A DC CHOPPER USED AS AN ADJUSTABLE CURRENT BYPASS SHUNT*

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Why Bypass Shunts?

When two or more magnets are operated in series from a common power supply, a shunt path that will bypass a fraction of the current around a magnet may be used when it is desired to make adjustments in the relative strength of magnets. One reason for using the bypass shunt rather than a separate power supply may be that it is generally less costly to purchase one large power supply than many smaller ones. Another reason may be that less stringent requirements will be imposed on power supply accuracy, because sometimes it is more important to maintain relative than absolute accuracy between magnets. An example is the case of a doublet consisting of a focusing and defocusing quadrupole of strength f_1 and f_2 separated by a distance d. For such a system the effective focal length is given by

$$f = \frac{f_1 f_2}{d + f_2 - f_1}$$

Because the denominator involves the difference between f_2 and f_1, the change in f as a result of a change in magnet current can be minimized if f_2 and f_1 track, i.e., their values change proportionately.

In a synchrotron machine of the separated function magnet type, if the quadrupole magnets can be made to change exactly together with the bending magnets, the result will be no shift in the betatron tunes, but only a shift in energy. In the SPEAR ring this feature is used to advantage. Selected groups of quadrupoles that have a particularly pronounced effect on the machine tunes were designed to operate at a current slightly less than the bending magnet current. These quadrupoles are then energized in series with the bending magnets, except for an adjustable current bypass shunt, capable of diverting up to 20% of the total current, as shown in Fig. 1. In preliminary calculations it had been

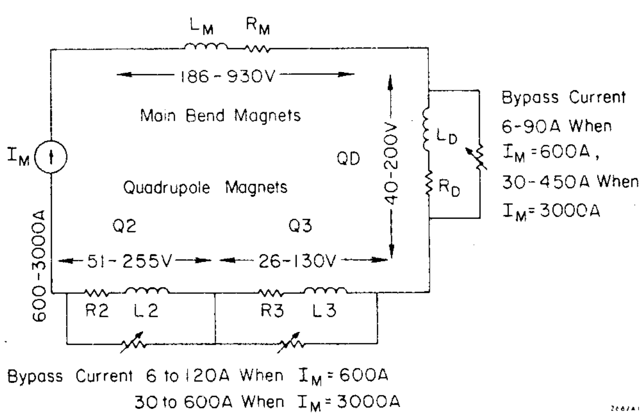

FIG. 1--Magnet current bypass shunts for SPEAR.

determined that if the bending magnet current remained unchanged, a change in current of 0.03% in the most sensitive group of quadrupoles could cause a tune shift of 1%.[1] Consequently, if the maximum bypass current did not exceed 20%, the precision with which this bypass current must track the bending magnet current could be roughly 5 times lower, or 0.15%. Thus it became a simpler problem to build one well regulated constant current power supply for the bending magnets together with reduced accuracy bypass shunts, than to build separate power supplies for each group of magnets, all kept to within 0.03% of each other.

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Types of Bypass Shunts

The simplest form of bypass shunt is a resistor in parallel with a magnet. If the temperature rise in the resistor and its temperature coefficient of resistance match those of the magnet that is bypassed, then the ratio between all currents will stay the same for slow changes in temperature and power supply voltage. This will not hold true however during transient changes in the circuit, unless also the inductance-resistance ratio of the bypass resistor matches that of the magnet. With such a resistor it is difficult to adjust the current, hence it is not very convenient or flexible.[2]

A continuously controllable bypass shunt may also be built using a transistor bank, in series maybe with a resistor, designed to work just as an ordinary constant current regulator. At SLAC such transistorized current bypass shunts are used, but have not been built for operating voltages above 50 volts and total power in excess of 5 kW. They were built to be controlled independently or to track a signal proportional to the main magnet current. Larger units that use many series-parallel connected transistors can be built reliably, but they are expensive and will on rare occasions fail catastrophically, requiring replacement of whole banks of transistors.

