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A BIPOLAR, HIGH PRECISION, LOW RIPPLE POWER SUPPLY

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Summary

A ±600 V, ±50 Amp high precision SCR power supply has been developed for use in the Energy Doubler Correction system. The bipolar output is accomplished by means of a dual converter with circulating current for smooth zero-crossing current transitions. Absolute accuracy better than ±.025% is achieved with a high precision transductor, current reference, and other high quality components. Stability is better than 2.5 ppm/°C and voltage ripple is less than 30 mV peak to peak. Low ripple is achieved through the use of bipolar series-pass transistor bank. The dual converter (plus a passive filter) acts as a pre-regulator for the transistor bank, which has a dynamic range of 30 volts. Ripple attenuation of the transistor bank is a minimum of 60 dB from DC to 2 kHz. Microvolt level noise and pickup in the power supply regulator ultimately set the ripple level in the power supply output. A special "active ground" circuit is included to filter the common mode ripple which is inherent in SCR supplies.

Introduction

The Fermilab Energy Doubler High Order Correction Element System has eleven series strings of magnets. The strings are made up of either quadrupole, sextupole, or octupole elements and range in length from 4 to 90 magnets. Different correction elements have differing accuracy requirements. Thus, there are a variety of power supply requirements. The approach we have taken is to design one power supply to meet the most stringent requirements. Except for transformer tap changes and minor compensating circuit changes, that power supply is used for all the different loads.

The most difficult requirement to meet is the low ripple required by the quadrupole circuits. From phase space considerations as related to slow extraction, it can be shown that the maximum peak ripple current, ΔI should be:

$$\Delta I \text{ (amps)} = 50 \times 10^{-5}/f \text{ (Hz)} \qquad (1)$$

to limit beam modulation to 10%.[1] The ripple voltage dictated by equation 1 is 120 mV peak for the 41 henry tune quad load. Design of the power supply system is strongly influenced by the magnet current ripple requirement.

The design approach taken for the power supply is shown in Figure 1.

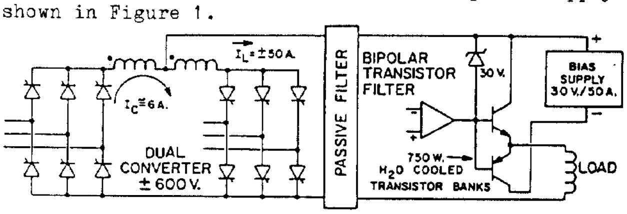

FIGURE 1 - Power Supply with Transistor Filter

An SCR dual converter (D/C) is used as a pre-regulator for a bipolar transistor voltage regulator/filter. The dual converter has been described in detail in reference 2. The active filter approach to ripple reduction described in reference 2 has been changed to a series pass approach due to the relatively poor transient response encountered with the active filter. In addition to better transient response, the newer approach provides a factor of 15 lower ripple than the active filter. For purposes of discussion, the remainder of this paper deals mainly with the high precision power supply as applied to the tune quadrupole circuit. The load consists of 90 magnets with an inductance of .455 H each distributed over 4 miles with a folded bus structure. The power supply is rated for ±600 V at ±50 A DC.

Power Supply Performance

In the Doubler Correction Element system, the stability of the power supply is more important than absolute accuracy. Both characteristics are determined primarily by the 1) high precision transductor (DCCT), 2) waveform generator (analog reference), and 3) resistors and op amps in the front end of the current regulator. Table 1 shows the contribution of each of these factors to the overall system performance.

FACTOR	ABSOLUTE ACCURACY		STABILITY	
	OFFSET	GAIN	OFFSET	GAIN
TRANSDUCTOR	*±10ppm of F.S.	*±100ppm	*±.6ppm of F.S/C°	*±1ppm/C°
WAVEFORM GENERATOR	†0	*±50ppm	*±.2ppm of F.S/C°	*±.77ppm/C°
RESISTORS	0	±50ppm	0	±.6ppm/C°
OP-AMPS (OP-07EZ)	±15ppm of F.S.	1ppm	±.1ppm/C°	0

* = MEASURED † = ADJUSTED TO 0

Table 1 - Offset and Gain Errors for Power Supply

Thirteen high precision transductors rated at ±50 Amps were purchased from Holec of Holland for the correction power supplies. The offset TEMPCO's were measured and found to vary between .1 and .6 ppm/°C while the gain TEMPCO's varied from .1 to 1 ppm/°C. All units met the manufacturer's specifications. However, the better units with .1 to .2 ppm/°C TEMPCO's will be used in the most critical circuits. The waveform generator specifications are discussed in another conference paper. Precision Vishay resistor networks, type 300144C (absolute tolerance ±.01%, matching ±.001% and tracking ±.2 ppm/°C) are used in all critical locations. Only the network matching affects the accuracy and stability of the system. High quality op-amps, PMI OP-07EZ in ceramic packages are used throughout the current regulator.

