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A FOUR QUADRANT MAGNET POWER SUPPLY FOR SUPERCONDUCTING AND CONVENTIONAL ACCELERATOR APPLICATIONS

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SUMMARY

Modern conventional and superconducting accelerators often require bipolar power supplies capable of operating with high precision from zero to full output. An SCR type power supply comprised of two SCR bridges and operating with circulating current does an excellent job of satisfying this difficult requirement. Power supplies of this type are often called four-quadrant or dual converter power supplies with circulating current. The basic principles and design considerations of this converter are discussed with particular emphasis on the advantages of the converter. Application of the dual converter to high precision bipolar magnet current control within the Fermilab Saver/Doubler project is presented.

INTRODUCTION

A four quadrant power supply is a power supply which can supply a bipolar output voltage and source or sink current with either output polarity, thus supplying or sinking energy. One application of a four-quadrant supply is to trim (increase or decrease) the current in one or more elements of a series connection of magnets as shown in Figure 1. The trim supply tries to drive the remaining magnets in the series connection. However, as long as the main supply is current regulated, the main supply current cannot change and the trim supply only affects the current through the element to which it is connected. In this application the power supply and power cables must be protected in the event of a power supply failure. For example, if the trim supply uses SCR bridges and if 1) an SCR fails to commutate or 2) AC power to the supply is lost, a short circuit through the supply will occur and the main power supply current will attempt to bypass the magnet being trimmed by passing through the trim supply. To prevent this, the power supply disconnect switch must be opened and an alternate path provided for the trim supply current.

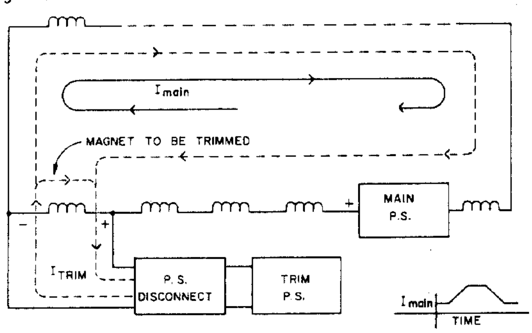

FIGURE 1 - Four Quadrant Power Supply Application

Another application is a bipolar power supply with a voltage range from 0 to full output. Accelerator correction magnet systems ofter require this type of supply.

Various approaches are often taken to these power supply designs for different voltage and current requirements. For low voltage and low current applications, a transistorized supply is usually used.

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For higher voltage and power applications, SCR bridge circuits become more practical. When energy is to be absorbed by the supply, the SCR's operate in the invert mode and feed power back into the AC mains rather than dissipate power within the supply. Since a number of Energy Saver applications require low band-width, high voltage supplies, ±480v at ±50A, the SCR approach was chosen.

BASIC PRINCIPLES

A generalized dual converter shown in Figure 2 is comprised of 2 cross-coupled SCR bridge converters each capable of operating as a rectifier or an interter. One converter is arbitrarily called the positive converter and the other called the negative converter. The positive converter supports positive load current, while the negative converter supports negative load current. Combining the outputs of the 2 converters provides four-quadrant operation of the power supply.

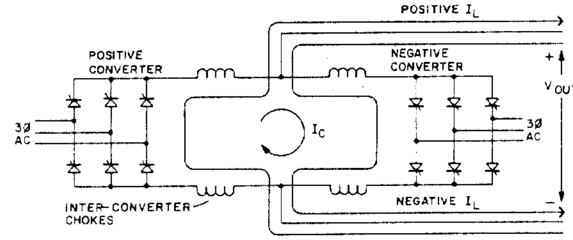

FIGURE 2 - Generalized Dual Converter

The dual converter in Figure 2 is commonly operated in two different modes: 1) the non-circulating current mode and 2) the circulating current mode. In the non-circulating current mode, only one SCR converter operates at a time with the gating pulses blocked to the other converter. When a current reversal is required, a logic system detects the load current reaching zero, blocks the converter which was conducting and then after an appropriate delay, unblocks the other converter. In the non-circulating current mode, the inter-converter chokes shown in Figure 2 are not required. With the circulating current mode, both the positive and negative converters operate simultaneously. The firing angles of the two converters are controlled so that the average voltage at the output of each converter is essentially the same. Equal output voltage is accomplished by setting the positive converter firing angle, α_p, and the negative converter firing angle, α_n so that $\alpha_p + \alpha_n = 180°$. Thus at all times one converter is acting as an inverter and the other as a rectifier. Although the average converter voltages are the same, instantaneous voltage differences exist which can drive large AC currents between the converters. To limit the AC current which would flow, chokes are placed between the converters. Sufficient average current is allowed to flow between the converters to keep the instantaneous circulating current always greater than zero. Thus, both converters are kept in conduction for all output levels including zero.

