Maximum Let-Through Currents in the APS Storage Ring Quadrupole, Sextupole, and Corrector Magnets

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Abstract

Limits are described for the maximum magnet currents, under specified fault conditions, for the storage ring quadrupole, sextupole, and corrector magnets.

Introduction

In computing the maximum let-through current for the magnets for the storage ring, several factors must be considered. In general, the maximum current likely to occur even under fault conditions is less than the maximum theoretical DC current given the magnet resistance and the maximum available DC voltage.

The first level of protection against magnet current overloads is the over-current interlock that is built into the converter electronics package. The threshold is set to approximately 110% of nominal maximum levels. However, in the event of a fault in the over-current interlock circuit, we rely on input fuses to protect the system.

System Description

Quadrupoles, sextupoles, and correctors each are powered using individual switch-mode power converters. Each converter is fed with an unregulated DC voltage from one of four raw DC supplies that feed a total of 74 converters in each double-sector of the storage ring. Figure 1 shows the arrangement of raw DC supplies, power converters, and associated magnets.
The quadrupole and sextupole power converters are switched-mode “buck” converters. The basic elements of the converter are shown in Figure 2, with a more detailed schematic provided in Appendix A.

These converters provide a unipolar regulated output current by regulating the duty factor of the IGBT switch that runs at 20kHz. The average voltage across the magnet is a function of the input voltage and the duty factor of the IGBT.

During the *on* period of the IGBT, current flows from the raw DC supply through the IGBT and the load. During the *off* period, the load current circulates through the freewheel diode. Since the duty factor of the IGBT cannot physically exceed 100%, the output voltage will be less than the input voltage. The average load current is a function of the average load voltage and the load resistance. However, since the input and output powers must be equal (neglecting losses), and since the average load voltage is less than the input voltage, the average load current will be greater than the average input current. In effect, the converter acts as a DC transformer.
The maximum duty factor of the IGBT is limited by the electronics package to 50% in the quadupoles, and to 60% in the case of the sextupole.

