PEP MAGNET POWER SUPPLY SYSTEMS *

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General

The dc electrical requirements of the PEP magnets fall mainly into two categories: (1) high power and current of single polarity and (2) low-power bi-polar. The first category will be thyristor-chopper controlled off common 600 V dc busses. The second group will utilize continously controlled push-pull transistor actuators.

The magnets are distributed around the ring in six arcs with straight-sections (where the interaction regions are) in between. Larger and small magnet power supplies, R.F. stations, and Instrumentation and Control (I & C) stations are located in buildings over interaction regions 4, 8, and 12. There are additional I & C stations and trim and steering supplies located in small buildings over the remaining regions 2, 6, and 10. Because the main control room is at Region 8 all the current-regulated chopper controllers have been placed at that location. The additional supplies in regions 12 and 4 are only needed in the bend and QF and QD quadrupole circuits where the number of mangets is large. These are slaved to masters in region 8.

There are the following major families of magnets: (1) the bends and Q1s and Q2s (insertion quads), (2) nine quadrupoles, and (3) seven sextupoles. The numbers of magnets in each circuit range from 192 bend and 24 insertion quads in series, to those quadrupole families with only 12 magnets around the ring

All of the above listed families will be run from choppers except five low powered sextupole circuits. There is not room for listing of all the magnet families and their voltage and current requirements for from 5 to 18 GeV operation. The bend circuit requires 1858 volts at 1319 amps or 2450 kW total at 18 GeV. Four 600 volt supplies will be used, two in 8, and one each in 12 and 4. The nine quadrupole circuits requires a total power of 2264 kW. The bulk of the supplies are at region 8, with two circuits, the QF and QD, composed of 60 and 48 magnets respectfully, also requiring supplies at 12 and 4. Except for the 1QD circuit with 36 quadrupoles and two supplies at region 8, the remaining quadrupole circuits are composed of twelve magnets with a single supply at region 8. The voltage drops in circuits supplied from a single location vary from 293 to 538 volts at the 18 GeV operation level.

The Injection and Beam Transport Magnet System is also divided into a number of families of Bends and Quadrupoles. Except for the magnets that are common to both transport lines, the circuits are identical in the North and South Injection Tunnels (NIT and SIT). The power supplies for the Injection and Transport System will be located at the end of the existing building over the linear accelerator at Sector 30. The injection components are designed for a maximum of 15 GeV operation with 800 amps in the Bends and 100 amps in the Quads. There are both families and individual magnets to be separately controlled. The level of performance required here is ± 0.1% rather than ± 0.01% needed on the main ring circuits. Various combinations of controllers are still being considered for the Injection System.

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The great bulk of the individually controlled supplies are those needed for vertical and horizontal steering and trimming. There are twenty-four Q1 and Q2 insertion magnets in the ring, each with a 100 amp, bipolar trim requirement. There can be up to eight vertical and eight horizontal steering points used in each arc, and pairs of vertical and horizontal steering magnets required on each side of each interaction region. In addition there are rotated quads and five sextupole circuits to be powered. The injection system additionally has multiple trim and steering requirements.

The great part of these low power needs can be satisfied by ± 40 volt at ± 10 amp power modules. These will be push-pull transistor output stages mounted on water-cooled heat-sinks with all p.c. board mounting. There will be 16 channels per 10-1/2" high standard chassis. A plug will connect this chassis directly to the CAMAC bin for analogue reference and current-monitoring signal transmission. The ± 100 amp actuators will also use water-cooled heat sinks with two channels per chassis. In both cases the high-current actuators will be in the rear of the chassis, separated from the front by a p.c. board on which mounts all the control and low level circuit cards, accessible from the front through a door. The dc supplies for these chassis will be large and unrefulated, feeding many chassis, and the power will be shut off to all units when it is necessary to work on any one.

The large chopper controllers will each have transductors for monitoring their current and feeding-back for comparison with the reference level from a 16 bit DAC. An additional group of transductors will monitor each of these circuits and will all be read by the same Digital Voltmeter through a channel selector. These transductors will also have an additional winding on them so that a current reference can be periodically used to drive all these windings in series. With the main current off this reference current read on the DVM through each unit will clarify if there has been drift in any of the transductors with respect to each other, the load resistor being the most suspect.

