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AVAILABILITY MODELING OF THE SOLID-STATE POWER AMPLIFIERS FOR THE CERN SPS RF UPGRADE*

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Abstract

As part of the LHC Injector Upgrade program a complete overhaul of the Super Proton Synchrotron Radio-Frequency (RF) system took place. New cavities have been installed for which the solid-state technology was chosen to deliver a combined RF power of 2 MW from 2560 RF amplifiers.

This strategy promises high availability as the system continues operation when some of the amplifiers fail. This study quantifies the operational availability that can be achieved with this new installation. The evaluation is based on a Monte Carlo simulation of the system using the novel AvailSim4 simulation software. A model based on lifetime estimations of the RF modules is compared against data from early operational experience. Sensitivity analyses have been made, that give insight to the chosen operational scenario.

With the increasing use of solid-state RF power amplifiers, the findings of this study provide a useful reference for future application of this technology in particle accelerators.

INTRODUCTION

Two new RF powering systems with a peak power of 2 MW each have been installed in the Super Proton Synchrotron (SPS). The 200 MHz solid-state RF powering system, illustrated in Fig. 1a, has no RF circulators and uses a mix of cavity-combiners and 3 dB-combiners to provide the power from 2560 solid-state amplifiers, distributed over 2x16 towers that are shown in in Fig. 1b [1], to the cavities. At the tower level, the outputs of up to 80 RF modules, each containing a power supply and two solid-state amplifiers, are combined in an 80:1 cavity-combiner. The outputs of the 16 towers are connected to a four stage 3 dB-combiner and transmitted via a coaxial feeder-line to the cavity. Only 72 of the up-to 80 RF modules are required for SPS operation. This power margin ensures high operational availability of the system. Similar redundant systems using solid-state technology have been implemented at SOLEIL [2] and ESRF [3]. Exceptionally high availability of the systems was reported [4, 5].

The goal of this study is to develop a quantitative model of the operational availability of the RF powering system for SPS and use it to identify the best operational strategy considering current and future operation.

METHODOLOGY

The integrated system analysis, modeling, and simulation methodology follows the Digital Reliability Twin paradigm [6]: A quantitative reliability model is generated based on expert interviews, engineering documentation, testing data, operational data of comparable systems, and manufacturer data. In line with the Design Review Based on Failure Mode method [7], a detailed system analysis is carried out with particular attention for novel parts of the system. The resulting reliability model is combined with an operational model and a Monte-Carlo engine (AvailSim4) to simulate potential future operational scenarios and different configurations of the system. The results of these simulations serve as evidence for decision making. The modeling can be refined whenever new operational data are available.

Definitions

For the correct interpretation of the results, the following statistical concepts are introduced. The concerned system is defined as shown in Fig. 1a. It is considered operational when it delivers the required output RF signal towards the RF cavity while its inputs (RF input signal, electrical supply) are within their specification. A failure occurs when no output is delivered despite the inputs being within specifications.

The system failure rate λ is the number of failure occurrence per unit of operational time. It is the sum of individual sub-system failure rates $\lambda = \sum_i \lambda_i$. The mean-time-between-failure (MTBF) of a sub-system is the inverse of its failure rate $\mathrm{MTBF}_i = 1/\lambda_i$. The mean-time-to-repair (MTTR) is the average duration to restore a sub-system after it has failed.

The system availability is the fraction of time a system is available out of the overall time it is supposed to be operational. It can be approximated as $A \approx 1 - \sum_i u_i$[1], with, $u_i = (\textit{downtime of subsystem } i)/(\textit{total time})$, being the individual un-availability contributions of the sub-systems.

System Analysis and Parameterization

Table 1 shows the obtained reliability model parameters in terms of estimated lower bound of MTBF at 90% confidence (pessimistic estimate), MTBF point estimate (most likely value), the type of MTBF distribution, MTTR point estimate, the type of MTTR distribution, and the fault logic for each sub-system. These are discussed in the following.

The overall MTBF of an RF module was estimated by the manufacturer as 346720 hours [8]. To reflect uncertainties of this estimate, potential future aging problems, and inherent pessimistic assumptions of the reliability estimate, a sensitivity analysis on this parameter is carried out (by using [1773360, 246720, 693340] h for both lower bound and point estimate). A second sensitivity analysis is carried out

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[1] The equation is exact when no simultaneous downtime of sub-systems occurs, which is almost always the case for the considered system.

