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EFFICIENT RECUPERATIVE 4-QUADRANT POWER SUPPLY FOR SUPERCONDUCTING SOLENOIDS

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ABSTRACT

An efficient recuperative 4-quadrant power supply with quench protection for superconducting solenoids was developed and built. It is designed for continuous ±24 V, ±14 kA ramping with a 5 MJ capacitor bank and an efficiency better than 96 %. Its smart filter design allows ripple voltages below 10 mV and frequencies up to 100 Hz. The bidirectional 900 V quench protection system has a reaction time of 2 ms. The system design is cost effective, compact, modular, redundant and can be easily scaled.

Keywords: 4-quadrant power supply, solenoid, super conductors, energy efficiency

1. INTRODUCTION

Superconducting solenoids usually store high energies. In many applications like accelerators, energy is cycled for beam forming and steering. This usually is requiring large power supplies and is generating high losses. We have developed and built a highly efficient and compact supply system for such solenoids, which consists of a 4-quadrant converter, a capacitor bank, power loss compensation supply, quench protection and sensing technology. The basic idea is to have a 4-quadrant converter, which can transfer the energy from the capacitors to the solenoid and back (figure 1). This way power loss is reduced mostly to the bus-bars. The power supply and the power drawn from the grid can be much smaller (typically 10 %), since only the power loss needs to be compensated.

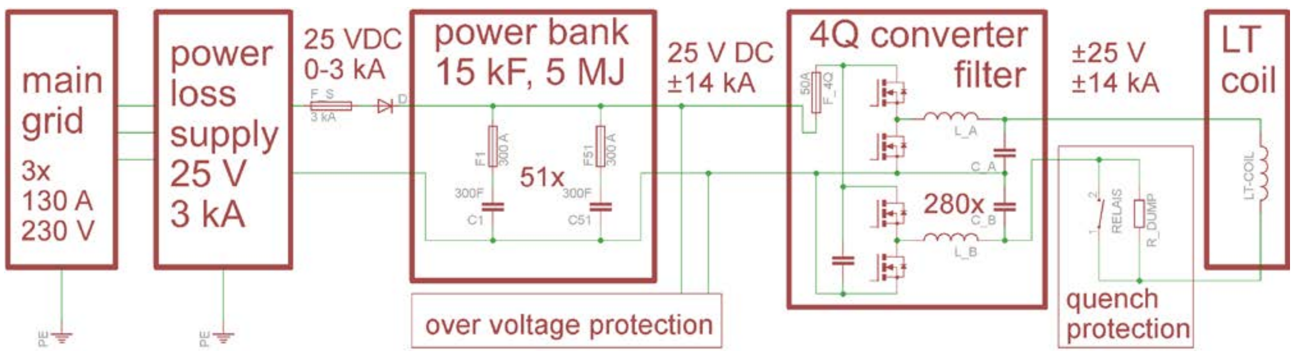

Figure 1: Recuperative 4-quadrant power supply scheme

2. DEVELOPMENT AND CONSTRUCTION OF MODULES

2.1. 4-Quadrant converter

The basic function of a 4-quadrant converter is to transfer a directed supply voltage *UB* into any voltage between positive and negative supply voltage. Since analogue techniques generate great losses, we use low loss semiconductor switches and coils for filtering. The ideal relation *pwm* between on and off (**P**ulse-**W**idth-**M**odulation) represents the output voltage *UA* of one driver:

$$UA = UB * pwm \qquad \textit{Equation (1)}$$

For a 4-qudrant converter a second negative driver is needed to allow negative output voltages *UB*:

$$UB = UB * (1 - pwm) \qquad \textit{Equation (2)}$$

The output voltage *UC* will be:

$$UC = UA - UB = UB * (2 * pwm - 1) \qquad \textit{Equation (3)}$$

The output current *IC* ideally scales inverse to the input current *IB*:

$$IC = IB/(2 * pwm - 1) \qquad \textit{Equation (4)}$$

So the output power *PC* ideally is identical with the input power *PB*:

$$PC = UC * IC = UB * IB = PB \qquad \textit{Equation (5)}$$

The real losses in such a structure are mainly due to the on resistance of the semiconductors, switching losses and filters. They scale with switching frequency and square current.

2.1.1. MOSFET switches

The selection of semiconductor switches is depending on many parameters. Most important are supply voltage *UB*, current *IC*, switching frequency *f*, size, power loss and price. Each semiconductor switch has two more parameters: switching time *ts* and on resistance *Ron*. Power loss per driver *PD* can be estimated as sum of on time losses determined by *IC* and *Ron* and transient losses with full voltage and coil current during switching:

$$PD = IC^{2} * Ron + UB * IC * 2 * ts * f \qquad \textit{Equation (6)}$$

Depending on the filter design there can be even more losses caused by ripple currents.

