DESIGN AND PERFORMANCE OF PEP DC POWER SYSTEMS

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Introduction

The PEP Magnet Power Supply System represents a
significant departure from previous technology with
the goal of improved performance at lower cost. In
nineteen of the magnet families around the ring,
"Chopper" power supplies are used. The many choppers
are powered from two 2 MW DC supplies, and control
the average power to the various magnet loads by
pulse-width modulation at a 2 kilohertz repetition
rate. Each chopper utilizes SCR's for switching, and
stores sufficient capacitive energy for turn-off on
command. Most of the energy is recirculated,
resulting in high-efficiency. The two kilohertz
chopping rate allows a one kilohertz unity-gain
bandwidth in the current-regulator loop, and this
wide bandwidth, coupled with low drift components in
the error-detection system, provides a high-
performance system. The PEP system has also shown
that the chopper system is economical compared to
standard multi-pulse controlled-rectifier.

Before going into the Chopper system in more
detail, it is appropriate to briefly describe the
overall PEP Power Supply system. Additional detail
on various aspects of the systems is available in
previous conference papers,[1] so only the barest
introduction will be given here. There are 240 power
supplies in the system, each current regulated to a
set-point provided by the digital control system.
The supplies fall into three major catagories: the
Ring, Injection-transport, and Trim and Steering
Systems.

Ring System

The Ring system is made up of the Choppers and
the DC supplies that feed them. A simplified
schematic is shown in figure 1, the SCR Choppers
represented by switches. There are twenty-four of
the 500V, 500A choppers, and two of the 500V, 1400A
choppers. All of these supplies are located in
standard racks at the Region 8 surface-building as
shown in Figure 2. These supplies provide separately-
controlled, current-regulated power to the following
families of magnets: one Bend circuit, nine Quad-
rapole circuits, eight Sextapole circuits, and one
Wiggler circuit. These magnet families are all
series connected strings of magnets around the 6,575
foot long ring. Those families with more than 12
magnets in series require two choppers in series to
achieve the required voltage. There are additionally
boost supplies located at regions 12 and 4, one set
for the 1400 amp Bend circuit, and the other set for
one of the Quadrapole circuits.

Three of the rows of racks in Fig. 2 each contain
eight choppers (all the 500A choppers). The row in
the middle houses the two 2MW DC power supplies which
feed all the choppers. The soft ground (100Ω) for
the whole system is located electrically between the
two supplies, so that the maximum voltage away from
the ground on any magnet circuit is ±600 volts in

normal operation. The two 1400 amp Bend choppers are
located next to their respective + and - DC supplies,
and fed from the output busses (located at the top of
the DC supplies) through low inductance (0.8μh),
parallel bus feeds. The rest of the 500A choppers
are fed from the output busses through 4/0 quadraflex
cables run through cable trays above the racks.

At the aisle-end of the row of racks containing
the DC supplies and 1400A choppers, there are two
racks housing all control equipment for the chopper
system (Fig. 3). This equipment includes the
following: CAMAC crates for input/output communi-
cation with the PEP Central Control Computer, CAMAC
crates containing all the Chopper Controllers, a
multiplexer and Digital Voltmeter for sampling magnet
current levels in all the monitoring transductors
(also the levels of the Loop transductors and
references if necessary), cross-connect relay
modules, and appropriate power supplies. There are
up to eight Chopper Controller Cards per CAMAC
crate. Each card contains a complete chopper control
system from the input 16 bit reference word, clock
signal, and feedback transductor signal, to the
output firing pulses for the chopper and commutator
SCR's (turn-on and turn-off pulses) of the associated
chopper unit. Each of the pulses is conveyed from
the short (upper) edge-connector of the CAMAC-card
through a 50 Ω coaxial cable-connector system to a
pulse transformer (insulated for 1600V) mounted in a
shielded-box on the chopper unit.

There is a Chopper Crate-Controller card in each
of the four CAMAC crates which distributes both
digital command words and appropriately phased clock
signals to each of the chopper cards. The clock
signals are phased so as to minimize the rms current
flowing in the large capacitor bands on the output of
each DC feeder supply. The clock card outputs
signals on four plugs which can be cabled to any of
the Crate-Controller cards. The clock (which is in a
separate card) can be either free-run with the
frequency adjustable via a front-panel potentiometer,
or line-frequency-locked through a phase-locked
loop. The VCO generates 26 kHz which is then
counted-down to give the various phased-clock signals.