One important advantage to having circulating current is that the power circuit has a natural freedom for current to flow in either direction at anytime. A load current reversal is an inherently smooth process, not dependent on control systems to detect the load current and block or unblock the power circuits. The

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load current does not have glitches and the power supply does not have dead-bands, as with non-circulating current operation. A second advantage in some cases is that a dual converter with circulating current generally has less output ripple than a single converter. This is particularly noticeable at zero output voltage where the converter with circulating current has zero output ripple while the converter without circulating current has maximum output ripple. Figure 3 shows pertinent dual converter waveforms at various firing angles. The positive or negative converter waveform is the converter output waveform which would be present in the non-circulating current mode. Figure 4 shows more graphically how the fundamental harmonic in the output waveform of a dual converter with circulating current compares to a single converter versus firing angle.[1] The same type of pattern with more humps occurs for all higher harmonics. A third benefit from the circulating

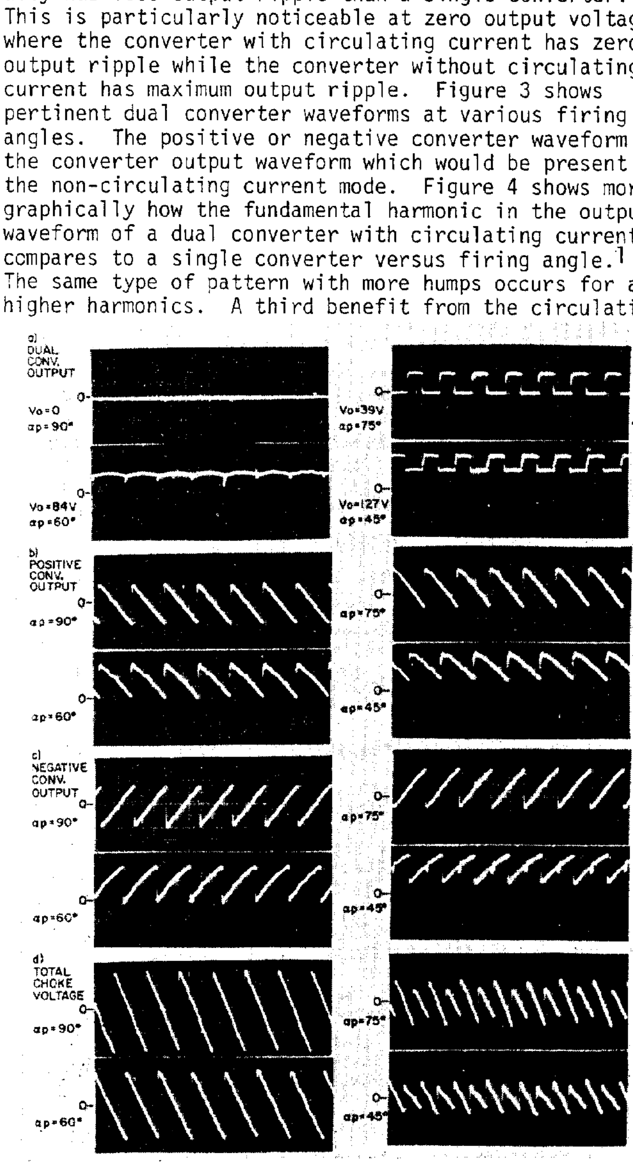

FIGURE 3 - Dual Converter Waveforms, 100V/Div, 2ms/Div

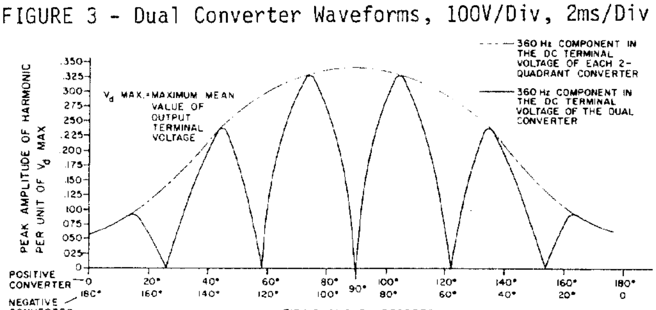

FIGURE 4-Comparison of Dual and Single Converter Ripple

current mode of operation is that the transfer function between firing angle and mean DC terminal voltage is a simple cosine function. Thus, a perfectly linear transfer function between input control voltage and DC output voltage can be readily obtained. The disadvantages of operating with circulating current are that additional chokes are required between the two converters and an additional regulator is needed to control the circulating current. Nevertheless, this mode was chosen for several of the Saver/Doubler correction element power supplies because of the advantages mentioned and the relative ease of operating with circulating current.

DESIGN CONSIDERATIONS

The three-phase power connections to the 2 converters shown in Figure 2 can be obtained from separate but identical secondaries of a common transformer or from a common secondary winding of a single transformer. For these two approaches, the SCR timing signals, the individual converter output waveforms, and dual converter output waveforms are identical. However, there are significant differences. With common secondary windings for the two converters, inter-converter chokes are required in both the upper and lower inter-converter connections as shown in Figure 2. The chokes are required to prevent shorting the transformer secondary due to SCR's which are simultaneously conducting in the positive and negative converters. Another, more subtle difference also exists. The amount of circulating current between the converters is related to the instantaneous voltage across the inter-converter chokes and the inductance of the chokes. It can be shown that with a common secondary, the maximum volt-time integral applied to the upper and lower inter-converter chokes is approximately 3.5 times larger than the maximum for separate secondary windings.