Fermi National Accelerator Laboratory

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Four Quadrant 250KW Switchmode Power Supply for Fermilab Main Injector

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FOUR QUADRANT 250KW SWITCHMODE POWER SUPPLY FOR FERMILAB❶ MAIN INJECTOR

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Abstract

A +/-700 volt,+/-350 amp switchmode power supply has been developed for Fermilab Main Injector Sextupole Correction System. The four quadrant operation is accomplished by using four IGBTs in an H-bridge configuration with a switching frequency of 10 KHz. Current regulation bandwidth of 300 Hz is achieved with stability better than 250 ppm of rated current by using a high precision current transducer. The H-bridge outputs are filtered resulting in a maximum output voltage ripple of 2.5 volts peak to peak. The power supply has power conversion efficiency better than 80% and works at near unity power factor throughout its operation. The critical considerations involved in this power supply are low inductance bus plate and snubber design, selection and thermal management of IGBTs, IGBT gate drive, PWM output filtering, and fiber optic controls. The paper will discuss the design and performance of the power supply.

1 INTRODUCTION

The Fermilab Main Injector Sextupole Correction System consists of a horizontal and a vertical ring for chromaticity compensation[1] [4] to achieve high intensity stable beam during 8.9 *GeV/c* to 150 *GeV/c* proton and anti-proton acceleration and deceleration. Each ring is constructed of 54 sextupole magnets connected in series and powered by a four quadrant 250*KW* switchmode power supply. The Sextupole system requires operating current between -25 amps and 350 amps with a current step as high as 40 amps in 10 ms at 20.5 *GeV* transition (25 amps). The system also requires 8-hour DC current stability at injection level (0-20A) to be better than +/-25mA. Regular thyristor type power supplies are not suitable for this application because of bandwidth and bipolar current operation requirements. The successful development of a four quadrant 2*KW* switchmode power supply using MOSFETs[2] at Fermilab motivated us to investigate the H-bridge switching topology by using IGBTs for much higher power level switching. Recent technology developments in high power and fast switching IGBT technology have made our design become practical. Three units of the four quadrant 250*KW* switching power supplies with voltage output of +/-700 volts and capability of driving +/- 350 amps current have been developed and built for the project.

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2 POWER SUPPLY DESIGN

2.1 Power supply Circuit

Figure 1 shows the circuit diagram for the power supply. The H-bridge is constructed of four IGBT switches *S1*, *S2*, *S3*, and *S4*. The pulse width modulated (PWM) output of the positive half bridge (*S1* and *S2*) is filtered by the top filter and the output of the negative half bridge (*S3* and *S4*) is filtered by the bottom filter. The voltage difference between the two filtered outputs is the voltage output of the power supply.

The switching pattern of the IGBTs is also shown in Fig. 1. The summation of the duty factor of *S1* and *S3* is always unity. For a given S1 duty factor of *DF1* and H-bridge DC input voltage of Vin, the voltage at the top filter output will be *DF1*Vin* and the voltage at the bottom filter output will be *(1-DF1)*Vin*. The power supply output voltage will be *(2*DF1-1)*Vin* with a ripple frequency twice the 10 KHz switching frequency. The power supply will have zero volt output when IGBTs are switching at 50% duty cycle. The power supply output voltage can be controlled by varying the duty factor *DF1*.

The 800 volt H-bridge DC input voltage Vin is derived from a 12-pulse diode rectifier. The rectifier filter is a Praeg filter[3] with the second order roll-off frequency at 60 Hz. The capacitor banks are sized to absorb the energy returned from the inductive load (160 mH and 1.55 ohms) at 350 amps during a trip condition. The 18.2mF total capacitance at the rectifier output limits the transient voltage to 1.2 KV in the worst case. A 9 μH cable inductance was added to limit the amount of high frequency current through the low frequency capacitor banks (4.5mF and 13.5 mF), and thus avoid capacitor over-heating. Most of the high frequency current goes through the 224 μF high frequency capacitor bank.

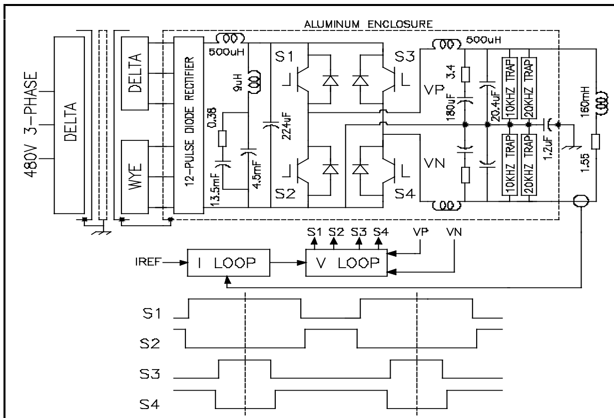

Figure 1 Power supply Circuit

2. 2 Low Inductance Bus Plate and Snubber Design

The energy stored in the bus parasitic inductance causes transient voltages during IGBTs switching. The 224 μF high frequency capacitor bank consists of 40 capacitors each rated at 5.6μF/1.5KV. Each capacitor has low ESL (23 nH) and is rated 35 amps RMS current at 60 ℃. These capacitors are connected in parallel and distributed around the four IGBTs. The IGBTs, high frequency capacitors, and bus connections are packaged in a laminated bus structure to reduce the bus parasitic inductance. The laminated bus structure is constructed using 1/8” copper plates with 1/8” thick G-10 sheet for insulation layers. The bus equivalent parasitic inductance has been reduced to about 15 nH.

