EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2012-014

Impact of Modularity and Redundancy in Optimising the Reliability of Power Systems that Include a Large Number of Power Converters

Daniel Siemaszko, Serge Pittet
CERN, Geneva, Switzerland

Abstract

CERN is working on a new particle accelerator that will require a very large number of power converters. In that view, the reliability of the whole powering will be a major issue. The use of a redundancy and modularity may help increasing the overall machine availability. However, the reliability of the redundancy system must be high enough to add a significant improvement when compared to simple module systems. This paper suggests a comparative study of several modular and redundant configurations for optimising power converters reliability and draws some conclusion from what has been achieved in the LHC previous experience.

Presented at Presented at the 15th International Conference on RF Superconductivity, SRF2011
25-29 July 2011, Chicago, USA

Geneva, Switzerland

January 2012

Impact of Modularity and Redundancy in Optimising the Reliability of Power Systems that Include a Large Number of Power Converters

Daniel Siemaszko, Serge Pittet

CERN – European Center for Nuclear Research
Electronic Power Converter group (TE-EPC)
CH-1211 Geneva 23, Switzerland
Phone: +41 22 767 2279
Fax : +41 22 767 5300
serge.pittet@cern.ch

Abstract

CERN is working on a new particle accelerators that will require a very large number of power converters. In that view, the reliability of the whole powering will be a major issue. The use of a redundancy and modularity may help increasing the overall machine availability. However, the reliability of the redundancy system must be high enough to add a significant improvement when compared to simple module systems. This paper suggests a comparative study of several modular and redundant configurations for optimising power converters reliability and draws some conclusion from what has been achieved in the LHC previous experience.

Keywords
Modularity, Redundancy, Large system availability, Power converters reliability, Saved failure rate.

1. Introduction

CLIC (Compact Linear Collider) is an on-going study including CERN and several contributors which aim to build a new type of particle accelerator, aiming for energies that have never been reached so far. Its principle relies on the energy transfer between a drive beam and the main beam in dedicated RF structures. The production of the drive beam will require more than a thousand high voltage pulsed modulators. The energy transfer system between the drive beam and the main beam will contain more than 40'000 magnets to be powered with individual dedicated currents.

The focus of this study is on the optimisation of the reliability of the whole powering system for maximising the overall machine availability. The amount of power converters would bring the overall mean time between failures to few hours only, therefore a failure tolerant strategy using redundancy and/or modularity becomes compulsory [1-5].

Redundancy can be achieved within several configurations, namely serial, parallel or with hot spares. Each strategy has its own technical issues when it comes to accuracy of its redundant system and the handling of failures. For instance, when a module fails, its bypass must be ensured by a dedicated crowbar in the serial configuration, or by the opening of the circuit in a parallel configuration.

The efficiency of the bypass is here defined by the probability of saving a failure by redundancy. Depending on its rate, the use of modular/redundant systems may add more failures to the global system than without using redundancy. At the end, the reliability of a system relies mainly on its ability to bypass its failed components.

Based on CERN previous experience of redundant systems implemented in LHC, this paper has the purpose to give some directions to go for implementing future accelerator power systems.

2. Redundant configurations

Within the following configurations, the most important aspect for reliability is the accuracy of the redundancy system. When a failure occurs, the isolation or the bypass of the failed part must be ensured in order to keep on operating the whole power converter. Three configurations are studied.

2.1. Serial redundancy

In a serial configuration, as in Fig. 1 and typically in an MMC topology [6], all converters are rated for the same nominal current and the load voltage is shared in between all active modules. The redundant modules are either all connected, so all modules are operating at reduced voltage, or bypassed and inserted in the system when a failure occurs.

The bypass is a crowbar, turned on actively or waiting on the detection of a sudden voltage rise. Its function is both a protection system and an active bypass from the remaining modules. The reliability of the bypass switch is crucial in the system. It must act as a protection crowbar but it must not be turned on during operation.