Injection-Transport System

Power supplies for the transport magnets are
located in three locations: at Sector 30 of the
Linac building, where the North and South Injection
Transport tunnels veer off from the linear
accelerator for the PEP ring, and at the surface
buildings at Regions 8 and 10, where the tunnels join
the ring. The bulk of the power supplies are located
in Sector 30, feeding the separately controlled but
identical achromatic Bend families and Quadrupole
magnet families in both tunnels. The remaining Bend,
Quadrupole, and Bump magnets are fed from supplies in
Regions 8 and 10. All of these supplies are 6 pulse,
AC-line commutated SCR circuits purchased
commercially. The requirements of these circuits are
currents regulated to ±0.1% , compared to ±0.01% for
the main-ring chopper systems.

Trim-and-Steering System

This system is by far the most numerous of those employed at PEP, with 170 units installed in all the surface buildings and Sector 30. Most of the units are used for bipolar trim-and-steering applications with a rating of ±37V at 60A but some are used as unipolar 120A units and others as 30A shunts around Bend magnets in the injection-magnet families. These units are used as power sources in conjunction with ±42V, 1000A power supplies. The power supply is located in the bottom of a double rack, and up to 24 actuators are mounted above it and plug into feeder busses extending up the center of the double rack. There are nine of these double racks used at PEP. The reference signals for both these units and the Injection comes from a CAMAC crate located nearby in an adjacent rack. The analog signals are developed in 12 bit D/A^S in the CAMAC crate and processed through a Distribution chassis. With this brief description of the PEP system, the rest of the paper will concentrate on the chopper system.

The Chopper as a System Component

As stated in the introduction, the dual promises of high performance and economy fueled interest in using choppers as the controlling element in the PEP magnet-power-supply system. Both of these goals have been possible because of the particular nature of the load placed on the supplies and the favorable logistical nature of the PEP magnet system. Neither of these aspects are unique to the PEP system, and therefore choppers should see application beyond those now in use at PEP.

Early measurements on the first prototype PEP Bend and Quadrupole magnets in 1976 confirmed that the magnets were effective filters between applied AC voltages and their corresponding currents. Subsequent measurement have shown that with the additional shielding of the aluminum vacuum pipe, the attenuation of all frequency terms from a chopper running at 2.16 kHz is sufficient to reduce the magnetic field variation to less than ± 0.01% in the bend magnets. The field measurements were made with a vacuum pipe and $\dot{B}$ coil that extended well beyond the end of the magnet coil, so as to measure any contribution of the stray field at the ends of the magnet. The magnets are laminated because of the construction technique used in their fabrication, but individual laminations were not coated, so there was no guarantee they would be wideband units. With this type of magnet as a load the high-frequency operation of the chopper either eliminates or minimizes the need for filtering the output voltage of the power supply.

With a chopper there is no firing circuit unbalance to introduce subharmonics as in a 6 or 12 pulse cont-rolled rectifier. Running at 2.16 kHz the chopper current-loop unity-gain bandwidth can be as high as 1 kHz The chopper therefore has substantial gain for any low-frequency voltages coming from the rectifiers. The one kHz unity-gain bandwidth of the chopper also provides relatively fast transient response to changes in the reference and reduction of line perturbations. Closing the loop at a frequency within a factor of two of the repetition frequency is generally not possible with line-commutated, multi-phase firing-circuits because oscillations develop at the sub-harmonic frequencies. The wide bandwidth of the chopper coupled with currently available operational amplifiers of very low drift and noise, provide the means for ± 0.01% current regulation with 1 kHz bandwidth in the megawatt power range with better than 95% effciency.