Another alternative is the use of a dc chopper, shown in elementary form in Fig. 2. It consists of a switch controlled

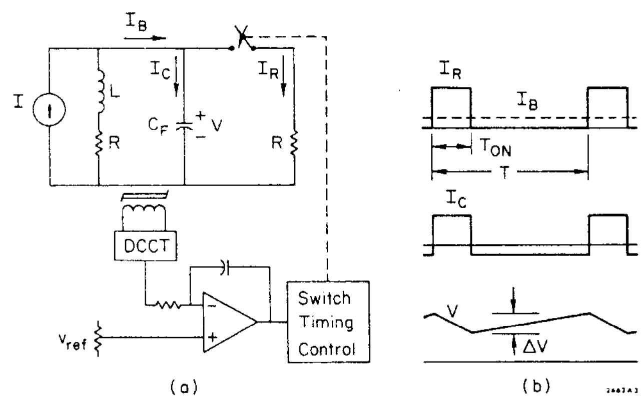

FIG. 2--(a) Elementary chopper and control circuit; (b) voltage and current waveforms.

in such a way that either the length of time the switch is held closed or the frequency of switch closures is varied. The filter capacitor C_F is necessary because the alternating current components in the rectangular current waveform in the chopper require a path other than a magnet with inductance. To increase the speed of response of the average current in the bypass shunt when the current reference is changed, the chopping frequency is made high and the capacitor C_F is kept as small as possible. The attractive feature of the chopper is that the power, rather than being dissipated in the active device or switch, is dissipated in the resistor. Low loss electronic switches can be built using switching power transistors or thyristors, with the latter being preferred for high current and voltage applications.

SPEAR Bypass Current Shunt Requirements

The main SPEAR magnet power supply system, shown in simplified form in Fig. 1, required three bypass shunts so that the current in each group of quadrupoles could be reduced to values 1 to 20% lower than the bending magnet current, for values of the latter between 600 and 3000 amperes. It was decided to build a chopper using thyristors, borrowing

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heavily from work already done in industry for this type of device.[3,4] Transistor banks, either as continuously controlled current amplifiers or as choppers were discarded because of the high voltage and current requirements.

To stay within the magnet field ripple tolerances and to cover the desired control range, a chopper operating in the fixed pulse width and variable frequency mode would have had to cover a minimum range of 50 to 1000 Hz. The main magnet power supply at SPEAR is a conventional 6 pulse rectifier supply with LC filter having 360 Hz ripple in the output, and with a measured regulator bandwidth of about 15 Hz. It appeared that there was a possibility of disturbing the main magnet power supply with beat frequencies that result from the difference between chopper and ripple frequency. It was not confirmed whether or not this problem was real, but it was judged prudent to rule out a variable frequency chopper in favor of a variable pulse width chopper, operated synchronous with the power line frequency.

The PWM Chopper

In a variable pulse width, or pulse width modulated (PWM) chopper, the switch is closed at a fixed repetition rate, and the average current that is passed is controlled by the length of time that the switch is held closed during each cycle.

It is generally desirable to use a high chopping frequency to improve system speed of response. A chopper that behaves effectively as though it were running at a higher frequency is shown in Fig. 3. The magnet circuit has been

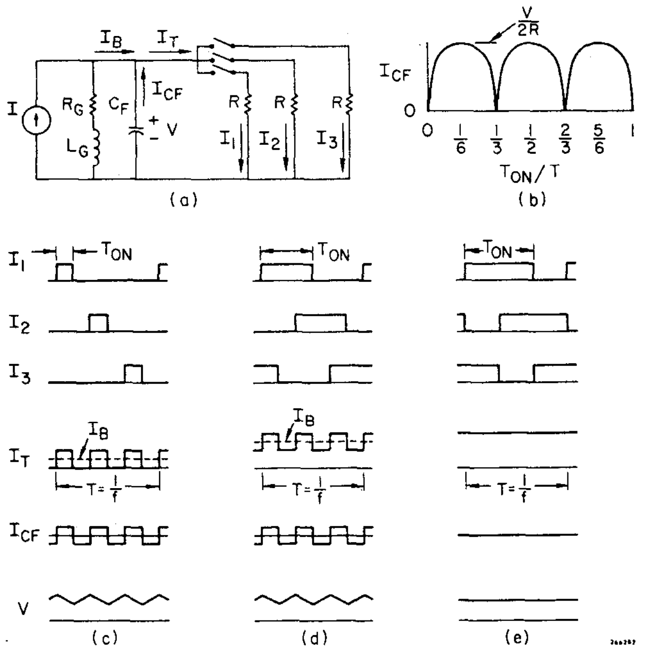

FIG. 3--(a) Idealized 3-phase chopper; (b) filter capacitor current; (c) $T_{ON}/T=1/6$; (d) $T_{ON}/T=1/2$; (e) $T_{ON}/T=2/3$.

