Switching Power Supply Regulation of Storage Ring Magnets†

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INTRODUCTION

Future accelerators will require greater flexibility in the design and implementation of their optical functions. One of the most cost effective solutions for the powering of linear and non-linear focussing elements is the use of modern, high efficiency switching power supplies. These types of power supplies are in use in a number of accelerators[1,2,3] and being planned for accelerators under construction[4,5]. This paper will focus on non-resonant switching regulators and discuss the general configuration of a system of magnet power supplies, the principles of the electronic circuit designs, the typical cost of such a system and the power supply performance, including regulation, stability and reliability. It will also present some general diagnostics for systems of large numbers of power supplies and some discussion of the operational benefits from the individual powering of all focussing elements. Since 1977 this type of chopper regulator has demonstrated its excellent performance for the independent control of the quadrupole, sextupole and steering magnets in CESR (Cornell Electron Storage Ring); a number of practical considerations from this experience will be included throughout the discussion.

BASIC SYSTEM AND CIRCUIT DESIGN

A typical chopper magnet power supply system would have a set or sets of regulated DC buses providing the raw DC power to the chopper regulators located along the accelerator near the magnetic elements. Figure 1 shows the configuration in use in CESR. For each half of the ring the primary power for the magnet system is supplied from a regulated 65 VDC power supply with load and line regulation better than a few tenths of a percent. The negative side of the power supply is connected to the ground return bus and to earth ground through a fault protection circuit; due to the load current the voltage of this return bus will rise a few volts above earth ground at the far end of the ring. At a typical magnet station there are unipolar chopper regulators for the quadrupole and sextupole magnets and bipolar choppers for the steering corrector magnets. The high precision quadrupole chopper supply has a DC current transformer (DCCT) as the current regulating element, while the lower precision sextupole and steering choppers use shunts for regulation. Each chopper's connection to the positive supply bus is fused to protect against the chopper developing an internal short. The control, protection and regulation circuitry for each chopper supply is situated on a separate circuit board in a crate.

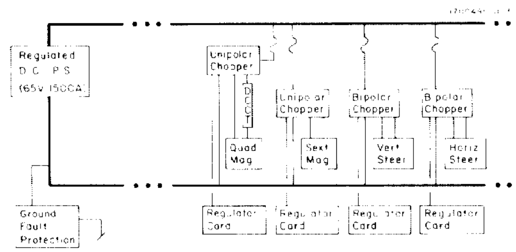

Figure 1. CESR chopper power supply system configuration.

The unipolar chopper circuit is described as a reverse biased fast recovery diode across the magnet and a switching element that periodically connects the magnet between the DC power buses. When the switch is closed, current is drawn from the DC mains through the magnet. When the switch opens, the magnet current continues to flow through the fast recovery diode. A very convenient current regulating method has the switching element operating at a fixed frequency with pulse width modulation. For conventional magnet impedances bipolar transistors or FET's are the preferred choices for the switching elements due to their low "ON" resistances. The choppers in operation in CESR are based on bipolar transistors, while the newer APS design utilizes FET's.

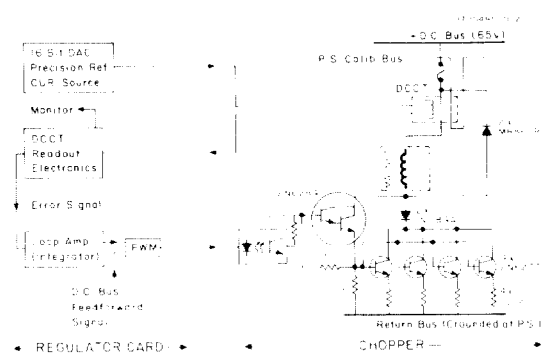

Figure 2. CESR unipolar precision DCCT regulated 100 A chopper power supply block diagram.