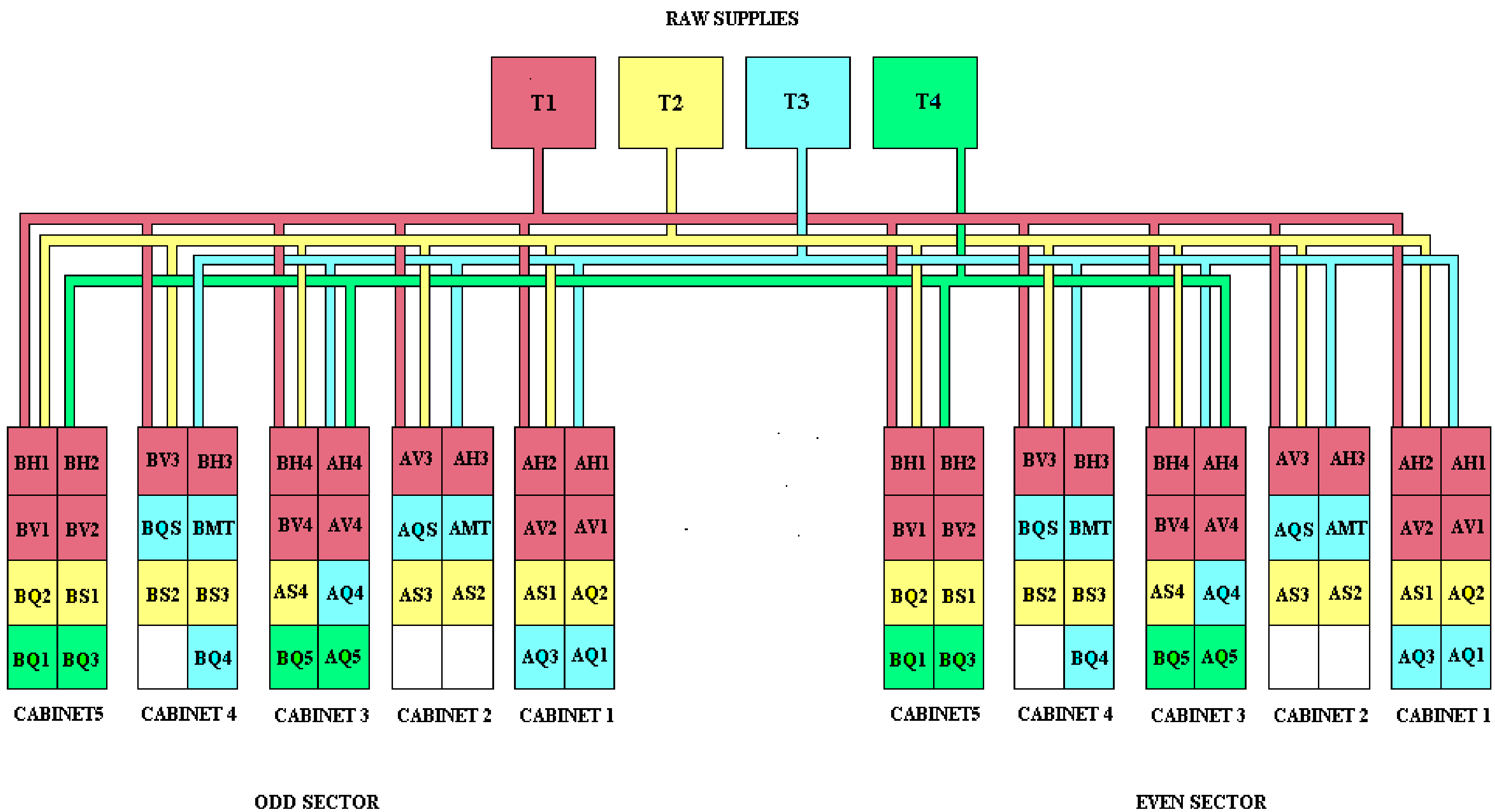


Figure 1 – Arrangement of Raw DC Supplies, Power Converters, and Associated Magnet

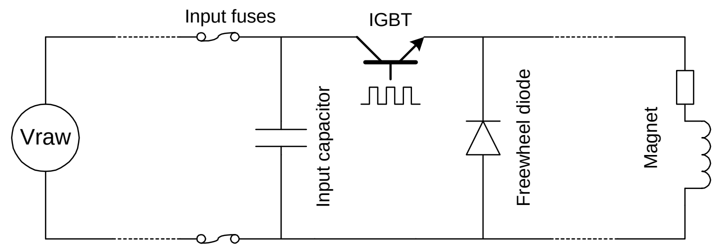


Figure 2 – Key Elements of Quadrupole/Sextupole Power Converters

The corrector power converters use an 'H'-bridge arrangement to provide a bipolar output. The arrangement is shown in Figure 3, with a detailed schematic provided in Appendix A.

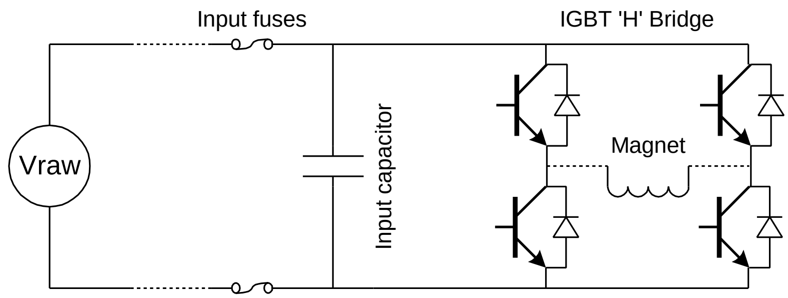


Figure 3 – Key Elements of Corrector Power Converters

In this case, appropriate pairs of IGBTs are pulse-width modulated depending on the required direction of the magnet current. The principles of regulation and the relation between load current and input current are the same as the unipolar case. In this case, the electronics package provides no limit on the maximum IGBT duty factor that can be applied.

In both converter designs, the input fuses protect against overload conditions.