AC and DC Distribution (See Figure 1)

A 12.47 kV radial-feed system supplies AC power to all the Interaction Region Buildings. In Region 8 the dc power for the magnets is supplied through two 2000 kVA, 12.47 kV/480 V transformers. The transformers will be oil-filled, outdoor, substation units, with air-circuit-breakers on each secondary, and a common hi-voltage fused interupter on the primary. The 480 V feeds will come into molded-case circuit breakers inside the building before going to the three-phase full-wave bridge rectifiers. Using two 2000 kVA transformers puts the breaker fault duty at 42,000 amps rms symmetrical, which is comfortable for both the ACB and hi-interrupting molded case units. Each ACB will be separately electrically operated from the building or in common with all ACB's from a master trip button. The ACB's have a far higher rated number of operations at rated current than the molded-case units, which are satisfying the NEC local disconnect requirements.

One transformer is delta-delta, the other is wye-delta in order to minimize the harmonics in the 13 kV feeder current. Distribution transformers are applied to rectifier service here because there is not frequent turn-on with the related in-rush current on the primary. Therefore the transformer does not have to be braced beyond that required for distribution service. The higher-order harmonics in the primary and secondary currents in rectifier service cause increased eddy-current losses in the conductors as a function of their height to width ratio. The 10% increase in KVA rating necessitated by these losses is encompassed by the range in standard transformer sizes.

Utilizing the standard 480 V secondary voltage provides a L-C filtered rectified output of somewhat greater than 600 volts. The two bend, eleven quad, and two sextupole choppers are divided between the two dc supplies. There are two sizes of choppers, the bend choppers rated for 1400 amps max, and all the others for 400 amps. All of the choppers will run at a fixed repetition rate somewhere between 1 and 10 Kilohertz with a clocked turn-on, and error-signal controlled turn-off. In order that all the choppers not turn-on at once with the associated high current loading on the common capacitor bank, the chopper turn-on signals will come from a ring counter fed from a master clock. The reduction of the rms current from the capacitor bank substantially reduces the number of capacitors required.

The currents for the Bend and all the Quad circuits will be carried around the ring by circular, water-cooled, aluminum conductors mounted in trays. The remaining conductors for the lower current sextapoles, rotated quads, trims, and steering magnets will be air-cooled in trays. The Bend and Quad circuits will run around the entire ring with no return conductor. The trim and steering currents will be fed from the building at each interaction region to magnets up to halfway around each adjacent arc. There will be links at each straight section where the main circuits can be opened to facilitate isolation of fault to ground locations.

The 600 V DC bus level is appropriate not only because it is rectified from a standard 480 V distribution transformer, but also because it is a recognized maximum rating for standard cable insulation. With a soft ground established between the two DC supplies in Region 8, the maximum voltage to ground is 600 volts. In circuits utilizing both supplies at Region 8, a bolted fault at either output would raise the other output to 1200 volts with respect to ground before the fault protection operated. Differential current sensing will be used at outputs of the choppers to detect ground currents.

The circuits requiring more drive than the 1200 volts available from the two busses at Region 8 will have supplies at Regions 12 and 4. These supplies will also be 600 volt maximum supplies, run as slow response, open-loop slaves to the corresponding current-controlled unit at Region 8.

The econimics of the Region 8 arrangement are such that no additional transformers or switchgear need be purchased beyond that required for basic AC distribution. The necessity of shutting down the whole supply system when any individual chopper-controller is malfunctioning is entirely in keeping with the fact that the beam will be lost for the same reason and therefore all the supplies might as well be off.

The various low-voltage, low-current requirements will be supplied from a ± 40 volt bus in each region.