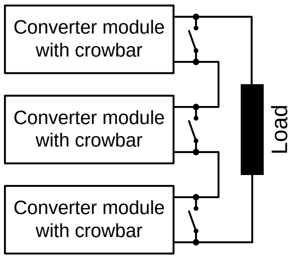

Fig. 1. Serial redundant configuration.

2.2. Parallel redundancy

In a parallel configuration, as in Fig. 2 and typically in interleaved converters [3], all modules are rated for the nominal operation voltage, and the load current is shared in between all active modules.

The bypass switch must operate as a fuse when one of the modules fails into short circuit so it does not draw the current from all other working modules. It must be sensitive enough for opening on sudden current surge, but must stay closed when a neighbour module fails.

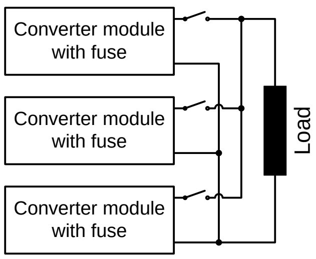

Fig. 2. Parallel redundant configuration.

2.3. Hot spare

The principle of the hot spare approach is to keep a working power converter ready for replacing failed unit. When any failure is detected, the power converter is directly replaced by the hot spare through human action or through a connection system as presented in Fig. 3. This method reduced the mean time to repair (MTTR) to a minimum since it allows running the converters immediately at once and postponing the diagnosis phase.

The connection switches presented in Fig. 3 can be mechanical but their configuration grows in complexity when one spare covers more power converters. If one converter of a group fails, the hot spare can replace any converter of the group by bypassing the failed converter and connecting the spare to the corresponding load. This method is easily combined with a modular/redundant approach.

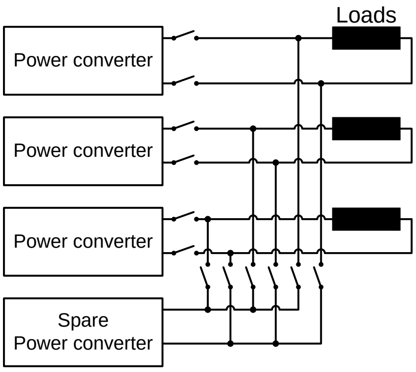

Fig. 3. Hot spare configuration.

3. Effect of redundancy/modularity on reliability

Common sense would suggest that increasing redundancy in a power system is the way to ensure its reliability. It is not necessarily true, since adding modules to a power converter lowers its mean time between failures proportionally and relies on the reliability of the bypass system. On the other hand, modularity increases the reliability of individual modules. Indeed, the reliability of a semiconducting device depends on its temperature which is kept lower when the power is shared in between modules with some derating [7].

A simple analytic model for analysing power systems reliabilities, as suggested in [8], shows the impact of the mentioned parameters on the global reliability and availability of the whole system.

3.1. Parameters

The reliability of a power converter, containing N modules plus R redundant modules, is a function of the reliability of its modules commonly denoted as a failure rate λ. The factor κ standing for the proportion of failures saved by redundancy has been introduced in [8] for assessing the accuracy of the redundancy system in percents. A high value stands for a highly accurate system that does not induce additional failures to the system. Finally, the horizon time h is defined as the mean time between technical stops for the whole accelerator during which the failed modules that have been saved by redundancy can be replaced. The mean time to repair includes the machine cool down, the time to call a technician and let him go into the tunnel for changing the failed module. Finally, a system of 1000 converters is here considered. The values used for the study are given on Table 1.

Table 1
Parameters for estimating the reliability of power converters

Parameters	Indices	Values / Range
Number of modules	N []	1-4
Number redundant modules	R []	0-2
Failure rate in individual modules	λ [h^{-1}]	$3 \cdot 10^{-6}$
Failures saved by redundancy	κ [%]	60-96
Horizon	h [days]	10-200
Mean time to repair	MTTR [h]	5
Number of converters	N_{PC} []	1000

The failure rate is assumed to be constant, as the machine life time is about 10 years. The design of the power converters will be done in such a way that the operation time fits the flat top reliability bathtub curve as illustrated in Fig. 4. The early age effects will not be considered here.

