ELECTRICAL DISTRIBUTION FOR MACHINE PROTECTION SYSTEMS: HOW TO ENSURE SAFE POWERING AND HIGH AVAILABILITY?

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Abstract

The LHC machine protection system is powered by 64 Uninterruptible Power Supply (UPS) units distributed over the whole LHC tunnel. In this paper, the UPS distribution network is reviewed, highlighting the major improvement that was made in 2009 in order to provide redundancy in the powering. Although this important change has been considered as successful for the machine protection system, all other users have been strongly affected by the reduced availability that resulted from this modification. Indeed, the same UPS power distribution network is also employed for supplying other users (e.g. cryogenics) where the main constraint is availability in order to reduce LHC downtime. During the first long shutdown (LS1), the existing UPS units will be replaced in order to increase reliability in the electrical distribution. New UPS configurations have also been studied to improve both safe powering and availability for all users. Finally, a word about LHC machine availability with respect to electrical perturbations is given.

INTRODUCTION

The LHC machine protection system protects all equipment of the LHC accelerator against uncontrolled release of energy stored in the magnet system and the particle beams. The machine protection system requires safe electrical power supply, i.e. without any interruptions even in case of problems with the mains grid. Indeed a perturbation on the mains results often in a beam dump and, in some cases, requires an energy extraction from the superconducting circuits. When this occurs, the machine protection system, and in particular the quench protection system, must remain active to orderly carry out the shutdown procedure of the accelerator. The machine protection system, as well as all critical equipment around the LHC which does not withstand any power cut, is thus connected to UPS systems. In case of mains failure, the UPS systems continue to power, for a limited time, this critical equipment.

A problem arises when the UPS distribution network fails itself. Safe powering of the machine protection system must be guaranteed in all events, also in case of an internal failure within the UPS network distribution. Different measures were taken in 2009 to make the UPS power distribution network completely fail-safe. However, after three years of LHC operation and several UPS failures encountered, the UPS units will be replaced during the LS1 and new UPS configurations will be implemented in order to substantially increase the reliability and availability of safe power distribution for all users connected.

USERS REQUIRING SAFE POWERING

The UPS power distribution network supplies all critical equipment which does not tolerate any mains perturbations and which must remain powered and active in case the mains failure would last several minutes. The most critical system, the machine protection system, requires safe powering in all events and especially for initiating and carrying out the safe shutdown procedure. The machine protection system is mainly composed of the Quench Protection System (QPS), the beam dump system and the beam loss monitor system. The 10 min autonomy provided by the backup battery of the UPS units is defined by the QPS. It corresponds to more than twice (safety margin) the time required for extracting the energy stored in the magnet system and during which the QPS must remain active for quench detection and, if necessary, for protecting the superconducting circuits.

Other critical systems around the LHC tunnel require also safe powering, in particular cryogenics and vacuum control systems. Although the loss of these systems will not directly jeopardize the protection of the LHC machine equipment, the machine run will most probably be terminated whenever these systems are no longer available. So these systems demand a very high availability from the UPS systems in order to minimize LHC downtime.

UPS SYSTEMS AND DEFINITIONS

In this paper, a UPS unit refers to a single UPS apparatus while a configuration of two or more UPS units is called a UPS system.

UPS Topologies

A UPS unit protects sensitive loads when the input power supply deteriorates; whenever the input power fails it continues to provide power to these critical loads up to a maximum time defined by the capacity of the backup battery. Conventional UPS units use the double conversion topology. In normal conditions, the rectifier converts AC to DC power and feeds the inverter while maintaining the battery in charge. The inverter converts DC back to AC power and feeds the load (see Fig. 1). In case of input power failure, the load remains powered by the inverter using the battery stored energy. The load is automatically transferred to the mains (via the bypass) in case of inverter failure. This transfer is instantaneous and without any perturbations for the load as long as the inverter is synchronised to the bypass AC source.

The UPS units which date back to the initial LHC installation are of delta conversion type. This hybrid topology uses an additional AC to AC power path, so-called “pure power path” in parallel to the similar converter/inverter connection with a common battery (see Fig. 1). This power path allows the mains in series with a transformer to contribute to the direct powering of the load. The delta conversion topology also uses a bypass line, but contrary to the double conversion one, it does not provide dual inputs for connecting two independent input sources.

