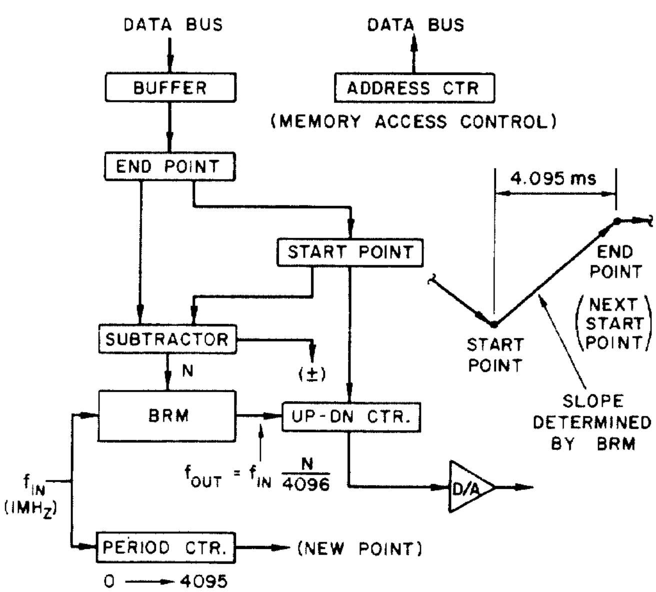


Fig. 5. Digital Function Generator Block Diagram

## The Digital Function Generator

Each digital function generator is packaged on a 5 in. x 9 in. wire-wrapped printed circuit board. It contains about 50 digital logic devices, a 12-bit digital-to-analog (D/A) converter, and linear amplifiers. All generators are identical with operating frequency, computer memory range, and other variations being determined by connections made to the plug-in socket.

Fig. 5 is a block diagram of the generator showing the major functional parts. The technique used is essentially the same as that used in the CERN multi-function generator.[1] An up-down counter driving a D/A converter is the central feature. Its counting rate, and therefore the slope of a straight line vector, is determined by a binary rate multiplier (BRM). The BRM output frequency is proportional to a numeric input. The BRM is a totally digital device and does not produce absolutely monochromatic frequencies, however, the up-down counter is never more than one count in error. This design differs from that of CERN in that it uses a constant period between break points. It is then possible to calculate the BRM input necessary by subtracting the start amplitude from the end amplitude for each vector. A period counter determines when the end point is reached and the new start point value is set into the up-down counter to correct for any error in the BRM frequency.

Since the installation of the system, two complex features providing additional operator conveniences have been added to the software with trivial control panel additions being necessary. Since most of the manipulative properties of the system are defined by the software, changes can be implemented off-line in another computer and installed in the system with a minimum of disruption.

## Acknowledgments

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## Reference

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