Chopper Controller

The basic specification placed on the current-regulated chopper controller is that the field in any magnet shall not vary more than ± 100 parts per million of its setting for all line voltage and load perturbations, over the range of 25-100% of the maximum rated current. Using 16 bit D to A's is a requirement. The stability specification is expressed in terms of the required field quality rather than on the current because of very substantial eddy-current shielding provided by the 1/4" thick vacuum pipe. Thus the current ripple due to the pulse-width modulated chopper operation can be greater than 1000 ppm at a one kilohertz chopping-rate and the field ripple will still be with tolerance. Tests made on vacuum pipes have shown an attenuation of approximately 1/10 from current to field ripple. The chopper output will be filtered to minimize high-frequency coupling to other circuits in the ring.

The chopper controller is imbedded in a standard current regulator loop employing a transductor for current sensing. The signal level required from the amplifier for the firing circuit is 10 volts. Pulse transformers are used to couple the firing pulses to the thyristors. A significant improvement in overall system performance is achieved by a voltage-feed-forward system from the unregulated dc bus. Because of the forced-commutation turn-off nature of the chopper, as opposed to line-voltage zero-crossing commutation, the output of the chopper can be controlled on the turn-off end of the output pulse, with the turn-on coming from the clock. This controlled turn-off from a comparison between a ramp and the current-loop error signal provides a simple realization of the voltage-feedforward. The unregulated dc bus determines the slope of the ramp through an integrator that is zeroed at each clock-pulse. Therefore a higher line-voltage means an earlier turn-off during the actual period when the perturbation occurs, and effectively constant volt-seconds to the load. Line voltage changes occurring during the off-time when the free-wheeling diode is conducting do not effect the load current or the integrator until the next on-time. Tests on a 360 kW prototype chopper running at 1 kilohertz show a reduction of at least 1/10 in a sine-wave introduced through a mag-amp acting as the dc bus. The tests were run to 30 hertz (as high a frequency as possible with the Magamp).

There are many possible circuits for realizing the forced turn-off of the chopping-thyristor, both of the voltage and current variety. The most common voltage-controlled circuit is the Jones circuit, where a commutating capacitor is placed across the main chopper thyristor (which is already conducting) by turning-on a second thyristor in series with the capacitor. The capacitor must have sufficient capacity such that when the maximum magnet current is commutated to it the chopper thyristor is kept back-biased for longer than its turn-off time (T_{off} = 10-30 μsec, depending on voltage and current rating). The capacitor voltage continues through zero until the V_{supply} is reached, when the magnet current commutates from the capacitor to the free-wheeling diode. The time that this reversal of the capacitor voltage takes is inversely related to the magnitude of the magnet current, whereas the ON time if proportional to the current. So a minimum allowable current level is reached when the capacitor voltage does not get beyond zero before the next period. Then there is no voltage to use on the turn-off in the next period.

Another way to get to the minimum output current is by knowing that the power going from the capacitor to the load can be expressed as

$$\frac{1}{2} C(\Delta V)^2 f = I^2_{min} R_{magnet} \qquad (1)$$

The added voltage from the commutating capacitor being in series with the source voltage during commutation raises the ripple voltage across the magnet.

A circuit which has completely eliminated the minimum ON time and also does not raise the load voltage to twice the supply voltage during commutation is shown in Figure 2[1]. Here the capacitor voltage is developed across the series choke and thus turns off the thyristor by bucking the supply voltage, giving an immdeiate voltage turnoff and current commutation to the free-wheeling diode at the output. During the OFF period the current in the series choke is kept circulating by means of the diode around it and at a higher value than that of the load current. Thus at the turn-on pulse the load current can immediately flow through the choke and thus not experience any turn-on time constant.

