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THE RAPID CYCLING SYNCHROTRON EXTRACTION KICKER MAGNET DRIVE SYSTEM*

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Abstract

The Rapid Cycling Synchrotron (RCS) accelerator of the Intense Pulsed Neutron Source-I (IPNS-I) at Argonne National Laboratory utilizes a fast kicker magnet to provide single-turn extraction for a 500 MeV proton beam at a 30 Hz rate. The single-turn, 0.89 m long ferrite magnet is broken up into two identical cells with four individual windings. Each winding requires a 4863 A magnetizing current into a 7.0 Ω load with a rise time of less than 100 ns and a flattop of about 140 ns. Pulse forming network (PFN) charging and switching techniques along with the components used will be described.

Introduction

The power supply system was divided into two identical sections which individually pulse each cell of the fast kicker magnet's two-cell design.[1] Although required to operate at 30 Hz, the system was designed to accommodate the future upgrade of the RCS from 30 Hz to a 45 Hz machine. System reliability and ease of maintenance were of prime importance.

Specifications

Each of the four magnet windings are to be driven from individual PFN's with a characteristic impedance of 7.0 Ω providing a 4863 A magnetizing current adjustable to ± 10% with an overall system rise time of $\leq$ 100 ns and a flattop of at least 140 ns. Allowing 10 ns jitter with a magnet cell rise time (L/R) of 78 ns requires the basic power supply system to have a rise time of $\leq \sqrt{100\ \mathrm{ns}^2 - 88\ \mathrm{ns}^2} = 47.5$ ns.

Although the present pulse repetition rate (PRR) requirement is 30 Hz, the system will be designed to accommodate the future RCS upgrade to 45 Hz. The system must also be capable of operating at PRR's of 1 Hz, 5 Hz, 10 Hz, and 15 Hz and maintain a regulation of less than 1%.

Pulse Forming Network

Supplying a 4863 A pulse from a 7.0 Ω PFN into a 7.0 Ω magnet termination requires charging the PFN to a voltage of 4863 A x 7 Ω x 2 = 68 kV. Obtaining the correct pulse flattop of 140 ns with a rise time of 100 ns requires the total propagation time of the PFN to be $\frac{140\ \mathrm{ns} + 100\ \mathrm{ns}}{2} = 120$ ns.

In view of these requirements, each PFN was constructed by paralleling two 14 Ω, 100 kV, Belden type YR-10914 pulse rated coaxial cables. With an inductance of 98.4 nH/M and capacitance of 455.9 pF/M, the propagation time of the cable is $\sqrt{LC} = 6.70$ ns/M. Each PFN cable length, therefore, is $\frac{120\ \mathrm{ns}}{6.70\ \mathrm{ns/M}} = 17.9$ M.

High voltage insulation and cooling, via water cooled heat exchangers, was acquired by constructing the system in oil-filled tanks. Segregating each power supply section into separate charge control and thyratron discharge tanks allows both ends of the PFN cables to be terminated in oil.

Series Charge Control Regulator

Insuring equal voltages on all PFN cables needed per magnet cell requires charging from a common series voltage regulator. Allowing for the + 10% adjustment requested, the system was designed to operate with a maximum PFN voltage of 75 kV at a PRR of 45 Hz. For 45 Hz operation the allowable charge time selected is 18 ms and for 30 Hz operation 28 ms. With PFN parameters and charge times fixed, the series regulator and operating power supply requirements can be determined.

The total capacitance of PFN cables to be charged is 4 x 18 m x 455.9 pF/m = 32.82 nF. Charging current for 45 Hz operation:

$$I_c = C\,dv/dt = 32.82 \times 10^{-9} \times \frac{75 \times 10^3}{0.018} = 136.77\ \mathrm{mA}.$$

Power dissipation of the series regulator:

$$P_{AV} = V_{AV} I_{AV} = \frac{(75 \times 10^3) \times (136.77 \times 10^{-3})}{2} \times \frac{0.018}{0.022} = 4.20\ \mathrm{kW}.$$

The cascade-type circuit of Fig. 1 is used as the series voltage regulator and is controlled with a single bias and switching module. Four EIMAC type 8960 pulse modulator tetrodes, each rated for 1.2 kW at 50 kV, were selected as series control elements.

The bias and switching module of Fig. 2 receives an on-off infrared gate pulse generated by the logic level voltage control feedback loop. Pulsing both control and screen grids of the master tetrode provides sufficient drive to charge the PFN's to a predetermined voltage within the allotted time. Both grid gate signals are generated simultaneously with the circuit's main switching transistor, a 2N6214. Fine tuning of the charge time is acquired by adjusting the pulse level on the control grid with a motor driven 10-turn potentiometer.