The current loop response is determined primarily by the power supply compensating circuits, passive filter, and load. One compensating circuit completely compensates for the passive filter characteristics at the frequencies of interest. Another compensates for the eddy current effect in the load magnets.

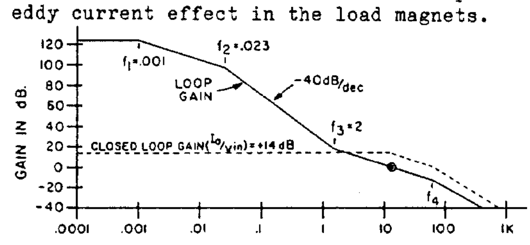

FIGURE 2 - Current Loop Frequency Response

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Figure 2 shows the Bode plots of the pertinent factors which characterize the system. The open loop gain crosses 0 dB at about 12 Hz resulting in a power supply rolloff at 12 Hz. A high frequency rolloff at f_4 helps to quickly decrease the gain at higher frequencies and thus reduce noise problems. The lag-lead network formed by the corners at f_2 and f_3 results in increased gain below f_3 but more importantly, improves the response of the power supply during a ramp. The difference between the analog reference signal and the output current is reduced by the ratio of the frequencies f_3/f_2. For a ramp of +5 A/sec, the steady-state difference between the input and output signals would be 66 mA without the lag-lead network and only .76 mA with the network. Low output ripple is achieved by means of the transistor filter and active ground.

The Transistor Filter

To filter a broad band of ripple frequencies (15 Hz → 1440 Hz) we use a series-pass transistor bank as a voltage regulator, with the Dual Converter acting as a pre-regulator. The Dual Converter tracks the transistor output, supplying an average collector voltage of 15 volts. The tracking is done through a combination of dead-reckoned matching and slow, corrective feedback.

Use of a pre-regulator and transistor bank is a standard approach in many medium-power regulated supplies. The more novel aspects of this transistor bank stem from two requirements it must satisfy: 1) the transistor output must vary over a ±600 volt range, and 2) it must conduct current in both directions.

Coping with High Voltage
The Transistor Drive Reference

Two competing methods of controlling the transistor bank are diagrammed in Figure 4. In part A, the op-amp controlling the transistor is referenced to the negative D/C terminal, as is standard in most supplies. In our application, however, this op-amp would need an output range of ±600 V, and an output current of 10 mA. Such devices are not yet commercially available, which leads us to consider circuit B. Here the op-amp is referenced to the positive D/C terminal and needs an output range of only 30 volts. All high-potential differences in this circuit are spanned by standard iso op-amps.