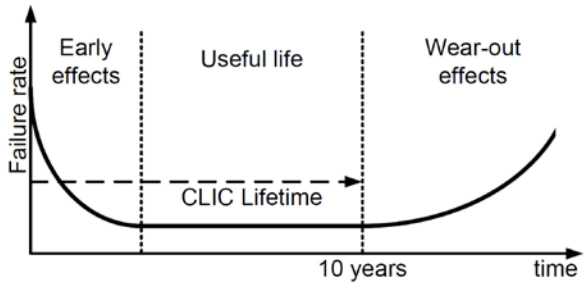

Fig. 4. CLIC life time.

3.2. Reliability model

Several equivalent models can be used for estimating the reliability of a modular power converter [8]. The relationship given by Equ. 1 is based on a common standard combinatory model [9], written as a function of all parameters given in Table 1. κ is the key parameter describing the accuracy of the redundancy system. Its significance in terms of components is discussed later in this paper.

(1)

with :

The distribution of failures is assumed to be independent identically distributed which allows the use of Markov chains for computing the reliability of a power converter as well as the use of Poisson failure distributions. As Shown in [8], all three models give similar results when it comes to the reliability of the power converter itself.

3.3. Reliability of redundant configurations and impact on availability

The relationship given by Equ. 1 is computed for several configurations of modules and redundant modules. As illustrated by the following figures, the parameter κ has as a crucial impact on the reliability of the whole power converter. The study has been carried out with the assumption that the reliability of one module is constant no matter how modular is the converter. It is also assumed that failed modules are replaced during technical stops, even when saved by redundancy.

As illustrated by Fig. 5, if the reliability of the bypass system is poor, namely κ=60%, then redundancy adds in fact more failures than the simple configuration with a single power converter. The reliability of any configuration containing several modules is brought down due to the fact that statistically there is more failure with the use of more modules and the machine availability is therefore strongly affected.

Fig. 6 shows that when κ=80%, some redundant configurations become more reliable than the single module converter. However, having two redundant module still adds more failures than using only one. In the meanwhile the availability prediction shows that the improvement allowed by redundancy is not yet significant.

Finally, when κ=96%, as illustrated in Fig. 7, then redundancy adds a significant improvement in both reliability and availability. This shows the importance of the careful design of the bypass system and the failure diagnosis. This set also shows that the most reliable configuration remains a single module power converter with one redundant module only, independently from the κ factor.

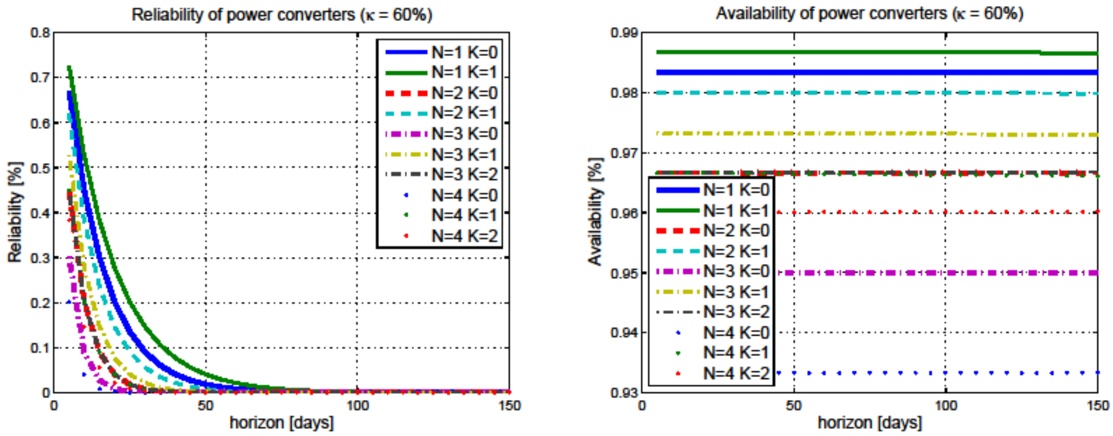

Fig. 7. Reliability and availability of a system of modular redundant power converters with κ=60%.