Isolation between the two PFN sets and the series regulator is provided with wire-wound 100 W resistors. Due to the inherent inductance of wire-wound resistors, additional isolation is provided during the rapid discharge cycle of the PFN's. American Components' high voltage resistors type ROX-4 were used for the tetrode dividers, and type ROX-3 for the voltage feedback divider and thyratron gap dividers in the thyratron discharge circuit.

Thyratron Discharge Circuit

English Electric Valve type CX-1192 thyratrons are used as PFN discharge switches. They were selected for their low jitter, voltage, and current handling specifications. Mounted in coaxial housings to minimize stray inductance, each thyratron has plug-in printed circuit cards for bias and trigger control modules. Figure 3 shows the schematic diagram of the discharge circuit and the connection to the magnet and load assemblies. Preserving the system impedance, magnet and load transmission lines also use the Belden YR-10914 coaxial cable.

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Each of the four thyratrons required for the entire system receives individual trigger pulses. Relative timing of the trigger pulses are fine-adjusted at the control logic level so that all magnetizing currents appear at the magnet in coincidence. A detailed schematic of the thyratron trigger amplifier and pulser is shown in Fig. 4. The main triggering transformer, T1, has a 42-turn secondary driven by six individual four-turn primaries in parallel and wound on a double Indiana General type F626-12, Q1 toroidal ferrite core. Protection against the destructive voltage spike appearing on the thyratron grid during triggering was remedied by use of MCG Electronics type TSD transient suppressors at the thyratron grid, pulser transformer primaries, and the pulser drive transistors. With anode voltage off, the photograph of Fig. 5 shows typical thyratron grid triggering pulses imposed on the negative hold-off bias.

Terminating Loads

Designed to resemble a lossy transmission line, each load assembly contains a series stack of fourteen 1.0 Ω Carborundum type AS, washer style power ceramic resistors separated by silver-plated copper cooling fins. Details of the assembly are shown in Fig. 6.

Assuming negligible magnet losses, each load is capable of absorbing and dissipating the maximum peak and average energy stored in one length of PFN timing line. Operating with 75 kV on the PFN's at 45 Hz requires each load to absorb a peak current of

$$\hat{I} = \frac{\frac{75 \times 10^3 \text{ V}}{2}}{14 \ \Omega} = 2679 \text{ A}; \quad \text{for peak power}$$

$\hat{P} = (2679 \text{ A})^2 \times 14 \ \Omega = 100$ MW. Under these conditions, the average power dissipation requirements are $P_{AV} = 1/2 \ (455.9 \text{ pF/M}) \ (18 \text{ M}) \ (75 \times 10^3 \text{ V})^2 \ (45 \text{ Hz}) = 1039$ W.

Maximum specified ratings for each type 915 WS resistive element are 70 W, 5 kV, and current of 3588 A. Enhancement of power dissipation by about a factor of two with forced air and cooling fins provided a very conservative design.

Control Logic

Operating in tandem, the two power supply sections are linked together by common charging voltage reference, charge command, and trigger command signals. A simplified block diagram of the control logic is shown in Fig. 7. Fixing the time between charge and trigger command signals maintains system regulation regardless of the operating repetition rate selected. Although actually triggered from a beam fast Q signal, the system has an automatic trigger if beam is not present.

Efficient single-turn extraction requires correct kick angle and precision trigger timing with respect to the proton beam. Remote controls accessible to the machine operator are the PFN charge voltage reference and timing adjustment of the variable delay trigger generator.

Results

Preliminary testing of the power supply system was limited to 30 Hz due to the current limitation of the unregulated high voltage main power supply. The basic system rise time pulsing into the terminating loads without the magnet was measured to be 30 ns.

Operating experience has proven the cascade type charge circuit, charge control bias and switching module, and thyratron control circuits to be very reliable and virtually maintenance free.

Summary

Thirty hertz operating conditions require three series charge regulator tetrodes for an average power dissipation $P_{AV} = 2.80$ kW and two adjustable unregulated high voltage power supplies capable of 150 kV with a current capacity of at least 100 mA. Each of the four individual PFN discharge circuits are able to produce a pulse current of 5357 A with a rise time of 30 ns into a 7.0 Ω coaxial load.

Conversion of the system to its designed 45 Hz operation requires inserting an additional series PFN charge regulator tetrode and upgrading the high voltage unregulated power supplies to a 200 mA current capacity.

