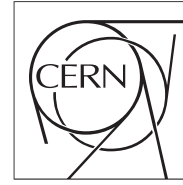


The Compact Muon Solenoid Experiment
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The CMS ECAL Control and Safety Systems Upgrades during the CERN LHC Long Shutdown

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Abstract

The Electromagnetic Calorimeter (ECAL) is one of the sub-detectors of the Compact Muon Solenoid (CMS), a general-purpose particle detector at the CERN Large Hadron Collider (LHC). The CMS ECAL Detector Control System (DCS) and the CMS ECAL Safety System (ESS) have supported the detector operations and ensured the detectors integrity since the CMS commissioning phase, more than 10 years ago. Over this long period, several changes to both systems were necessary to keep them in-line with current hardware technologies and the evolution of software platforms. The acquired experience of long-term running of both systems led to the need of major modifications to the original design and implementation methods. Such interventions to either systems, which require mid- to long-term validation, result in a considerable amount of downtime and therefore can only be performed during long LHC shutdown periods. This paper discusses the software and hardware upgrades to be carried out during the LHC Long Shutdown 2 (LS2), with emphasis on the evaluation of design choices concerning custom and standard industrial hardware.

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THE CMS ECAL CONTROL AND SAFETY SYSTEMS UPGRADES DURING THE CERN LHC LONG SHUTDOWN 2*

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Abstract

The electromagnetic calorimeter (ECAL) is one of the sub-detectors of the Compact Muon Solenoid (CMS) experiment, a general-purpose particle detector at the CERN Large Hadron Collider (LHC). The CMS ECAL detector control system (DCS) and the CMS ECAL safety system (ESS) have supported the detector operations and ensured the detector's integrity since the CMS commissioning phase, more than 10 years ago. Over this long period, several changes to both systems were necessary to keep them in-line with current hardware technologies and the evolution of software platforms. The acquired experience of long-term running of both systems led to the need of major modifications to the original design and implementation methods. Such interventions to either systems, which require mid- to long-term validation, result in a considerable amount of downtime and therefore can only be performed during long shutdowns of the experiment. This paper discusses the software and hardware upgrades to be carried out during the LHC long shutdown 2 (LS2), with emphasis on the evaluation of design choices concerning custom and standard industrial hardware.

INTRODUCTION

The electromagnetic calorimeter (ECAL) is one of the sub-detectors of the Compact Muon Solenoid (CMS) [1] experiment, a general-purpose particle detector at the CERN Large Hadron Collider (LHC) [2]. The CMS ECAL is composed by three partitions: barrel (EB), endcaps (EE) and preshower (ES). The sub-detector control and safety systems were designed according to the individual requirements of each partition.

The EB and EE partitions have similar hardware and software requirements for the control and monitoring of the powering systems, monitoring of the on- and off-detector environment, and protective/safety actions. Therefore, an integrated Detector Control System (DCS) [3-4] and the so-called CMS ECAL EB/EE Safety System (ESS) [3-4] were implemented for these partitions.

The ES DCS was implemented separately and integrated with the EB/EE only afterwards at the supervisory layer, while the ES safety system is based on the CMS tracker safety system [5] architecture and has no integration with

the ESS. The CMS ECAL ES safety system is not discussed in this paper.

To keep the control and safety systems in-line with the current hardware technologies, the evolution of software platforms and new sub-detector operational requirements, several modifications to their original design have been applied over the past 10 years. Furthermore, the experience acquired through the sub-detector's daily operation also allowed the identification of improvements and extensions to these systems.

Prior to any modification to the control and safety systems, a full analysis of their impact to the sub-detector operation is performed. Minor modifications, such as improvements to user interfaces, are transparent and can be applied at any time. Modifications requiring short-term validation, that might disturb or interrupt the sub-detector operation, are applied during the LHC technical stops (TS), which normally last for one or two weeks. Minor modifications to the core of either systems or requiring mid-term validation are scheduled for the LHC year-end technical stops (YETS), which normally last for a few months. Major modifications requiring long-term validation can only be carried out during the LHC long shutdown (LS) periods, which last for a few years.

