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High-Current Low-Voltage Power Supplies for Superconducting Magnets

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***Abstract*—In a synchrotron accelerator, the beam trajectory is controlled thanks to magnets, where superconducting technology allows to generate very strong magnetic fields. This was a key element in the construction of the Large Hadron Collider (LHC), the world largest accelerator. Such magnets need special power supplies providing very high DC current under low voltage. In the frame of High Luminosity-LHC (HL-LHC), stronger superconducting magnets are developed and require enhanced supplies. This article reviews the present power supply topologies and introduces new concepts: HL-LHC project offers an opportunity for upgraded system, increased operational performances as well as integrated energy storage to recover energy from the superconducting magnets.**

I. INTRODUCTION

For fundamental physics research, and especially for high-energy particle physics, superconducting magnets play a crucial role in particles accelerators: controlling the particle beam trajectory and focusing the beams for the experiments. Creating this strong magnetic field is done by circulating high-current - several kilo-amperes - in superconducting coils of the superconducting magnets; in the present Large Hadron Collider (LHC) [1] dipole magnets operate up to $8\,\mathrm{T}$. Feeding those magnets with the adequate current is where energy conversion and conditioning technologies appear in the form of power supplies to interface the superconducting load with the electrical grid [2]. Because of superconducting magnets intrinsic properties (large inductance with zero resistance) high currents can circulate through it without any losses. This results in need of special power supply able to deliver a very high DC-current under few volts [3]. The resistance in the system only comes from the copper cables needed to connect the power supply to the superconducting magnet. This peculiar configuration leads to fundamental asymmetry in the ratings (high-current, low-voltage) which implies to use semiconductors in an unusual range considering their specifications.

A superconducting magnet is an electromagnet made from coils of superconducting wires. They are able to produce intense magnetic fields because of the large amount of current that wires can carry without any losses. To enable this, all materials should be cooled down to low temperature ($1.9\,\mathrm{K}$ or $-271.25\,^{\circ}\mathrm{C}$) in a cryostat assembly to obtain superconductive behaviour. There are various types of magnets playing different roles in particle accelerators: bending, focusing or correcting the beam.

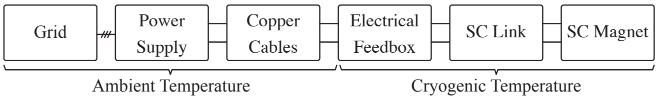

Fig. 1. Simplified superconducting magnet powering scheme.

The ones relevant for this paper are, so-called, Inner-Triplets (IT), whose role is to provide the final focusing of the beams before collision in the Interaction Points (IP) [4] (the place where experimental data are collected). As the power supplies cannot be located close to the superconducting magnet due to the induced beam radiations, a special SuperConducting link (SC) is needed to bring the DC current to the superconducting magnets. The two worlds of warm and cold powering need to be interfaced through an electrical feedbox [5], c.f. Figure 1.

CERN launched a project to upgrade the LHC, called High Luminosity LHC (HL-LHC) [6], with objective to improve the luminosity of the two main experiments ATLAS and CMS. The goal is to increase the collision rate by an order of magnitude by rising up the beam brightness, reducing the size of the beam when colliding and considering few others parameters. This requires to upgrade the Inner-Triplets magnets for much stronger ones, reaching a magnetic field of $12\,\mathrm{T}$, corresponding to $18\,\mathrm{kA}$ DC current. Presently, energy stored in the IT magnets is not being recovered, and during the ramp-down phase, it is dissipated in the copper cables during a free-wheeling process, whose internal resistance together with magnet's inductance, define the time constant of the circuit. However, in the new HL-LHC integration layout, power converters will be located in the underground gallery, much closer to the IT, significantly reducing resistance of the circuit, which leads to an increased time constant of the circuit. Due to cycling nature of LHC accelerator, the IT magnets ramp-down phase shall be performed with the same time constant as the other magnets. Those requirements have initiated the ongoing research with focus on the possibility to recover this energy. Novel propositions to improve the system with addition of energy storage elements is evaluated and constitute the base for further developments.

This paper provides the requirements for superconducting magnets and presents existing power supply topologies already used at CERN. Finally, details are provided about the research, development and areas of improvements for future high-current power supplies for the HL-LHC upgrade.