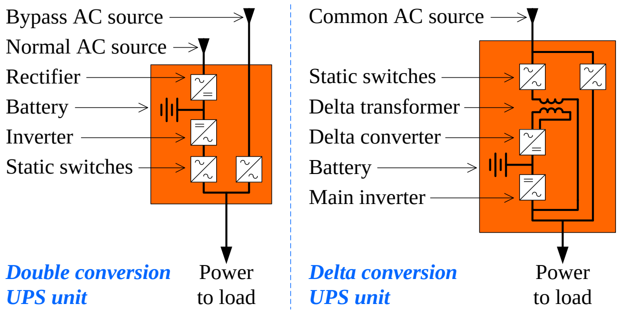

Figure 1: Comparison between UPS topologies.

Redundant UPS Systems

To increase the availability of a UPS-based installation for providing safe powering to critical loads at any given time and hence to minimise downtime, UPS units can be connected in parallel to the same downstream distribution switchboard. In this so-called parallel-redundant configuration, the load is equally shared between both units. In case one of both UPS units fails, the load is automatically transferred to the remaining unit without any perturbations. This parallel-redundant configuration requires a CAN bus (Controller Area Network) for communication between both UPS units. However, it may happen that the failure of the first UPS unit leads to the stop of the second and consequently, to the loss of power to the load.

An alternative to the parallel-redundant configuration is the “stand-by redundancy” where a backup UPS unit feeds the bypass line of the UPS unit being in the front line and supplying the critical loads. In case of failure of the latter, the load will be automatically transferred to the bypass and will end up supplied by the backup UPS unit. This configuration strictly requires no communication bus. Though very rare, the case when the front UPS unit fails to transfer to its bypass line has also to be considered. Nevertheless UPS literature reports that higher availability is obtained with this “natural” redundant configuration. This configuration is optimum for double conversion UPSs since the normal AC source of the front UPS unit can remain wholly independent from the normal and bypass AC sources supplying the backup UPS unit.

LHC UPS DISTRIBUTION NETWORK

Overview

The UPS distribution network dedicated to the LHC is shared out over 32 zones located in the underground infrastructures in order to cover all loads requiring safe powering. In particular, UPS systems are located in the 16 RE alcoves located around the LHC tunnel, each one covering up to 1.2 km for electrical distribution in the tunnel. In addition, UPS systems are installed in the service caverns of the 8 LHC points for supplying all critical loads around the interaction points. Finally, UPS systems are located in UA bypass tunnels on either side of US service caverns in LHC even points (8 UA tunnels in total) for supplying all critical electronic racks.

Original UPS Distribution Network

Each of the 32 zones was equipped with 2 parallel-redundant delta conversion UPS units connected to a single distribution switchboard (see Fig. 2). In each zone, the entire equipment requiring backup from a UPS system was supplied via the so-called F3 power distribution lines running in the LHC tunnel, F1 and F2 distribution networks being reserved to other equipment demanding normal power supply.

Magnet Powering Interlock with UPS Systems

Since the beginning, the status of the UPS systems has been fed into the Powering Interlock Control (PIC) system [1]. When a UPS system cannot back up its load, powering of all the magnets that are protected by the QPS equipment supplied from this non-available UPS system must be stopped. In each zone, the UPS systems are connected to the remote PIC controller by means of hardwired current loops. At the level of the UPS units, alarm relays providing dry contacts are used for the cabling of the interlock link. The PIC interlock logic is based on the information given by each UPS unit and consolidated for redundant UPS systems (with two UPS units).

At that time, it had been accepted that a machine run could continue if one of the two UPS units composing a redundant system would fail. Nevertheless, at the end of the machine run, an intervention was mandatory for repairing and restoring the redundancy within the faulty UPS system, i.e. a new machine run could only start when all 32 redundant UPS systems were fully operational. With such UPS configurations, all end users could thus benefit from the UPS redundancy.

FIRST UPS NETWORK CONSOLIDATION

After the accidental rupture at 9 kA of a bus-bar interconnection in September 2008, the QPS system was reviewed, and substantially changed and upgraded in 2009 [2]. The initial QPS system was complemented with a new QPS system which also performs as redundant system in some cases. In addition, maximum reliability of the QPS system was assured by duplication of every safety channel. However, the review of the QPS system also pointed out that the whole UPS distribution network was not completely fail-safe [3] and that it presented single points of failure. For instance, a short circuit inside the power distribution switchboard downstream a UPS