This paper provides short descriptions of the CMS ECAL DCS and ESS with references to previous publications where further details can be found. The main focus of this paper will be on the major upgrades which are being carried out during the LHC long shutdown 2 (LS2).

THE CMS ECAL CONTROL SYSTEM

Software

For the high-level process supervisory management, the supervisory control and data acquisition (SCADA) architecture was implemented with the Siemens WinCC Open Architecture (WinCC OA) [6] control system toolkit. To add specific functionalities, CERN Joint Controls Project (JCOP) [7] and CMS DCS [8] frameworks are extensively used. The control software runs in two redundant sets of three servers, partitioned in individual components per sub-system or service. The integration of these components into a single application is realised with an additional component called the CMS ECAL Supervisor, which uses a finite state machine (FSM) mechanism to summarize the sub-systems status per sub-detector partition and to issue/propagate commands to the hardware. In addition, the

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CMS ECAL Supervisor also handles the protective actions, by identifying potentially harmful scenarios and bringing the sub-detector to a safe state prior to safety actions at the hardware layer. The CMS ECAL DCS is integrated to the CMS DCS through the same FSM mechanism, allowing the CMS technical shifter (operator) to perform a pre-defined set of actions on the EB/EE/ES partitions. Further details regarding the CMS ECAL DCS software and the preventive/protective actions are available in [3].

Hardware

The control system hardware comprises the interfaces between the CMS ECAL DCS software and the powering systems, the temperature and humidity readout hardware, and all the other devices used to extend monitoring and controls at the infrastructure level (i.e. devices to read out the internal parameters of the power factor correction (PFC) units for the low voltage (LV) power supplies, devices to remote power cycle the high voltage (HV) crates/boards using hardwired signals, etc).

To allow for redundancy at the software level, all hardware interfaces were replaced or adapted to Ethernet. Further details regarding the CMS ECAL DCS hardware are available in [3].

THE CMS ECAL EB/EE SAFETY SYSTEM

The safety of the CMS ECAL EB/EE partitions is ensured by a fully redundant programmable logic controller (PLC) system. The system is able to take actions with the granularity of supermodules (SM) [1] and half endcaps (DEEs) [1]. The temperature inside the SMs is measured by four redundant sensors pairs. From the safety system's perspective, each DEE volume corresponds to two SMs and therefore the temperature inside the DEEs is measured by eight redundant sensors pairs. Hardwired failsafe interlocks for the LV and HV systems are triggered in case of problems with the cooling system or overheating inside the detector, either caused by lack of detector cooling or faults in the on-detector electronics. Water leak detection sensors are installed inside each SM and DEE. Hardwired failsafe interlocks for the cooling system are triggered in case of water leak detection inside the EE partitions (the actions based on water leak detection are disabled for the SMs due to problems during the sensors installation, which compromise the readout data). Lack of cooling flow to the LV power supplies or water leak detection inside the LV racks trigger hardwired failsafe interlocks for all LV power supplies inside the concerned rack and also to the corresponding HV power supplies for the affected SMs. The heartbeat of the ESS PLC is monitored by the CMS detector safety system (DSS) and in case of its absence, the DSS takes all the necessary actions to ensure that the CMS ECAL is in a safe state. Hardwired signals from the CMS magnet control system (MCS) trigger the shutdown of the CMS ECAL HV in case of unstable conditions of the magnet (i.e. ramp up/down, fast discharge, etc).

Further details regarding the CMS ECAL ESS are available in [3].

THE UPGRADES DURING THE LS2

Safety System Power Distribution

The original 24VDC power distribution was able to supply up to 10A to the PLC system and to all the safety-related hardware installed in the same rack. With the deployment of the new temperature readout system, the required power at stable condition would exceed 80% of the available capacity. Transients' conditions could cause a system overload, the full shutdown of the PLC system and consequently of the CMS ECAL. To avoid such events, the system was upgraded to deliver up to 20A.