Economics of Chopper System

The economics of the PEP system are based on the fact that the beam cannot be stored in the ring unless all the families of magnets are operating and performing satisfactorily. Therefore, if any of the power supplies are not operating correctly or there is a trip-off in any one of them, it is permissible that all the power supplies be off. This commonality of demand on the supplies allows a similar commonality to exist on the feeders coming to the chopper power supplies: all the choppers are fed in common from either the positive or negative DC supplies, with no switchgear interposed between the DC supplies and the chopper controllers. The 2.0 MW DC supplies in turn are each fed from 2.5 MVA, 13KV/480V transformers, located outside the building, and with secondary breakers at the transformer pad and at the 2500A feeder entrance to the building.

These two standard distribution transformers and their related breakers at the pad and the building entrance are the only transformers and switchgear in the system, and they would have been provided as part of the normal AC utility-distribution system to the power-supply area independent of what kind of power supplies were used. So the cost of transformers and switchgear is eliminated from the power-supply expense. The circuit breakers employed operate as ON-OFF contactors as well as circuit breakers. There is a fast-acting current-limiting fuse on the incoming lead that is not at common on each of the choppers, which acts if the chopper internal fast-turn-off does not commutate off a fault current.

The cost of the choppers under the condition described above is as follows (with DC busses):

(1) Cost of 500 V, 500 A chopper	$10,600	($42/KW)
(2) Cost of 500 V, 1400 A chopper	$12,700	($18/KW)
(3) Cost of 2MW DC feeder supplies	$54,000	($27/KW)

These figures are not estimated figures, but represent the totals accumulated in the three accounts during the construction of PEP. The grand total of $441,500 in the Chopper and DC supply accounts represents the costs for twentyfour small and two large choppers, the two DC feeder supplies at Region 8, and additionally the two 840 KW Bend Booster supplies at Regions 12 and 4. The chopper costs include the cost of the separate monitoring and loop transductors used in each chopper, and all the chopper controller cards, clock cards, crate controller cards, and modified CAMAC crates that make-up the controlling system. Installation costs are not available because they are part of a far larger Electrical Construction contract performed by a private contractor.

The maximum power capacity of all the choppers just described plus the two bend boost supplies at regions 12 and 4 is 9MW, whereas the maximum power required by all the ring magnet families at 18 GeV beam energy level is only 5MW. The sum of all the DC supplies at Regions 8, 12, and 4 is 5.7 MW; this number more closely matches the maximum power required. The discrepancy occurs because many of the sextupole and quadrupole circuits require less than the maximum voltage and current available from the choppers. The cost of the chopper units is optimized at the given current and voltage values based on the ratings of the fast turn-off SCR used (the Westcode R220). Therefore unless a future application could be matched closely to the chopper ratings the cost per KW figures are not directly applicable. A more accurate comparison for the specific PEP case is to

take the total construction cost of $442K against the 5MW, for a figure of $88/KW.

The 1400A chopper is much more economical than the 600A unit because to raise the current rating of the chopper unit from 600A to 1400A basically requires only the addition of a second SCR of equivalent size to that already in operation, increasing number of $5\mu fd$ commutating capacitors from 3 to 10, and increasing the current capability of the bussing as required. Additional cooling air on the capacitors and snubbering were also required. But the great bulk of the cost in the rack fabrication, transductor and chopper controller remained essentially the same.

Performance and Operation

The choppers have performed their function as ±0.01% current regulators up to highest expectations. The current-monitoring multiplexed Digital Voltmeter, a Hewlett Packard 3455, shows performance better than the ±0.01% required. At higher performance levels than ±0.01% , both the monitoring and loop transductors have to be called into question, particularly with respect to line voltage variations.

The choppers have also operated reliably; most of down-time during the first year of operation has been from other parts of the power supply system. Two types of chopper hardware failures have occurred, and both of these only two or three times. The snubber-capacitor across the free-wheeling diode has failed, which then causes the diode to fail and possibly the chopper SCR to fail also. A different capacitor will soon be installed to correct this problem. The water-cooled resistor has also failed due to localized heating of the carborundum resistor near the ends. A new means of connection is now being tested.

