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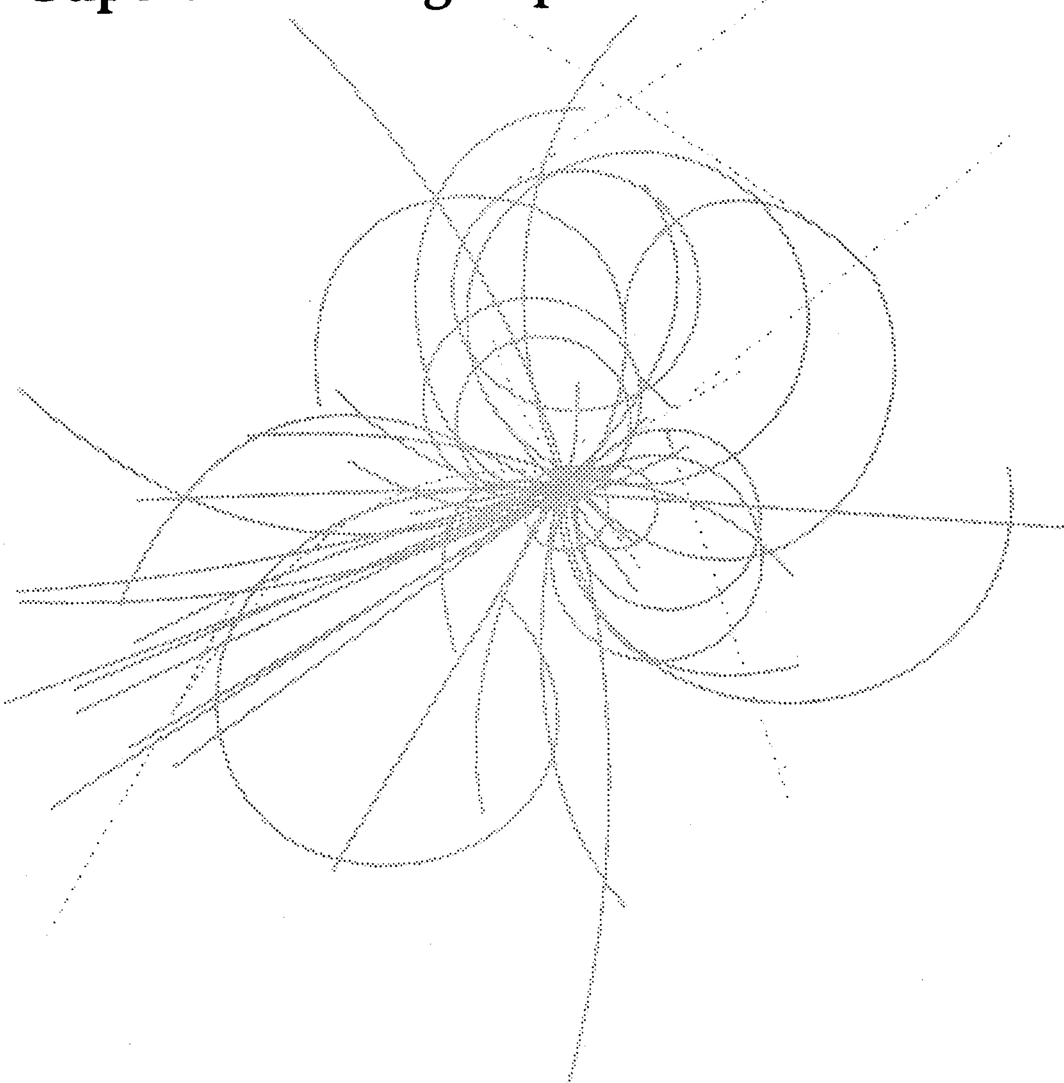

Reliability Analysis for LEB Ring Magnet Power System in SSC

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Abstract

The LEB ring magnet power system contains six subsystems, supervisory control, power supplies, regulation, DC bus, resonant cells, and fault sensing network. The system availability of the total LEB RMPS is required to be 0.999. The work in this paper is to allocate the overall LEB RMPS reliability requirement into reliability requirements for each of the subsystems and lower-tier items. The Feasibility-of-Objective technique combining with engineering experience is the key for the allocation. MIL-HDBK-217F is used to derate SCR components.

I Introduction

The superconducting super collider (SSC) is a technologically advanced high-energy physics research facility. The SSC complex is a cascade system including a linear accelerator and four synchrotron rings, LEB, MEB, HEB, and Collider. A successful mission of such a complex system depends on the reliability of all its cascade accelerators as well as all their subsystems.

The ring magnet power system (RMPS), including LEB RMPS, MEB RMPS, HEB RMPS and Collider RMPS, is one of subsystem of the SSC complex. In addition to the technical requirements, such as voltage, current, and operating waveforms, reliability requirements are also assigned to ring magnet power system. In this paper the LEB RMPS is used as an example to analyze the reliability allocation.