The new power distribution features two 24VDC/20A supplies connected to independent 230VAC sources. The outputs of these supplies are connected to uninterrupted power supply (UPS) modules, which manage the charge and the use of 5Ah LiFePO batteries. The outputs of these UPS modules are then connected to a redundancy power module. As this redundancy power module can provide the full current of both inputs in parallel, in this case up to 40A, a 20A circuit breaker was installed close to its output to allow the use of wiring with suitable cross sections according to the 20A design. Based on the environment conditions at the installation site, the expected lifetime of the LiFePO batteries is around fifteen years, implying a considerable reduction in maintenance efforts when compared to the former batteries, which had to be replaced every two years. Individual circuit breakers to decouple the batteries were also installed to ease their replacement. In case of a full power cut, the new UPS system can support the complete safety system for approximately 60 minutes.

Safety System Temperature Readout

The original design of the CMS ECAL safety system hardware was based on a combination of commercial-off-the-shelf (COTS) and custom made (CM) devices. The COTS hardware consists of redundant PLC central processing units (CPU) from the SIEMENS 400-series, serial communication modules and digital input/output (I/O) modules from the SIEMENS 300-series.

The decision of using CM hardware for the interlock system at the time of first implementation was driven by the cost difference between the purchase of twenty-two 8-channel digital output (DO) modules with mechanical relays and the purchase of six 32-channel DO modules with solid state relays (SSR) to drive external mechanical relays of a CM unit (featuring additional integration of digital inputs (DI) for a complete and user-friendly display of all interlocks per partition in their front panels). This solution is not optimal, as it introduces complexity to the cabling and an additional layer of unnecessary components, resulting in a negative impact in the system's overall reliability. Nevertheless, the extremely low failure rate over the past 10 years supported the decision to maintain this part of the system untouched until the LHC LS3.

Another cost-based decision for CM hardware was made for the temperature and water leak detection readout system. Unlike the interlock system, the units designed to read

out the 352 temperature sensors and 40 water leak detection sensors presented several issues during the past 10 years. The custom and very basic software protocol, implemented for the serial communication via RS-485 with the SIEMENS CP341 modules from the PLC system, introduced a strong timing dependency, which compromised the system's redundancy and randomly, even the system's initialization routines. Moreover, during this period, multiple CP341 modules presented failures and had to be replaced. Similar failures were also reported in two other test systems and the problem of these communication modules was never understood.

Two solutions to overcome the issues described above were considered. The first was a complete re-writing of the PLC code and the implementation of a standard and robust serial protocol for the communication between the PLC system and the CM readout units. This would require changes to the code of the obsolete programmable interface controllers (PIC) of the CM readout units and would not address the CP341 failures. The second and selected choice, the complete replacement of the CM readout units by COTS Analog Input (AI) modules from SIEMENS, addresses all the existing issues and increases considerably the overall system's reliability.

Although the implementation of such a solution is simple, the environment and specific constraints at the CMS experiment imposed some interesting challenges for this upgrade. The SIEMENS AI modules are not certified for the radiation levels which the original installation location is exposed to and therefore had to be installed outside the underground experimental cavern (UXC). Patch panels had to be installed to connect extension cables between the UXC racks and the chosen location for the AI modules at the underground service cavern (USC). Manipulating cables and connections which were done thirteen years earlier is never an easy practice, so a well-defined procedure and some special infrastructure to minimize the impact of this intervention had to be established. Patch panels were designed with the exact same layout as the placement of the CM readout units' connectors, to allow the disconnection of these units and the fixation of the existing connectors at the exact same place, in this way preserving the cables' bending angle and the existing routing length.

The original design has the readout of the temperature sensors over two wires and the resistance compensation for the cable lengths added in the software. In order to minimize the effects of the additional cabling, the extension cables use four wires for the temperature sensors readout.

To preserve redundancy at the temperature sensors level, each sensor from a redundant pair was connected to a different AI module of a different process field bus (PROFIBUS) [9] branch. To allow such distribution, some complexity had to be added to the wiring. An example of this sensors' distribution is presented on Figure 1.