II. EXISTING TECHNOLOGIES AT CERN

The superconducting magnet power supply role is to provide a large amount of current in a controlled way and with high precision. To achieve that, parallel connection of sub-converters is often used to reach the desired ratings. This approach contributes to the modularity and adds redundancy to the power system which has been introduced in the early stages of the LHC design. Other constraints should be considered as well in terms of integration:

- The overall volume of the system should be kept low, because of the peculiar location of the power supplies: usually a confined space in an underground area such as a technical gallery.
- The losses should be carefully managed as the heat should be mainly evacuated by the water cooling system. For instance, the use of soft switching technique [7, 8, 9] helps to minimize switching losses in semiconductors.
- The availability of the power systems should be kept very high in order to maximize the collision time for the experiments.
- Grounding of the magnets imposes a requirement for a galvanic isolation inside the power supplies.
- EMC (Electromagnetic Compatibility) IEC61000, level 4 must be respected because of the proximity with other sensitive systems like cryogenic instrumentation or quench protection systems.
- Impact on CERN power grid should be considered and techniques for peak shaving and perturbation rejection are favored.

This is a non-exhaustive list of the constraints that underlie the design of any power supply for particle accelerators. The most important criteria in the evaluation of a new design are the electrical performances, namely DC voltage ripple and output current stability. For the particle accelerators, magnet current must be controlled very precisely (10 parts-per-million), as it impacts the magnetic field seen by the particles and any variations would result in an unwanted modification of the beam trajectory, which could lead to a premature beam dump. The Inner-Triplets magnets are even more sensitive to the power supply performances because of their critical position in the accelerators and strong impact on the beam optics.

TABLE I
POWER SUPPLY PARAMETERS.

Supply	Ratings		Operation	Cooling
	Voltage [V]	Current [A]		
PC1	+ 8	+ 8000	1-Quadrant	Water
PC2	+ 8	+ 6000	1-Quadrant	Water
PC3	± 10	± 600	4-Quadrant	Water, forced air

To power the present Inner-Triplets magnets, two families of switch-mode power supply have been developed over the years: 1-Quadrant type for the main circuit and 4-Quadrant type to locally trim the current across one magnet [10, 11]. Their powering scheme is provided in Figure 2, the power supply parameters are gathered in Table I. All of those power supplies are by nature low-voltage high-current. The power supplies operate as current controlled voltage source whose command signal comes from the control center and is processed through a decoupling matrix to give their set-point. The overall electrical system can be seen as voltage sources feeding a RL load (the R of the copper cables, the L of the superconducting magnet).

As already mentioned, all of the existing low-voltage high-current power supply topologies rely on the paralleling of several converter stages. As commercially available semiconductors are not available with suitable ratings, paralleling allows to reach higher currents, adding the modularity and redundancy (highly valued criterion) to the design, while simplifying the maintenance.

The power part is surrounded by different systems, whose integration and the relations with various auxiliary systems is depicted in Figure 3: there are several layers of control to ensure a proper coordination of all the power system, and ensure both material and personal safety.

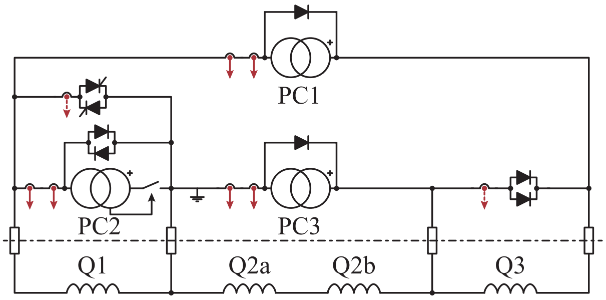

Fig. 2. Actual Inner-Triplets powering scheme.

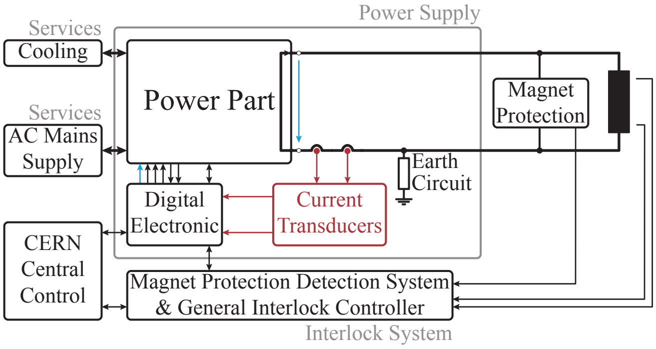

Fig. 3. Simplified integration of power supplies. Thin line represents signals while thick ones represent power exchange between entities.

