

CERN-PS MAIN POWER CONVERTER RENOVATION: HOW TO PROVIDE AND CONTROL THE LARGE FLOW OF ENERGY FOR A RAPID CYCLING MACHINE

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Abstract

The PS accelerator (Proton-Synchrotron) at CERN, which is part of the LHC injector chain, is composed of one hundred magnets connected in series. During a typical acceleration cycle (taking 2.4 seconds), the active power at the magnet terminals varies from plus to minus 40 MW. As this large active power variation was not acceptable to the electrical network, a motor-generator set (M-G) was inserted between the grid and the load. The M-G set (of 1968) acts as a fly-wheel with a stored kinetic energy of 233 MJ and the magnets are fed via two 12-pulse thyristor rectifiers. A renovation or replacement of the installation is planned in the near future as part of the consolidation of the LHC injectors to avoid any major breakdown, to improve overall availability and to reduce operation and maintenance costs. This paper presents a first comparison of technical solutions available to build such a power system and the strategy that will be applied for the up-grade of the system.

PS MACHINE CYCLES

The PS accelerator at CERN is composed of one hundred main magnets connected in series. The impedance of this magnet string is $0.9 \text{ H} / 0.35 \Omega$. The shape of the magnet current is trapezoidal: the rise and fall times are 0.7 s and the flat-top is 0.3 s. The pulse repetition frequency is $\leq 0.4 \text{ Hz}$. Concerning the shape of the active power at the load during a typical acceleration cycle, it rises almost linearly from zero to 40 MW within 0.7 s, drops to 10 MW with a dP/dt of -1 MW/ms , remains at 10 MW during the current flat-top, falls to -40 MW ($dP/dt = -1 \text{ MW/ms}$) and returns to zero while energy is transferred from the magnetic field back to the AC mains. The apparent power at the mains is similar in shape to the load current and has a peak value of 65 MVA. The shape of the current, the voltage and the active power at the load are shown in Fig.1.

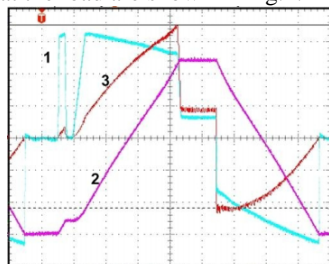


Figure 1: PS chronograms for a 26 GeV/c cycle.

- 1: Voltage 2.5 kV/div, 200 ms/div
- 2: Current 1 kA/div
- 3: Active power 10 MW/div, at the magnet terminals.

A train of 2.4 s long acceleration cycles, having similar shape but different peak currents, is embedded within a so-called super-cycle of up to 43 s to serve different physics users. On average the PS operates around the clock for 5000 hours a year (8760 hours).

PRESENT POWER SYSTEM

To avoid drawing the power pulses directly from the internal 18 kV CERN AC-mains ($P_{cc} = 600 \text{ MVA}$), an M-G set is inserted between the mains and the load. The motor is connected to the 18kV network by a 7 MVA transformer and drag the 80 ton rotor of the generator at 1000 rpm. The generator drives a 6.6 kV network feeding the four 12 MVA transformers of the rectifiers, which power the magnets by delivering a voltage of 9 kV and a DC current up to $5.5 \text{ kA}_{\text{peak}}$ ($3.2 \text{ kA}_{\text{rms}}$, limited by the magnets). The M-G set, which acts as a fly-wheel with a stored kinetic energy of 233 MJ at nominal rotating speed, evens out the pulsed power to be delivered by the mains. The motor power is controlled via frequency converters exciting the rotor windings and is kept roughly constant at 6 MW. During continuous operation the rotating speed of the M-G set varies, i.e. the speed is brought to over-synchronism (up to +2 % of nominal speed) between PS acceleration cycles and falls (to -2 % minimum) during a cycle. A principle diagram of the present power system is shown in Fig.2.

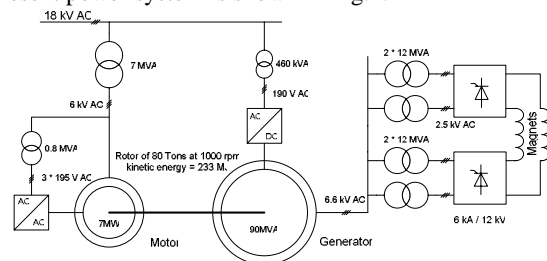


Figure 2: Present PS power system with M-G set.

