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MACHINE PROTECTION SYSTEM FOR TEX FACILITY

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Abstract

In the context of LATINO [1] (Laboratory in Advanced Technologies for INnOvation) and Rome Technopole Projects [2] founded by Regione Lazio and NextGenerationEu and directly involved in the EuPRAXIA@SPARC_Lab flagship project, a X-band testing facility (TEX) has been established at Frascati National Laboratories of INFN. TEX is dedicated to the examination of radiofrequency X/C-band, aiming to develop and test the technologies and systems of a particle accelerator operating under such conditions. Given the complex nature the devices linked to the project and the advancement of technology to the forefront of the state of the art, the Manchine Protection System (MPS) characterized by high reliability, availability and safety in accordance with IEC-61508 standards is imperative to have. Currently a prototype MPS designed to autonomously initiate procedures to control operations and avert anomalies is in development. An EPICS supervisor oversees the management of all devices and monitoring connected subsystems. Additionally, a real-time interlock system based on distributed FPGA is employed to swiftly respond to vacuum and RF interlocks before the next RF pulse.

INTRODUCTION

TEX (TEst stand for X-band) [3] is a X-band (11.994 GHz) test facility located at Frascati National Laboratories of INFN aimed at development RF structures and systems for X-band for high power in preparation for EuPRAXIA@SPARC_LAB activities [4] [5]. It is also becoming a user facility with the C-band linac construction called Fringe. The TEX layout is composed by a control room, a bunker, a rack room with the principal control systems, the data record systems under EPICS protocol and the X/C-band LLRF chassis. The power RF system is completed by the modulator zones. In order that each system correctly works and not causes damage, a Machine Protection System (MPS) is in development. The MPS is a system controlled under FPGA ables to monitor the interlocks and prevent the anomalies interfacing with the machine timing and the Personnel Safety System (PSS) managing independently the safety maneuvers according to the repetition rates (100 Hz, 400 Hz). The devices under MPS control are vacuum and RF power systems and all sensitive parameters that need to be checked to safeguard the functioning of the machine (BOC temperatures etc.). The setup is designed to respect the IEC 61508 standard in terms of reliability, availability and safety.

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TEX FACILITY

The TEst stand for X-band (TEX) framework is based on three pulsed solid state modulators feeding an X/C-band klystron tubes. The layout is shown in Fig.1. The LLRF

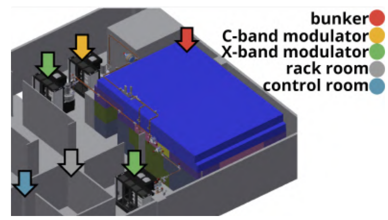

Figure 1: TEX layout.

pulse generated by a Libera Low Level RF systems located on rack room are amplified by a commercial solid state driver amplifiers realized by Microwave Amps [6]. The power source produce up to 50 MW X-band RF pulses with 100 Hz repetition rate and 25 MW X-band and 20 MW C-band RF pulses with 400 Hz repetition rate. The klystron operating at 100 Hz is powered by a ScandiNova k400 and the klystrons operating at 400 Hz ares powered by a ScandiNova k300 solide state modulator located on modulator zones [7]. Each modulator is equipped with an integrated Backhoff PLC to detect interlocks. The LLRF chassises have an integrated interlock detection system linked to the measurement of the VSWR. The high vacuum system is composed by NEG-Ion Pumps (IP) and Cold Cathode (CC) vacuum gauges. The CCs are managed by 9 Pfeiffer TPG500 [8] controllers equipped with ethernet channels for communication. The IPs are managed by 4 Agilent 4UHV [9] controllers and by 27 Agilent IPCMini controllers also equipped with ethernet channels. They are located at rack room. Inside the bunker there are 2 X-band accelerating structures, a electron gun [10] and C-band accelerating structure (Fringe), two pairs of 3D printed RF loads for X-band lines and a dump to waste the energy of the Fringe electron beam. A diagnostic system for X-band line composed by Faraday cup downstream and upstream, toroid and Cherenkov BLM is also tuned. The facility is equipped with two dry coolers to ensure a functional temperature and guarantee correct heat dissipation. To monitor the temperature sensitive devices the PT100 probes are allocated on the modulators, three for each klystron, and on the X-band BOC placed on the bunker roof. The data storage and control system is manage on EPICS framework deployed on IOC. EPICS generates Process Variables (PV) starting from raw data (signals from sensors) according to the Channel Access protocol used to communicate with the network using ethernet ports. The all

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systems are managed using user interfaces located at control room.

