B-FACTORY INTERMEDIATE DC MAGNET POWER SYSTEMS RELIABILITY MODELING AND RESULTS*

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Abstract

The B-Factory is a high-energy physics facility for studying matter versus anti-matter asymmetry. It utilizes 200 Intermediate DC power systems, employing 2.5 to 17kW switchmode converters, to supply beam-shaping magnets with regulated current. Redundancy and modularity were considered to maximize reliability and minimize mean time to replace (MTTR), within technical limitations and cost constraints. Described are the configurations that were considered and reliability prediction models. The SLAC decision to employ a single converter was sound. However, 2 years of operation have confirmed that converter reliability must be improved.

INTRODUCTION

The B-Factory was authorized on the premise that the B-Mesons would be generated at factory production levels. Like a commercial factory, the facility must achieve high availability in order to obtain meaningful experimental data to justify its cost and continued operation. The facility utilizes 200 Intermediate DC Power Systems. In view of the large number of systems, it was important to address the issue of availability from the onset of the design and engineering processes.

REQUIRED AVAILABILITY

The target availability for the B-Factory is ≥ 76% [1] over a 9-month "mission" interval. This is further broken down into availability allotments for various facility subsystems. The allotment for all the DC Magnet Power Systems is 97% [1]. The 200 intermediate power systems are a subset of the DC Magnet Power Systems and must achieve ≥ 98% if the overall facility availability target is to be met.

POWER SYSTEM DESCRIPTION

A magnet power system typically consists of the subsystems and components shown in Figure 1. The dashed line components have their own availability budgets and are not discussed here.

The converter controller is an integral part of the current stabilization loop. It also communicates the magnet current and converter status to the B-factory operators via global control.

Off-line, switchmode, pulse-width-modulated, 2.5kW to 17kW converters furnish precise, controlled, and almost pure DC current to the magnets.

A high precision zero-flux transductor forms an integral and important part of an external current stabilization loop. Verification is provided by a monitor transductor.

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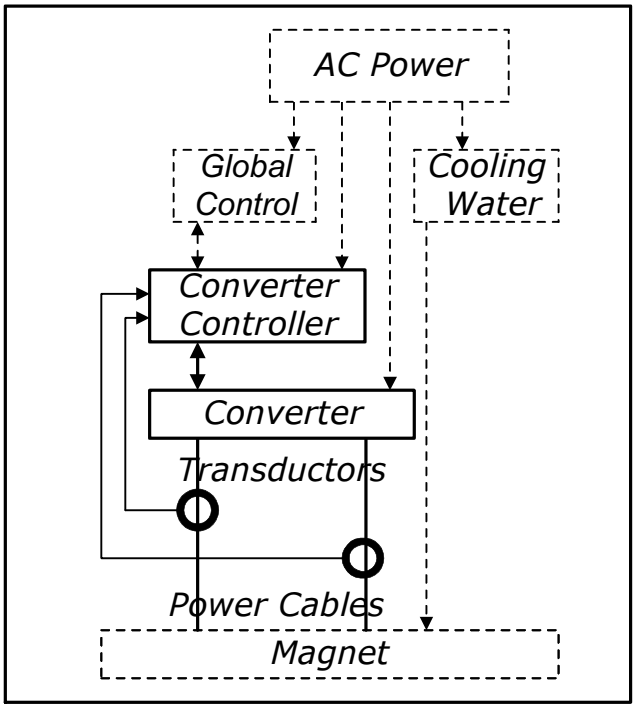

Figure 1: Power System Block Diagram

DC power cables range in size from 2/C#6AWG to 500kcmil. They are stranded copper, NEC type TC rated. The cable connectors vary, ranging from miniature, multi-pin electronic connectors to large power lugs.

RELIABILITY MODELING

The reliability block diagram shown in Figure 2 represents the power system. Since all components are crucial, the reliability block diagram consists of series-connected components.

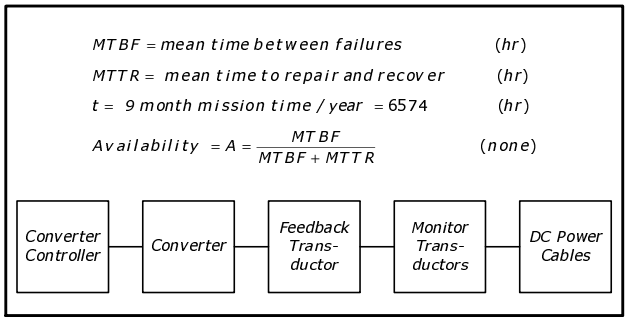

Figure 2: Definitions And Reliability Block Diagram

Failure analysis using MIL-HDBK-217, Parts Stress Method at 30C, with ground benign conditions yielded the component MTBF values shown in Table 1.

