POWER SUPPLIES FOR MAGNETS

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Abstract

At the National Accelerator Laboratory excitation of magnets in the beam lines external to the accelerator requires power supplies with widely varying output ratings and a stable behavior in non-Laboratory environments. The problem was solved by the design of a single power supply with nine different dc power arrangements using the same primary ac connection. This paper contains a description of this twelve phase 500 kW power supply in which the four internal 100 V, 1250 A half-wave units can be interconnected in different ways. This is followed by a description of the components of the power circuit, the design of the regulator and the control system.

The paper concludes with a description of the mechanical arrangement of the power supply and a report of the performance obtained.

Introduction

Unlike the earlier proton accelerator facilities where the external proton beam lines and secondary particle beam lines were generally set up in large environmentally controlled experimental halls, the experimental area facilities at the National Accelerator Laboratory mostly consist of long beam line enclosures with small service buildings spaced far apart (Fig. 1). The power supplies providing excitation current for conventional room temperature magnets for these beam lines are housed both in the enclosures and in the service buildings; in some cases, under severe environmental conditions. These environmental conditions plus the need for power supply regulation of the order of 100 ppm establishes the requirement for well regulated power supplies.

In addition to stability, the fact that the primary beam momentum will be varied from 50 GeV to 500 GeV with multiple momentum ranges of the secondary beams at each of the primary beam settings caused us to consider power supplies with flexible arrangements for output currents and voltages. In order to conserve power we also decided that the supplies should be programmable and capable of following uni-directional current reference pulses similar to the main ring pulse but with a faster rise time and the same stability requirements on the flat top as they have in the dc mode of operation.

Another factor which was taken into consideration in the preparation of the initial request for proposals to build these power supplies was that we wanted to limit the types of power supplies to be employed in the experimental areas for improved interchangeability, ease of maintenance, and fewer spare parts. To some extent, our earlier decision to use main ring type quadrupole and dipole magnets and external proton beam quadrupole and dipole magnets for the bulk of the beam transport needs aided us in this and we could dictate the current and voltage limitations for subsequent magnets which were designed at National Accelerator Laboratory; but the problem of powering magnets brought to us by user groups would still be with us.

Our request for proposals for the initial requirement of high current power supplies was prepared so that prospective suppliers would quote on two types of power supplies: 500 kW with 5000 A and 350 kW with 5000 A each with full current transformer taps at 100%, 70%, and 40% to correspond to the power settings we required due to the various load impedances. The specifications for the power supplies were based on using a six-phase rectifier system. We planned to order approximately 20 each of the two types of power supplies or 40 of the larger type if the costs were comparable; with options for additional quantities if awarded by a certain time.

When the proposals were analyzed, it became clear that for a production run of about 40 units, the cost for the 500 kW power supply with different voltage settings compared favorably with the cost of twenty 350 kW supplies

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*Operated by Universities Research Association, Inc. under contract with the United States Atomic Energy Commission and twenty 500 kW supplies. The Transrex Division of Gulton Industries was awarded the contract and proceeded to design a prototype six phase 500 kW supply. The tap settings were changed to 100%, 50%, and 25% to obtain a better balance over the range of loads to be employed.

Subsequent to the award, it was recognized at National Accelerator Laboratory that in the future, when upwards of 100 of these large power supplies were likely to be in service simultaneously, the power factor of the six phase power supplies would in all likelihood be low enough to require power factor correction. The problem was discussed with Transrex and the system was changed to a 12 phase system after the completion of one supply with a six phase system. Later on, as the requirements for the Proton Laboratory beam layouts became clearer, there was pressure to change the earlier decision on limiting the types of supplies in the experimental area and to allow two more types to be purchased; one to be approximately a 2000 A, 150 V supply and the second to be a 1200 A, 400 V supply. It was at this time that we came up with the idea that whereby interconnecting the four 100 V, 1250 A half-wave units, on our already existing 12 phase, 500 kW supply, we could make a series parallel connection to obtain 200 V, 2500 A, and in a total series connection, we could obtain 400 V and 1250 A. Since we planned to retain the primary taps, we now would have what we were looking for all along -- a very stable, programmable power supply with flexible enough voltage and current arrangements to meet all of our experimental area requirements from 1000 A to 5000 A and 25 V to 400 V. The proposed changes were discussed with Transrex and the final detailed design of the new system was made by them. The development of this flexible power supply has been mutually accomplished by National Accelerator Laboratory and Transrex and has worked out very satisfactorily in the Proton Laboratory beam transport area and in the Neutrino Laboratory. Additional supplies have been installed in the Meson Laboratory and in the Proton Laboratory. They will all be in service by the end of this year. We are now considering the addition of reversing switches and filters; although, as far as the latter is concerned, our experience to date indicates that external filtering will not be required in most cases. The cost of the power supply described in this paper is approximately $35 per kW.