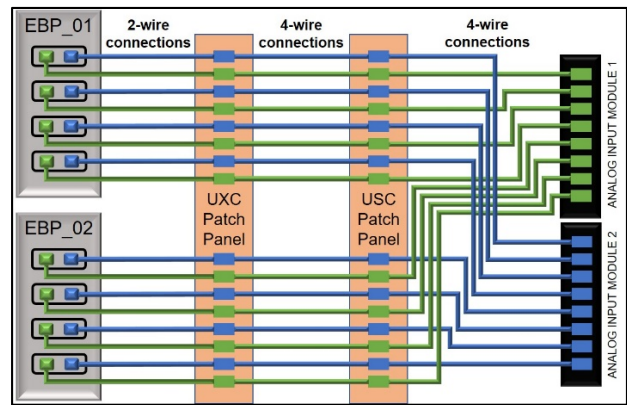


Figure 1: Example of wiring diagram to preserve redundancy at the temperature sensors layer.

To allow symmetry and full redundancy at the PROFIBUS layer, the 45 AI modules (44 for temperature readout and 1 for the EE water leak readout) were distributed in six branches.

The hardware and cabling were deployed at the beginning of the second semester of 2019. Adapters with a set of known resistance values were used to test the new wiring and to validate the mapping between the UXC patch panel and the AI modules. Once these tests were successfully completed, the cables between the patch panels and the sub-detector were, one by one, systematically connected and the readout data verified.

The original CM temperature readout units were designed with a common return line for all eight sensors per SM, as well as a common ground for all the 32 channels per unit. During the first ESS commissioning thirteen years ago, four temperature sensors connected to two different units presented low impedance between one wire and the ground, which compromised the readout of all sensors sharing the same return line. To overcome the effect caused by these sensors, they were physically disconnected. As the new temperature readout architecture does not have common return lines, these sensors were connected and included in the ESS, which has now 100% of operational sensors.

To ensure the correct sensors' mapping at the PLC code according to their placement inside each detector partition, the LV was used to produce heat on different sectors of each partition, enabling the verification of all temperature sensor's location.

The successful implementation of the new temperature readout system allowed the deployment of a less complex and more maintainable PLC code, which is discussed in the next section.

Safety System PLC Code

For many years, the CMS ECAL ESS PLC code has been supported by the CMS tracker DCS experts. To ease and ensure the long-term support and maintenance, standardization across the safety systems supported by these experts became necessary. The use of a non-standard software protocol for the temperature readout did not allow the complete deployment of their solution and a hybrid version of

the PLC code was temporarily implemented. With the upgrade to COTS hardware, their standard code was adapted according to the CMS ECAL specifications and deployed. A procedure for the full validation of the CMS ECAL safety action matrix was established and this process is ongoing.

All PLC CPUs and PROFIBUS redundancies, which in the past had many issues due to the CM hardware handling, have been properly implemented and successfully validated. Organization blocks (OB) were configured to log redundancy issues and a dataset was prepared to propagate this information to the CMS ECAL DCS.

Re-distribution of LV Power Supplies Data Buses

The original implementation of the controlled area network (CAN) bus protocol for the control and monitoring of the CMS ECAL LV power supplies had the 136 nodes distributed among 10 buses. This distribution was not balanced, with the number of nodes varying from 7 to 30 per bus. According to the characteristics of the physical layer employed, 30 nodes would be at the edge, but theoretically still within the specifications. Some issues, such as lost frames, were noticed but typically absorbed by different DCS layers and never affected or compromised the control, monitoring or availability of the LV system. With the installation of CAN-Ethernet converters to allow the implementation of software redundancy [10], the general increase in latency potentialized the communication issues on the buses running at the limit of their specification. After an extensive analysis of these issues, a more balanced distribution of devices per CAN bus was considered mandatory. Such intervention required a mid- to long-term validation, and therefore it was carried out at the beginning of the LHC LS2. The two buses containing 30 devices were split in four buses with 15 devices and the data server and the DCS software reconfigured accordingly. The initial tests were successful and the validation is still ongoing, to be concluded by the end of the LHC LS2. The new CAN buses' distribution is presented by Figure 2.