There are different types of semiconductor switches. The most important ones are metal-oxide-semiconductor field-effect transistors (MOSFET) and insulated-gate bipolar transistors (IGBT). Since IGBT's have a voltage drop greater 0.7 V they are predestinated for high voltage applications. For typical application this limit is around 80 V. For our application we found a MOSFET with 40 V, *Ron* = 1.5 m**Ω**, *ts* = 238 ns most applicable. With 2x280 drivers it would lead to a static loss of 1050 W at 14 kA. The dynamic loss must be optimized with the filter design, which determines the switching frequency. In our case *f* = 40 kHz was found as optimal, what should lead to a worst case switching loss of 6664 W at 25 V and 14 kA. The total power loss of the chosen MOSFET's according equation 6 would be *PD* = 7714 W.

2.1.2. Filter design

The filter design is most critical for electromagnet interference. A 4-quardrant converter could work highly efficient with a superconducting coil without filter - if possible. Since most high field applications require very low electromagnetic interference, this part is essential. A typical ideal inductivity L - capacity C - filter would have the following triangle shaped ripple current with maximum IR:

$$IR = \frac{UB}{8*L*f} \qquad \textit{Equation (7)}$$

and a parabolic shaped (almost sinus) ripple voltage UR at the capacitor with inner resistance RC:

$$UR = \frac{IR}{8*C*f} + IR * RC \qquad \textit{Equation (8)}$$

The resonance of L-C-filter must be chosen between switching frequency and maximum output frequency. For high efficiency the quality of this filter must be high and it must be ensured that it is driven out of resonance.

A filter for the full current could be done with two air coils with 400 nH and two capacitors of 3 mF with 200 A ripple current. The voltage ripple would be around 208 mV. The power loss would be around 2x850 W.

Since we wanted to have a modular approach and very low ripple, we have chosen a multi phase approach, where each driver works in a different time slot and has its own filter. This way all ripple currents are compensating against each other and the voltage ripple is reduced by the number of drivers. We are using a 280x2 phase topology, where always 2 phases with a half period delay are working on the same capacitor. With this constellation the worst remaining ripple current of two phases is at pwm = 50 % with IR*1/2 and doubled frequency. The voltage ripple reduces to 1/4. Since all drivers are working in a different time slot, the ripple voltage divides by the number of drivers. For our chosen inductors with L = 10 µH and capacitors with C = 120 µF and RC = 18 mΩ we would have a maximum ripple voltage at each driver pair of 121.2 mV. If we assume ideal averaging between all drivers and constant pwm, we get 0.43 mV ripple voltage in total.

The maximum power loss inside the filter can be approximated from the DC-loss inside the coils which is 2.4 mΩ * (25 A)² *2*560 = 1680 W and the ripple loss inside the capacitors which is roughly IR^2*RC*0.7*2*280 = 108 W. Since all ripple currents are averaged over many drivers, the filter capacitor losses can be neglected.

Not to be neglected are losses of the supply capacitors which have 18 mΩ / 8 inner resistance. They have to carry the full current and cross switching currents. A rough worst case approximation of losses would be (50 A)² * 18 mΩ / 8 * 280 = 1575 W.

2.1.3. Current, voltage, temperature sensing and protection

Each driver is continuously monitoring current, voltage and temperature. If any value exceeds the predefined limits, the system shows a warning or shuts down. Temperature sensors are placed on MOSFET's, capacitors and coils. All drivers also have hardware protection and melting fuses in all power lines. In case one driver breaks, fuses isolate this driver from all other. The power loss of all fuses is in the range of 3 W * 280 = 840 W. Current measurement is done with offset compensating Hall-sensors with negligible losses.

2.1.4. Measurement results

First measurements at full current with shorted output show a power loss of 50 W per 50 A-board (worst case). For 14 kA this would be 14 kW. If we take the power loss from the theoretical considerations we should have 7714 W + 1680 W + 108 W + 840 W + 1575 W = 11.9 kW. There are some addition losses from the wires on the board causing voltage drops in sum 100 mV * 50 A * 280 = 1.4 kW. This is close to the measured result and would result to a worst case full power efficiency of 1-14 kW / (14 kA * 25 V) = 96 %. The power loss is reducing with *pwm* level, since ripple currents are getting lower. With *pwm* = 100 % there would be no ripple and switching losses and the efficiency would be around 5 kW / (14 kA * 25 V) = 98.6 %.