Description

The power supply is a 500 kW twelve phase unit with a unique arrangement of secondary connections, whereby the dc output of the power supply is able to provide a wide range of voltages and currents. The output characteristics of the power supply are shown in Table I.

Rather than using the conventional winding technique in the primary in which taps are added at discreet points along the winding, the power supply has a quadrifilar wound primary. This allows the primary to be reconnected to change the basic power rating of the power supply. The electrical equivalent to 25%, 50% and 100% full current, non-load changing taps are available.

The rectification of the ac power and the control of the resultant dc power is done by phase control of thyristors in a 12 phase, half-wave double star connection located on the secondary side of the power transformers. Full current rated free wheeling diodes across the power supply output are included.

Stability of the output current is obtained by a self contained current and voltage regulator shown in a simplified block diagram in Fig. 2. The regulator is designed to be stable over a load resistance range from two milliohms to 1000 milliohms and time constants ranging from 1/2 to 3 seconds. It was anticipated that the output current would be stable to better than 0.01% long term in the presence +5%, -7% line voltage changes and a 10% change in load resistance.

The power supply is complete with its own interlock chain with protective devices installed to detect abnormal conditions, which, when activated will shut down the power supply.

Output

The basic power rating of the power supply was determined by considering the types and distribution of the magnet loads. Currents approaching 5000 A for some of the bending magnets and quadrupole magnets used in the experimental area of the Laboratory are required during a 500 GeV operation. Likewise, some magnets in the high impedance range were also contemplated for use in the experimental area. For these magnets, currents approaching 1200 A are required for maximum excitation. Typically up to five magnets can be series connected to one power supply. In cases where more than five magnets are required to be series

TABLE I. Output Characteristics

Secondary Connections	Maximum dc Voltage (100% Connection) (volts)	Maximum Available Output Current (amperes)	Minimum & Maximum Load* (milliohms)	Maximum Available Power Primary Connection 25% (kilowatts)	50%	100%
Parallel	100	5000	2.5 - 20	125	250	500
Series-Parallel	200	2500	10 - 80	125	250	500
Series	400	1250	40 - 320	125	250	500

*The minimum value of the range was determined by considering that the maximum output current may be drawn to 50% of the rated output voltage on each primary connection.

connected, up to three power supplies can be added to achieve the higher voltage. In this mode of operation only one supply is current regulated while the others are voltage regulated. In those cases where two or more power supplies need to be parallel connected to increase the total available current, an external current sensor and regulator amplifier would need to be provided. Then, the power supplies would be operated as voltage regulated units. The open loop gain of the voltage amplifier is high enough to insure stability and equal loading of the power supplies.

The ratings of all the components of the power circuits meet the NEMA standards for overload conditions; that is, 120% for two hours. Also, the power supply may be pulsed to 7000 A on a 50% duty cycle.

Conversion Frequency

The choice of the conversion frequency was made by considering the overall effects of many of these power supplies operating simultaneously on our primary ac distribution system. At the Laboratory, the primary power to the equipment areas is fed by buried 13.8 kV, 3 phase feeders to strategically located, outdoor type unit substations of the 1500/1900 kVA, 480 V, 3 phase class. Several power supplies are connected to a single unit substation, thus raising the possibility of power supply interactions, or cross talk. The severity of this problem can be reduced, although probably not eliminated, by operating at a high conversion frequency. This improvement occurs because the input line currents contain less harmonic currents at the higher conversion frequencies. Therefore, selective filtering of the ac synchronizing voltages for the thyristors gating amplifiers can be done without incurring large phase shifts at the primary voltage frequency. Additional benefits arise because the overall conversion efficiency is improved. In many cases the higher conversion frequency has also eliminated the need for filtering of the output of the power supply.

Our choice was then the twelve phase (720 Hz) conversion frequency over the more conventional six phase (360 Hz). In some power supply designs, this decision could have resulted in twice as many thyristors as the six phase design; however, in our case the same number resulted due to the basic 5000 A output current requirement.

Input Power

The input to the power supply is the utility standard 460 V, 3 phase, 60 Hz power. This is fed to the internal circuitry through a 1000 A molded case, air insulated circuit breaker with a 35,000 A interrupting capacity.

