IMPROVING THE COMPACT MUON SOLENOID ELECTROMAGNETIC CALORIMETER CONTROL AND SAFETY SYSTEMS FOR THE LARGE HADRON COLLIDER RUN 2

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Abstract

The first long shutdown of the Large Hadron Collider (LS1, 2013-2015) provided an opportunity for significant upgrades of the detector control and safety systems of the CMS Electromagnetic Calorimeter. A thorough evaluation was undertaken, building upon experience acquired during several years of detector operations. Substantial improvements were made to the monitoring systems in order to extend readout ranges and provide improved monitoring precision and data reliability. Additional remotely controlled hardware devices and automatic software routines were implemented to optimize the detector recovery time in the case of failures. The safety system was prepared in order to guarantee full support for both commercial off-the-shelf and custom hardware components throughout the next accelerator running period. The software applications were modified to operate on redundant host servers, to fulfil new requirements of the experiment. User interface extensions were also added to provide a more complete overview of the control system. This paper summarises the motivation, implementation and validation of the major improvements made to the hardware and software components during the LS1 and the early data-taking period of LHC Run 2.

INTRODUCTION

The Compact Muon Solenoid (CMS) [1] is a general-purpose particle physics detector built for the Large Hadron Collider (LHC) [2] at CERN. The CMS detector is composed of several types of sub-detectors: trackers, calorimeters and muon chambers. Based on the technical specifications and requirements of each sub-detector, custom Detector Control Systems (DCS) were designed, implemented and commissioned. A central CMS DCS [3] infrastructure provides general and common services, as well as the unification of controls and monitoring of all sub-detectors. A central CMS Detector Safety System (DSS) [1] is responsible for all off-detector safety-related matters. In addition, individual sub-detector safety systems are also available to provide extensions to the CMS DSS to guarantee the on-detector safety and integrity. The experience acquired during the first LHC long run (March/2010 – February/2013) ensured a better understanding of the detector operation and consequently the identification of possible fields for improvements to the DCS/DSS software and hardware components. The first long shutdown (February/2013 – June/2015) of the accelerator provided an opportunity for the implementation of most of these improvements, systems extensions and the preparation of even more robust, efficient and reliable systems for the LHC Run 2. This paper discusses the main improvements made to both DCS and DSS of the CMS Electromagnetic Calorimeter (ECAL) [1] throughout the periods described above. Focus is given to hardware upgrades and system consolidation.

Full details of the architecture of the CMS ECAL DCS have been reported previously [4,5].

CMS ECAL DCS OVERVIEW

This section presents a general description of the CMS ECAL DCS software and hardware. A simplified block diagram of the complete system is illustrated in Fig. 1.

Software

The CMS ECAL DCS application has been developed with a Supervisory Control and Data Acquisition (SCADA) software package named SIMATIC WinCC OA from SIEMENS, formerly Process visualization and control system II (PVSS II) from ETM. To facilitate the development process, the JCOP Framework [6], developed by CERN to provide extensions to WinCC OA for the high-energy physics domain, is extensively used. Through a Finite State Machine (FSM), manual and automatic commands are issued to lower nodes and node states are propagated and summarised upwards. Furthermore, the main control and state monitoring of all sub-detectors are accessible to the CMS DCS via the FSM to enable global CMS control.

The partitioning of the control nodes follows the sub-detectors architecture, in this case: CMS ECAL Barrel (EB), CMS ECAL Endcaps (EE) and CMS ECAL Preshower (ES).

Hardware

The DCS hardware comprises all devices used for connection to the low voltage and bias voltage powering systems, the electronics for environment monitoring and for additional support services, such as remote crate power cycle units and bias voltage current measurements.

Due to software changes at the CMS DCS level, presented in the section "*Controls Software Redundancy*", all field buses are being converted to Ethernet, allowing their physical decoupling from the DCS servers.

Spare parts and, in some cases, complete spare units are available to provide full and optimal support in case of hardware failures.