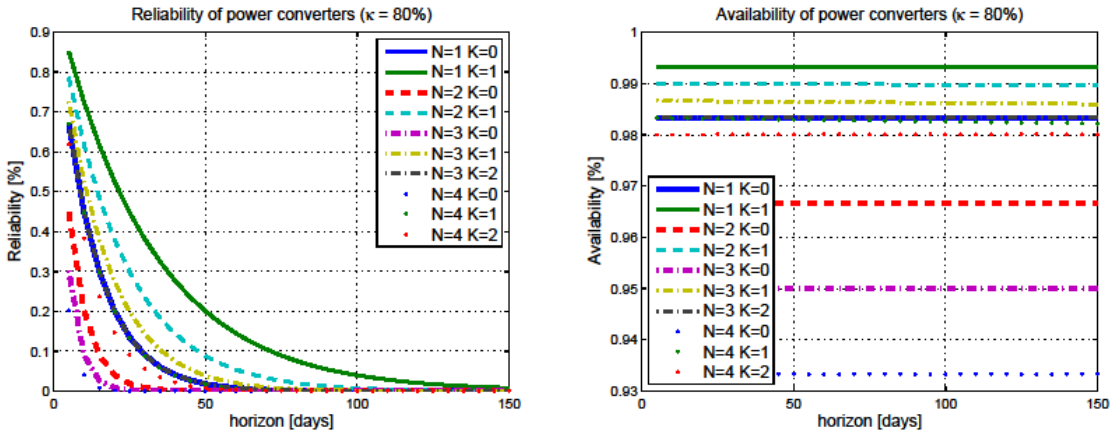

Fig. 6. Reliability and availability of a system of modular redundant power converters with κ=80%.

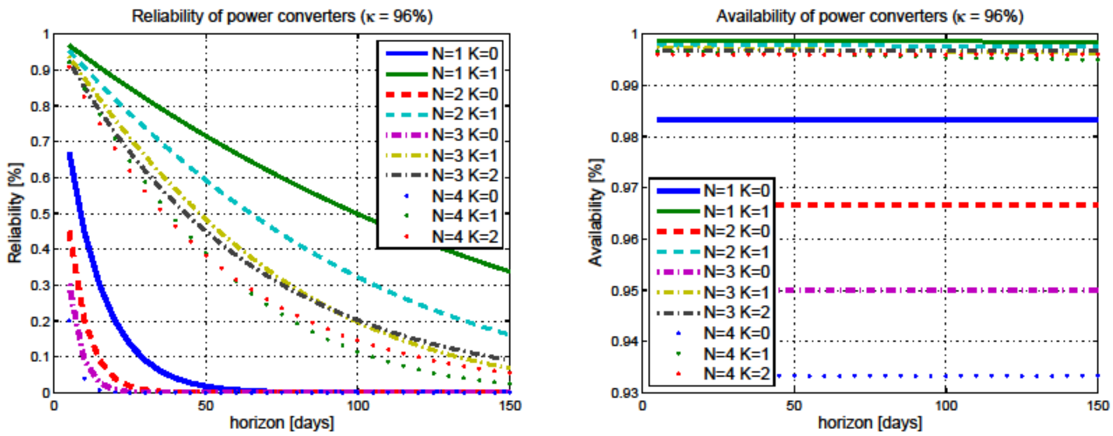

Fig. 5. Reliability and availability of a system of modular redundant power converters with κ=96%.