In the larger chopper-power-supply system there have been two sources of operational difficulty: erratic operation of the 2MW DC power supplies, and erroneous digital-word reception at some of the chopper DACs. The most recent difficulty (in February) was the failure of one of the 2.5MVA distribution transformers feeding a DC supply; one of the 13KV leads was not securely connected internally to a stud on the transformer, and arced in the oil unitl a phase-to-phase short was initiated. This transformer arcing intermittently may account for some of the power supply difficulties over the past year, but it seems clear that the firing circuit is unreasonably sensitive both to line voltage noise and the characterisitics of a flip-flop used in the zero-crossing part of the circuit. The SCR-bridge and firing circuit, both mounted on a large panel, were purchased from Research, Inc. (RI), as a package, and subsequently mounted in a double-rack along with the LC filter, bussing, shorting-bars, etc., to become one of the four DC supplies used. Because the supplies are not used as current regulators, but as low-performance bus-supplies for the choppers and slave-supplies in the Bend circuit, using only one zero-crossing per cycle was not a problem. The fast turn-off under fault (sensed by current-tranformer), and advertised insensitivity to line-voltage noise were desirable features. The firing circuits turned out to be very sensitive to the line voltage when operating above 1MW, and during the very-short P.S. check-out period (two weeks before PEP operation), were a source of grave concern. After various filtering schemes were unsuccessful, phasing the units from a separate feeder was finally adopted and is still in use.

During the initial P.S. checkout period, and

given the substantial difficulties with the DC supplies, it was very encouraging that the choppers were well-behaved and exhibited no problems of interaction due to running in parallel and series, or false triggering due to noise from other choppers. Two choppers had been run in parallel during the development program at LBL, but the series operation had never been attempted. A situation where noise of some kind is involved has arisen at 14.5 GeV operation during the "filling" operation of the ring where the Injection Bump magnets are ramped. In performing this operation on a non-chopper supply, the computer also sends "refresh" words to the choppers. In one group of choppers whose controllers are located in a particular CAMAC crate one chopper would randomly receive an incorrect reference word for a short period and cause the beam to "dump", and the "glitch" detector to indicate on the responsible chopper. The problem proved to be insensitive to the components involved, and more careful grounding of the two control racks seems to have solved the problem at the 14.5 GeV operation level, but why just one crate was involved is still a mystery.

Electromagnetic noise also appeared on the output of sensitive spark-chamber amplifiers in the experimental-hall at Interaction Region 8. The addition of air core chokes to both sides of the chopper outputs reduced the rise-time of the voltage output and reduced the noise below the detector threshold level. Similar noise problems for the experimenters at regions 4 and 12 from the Bend Booster supplies in those regions were solved by activating the LC filters already existing in the supplies.

Chopper and System Design

There is one aspect of the Chopper System design that is very closely tied to both operations and Chopper design: the output voltage range of the chopper. There are a variety of possible chopper circuit configuarations to perform the basic function of turning-off the output voltage (V_O) on command. Of these various circuits only two will be discussed here: the current-commutated (Fig. 4 and 5) and the voltage-commutated circuits[2]. The current-commutated-circuit (CCC) turns off the ON series SCR (labeled CR1) by circulating current through the reverse diode D1 across CR1 during the second-half-cycle of the ringing period of the high-Q resonant circuit (the first-half-cycle is through initiating CR3). The forward-voltage of D1 reverses biases CR1 during the time when the ringing current is greater than the load current (I_L): this time must be greater than the turn-off time (t_{off}) of the SCR at maximum I_L. The CCC has the advantage of being very efficient (because of the total cycle of ringing voltage), and generating relatively low reverse-recovery voltages; coupled with the disadvantage of having a minimum output voltage determined by the ratio of the ringing period of the LC circuit to the total period of the cycle of operation (the input and output are connected during the ringing period).

$$V_{min} = (T_{LC}/T_{per}) \ V_B = (rep \ rate/f_o) \ V_B \qquad (1)$$

The voltage-commutated circuit (VCC) has the advantage of providing full-range voltage control, counterbalanced by a propensity for large voltage spikes appearing across the commutating SCR during reverse-recovery. The voltage spike, even though below the rating of the SCR, occurring immediately following high-current conduction in the SCR, causes

high failure rate. Independent of which commutating circuit is used, there is a minimum allowable inductance that must effectively appear in series with the chopper SCR. This inductance is necessary to control the rate-of-change of current with time (I) upon turn-on of the chopper SCR.