Power Conversion

Circuit

In the original stages of design it was tempting to consider obtaining the 720 Hz output ripple by utilizing only one rectifier transformer with four zig-zag secondary windings displaced by 15°. Careful study of the mechanical interconnections required showed that it would be more economical to utilize two transformers with identical secondaries but with their primaries shifted by 30°. Therefore, the primaries were designed to be delta in one transformer and wye in the other. In addition to the 720 Hz output ripple, it had been decided to provide four separate and distinct 100 V sections, each one with a capability of 1250 A. It became evident that the best rectifier circuit to obtain these outputs was a six phase star with interphase transformers (Fig. 3). One half of each secondary would then provide the required 100 V at 1250 A.

The four separated 100 V power sections are then added in a series connection, keeping the two interphase transformers in the circuit, to achieve 400 V at 1250 A. Paralleling the two secondary halves of each power transformer and adding them in series gives an output of 200 V at 2500 A. Likewise paralleling both power transformer sections through the third interphase transformer gives an output of 100 V at 5000 A.

The primary winding of the two power transformers are wound as four separate, but parallel, windings. Thus, through a conveniently located tap board, the four primary windings can be connected either in series, series-parallel, or all in parallel to obtain the 25%, 50%, and the 100% connections. This provides the flexibility to properly match the power required by the load to the rating of the power supply, thereby minimizing the installation costs. The basic power rating of the power supply is 500 kW when all the primary windings are connected in parallel. It can be changed to 250 kW in a series-parallel connection or to 125 kW when all the windings are series connected.

Thyristors

The thyristors were selected to provide a 25% junction temperature margin and 200% rated-to-applied inverse voltage rating. Cooling water was available at 113°F, maximum, with flow up to 8 gpm at differential pressures to 150 psig, maximum. The PSI H1400 (1400 A rms) provided a single device with adequate ratings to meet all the requirements.

This large area thyristor (48 mm diameter) requires hard firing of the gate to maximize its dI/dt rating. A gate firing circuit using capacitor discharge provides about 20 V open circuit, 2 A short circuit with a rise time of 0.15 microsecond. This peak gate pulse decays to 400 mA in 50 microseconds and continues for a total width of about 1 millisecond. The gate circuit electronics was located close to the thyristors and includes the resistance-capacitance dV/dt networks, transient voltage suppressors, and the output isolated pulse transformer.

Firing circuits located in the electronics assembly transmit the 24 V peak triggering pulses on coaxial cable to the gate firing circuits. The firing circuits employ a linear ramp which is compared to the control input signal to trigger a monostable multivibrator to produce the firing pulse. The ramp is gated on-and-off by a phase related 50 V ac line signal. The high amplitude of this line signal, plus some filtering, ensures a noise free, 180 degree ramp. The ramp has a peak amplitude of 10 to 12 V so the input control signal range must be zero to 11 V. This high amplitude improves tolerance to signal harmonics as well as noise.

Free Wheeling Diodes

The freewheeling diodes were originally selected to carry 5000 A continuous dc with a 25% temperature safety margin. This required using three PSI-HD2500 diodes in parallel. The reconnectable secondary configuration used one freewheeling diode in each of the four half-wave star sections so the diode might have been changed to a HD2000, but use of the HD2500 continued in the production run. This provides a derated, continuous current capability of 6400 A.

Power Transformers

The nominal rating of each transformer is 350 kVA; however, this rating is misleading inasmuch as the transformer should include other sources of unusable kVA, mainly low line, stray losses and tertiary currents. Of these elements the most difficult to reconcile with the overall design is the stray loss element. It is a function of not only load conditions but also conductor size and shape. By careful selection of conductor, stray losses can be reduced considerably. On the other hand, a poor choice can result in losses that are, in magnitude, even as high as the normal conductor I^2R losses. Another important aspect is the 180 Hz current component. To reduce this current, a tertiary winding is required in the wye primary, double-wye secondary transformer.

To obtain outputs of 25%, 50%, and 100% of full voltage, it was decided to quadrifilar wind the primaries of the transformers. That is, each primary is wound with four insulated conductors. These conductors can be connected in series, series-parallel, or parallel to obtain the desired outputs. The advantages of this method of winding over the inclusion of discreet taps on the windings far outweigh the disadvantages. Among the benefits is the fact that the absolute value of the leakage impedance remains constant at any tap. Another advantage is that because the winding is symmetrical, all the windings carry the same current for a given load current regardless of the tap. Still another advantage, tap changing is done in the primary where currents are lower and no overwinding is necessary. The only major disadvantage of this arrangement is caused by the fact that under certain connections the voltage gradient between turns can be very high and thus extreme care is required in the design and construction of the primary windings.

The water cooled secondary windings are wound over the electrostatic shields. These secondary windings are wound bifilar (two in hand) and insulated from each other. Each winding represents one half (line to neutral) of one three phase system. To obtain as much benefit from the water cooling as possible, primary and secondary are tightly coupled and, therefore, the leakage reactance is low.