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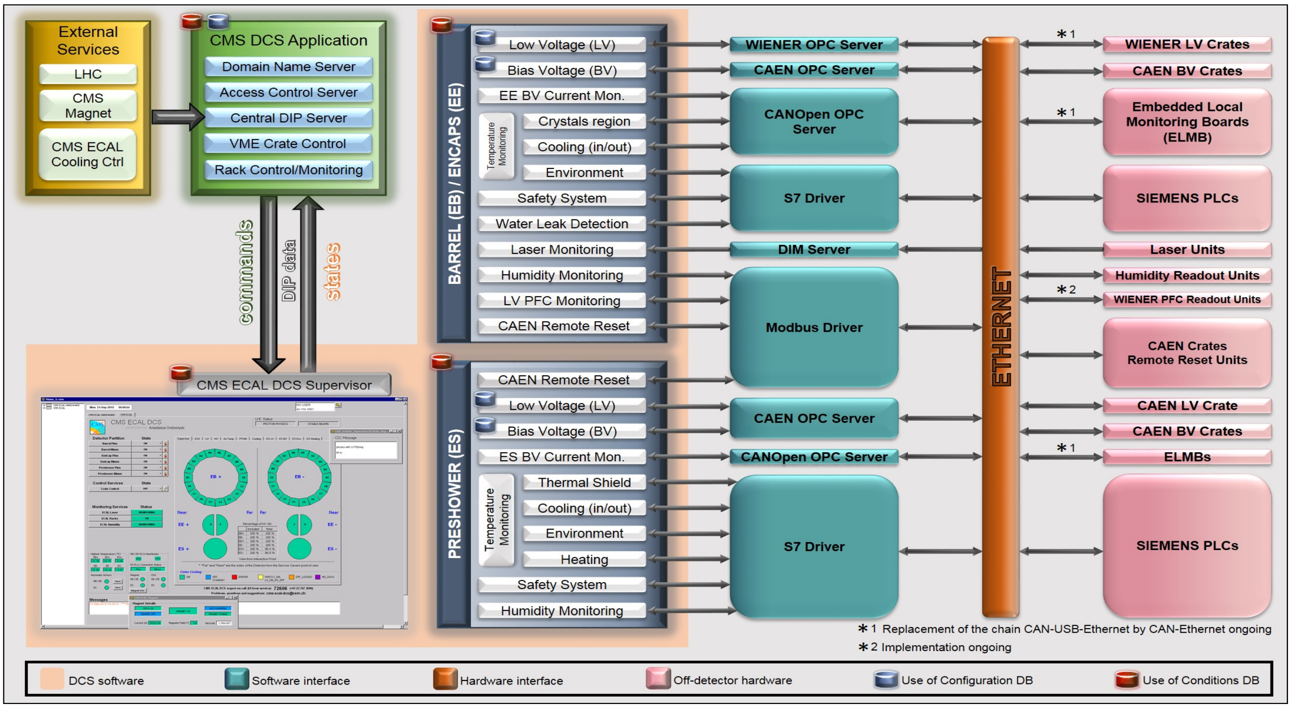

Figure 1: Simplified block diagram of the CMS ECAL Control System.

CMS ECAL DSS OVERVIEW

Designed to ensure the calorimeter safety and integrity, the CMS ECAL DSS [4,5] is based on a fully redundant SIEMENS Programmable Logic Controller (PLC) system with hardwired connections and interlocks to all relevant systems to ensure real-time actions in case of harmful conditions. Furthermore, it provides complementary resources to the main CMS DSS by monitoring parameters such as the cooling flow status and water leak detection for the low voltage power supplies racks.

UPGRADES AND IMPROVEMENTS

Controls Software Redundancy

Following a requirement from the central CMS DCS for running the complete control system in a redundant hot standby mode, with one set of servers installed in the experiment service cavern and another in the surface data centre, all sub-detectors had to confirm compatibility of their control system applications with this new operating environment. The preparation consisted of changes to the SCADA software and the adaptation of all hardware connections to Ethernet. The latter will be discussed in the next section "*Hardware Interfaces*".

In line with the implementation of software redundancy, a complete project for merging the CMS ECAL DCS sub-applications to run in fewer servers was carried out. Applications were initially combined based on their role and in a second step grouped according to their software interfaces to the hardware. As an example, all bias voltage applications were re-designed to run side-by-side, and then grouped with the Preshower low voltage application that shares the same CAEN Object Linking and Embedding for Process Control Data Access (OPC DA) Server.