The LEB RMPS contains six subsystems: supervisory control, power supplies, regulation, DC bus, resonant cells, and fault sensing network. The work in this paper is to allocate the overall system reliability requirement into reliability requirements for each of the subsystems and lower-tier items.

A brief background review for the reliability analysis is given in Section II. An allocation technique, Feasibility-of-Objective, is applied to allocate the system reliability requirements in Section III. Reference [6] is used to derate the key components, thyristors, in Section IV. Summary and further discussions are given in Section V. The paper shows a very intuitional way of applying the reliability theory to practical engineering design.

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II Background

Three types of part failures take place within the life time of electronic equipment: quality defect failures, reliability failures, and wear-out failures. Part quality defect failures, which are the causes of infant mortality, can be reduced by strict quality control and burning in process. Electronic components usually do not experience wear-out failure, because they are normally replaced due to obsolescence before wear-out. The reliability failure induced by electrical and thermal stresses is the issue to be studied here.

During the useful life period of electronic equipment, the failure density function obeys Poission process:

$$f(t) = \lambda e^{-\lambda t} \qquad t > 0. \tag{1}$$

The cumulative failure function is derived by integrating the failure density function over a time period. It represents the probability of failure over the time period $t > 0$:

$$\begin{aligned} F(t) &= \int_0^t f(t)dt \\ &= 1 - e^{-\lambda t}. \end{aligned} \tag{2}$$

The reliability function gives the probability of survival over the time period $t > 0$.

$$\begin{aligned} R(t) &= 1 - F(t) \\ &= e^{-\lambda t}. \end{aligned} \tag{3}$$

The failure rate function $H(t)$ of the equipment is

$$\begin{aligned} H(t) &= \frac{f(t)}{R(t)} \\ &= \lambda. \end{aligned} \tag{4}$$

It represents the probability that a component will fail in the time interval $t + \Delta t$, given that it has survived to time t, where $t > 0$. The failure rate is constant for systems obeying Poission process.

If a system contains N subsystems, the reliability of the system is

$$R(t) = \prod_{i=1}^{N} R_i(t) = e^{-\sum_{i=1}^{N} \lambda_i t}, \quad (5)$$

where $R_i(t)$ is the reliability function of the i-th subsystem, λ_i is the failure rate of the i-th subsystem. Equation (5) shows a very important feature of non-redundant electronic system: the failure rate of the system is the arithmetic sum of the failure rate of all its subsystems, which is the basis of the analysis in this paper.

III Reliability Allocation

The reliability requirement is assigned to the LEB ring magnet power system. The task here is to specify the reliability for all subsystems such that the reliability for the whole system is satisfied.

Feasibility-of-Objective Technique

The Feasibility-of-Objectives technique[1] is employed to allocate the system reliability requirements. This technique was developed primarily for allocating reliability in repairable electromechanical systems. Subsystem allocation factors are computed as a function of numerical ratings of system intricacy, state of the art, mission performance time, and environmental conditions. Each rating, on a scale from 0 to 10, is estimated using engineering judgement based upon experience. The basic equations for a system with N subsystems are

$$\lambda_s T = \sum_{i=1}^{N} \lambda_i T, \quad (6)$$

$$\lambda_i = C_i \lambda_s, \quad (7)$$

$$C_i = \frac{w_i}{w}, \quad (8)$$

$$w_i = \prod_{j=1}^{4} r_{ji}, \quad (9)$$

$$w = \sum_{i=1}^{N} w_i, \quad (10)$$

where,$i = 1, ..., N$, $j = 1, ..., 4$, λ_s is system failure rate, T is mission duration, λ_i is the failure rate allocated to the i-th subsystem, c_i is complexity of subsystem i, w_i is composite rating for subsystem i, and r_{ji} is the j-th rating for subsystem i.

First Level

The LEB RMPS system tree is shown in Fig. 1. For simplicity, only one of the branches, the power supply branch, is indicated here, since the analysis for other branches will be similar. Along the indicated branch, reliability allocation takes three levels. The first level is from the LEB RMPS to its first level six subsystems: supervisory control, power supplies, regulation, DC bus, resonant cells, and fault sensing network. The second level is from the power supplies to its three subsystems: power distribution, SCR converters, and output filters. The third level is from the SCR converters to its three subsystems: power stage (45 thyristors), gate drives, and water cooling. The subsystem categorization is not unique, but highly depends on designer's preference. In this case, the subsystem categorization is formed according to the natural task groups.