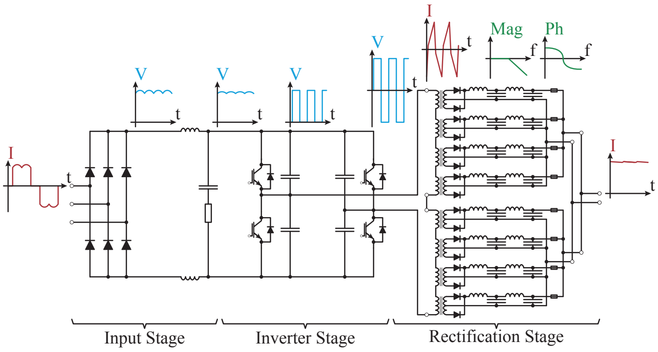

Fig. 4. Basic sub-converter of a 1-Quadrant power supply family, rated 2 kA, 8 V.

Fig. 5. 1-Quadrant sub-converter output module - rectification stage is composed by two of these units.

A. 1-Quadrant Power Supply

The family of 1-Quadrant power supplies is designed in modular fashion, with many sub-converters in parallel, where topology of a basic one is shown in Figure 4. Each input module has a simple diode rectifier, providing a DC link voltage to the full-bridge soft-switched inverter of a DC-DC converter. Galvanic isolation is achieved by means of several medium-frequency transformers, connected in series on the primary side, with center-tapped rectifiers connected in parallel on the secondary side. Output of each rectifier features second order low-pass filter providing attenuation of the voltage ripple. Illustrative waveforms of different stages are shown in Figure 4 as well. Several sub-converters are then parallelized to achieve higher currents with the possibility to integrate active $N + 1$ redundancy: e.g. a 6 kA power supply is composed by 4 sub-converters rated at 2 kA. As any 1-Quadrant power supply, the ramp-down of the magnet current relies on the resistance of the cables in combination with free-wheeling diodes in the power supplies to provide a current path.

The module is actually a high-frequency current source controlled by a 1 kHz bandwidth voltage loop, where the phase-shifted PWM operates at 20 kHz. Having multiple rectifier output stages ease the design of the magnetic parts, allow to use lower-rated fuse for the protection of the whole system, and bring the high availability required for LHC system: such a module can be up and running even if a secondary is fused out. Modularity greatly helps for the assembly and maintenance of the complete system, keeping the form factor of basic building block rather compact, and enabling the quick swap of module in case of fault.

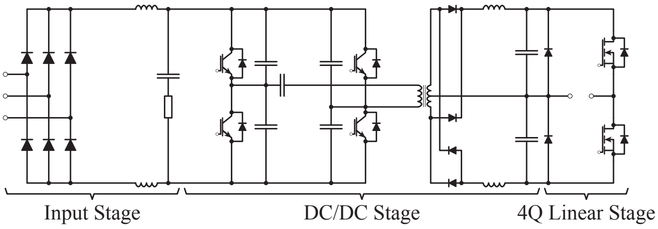

Fig. 6. Basic sub-converter of a 4-Quadrant power supply family, rated 600 A, 10 V.

Fig. 7. 4-Quadrant sub-converter module.

B. 4-Quadrant Power Supply

The topology of a 4-Quadrant power supply is very close to the previously described 1-Quadrant topology, but with only a single module rated 600 A, 10 V. The input stage is rather identical and based on a simple diode rectifier followed by phase-shifted galvanically isolated converter with center-tapped rectifiers on the secondary side.

The output is designed around a linear stage relying on power MOSFET which provide the 4-Quadrant operation. They behave as gate voltage controlled current source. In this case, the power supply is not regenerative, only the last stage operates in 4-Quadrant mode where all the energy recovered from the magnet is dissipated as heat inside the power semiconductors. More recently, redundancy feature and tolerance to radiation has been developed by CERN for this type of converter [12].

While the efficiency of this kind of system is not very high, precision and accuracy in operation are achieved thanks to the linear output stage: 10 parts-per-million (ppm) are guaranteed over 30 min, 500 ppm over a year.

III. RESEARCH AND DEVELOPMENT AT CERN

Based on the current power supply technologies and identified areas for improvement, new power supply types are required for the upgrade of LHC accelerator, overcoming limitations of deployed technologies.

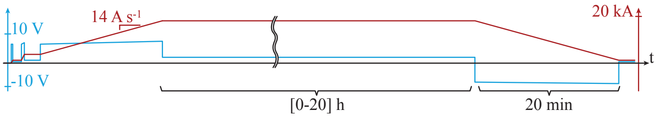

Fig. 8. Current and voltage profile of a typical cycle for the Inner-Triplets magnets.

