THE POWER SUPPLY SYSTEM, CONTROL, AND RESPONSE OF THE NAL MAIN ACCELERATOR *

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I. Introduction

The NAL main accelerator is larger and has a more complicated accelerating cycle than earlier synchrotrons. In addition, primary design goals were utilization of the electric-power supply network for energy storage and the inclusions of the possibility of later increasing the peak guide field to achieve higher proton energies. All these factors have posed new design problems; our solutions of these problems are discussed in this paper, together with a report of our experience in initial operation of the system.

We note that the concept of utilizing the power network for energy storage is not new; it has been discussed previously and has been utilized on an emergency basis at RHEL and CERN when local energy-storage components had failed. It was just these failures of costly devices that impelled us to incorporate in the design a non-local and hopefully more reliable energy-storage system.

The main accelerator was designed to reach the original peak energy of 200 GeV with a relatively modest guide field, 9kG. The magnets themselves were designed to provide good field quality up to 22.5 kG, so that at a later time the peak energy could be increased to approximately 500 GeV by the addition of more power supplies, but without any changes in components in the accelerator tunnel. The increase in energy could therefore be achieved without a long shutdown of the NAL research program.

In fact, this option for increased energy has already been exercised. The power-supply system utilizes thyristor rectifiers, and advances in their technology in the last few years has made it possible to procure thyristor systems of 500-GeV power capability at a lower cost than was originally estimated for 200-GeV systems. We are therefore building a 500-GeV system.

Extensive theoretical studies were carried out in collaboration with the Commonwealth Edison Co., the electric power utility, to investigate the effects of the pulsed load on the power network at the 200-GeV level. It was concluded that these effects were acceptable to the power company. Similar studies at the 500-GeV level have not been completed and it is possible that operating experience will show that some local energy storage is necessary at 500 GeV.

II. The Over-All System

The peak field and power requirements of the system are summarized in Table I. The overall currents and voltages required for the bending magnets and quadrupoles are shown in Figs. 1 and 2.

Table I. Power-Supply Requirements

Peak Magnetic Field	22.5 kG
Peak Excitation Current	7,000 A
Peak Excitation Voltage	
Bending Magnets	40,000 V
Quadrupoles	12,000 V
Peak Stored Energy	250 MJ
Average Power Loss	82 MW rms
Current Regulation	
Injection	.01%
Flat-top	.1%

The main accelerator is, of course, a separated-function synchrotron; in order to achieve the flexibility of operation inherent in this design, the bending magnets and quadrupoles are powered independently. Furthermore, the horizontally focusing (F) and vertically focusing (D) quadrupoles can be varied independently.

In order to avoid a dipole field from current flowing one direction in the distribution bus around the accelerator, the bending-magnet and quadrupole busses are folded connections. Equal and opposite currents flow in adjacent busses. All F quadrupoles are on one quadrupole bus and all D magnets on the other, as shown in Fig. 3. With this arrangement of F and D excitation, the horizontal and vertical betatron wave numbers ν_x and ν_z and be varied independently. The busses are installed above the magnets in the tunnel and are shielded by water-cooling piping.

The power supplies are subdivided and uniformly distributed around the ring in order to minimize the voltage to ground in both the magnet ring and the power supplies. See Fig. 4. Twenty-four above-ground service buildings have been built around the ring to house the supplies. There are two bending-magnet supplies in each service building, one connected to each bus, and one quadrupole supply in each alternate service building. The 60 power supplies are identical, thus providing simplicity in operating procedures and complete interchangeability of parts.

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Work performed under the Auspices of the U. S. Atomic Energy Commission.

III. Power Supplies

The individual supplies are 12-phase secondary thyristor phase-controlled rectifiers. Their ratings are given in Table II.

Table II. Individual Power-Supply Ratings

Maximum No-Load Voltage	950 V dc
Full-load rms Current	3300 A dc
Peak Current	7000 A dc
Voltage at 7000 A	850 V
RMS Power	3 MW
Peak Power	6 MW

Each individual supply consists of an outdoor substation, an indoor rectifier, and a control chassis. Figure 5 is a simplified circuit diagram of a power supply.

A. Outdoor Substation

The outdoor substation is comprised of a manual disconnect, vacuum breaker, and transformers. The transformers consist of two cores in one convection-cooled oil-filled tank. Each core is wound with a so-called extended-delta primary with wye secondary. The two transformers are phase shifted with respect to each other to obtain a 12-phase transformer configuration. Each transformer has a secondary voltage of 350 volts rms line-to-line wye with the neutral brought out. The primary is 13.8 kV. The primaries of both transformers are paralleled and supplied through a vacuum contactor. The vacuum contactor is used to turn on and off the supply as well as its use as a breaker for secondary faults. The vacuum breaker was chosen because of its speed of response and large number of operating cycles without maintenance.

To ensure safe maintenance of the rectifiers, the vacuum contactor is preceded by a manual disconnect on the 13.8 kV primary side. The disconnect is key-interlocked with the rectifier cubicle for safe maintenance. The substation equipment was manufactured by ITE Imperial Corporation.

B. Rectifiers

The rectifier is based on a modular concept; each module is a complete rectifier by itself. Modules are then series and parallel connected to develop the voltage and current requirements. Each module is rated for 475 volts dc at 2500 amperes dc, 6-phase 1.2 MW.