simplified by replacing it with a current source I and a shunt impedance that includes resistance and inductance. Instead of a single chopper there are three choppers operating at the same frequency but displaced in time by 120 electrical degrees. An analysis of the current waveforms shown for this three-phase chopper leads to some generalizations about any PWM chopper consisting of n phases or branches shifted by 360/n degrees. Each resistor is now n times greater and the current in each branch n times smaller than it would be if a single chopper were used. The ripple frequency of the filter capacitor C_F current and voltage is n times the chopping frequency, and the amplitude of the ripple current is n times smaller. Furthermore, if it is assumed that the current in each phase is essentially of rectangular waveshape, then the ripple has maxima and minima. If T_{ON}/T is the fraction of time each switch is closed, then the rms value of the rectangular current in filter capacitor C_F is

$$I_{CF} = 0 \quad \text{for} \quad \frac{T_{ON}}{T} = \frac{0}{n}, \frac{1}{n}, \frac{2}{n} \cdots \frac{n}{n} \tag{1}$$

and has a maximum value of

$$I_{CF} = \frac{V}{2R} \quad \text{for} \quad \frac{T_{ON}}{T} = \frac{1}{2n}, \frac{3}{2n} \cdots \frac{2n-1}{2n} \tag{2}$$

where V is the average capacitor voltage.

The peak-to-peak voltage fluctuations of the capacitor voltage are computed from the currents, and are given by

$$\Delta V = \frac{1}{C_F} \frac{V}{2R} \frac{T}{2n} \tag{3}$$

where T is the duration of a full chopper cycle. Equations (2) and (3) give the design criteria for selecting the size and rating of filter capacitor C_F.

The following numerical example is from the PWM chopper bypass shunt built for the Q3 quadrupoles at SPEAR. A three-phase chopper was built rated 130 V, 600 A total or 200 A per phase, operated at 60 Hz. The resistors were chosen to be .5 ohm each. Thus T=16.7 ms, n=3, R=.5 ohm. Ripple frequency becomes 180 Hz. Equation (3) indicates that a filter capacitor $C_F = 50,000\,\mu f$ will keep $\Delta V/V < 0.06$. From (2) the capacitor current is $I_{CF} = 130$ A maximum, which occurs when $T_{ON}/T = 0.167$, 0.5, and 0.833. This is within the current rating of available electrolytic capacitors.

The Jones Chopper

The Jones chopper was chosen for this application because of its simplicity and its economy in parts. The particular variation that is shown in Fig. 4 simplifies mechanical assembly of a three-phase chopper in which the circuit of Fig. 4 must be repeated three times, because all nine thyristors and diodes can be mounted on a common heatsink.

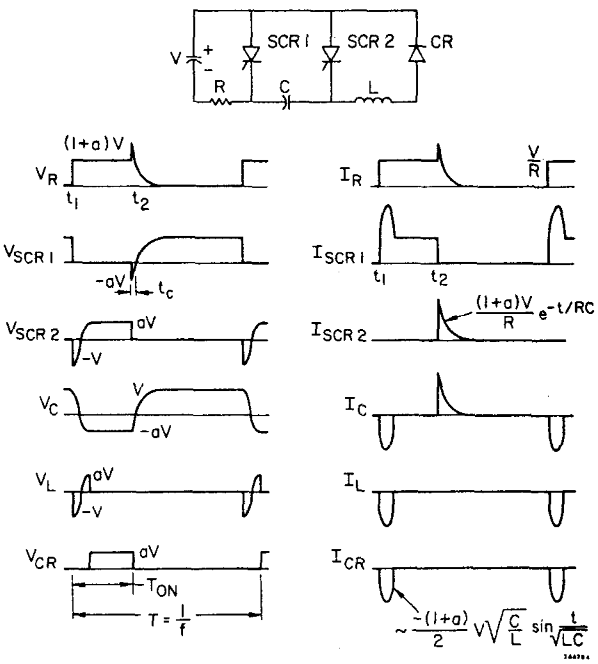

FIG. 4--Jones chopper.