A Snubber circuit (Fig. 2) is used to limit surge voltages during high power and high frequency switching. Snubber capacitor *Cs* is charged to DC bus voltage *Vin* through *Rs*. When IGBT *S1* turns off, parasitic inductance in the DC bus causes a transient voltage across *S1*. The snubber diode *Ds* turns on and diverts the energy stored in the parasitic bus inductance into the snubber capacitor *Cs* as soon as the voltage exceeds the DC bus voltage.

A surge voltage similar to the turn-off surge can occur when the free-wheeling diode recovers. Assume that the lower IGBT *S2* in Fig. 2 is off and the load current I_L is circulating through the free-wheeling diode of the upper IGBT. When the lower device turns on, the current in the free-wheeling diode of the upper IGBT decreases as the load current begins to commutate to the lower IGBT and becomes negative during reverse recovery of the free-wheeling diode. When the free-wheeling diode recovers, the current in the bus quickly decreases to zero resulting in a transient similar to turn-off operation. *Cs* and *Rs* can be calculated using bus parasitic inductance *Ls*, allowable DC bus voltage overshoot Δ*V*, maximum operating current *I*, and the switching frequency *f* (Fig. 2). By using the low inductance bus plate and snubber design, the IGBT transient voltage overshoot is less than 5% at Vin of 800 volts and *IL* of 350 amps.

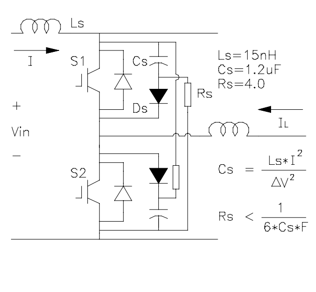

Fig 2 Snubber circuit

2.3 IGBT Selection and Thermal Management

We selected the Eupec FZ 1.6KV/1.2KA IGBT for this project because its voltage rating was adequate (more than 75% above the DC supply voltage) and because its switching characteristics allowed us to use it without paralleling devices and to still maintain reasonable junction temperatures. Temperature problems with other devices early in the development led us to carefully evaluate dissipation in the IGBT. Due to the difficulty of measuring currents in our low-inductance structures, we made our dissipation measurements using calorimetry. We determined that the IGBT dissipation was 2.4 *KW* while switching 350 amps at 800 volts at 10 KHz with a 90% *DF*. This compared nicely to the 2.6 *KW* number calculated from the data sheet. We also measured the thermal impedance of the IGBT baseplate with respect to inlet water temperature while mounted on the Eupec heat sink. The result was a rise of 10 °C/*KW*. These results lead to a calculated maximum junction temperature of 98 °C with inlet water of 35 °C.

We normally design systems to maintain junction temperature below 80 °C for optimum reliability. In this case we accepted the slightly elevated levels as a trade-off to developing a circuit with paralleled devices. We had also lowered our switching frequency from 30 KHz to 10 KHz in order to make the single device structure realizable.

2.4 IGBT Gate Drive

The IGBT gate drive is built with a Concept drive (IGD-515EI) and is capable of driving IGBT gate with +/– 15 V and a peak current of +/-15 amps. Very low input to output isolation capacitance (< 10 pF) with fiber optic controls are essential for eliminating noise problems caused by ground loops and capacitive coupling in the rapid turn-on and turn-off environment. The gate drive has an IGBT over current protection circuit to turn off the IGBT in less than 8 μs in case of IGBT over current.

2.5 EMI/RFI Shielding

A disadvantage of switchmode power supplies is the generation of EMI/RFI noise. In order to control the radiated noise at a minimum acceptable level, a ½” wall aluminum enclosure is used to shield the entire high power and high frequency switching circuits. Primary and secondary shields were installed in the power transformer with the secondary shield tied to the aluminum shielding enclosure. The shielding enclosure is mounted within and isolated from the power supply cabinet. A single point ground is used for safety purpose (Fig. 1). The primary shield in the transformer reduces EMI/RFI from feeding back into the 480 lines. Additional line filtering further attenuates the noise. Fiber optic links are used for control and status read back between control electronics and the shielded high power switching circuits.

2.6 H-Bridge Output Filtering

The H-bridge output is filtered by a second order damped filter. The filter has -3dB roll-off frequency at 800 Hz with additional 10 KHz and 20 KHz traps. The filter reduces the peak to peak ripple voltage to 2.5 volts (Fig. 6). This meets our specification for both load ripple and radiated energy from tunnel cables.