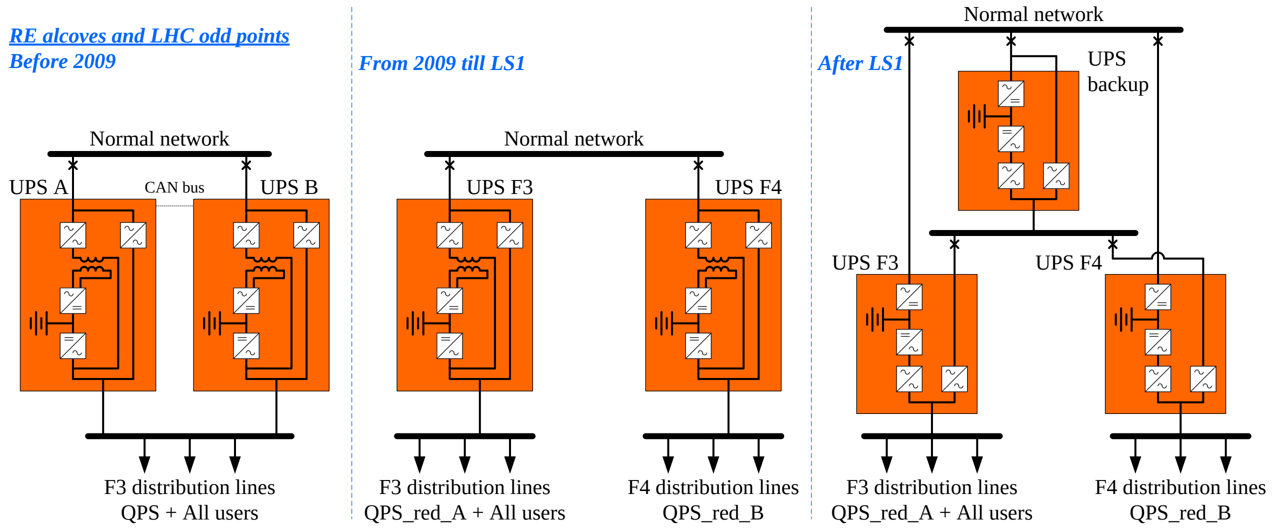

Figure 2: UPS power distribution network and its upgrades in the RE alcoves and the LHC odd points.

system, although extremely unlikely, could lead to the power cut of all QPS equipment protecting 92 main magnets (half an arc of the LHC machine). Consequently, major consolidation of the UPS distribution network took place in 2009 in order to make the UPS systems and the downstream distribution truly redundant.

Two Independent and Safe Power Paths

In order to supply redundant components of the QPS equipment, two independent power paths were requested that had to be supplied by independent UPS systems. The following measures were then taken in each of the 16 RE alcoves and 4 LHC odd points: a completely new distribution network, so-called F4 as a backup to the F3 distribution network, was created by pulling new cables and installing new distribution boxes in the whole LHC tunnel. Then the parallel-redundant UPS system in these zones was reconfigured as two independent UPS units (see Fig. 2), one dedicated to the original F3 distribution network (referred to as UPS F3) and the second for powering the new F4 distribution network (referred to as UPS F4). The new F4 distribution network was strictly reserved to redundant QPS equipment whilst all other users remained connected to the original F3 distribution network. However, other critical machine protection systems with redundant equipment quickly followed the QPS system and took advantage of a safe and redundant powering.

Overall Availability Reduced

The PIC interlock logic had to be adapted to this new distribution layout: the failure of one of both UPS units had to trigger the magnet powering stop. Indeed, in this configuration, all QPS systems would have lost their redundancy in case of a power outage, being only fed by a single operational UPS unit. Half of the redundant QPS equipment on UPS was the strict minimum for ensuring protection of the magnet system during the power ramp down procedure. Evidently, the repair of the faulty UPS unit was mandatory in order to be able to start again machine powering.

This new UPS configuration had a huge impact on the other users connected to the F3 distribution network only. They were no longer supplied by a parallel-redundant UPS system, but by one single UPS unit, losing drastically in availability. Moreover, the modification of the operating rules when losing a UPS unit strongly affected the machine availability. This also put an additional burden on the EN-EL Group, who operates these UPS units and had to repair and restart the faulty UPS system as soon as possible in order to reduce LHC downtime.

Full Redundancy in LHC Even Points

In UA tunnels, the redundancy of the powering for the QPS equipment was obtained by using the parallel-redundant UPS system located in the adjacent US cavern. Likewise, the redundancy of the F3 power distribution lines in the tunnel that were supplied by the UPS system in the US cavern, was established by pulling new F4 power distribution lines, which were connected in turn to the parallel-redundant UPS system located in the UA tunnel (see Fig. 3). This solution had the great advantage of not breaking the existing parallel-redundant configuration of the UPS systems while preserving the PIC interlock logic in these zones.