Bases for the Calculations

1. Normal AC line variations cause the raw DC voltages to increase to as much as 110% of the rated levels.
2. All raw supplies are assumed to be on their maximum output taps.
3. Magnet resistance and inductance numbers were used.
4. It is assumed that the manufacturer's fuse data is correct.
5. There are two fuse ratings used in the storage ring converters. We allowed for the possibility that the wrong (higher-rated) fuse was installed in the sextupole and corrector converters.

Fault Conditions Assumed

1. The converter regulator tries to regulate to a current above its maximum setpoint value.
2. The overcurrent circuit in the converter fails.

Observations about the fault conditions assumed

1. It is assumed that the maximum IGBT duty factor is limited by the electronics package. Note that the circuit that performs this limiting is no less likely to fail than the overcurrent protection circuit, and in fact the duty factor limit is configured using jumpers.

2. A fault in either the overcurrent protection circuit or in the maximum duty factor limiter could go undetected for a considerable time since they are not called to perform any function until there is a fault that causes the current to exceed normal levels.
3. The most likely fault condition is that an IGBT fails, going short circuit. In this case, the magnet current rises exponentially and will blow the fuses in a fraction of a second. This condition is not examined in detail because of the relatively short time scales involved.

Calculated Maximum Magnet Currents

Table 1 shows the characteristics assumed for the calculations. The magnet resistances were taken from the rating plates of representative production magnets. Maximum input voltages are 110% of the nominal raw DC voltage.

Table 1: Magnet and Power Supply Characteristics

Magnet Type	Resistance (milli-ohm)	Max Input Voltage (V)	Normal Fuse Rating (A)	Max Setpoint (A)
0.5m Quad	29	44	250	450
0.6m Quad	34	44	250	450
0.8m Quad	43	68	250	450
Sextupole	105	68	150	250
Horz. Corrector	70	79	150	150
Vert Corrector	98	79	150	150

Calculated maximum magnet currents are provided in Table 2. The maximum possible magnet current is obtained from the maximum input voltage and the magnet resistance. The maximum current with the IGBT duty factor limited to the nominal circuit maximum is then computed from the maximum possible current and the maximum IGBT duty factor. The input current is the magnet current multiplied by the duty factor. Fuse blow times were obtained from the manufacturer's time-current graphs for the relevant fuse. These graphs are provided in Appendix B. **Note that the fuse blow times shown are approximate.**

Table 2: Maximum Magnet Currents Assuming IGBT Duty is Limited

Magnet Type	Vmax / R (Amp)	Max IGBT Duty (%)	Max Magnet Current (A)	Max Input Current (A)	Time for fuse to blow (sec)
0.5m Quad	1517	50	758	379	>10000
0.6m Quad	1294	50	647	323	>10000
0.8m Quad	1581	50	791	395	>10000
Sextupole	648	60	388	233	>10000 (150A fuse) >10000 (250A fuse)
Horz. Corrector	1131	100	1131	1131	<<1 (150A fuse) 0.3 (250A fuse)
Vert Corrector	808	100	808	808	~0.1 (150A fuse) 10 (250A fuse)

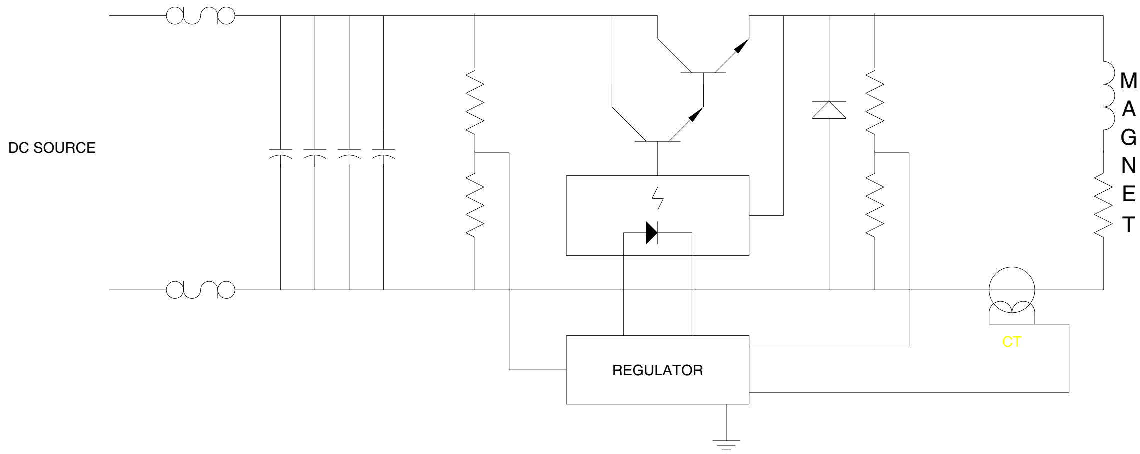
It is evident that in the case of the correctors, potentially very large current can flow under fault conditions because the IGBT duty factor is not limited. Since the fuse blow times depend heavily on the current flowing through them, Table 3 contains additional data that show possible magnet currents and fuse blow times for different IGBT duty factors.

