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RECENT EXPERIENCE FROM THE LARGE-SCALE DEPLOYMENT OF POWER CONVERTERS WITH MAGNET ENERGY RECOVERY

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Abstract

A new powering solution was deployed at CERN for transfer lines in the injector complex as part of the LHC injectors upgrade. The new powering uses regenerative power converters to recycle the magnet energy between physics operations. This work gives an overview of the developed technology, the way it is used in the accelerators complex and some results of first period of operation with beam.

INTRODUCTION

The consolidation and upgrade projects that are performed, approximately, every four years at CERN are important for the performance improvement of the particle accelerators. In addition, recent developments on the climate front, imply new requirements for sustainable operation and energy consumption reduction.

A new power converter family named Sirius [1] has been developed to improve the magnet current regulation stability (half-hour) and 24-hours reproducibility precision from more than 100 parts per million (ppm) to under 20ppm. Additionally, new requirements were set for a faster transition of the magnet field from one accelerator user to the next. These requirements imply new faster and more precise magnetic pre-functions in transfer lines such as the TT2, guiding particles from PS to the SPS accelerator.

This paper discusses some of the powering requirements in the injector's complex and presents the features of the new Sirius converter family and the associated tools to monitor and maintain the new converter farms.

The last section presents the results of measurements performed recently after commissioning of the East Area facility [2]. As a flagship energy saving project for CERN, East Area now operates with a 94% energy economy in comparison to the pre-upgrade operation. The impact of this optimisation exercise on the electrical network infrastructure opens the way for other self-funded projects in the accelerator facilities.

FACILITY DESCRIPTION

Three key facilities at CERN benefited from the consolidation and renovation programmes to renew their powering architecture; a total of 140 power converters were installed in the TT2 Transfer line between the PS and the SPS, in the Booster Transfer line from the Booster to PS and to ISOLDE and finally in all transfer lines from PS to the new East Experimental Area. An example of the diverse magnet loads that are powered by the new converter family is illustrated in Fig. 1.

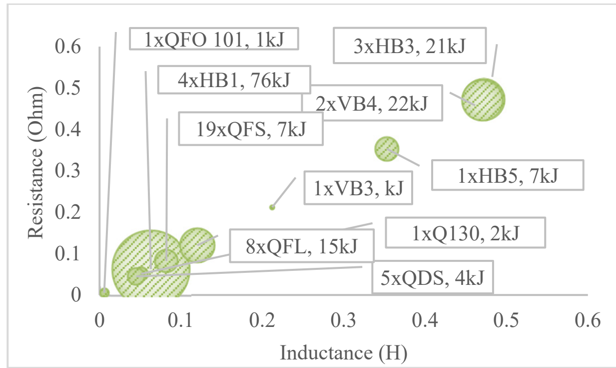

Figure 1: Inductance and resistance value of the magnet loads in the TT2 transfer line. Bubble size corresponds to the energy stored by the magnet.

The first challenge that is a consequence of the different electrical characteristics of magnets is the wide variation of the recyclable energy (stored in the magnetic field) that varies from as low as few kJ to almost 100kJ.

An additional challenge for the new power converters design was related to the wide voltage requirements due to the fast cycling needed under so different load inductance values.

The development of a standard powering system for such a diverse user environment required significant modularisation of the design. Furthermore, in certain cases a double powering scheme has been applied where two smaller power converters are used, instead of a larger one, to power separately the two coils of a single electromagnet. This allows reuse members of the Sirius converter family, instead of developing dedicated converter for specific magnets, to benefit from a standardisation effort and from a more cost-effective large-scale manufacturing.

POWER CONVERTERS

A new power converter family, called Sirius, was designed in the laboratory and mass produced in industry. The power converter is modular with up to four power bricks and each brick has a rated output of 450A peak and 450V. The topology used is an H-bridge IGBT converter operating at 6.5kHz with a front-end diode rectifier with a boost regulator operating at 13kHz for the dc-link voltage regulation.

The power converter, see conceptual drawing in Fig. 2, recycles the magnet's field energy using the DC-link capacitors as energy storing units. To account for the very diverse load size and energy requirements the power

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converter also employs a modular energy storage with 30kJ units comprising commercial aluminium electrolytic capacitors for cycling applications.

Special requirements for the semiconductor power stack lifetime were set because of the demanding cycling regime in particle transfer lines. The IGBT modules are build using an AlSiC (aluminium-silicon carbide) substrate technology with high thermal conductivity, in order be less prone to delamination due to thermal cycling [3]. Combined with very efficient water cooling the lifetime is expected to more than 200 million cycles.