[4] Since it is important to minimize the circulating current to minimize losses, the chokes for the single secondary design should have 3.5 times the inductance of the dual secondary design to have equivalent ripple current. However, a simple comparison of inter-converter choke size is not adequate since the dual secondary transformer is obviously larger. In a design exercise for a 4KW dual converter, it was found that the magnetics materials cost and weight for the single secondary design was larger than that for a comparable dual secondary design.[4] Thus primarily because of the weight advantage, the dual secondary design was chosen. As a result, chokes are only required in one connection between the converters as shown in Figure 5.

Several design options exist for the inter-converter chokes. Two separate chokes or one pair of coupled chokes as seen in Figure 5 can be used. The dual converter performs differently if coupled or uncoupled chokes are used. With two separate but equal chokes, where $L_1=L_2=L$, the output impedance of the converter is L/2 and the inter-converter inductance to limit ripple current is 2L. With a coupled choke, having aiding mmf's the output impedance is zero and the inter-converter inductance to limit ripple current is 4L due to the mutual inductance of the coils. Thus, the coupled choke is more effective reducing the ripple current between the converters which lowers the required circulating current to keep both converters operating. Furthermore, the coupled choke results in a smaller overall choke design since the total magnetic structure

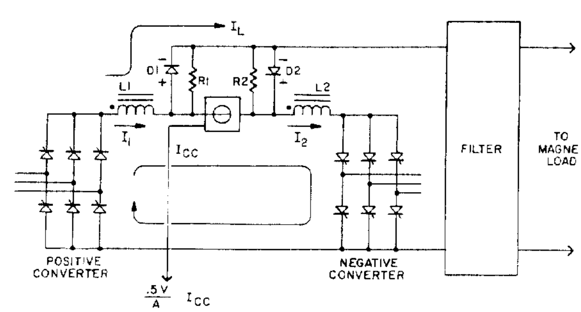

FIGURE 5 - Dual Converter with Coupled Chokes

need only be sized for $I_L(\max)+2I_{cc}$ instead of $2I_L(\max)+2I_{cc}$.

The third design factor considered is how to measure the circulating current. The simplest way, which is shown in Figure 5, is to place a current transducer between the converters and add diodes to shunt the load current around the transducer. To insure clean current reversals when load current changes diodes, small resistors (5Ω) are placed in parallel with each diode. When positive load current exists, as in Figure 5, diode D1 handles most of the load current while each resistor passes about .2A flowing through R_2 and the circulating current transducer introduces a negligible .2A error in the circulating current regulator. Control of the circulating current is obtained by retarding slightly all of the firing angles in the positive converter with respect to the negative converter. Reference 4 covers operation of the circulating current regulator in greater detail.