An example of a unipolar chopper is found in Figure 2. This is a high precision quadrupole regulator used in CESR. The regulator electronics are separated into two parts, the high power switching chopper and a regulator card with its own

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electrically isolated ground. This isolation is necessary because the chopper's common is connected to the return bus, possibly a few volts above ground, and generally there can be significant switching noise present on this return bus. The regulator card needs to be in a low noise environment for the best regulation performance and to permit easy control system interconnections. As shown in figure 2 to obtain the 100A maximum switching current, four 2N6277 transistors are driven as emitter followers (the emitter resistors providing current sharing) by a high current gain darlington stage. The magnet's current is is measured by a magnetically shielded DCCT, which measures the flux difference between a 1000 turn winding driven by a precision reference current and a single turn winding for the magnet's current. The DCCT is connected in the circuit at one of the DC bus potentials to minimize the EMI (electromagnetic interference) induced by the switching transients. A 16-bit DAC (digital to analog converter) provides the source for the precision reference current for the DCCT. The DCCT's error signal is detected in a sampled second harmonic demodulator circuit, which provides two independent error signals, one for monitoring and the other for regulation. To obtain improved DC stability, the loop amplifier is an integrator making use of the high open loop opamp gain at low frequency and a lag network to compensate the magnet's pole (at 0.3 Hz). The loop amplifier's signal feeds a pulse width modulator (PWM) circuit having a feedforward input from a differential bus voltage monitor. This feedforward network reduces by a factor of 100 the effect of transient changes on the DC mains at frequencies above the closed loop bandwidth of the current regulation loop. The APS design uses a Hall switch to accomplish the same wider bandwidth compensation for transients. The PWM circuit drives an opto-coupler connected to the chopper's darlington transistor stage.

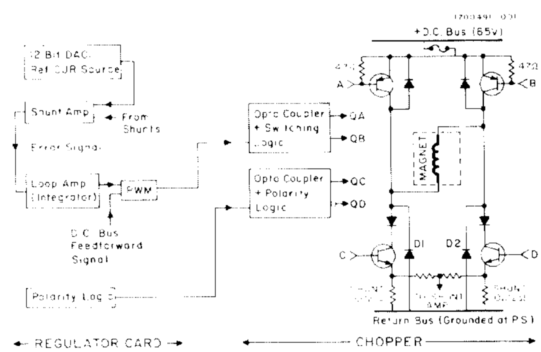

Figure 3. CESR bipolar shunt regulated chopper power supply block diagram.

The bipolar chopper regulator bears some important differences from the unipolar chopper mentioned above. Figure 3 shows the steering chopper in use in CESR; it uses a 12-bit DAC for a reference current source and a shunt for current regulation and monitoring. Aside from the additional polarity control logic the regulation loop circuitry is similar to that described above. The major difference is in the chopper's circuit configuration. For an explanation choose the polarity such that the current passes through the magnet from top to bottom. Transistors labeled Q_c and Q_d are the polarity determining switches and the transistors labeled Q_a and Q_b are the switching transistors. In this case Q_c is on and Q_a and Q_d are off. Q_b is driven with the PWM switching signal so that, when Q_b is on, current is drawn from the positive bus through the magnet and through Q_c to the return bus. When Q_b switches off, the voltage at the top of the magnet swings negative causing the diode, D_2, to conduct so that current flows from the magnet through Q_c to the return bus and back to the magnet via D_2. There are two shunts at the emitters of Q_c and Q_d; these are summed with resistors to give a polarity-independent shunt signal. A pair of waveforms from an operating steering chopper is shown in figure 4. CH1 is the voltage across the magnet, while CH2 is the AC coupled magnet current displaying the current ripple in a magnet with a short L/R time constant. The bipolar chopper supply has a dynamic range of 1000 to 1.

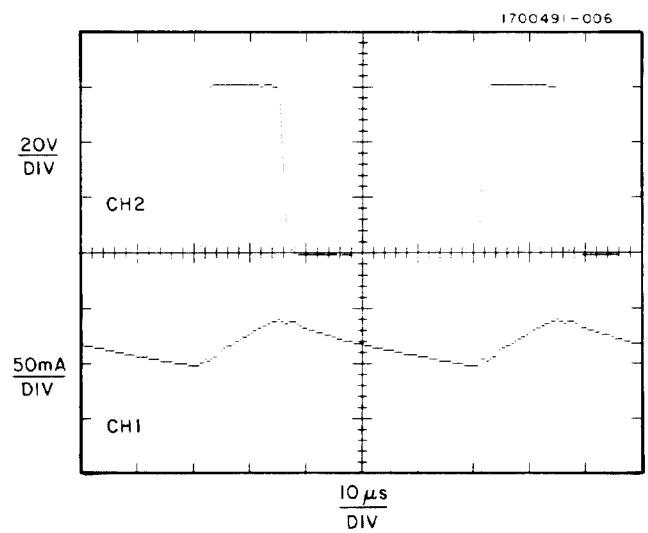

Figure 4. Switching waveforms from a CESR bipolar chopper operating at 6.25 Amps. CH1 is the voltage across the magnet and CH2 is the AC coupled magnet current ripple.

