Jinst
Published by IOP Publishing for Sissa Medialab

Received: *October 21, 2022*
Accepted: *December 5, 2022*
Published: *February 23, 2023*

Topical Workshop on Electronics for Particle Physics
Bergen, Norway
19–23 September 2022

Modern high-availability multi-stage power distribution system for the CMS phase-2 upgrade

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Abstract: The operation of CMS at the HL-LHC requires an upgrade of the readout electronics. These new modern micro-electronics require power at precise voltages between 1.2 V and 2.5 V. We will deliver this power using a 3-stage system, comprising AC-DC conversion to 380 V DC followed by radiation-tolerant 12 V DC-DC power converters feeding radiation-hard point-of-load DC-DC converter. We have studied an industrial 380 V AC-DC conversion system, featuring hot-swappable 3 kW power modules, stackable up to ∼1 MW system. Such systems are candidates for the first conversion step, feeding custom power supplies accepting 400 V DC input voltage. Our tests on one of the commercially available systems purchased from Eltek demonstrated that the system complied with our requirements, most notably in terms of maintainability, availability and power quality. A few measurement plots perceived by authors as particularly interesting are discussed in this contribution.

Keywords: Voltage distributions; Modular electronics; Radiation-hard electronics

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https://doi.org/10.1088/1748-0221/18/02/C02053

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1 Introduction

Operation of the CMS experiment at the HL-LHC generally requires at least an upgrade of the readout electronics in order to cope with the higher instant luminosity and level-1 trigger rate. Modern micro-electronics ICs require power at precise voltages between 1.2 V and 2.5 V [1]. In the vicinity of the CMS detector, stray magnetic field and radiation is present, limiting the use of commercial power supplies. An area without the radiation and magnetic field constraint is available more than 100 m away from the powered micro-electronics. To efficiently transfer electrical energy from the power grid to the electronics, a 3-stage conversion system will be used, comprising AC-DC conversion from the 3-phase power grid voltage to 380 V DC followed by radiation-tolerant 12 V DC-DC power supplies feeding radiation-hard point-of-load DC-DC converters. A common powering system is being developed for the CMS Electromagnetic Calorimeter Barrel (EB), the MIP Timing Detector (MTD) and the Endcap Calorimeter (EC) [1–3]. It comprises 5052 power channels (60 W, 120 W, 240 W) with a total capacity of ~660 kW. The scope of the system may be also extended to the Tracker applications. Section 3 of this contribution provides information about one commercial system, which was tested as a component for the first stage in the voltage conversion chain. Section 4 provides a few measurement examples not included in the specification provided by a manufacturer while useful when engineering a 380 V DC power distribution systems in various applications including particle physics detectors and accelerators.

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2 System topology

2.1 Motivation for the use of three conversion steps

System topology schematic is shown in the figure 1. The concept of three conversion steps is driven mainly by two factors: a need of reducing joule heating losses; available areas for electronic equipment that vary significantly in presence of radiation. Electronic components used in power electronics equipment are sensitive to radiation and, therefore, special design techniques must be used to mitigate the risk of failure [4]. Conversion steps operating in hazardous radiation are often custom designs where complexity is often reduced to a minimum and dedicated assessment of risks is done to balance the risk originating from radiation-induced failures. Reduction of complexity was the main driving factor to keep AC/DC conversion including power factor correction circuitry away from elevated radiation level areas.

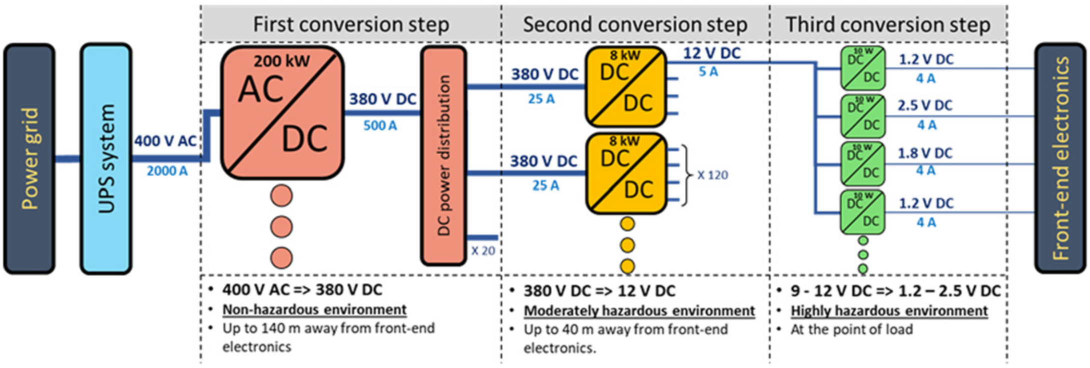

Figure 1. Schematic of the power conversion chain concept for the CMS phase II upgrade.