Acknowledgments

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Reference

1. D. E. Suddeth and G. J. Volk, "Rapid Cycling Synchrotron (RCS) Single Stage Kicker Magnet," IEEE Conference Records of 1980 Fourteenth Pulse Power Modulator Symposium, pp. 289-291.

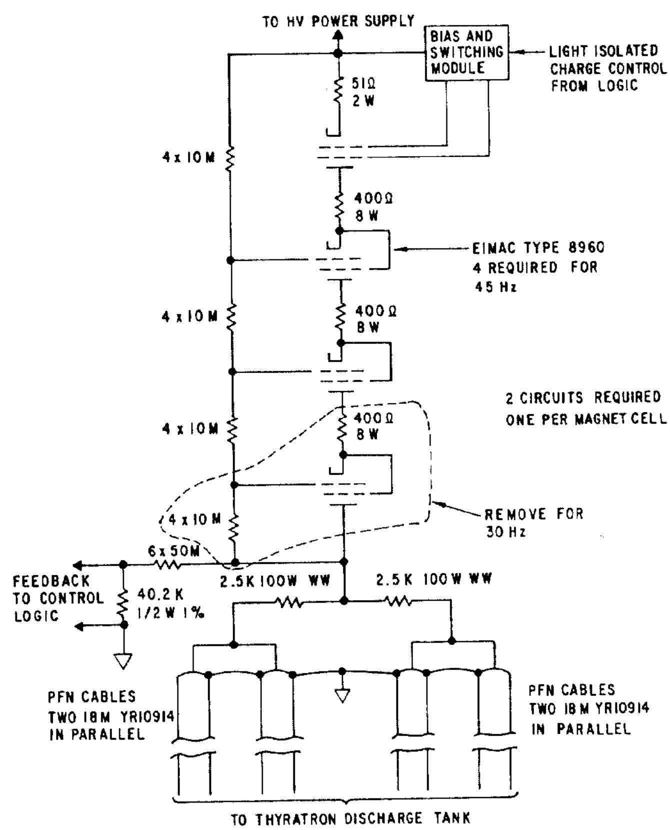


Fig. 1 Cascade Charge Circuit

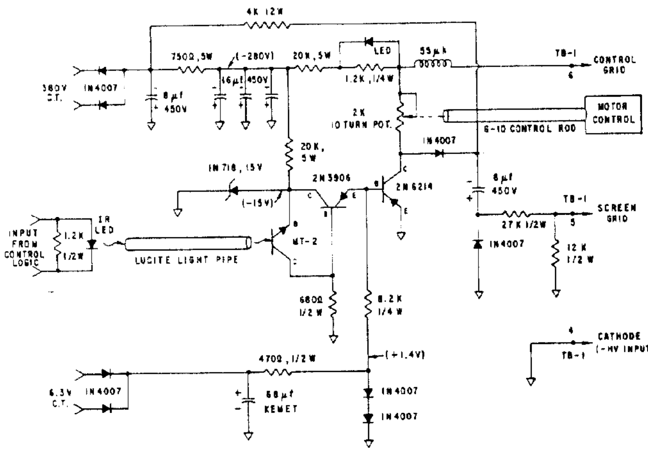
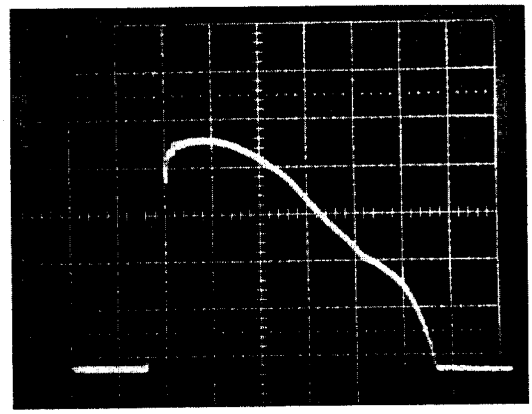


Fig. 2 Bias and Switching Module



100 V/Div.

100 ns/Div.