The PS power system with the present M-G set came into operation in 1970. The three main power electronics components of the PS power system are:

- The excitation of the generator (in operation since 1995), which consists of two parallel connected 6-pulse thyristor rectifiers (255 V, 1400 A each).
- The frequency converter of the motor (in operation since 1995), consisting of three sets of anti-parallel 6-pulse thyristor bridges (110 V, 1400 A each) and designed for an operating frequency range of $\pm 2.5 \text{ Hz}$.
- The magnet power converter (in operation since 1978) composed of two 12-pulses thyristor rectifiers working in series. Each of them includes two series connected

6-pulse bridges fed by separate transformers. One recalls for completeness that each valve of a 6-pulses bridge consists of nine thyristors, namely three parallel connected sets of three series connected devices.

The conclusions of an independent audit state that in spite of its age, the M-G set could withstand ten or fifteen more years of operation. The high level of maintenance shall be maintained to achieve this expected life time. Afterward the replacement of such a machine will be unavoidable. The weak parts of the system are the thyristor rectifiers and the associated electronics due to their age and to the limited upgrade done during the past fifteen years.

NEW SOLUTIONS

Due to the age of the M-G set a study has been launched within the consolidation framework, to evaluate possible solutions to replace the present power system.

Kinetic storage system

The present rotating machine has been built by a special department of SIEMENS (Pulsed generators, Berlin, DE) which was suppressed in the nineties due to poor market. The market, for this type of machine, was for short-circuit equipment tests which are now done directly on strong power networks. Buying such a machine today would require a special study done by the motor-generator suppliers and their interest is very low. Another possible solution is to use very fast rotating machines (10'000 rpm) which are under development. The main problem is that there is no industrial supplier for this type of equipment at the needed ratings. In conclusion, the motor-generator set is still a possible solution to realize such a power system but there are no more standard and industrial products on the market to cover our application.

Direct network connection

The first solution without an M-G set is to connect the power thyristor rectifiers directly to the electrical network. The connection of such a load to the network needs the approval of the local electrical distributor. This is possible and accepted by the distributor only if the power converter is connected to the 400 kV network. This network has a short-circuit power of 10'000 MW which allows pulsing of 60 MW at 1 Hz. This solution requires a 90 MVA 400 kV/18 kV transformer, supplying a 4 km long line to feed the power converter. Moreover, a local reactive power compensator is required to manage the reactive power generated by the thyristor rectifiers and harmonic filters must also be installed (figure 3). The advantage of this solution is to be based on industrial products. The drawbacks are the cost and the risk of polluting the CERN network which supplies other very accurate power converters. Moreover, perturbations such as thunderstorms will be stronger when compared to the 6.6 kV network generated by the M-G set.

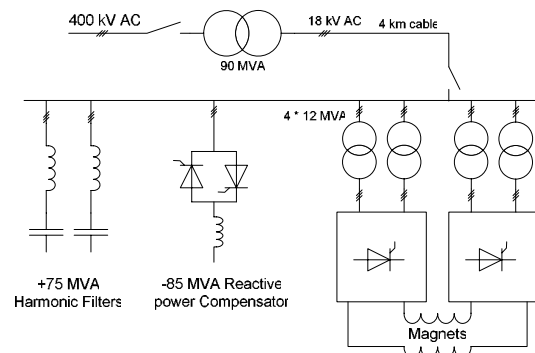


Figure 3: Solution with direct network connection.

Inductive storage system

If the power does not come from the network, an energy storage system must be installed between the network and the load. One possible solution is to use a Superconducting Magnet Energy Storage (SMES) system. The idea is to store the energy in the magnetic field of a choke, $W = 0.5 \times L \times I^2$. Superconducting technology is required to get a very high field and a compact solution. Superconductors allow a high current density and high field strength (few Tesla) and high inductance value. The design of such a SMES for the PS power system has been done by ITP (Forschungszentrum) Karlsruhe. One possible solution is to have one large SMES of 40 MJ (4 Tesla, 6 kA) in one cryostat. The main difficulty is to integrate the SMES within the power system. The first alternative is to keep the thyristor rectifier for the magnet and to connect it to the 18 kV network. The SMES would be connected to the same network via a second thyristor rectifier as illustrated in figure 4.

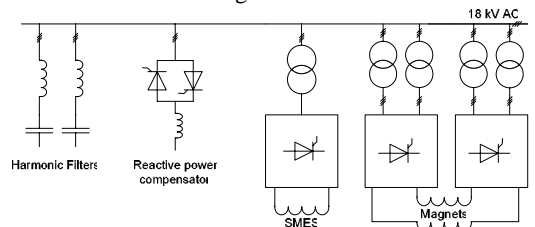


Figure 4: SMES solution with thyristor technology.