$$L_{min} = V_B / \dot{I} \qquad (2)$$

The VCC was the initial choice to satisfy the early PEP requirements of 300V at 1200A for the Bend magnet circuit. The prototype chopper worked well at this supply voltage level, because the sum of V_B and the transient voltage was no more than 800V on 900V rated SCR's with moderate snubbers. When the magnet design changed and 600V operation was more appropriate, the reduction of transient voltages to acceptable levels became more difficult and costly and put far more uncertainty on long-term reliability. A quick circuit reconfiguration to current commutation was done, and immediate successful operation of the circuit, simplicity of operation, and easing of the transient problems resulted. It was then determined that the range requirements of the circuits could be satisfied with the chopper minimum of $V_0 = 0.15$ V_B, where V_B varies above 100V proportional to beam energy. The SCR Bus supplies were originally chosen over diode-bridges primarily because of the quick turn-off feature and low cost ($8/KW) of the Research, Inc. packaged controller. But now the controlled-output capabilities would also be used to follow a programmed input.

On the basis of the variable-voltage DC bus operation, the non-minimum output, current-commutated chopper was adopted for PEP. Since achieving operating status the minimum output of selected sextupole choppers has been lowered from 14% to 2% by running them from a 360 hertz clock rather than the 2.16 kHz clock used on the rest of the choppers. The decision to adopt the CCC has been justified by the excellent reliability the choppers have shown in service, but unfortunately leaves unanswered what additional development and cost the wider-range VCC would incur to achieve reliability.

Designing the current-commutated-chopper does not involve changing any of the basic circuit elements shown in Fig. 5, and therefore only the L, C, R, and L_B values are available as variables. The R is the least useful of the variables, serving to reduce the "ring-up" value of V_c above V_B during the period between commutation. If a satisfactory design can be achieved without R, it can be eliminated, resulting in a more efficient design. An additional variable not shown in Fig. 5 is the effective Q of the LC circuit. Selection of component values involves more than a simple LC circuit because of the final part of each commutation cycle. After D1 has carried the ringing current I_c that is greater than I_L for a long enough period to allow CR1 to recover, D3 stops conducting and I_L flows through C and L. Shortly after, when V_c becomes greater than V_B, the free-wheeling diode D3 starts conducting, and the capacitor voltage V_c increase in magnitude by:

$$\Delta V_c = I_c / \omega_1 C \qquad (3)$$

during the $\pi/2$ period that I_L commutates to D3. In the pictures shown in Fig. 5, conditions are such that D1 ceases conducting and D3 starts conducting at the same instant. The inductance of the bus, L_B, enters into the circuit during this last part of commutation, and enters Eq. 3 through

$\omega_1 = [(L_1 + L)c]^{-1/2}$.

Depending on the parameters involved in each application, the ringup voltage ΔV_c can be a help or a hindrance. The limiting parameter for the PEP choppers turns out to be a maximum allowable capacitor voltage of 750V at the start of the commutation. Although specified for 1000V operation in this circuit, long-term failures occur due to thermal effects when the value of V_c exceeds 750V. With the capacitor voltage limitation, the DC bus voltage is not allowed to exceed 500V, where all the 18 GeV current requirements can be met. An opposite example, where the ringup voltage is desired, is in a group of choppers used for PEP experimenter magnets, where the $V_B = 120V$, and the $\Delta V_c = 339V$. The Bend, Quadrupole, and Experimeter choppers are listed in Table 1 with the appropriate parameters as three design examples.

Previous to discovering the long-term failure-mode in the commutating capacitors at approx. $E_{pk} = 700V$, the circuit was run to $E_{pk} = 900V$, with the R220 used for CR3 rated at 1200V. The R220 has a $T_{off} = 15$ μsec for voltage commutation, and a $T_{off} = 17$ μsec rating for current commutation (only 1 volt reverse voltage applied). Used also for CR1, the R220 with a $1000A_{rms}$ rating is used singly for the lower current choppers, and doubly with alternate pulse firing for the 1400A choppers. The 250kW and 700kW ratings on the choppers are because of the capacitor voltage limitation (otherwise 360kW and 840kW are appropriate at $V_b = 600V$).