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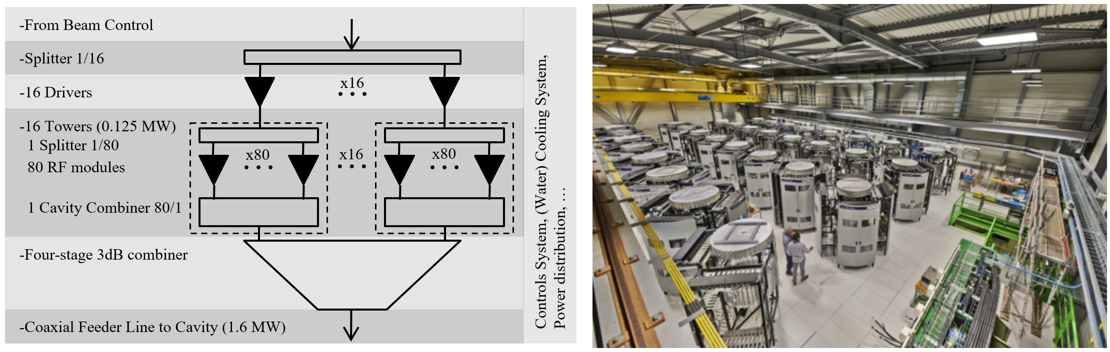

(a) (b)

Figure 1: (a) Overview of the RF powering. (b) The 2 x 16 towers housing 80 RF modules each.

Table 1: Simulation Input Data

Sub-System	MTBF 90% [h]	MTBF (point estimate) [h]	MTBF Distribution	MTTR [h]	MTTR Distribution	Fault Logic
RF module	[173360, 346720, 693440]		Exp.	1	Fixed	16 x (72 oo n)
Driver	158114	420768	Exp.	1	Fixed	16 x
Controls	31500	72300	Exp.	2	Exp.	1 x
Cooling, Combiners, Loads, Feeder	62000	144000	Exp.	24	Exp.	1 x
SPS shadow events	243	173	Exp.	5	Fixed	Providing repair opportunities
Maintenance Stop	1680	1680	Fixed	24	Fixed	

by varying the number of installed RF modules *n* from 72 (no redundancy) to 75 (up to three faulty modules tolerated).

The MTBF of the Driver SSPAs was identified in a reliability test of 64 units over 18 months. The Controls, Cooling, Combiners, Loads, and Feeder lines (referred to as 'Other' in the Results section) are iterations of previous systems that have proven high reliability at CERN. Hence, the parameter estimates are determined from the demonstrated reliability of comparable systems in other installations with similarity-based scaling laws employing parts-count complexity approximation and confidence-limit estimation methods (section 8.3.2.5.2 of [9]).

The SPS shadow events (SPS failures leading to interruption of operation for more than five hours) and regular Maintenance Stops (MS) provide opportunities for repairs. The MTBF of shadow events has been determined from SPS operations data of 2018. The time spent in shadow events or MS is not counted as operational time.

Simulation in AvailSim4

A Monte-Carlo simulation of future operational scenarios and different system configurations is carried out using AvailSim4. It is a CERN in-house software development for discrete-event-simulations of particle accelerator operation.

To accumulate sufficient statistics, the system has been simulated on a computing cluster for an equivalent of 3000 years of operation. The range of evaluated system configurations is provided in the Results section.

RESULTS

This section presents the simulation results for the studied system configurations. In the reference configuration, faults covered by the redundancy (RF module faults) are being exchanged during shadow events or MS. All other faults that lead to an interruption of operations are repaired immediately.

The simulation results of the reference configuration using pessimistic parameters (90% confidence lower bounds) are shown in Figs. 2a and 2e, respectively. The results of the same configuration using less pessimistic point-estimates are shown in Figs. 2b and 2f, respectively.

The failure rates and un-availability are higher for the more pessimistic estimation method. Moreover, the contribution stemming from the RF modules is decreasing once redundancy is employed. Already two additional RF modules almost completely screen RF module failures from operations for all studied MTBF values.

Subsequent configurations are all based on the point estimates. Figures 2c and 2g show a configuration in which faulty RF modules covered by the redundancy are only being exchanged during MS and not during shadow events. In comparison to the reference configuration, the fault-tolerance effect is noticeably attenuated.

Finally, Figs. 2d and 2h show a modified system with redundant drivers by adding a combiner and splitter between the drivers and the towers and by employing the same repair policy as is used in the reference configuration for RF mod-