DESIGN CONSIDERATIONS AND PERFORMANCE

The fourteen years of reliable service of the more than 325 chopper power supplies in use in CESR provides a large sample of regulators with a long term operating experience. Designed in 1975 using bipolar power switching transistors, the chopper regulators have been in operation with power capacities up to 18KW. Table 1 gives some of the parameters for different unipolar and bipolar regulators in use in CESR and planned for use in APS. As table 1 indicates the chopper power supplies tend to favor higher resistance magnets; this is the case for the following reasons. First, for a given saturation voltage of the switching devices one portion of the chopper's dissipated power contribution comes from the product of the duty cycle, the magnet's current and the saturation voltage. To obtain the lowest losses and highest efficiency, the magnet's voltage should be as large as possible for a given magnet's current. The second reason for larger magnet resistances is that practical switching devices are presently limited to total switching currents of 100-150 A per device and, to avoid having to parallel many devices, lower magnet currents are favored. In the cases of CESR and APS the quadrupole magnets have resistances in the range of 0.04 to 0.5 Ω.

Table 1. Summary of chopper regulator characteristics

Accelerator	Regulator Type	Magnet	Command Resolution	Max. I (Amps)	Max. V (Volts)
CESR	Unipolar	quadrupole	16 bit	100	60
CESR	Unipolar	transfer bend	16 bit	300	60
CESR	Unipolar	sextupole	12 bit	40	60
CESR	Bipolar	H & V steering	±12 bit	±12.5	60
APS	Unipolar	quadrupole	17 bit	468	22
APS	Unipolar	sextupole	13 bit	214	23
APS	Bipolar	H steering	±13 bit	±125	26
APS	Bipolar	V steering	±13 bit	±99-148	14-19

The maximum allowable magnetic field ripple will favor a higher chopper switching frequency and longer magnet's L/R time constant (approximately 0.5 seconds for both CESR and APS.) Additionally, due to eddy currents in the beam pipe, the effect of the magnetic field ripple will be reduced within the beam pipe; for most common beam pipes this cutoff begins at frequencies of 100 to 1000 Hz. Also at the higher frequencies the magnet itself becomes lossy from eddy currents so that the largest variation in the field will be in the region of the fringing fields, typically a small fraction of the magnetic length. The choice of a higher switching frequency for a reduction of the current ripple is counterbalanced a need to reduce the power losses due to switch transition. Since these losses are proportional to the switching frequency, lower frequencies are favored, but should be above the human audio range. With these provisions switching frequencies in the range of 20-50 KHz should continue to be favored in the future. For the case of CESR and APS both with 20 KHz switching frequency and quadrupole magnets with 0.5 second time constants, the peak to peak current ripple at a 50% duty cycle is approximately 5×10^{-5} of the magnet's current.

As mentioned earlier the two most practical choices for the switching elements in the choppers are power switching bipolar transistors and power switching FET's. The bipolar devices have been available for the last 15 to 20 years and there have been some improvements in packaging and power handling capabilities over this period. However, rapid advances in the power MOSFET technology has lead to higher current devices (e.g. 150 A MOSFETs vs. 25 A bipolars) with comparable switching speeds. The absence of the the second breakdown phenomenon in the FET's permits higher switching voltages than are practical with bipolar devices. The reproducibility of the transconductance characteristics of the MOSFET's permits a much greater control of the device's switching current and eliminates the need for emitter resistors when paralleling bipolar transistors. As an example of MOSFET advances, the CESR quadrupole chopper's driver stages and main switching transistors can be replaced with an integrated circuit capable of driving capacitive loads and a single power MOSFET, greatly simplifying the parts count and cost of future chopper systems.

One of the reasons for the excellent reliability of the CESR choppers (mentioned below) is due to the conservative design specifications. In particular, the maximum designed power dissipation in the switching devices was approximately half of the maximum specified for those devices. Also the factor of three to four allowance for degradation of the bipolar transistor's current gain over the operational lifetime of the chopper allows some margin against a significant increase in the saturation voltage of the transistors over time and the associated increase in dissipation.