The measured voltage ripple of one board (2 drivers) is at 140 mV peak-peak at *pwm* = 50 %. Parasitic capacitance spikes from the coils are reaching up to 200 mV. At *pwm* = 0 % the ripple voltage goes below 20 mV. With all drivers in parallel the total ripple voltage should be below 1 mV.

Measurements from the complete system are not done jet.

2.2. Capacitor bank

The capacitor bank stores the energy for and from the super conducting magnet. The total capacity *CB* must be selected according maximum *UB_max* and minimum *UB_min* voltage allowed and the total energy *EM* inside the magnet:

$$CB > \frac{2*EM}{UB_{max}^2 - UB_{min}^2} \qquad \text{Equation (9)}$$

Additional effects that need to be considered are aging and cell inhomogeneities. For efficiency the inner serial resistance must be small. So more capacity usually leads to less resistance and more efficiency.

2.2.1. Cell selection

We have designed our supply for magnets with *EM* = 0.5 MJ, *IC* = 14 kA and ramping voltages up to *UB_min* = 22 V. Typical capacitors for this application are double layers super capacitors with a cell voltage of 2.7 V. They are designed for 1 million cycles with capacity loss less than 20 %. Aging increases with temperature and loaded voltage.

We have chosen a stack of 51 blocks with each 10 cells of 3000 F in series. The total capacity is *CB* = 15.3 kF. This is with 100 % security to allow some degradation of the cells. The maximum voltage *UB_max* is set to 25 V whereas 27 V could be possible. The reason is aging effects and inhomogeneities of the single cells. The maximum current per cell is 275 A. With the inner serial resistance of 3.5 mΩ per block the maximum loss is at 265 W. If we assume worst case continuous full voltage ramping up to 14 kA, the average power loss of all capacitors is $(14\ \text{kA})^2/(3*51)$ * 3.5 m□ = 4.5 kW.

2.2.2. Balancing

Each cell has a different capacity and inner parallel resistance from production. The homogeneity typically is better than 95 % of the same batch. During operation it must be ensured that no cell has more than 2.7 V. With setting the maximum block voltage to 25 V a cell homogeneity of 85 % is sufficient at full current. The second aspect is the inner discharging resistance and current in the range of 5 mA which can lead to disbalancing over a longer time.

We have developed a capacitive balancer, which continuously balances the low currents by equalizing the cell voltages. An external capacitor is charged from the cell with the highest voltage and then discharged to the cell with the lowest voltage. This system can also monitor all cell voltages and temperatures.

2.1.3. Current, voltage, temperature sensing and protection

Each cell block has its own fuse of 300 A, temperature sensor and balancer. This makes one block independent of all others and gives redundancy in case of failure. Each balancer is monitoring the voltage of all cells, fuse and temperature sensor. If any value is out of range the system can be shut down. The system can keep operating if one fuse (cell) is blown as long all other values are within range. The maximum energy will be reduced then. For temperature protection all cells have active air cooling.

2.3. Quench protection

Superconducting magnets need protection in case of loss of superconductivity (quench). In this case the energy must be extracted as fast as possible to avoid damages. Electrical energy extraction is limited by the maximum allowed quench voltage *UQ* of the magnet and thereby the extraction power *PQ* = *UQ* * *IC*. The quench voltage typically is in the range of 1 kV.

2.3.1. Quench detection

Starting quenches show in partially rise of resistivity and voltage drop. Typical devices are monitoring symmetry magnet voltage and voltage drop along current leads. Depending on the magnet construction there is also the option to use a mutual induction wire for direct voltage drop measurements. Our developed quench detection system is capable of all three types.

2.3.2. Power switch

In case of a quench a negative high voltage *UQ* must be allowed at the magnet, 40x higher than the supply voltage of 25 V. For that the bus-bar needs to be opened very quickly. This switch must handle the fully current at the quench voltage, what results in a switching power of 14 MW.

We have chosen multiple a fast acting relays, which allow fast separation and low loss operation. During operation the relays are closed with a low inner resistance. The voltage drop should be maximal 100 mV. In case of a quench the relays are opened within 2 ms. This short time allows very small snipper circuits. As soon as all relays are open the current flows over the dump resistor and the voltages goes up to *UQ*.

2.3.3. Dump resistor

The dump resistor takes the energy of the magnet in very short time. It has to carry the full current *IC* and to withstand the full voltage *UQ* and power of 14 MW. Is must be non-inductive to avoid voltage peaks above *UQ*. The thermal mass must be higher than the magnet energy divided by the allowed temperature rise. The initial resistance must be *UQ*/*IC*. With higher temperature, *IC* is lower and the resistance can be higher for faster extraction.