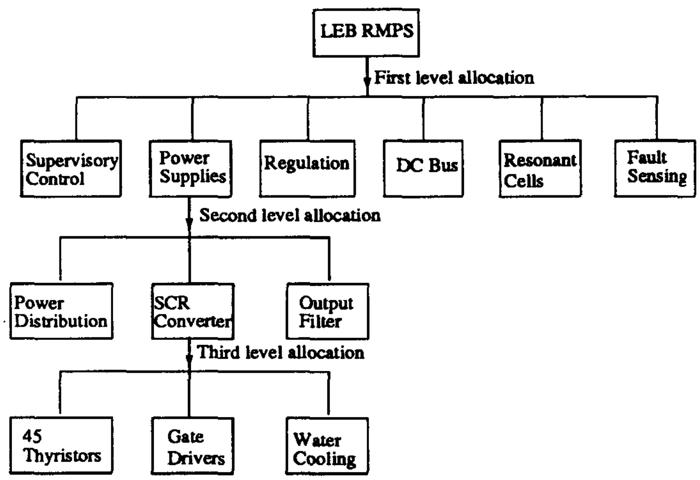

Figure 1: LEB RMPS structure

The reliability requirement assigned to the LEB RMPS is an availability[2] of 0.999. Availability of a system is defined as:

$$A = \frac{SUT - UDT}{SUT} = 1 - \frac{UDT}{SUT} = 1 - \frac{MDT}{MTBF} = 1 - MDT \cdot \lambda_s, \quad (11)$$

where SUT is scheduled up time, UDT is unscheduled down time, MDT is mean down time for repair, MTBF is mean time between failure and λ_s is the system failure rate.

$$MDT = \frac{UDT}{number - of - failures}, \quad (12)$$

$$MTBF = \frac{SUT}{number - of - failures}, \quad (13)$$

$$\lambda_s = \frac{1}{MTBF}. \quad (14)$$

The LEB RMPS has similar structure and scale as the Booster Synchrotron Gradient Magnet Power System in

Item	Intricacy (r1)	State of the art (r2)	Performance time (r3)	Environment (r4)	Overall Rating (wk)	Complexity (ck)	Allocated λ (per 10^6 hr)
Supervisory Control	6	3	10	1	180	0.263929619	600
Power Supplies	7	2	10	1	140	0.205278592	467
Regulation	8	4	10	1	320	0.469208211	1066
DC Bus	0.2	1	10	1	2	0.002932551	7
Resonant Cells	2	1	10	1	20	0.029325513	67
Fault Sensing Network	2	1	10	1	20	0.029325513	67
Total					682	1	2273

Figure 2: First Level Allocation

Item	Intricacy (r1)	State of the art (r2)	Performance time (r3)	Environment (r4)	Overall Rating (wk)	Complexity (ck)	Allocated λ (per 10^6 hr)
Power Distribution	1	1	10	1	10	0.071428571	33
Thyristor Converter	6	2	10	1	120	0.857142857	400
Output Filter	1	1	10	1	10	0.071428571	33
Total					140	1	467

Figure 3: Second Level Allocation

Fermi Lab; therefore, Fermi Lab failure data[5] are utilized to estimate the mean down time. The mean down time for the Fermi Lab Booster Synchrotron Gradient Magnet Power System is $MDT|_{Fermi} = 0.48(hour)$. The LEB RMPS is designed with unified modular structure, the mean repair time will be improved by 10%. The MDT used for SSC LEB RMPS is $MDT|_{SSC} = 0.44\ hour$. In order to meet the availability of 0.999 for the whole system, the system failure rate needs to be less than

$$\lambda_s = \frac{1-A}{MDT} = 2273/10^6 hours. \tag{15}$$

Numerical ratings of system intricacy (r_1), state of the art (r_2), mission performance time (r_3), and environmental conditions (r_4) for each subsystem, shown in Fig. 2, were determined according to the engineering experience[3][4]. The reliability requirements for six subsystems are estimated by the Feasibility-of-Objective technique discussed in Section II. The results are shown in Fig. 2. After the first level allocation, it is found that the power supplies must have failure rate less than $467/10^6 hours$ to achieve the overall LEB RMPS reliability.

Second Level Allocation

The power supply system is further divided into three subsystems: power distribution, SCR converters, and output filters. Numerical ratings for system intricacy (r_1), state of the art (r_2), mission performance time (r_3), and environmental conditions (r_4) for each subsystem are indicated in Fig. 3. The reliability requirements for these three subsystems are determined by Feasibility-of-Objectives analysis. The results are shown in Fig. 3. After the second level allocation, it is found that thyristor converters must have failure rate less than $400/10^6 hours$ to achieve the overall power supply system reliability.