Chopper power supplies are excellent power converters with the example of CESR choppers having measured efficiencies at or above 95% at full current. The efficiency can be approximately calculated from the power delivered to the load and the losses from the switching transients and from the ON-state dissipation in the switching elements. The total load power as seen by the magnet bus, P_L, is

$$P_L = I_M^2 R + \frac{1}{2} V_B I_M (\tau_R + \tau_F) F + V_{sat} I_M \tau_d F \quad (1)$$

where I_M and R are the magnet's current and resistance, V_B is the bus voltage, τ_R and τ_F are the switching element's rise and fall times, F is the switching frequency, V_{sat} is the switching element's saturation voltage drop and τ_d is the switching element's ON time. The terms in this equation are respectively the load power, the switching transient losses and the ON-state dissipation losses. The switching element's ON time is itself given by

$$\tau_d \cong \frac{I_M R}{V_B F} \qquad (2)$$

and from these equations the efficiency, η, may be approximated as

$$\eta \cong 1 - \frac{V_B (\tau_R + \tau_F) F}{2 I_M R} - \frac{V_{sat}}{V_B} \qquad (3)$$

From this equation it is clear that the chopper's efficiency is the highest at the maximum magnet current and that reducing the rise and fall times and saturation voltage of the switching elements improves the efficiency. One additional fact to consider about using any high efficiency power converter from a regulated source, i.e. the DC bus power supply, is that the power converters appear to the power supply as a negative resistance load. Care must then be taken to stabilize the main power supply's voltage regulation loop.

The chopper regulators in CESR have demonstrated an excellent record for stable long term performance. For the case of the high precision quadrupole choppers the measured regulation is within ±10 PPM FS (parts per million of full scale) and the maximum deviations over a 36 hour period are within 50 PPM FS. Periodic checks of the quadrupole regulators' current calibration have been undertaken using a special calibration winding built into each DCCT. The calibration system has a resolution of 40 PPM FS and found no changes in calibrations for periods of one year above 100 PPM FS which were not due to major hardware failures.

The chopper power supplies in CESR have given very reliable service over the 14 years of operation. The performance for the calendar year 1990 is fairly typical of the chopper power supply reliability. During 1990 there were 21 failures of power supplies, 11 of these attributable to choppers, 8 to regulator cards and 2 cases in which both were replaced. This gives a failure rate of 1.75 chopper supplies per month during operations and a mean-time-to-failure of 15.5 years. Since in the early days of operations there seems to be a somewhat higher failure rate after the accelerators have been powered down several days (presumably due to the thermal cycling of components), a procedure of running all magnet supplies for 8-16 hours prior to the accelerator startup tends to induce failures in supplies suspected of early breakdowns.

The actual expenses for the assembled CESR chopper hardware in 1977 dollars was used to figure the per piece costs in Table 2. An estimate of the per piece expense for equivalent hardware in 1991 dollars is also included in Table 2. The reason that some of the 1991 costs have risen less than inflation is that prices of many of the electronic components have fallen over this period of time.

Table 2. Per piece costs of chopper regulator hardware for CESR

Component	Actual Cost in 1977 $	Estimated Cost in 1991 $
Chopper regulator chassis	$120-200	$250-333
DCCT regulator circuit card	$410	$570
Shunt regulator circuit card	$112	$235
Transductor (DCCT)	$46	$125

Before finishing chopper design considerations, some space must be devoted to the question of chopper induced EMI. It is important to realize that the CLEO detector operates with no EMI problems having magnets driven by choppers within 1.3 m of 18,000 preamps with a threshold sensitivity of 25 μV and a 10 nsec risetime. Although this has not been a very serious problem for the open frame choppers in CESR, some effort has been spent understanding and reducing the major source of EMI in the chopper circuit. The EMI occurs during the switching transients with the dominant source occuring at the time that the transistor switch begins conduction. As these transistors begin to conduct the full magnet's current and the fast recovery diodes begin to shut off, these diodes conduct a large current pulse which removes the charge stored in their junctions. In the original chopper design the switching transistors were driven into conduction rapidly with something like a factor of 3 to 4 overdrive of the base current. This permitted the diodes to conduct 300 to 400 A peak currents lasting roughly 20 nsec. This pulse effectively couples to the cables leading to the magnet which behave like a combination transmission line and antenna. The modification made to the CESR choppers was to increase the switching time of the transistors by about 50% and use the impedance of the emitter current sharing resistors with a voltage clamp on the base of the darlington driver transistors to make an effective current limiter for the drive transistors. The net effect was to reduce the peak surge current from the fast recovery diode turning off and to lengthen the duration of surge pulse, both effects reduce the EMI. One other technique is to run the magnet leads within a shielded braid, grounded at the magnet, and to AC terminate each lead of the effective twinax transmission line into its characteristic line impedance. Although the bypass capacitors do increase the rise time of the switching voltage across the magnet's coils the dominate effect is to shield and terminate the noise pulse which would have rung back and forth along the cable.