LHC UPS REPLACEMENT PROJECT

Over a few years of LHC operation, the failure rate of UPS units based on hybrid delta conversion topology was globally very high compared to the conventional double conversion UPS units also in operation at CERN [4, 5]. In particular, the failures of non-redundant UPS units in the LHC tunnel demonstrated, to our expense, the lack of reliability of this type of UPS equipment. Together with the loss of support from the manufacturer, who had stopped the production at the time the delta conversion

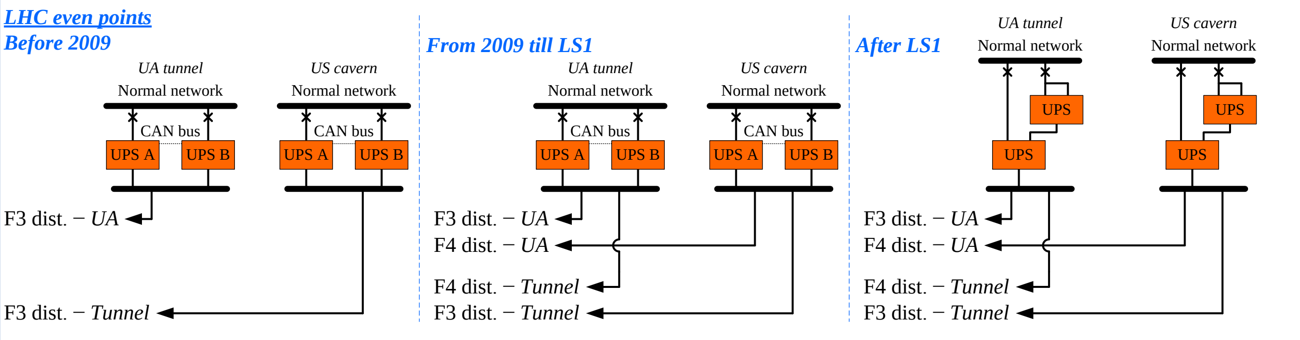

Figure 3: UPS power distribution network and its upgrades in the LHC even points.

UPSs were installed all over CERN. Based on these observations, the anticipated replacement of all delta conversion UPS units was proposed [4] and finally approved for an implementation during the LS1. So a total of 102 delta conversion UPS units, including the 64 dedicated to the LHC machine, will be replaced by new double conversion UPS units during the LS1.

NEW UPS CONFIGURATIONS

Restoring Redundancy within the UPS Systems

The introduction in 2009 of independent F4 power distribution lines dedicated to redundant machine protection equipment has been considered as a success and, for this reason, will be kept unchanged after the LS1. In the 16 RE alcoves and 4 LHC odd points, the UPS F3 and F4 will be replaced one to one with conventional double conversion UPS units during the LS1. But also, an additional UPS unit will be added in each zone for feeding the bypass line of the first two UPS units (see Fig. 2). In this “stand-by redundant” configuration, the third UPS will act as a backup for the two UPS units on the front line and will consequently restore the redundancy within the UPS system.

In the LHC even points (US caverns and UA tunnels), the UPS power distribution networks as well as the UPS systems were already fully redundant and thus will not be changed during the LS1. As shown in Fig. 3, the two parallel-redundant UPS units in each of these zones will be replaced by two double conversion UPS units connected in “stand-by redundant” configuration since this latter is considered as more reliable.

New Powering Interlock Rules

Based on the modifications brought to the UPS configurations, the UPS-related PIC interlock rules governing the magnet powering interruption will also be changed. In a three-unit UPS system, the failure of any of the three units will not stop the magnet powering provided that the latter transfers the load without any perturbation to its bypass. Indeed, it can be demonstrated that with one faulty UPS out of three, both F3 and F4 power distribution networks remain supplied by two independent UPS units. Hence, the non-availability of one of the three units within a UPS system will not inhibit the operation of the machine, leaving time for the EN-EL Group for preparing the repair intervention. Moreover, the repair may be scheduled together with access for other maintenance, further reducing the impact on the machine availability. Of course, the PIC system will definitely stop the magnet powering if a second UPS unit would come to fail within a system having already one unit down.

In UA tunnels, the failure of one of both UPS units will not trigger the PIC system. Even the failure of one unit of the corresponding redundant system in the adjacent US cavern will still be transparent for machine runs. However, the failure of the second and remaining unit in one UPS system will definitely stop the magnet powering.

Whatever the UPS system configuration, if one of the front line UPS units (powering directly the critical loads) would fail to transfer to its bypass, the UPS user permit to the PIC will remain valid. However, in this event, the magnet powering stop procedure will be triggered by the users’ equipment itself. The PIC will not act in this case but this situation is exactly the same if full or part of the power distribution network downstream the UPS system goes down (e.g. due to a short circuit). This worst case failure scenario has been accepted since 2009 when independent and backed-up power paths were introduced.