Because the capacitor ringup voltage, ΔE_c, affects the peak ringing current and therefore the t_{off} applied to CR1, the load current I_L has to rise with a $\tau \gg T$ period, to allow V_{cpk} to build-up in step with I_L. This condition is satisfied with inductive loads. With series choppers, both choppers have to be enabled simultaneously and the same buildup occurs in both units. If one of two series units is turned on first, the current from the first will flow through the free-wheeling diode D3 of the second unit until it is turned on. At the time the second unit is fired, if the I_L has reached a current higher than that which can be successfully commutated with just V_B stored on the commutating capacitor, the second unit will "latch-up" at full output.

To determine the chopper system efficiency, both the DC supplies, the bus and the chopper losses must be included. Without transformer losses to consider as part of the power supply, the rectifier itself loses less than 1 percent of rated power. The combination of bus and chopper losses are also less than 1 percent, so the overall efficiency should be 98 percent.

Conclusion

The chopper system provides a new approach to high-performance magnet-power-supply systems. Its performance and efficiency are superior and cost less than comparable size transformer-controlled-rectifier supplies. The problem of radiated EMI noise to the surrounding environment has to be reduced with choppers just as with 6 pulse supplies. Ripple in the magnetic field is lower if the magnet is laminated through high chopping rates. Minimum output-voltage requirements must be considered in the choice of the chopper circuit used. Two areas are particularly appropriate for chopper application: (1) large power supply systems with a common DC supply where the system using the power is disabled whenever any individual chopper must be shut-down, and (2) retrofitted on existing supplies where higher performance is required.

Chopper	I_{Lm}	V_B	L	L_B	C	ω	$ω_1$	Z_0	$ΔE_c$	V_{cpk1}	V_{c2}	I_{pk2}	t_{off}
	(A)	(V)	(μH)	(μH)	(μfd)	$(×10^{-3})$	$(×10^{-3})$	(Ω)	(V)	(V)	(V)	(A)	(μs)
Bend	1400	500	2	0.8	50	100	85	0.2	328	828	680	3059	21.9
Quad	500	500	7	3	15	97	82	0.68	250	813	601	795	18
Exptl.	600	120	5	3	25	89	71	0.45	339	459	459	920	19.2

Note: $ω_1 = [(L + L_B)C]^{-1/2}$, $ΔE_c = I_c/ω_1 c$, $ω_0 = (LC)^{-1/2}$, $Z_0 = (L/C)^{1/2}$,

$V_{cpk1} = V_B + ΔE_c$ = peak V_c at end of ringup,

$V_{c2} = V_{cpk1}e^{-t/RC} = V_c$ at beginning of commutation (with $R_B = 50Ω$ $R_Q = 100Ω$

$I_{pk2} = 0.9 V_{c2}/Z_0$ = peak ringing current of 2nd half-cycle with Q = 25,

$t_{off} = (90 - sin^{-1} I_L/I_{pk2}) (90)^{-1} (Π/ω_0)$ = time of ringing current above I_L.