MPS PROJECT OVERVIEW

The manuscript goal is to describe the MPS project prototype, a Machine Protection System [11] to implement on TEX facility. This system in addition to detect interlocks, activates the optimisation operations, monitors performances and prevents anomalies by interfacing with both the machine timing and the Personnel Safety System (PSS) [12]. To ensure that the MPS is safed in terms of functional safety, i.e. to guarantee the correct system functioning and to adopt the necessary risk reduction measures, it has to comply with the IEC 61508 standard [13]. This standard establishes requirements starting on risk analisys to ensure that systems using electrical, electronic or programmable electronic (E/E/PE) elements are designed, implemented, operated and maintained to provide the required Safety Integrity Level (SIL) guaranteed by a Safety Instrumented Function (SIF). The project flow, described by first part of V-model shown in the Fig. 2, involves the creation of the prototype starting from the *Verification Phase* establishing the necessary system requirements and taking into account the specifications according to the preliminary requirements.

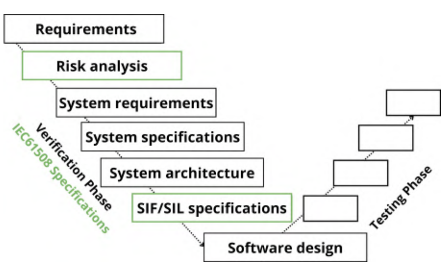

Figure 2: Project flow (V-model).

Requirements and Risk Analysis

MPS for TEX must be able to keep under control the following subsystems schematized in the Fig. 3.

These subsystems have to be classify in terms of timing re-

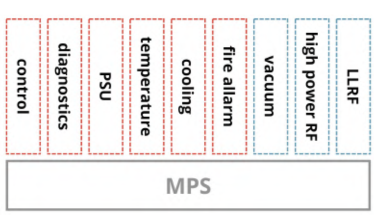

Figure 3: MPS controlled systems.

sponse in order to define the MPS requirements. The critical subsystems defined request fast interlock response and are highlighted in yellow; less critical subsystems are identified in blue, in accordance with the overall configuration analysis. The supervision of these structures is aimed at guaranteeing the integrity of all machine devices, with particular attention to protection of the klystrons ceramic windows.

System Requirements (SR)

The starting point for advancing the V-model of the project aimed at defining the MPS architecture was to specify the System Requirements (SR). The MPS should be able to monitor and record vacuum, RF, temperature and diagnostic signals and provide automatic procedures to manage operations in response to potential problems. All procedures have to be activated without conflicts with the PSS and fire allarm enabling signals and according to repetition rates.

System Specifications (SS)

According to the V-model, after the system requirements definition the System Specifications (SS) were set. The goal was to draw up the functional specifications and devices to be used for the final creation of the prototype. At the first time, the main control system to provide automation operations according to response time constraints has to be composed by CPU, FPGA and an I/O interface. Such a system can be implemented using 2 NI cRIO-9057 controllers [14] with Intel dual-core 1.33 GHz, 4GB SSD, Xilinx Artix-7 40 MHz programmed using LabVIEW. One of these deals exclusively with monitoring the temperature signals from the PT100. Different types of I/O modules as NI-9425, NI-9220, NI-9401, NI-9476 and NI-9216 [14] are used to capture/send different type signals. All devices have to be linked to cRIO from EPICS IOC according to Channel Access protocol. The control room must to monitor the MPS activity using LabVIEW User Interfaces (UI).In the circumstance of power failure event, the Power Supply Units (PSU) connected to both cRIO have to be connected to an Uninterruptible Power Supply (UPS) in order to guarantee system continuity for at least ten minutes after its deactivation. The connection between the UPS and the cRIO must be monitored from MPS with a specific watchdog signal. Furthermore, the waveforms of signals coming from diagnostics system have to be controlled using the specific algorithms with detection mask implemented on FPGA.

System Architecture

Once the System specifications drawn up, the system achitecture shown in Fig. 4 was defined. It is divived to 4 macroblocks. The devices under MPS control, linked using Channel Access protocol to EPICS IOC, communicate with cRIO. All the system is monitoring from LabVIEW User Interfaces.