Interphase Transformers

There are two 180 Hz, 1250 A and one 360 Hz, 2500 A transformers. All of them are water cooled. Because there is a full thyristor phase back requirement and also because the rectifier transformer leakage reactance is low, the 180 Hz units are designed to support a voltage time integral of about 300 V msec. The 360 Hz unit is designed for about 70 V msec. Additional important considerations in the design of interphase transformers are stray losses, audible noise and dc unbalance. Audible noise is reduced by careful arrangement of core clamping devices and proper selection of core material and shape. The unbalance effects of the dc component of the current are minimized by the inclusion of an air gap in the magnetic path. This gap is designed for approximately 20% unbalance.

Regulators

Design

The output current of power supplies used in particle physics applications must have excellent stability in both the short term and long term. As a design objective, a stability of 0.01% of full output was chosen. This figure is achievable in phase controlled systems providing that the regulator design is carefully done.

The power supplies are generally operated in buildings where the ambient temperature may change by 40°C. The line voltage which supplies ac power to the power supply also is characterized by both fast and long term changes. At the Laboratory, 5% changes are not uncommon. The line voltage can be seen to dip by about 0.5% just due to the operation of the accelerator alone.

Although most of the copper conductors in the magnets are water cooled, they still exhibit a change in resistance due to the change in temperature. This change can be as much as 10 to 15%.

A necessary feature in phased controlled rectifier systems to which inductive loads are connected is a two loop regulator. The inner loop is a voltage regulator in which the raw output voltage of the power supply is stabilized primarily against fast line voltage changes. The voltage loop is generally characterized by a modest open loop gain and a large bandwidth. The outer loop in the power supplies has the output current as the controlled parameter. The function of this loop is to regulate the output against load changes which generally occur slowly. Therefore, the current loop is characterized by a high open loop gain, but with a restricted bandwidth.

The regulator design parameters are shown in Table II below.

TABLE II. Regulator Design Parameters

Voltage loop	
open loop gain	50 dB
closed loop bandwidth	10 Hz
closed loop gain	
parallel connection	20 dB
series and series-parallel connection	40 dB
Current loop	
open loop gain	80 dB
unity gain closed loop bandwidth	5 Hz
closed loop gain	0 dB

Loop Stabilization

A first order control system is desirable in both the current and voltage regulators. This type of control system is characterized by an open loop response that has a -6 dB/octave roll off. The overshoot in the response of the system is therefore minimized when the input undergoes step changes. This feature is required when the power supply is to be programmed. It is necessary to adjust the frequency response of the current regulator to match the various magnet resistances and time constants to achieve the desired response.

Voltage Loop

A detailed block diagram of the regulator system is shown in Fig. 4. By means of the switch at the input of the voltage regulator it is possible to operate the power supply as a voltage regulated or current regulated system or to operate from an external analog signal.

The voltage regulation mode loop remains closed as an inner loop when the system is operated in the current mode. This feature provides fast correction for such disturbances as line transients. In addition, the inner voltage loop provides a constant gain over the entire control range.

Series operation of the power supplies with grounded controls requires either isolated detection of output voltage or a high common mode rejection (CMR) circuit. The CMR approach chosen uses a Type 741 operational amplifier with both null and CMR adjustments. This circuit provides 0 - 10 V dc for either the 100, 200, or 400 V dc outputs.

Because no power filters are used in the supply, the voltage loop requires a filter for the 720 Hz and higher frequency noise. The active filter employed provides typically 50 dB attenuation of the 720 Hz ripple. The phase contribution of this filter at 60 Hz is only -60° typically. This small phase shift allows the voltage loop to be closed with a corner frequency (-3dB) in excess of 10 Hz. This provides a response time to correct line disturbances of about 20 milliseconds. The loop gain of the voltage loop provides regulation of better than ± 0. 1%.

Current Loop

The current loop uses a type 725* operational amplifier for very low noise and temperature coefficients but very high gain. A two stage, resistor gain control is used to simplify gain changing and minimize parameter changes seen by the operational amplifier. The basic lagging corner frequency (0. 00045 Hz) of the current loop is set by feedback on this amplifier with a 20 megohm resistor and 18 microfarads capacitor. Its first order gain roll off ("integrating") continues until a leading corner frequency is reached that matches the magnet load time constant lag frequency (Fig. 5). This assures a first order, stable system throughout the system bandwidth. The loop gain, which always exceeds 10, 000 (80 dB), provides a gain bandwidth of 5 Hz.