The reduction from fourteen to three servers was a fundamental step towards the redundancy implementation. The software layer for the switchover mechanism was implemented by the CMS DCS group [7].

Hardware Interfaces

To allow the implementation of redundancy at the software level, the DCS servers had to be physically decoupled from the hardware. The Ethernet layer was chosen to ease the logical switchover between the two identical, but geographically separated, sets of servers. No changes were required for the connections to the PLCs and to the Arduino-based devices, which were originally Ethernet-based. To realise the connection to the EB/EE humidity readout units, commercial Modbus RTU-Ethernet adapters were selected and installed. Several approaches were evaluated for conversion of Controlled Area Network (CAN) buses. As no commercial CAN-Ethernet device was available at the beginning of this project, a chain of CAN-USB-Ethernet was tested. This solution worked for buses with few devices and/or low data traffic, but issues were identified with large, heterogeneous CAN hardware installations running in parallel on a single server. Furthermore, the latency added by this implementation triggers a significant number of false positive hardware disconnection timeouts.

In 2014, a commercial multi-port CAN-Ethernet adapter that fulfils the system requirements became available. Together with the necessary changes to the WIENER OPC server, the Triplicated AnaGate CAN Quattro was exhaustively tested and certified for installation at the end of 2015 [8].

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Remote Reset of CAEN Mainframes

A complete analysis of all expert interventions during the LHC Run 1 enabled the identification of the most common failures and sources of the experiment downtime related to off-detector hardware. In particular, two cases were identified related to the CAEN mainframes that provide the bias voltage for the whole CMS ECAL and the low voltage for the Preshower. The first, the fact that after a power cut, some mainframes were not properly initialized and required a human intervention to perform a full reset. The second, occasionally, the communication with the mainframe was interrupted and only restored by a reset of the mainframe Central Processing Unit (CPU) controller. The minimum time of thirty minutes to identify the problem, access the experiment cavern and reset the faulty controller motivated the implementation of a remote reset unit, accessible through the main CMS ECAL DCS supervision panels.

As no commercial devices were suitable for an easy integration to the controls software, microcontroller-based units were developed. Each unit features fourteen ports and an implementation of Modbus over TCP on an Arduino Ethernet [9] for communication with the native Modbus driver from WinCC OA. The unit can issue Transistor-Transistor Logic (TTL) pulses with lengths of 200 ms for resetting only the CPU controller and 1000 ms for a full mainframe reset. A user-friendly panel allows the detector experts to trigger both actions in a few minutes for any of the twenty-three existing mainframes.

WIENER PFC Monitoring System

Another outcome from the analysis of the CMS ECAL DCS expert interventions was the need of an extension for the EB/EE low voltage application to read out the WIENER Power Factor Corrector (PFC) parameters. The failure of these devices was one of the most common hardware issues since the commissioning of the CMS detector. The monitoring of internal parameters might provide an opportunity to detect issues and schedule interventions prior to a total failure of the device during the detector operation.

To profit from the existing Modbus driver of WinCC OA, the readout Printed Circuit Boards (PCB) feature Modbus over TCP implemented with an Arduino Yún, which controls four ADG726 (dual 16-port multiplexer) to switch the RX and TX lines for up to 64 devices. In addition, the 5V and 9V required for the PFC serial circuit are permanently provided.

Humidity Monitoring System

The original design of the EB/EE Humidity Monitoring (HM) [4,5] system did not take into account the lengthy cables between the probes inside the detector and the readout hardware, which for some probes reaches more than 100 meters. The additional capacitance introduced by the cables and seen by the humidity transmitters imposed a limitation on the humidity readout range to 60 – 80%. To overcome this issue, a custom readout unit featuring very low frequency (1 Hz) transmitters was designed. To evaluate any possible degradation of the probes due to their operation out of the manufacturer specifications, tests setups were built at CERN and in Belgrade. After more than a year of evaluation, the new hardware was certified for installation in the experiment.

A calibration procedure was developed and each individual readout channel was calibrated using the same type of probe from the experiment, inserted in a controlled humidity unit with a very precise humidity sensor as reference. The new readout units were installed in the experiment and are able to measure from 10 – 80% relative humidity.