DUAL CONVERTER FILTERING

The superconducting load inductances in the Energy Saver/Doubler for the dual converters range from 2H to 45H. Nevertheless, substantial filtering of the converter output must be done to meet the very tight current ripple requirements. Ripple in the power supply output is caused by the following factors in the order of their significance: 1) switching nature of the SCR-type power supply, 2) transformer imbalance, 3) firing circuit imbalance, and 4) modulation at 15Hz of the 3-phase power line by the Fermilab booster accelerator. The converter inherently has strong harmonics at multiples of 360Hz. These harmonics are modulated by factors 2, 3 and 4 to form a complex spectrum. The 360 and 720Hz components are initially reduced by a passive filter with tuned traps as shown in Figure 6. Subsequent filtering to these harmonics

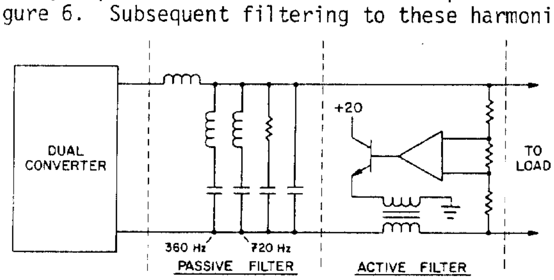

FIGURE 6 - Dual Converter Filtering

is done by an active filter. Small amounts of transformer imbalance introduce harmonics at multiples of 120 Hz which modulate all the inherent harmonics in the converter output. Small firing circuit errors result harmonics of 60Hz which again modulate the inherent ripple components in the converter output. Thus, all harmonics of 120 and 60Hz can appear in the converter output due to transformer and firing circuit imbalance.

Reduction of the output harmonics at multiples of 60 and 120Hz are handled in a similar manner. First within the power supply itself, tuned circuits at 60 and 120Hz form a voltage feedback loop which reduces some of the imbalance errors. Approximately 20db attenuation of the 60Hz components is achieved in this manner. Reference 2 describes this technique in more detail. For further attenuation of the 60 and 120Hz an active filter is used. Figure 6 shows an active filter in a very simplified form. The converter output ripple voltage is sensed by means of a resistor divider and fed to a number of notch filters which are tuned to the harmonics which are to be removed. The outputs of the notch filters are summed and amplified by a transistor amplifier which drives the primary of a transformer. The transformer is connected into the output in such a way as to buck-out the ripple seen at the load. Substantial reduction in ripple harmonics can be achieved rather easily in this way.[3]

In addition to the ripple factors already discussed, modulation of the power line by the Fermi Booster Accelerator introduces low frequency ripple which becomes a problem in critical applications. The Booster which runs at 15Hz introduces line components at multiples of 15Hz. These components modulate the inherent ripple components resulting in output harmonics such as 345 and 375Hz. The most troublesome components are the 15 and 30Hz components since they are relatively large and low in frequency. Reducing the Booster harmonics with the active filter would compromise the performance of the active filter. Passive filtering is impractical. Therefore, tuned voltage feedback circuits are used within the dual converter. With amplifiers tuned to 15, 50, and 45Hz, these harmonics are essentially removed from the output waveform in the same way some of the 60Hz is removed.

The results of the three types of ripple reduction used with the dual converter is shown in Figure 7. The

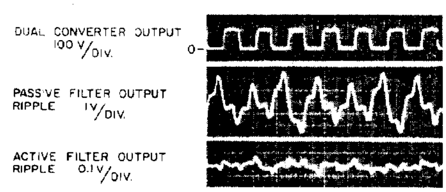

FIGURE 7 - Dual Converter Filter Waveforms

raw output of the dual converter is shown in Figure 7a at the point where ripple is the highest, $\alpha\rho=75^\circ$, v_o = 80V peak-to-peak. After the passive filter, the ripple is reduced to about 2V peak-to-peak. The active filter further reduces the output ripple to about 70mv peak-to-peak which meets the needs for the Energy Saver/Coubler Correction element system.

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