Single System Availabilty		
Component	MTBF	Availability
Controller	110,000	0.9999818
Converter	60,000	0.9999667
Transductor 1	381,500	0.9999948
Transductor 2	381,500	0.9999948
Cables	14,000,000	0.9999999
System	32,184	0.9999379

200 System Availability

$MTBF_{200} = 160.9$ hours

$A_{200} = A_1^{200} = 0.9999379^{200} = 0.9876564$

t=6574 hrs/year MTTR=2 hrs components/system

Table 1: Calculated Single & 200 System Availabilities

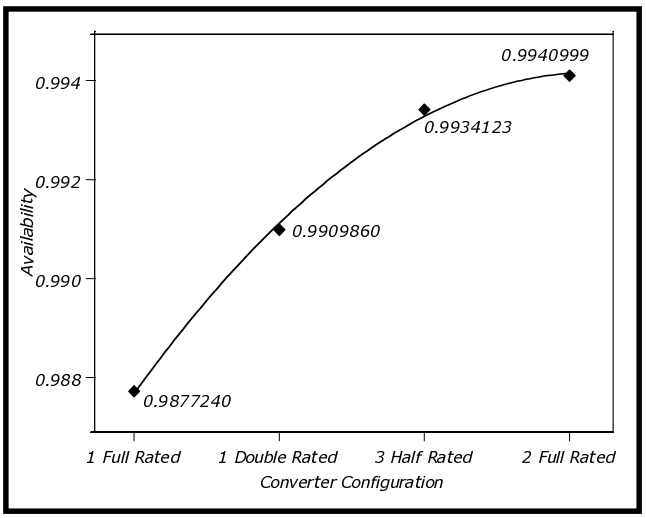

Figure 3: 200 System Availability Vs PS Configuration

The calculated 0.988 availability would satisfy the project requirement, however, it was considered prudent to see if the availability could be improved. It was recognized that the calculated values might be optimistic.

CONVERTER REDUNDANCY

It is apparent from Table 1 that the converter exhibits the lowest availability. Oversized and redundant converters were examined as a way of increasing system availability. Various configurations were studied, 3 of which are listed below:

- 1 double-rated converter delivering 1/2 rated power (no redundancy).
- 3 paralleled, half-rated converters each delivering 1/3 rated power (2 out of 3 redundancy).
- 2 paralleled, full-rated converters each delivering 1/2 rated power (1 out of 2 redundancy).

These configurations do yield increased converter MTBF, conservatively in linear proportion to the ratio of rated power to delivered power. The MTBF is further enhanced when converters are paralleled as "k out of N redundant converter systems". The 200 converter system availabilities improve to the values shown in Figure 3.

NOTE ON PARALLELED CONVERTERS

When converters are parallel connected, load current sharing is essential, particularly during transient conditions. Master-slave arrangements suffer from the weakness that, when the master fails, the entire system fails. A "democratic" load-current-sharing scheme [2] in which all converters are responsible for carrying their fair share of the load current is better. Failure of one converter simply forces the other converters to assume and share the failed converter's load. The converter design must include single-point failure immunity so that the failure of one converter does not cause all the paralleled converters to fail [3] and actually lower system availability.

MODULARITY & HOT-SWAP

Calculations showed that converter availability could also be improved by reducing MTTR. Modular, easily replaceable, and to a lesser extent, hot-swappable converters were considered in an attempt to reduce the converter replacement time of 2 hours.

COST AND SIZE CONSIDERATIONS

SLAC analyzed the costs associated with over-sizing or adding parallel-connected, redundant converters. An oversized converter simply costs more. Redundant converters not only cost more because of quantity, they also cost more because they must incorporate circuitry for single-point failure immunity [3]. The converter controllers would also have to be more complex to control and monitor the status of 2 or more converters. System size and space also increase.

B-FACTORY DECISIONS

The calculations indicated that single converter systems would meet the availability goal of 0.98. Realizing the constraints of cost and facility space, it was decided to go with a single, full-rated, non-redundant converter in each intermediate power system.