An analysis of how the chopper works usually assumes that the voltage source V is fixed. We can make this assumption if the ripple voltage on filter capacitor C_F is small, and if the magnet time constant is such that within a reasonable number of cycles after the chopper is started, an equilibrium condition is reached in the division of current between magnet and bypass. With both SCR1 and SCR2 initially off, the circuit then works as follows. SCR2 is triggered first, and commutating capacitor C charges to V along an exponential determined by RC. SCR1 is triggered next, thus closing the switch. But turn-on of SCR1 also established a path that allows C to discharge through SCR1, L and CR, with a ringing frequency determined by $\sqrt{LC}$. Because of the diode the oscillation is stopped after just one-half cycle, and C is left with a charge of opposite polarity. The circuit is now ready so that the next time SCR2 is triggered, the full capacitor C voltage is applied across SCR1 long enough for SCR1 to turn off and recover its forward blocking characteristics. C recharges now once more to V. This terminates the current pulse through R, effectively opening the switch. The circuit is again ready to allow turn-on of SCR1.

The crucial problem in the design and operation of a chopper using thyristors is commutation failure, i.e., failure of SCR1 to turn off. When this happens C cannot recharge, and SCR1 stays on indefinitely. The only way to get the Jones chopper going again is to shut down the circuit in some other way, and start anew. The following are some guidelines for the design of a Jones chopper current bypass shunt, as they were developed for the SPEAR magnet power supply system.

Main Power Circuit Components

Included under this category are the load resistor R, thyristor SCR1, and filter capacitor C_F. The requirements for C_F were discussed earlier, with the assumption made that the current in C_F had a rectangular waveform. In the Jones chopper, even though C_F must also supply the short duration pulses required to recharge C, these contribute little to the current rating of C_F as determined from (2). High quality computer grade electrolytic capacitors can be used.

The resistor R in each branch of an n-phase chopper should have a value given by

$$R = \frac{nV}{I_B} \frac{T_{max}}{T} \left(1 - \frac{I_B}{I}\right) \qquad (4)$$

where I is the main circuit current, I_B the corresponding total bypass current, V the voltage across the bypassed magnet if there were no bypass current, and T_{max}/T the fraction of time each switch is closed for maximum pulse width. The latter can never be unity without causing commutation failure, but at least 0.9 should be attainable.

For the SPEAR bypass application the values of R thus determined were about 1 ohm and 50 kW in two cases, and 0.5 ohm and 25 kW in the other. A compact assembly of three resistors for each bypass shunt was built out of water cooled stainless steel tubing, wound into concentric coils about 0.4 m in diameter. Coupling between the coils was reduced by winding each coil back on itself, effectively making it a bifilar resistor. Inductive coils, as long as they do not couple to each other or cause other problems because of the pulsating currents, can still be used without harm if a freewheeling diode is placed across each resistor. Thyristor SCR1 must be rated to carry the maximum current in each branch of the chopper, which occurs at 100% conduction. Forward and reverse breakdown voltage ratings are V, plus a safety margin. The maximum reapplied forward voltage rate of change is $dv/dt = 2V/RC$. The maximum rate of current rise is V/L_s where L_s is stray inductance in R. A highly inductive load R with a freewheeling diode might increase di/dt, because at turn-on time the current rises almost instantaneously to the existing value of the load current. The only special requirement for SCR1 is that it should be a fast turn-off device. Thyristors rated 550 A and 600 V are available with turn-off times of 20 μs.