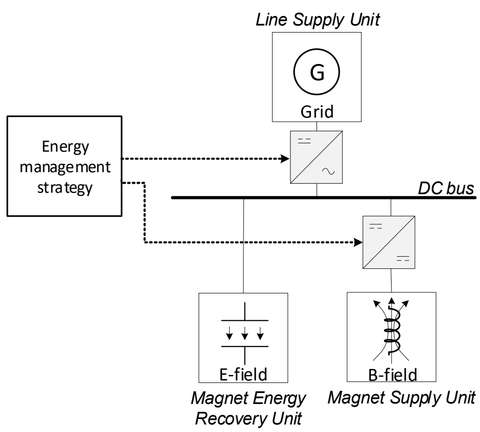

Figure 2: In a Sirius converter energy is being exchanged via a dc-link among three units; the grid-supply, the energy storage and the magnet supply.

Sirius is a large farm of power converters with an aggregate installed output power of more than 50MW. For a more efficient maintenance a remote monitoring facility has been developed.

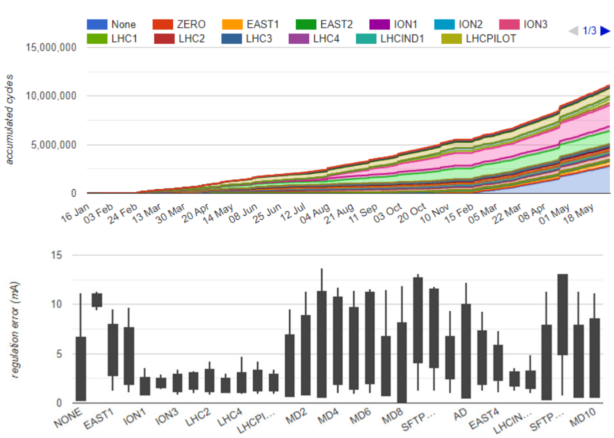

Figure 3: Data from a power converter in TT2 powering a large bending magnet (F16.RBHZ117). Top graph illustrates the accumulated number of cycles played for different accelerator users in present year and the bottom plot shows the spread of regulation precision for different accelerator users (67% of samples are within boxed area).

Using the CERN proprietary function control generator built into each power converter, several variables are observed for statistical and maintenance planning. An example of the monitoring results showing the count of user cycles, the monitoring of the precision of the power converter in time and with different users and the evolution of the energy storage state-of-charge are illustrated in Fig. 3 and Fig. 4. Using this data, preventive maintenance can be performed according to a maintenance schedule corrected for each power converter using real time running data.

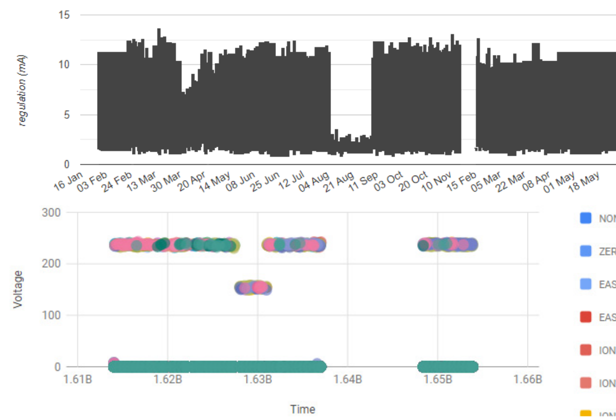

Figure 4: Data from a power converter in TT2 powering a large bending magnet (F16.RBHZ117). Top graph illustrates the evolution of the maximum regulation error over time. The bottom plot illustrates the energy storage state-of-charge (voltage) as a function of time for different users.

Since the commissioning of the first converters in 2019 a total of 850,000, 000 cycles were performed by all Sirius without any downtime, other than external interlock systems and control software/hardware issues.

In the accelerators domain, the reproducibility of the power converter output current is a key performance index. Using automated scripts the performance is evaluated 50ms into the magnet current flat-top, every 10 seconds for a total duration of 24 hours.

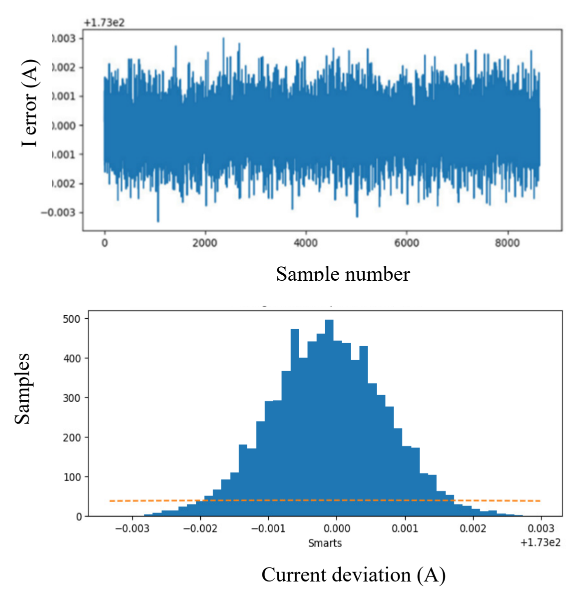

Figure 5: Output current value variation recorded over a period of 24hours. During the magnet current was set to 173A and a deviation of +/-0.003A was recorded that corresponds to 5ppm.