4. Integration of real components and bypass systems

It is not a simple task to give a proper figure for assessing the reliability of a bypass system, since it is supposed to work on seldom occasions, namely when a failure occurs. It has been shown in previous figures that the reliability of a given redundant system is very sensitive to the value given to parameter κ, but its adequate prediction relies on probabilistic events. Besides, actual reliability figures from physical components are rarely available if not drawn for specific conditions only. However, statistics can still be deduced from existing systems and then included in the design stage of failure tolerant systems.

4.1 Probability of saving a failure: meaning of parameter κ

The probability of saving a failure has an assigned value that can be measured on existing systems. This parameter relies on different procedures including diagnosis and actions, having a whole set of multiple conditional probabilities as described in [10]. It also relies on the reliability of the bypass system itself, which usually consists of a control system together with one or several physical components.

The value of κ is defined statistically when analysing failures from a given system. When it comes to the design stage of a failure tolerant system using redundant components, each type of failure must be predicted with their own failure handling procedure.

4.2 Reliability of bypass systems

A crowbar system built with semiconductors has a typical failure rate of some 100FIT [11]. When built with IGBTs, one can use reliability models as presented in [5]. Thermal and environmental effects can be predicted and their impact on the reliability of a semiconducting device is well known.

The reliability of a fuse, breaker, or disconnecting switch in network applications shows failure rates of some 1,000FIT [12]. Compared to classic breaker system, a more reliable way seems to rely on vacuum technology. According to [13], some vacuum interrupters show MTBF values of some 15,000 years (meaning a failure rate of some 7 FIT).

Those values tend to show that a crowbar system will be preferred to a circuit breaker or fuse based bypass system because of their smaller failure rate, meaning that a serial connected modular system would be preferred to a parallel system. However, a control circuit, with usually some 1,000FIT, is still needed and might ignite the crowbar on unwanted occasions. If a parallel system is still wanted then vacuum technology seems to be the most reliable solution, besides vacuum circuit breakers seem to be fully controllable [14].

4.3 Study of data from LHC experience

The Large Hadron Collider (LHC) built at CERN has been running for few years now. In many places redundant systems have been implemented in a parallel configuration. Concise data is carefully collected regarding their failures and the reliability of their redundant systems.

The used modules are basic rectifiers with an inverter on the grid side and an HF transformer with rectifier modules on the load side. The number of implemented modules, between 2 and 8, depends on the current to reach in the corresponding magnets. Every converter is implemented with one redundant module. During operation, all modules are operating at reduced power, and when a failure occurs, the failed module is bypassed. Most of failures are simply bypassed through control by setting the reference to zero, but a fuse is still implemented on the load side in case of the failure of the output rectifier.

There are several statistics that can be drawn, namely on converter failures and accuracy of redundancy. Since the power converters have been put to operation only recently, 'early age' effects are still present in the failure occurrences. In the 935 considered converters, for 300 days of operation there were some 103 failures in which 30 needed an intervention, if failures due to water system and grid flickers are not considered. When comparing the number of failures with the failures that actually required intervention, there is a factor of about 70% of saved failures. This proportion does not exactly correspond to the rate that has been defined with factor κ, because it also includes the failures occurring in converters where redundancy has been already activated for a previous failure. Besides, this proportion includes different types of N+1 converters with the number of modules ranging from 2 to 8. This figure is still assuring since it definitely shows that redundancy works and reduces the number of actual interventions on the power converters.

A curious event shows that some thyristors are unexpectedly triggered with a rate of 5 months for 100 units. This corresponds to an MTBF of 360,000 hours (or some 2,700FIT) per thyristor. The failure mechanism is not yet understood but it appears that the installed fuse do not burn as expected with the occurrence of a failure in either the input stage or the output stage rectifier. The problem is due to the fact that the superconductive loads have very low impedance which is comparable with the load of fuses. Then in short-circuit, the fuse cannot blow since its current is not sufficient.