3 PERFORMANCE

Preliminary tests were conducted on the power supply with the Main Injector Sextupole ring. The current slew rate of the power supply was limited at 4000 A/Sec. Figure 3 shows the power supply current and voltage during a typical ramp with bipolar current operation (-25 to 350 amps) and 4000A/Sec current step at transition.

The current loop frequency response was tested as indicated in Fig 4. Current regulation bandwidth has been achieved at 300 Hz. The DC current 8-hour stability in injection regions (0 to 25 A) is better than +/-25 mA. Figure 5 shows the current regulation error of +/- 78 mA at 350A (CH1=40A/V, CH3=2A/V). Our first operational problem was excessive ripple due to a bad connector on our current feedback signal. The second problem was also excessive power supply voltage ripple due to noise pickup in the current transducer electronics. This last problem was solved by using a later version of the transducer electronics with improved noise rejection.

Two power supplies were in operation during Main Injector commission between October 98 and January 99. The Main Injector achieved greater than 1E13 protons/6 batch intensity at 150 Gev.

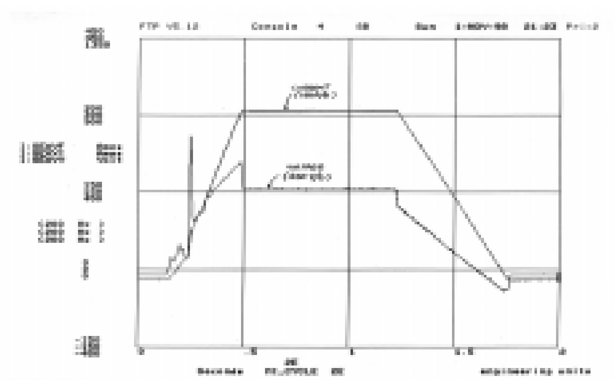

Figure 3 Typical Power supply Voltage and Current

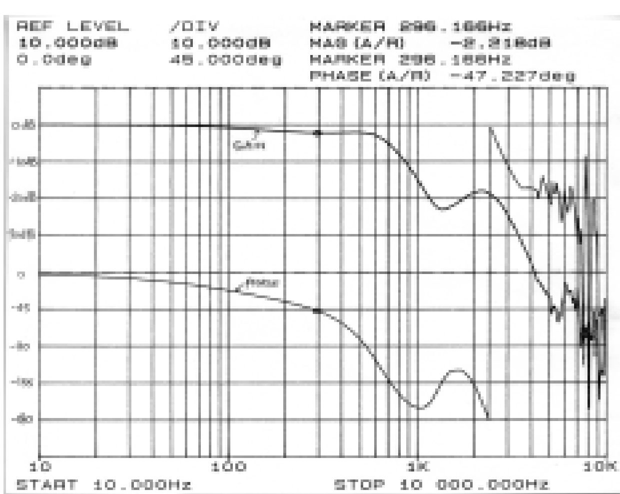

Figure 4 Current Loop Frequency Response

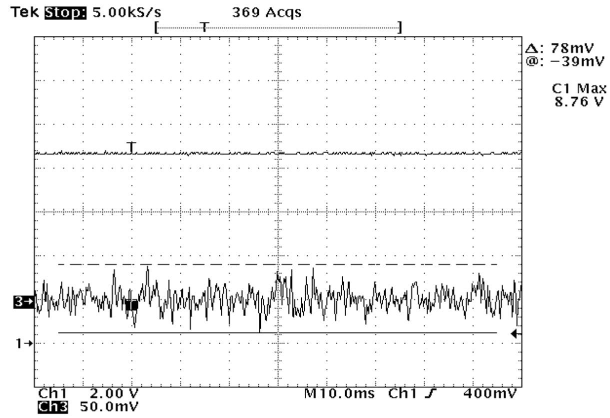

Figure 5 Current Regulation Error of +/- 78mA at 350A

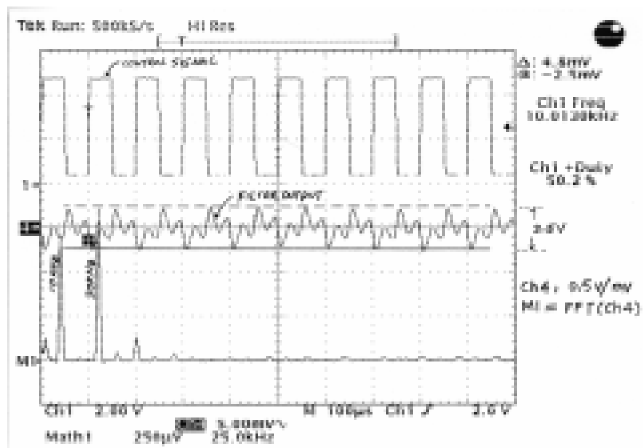

Figure 6 Power Supply Voltage Ripple

4 CONCLUSION

The test results on the four quadrant 250*KW* switchmode power supplies indicate successful application of IGBTs in switchmode power supplies for wide bandwidth and high power operation.

5 ACKNOWLEDGEMENTS

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