2.2 Conversion steps description

Precise voltages between 1.2 V and 2.5 V will be delivered using the following stages:

(1) **First conversion step** from 400 V AC to 380 V DC will take place up to 140 m away from detectors in a non-hazardous environment using commercial components and a dedicated fanout system. The choice of 380 V DC as an intermediate voltage was driven by the growing market of high-availability 380 V DC power systems used in data centres where continuous operation is a crucial requirement. Additional important factors for this conversion step are high efficiency and maintainability by non-expert personnel. The high power factor is also an advantage.

(2) **Second conversion step** from 380 V DC to 12 V DC will take place as close to electronics as possible, up to 40 m away from detectors. At this location moderate radiation environment with total ionizing dose (TID): 32 Gy, high energy hadron (HEH) fluence: $2 \times 10^{11}\,\mathrm{cm}^{-2}$, neutron fluence (1 MeV equivalent): $1 \times 10^{13}\,\mathrm{cm}^{-2}$ and stray magnetic field of up to 120 mT are expected, therefore, custom, radiation-tolerant power supplies are being developed which are suitable for these environmental conditions. Additionally, these devices will feature over-voltage protection, implemented with analogue circuitry,

thus not under control by the on board micro-controller, to mitigate or eliminate the risk of permanent damage of the point of load conversion step. This protection will disable switching and short-circuit the output of the power supply channel within a millisecond after exceeding a desired voltage threshold to cut the electrical energy transfer to the load.

(3) **Third conversion step** from (10–12) V DC to (1.2–2.5) V DC, voltages appropriate for modern micro-electronics operating in harsh radiation environment with total ionizing dose (TID): 10 kGy, high energy hadron (HEH) fluence: $3 \times 10^{13}\,\mathrm{cm}^{-2}$, neutron fluence (1 MeV equivalent): $3 \times 10^{14}\,\mathrm{cm}^{-2}$ and magnetic field (of up to 3.8 T). These ASICs, called bPOL12V [5, 6] are usually the final conversion step at the point of load providing power in chunks of maximum 10 W per converter and a typical efficiency of (65 to 80)%. In some places this conversion stage will be followed by linear regulators, which provide a supplementary noise filtering for particularly sensitive electronics.

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3 Evaluation of a commercial system suitable for the first conversion step

3.1 Device under the test

The first conversion step will operate in a radiation-free environment. Therefore, we aim at using a commercial off-the-shelf (COTS) system. Three solutions available on the market were selected for further evaluation: Eltek, Vertiv and TDK Lambda. A comprehensive study was carried out on a solution proposed by Eltek (see figure 2) — a small-scale system that has all the crucial components of a full-scale system: a control unit and four power bricks of 3 kW each [7]. The control unit provides an interface for remote control, signaling errors and ensures uniform load distribution. Power bricks are AC/DC converters which communicate with the control unit but may also work independently if the control unit fails. A full-scale system is composed of many such power bricks and may provide up to 1 MW of power to a common busbar.


HMI communicating with a control unit.

Four hot-swappable power brick delivering up to 3 kW of power each.

Figure 2. Device under test purchased from Eltek consisting of main functional blocks of a large-scale system providing up to 1 MW of power.

3.2 Aims of the study

The overarching goals of the evaluation study were the following:

- Get familiar with components and control of an industrial 380 V DC system.
- Determine steady-state and transient electrical responses of the AC/DC conversion system that may occur in various realistic scenarios.
- Assess the possibility of integration with existing CMS infrastructure.

4 Results

Various electrical measurements were performed to assess behaviour of the 380 V DC system. Four plots were selected to show cases which the authors consider particularly interesting.

4.1 Providing output power in the event of power module failure

One of the most appealing features of the system is a high degree of redundancy which ensures high availability of output power. Failure of one or a few power bricks does not affect output voltage because the remaining modules will instantly supply the missing power. Additionally, output power is delivered even if a control unit fails. This feature was extensively explored and example power waveforms for an operation of three power bricks are presented for two cases: controller module enabled (figure 3) and disabled (figure 4). Since there is no direct access to currents provided by each module, the test was conducted on three power modules where each module was supplied with different phase from a 3-phase electrical outlet. Then, the power consumption at each phase was measured with a Fluke 1775 power analyzer to assess the fraction of load supplied by each module.