In an attempt to cement the 60,000-hour MTBF, the converter manufacturers were required to evaluate MTBF during the design and improve weaknesses that were discovered. Environmental stress screening was also used to further identify the weaknesses not discovered by paper evaluation.

Modularity and hot-swap were not implemented because modular converters possessing the features needed were simply not available at the time of B-Factory design and only a minor portion of the 2-hour MTTR would be actually needed to replace a failed converter.

OPERATING RESULTS

The first group of 70 Intermediate DC Power Systems (with converters provided by Manufacturer A) began operating during December 1997. The remaining 130 power systems (with converters provided by Manufacturer B) began operation a year later. All 200 systems have since been in continuous operation, except when the facility has been shutdown for planned installation of additional systems and physics diagnostics. A total of about 2.6 million operating hours have been logged. The actual availability of components and the 200 power systems is tabulated in Table 2.

Component	MTTR Hrs	Failures	MTBF Hrs	Availability
			1 System	
Controller	2	9	288,889	0.9999931
Converter	2	102	25,490	0.9999215
Transductor 1	4	2	1,300,000	0.9999969
Transductor 2	4	2	1,300,000	0.9999969
Cables	12	1	2,600,000	0.9999954
System		116	22,414	0.9999039
			200 Systems	
Controller			1,444	0.9986173
Converter			127	0.9845501
Transductor 1			6,500	0.9993850
Transductor 2			6,500	0.9993850
Cables			13,000	0.9990778
System			112	0.9811321

Table 2: Two-Year Operating Results

FAILURE DETAILS

Controller Failures

Three of the 9 controller failures are attributable to the failure of a small off-line DC power supply in the controller. The controllers performed better than anticipated.

Converter Failures

Table 2 shows that the 200 power systems achieved 0.981 availability and met the 0.98 goal. The converters could have performed better. Their problems are summarized below.

Manufacturer A - 64 Failures

- 1 input AC circuit breaker mechanical failure. No action needed or taken. This is a random failure.
- 6 rectifier bridge failures, causes still under investigation.
- 18 failures due to an incorrect part in a comparator circuit or an incorrect calibration of the current overload circuit caused spurious “loss of auxiliary power” faults. Both problems have been corrected.
- 39 nuisance trips, for which no cause yet found.

Manufacturer B – 38 Failures

- 1 input AC circuit breaker mechanical failure.
- 7 AC input connectors that overheated due to loose terminal screws. The manufacturer now tightens screws to a torque specification and has entered connector work onto a QA assembly traveler.
- 5 diode rectifier bridges that failed because of AC over-voltage transients during converter turn-on and turn-off. Phase to neutral snubber circuits corrected the problem.
- 3 low line detectors that required calibration and were corrected.
- 22 problems with circuit board voltage breakdowns. The problem stems from uncontrolled environment dust that accumulates during the day and then turns into mud with the evening fog. Conformal coatings are under consideration.
- There were also 7 fan failures, listed here only for reference. These were replaced during machine downtime and no availability loss was incurred.

CONCLUSIONS

The approach to estimate and confirm system reliability and availability is relatively straightforward.

Converters are the weak link. Redundancy can dramatically improve availability. However, more is involved than just paralleling converters. To be effective the converters must be protected against single-point failures.

Democratic load-current-sharing is preferred over master-slave schemes, particularly if more than 2 converters are parallel connected. Even when 2 converters are connected in parallel the master-slave scheme is not ideal because master loss also disables the slave.

In some situations modularity and hot-swap capability will not significantly reduce MTTR and therefore offer minimum benefit.

Systems with redundant converters cost more, depending upon the converter configuration, which in turn is dictated by how much availability is needed.

For the B-Factory situation, the target availability was attained. SLAC made the right choice by employing just a single converter in each power system. Power system cost and space were minimized

ACKNOWLEDGMENTS

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REFERENCES

[1] PEP-II (B-Factory) internal Technical Note 100, July 18, 1995

[2] Milan Jovanovic, David Crow and Lieu Fang-Yi “A Novel, Low-Cost Implementation of “Democratic” Load-Current Sharing of Paralleled Converter Modules”, IEEE Transactions on Power Electronics, Volume 11, Number 4, July 1996.

[3] Paul O’Boyle and Steve Kugler “Redundancy and Hot Swapping Keep Systems Running”, Electronic Design, November 1997