Three modules are paralleled for the 7000 ampere peak current requirement and then seriesed with a second set of three paralleled modules to obtain the required voltage.

The modules consist of a water-cooled full-wave 6-phase bridge of thyristors plus two bypass thyristors. The module is complete with snubber networks, arc-back detectors, and gate-driving circuits. The gate drivers are isolated from ground by an rf link that enables the thyristor to receive a dc gate drive. The input to the drives is grounded

DTL logic level compatible. The modules are mechanically laid out to minimize space and to distribute the currents to minimize cross-talk between gates. The parallel modules are balanced by utilizing the connection impedance in the modules as well as the connection between the modules and the outdoor substation.

The size and power levels of each module was accomplished by the latest in high-current thyristors produced by Power Semiconductors, Inc., their 1400 ampere rms Astro-Pack.

The rectifier cubicle supports and connects the modules. A passive filter is included to remove the high-frequency ripple resulting from rectification. The filter has little effect on the 720 Hz, fundamental power-supply ripple. The cubicle also contains a manually operated short-before-open switch to isolate the magnet bus from the power supply.

C. Control Chassis

Each of the power supplies is equipped with a digitally controlled Thyristor Firing Circuit. The firing circuit is completely digital except for an analogue line signal. A digital word generated either locally or through the Main-Accelerator Multiplex Systems² sets the firing phase angle of all 12 gate drivers. Each supply has an all-digital program generator with break points established either locally or through the Main Accelerator Multiplex System. Each supply can therefore be set to a program established from the Main Control Room and the program can be changed at will without visiting the power supply.

From the required voltage waveform, Fig. 2, it is clear that not all of the power supplies are needed to operate at one time. To have the supplies on at such times would result in a large amount of reactive power on the supply power lines, as well as difficulties in current regulation. Power supplies will, therefore, be sequenced on as needed.

If 200-GeV operation is scheduled, half the individual power supplies will be disconnected by the manual switch at each power supply. This will be done in a scheduled way to minimize the voltage-to-ground problems. During the pulsing, the remaining supplies are bypassed by use of the bypass rectifier and brought on as needed. The waveform generator determines the bypass conditions.

All but two of the bending magnet supplies and all but two of the quadrupole supplies are programmed. The remaining two supplies are field regulated. An example of the system is shown in Fig. 6. The field regulation will be accomplished in a 3-ft bending magnet and quadrupole in series with the bus. A field probe feeds back digitized field conditions to the power supply computer, which will readjust the firing angles of the

regulated supplies. This regulated supply will operate at injection to provide a stabilized current control. The power-supply computer re-assigns the programmed supply programs in accordance with line and load variations. The computer also incorporates a self-correcting function generator that works with the regulated supplies to improve the long-term stability.

IV. Costs

We summarize below in Table III the costs of the major elements of the system. No included are 13.8-kV cabling, tunnel distribution, installation, and some small miscellaneous costs; these items are not yet complete.

Table III. System Cost

(thousands of dollars)

Substations	1500
Rectifier modules	1000
Controls (including computer)	150
Cubicles, disconnects, cabling	250
Total	2900

The total system is capable of an rms power dissipation of 180 MW, although in this pulsed mode it does not run at this level. The unit cost is therefore approximately \$16 per kW.

V. Magnet Response

The bending-magnet system does not provide a simple load impedance. It is, in fact, a delay line; the magnets have a relatively large capacitance to ground, arising from the conductors' large surface area to ground and thin groundplane insulation. The magnets therefore respond not as a simple inductance-resistance load but as a lumped-parameter delay line. Each magnet has a delay of approximately 6 μ sec resulting in a propagation delay of approximately 4.6 msec for the entire ring. The normal losses of the system are relatively low, resulting in a standing-wave Q of about 4. The propagation time of the magnets will be changed by a shunt resistor across the magnets, to eliminate the inherent control problems, as well as possible detrimental effects on the injection orbit. The choice of a 10 Ω shunt resistor gives a reasonable compromise between magnet-current misbalance and propagation time. The standing waves will be critically damped with an overall propagation time of about 2 msec.

VI. Operational Experience

Each of the modules is pretested before insertion into a power supply at full current (2500 A), low voltage and low-current full voltage. The first complete power supply has been pulsed to 450 GeV (approximately 6000 Amps) and run for 24 hours at pulsed 400-GeV operation. These tests were limited by a "soft" temporary 13.8-kV power line.

A subsequent supply has been run on the real source impedance from the Master Substation. Current regulation was obtained from this supply of 0.1% during operation at 20 Amps (1GeV) on the magnets of Sector A (the first sixth of the ring). The regulation has been programmed through the power-supply control computer. Multiple-supply operation has yet to be tried.

References

- 1) R. L. Cassel & J. E. VanNess, "Direct Powering of the 200 GeV Synchrotron Magnet From the Utility System," IEEE Trans. Nucl. Sci. NS-16, 672, (1969)
- 2) D. F. Sutter, "A Multiplexed Control System for the NAL Main Accelerator." This Conf., Paper No. F-32

Figure 1.

Figure 2.

Fig. 3. Main accelerator power supply distribution.

Fig. 5. Main accelerator power supply single line.

Fig. 4. Voltage to ground vs distance.

Fig. 6. Power supply program main power supplies.