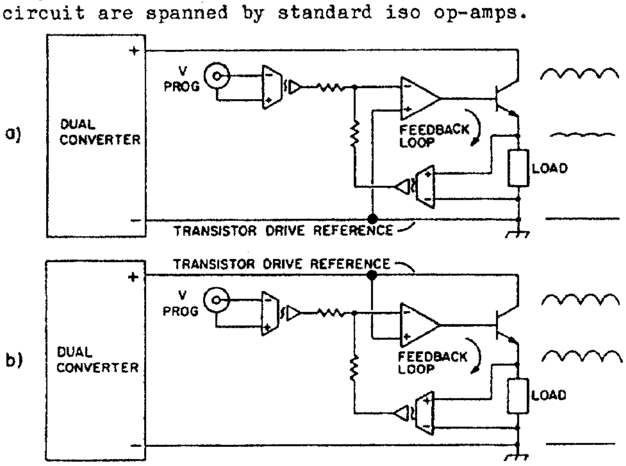

FIGURE 4 - A Tale of Two Circuits

This configuration solves the voltage problem, but it has one drawback: as it stands, circuit B has significantly less filtering capability than circuit A. Both circuits attenuate Dual Converter ripple by an amount equal to their loop gains at the ripple frequency, but if you imagine the loop gains to be zero at a particular frequency, circuit A still attenuates ripple while circuit B does not. At zero gain, the op-amp holds the transistor base voltage flat with respect to the op-amp reference. The waveforms in Figure 4 show that the circuit B reference imposes the full D/C ripple across the load, whereas the circuit A reference holds the base voltage steady. An attenuated ripple appears on the load in circuit A due to the imperfect collector-isolation of the transistor bank.

Recovering the Extra Filtering - The Bucker Signal

The extra filtering capacity can be recovered in circuit B by the use of a "bucker signal" which directs the transistor bank to do whatever the D/C negative terminal is doing, thus cancelling the ripple across the load. Figure 5 shows the addition of this signal to the system. It may seem as if the bucker signal inhibits the load voltage from changing at all, but as long as the op-amps have enough range for the feedback signal to overcome the bucker contribution, the normal response to control signals is maintained.

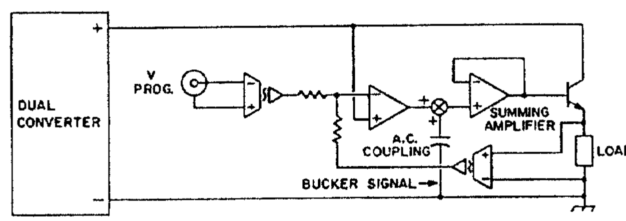

FIGURE 5 - The Bucker Signal

Ripple that gets through the bucker is further attenuated by the normal feedback process. In our system the feedback gain - BW product is 30 kHz. Figure 6 shows the ripple attenuation achieved by the feedback loop, the bucker signal, and the combination of both.

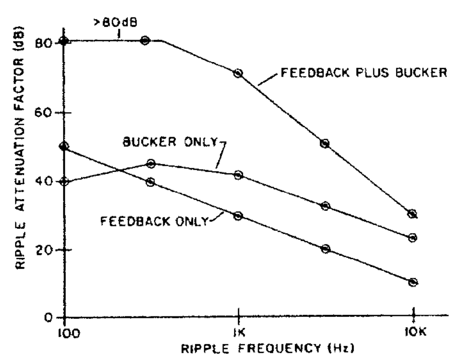

FIGURE 6 - Transistor Filter Ripple Attenuation

Bipolar Operation

To allow the transistor regulator to conduct current in both directions, we added a complimentary

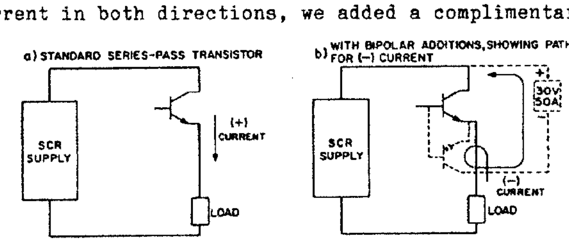

FIGURE 7 - The Bipolar Series-Pass Transistor Filter

transistor bank and a 30 V/50 A bias supply to keep the complimentary bank in its operating region.

Figure 7 shows an ordinary series-pass regulator and the bipolar unit. In the bipolar unit, positive current goes through the NPN bank in the normal fashion. Negative current flows through the PNP bank and the bias supply as shown. The filtering action and the control circuits of the transistor bank are unaffected by the addition of the bipolar circuitry.

Ripple improvement due to the transistor filter can be seen in Figure 8. At the maximum output ripple point (V_0 = 175 V DC), the ripple from the dual converter is 350 P-P.

D/C Output
500 V/div
2 ms/div
Passive Filter
Output 5 V/div
2 ms/div
Transistor Filter
Output 30 mV/div
10 ms/div

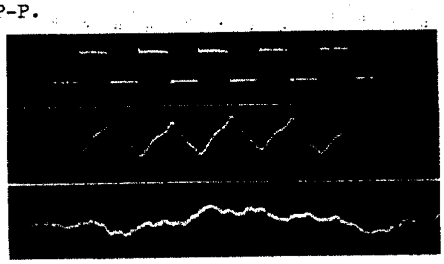

FIGURE 8 - Power Supply Ripple

After the passive filter, the ripple is reduced to 4 V P-P. The transistor filter further reduces the ripple to 30 mV P-P, which meets the requirement of equation 1. The small output ripple that remains is due to microvolt pickup at 60 Hz from the power section and 1/f op amp noise, both in the current regulator.