PTM Readout – Improved Power Distribution

The Precision Temperature Monitoring (PTM) is an ELMB [10] based system responsible for the temperature monitoring of the EB/EE crystals region and cooling. In the original design, three 12V power supplies, one for the analog, one for the digital and one for the CAN part, powered all ELMBs in parallel. An event where a single failure of one ELMB degraded operation of the whole monitoring system motivated the upgrade and improvement of granularity of the 12V power distribution.

Two sets of 3x12V supplies were installed, one for each half of the detector. A terminal block with fuse was installed for each power line at the experiment service cavern, allowing the disconnection of a possibly faulty ELMB without compromising the complete system.

Preshower Bias Voltage Monitoring

The Preshower Bias Voltage (BV) is distributed through a fully flexible matrix patch panel [11], where any input channel can be connected to any detector element or group of elements. For each individual line, a resistor bridge containing a reference resistor and branches to scale down the voltages are available to measure the current delivered to each output channel.

The period between the patch panel production and their installation in the experiment was insufficient for a complete evaluation of the readout and consequently for the definition of a proper calibration procedure. These tasks were performed later with a spare patch panel.

All readout channels were calibrated for current measurements with precision better than 2%. A complete and successful validation was carried out with several values of current from 10 µA to 2000 µA.

Due to a configuration featuring multiple grounds without proper isolation between them, a condition that was not previously tested, the results at CMS were not as expected. The patch panel that was removed from the experiment is currently being analysed.

Safety System Preparation for the LHC Run 2

A complete re-evaluation of the safety system PLC code and hardware was carried out to not only identify possible improvements but also issues related to ensuring long term support.

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- Replacement of PLC CPUs

The CPUs, which were operational throughout the LHC Run 1, reached the end of their life cycle in July 2015 and were discontinued by SIEMENS: no more spare parts, repair service or technical support. Both CPUs were replaced by a newer model, with full support guaranteed until October 2022. Spare parts for the complete PLC system are available 24/7 from the CERN PLC Spare Parts Critical Stock;

- Production of spare readout units

The non-commercial hardware comprises the units reading out the EB/EE water leakage and temperature sensors and the units handling the interlock signals. To ensure a number of spares representing a minimum of 33% of the complete system, four spare readout units were produced;

- Recovery mechanism for CP341 failures

The communication between the SIEMENS CP341 modules and the readout units described above is realised through a RS-485 bus with a custom protocol. Due to external conditions, such as electrical noise, associated with extremely sensitive conditions to trigger safety actions, communication issues have triggered unwanted detector shutdown events. To restore the communication to the readout units, a human intervention to power cycle the CP341 modules was required. A mechanism to recover communication without the need of a power cycle was implemented in the PLC code and is under evaluation. To avoid any impact on the system reliability, it currently can only be manually triggered. Once this mechanism is certified, an automatic recovery procedure will be implemented.

24/7 OPERATOR AND EXPERT SUPPORT

Since the commissioning phase of the experiment, the CMS ECAL DCS has maintained 24/7 support services to ensure the maximum availability of the calorimeter. Initially, three of the main developers of the system were responsible for the daily operation of the detector and expert support in case of failures. Due to the significant workload involved, the support scheme was reviewed and divided in two roles, operator and expert. The operator on-call can be any person from the experiment collaboration and, with some basic training, is able to handle the detector daily operations and basic failures, while the expert on-call provides the most advanced level of support, either to the operator or directly to other CMS ECAL experts for more complex failures or interventions. This solution has proven to be very efficient and results in more balanced workload and increases the pool of people who have operational knowledge of the CMS ECAL DCS.

A log of all system failures, related to both hardware and software, has been maintained by the operators and experts to allow further analysis and consequent improvements based on preventive actions. Furthermore, based on feedback from operators and shifters, the available monitoring resources and software tools are periodically revised and, if required, extended to improve the system operation and troubleshooting.

CONCLUSION

The CMS ECAL DCS and DSS successfully supported the detector operation during the LHC Run 1. By logging the CMS shifters and DCS on-call operators and experts activities for over three years, several fields for improvements were detected. The LHC LS1 provided an optimal opportunity for these upgrades and system extensions. Efforts were made to ease operations, by providing additional troubleshooting tools and extended user-friendly operating panels. Most of the changes discussed in this paper have already been deployed and an excellent support to the CMS ECAL is being provided during the LHC Run 2.

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