Total system regulation and stability of better than ± 0. 01% in an ambient environment specified from 15 to 55°C is achieved by use of an oven. The oven contains the precision current amplifier and the active references as well as additional regulators for the amplifier and an active filter with notches at 240 Hz and 720 Hz for operation into resistive loads or very low time constant magnets.

Reference Voltage Supply

The precision reference supply provides 10 V dc to a 1000 ohm externally connected potentiometer. Therefore, the reference was made short circuit proof by using a type 723* monolithic voltage regulator. The 723 is used with a precision reference diode to improve its stability.

Measurements of overall system warmup and temperature stability indicate a two-sigma temperature coefficient of -0. 001%/°C for 90% of the power supplies. Part of this negative coefficient is probably due to component aging and should be halved after about 200 hours of operating time. The oven regulates the steady state operating temperature to less than ±0. 2°C, so the system temperature stability is approximately ±0. 0002%.

Transductor

The transductor used to measure the output current is a unique patented Transrex design that employs a seven core sensing head. Two sets of three cores respond to load current in a differential manner and a feedback winding maintains a constant ampere-turn operating condition with a very high gain amplifier. The feedback current is an exact ratio of winding turns, and this current of about 1 A at full output current is read with an array of precision resistors.

The differential connection of the sense head eliminates the need of preregulating the input ac power to the head. The seventh core in the head provides direct high frequency response to load current changes. The characteristics of the transductor are listed in Table III.

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* Fairchild Semiconductor, Mountain View, California.

TABLE III. Transductor Characteristics

Sensitivity	500 A/V
Coefficients	
line voltage	5 ppm/% change
temperature	1 ppm/°C
Frequency Response (Nominal, -3 dB)	1000 Hz

Control System

Power Control

The power supply contactor is energized by means of a relay-based interlock and control system. All fault signals are connected into the control chain through auxilliary contacts of the sealed-in relays of the protective devices.

The ON-OFF control and the reset functions can either be operated locally or through a set of remotely located relay contacts. Local monitoring of the status of the interlock chain and fault indicators is provided.

Protection

The power supply is completely self protected against ac overloads and current unbalance, dc overloads and over temperature. The power thyristors and free wheeling diodes are protected against over temperature by means of bi-metallic thermostats placed on each device. In addition each power thyristor is protected by a Carbone-Ferraz 1250 A fuse. The operation of any of the protective devices will cause the interruption of the gate pulses to the thyristor as well as the opening of the primary ac contactor. Provisions are also included for remote load fault sensing.

Ground faults are detected by means of a current sensitive trigger fuse. Upon activation, the firing circuit input is shorted and the primary contactor is de-energized. The load is protected from excessive instantaneous currents by a 200 ohm current limiting resistor.

The control of the protective devices are included in sealed-in fault indication and control relays. The operation of the protective device will remain indicated until the operator, through the control system, resets the power supply.

Computer Control

In addition to the local control a limited number of remotely controlled operations can be performed. These functions include ON-OFF control and monitoring, fault monitoring and reset, and output current and voltage control and monitoring.

The power supply output is controlled by means of a reference voltage which is applied to the input of either the current loop or voltage loop amplifier. The output of the internal precision reference voltage supply is applied to the power supply input by means of a potentiometer driven by a pulse controlled stepping motor. The stepping motor and the multi-turn potentiometer were chosen to provide a resolution of at least 100 ppm. Application of 5 V, 50 microsecond pulses to the cw (increase) or ccw (decrease) inputs of the motor logic are required for operation of the motor driven potentiometer.

The power supply may also be programmed either by means of a remotely located waveform generator or an optional ramp and flat-top generator which may be added to the power supply. In either case, the rate of change in the output is generally dependent upon the time constant of the load and the available output voltage; and to a lesser degree, the speed of response of the power supply.

Mechanical

The components of the power supply are housed in a steel frame, free-standing structure designed for indoor use. Steel panels with front door accessibility cover the unit giving drip proof construction (Fig. 6). The dimensions of the power supply are 122 cm x 122 cm x 183 cm high (48 in. x 48 in. x 72 in. high) and the weight is 2700 kg (5900 lb). All power connections (ac and dc) are made at the top. Water supply and return connections are also made at the top.

All the electronics for the power supply, with the exception of the transductor electronics, are mounted in a NIMBIN assembly which is located on the front of the power supply. (NIM: AEC Standard TID-20893, Nuclear Instrumentation Module) The heavy duty components such as the main circuit breaker and contactor are mounted on an insulated panel board located about 36 cm (14 in) behind the front door.

The two main power transformers are located in the lower half of the power supply. Primary connection changing is done from the front. Each power transformer assembly also contains its own double wye interphase transformer. The combining interphase transformer for the delta-wye unit is located on the left side of the power supply, immediately behind the panel board.