Table 3: Corrector Magnet Currents at Different IGBT Duty Factors

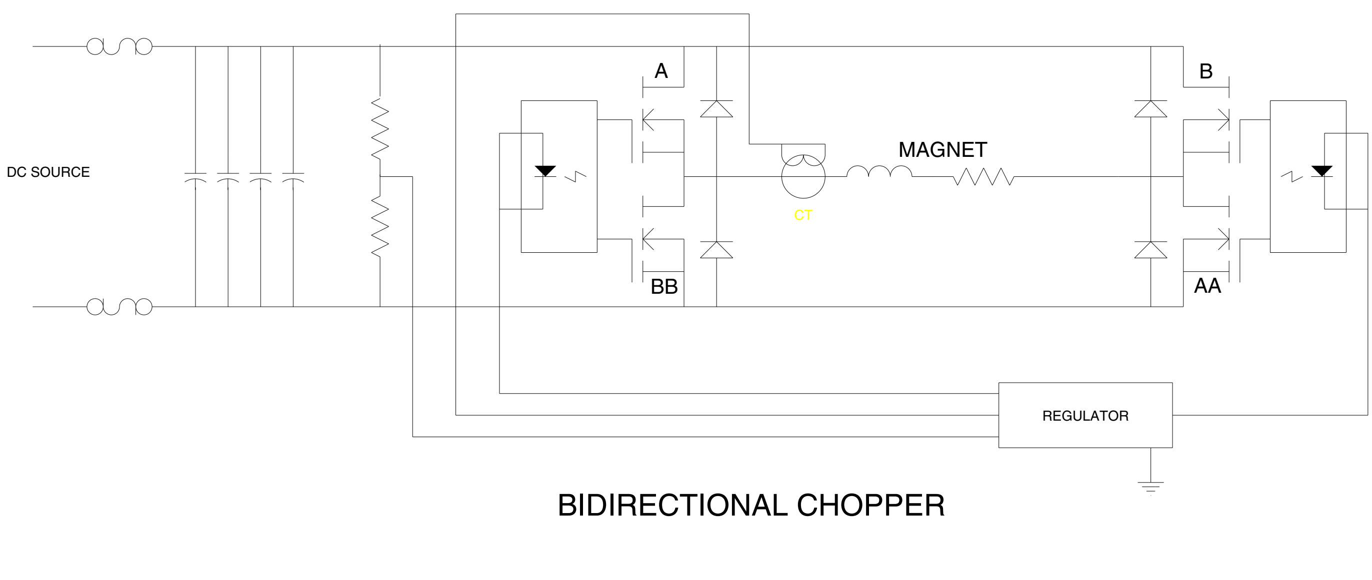
	Horizontal Corrector			
IGBT Duty (%)	**Magnet Current**	**Fuse Current**	**Time to blow (s) (150A fuse)**	**Time to blow (s) (250A fuse)**
50	565	283	>10000	>10000
70	792	554	5	400
90	1018	916	<<1	3

	Vertical Corrector			
IGBT Duty (%)	**Magnet Current**	**Fuse Current**	**Time to blow (s) (150A fuse)**	**Time to blow (s) (250A fuse)**
50	404	202	>10000	>10000
70	566	396	500	>10000
90	727	655	1	70