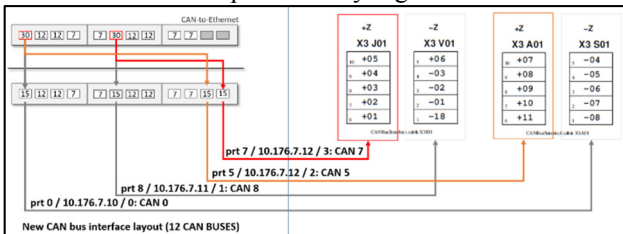


Figure 2: New CAN buses' distribution for the LV system.

CMS ECAL DCS Software

The constant evolution of computing platforms and continuous releases of software versions impose considerable challenges to the support and maintenance of the CMS ECAL DCS. The update roadmap in terms of operating systems (OS), SCADA versions, frameworks, and computing infrastructure is defined by the CMS DCS experts and adopted by all CMS sub-detectors' control systems.

The current computing hardware is reaching their end-of-life (EOL) and will be replaced by new and more powerful servers during the LHC LS2. In-line with this hardware upgrade, the OS migration to the Microsoft Windows Server 2016, the SCADA migration to WinCC OA 3.16, and the deployment of the latest CMS DCS and JCOP frameworks versions will be carried out.

The WinCC OA version 3.16 supports only UTF-8 encoding, and therefore the sources of existing projects using ISO-8859-1 need to be carefully analysed and modified to ensure compatibility with UTF-8. This includes the conversion of the user interfaces' code to a new eXtensible Markup Language (XML) format, the code refactorization to support Unicode string formats and, in some cases, the complete re-implementation of character vector-based functionality.

The Apache Subversion (SVN) service provided by CERN is being deprecated and the migration to the Git Service [11] is mandatory. The software for configuration management in the CMS DCS environment had to be replaced to support the new versioning system and the components' repository infrastructure. Hosted at CERN, and with a large number of new features, the CERN GitLab instance stores several repositories for the CMS ECAL DCS components. The adoption of the GitLab platform also implied a fundamental change to the storage and management policies of the DCS components, imposing requirements like the one-component-one-repository rule. This particular feature required a considerable amount of time to fragment and migrate each software component, while preserving the different versions and historical data across platforms. The rules to interface the new configuration management system have been also included as part of the CMS ECAL DCS development guidelines.

The migration of the object linking and embedding for process control (OPC) software interface and the OPC namespace of several hardware devices to the new OPC Unified Architecture (UA) is also foreseen to be carried out during the LHC LS2. The OPC UA introduces considerable changes to the way that different hardware is accessed, and it is not backwards compatible with the existing OPC configuration used in the CMS ECAL DCS. For this reason, an explicit migration and validation plan needs to be formulated and executed by the end of the LHC LS2.

CONCLUSION

The CMS ECAL DCS and ESS are undergoing major changes during the LHC LS2.

The replacement of the CM temperature readout units by COTS SIEMENS AI modules did not only increase the safety system's reliability, availability, and robustness, but also allowed other very important improvements, such as the proper configuration of redundancy in all safety systems layers, the deployment of a more standardized and maintainable PLC code architecture, and the reconnection of four sensors, extending the temperature monitoring coverage to 100%.

The deployment of a new ESS PLC code based on the CMS Tracker PLC code architecture will allow a much better support from the CMS tracker DCS experts.

The upgrade of the ESS power distribution to a 24VDC/20A UPS-based redundant system ensures that transient conditions cannot cause overload and consequent power disruptions, due to the load increase after the installation of the new temperature readout system.

The re-distribution of devices per CAN bus in the LV system allowed for an optimal load balancing. By reducing or eliminating communication errors, the LV system overall performance, reliability, and availability have been considerably improved.

Several changes are foreseen to all layers of the CMS ECAL DCS software, from upgrades to the computing hardware infrastructure to improvements of user interfaces at the supervisory layer, always in-line with the new guidelines and requirements.

The successful deployment of most of the major upgrades described in this paper, as well as the significant and smooth progress of all the other ongoing tasks, are extremely important steps towards the preparation of the DCS and ESS for the next CMS ECAL operational period.

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