Testing the Redundant Powering

If one considers the amount of power cables to be connected over the whole LHC machine, the connection to the wrong power distribution network is more than likely (and it already happened!) and could lead to the loss of redundancy within a critical protection system. Therefore the safe and redundant powering of the machine protection systems will be tested during hardware commissioning at the end of the LS1.

The main objectives of such a test are to check that the machine protection system is still fully operational when losing a complete redundant power distribution network. Technically, this means to verify that the equipment with dual power supply modules is powered by two independent power distribution lines and that true redundant equipment is supplied by redundant power paths. The test will also be the best opportunity to check the worst case scenarios, i.e. when losing a full redundant power distribution network without triggering at all the PIC system.

The test will typically consist in switching off the switchboard powering one power path (F3), and then repeat the same test by switching off the second switchboard powering the redundant power path (F4).

LHC OPERATION FACED TO ELECTRICAL PERTURBATIONS

Impact of UPS Failures on LHC Operation

Ensuring the protection of the LHC machine equipment is of course the most important; however, failures of the UPS power distribution network will also contribute to an increased LHC downtime. Table 1 lists the major UPS failures that occurred during three years of LHC operation, each one causing a machine stop. Table 1 also indicates LHC downtime for each event as well as the time duration from beam dump to beam injection again (when applicable). The cumulated LHC downtime due to UPS failures reaches thus 126 h over three years. With the new UPS configuration layouts being implemented during the LS1, all these events would have been completely transparent for LHC operation.

Table 1: UPS failures during LHC operation

Date	Most probable cause of the UPS failure	LHC downtime / beam to beam [h]
12.01.2013	Surge on 18 kV network	26.5 / 26.5
29.09.2012	Single event upset	9 / 10
01.10.2011	Single event upset	8.5 / 14.5
29.09.2011	Single event upset	8.5 / 9.5
03.05.2011	Single event upset	26 / 28.5
02.09.2010	UPS design issue	4.5 / n.a.
27.08.2010	UPS design issue	8 / n.a.
23.04.2010	UPS design issue	5 / 12
18.02.2010	UPS design issue	30 / n.a.

The last event in January 2013 remains the most worrying: 2 delta conversion UPS units, located 4 km apart, broke down exactly at the same time when a short circuit on an 18 kV cable termination occurred in one of the major substations in Prévessin, the failures on both UPS units being strictly identical. The most probably cause was a surge on the 18 kV network although strictly no other equipment was damaged. Following this event, a re-qualification test campaign has been internally launched at CERN in order to confirm that the new double conversion UPS units can withstand surge levels much higher than those required in the IEC standards.

Outside Electrical Perturbations

The operation of the LHC machine is often affected by outside electrical perturbations (see Fig. 4), causing inevitably LHC downtime.

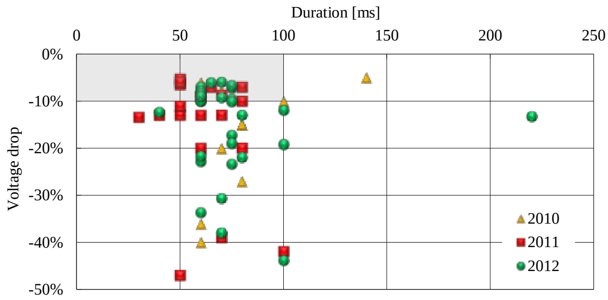

Figure 4: Voltage dips recorded on the CERN electrical network that led to LHC downtime (2010-2012).

The CERN electrical network is supplied by the French grid through a 400 kV line interconnected with the Swiss grid, providing good availability. However, the drawback is that CERN installations get exposed to many more outside electrical perturbations. A frequently asked question is "how to increase the quality of the electrical network"; actually the problem is not the quality of the power distribution network but rather the sensitivity of users' equipment to electrical perturbations. Indeed, it is recommended that standard equipment installed at CERN tolerates voltage drops of up to 10 % and lasting up to 100 ms [6]. Fig. 4 depicts this recommendation with a grey zone and shows that the LHC machine has very sensitive equipment. One means to reduce the sensitivity of the LHC to electrical perturbations would then be to act directly on the users' equipment and to increase tolerances on the input power supply modules.

CONCLUSION

The UPS power distribution network for the LHC has been substantially improved to ensure safe powering and high availability for all users. Though unwished, the first failure of a UPS unit occurring in the LHC after the LS1 will demonstrate the usefulness of the investment made to reshape the UPS network.

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