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During the latest evaluation campaigns performed in East Area, the performance of all converters was consistent to the requirement of 20ppm. A sample of measurements performed for a Sirius S power converter of a quadrupole magnet F61.RQNEG030 is illustrated in Fig. 5.

ENERGY CONSUMPTION

Following the example of the Power System for the PS (POPS) [4] and other power converters with energy recovery designed in the past, Sirius employs a two-stage power conversion with the following characteristics:

1. The front-end manages the instantaneous grid power in a way that limits it to a necessary maximum value.
2. The magnet supply unit operates in four quadrants for a bidirectional voltage and current to recover and recycle the magnetic field energy between physics operations.
3. Maximum output voltage is used during ramping to achieve lower RMS and faster current slopes.
4. A cycling operating mode is used rather than continuous magnet powering
5. A new RMS minimiser control algorithm that further reduces the RMS contribution of the current waveform before and after the physics operation

A measurement campaign [5] was performed after commissioning of the last converters in East Experimental Area to evaluate the impact of the new power converters to the loading of the electrical network and the potential cost economies due to the new operation mode.

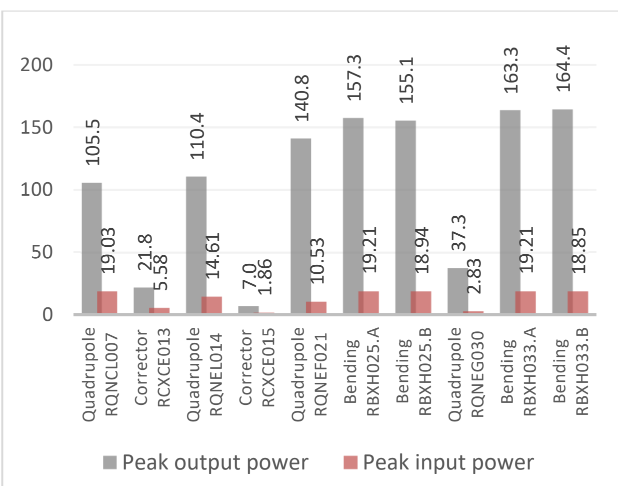

Figure 6: An important difference between the peak input and peak output power of power converters in F61 transfer line of East Area.

The dc-link in the power converter acts as a temporary energy storage providing and recovering the peak magnet power plotted in Fig. 6, while the input power remains capped to the moderate RMS value that represents the thermal power losses in the magnet and in the circuit.

The total input power of 21 power converters (transfer lines F61,F62,F63 and T08) is limited to under 300kW peak with an RMS value not exceeding 60kW as seen in Fig. 7. The same power converters deliver up to 1500kW of output power using the recycled magnet energy from the dc-link capacitors as seen in Fig. 8.

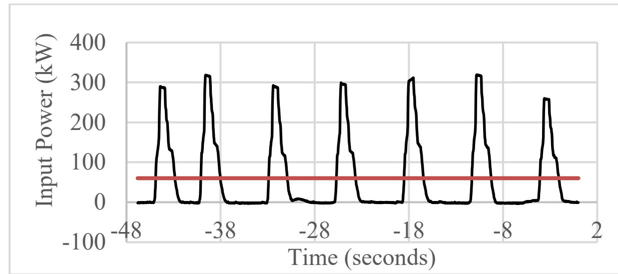

Figure 7: Total input power of all power converters in transfer lines F61, F62, F63 and T08.

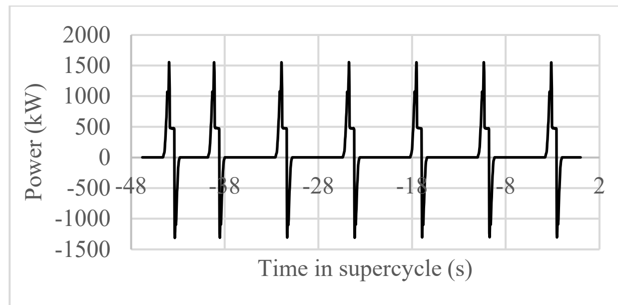

Figure 8: Total output power of all power converters in transfer line F61, F62, F63 and T08.

Based on energy utilisation audits performed in 2012 [6] and in 2021 (see Table 1), an economy of 95% was recorded following primarily the transitioning from continuous to cycling mode of operation of the power converters and as a result of the fast cycling and the RMS minimiser control algorithm.

Table 1: Energy Economy Figures

Audit Year	Consumption (MWh)	Savings (Relative to 2012)
2012	9128	-
2021	570	-93.8%

CONCLUSION

A number of particle transfer lines have been upgraded to improve their performance and consolidate their operation. The new powering system implemented a current regulation precision of better than 20 ppm. In addition, a faster transition of magnet field from one user to the next permits better utilisation of the transfer lines and more dense mission profiles. The faster current transition as well as in some cases the transition of operation from continuous magnet powering to cycling mode of operation resulted lower RMS current in the magnets, less losses to evacuate and a consequent economy which reaches 94% in the East Experimental Area compared to previous measurements from 2012.

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