We have chosen non-inductive winded 10 mm wire of zinced-steel as a low cost option. The length of the wire is variable and allows adoption on different magnet setups. For 14 kA and *UQ* = 900 V the initial resistance is 64.3 mΩ, the length around 33 m and the temperature rise about 43 K.

2.4. System assembly

Our system is assembled in three 19’’ racks (figure 2). The right rack contains 14 4-quadrant converter modules each for 1 kA. The other two contain 17 capacitor modules, one input protection module and one control module. The power supply for loss compensation is a stand-alone commercial device.

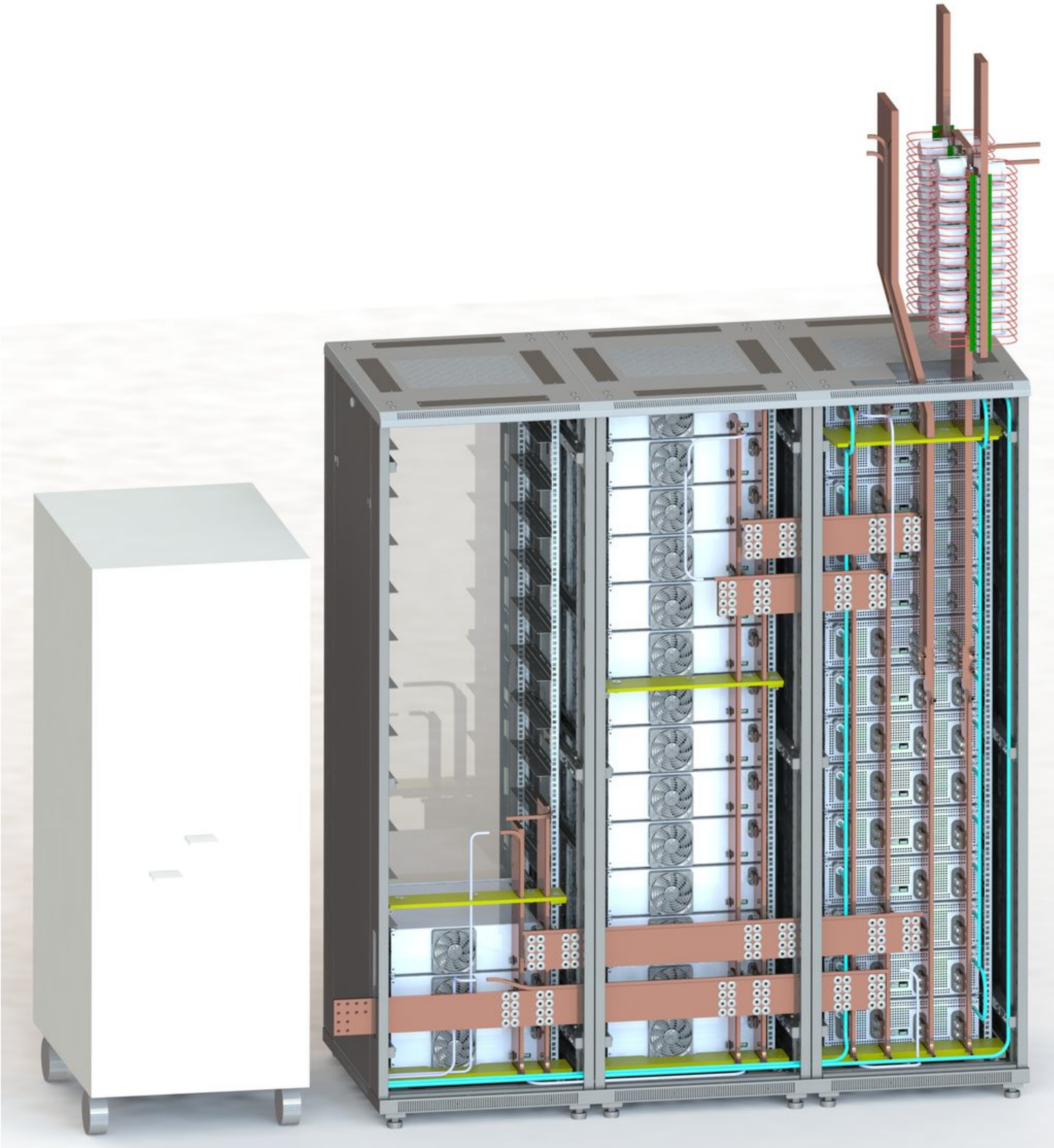

Figure 2: Recuperative 4-quardrant power supply cabinets. From left to right: power supply, capacitors and control, capacitors, 4-quadrant converters). On top quench protection switch.