Common-Mode Ripple

In order to minimize potential magnet insulation breakdown problems, the power supply/load system is floated, with 10kΩ resistors to ground at both P. S. terminals centering the voltage distribution about ground level. In the absence of a firm ground point, power supply common-mode ripple voltage comes into play. Although the differential ripple has been reduced to 30 mV, the common-mode voltage on both P. S. terminals is 150 V P-P, with a 180 Hz repetition rate. This amount of ripple applied to a load with transmission-line characteristics creates common-mode currents, so extra circuitry is needed to eliminate the problem.

The Source of Common-Mode Ripple

We were surprised by the magnitude of the common-mode voltage on a power supply that seemed virtually symmetrical. The mechanism may be of interest, since it applies to many SCR power supplies. Figure 9 shows a 3-phase bridge converter with a symmetrical passive filter.

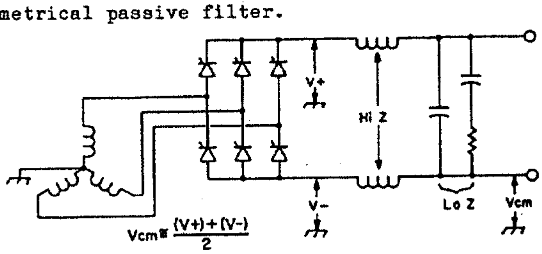

FIGURE 9 - The Source of Common Mode Voltage

For purposes of discussion, the transformer secondary neutral has been grounded. At ripple frequencies, the impedances of the filter system are such that it acts very much like an averaging circuit: the common-mode voltage (Vcm) is the average of V+ and V- terminals with respect to ground. Whenever an SCR on the upper bank fires, V+ jumps up and V- is unchanged. Vcm jumps up by 1/2 the V+ step. The opposite step occurs when a negative bank SCR triggers. In practical circuits the transformer secondary is rarely deliberately grounded, but it is always grounded by the transformer capacitance. A differentiated common-mode signal results, whose amplitude and shape are determined by the voltage-dividing effect of the transformer capacitance and the impedance-to-ground at the output terminals.

The Dual Converter transformer capacitance is approximately 40 nf. In lieu of grounding one of the P. S. terminals, the application of approximately 1 mf to ground is the next best way to reduce common-mode ripple to the mV level and still allow the power supply to float. To maintain balanced voltage-to-ground distribution during ramping, 500 µf should be placed on each P. S. terminal. Unfortunately, this would place 250 µf across the load and destabilize the transistor regulator.

The "Active Ground" Circuit

Our response to this situation has been to ground the negative terminal through an "active ground" circuit, which is a 1 µf capacitor amplified by an op-amp to look like 1000 µf. Figure 10 shows the essence of the active ground circuit.

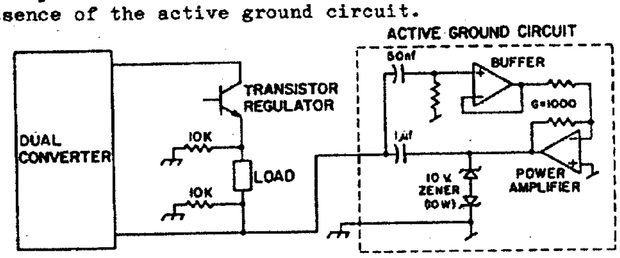

FIGURE 10 - The Active Ground

At ripple frequencies, the capacitor acts like a 1000 µf cap. At lower frequencies or for large voltage swings it is only 1 µf, and does not upset the voltage-to-ground symmetry during ramping.

Conclusion

We feel that the power supply configuration we have developed (Dual Converter with circulating current plus bipolar transistor regulator) is well suited to the requirements of the Correction Element system, and might be of use in similar applications. It combines the power capability of SCR supplies with transistor-like voltage quality, and has inherently smooth 4-quadrant operation. As we enter the operational phase, we expect the high-quality instrumentation components to result in precise, current control.

References

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