The secondary series-parallel connections are made with water cooled links. The links are accessible through the side panels. About 8 links are required to be moved in changing from one connection to another. Experienced technicians can change the connections in about one hour.

The thyristors and free wheeling diodes are located at the rear of the power supply (Fig. 7). There are four separate assemblies, one for each half-wave star section. Each assembly is complete with its own free wheeling diode. The bus-bar from the power transformer secondary is connected to the thyristor heat sink through the current limiting fuse.

The transductor head and its electronics are located at the top of the power supply. Access to the transductor is through hinged panels on the top and side of the power supply.

Cooling

All major heat dissipating elements are cooled by a three branch water system. Water enters and leaves the power supply through connections made on the top of the unit. The thyristors, freewheeling diodes and all the magnetics are water cooled. A total flow of 4-1/2 gpm at a pressure drop of less than 55 psig for ambient temperatures to 40°C is required. For ambients to 55°C, 5-1/2 gpm flow with a 100 psig pressure drop is required.

Conclusion

A total of 85 500 kW power supplies are on order, 45 of which are of the type described in this paper. About 25 of the 45 units have been received and about 20 of these are now in routine operation, using various connections, in the Neutrino, Meson and Proton area beam lines and in other parts of the external beam transport system.

In addition to the standard factory tests which were made at the time the equipment was delivered, some additional tests have been made both at the Laboratory and at the manufacturing facility of Transrex.

The harmonic content of the input line current was measured on a power supply with a series-parallel connected secondary and operating on the 100% primary connection. The load was a 95 milliohm water cooled resistor. The results of this analysis, presented in Table IV, demonstrate the benefit of operating at the higher conversion frequency. The total harmonic content was about 4.4%. It would be expected that with an inductive load the harmonic currents would be smaller.

TABLE IV
Harmonic Analysis of the Input Line Current

Harmonic Number	Frequency Hz	Harmonic Current (% of fundamental)
1	60	100.0
11	660	3.7
13	780	1.5
23	1380	1.0
25	1500	0.5
35	2100	0.5

The stability of the output current with the regulator in the current mode was measured. A Leeds and Northrup precision shunt, traceable to the National Bureau of Standards, was used to measure the current. The total change in current from a cold start was 600 ppm while the long term stability was 20 ppm. The measured short term stability was 40 ppm.

The output current ripple is dependent upon the time constant of the load and the amplitude of the ripple voltage from the power supply. The ripple current was measured on a power supply connected to a series arrangement of two National Accelerator Laboratory Type B2 magnets and one Type B1 magnet. The power supply was connected as a 100 V, 5000 A unit and the ripple current was measured at about 45% of the maximum output voltage which was the worst case. The time constant of the load was about one second. The ripple current measured at 60 Hz was 0.011% of the average value (1830 A) and was 0.003% at 720 Hz.

The operation of the power supply in the pulsed, current regulated mode was demonstrated and the results shown in Fig. 8. In this test a power supply was operated with the secondary in a parallel connection and the primary in the 100% connection. The load for the power supply consisted of three series connected type B2 bending magnets. The connected load resistance was 25 milliohm and the inductance was 24 mH, giving a time constant of 0.96 sec. From the current pulse shown in Fig. 8, the initial rate of rise of the current is 3300 A/sec which gives an inductive voltage of 79 V. The maximum resistive component voltage was 34 V. Because the power supply was voltage limited to 100 V the current pulse becomes rounded after 0.3 sec. Within the limits of the bandwidth of the current regulator and the available output voltage, the output current settled to the basic steady-state stability, characteristic of the power supply in about one second.

Acknowledgements

The authors wish to express their appreciation to Mr. Jan Ryk, National Accelerator Laboratory, for providing the stability and ripple current data and to Mr. Eugene Woods for providing assistance in obtaining the pulsed operation data.