Particle accelerators are characterized by cycling way of operation where the operational cycle is well defined. For the system of interest - Inner-Triplet magnets, overview of the new cycle is given in Figure 8. As it can be seen, after an initial ramp-up of IT magnet current during approximately 20 minutes, final value is regulated for several hours, prior to ramp-down phase that is of similar duration as ramp-up phase. New power supplies for HL-LHC upgrade will be located in underground galleries, closer to magnets and cable resistance is removed from the equation. Thus, there is a need to develop a new family of 2-Quadrant power supplies, where the ramp-down of the current is forced by applying negative voltage across the magnets. Because of that, the recovered energy during the ramp-down of a cycle could be used for the next ramp-up, or even injected back on the grid. Considering the specifications of the magnet, simple calculation is performed to get the amount of magnetic energy stored :

$$\nicefrac{1}{2} \times L \times I^2 = \nicefrac{1}{2} \times 0.255 \times (18.10^3)^2 \simeq 40 \text{ MJ} \quad (1)$$

This represents the amount of energy to ideally recover in each cycle, that could be then processed elsewhere in the system or used for the next cycle. Evidently certain amount of energy will be lost in the resistance of the system, the goal is to have it as efficient as possible to reuse most of that energy. The benefit of having an energy storage inside the power supply leads to a better controllability of the power flow, allowing a peak shaving of the input power which could have a major impact on the infrastructure cost for the electrical grid side.

Considering CERN specific requirements, electrical performances, reliability, modularity and availability are the most important key performance indicators. New 2-Quadrant power supplies have to comply with the integration scheme previously depicted. Requirements can be summarized as:

- Output power ratings (peak): $180\,\text{kW}$.
- Input power rating: minimal. The goal is to take advantage of the storage to support the peak power, which is more than the double of the flat-top power.
- Output voltage rating: $\pm\ 10\,\text{V}$.
- Output current rating: $+18\,\text{kA}$.
- Dynamics: $\pm\ 16\,\text{A}\,\text{s}^{-1}$ for a ramp-up/down in around $20\,\text{min}$. A typical cycle is given in Figure 8, where the current in standby mode of operation is different from zero, then, it rises for the injection level which is followed by the ramp-up to reach the nominal current - it can be maintained for hours, as long as the beam quality is good enough for the experiments and no problem appears anywhere else in the accelerator. Then, the magnet current ramps down to the standby level at the end of the cycle or in case of early stop of the system because of any fault. The average duration of a cycle is around $12\,\text{h}$.
- Lifetime expectancy of 20 years, accounting for 200 days of physics operation a year with 2 cycles expected per day.
- Load: Resistance $0.13\text{m}\Omega$, which represents around $20\,\text{m}$ of copper cables, and inductance: $255\,\text{mH}$, with the new configuration of HL-LHC and the new magnets corresponds to the series connection of Q1, Q2 and Q3.

To process the recovered energy, the existing dissipative solutions have some inherent limitations. Due to proximity of converter and magnet, they cannot be considered anymore to decrease the voltage in the magnetic load as the new time constant would be excessively high, and it would generate an excessive amount of heat. The research focus is put on the innovative and energy efficient approaches characterized with presence of energy storage elements. There are several possible technical approaches to implement these systems, as discussed in the following sub-sections.

A. *Feeding energy back to the grid*

Rather than temporary storing the energy, this advanced solution avoids the need for any energy storage and provides full control over the recovered energy as well as the power coming from the grid. While this approach provides certain benefits from the power quality and grid support point of view, it also has certain drawbacks when considered inside the CERN environment. A block diagram of this approach is given in Figure 9, where blocks represent converter functions and neglect actual technical implementation. Arrows indicate the direction of the power flow. Note that isolation (not shown in the figure) is mandatory and can be implemented either in front of AC/DC converter or inside the DC/DC converter. This approach is characterized with:

- Every converter stage needs to be fully bidirectional, namely full 4-Quadrant converter is needed even though objective is the 2-Quadrant converter.
- Every converter stage needs to be designed for the peak power, even though operational cycle requires this only during ramp-up and ramp-down phases. These intervals represent minor part of the overall cycle.
- The overall monetary value to inject energy back on the grid is negligible compare to the added complexity in the system.
- Due to modular design philosophy, there is a need for careful control coordination of multiple active rectifiers, adding complexity to the control system.

Fig. 9. Possible implementation of 4-Quadrant supply family, with energy recuperation functions, implemented in a topology fully reversible in current.

These are some of the arguments against approach to feed back energy directly to the grid, as the potential gains in flexibility and control of the power flow are drowned by its complexity - such kind of converter would be over-dimensioned, because peak power is only needed for a limited amount of time in the normal cycle definition and only 2-Quadrant operation is required for the application. This is in contrast with the simplicity, reliability and availability that are highly valued for the design of the converter, considering particularities of the application.