Fig. 5 Thyratron Grid Trigger Pulse

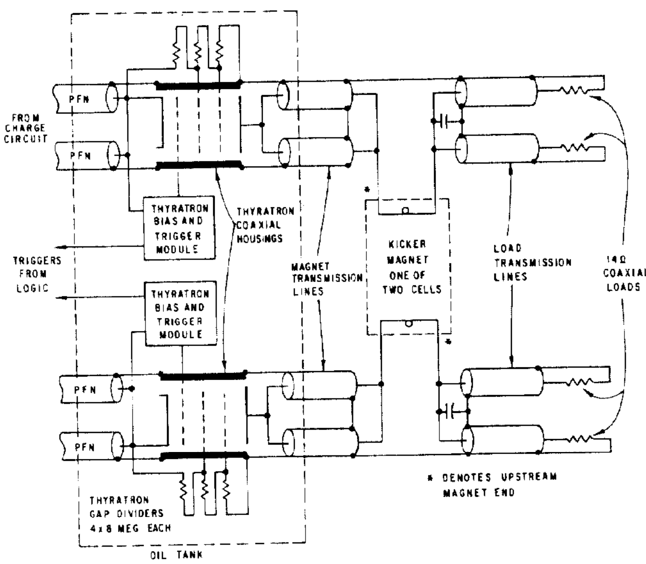


Fig. 3 PFN Discharge Circuit, Magnet and Load Connection

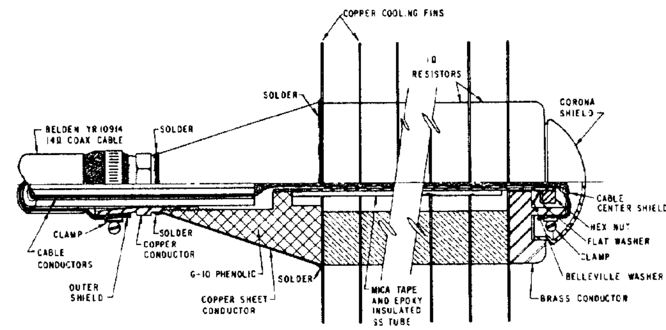


Fig. 6 Load Assembly

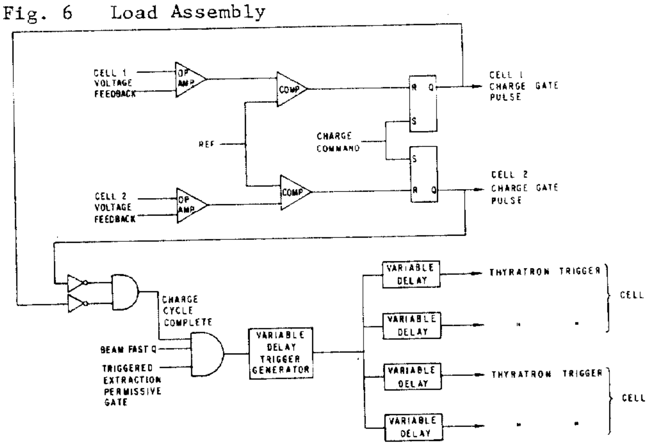


Fig. 7 Control Logic Simplified Block Diagram

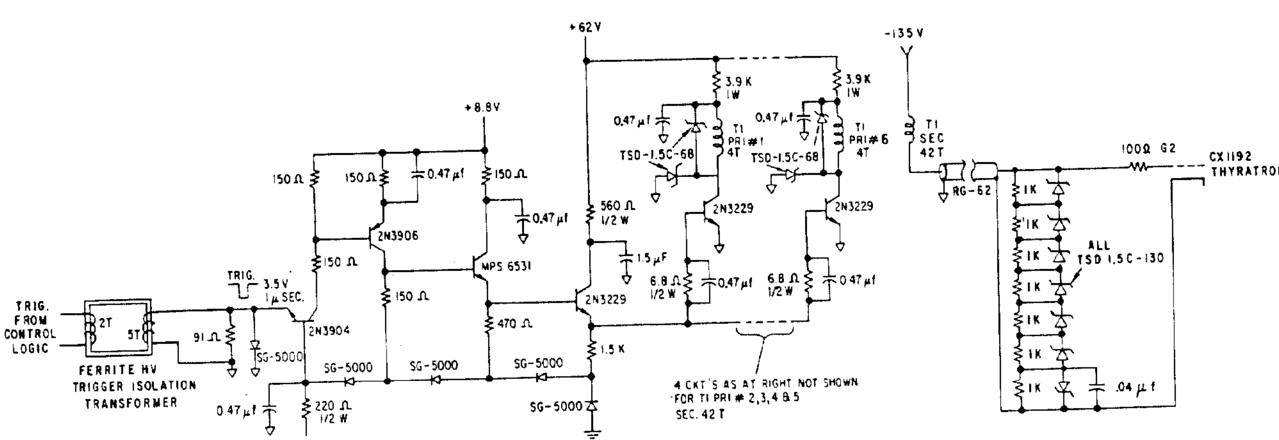


Fig. 4 Thyratron Trigger Amplifier and Pulser