SYSTEM DIAGNOSTICS IN USE IN CESR

The CESR chopper supplies have a number of protection circuits which will inhibit the chopper's current on a fault. These are a bus voltage monitor (trips at 80% of operating voltage), a temperature monitor on the water cooled heat sink, a transistor emitter over current trip and an over-voltage trip for the transistor collectors' saturation voltage. The latter two fault conditions were an attempt to limit the transistor's power to within the safe operating area of the transistors. As Implemented these latter two faults have generally not been too useful; future designers are likely to find success with a slightly more sophisticated transistor dissipation measurement. The first two fault circuits have been particularly useful, with the former limiting the bus surge currents during a main power supply fault and the over temperature fault sensor providing protection against a loss of cooling for the chopper (and also the magnet it services since the magnet's cooling is in series with the chopper's outlet water.)

In addition to the fault protection the CESR choppers have a magnet voltage monitor and a current regulation error tracking monitor (both having >100 Hz bandwidth); these signals are digitized by an ADC and can be accessed by the control system. The digitizing resolution of the current tracking error is 40 PPM FS for the DCCT regulated supplies and 300 PPM FS for the shunt regulated supplies. Although the CESR control system is capable of reading hundreds of voltage and regulation error signals at nearly 100 Hz in several second bursts, the obvious development for future designs would make use of the low cost of digital memory to locally provide a scrolling history of these signals.

The philosophy of the magnet power supply diagnostic software and displays at CESR has been developed with the intention of maintaining the minimum amount of "on-line" diagnostics (those which are running all the time), but to have a battery of tools available to the operator to be called on as needed. The only "on-line" diagnostic is a program which checks periodically that no chopper power supplies have tripped off; this suffices for the vast majority of problems. The most used off-line diagnostic is a window display of, for example, one of the magnet sectors; this display contains the magnets' name, set point, a bar graph of the tracking error, voltage readback and fault status. Besides finding the obvious types of errors, this diagnostic is even useful for regulators whose feedback loops have become slightly unstable: easily visible as quadrature oscillation between the tracking error and magnet voltage. Another diagnostic program reads and records the voltage and tracking error readbacks at rates up to 100 Hz in several second bursts for roughly 30 seconds; the results may be displayed as histograms of the readbacks enabling one to locate supplies that have atypical distributions (suggesting potential regulation problems) or as FFT's of the time response to locate oscillating supplies. A third diagnostic tool is useful when there are intermittent failures in the system; this is a program that runs continuously monitoring one or more classes of magnet supplies and writing records in a file whenever any of the readbacks are outside a prescribed tolerance. When the intermittent event occurs the file may be scanned for any supplies which had failed at the same time. The last diagnostic tool to be discussed cannot be used with a stored beam since all the power supplies are turned off and a current is run in series through the special calibration winding of each of the DCCT's; the precision reference current commands are adjusted to match the tracking when the supply is regulating. In the matter of a few minutes the calibration of all precision current sources may be checked to 40 PPM FS.

OPERATIONAL BENEFITS

There are, of course, many benefits from using chopper regulators which have been mentioned above. There are several operational benefits to the freedom to have independent powering of quadrupole and sextupole magnets and three are worth mentioning. The first is the flexibility of linear and non-linear lattice design. As an example, the flexibility of the powering of the CESR quadrupoles has permitted the operation of the ring from integer tunes of 7 up to 15. The second benefit is the ability to easily locate the beam position monitors with respect to the quadrupole centers, by moving the position of the beam in the quad until it no longer steers. The final advantage of the independent powering of the quadrupole magnets is the capability of measuring and correcting the beta functions at each quadrupole. This beta correction is a standard part of the lattice loading procedure at CESR.

CONCLUSIONS

Chopper power supply regulators have demonstrated excellent performance and reliability during the 14 years of operating CESR. They are a very practical, efficient and cost effective solution for providing independent current regulation for a storage ring's linear and non-linear focussing elements.

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