B. Storing and reusing energy

In this latter approach, the net gain can be highlighted in the following key points:

- Storage can act as an energy buffer between the grid and the superconducting load, providing flexibility in the powering strategy, peak shaving as well as robustness to grid perturbations.
- Sizing of the different stages can be made accordingly to their worst case stresses.
- The position and operating voltage of the storage elements represent a degrees of freedom that impact overall converter design.
- The energy storage elements can be modularized to respect the requirements in terms of availability and redundancy.

Within this approach several different implementations can be identified, considering energy storage elements that are either outside or inside of the main power flow. The benefit of having an energy storage inside the power supply leads to a better controllability of the power flow, allowing a peak shaving of the input power which could have a major impact on the infrastructure cost for the electrical grid side. With these configurations, grid size converter can stay passive and with reduced ratings, compared to a fully bidirectional solution. The required peak power on the grid side, can be greatly reduced.

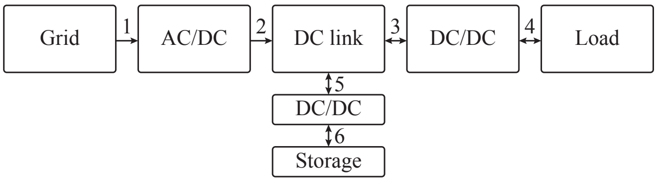

Fig. 10. Implementation of 2-Quadrant supply with energy storage, integrated outside the main power flow, on the high voltage side.

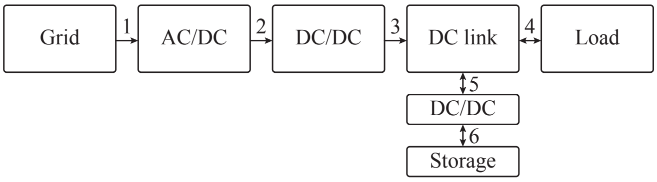

Fig. 11. Implementation of 2-Quadrant supply with energy storage, integrated outside the main power flow, on the low voltage side.

Fig. 12. Implementation of 2-Quadrant supply, with energy recuperation functions, integrated inside the main power flow.

Principal topology depicted in Figure 10 allows to split the power delivered to the load: one part can be provided by the grid and the other part can be provided by the energy storage element. The connection between the energy storage element and DC link is made through a dedicated converter. With diode rectifier serving the role of the AC/DC converter, DC link is relatively high and both DC/DC converters shown in Figure 10 would have to be accordingly designed and optimized. While the galvanic isolation is required on the load side, it may not necessary be required for the energy storage DC/DC converter, imposing certain constraints on the voltage variations of the energy storage elements. However, both DC/DC converters must be bidirectional and sized for the full power.

In an alternative realization, shown in Figure 11, energy storage is connected to the system on the LV side, closer to the superconducting magnets. This approach allows further simplifications, considering that main DC/DC converter can be made with reduced ratings and does not have to be bidirectional anymore. Existing power supply technologies at CERN, can be easily modified and adapted for new ratings, while energy storage DC/DC converter can be optimized considering operation with low voltages on both sides, but with relatively high currents dictated by the load.

The different scheme, presented in Figure 12 relies on the energy storage element to be used as a buffer between the grid and the load. It could be charged from the grid independently of the load behavior, through the input AC/DC converter of reduced ratings. In this case, input AC/DC converter has to be able to regulate its output voltage in a given range, defined by choice of the energy storage technology. This implies the galvanic isolation as part of the AC/DC converter. The DC/DC converter stage has to provide bidirectional power flow and must be sized for the full power.

Regarding the choice of the energy storage, super-capacitors and batteries appear to be the most suited technologies according to the time constant of the system and its energy and power requirements. Yet, considering the operational cycle, ratings and time constants of the system, batteries seems to be better choice. Moreover, increased interest in the technology, following electric vehicles trend, brings more efficient and reliable devices. Battery should recover/provide energy with the highest efficiency on a round-trip cycle to the load. Other storage technologies are currently being investigated to assess their feasibility for CERN applications, but this is outside the scope of this paper.

IV. CONCLUSION

A new type of power supply which should be able to deliver up to 18 kA with a very high current stability is needed for the upgrade of the LHC accelerator and more particularly the new Inner-Triplet magnets. Ramping down the magnet current in the same time as the ramp-up implies to deal with recovered energy, and thus developing new solutions to process it: if the energy is sent back to the grid, the grid has to support the magnet peak power; while the use of a local storage element would allow the grid to only cover the losses in the system, whereas the energy for the magnet will be stored locally and reused when cycling. This new concept for the powering of superconducting magnets will optimize the energy management and will reduce the operating and infrastructure costs.

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