Commutating Circuit Components

Devices identified as C, L, SCR2 and CR are all considered part of the commutating circuit. The first of these, capacitor C, is selected on the basis of turn-off requirements for SCR1. During the time that SCR2 is conducting and SCR1 is being turned off, C starts out with a negative voltage aV, where a is positive and less than unity, and charges to V along an exponential determined by RC. The time for the voltage on C to become zero is t_c, which must be greater than SCR1 turn-off time. Minimum size of C is thus given by

$$C = \frac{t_c}{R\,\ln(1+a)} > \frac{t_c}{0.69R} \quad \text{for } 0 < a < 1 \qquad (5)$$

In order to keep the size of C small, SCR1 must be a fast turn-off device, and a must be close to unity. The latter is accomplished if L, C, and CR, which are involved in charging C to -aV, have low losses. Particularly C should be a high grade commutating capacitor with low series resistance. In any case, C will probably have to be 3 to 4 times greater than calculated from (5) for reliable turn-off. The reason for this goes back to the assumption of a fixed voltage source V, and to a reduction in a when the chopper must operate with low supply voltage V.

The rating of SCR2 is critical only in that it must withstand high values of di/dt, limited only by stray inductance in the path comprised by C, SCR1 and SCR2. Voltage rating of SCR2 is V.

Selection of L will establish the minimum chopper pulse width, because turn-off of SCR1 cannot begin until after the voltage on C, which was V when SCR1 was triggered, reverses and becomes -aV. The duration of the half-cycle oscillation for voltage reversal on C, and hence the minimum chopper pulse width, is

$$T_{min} = \pi\sqrt{LC} \qquad (6)$$

The peak value of the half sinewave current pulse in L and CR is approximately

$$I_{CR}(\text{peak}) = \frac{1+a}{2} V \sqrt{\frac{C}{L}} \qquad (7)$$

The specified value of minimum bypass current will determine what T_{min} should be. The average current in one branch of an n-phase chopper is

$$I_R = \frac{V}{R} \frac{T_{ON}}{T} + \frac{(1+a)VC}{T} \qquad (8)$$

which for $I_R = I_{B\,min}/n$ and $T_{ON} = T_{min}$ gives

$$T_{min} = \frac{I_{B\,min} RT}{nV} - (1+a)\,RC \qquad (9)$$

The current rating of C and its associated cabling can now be calculated. If the pulse currents in C are short compared to a full chopper cycle, then the rms value of I_C is approximately

$$I_C = V \frac{(1+a)}{2} \left[\frac{C}{T}\left(\frac{2}{R} + \frac{\pi}{2}\sqrt{\frac{C}{L}}\right)\right]^{\frac{1}{2}} \qquad (10)$$

The chopper bypass for the SPEAR Q3 quadrupoles serves as a numerical illustration. $V = 130$ V, $I = 3000$ A, $I_{B\,min} = 30$ A, $C_F = 50{,}000$ μf, $R = 0.5$ ohm, $n = 3$. From (5), for $a = 0.6$ and SCR1 turn-off time of 20 μs, $C > 85$ μf; $C = 300$ μf was chosen. From (9), $T_{min} < 400$ μs; $T_{min} = 175$ μs was chosen, giving $L = 10$ μH from (6), and $I_{CR} = 560$ A from (7). From (10), $I_C = 50$ A.

An iron core inductance L can be used. The required number of turns N for a core of area A and peak flux B_m (all in MKS units) is

$$N = \frac{L\,I_{CR}}{B_m A} = \frac{1+a}{2} V \frac{\sqrt{LC}}{B_m A} \qquad (11)$$

The core should be provided with an air gap of total length ℓ, calculated from

$$L = \mu_0 N^2 A/\ell \qquad (12)$$

The inductors used in the choppers for SPEAR were made of 4 mil laminated C cores, $A = 2\ in^2$, two 1/8 in gaps, and 6 turns of #4 wire. The inductance calculated from (12) is $L = 9.2\ \mu h$, and peak flux B_m is below saturation in all cases.

An RC snubber network may be necessary across CR if a fast recovery diode is not used. None was required for the SPEAR choppers, although 0.5 ohm and 0.2 microfarads were placed across the cathodes of SCR1 and SCR2 because of stray inductance in the leads of C.