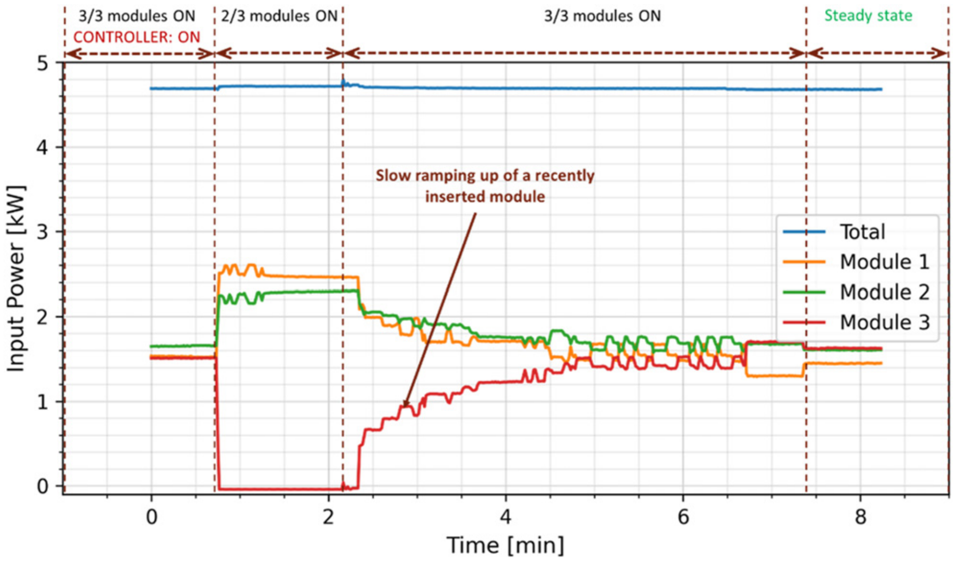

Figure 3. Load balancing among three power modules when a module is removed/inserted, and controller enabled.

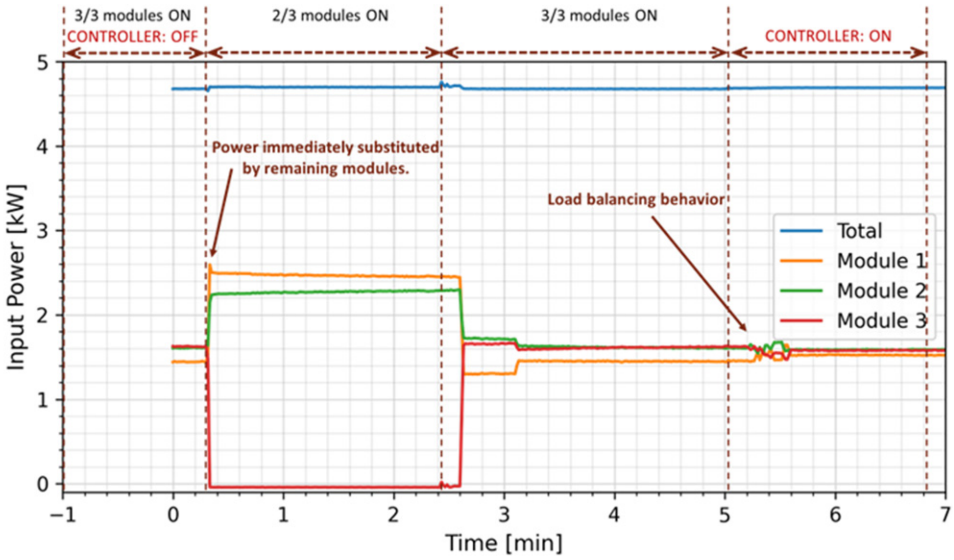

Figure 4. Load balancing among three power modules when a module is removed/inserted, and controller disabled.

4.2 Inrush current measurement

Each module is equipped with a soft-start functionality. Electrical current consumption starts at voltage zero-crossing and the current is following voltage sinusoidal shape from the very beginning ensuring good power factor (see figure 5). In our tests, the input current has never exceeded the maximum current consumption expected at steady-state full load.