The capacitor voltage is now interacting with the choke and free-wheeling diode around it rather than the load. The expression for power flow now involves an added diode term because, except for the short time when the capacitor is going from one polarity to the other, the current is circulating through the free-wheeling diode.

$$\frac{1}{2} C(2V)^2 f = I^2 R + I(t)E_{diode} \qquad (2)$$

When the appropriate pair of commutating thyristors are turned-on the capacitor plus the supply voltage appear across the choke and the current increases as energy is transferred to the choke. When the voltage across the capacitor has reversed and charged up to the supply voltage, the thyristors turn-off and the choke current again circulates through its free-wheeling diode, decreasing as power is lost in the resistance and diode drops. If the chopper thyristor is only on for a very short period (low output), then the circulating current through the diode around the choke is equal to that in the choke and the current increases on successive cycles until equation (2) is satisfied. The terms on the right hand side of the equation must be adjusted until it is satisfied at a current somewhat greater than the maximum load current. For instance in the 360 kW prototype at 300 Volt and 1200 amps, with a 40 μfd commutating capacitor, the power is 7.2 kW, or 2.5% of the rating.

When the chopper thyristor is ON the current in the choke free-wheeling diode is reduced to the difference between the choke and the magnet current, which means that the power lost in the diode is reduced during that time. The diode drop is additive to the source voltage driving the load during the ON time and thereby puts power into the load, raising the efficiency. The efficiency is therefore worst at low outputs, and improves at high output in proportion to how the losses of equation (2) are divided between the choke resistive losses and the diode drop.

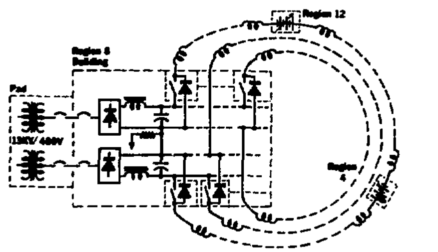

Figure 1. Functional layout of power supply with choppers

Testing & Construction Program

The testing program began with the 360 kW, 1 kilohertz chopper purchased from Peripheral Power Systems of Santa Clara, Calif., in January 1976. Extensive testing proved the chopper to be as expected in (1) effectively utilizing voltage feed-forward to reduce line-voltage perturbations by at least an order-of-magnitude, (2) a closed-loop bandwidth of at least 100 hertz, (3) full range control, and (4) current-limiting override on regular loop operation. The chopper is contained in a small cabinet (~ 2' x 2' x 6') which includes an input filter on the incoming dc bus of 50 μh. and 0.1 farad.

The only problems encountered were audible noise and infrequently missed output pulses. The audible noise was substantially reduced by dithering the basic 1 kilohertz rep.-rate from ~ 960 to 1400 hertz at a 120 hertz rate. This dither prevented standing waves from developing within the cabinet.

Missing output power pulses were detected by a digital chassis and occurred at an average rate of two per hour. There was a definite correlation with whether or not the Bevatron was operating (where the tests were being made), and yet filtering the a.c. control voltage, etc., was not sufficient to eliminate the misses. During Bevatron shutdowns there are not misses for at least 8 hour periods.

Components and equipment are now being purchased for an Engineering Prototype Power Systems composed of one 840 kW, 1400 amp chopper, and three 240 kW, 400 amp choppers supplied from a single 600 volt dc supply. Stainless steel, water-cooled tubes will be used for the necessary resistance in series with low voltage magnets to serve as loads. With the major technical aspects proven by the 360 kW purchased unit, the engineering prototype will provide means for testing multiple choppers fed from a common supply.

Conclusions

The 360 chopper was purchased for $6,950, or $17/kW. This cost includes the error amplifier through to the power filter, but no transductor. Adding $3/kW for the transductor and $5/kW for the rectifier-filter unregulated dc bus brings the price up to $25/kW. This price is very attractive for systems where all the power can be turned-off whenever there is trouble with an individual unit. The immediate future involves construction of an engineering prototype. Further down the line is serious consideration of techniques to handle the "trapped-energy" of the commutation circuit by other than dissipative means, so the operating frequency can be increased without the losses increasing proportionately.

Bibliography

1. Partridge, D. , "Circuit for Controlling the Conduction of a Switching Device", U.S. Patent 3, 652,874. March 28, 1972.

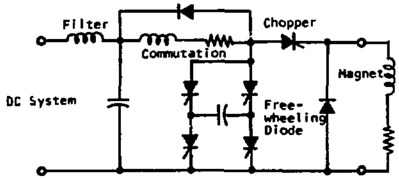

Figure 2. Chopper Schematic