Third Level Allocation

The SCR converter system is further divided into three subsystems: power stages (45 thyristors), gate drivers, and water cooling system. Numerical ratings for system intricacy (r_1), state of the art (r_2), mission performance time (r_3), and environmental conditions (r_4) for each subsystem are indicated in Fig. 4. The reliability requirements for these three subsystems are determined by Feasibility-of-Objectives analysis. The results are shown in Fig. 4. After the third level allocation, it is found that the 45 thyristors shall have failure rate less than $80/10^6 hours$ to achieve the overall SCR converter system reliability. Therefore, each individual thyristor must have failure rate less than $\lambda = 80/45 = 1.77/10^6 hours$.

Same concept and procedures are applicable for allocating reliability requirements along any branches and to any levels.

IV Component Derating

Thyristors are the key components for the power conversion. It is important to verify if the assigned reliability can be achieved and to decide how much derating is necessary

Item	Intricacy (r1)	State of the art (r2)	Performance time (r3)	Environment (r4)	Overall Rating (wk)	Complexity (ck)	Allocated λ (per 10^6 hr)
45 Thristors	3	1	10	1	30	0.2	80
Gate Driver	4	2	10	1	80	0.533333333	213
Water Cooling	2	2	10	1	40	0.266666667	107
Total					150	1	400

Figure 4: Third Level Allocation

to achieve it.

The failure rate for large disc type thyristor is given by [6]:

$$\lambda = \lambda_b \Pi_R \Pi_S \Pi_Q \Pi_E \Pi_T, \quad (16)$$

where λ_b is a base failure rate, Π_R is a current rating factor, Π_S is a voltage stress factor, Π_Q is a quality factor, Π_E is an environment factor, and Π_T is a temperature stress factor.

$$\lambda_b = 0.0022, \quad (17)$$

$$\Pi_R = (I_{T(RMS)})^{.40}, \quad (18)$$

$$\Pi_S = (\frac{V_{RWM}}{V_{RRM}})^{1.9}, \quad (19)$$

$$\Pi_Q = 2.4, \quad (20)$$

$$\Pi_E = 6, \quad (21)$$

$$\Pi_T = e^{-3082(\frac{1}{T_J+273}-\frac{1}{298})}. \quad (22)$$

The base failure rate for thyristor is determined by statistic studies. The current rating factor in Equation (18) shows that a larger current rating causes a reduction in reliability, because the thermal expansion is more severe for large diameter devices than for small diameter devices. On the other hand, if the current rating is too small, high current rating will cause over heating. Manufacturers provide

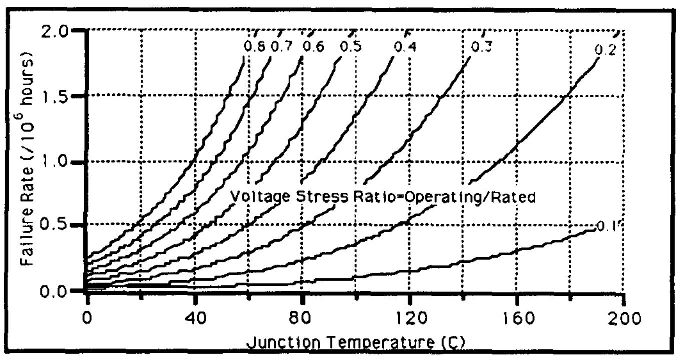

Figure 5: Failure Rate vs Voltage and Temperature Stresses

components with discrete levels of current ratings. A current rating nearest and above 0.7 derating is recommended by the Department of Navy[7]. [6] gives the quality factor values for standard commercial grade and military grades. It also gives the environment factor value for different application conditions, such as air conditioned, outdoor use, etc.. Among all the factors, only the voltage stress and the temperature stress factors are to be determined in the thyristors:

$$\lambda = 0.94(\frac{V_{RWM}}{V_{RRM}})^{1.9} e^{-3082(\frac{1}{T_J+273}-\frac{1}{298})}. \quad (23)$$

According to Fig.5, any combination of voltage and temperature stress below line $\lambda < 1.77$ will meet the failure rate requirement. However, there is a compromise between voltage stress and temperature stress. Larger voltage derating causes thyristor on-state voltage increase and component price increase, and lower junction temperature causes cooling system price increase. In the application of LEB RMPS, the voltage and temperature stresses are chosen to be 0.4 and $90°C$.

Similar analysis can be done for other components.

V Summary

The LEB RMPS design example demonstrates the concept and procedures for reliability allocation and derating. One important step in this technique is to use engineering judgement to determine the numerical ratings, r_1, r_2, r_3, r_4. Ratings are usually assigned by the cognizant design engineer based upon engineering knowledge and experience. However, they may also be determined by a group of engineers using voting method. Reference [6] provides a derating range. Within this range, an engineering judgement is necessary to determine which parameter to be derated more than another. The analysis technique can be used in the specification of electronic systems with any complexity and any number of levels.

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