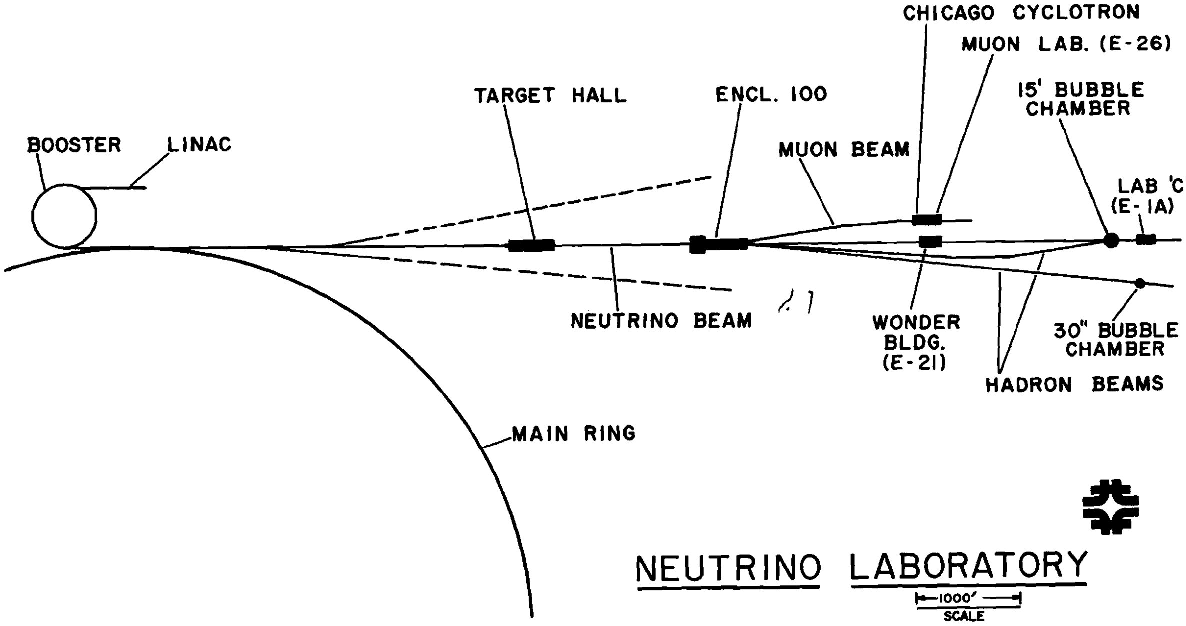

Fig. 1. Neutrino beam line. Many of the power supplies described are in the service buildings and equipment enclosures located along these beam lines. Similar conditions exist for the Meson beam line (to the left of the Neutrino beam line) and for the Proton beam line (to the right of the Neutrino beam line).

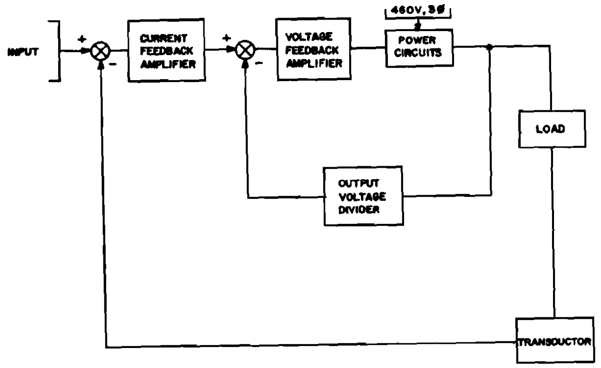

Fig. 2. Simplified Block Diagram

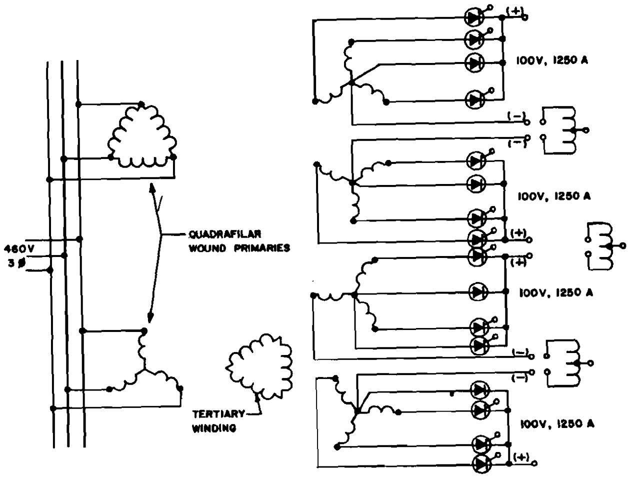

Fig. 3. Power Circuit. The thyristors shown are PSI Type H1400 and the diodes are PSI Type HD2500.

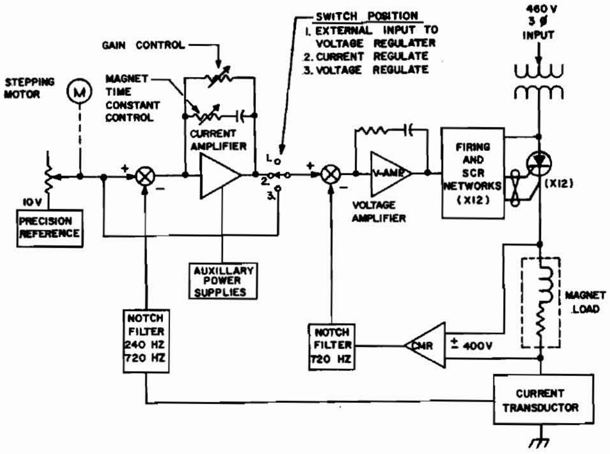

Fig. 4. Regulator System block diagram.