Appendix A – Converter Power Circuit Schematics



UNIDIRECTIONAL CHOPPER

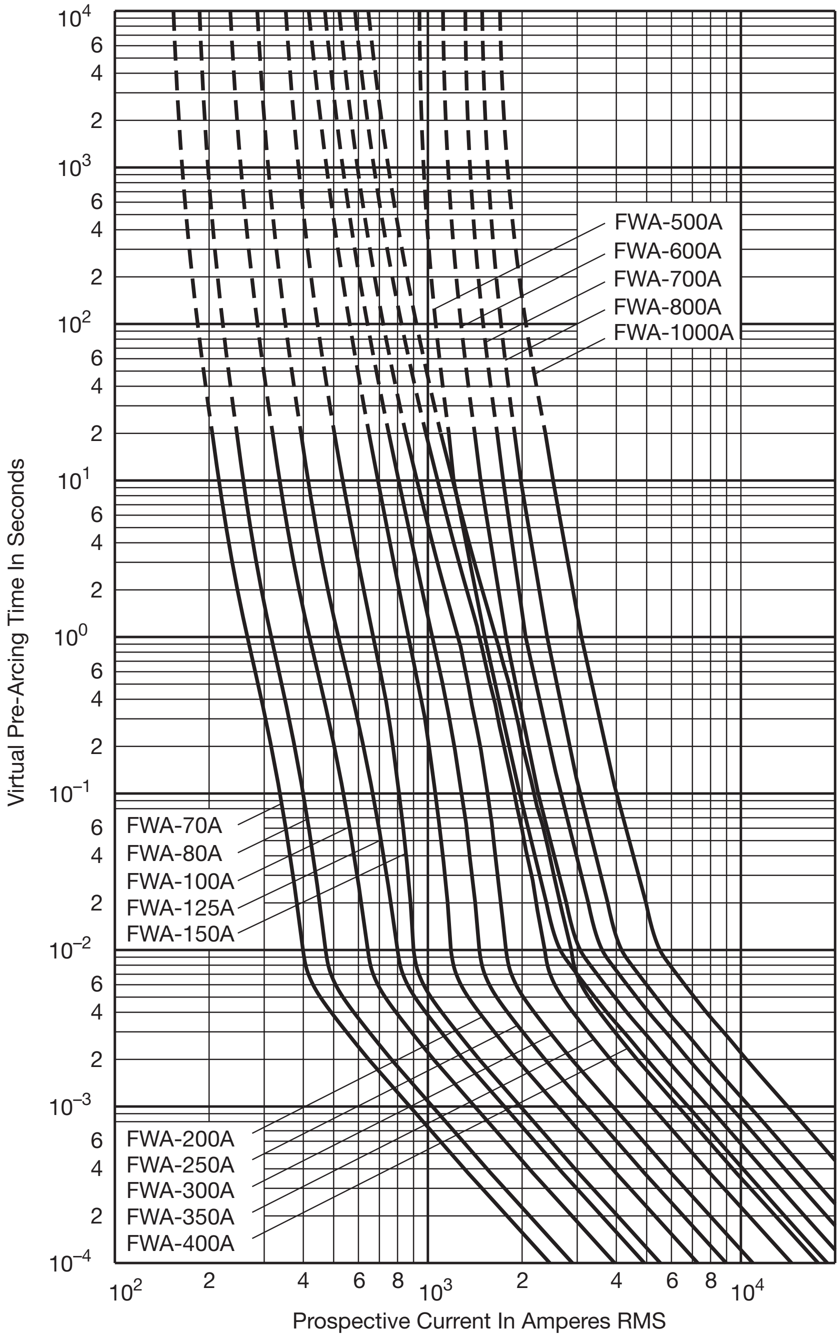


BIDIRECTIONAL CHOPPER

Appendix B – Manufacturer's Fuse Time-Current Curves

Relevant fuses are:

***Cooper Bussman* FWA250 (Quadrupole converters)**
***Cooper Bussman* FWA150 (Sextupole & corrector converters)**



Minimum Melting	Time-Current Characteristic Curves FWA 70A-1000A	Approved: NN	Page 1 of 3
		Rev. Date: SEPT-97	Pub. Date: JAN-98

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