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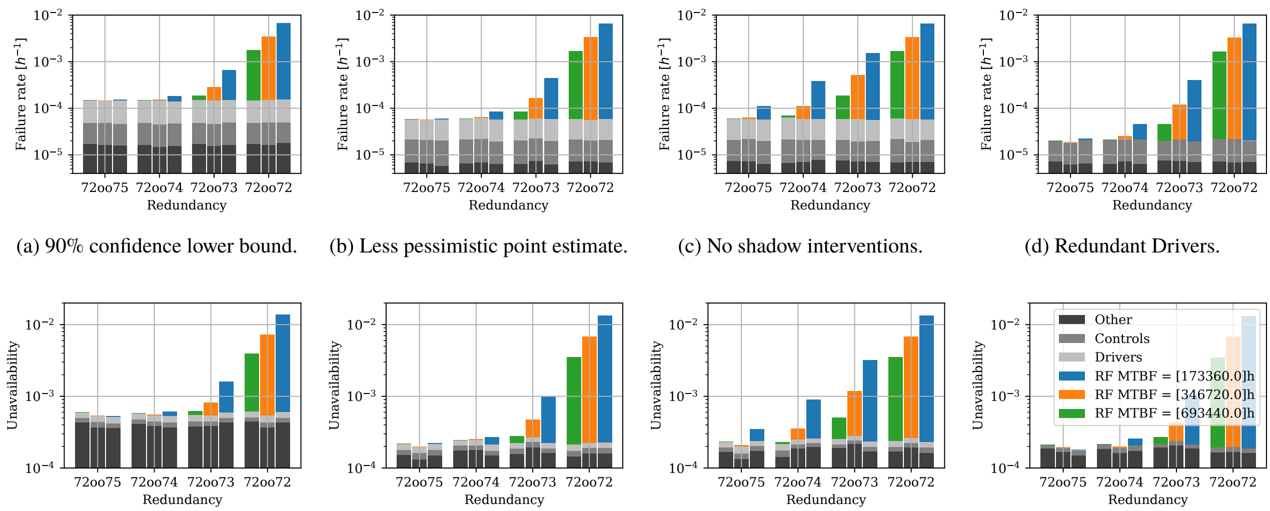

(a) 90% confidence lower bound. (b) Less pessimistic point estimate. (c) No shadow interventions. (d) Redundant Drivers.

(e) 90% confidence lower bound. (f) Less pessimistic point estimate. (g) No shadow interventions. (h) Redundant Drivers.

Figure 2: Top Row: System failure rate. Bottom Row: System unavailability. The results are shown as function of the number of installed modules (x-axis) and the MTBF of the RF-modules (three bars per Redundancy level). The colors indicate the attribution of failure rate and unavailability to sub-systems.

ules. This results in an almost complete screening of driver faults from operations.

Discussion of Results

Overall, the results underline the effectiveness of the chosen redundancy strategy. RF amplifier failures can be almost entirely screened from operation with 75 installed RF modules (which is well below the 80 modules that can be installed), if no common-mode failures occur. Comprehensive testing and qualification carried out during the development, manufacturing, and installation of the cavity combiner system gives high confidence that common-mode failures will not become an issue during operation. In addition, extensive monitoring is in place to identify any traces of such behavior.

Making drivers redundant would lead to a significant availability improvement and can be recommended. Similarly, performing repairs during shadow events improves the system availability. The expected number of RF module replacements is in the order of three per month, for which sufficient spares have to be maintained.

Comparison with First Operational Experience

Commissioning data indicates that the failure rate of the RF modules is lower than the estimation by the manufacturer. During ten weeks of commissioning only a single RF module power supply failed after a planned intervention that led to an unforeseen interruption of the cooling system.

Reliability Impact of Using Cavity-Combiners

Owing to the fact that the output power of the implemented cavity-combiner solution scales linearly with the number of intact RF modules, it can almost completely screen failures from operations with $n = 75$ installed modules. In other words, at a ratio of installed to required power of 75 to 72, almost all faults are screened.

Had 3 dB-combiners been used instead of cavity-combiners, the same powering ratio would have lead to a redundancy of 63oo64[2] since the output power would scale non-linearly as a function of the intact modules m:

$$P_{required} \leq (m^2/n^2) P_{installed} \iff$$

$$m \geq \sqrt{n^2 \frac{P_{required}}{P_{installed}}} = \sqrt{64^2 \frac{72}{75}} = 62.7.$$

Assuming the same RF module MTBF of 346720 h and repair of faulty modules during MS, the cavity combiner solution achieves an MTBF of 836000 h, which is an order of magnitude higher than the 3 dB combiner variant at an MTBF of 35500 h [10][3]. This illustrates that cavity-combiners can significantly increase the reliability and reduce the cost of an RF powering solution.

CONCLUSIONS AND OUTLOOK

An availability study of a solid-state RF powering solution using cavity-combiners is presented. The results show that the employed redundancy effectively screens failures of RF powering modules from operation even at moderate margins of installed versus required RF power. A similar 3 dB combiner based solution would achieve an order of magnitude lower MTBF at the same RF power margin.

The generated model can be adapted to optimize similar RF powering solutions requiring high availability, e.g., for accelerator driven systems such as MYRRHA [11].

[2] Note that $n = 64$ modules instead of 75 since 3 dB-combiners are 2^n combiners.

[3] See Eq. (1) on page 90 for calculation details.

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