2.4.1. 4-quadrant module

Each 4-quadrant module can contain up to 24 driver cards with 50 A each with of a total limit of 1.2 kA. For our system we have equipped each module with 20 driver cards with 1.0 kA in total. The modules have a hybrid cooling with cooling water for the MOSFET's and forced convection for everything else. The maximum temperature rise is below 20 K at full current. Without water cooling, the temperature rise is around 30 K.

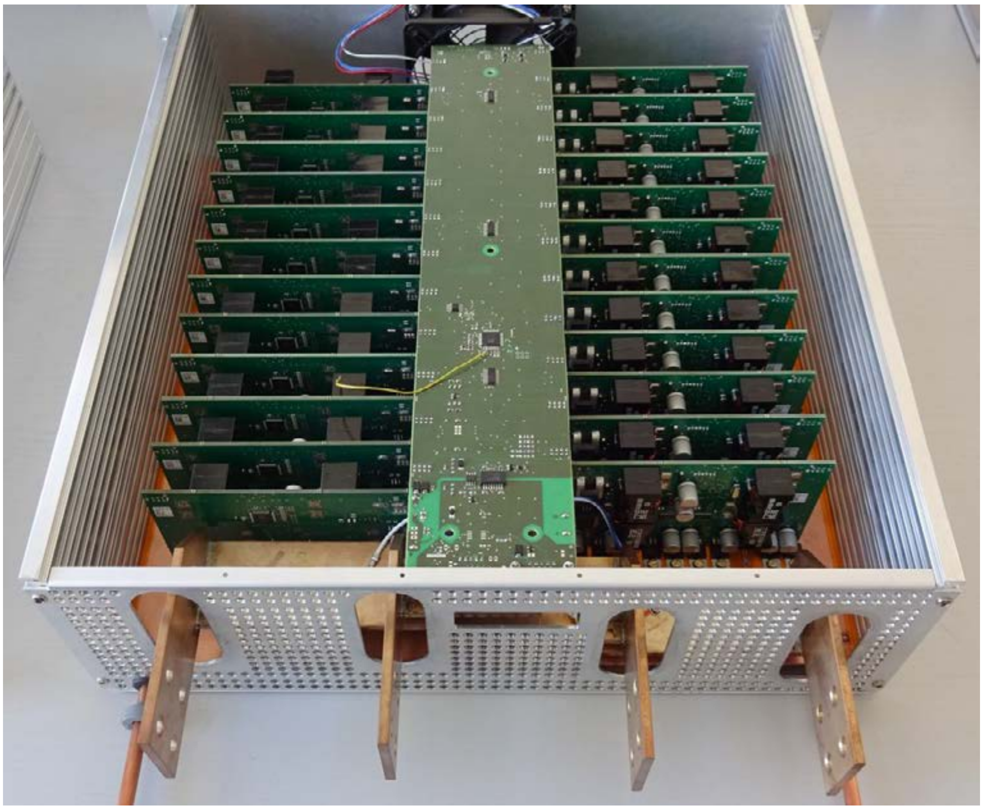

Figure 3: 1.2 kA, 25 V 4-quadrant converter module

2.4.2. Capacitor module

Figure 4: 900 F, 25 V capacitor module

A capacitor module consists of three capacitor blocks with a total capacity of 900 F. The design current is 900 A triangle peak. One board with one balancer for each block is installed. Cooling is done by forced convection.

3. CONCLUSIONS

We have developed and built a compact, energy efficient and modular supply system for superconducting solenoids. The average power loss of the 4-quadrant converter and the capacitors during continuous full voltage ramping up to full current is $(14\ \text{kA})^2/3 * (3.5/51+(2.4+1.5+0.1)/280)\ \text{m}\Omega = 5.4\ \text{kW}$. This results in a full power cycled ramping efficiency of $1-5.4\ \text{kW}/(0.25*14\ \text{kA}*24\ \text{V}) = 93.6\ \%$. The loss in steady state with controlled voltage and current at 14 kA is 14 kW with a ripple voltage below 10 mV. Final measurements after assembly have to be done.

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NOMENCLATURE

C	Electrical capacity (F)	U	electrical voltage (V)
T	temperature (K)	I	electrical current (A)
R	Electrical resistance (Ω)	P	electrical power (W)