FUNCTIONAL SAFETY

To comply with IEC 61508, during the definition of the system architecture and risk analysis, the Safety Instrumented Functions (SIF) for the Safety Instrumented System (SIS) and, for each of them, the Safety Integrity Level (SIL) were defined. The project SIS represents the MPS. The MPS can be classified as a Safety Instrumented

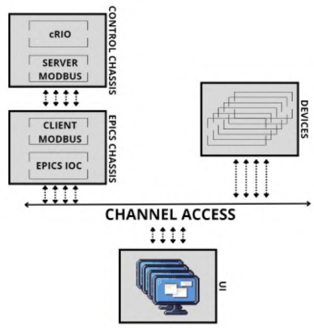

Figure 4: System architecture.

System (SIS) because was designed to preserve the integrity of the machine from hazardous conditions. For the SIS, the Functional Safety Functions shown in the Fig. 5 were defined: a real-time control and intervention on critical acceleration systems (SIF-1) and a supervisor (SIF-2) to monitoring the correct systems functioning and intervenes in front of interlock event using specific control routines. Based on fixed Risk Matrix (likelihood versus hazard

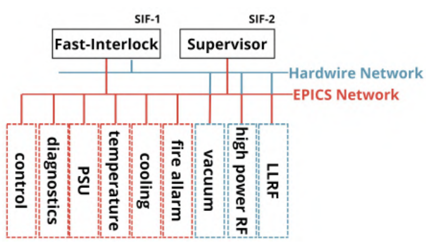

Figure 5: Functional Instrumentation System (SIF).

consequences) was possible to define the SIL required for a SIF. For both systems the likelihood of the hazard was assumed *Almost certain* while the consequences of the hazard was assumed *Minor*. The safety functions requested SIL-1. In the continuous mode the probability of failure (%) for SIL-1 must be between 10E-6 and 10E-5 [15].

SIF/SIL Specifications

During the MPS prototype study several factors had to be taken into consideration linked to feasibility and applicability of the project. In particular, we had to ensure the reliability of the system. The reliability is the failure system probability (%) under specific operative conditions into fixed timing window. From Risk Matrix the requested system reliability was established into 10E-6 and 10E-5 (SIL-1). To calculate this parameter is important to define the system availability. It is the probability that the system will remain active regardless of the number of failures already suffered. If the MPS prototype have not to ensure the requested reliability according to the IEC 61508 standard, it is necessary to modify the system architecture by introducing devices redundancy. The availability depend on the Mean Time Between Failures (MTBF) [15] of the system. From the failure rate it follows that the Mean Time Between Failures (MTBF), the average time between one failure and next, was between 10E5 h and 10E6 h for both SIF. Having defined the Mean Time To Repair (MTTR) as the average downtime divided by the number of faults expressed in hours and set at 30 days (720 h), the availability (calculated on the minimum MTBF in hours) was given by the Equation 1.

$$availability = \frac{MTBF}{MTBF + MTTR} \cong 99,9\% \qquad (1)$$

To calculate the reliability of the overall system it was necessary to consider the architecture of the system: the equivalent reliability of two objects in parallel increases compared to the reliability of the objects taken individually while that of two objects in series decreases. Once the overall Reliability Block Diagram [16] of the MPS system visible in Fig. 6 had been defined. The reliability of the system and therefore the MTBF was calculated on a useful life time of 20 years in the Equations 2 and 3. The power supply unit is a redundant and fail-safe system therefore it is not necessary to take it into consideration in this specific case.

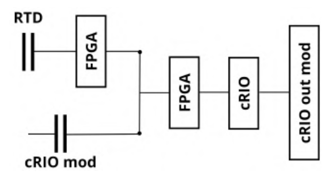

Figure 6: Reliability Block Diagram of MPS.

$$reliability = 2.66 \cdot 10^{-6} \qquad (2)$$

$$MTBF = 376237h \qquad (3)$$

The results was in line with the wanted requirements (SIL-1) therefore the system did not require redundancy. The probability that there will be one dangerous failure per hour in 20 years due to the failure of the MPS system is equal to 0.000266 %.

CONCLUSION

The philosophy behind the TEX MPS is to provide a fully automated system capable of operating accelerator equipment independently of operator activities, without impacting uptime. For these reasons, to manage the control of the devices under the MPS we chose to use FPGA controller because it is capable of running the software under specific timing requirements and providing the right reliability according to current regulations (IEC 61508). The first phase of the project described in this manuscript has been concluded. The software architecture project and the linked wiring are being developed.

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