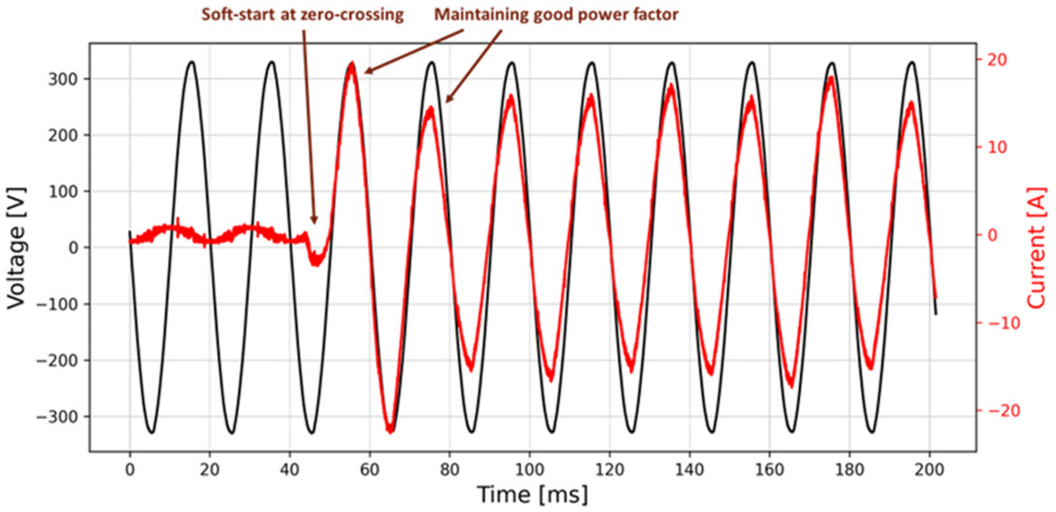

Figure 5. Inrush current and voltage acquired at the input of a power module.

4.3 Module insertion/removal transients

Output voltage transients during the insertion/removal of a module were measured. In the event of removing a module while it is delivering power, we did not observe deviations $>1\%$ of the nominal output voltage. Module insertion on the other hand produces a very short, but high magnitude transient oscillation of the output voltage (see figure 6). These oscillations are well filtered by the parasitic capacitance and inductance of 40 m of cable and consequently do not pose a threat to the subsequent conversion stage. However, cable protection elements at the location of the first conversion stage must have sufficient margin to cope with the measured over-voltage.

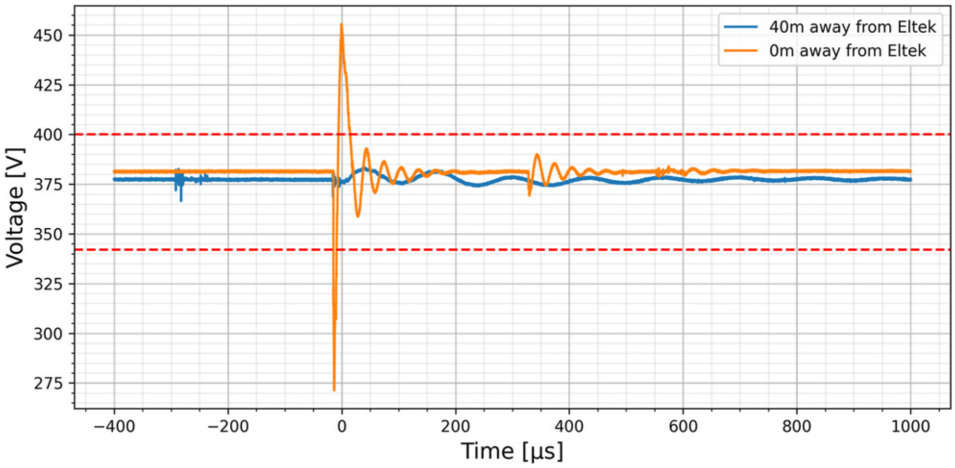

Figure 6. Output voltage transient recorded after insertion of a power module.

5 Conclusions

The use of three-stage voltage conversion for the CMS subdetectors enables the possibility for the first conversion step to use a fully commercial conversion system like those used in data centers. This comes with many advantages like high availability, easy maintenance by non-professional personnel, high efficiency (typically above 96%) and excellent power factor. The system provided by Eltek was evaluated with a set of electrical measurements and assessed as suitable for integration into the CMS power distribution concept presented in this contribution. Measurements revealed high-magnitude transient on a small-scale system (paragraph 4.3) and presence of such transient in a large-scale system must be assessed to select proper components for downstream cables protection. Other measurements (i.e. load regulation, load recovery time, periodic and random deviation, voltage stability) did not reveal any unusual features and were not included in this contribution. The system is designed in a way that output power availability is maximized by use of redundant power modules and by making the power modules self-sustainable in an event of control unit failure. Control algorithms ensure load share balancing and power factor correction.

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Acknowledgments

I'd like to express my deepest thanks to Michael Dröge and Christian Haller from ETH Zurich for excellent support in mechanical design, cabling of a test rack and components procurement.

This work was supported by the Swiss National Science Foundation with SNF FLARE 201476 grant.

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