Trigger Generator

Since it was decided to operate the chopper in synchronism with the power line, a system was developed in which the timing for the start pulses that fire SCR1 in each of the three phases is fixed by detecting the zero crossing of the voltage waveforms of an incoming 120/208 V, 60 Hz, three phase system. The chopper pulse width, and hence the time delay for the stop pulses that fire each SCR2 was controlled electronically by comparing a 60 Hz ramp with a dc control signal. Special features included in the trigger generator were minimum and maximum delay times for the stop pulses, set for about 250 microseconds and 16 milliseconds respectively. This was necessary because exceeding either limit can result in failure to commutate, i.e., failure of SCR1 to turn off because capacitor C had not yet charged to the appropriate voltage. Another feature was suppression of the start pulses to SCR1 for low power supply voltages. Because components such as thyristors and diodes have approximately fixed voltage drops, the supply voltage must be at least high enough so that thyristor and diode voltage drops and losses become relatively small, otherwise the final voltage aV on capacitor C will be insufficient to turn off SCR1. It was found that the chopper built for SPEAR did not work very well when the voltage across it was less than about 20 volts. Firing pulses to SCR2 are not suppressed, with the result that the voltage on the commutating capacitor is maintained, and the circuit is ready for operation whenever pulses to SCR1 are initiated.

The Chopper in a Feedback System

Calculation of the static gain of a chopper, useful in evaluating the steady state performance of a feedback loop (Fig. 2), is straightforward. For a trigger generator that uses a linear ramp to generate the time delay, a constant K (s/V) relates T_{ON} to some input voltage V_i. Thus from Eq. (8) the change in the average steady-state total bypass current ΔI_R or ΔI_B for an input voltage change ΔV_i is

$$\Delta I_B = n\Delta I_R = \frac{nVK}{RT}\ \Delta V_i \qquad (13)$$

Equation (13) indicates that the static gain is not constant, but increases with V which in turn increases with I.

Development of a transfer function that describes the transient circuit behavior is more difficult, and beyond the scope of this paper. A linear expression using Laplace transforms is not readily derived, not only because of the chopper action, but also because the supply voltage V is time dependent.

For the chopper bypass shunts used in SPEAR a simple integrator amplifier was used in the regulator (Fig. 2) such that the measured open loop system gain was unity at about 7 Hz. The cutoff frequency was fixed by the resonance of the circuit made up of L_G, R_G and C_F, which also occurs at about 7 Hz. Thus although the static accuracy of the regulator was made extremely high, speed of response and transient accuracy are limited.

Other Thyristor Chopper Circuits

There are several variations of the simple Jones chopper discussed in this paper, most of which aim at making commutating capacitor C smaller. Equation (5) shows that if the constant a which defines the negative voltage on C at the start of commutation can be made close to or even greater than unity, then C can be made smaller. For the same minimum pulse width, Eq. (6) shows that L can now be larger, and from (7), (9) and (10) that I_{CR}, $I_{B\,min}$, and I_c will perhaps also decrease. On the other hand, the voltage rating of all components will increase if $a > 1$.

In one such variation some inductance is intentionally added in series with each switch. In another variation[3] inductor L is replaced with a transformer. In both cases CR is replaced with a third thyristor SCR3, triggered at the same instant as SCR1. This is necessary if the voltage to which C is charged after firing SCR2 is greater than V, and is to remain at that value rather than discharge through a path formed by C, V, R, CR and L. In another variation[4] series inductance is also added to the switch and CR is replaced with SCR3, but the branch that contains L and CR in Fig. 4 is moved to a position directly across C. If a separate trigger is used for SCR3, occurring at least $\pi\sqrt{LC}$ seconds before SCR1 is fired, then it is possible to reduce T_{min} in Eq. (9) to zero so that for this case the minimum total bypass becomes

$$I_{B\,min} = (1+a)\,nVC/T \qquad (14)$$

Other thyristor chopper circuits have been designed (5) that offer unique features desirable in some applications. One such possibility, not considered here, involves the use of an external commutating voltage source to allow operation of the chopper at supply voltages V near zero. The value of any circuit complication must be weighed in terms of the additional cost, increased speed, and more reliable thyristor commutation.

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