The second and smarter alternative is to integrate the SMES inside the magnet power converter as shown in figure 5. This solution minimizes the high power conversion stages and thus the losses. Moreover, the reactive power compensator and its harmonic filters are not required, reducing the complexity. Nevertheless, the converter topology is not standard for such a high power and the design of a based on industrial products requires further study. Moreover, there is no semiconductor device available to build a switch-mode 40 MW DC/DC converter. Parallel or series connected devices and/or converters have to be introduced into the design to reduce the voltage or current stresses on the semiconductors.

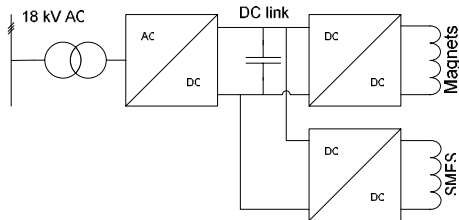


Figure 5: SMES solution with switch-mode technique.

The redundancy concept could be introduced in the power converter design. Since the power converter has to be split, it may consist of 4+1 independent power converters to allow operation even if one is broken (see figure 6). This topology also reduces the size of the SMES but multiplies its number. The design of a 15 MJ SMES is simpler and the down time in case of failure will be very low due to the fact that one spare will be available. Solutions with parallel or series connected power converters are under study including redundancy concepts.

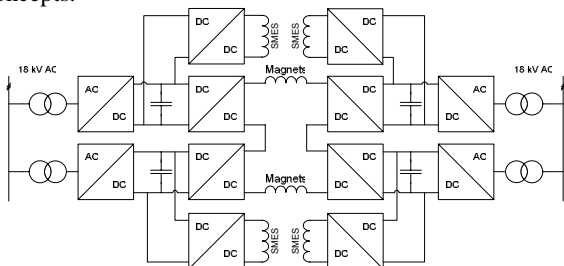


Figure 6: multi-converters concept.

Capacitive storage system

A second way of storing energy is to use capacitors. As the required voltage to the load is 9 kV, the only solution is to use classical film capacitors. Supercapacitor technology is not ready for operation at this voltage. The storage energy will be: $W = 0.5 \times C \times U^2$. The first design gives a capacitor value of 1.2 F with 6 kV capacitors. This required around 30 m³ (40 tons) of capacitors.

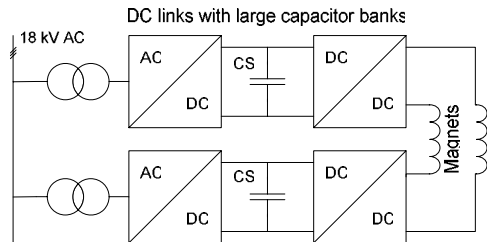


Figure 7: Solution with capacitor storage system.

The advantage of this solution is that the components are well-known and the power converter topology is classical (see figure 7). Nevertheless, the capacitors banks have to be split up into 100 kJ sections which shall be protected separately for safety reasons. A study has been started in collaboration with EPFL (Lausanne, CH) on this way of storing energy with the focus on redundancy, multiple DC/DC stages instead of one high power DC/DC

stage. Also in addition, the concept of flying-capacitors will be considered (see figure 8).

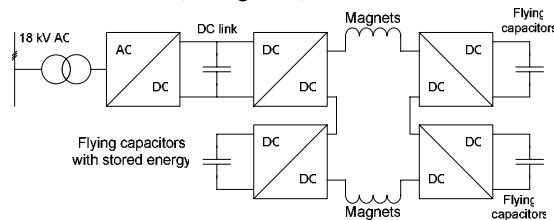


Figure 8: Flying capacitor concept.

The idea of this concept is to have only one AC/DC converter to make up the losses of the system combined with many independent DC/DC converters. The challenge is to control the DC link voltages during the PS cycles.

CONCLUSION

A study has been launched to evaluate the possible solutions to replace the existing PS power system including M-G set. Network solutions exist but require complementary studies to evaluate the impact on the power quality of CERN and the cost is expected to be comparable with the others solutions. Alternatives based on a local electrical energy storage system (capacitive or SMES) are under study and represent a good alternative to the kinetic storage system. Unfortunately, there is no industrial product available directly for our application. The strategy for the next five years is to upgrade the thyristor rectifiers and its electronics to suppress the weakest part of the PS main magnets power system. CERN will continue to study new power systems with energy storage to be ready to launch a project to replace the rotating machine in due time. The intention of this paper is to present an initial comparison of technical solutions to build a high power system for a rapid cycling machine. We hope it will stimulate exchanges and collaborations with various power system specialists from laboratories and industries who face similar challenges.

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