Acknowledgements

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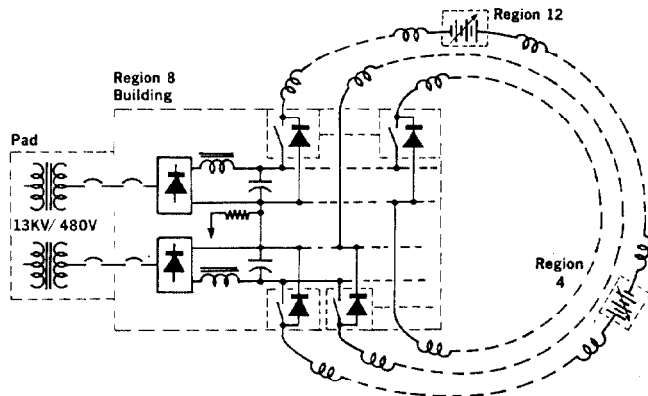   conductor Circuits", Wiley, N.Y, 1975, pp.
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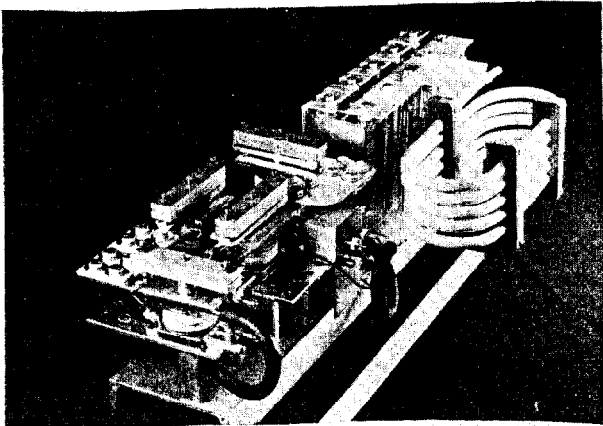Fig. 1 PEP Chopper System Functional Schematic
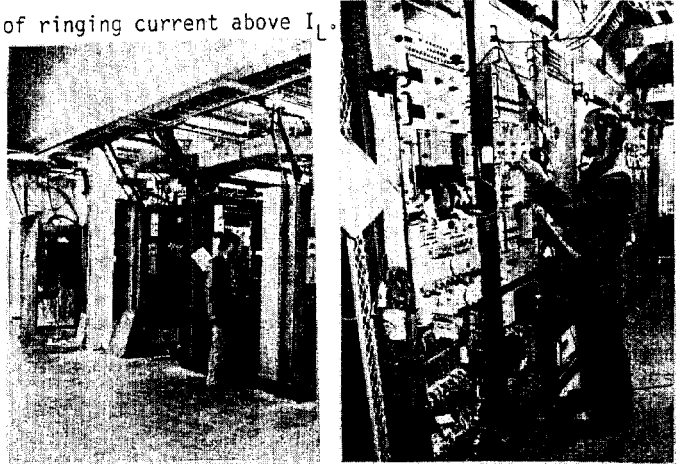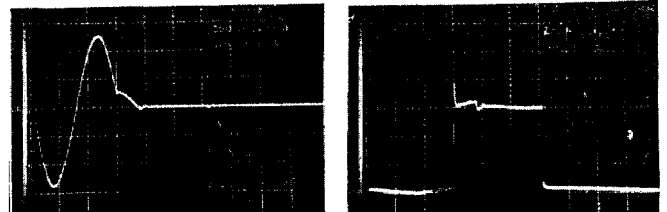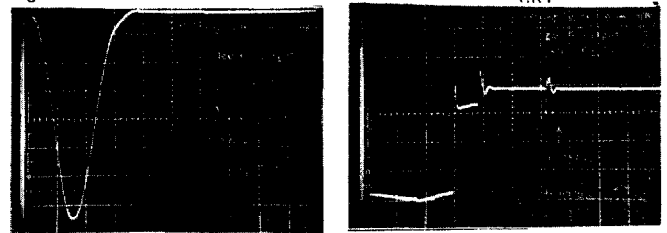

Fig. 2. Region 8 Chopper Racks   Fig. 3. Control Racks

I_c 400A/Div All pictures at 20μsec/Div V_{CR1}200V/Div

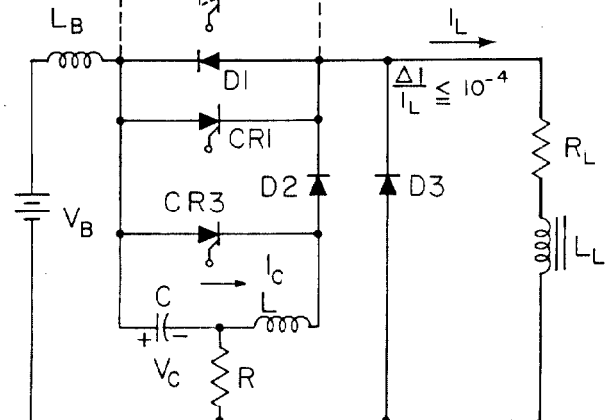V_c 200V/Div V_{CR3}200V/Div

Fig. 4 500A Chopper Module (hoses removed for clarity)

Fig. 5. Current-commutated Chopper Circuit