In both ways, the bypass system that is the most efficient in the current implementation is the simple control of the reference to zero, which works because of the HF isolation stage between the grid and the load.

5. Conclusions

This study shows several redundant configurations that can be applied in order to improve the reliability of a system containing a large number of power converters. Regarding the reliability of the bypass system, used for saving the converter by redundancy, one may prefer a serial configuration to a parallel if the crowbar technology appears to be more accurate than the use of a fuse. However, when the output load impedance is low, a parallel configuration should be implemented. In this case, the use of a fuse to bypass a failed module doesn't seem appropriate. Vacuum technology used in controlled circuit breaker seems to give much more promising results.

As for modular and redundant configurations, it appears that the best reliability figures are obtained with the use of one redundant module only. It seems that the use of more modules adds more possible failures to the system than it actually saves. When implementing a system of power electronics converters, one may tend to value simple and solid solutions.

References

[1] P. Bellomo, A. Donaldson, D. MacNair, B-Factor intermediate DC Magnet Power Systems Reliability Modelling and Results, Particle Accelerator Conference, Proccedings on, Chicago, 2001.

[2] P. Poure, P. Weber, D. Theilliol, S. Saadate, Fault-tolerant Power Electronics Converters: Reliability Analysis of Active Power Filter, Industrial Electronics, 2007, ISIE 2007, IEEE International Symposium on, Vigo, 2007.

[3] A.D. Dominguez-Garcia, P.T. Krein, Integrating Reliability into the Design of Fault-Tolerant Power Electronics Systems, Power Electronics Specialists Conference, 2008, Rhodes, PESC 2008.

[4] Y.W. Yak, T.S. Dillon, K.E. Forward, Bounded-set Approach to the Evaluation of the Reliability of fault-tolerant Systems. Part 1: Methodology, powered spares, Computers and Digital Techniques, IEE Proceedings, 1985.

[5] M.C. Magro, S. Savio, Reliability and availability performances of a universal and flexible power management system, Industrial Electronics (ISIE), 2010 IEEE International Symposium on, Bari, 2010.

[6] R. Marquardt, Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications, The 2010 International Power Electronics Conference (IPEC), Sapporo, 2010.

[7] C. Nesgaard, M.Andersen, Efficiency improvement in redundant power systems by means of thermal load sharing, Applied Power Electronics Conference and Exposition, 2004, APEC '04, Nineteenth Annual IEEE, 2004.

[8] D. Siemaszko, M. Speiser, S. Pittet, Reliability Models Applied to System of Power Converters in Particle Accelerators, 14th European Conference on Power Electronics and Applications, Nottingham, 2011.

[9] IEEE Std. 1413.1-2002, IEEE Guide for selecting and using reliability predictions based on IEEE 1413, 2002.

[10] J.J. Meeuwsen, W.L. Kling, Substation Reliability Evaluation including Switching Actions with Redundant Components, IEEE Transactions on Power Delivery, Vol.12, No. 4, October 1997.

[11] A. Welleman, W. Fleischmann, High Voltage Solide State Crowbar and Low Repetition Rate Switches, Pulsed Power symposium, 2005. The IEE, Hampshire, 2005.

[12]C. A. O'Meally, J. Burke, The impact of a ¨Fuse Blow¨ Scheme on Overhead Distribution System Reliability and Power Quality, Rural Electric Power Conference, REPC '09, Fort Collins, 2009.

[13] H. Schellekens, G. Moesch, J-M. Biasse, T. Hazee, B. Cabaret, Impact of Vacuum Switch-disconnectors on Reliability of MV distribution networks, 2010 China International Conference on Electricity Distribution, 2010.

[14]P.G Slade, W.P. Li, S. Mayo, R.K. Smith, E.D. Taylor, Vacuum interrupter, high reliability component of distribution switches, circuit breakers and contactors, Journal of Zhejiang University SCIENCE, 2007.