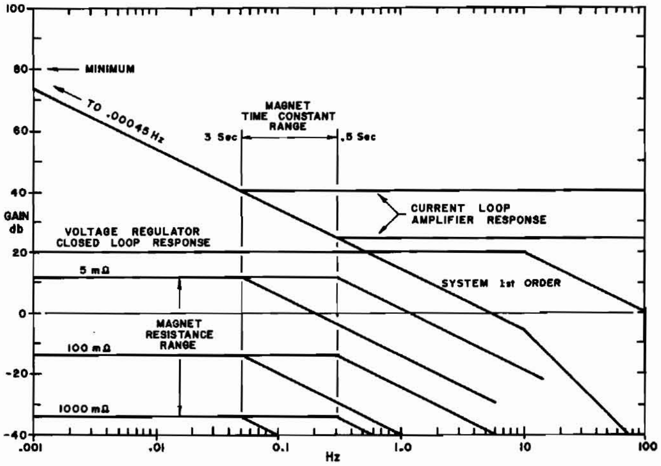

Fig. 5. Regulator System bode diagram.

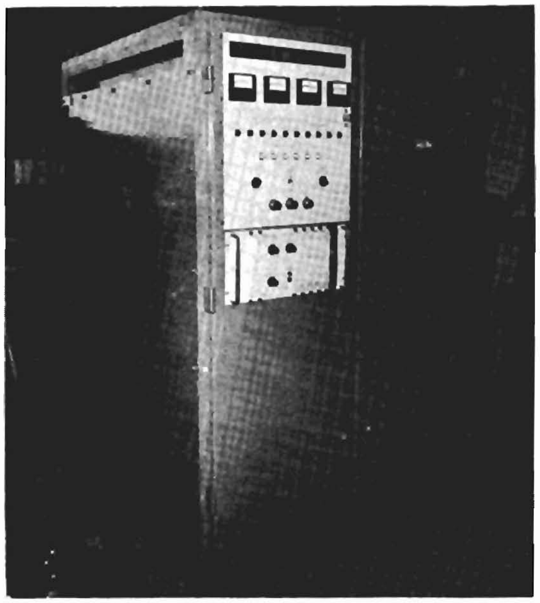

Fig. 6. Power Supply - Front View, external

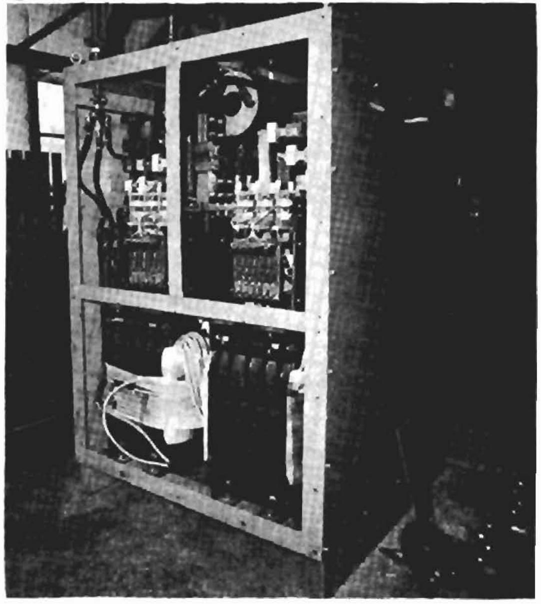

Fig. 7. Power Supply - Rear View, internal

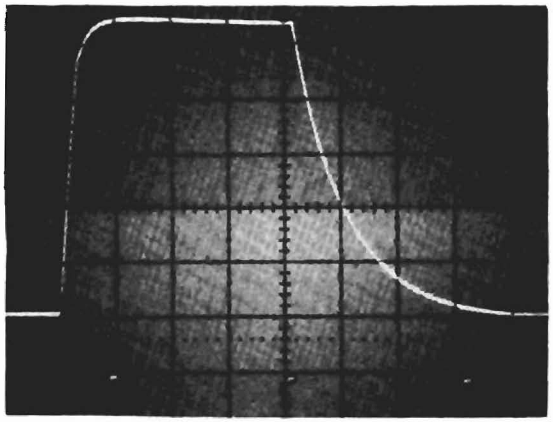

Fig. 8. Output Current Pulse.
Horizontal - 1 sec/cm
Vertical - 250 A/cm