Transient Behaviour of a Fast Micro Superconducting Magnetic Energy Storage (SMES)

(Measurements and Calculations)

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Abstract - **The transient behaviour of a modular 200 kJ micro SMES was investigated. The SMES was designed and built to provide high power pulses as required for particle accelerators and to improve power quality in the electrical grid. Fast charging and discharging of the SMES excites internal voltage oscillations in the magnet. In order to ensure that no dangerous transient overvoltages can occur, it is essential to know the resonant behaviour of the magnet. The resonant oscillations in the SMES have been calculated and measured. The dominant resonant frequency of a single coil increases from 60 kHz at 300 K to about 65 kHz at 4.2 K. A single coil of the modularly built six-coil-SMES was modelled as a strongly coupled R-L-C-network. The paper will describe the constructed SMES and the model used for calculations. The calculated transient oscillations correspond well to the measured internal voltages.**

Keywords: Transient analysis, SMES, transient modelling, power modulation.

I. INTRODUCTION

Problems of power quality improvement in the electrical grid, e.g. load levelling, frequency regulation, stabilization of power transmission, and compensation of load variations can be managed by a SMES (Superconducting Magnetic Energy Storage) based compensator system. The stored energy of a fast SMES can be released into the electrical grid to compensate voltage disturbances. Depending on the power converter, voltage sags can be compensated in less than one millisecond.

There are also numerous applications in power distribution and high energy physics where the customer has a predictible variable power demand, e.g. a particle accelerator, a rolling mill, a hammer forge. Depending on the drop of the distribution line voltage, a compensation of the time variant power consumption might be required. In this case, the compensator can be used to directly provide the repetitive fluctuating power of the load instead of supporting the terminal voltage of the utility grid.

The fast charging and discharging of the SMES is accompanied by rapid change of the SMES voltage. The energy transfer from a SMES at a high power level results in high voltages across its terminals. The polarity of the voltage across the SMES can vary at a 1 kHz rate up to ±800 V, depending on the converter control.

Switching the polarity of the SMES causes internal transient voltage oscillations within the superconducting coils. There is a repetitive excitation of the internal oscillations caused by the converter. Therefore, it is important to know the dominant resonant frequency as well as its magnitude and its damping, in order to ensure that no dielectric failure can occur.

In order to investigate the potential of a SMES for supplying pulsed loads under extreme charging and discharging conditions, a compact modular SMES was built. The transient behaviour of this SMES was measured and simulated. The calculations are based on a resonant circuit model of one coil which consists of a strongly coupled R-L-C network.

This SMES was used in two different projects that were based on the idea of supplying a fluctuating load directly with energy. The first application has been realised in a collabortion between the Forschungszentrum Karlsruhe and the Universität Karlsruhe [2]. The second cooperation occurred between the Forschungszentrum Karlsruhe and DESY Hamburg and resulted in the developement of a SMES based 1 MW power modulator [4], [5] for linear accelerators.

II. TWO SMES PROJECTS

A SMES based compensator and a power modulator system were built. These devices were used to investigate the transient behaviour of the fast SMES. These machines are briefly decribed below.

A. Power modulator

The potential application for this modulator is the next generation of linear supercolliders. The TESLA 500 machine planned for DESY Hamburg will require 10 GW pulses of 2 ms duration at a repetition rate of 10 Hz. Drawing these pulses directly from the grid would cause unacceptable voltage disturbances. Therefore, an intermediate storage of electrical energy, the SMES, is needed. The presently constructed device is a 1 MW model of a TESLA 500 modulator.

Fig. 1 shows the elementary SMES based power modulator circuit. The device consists mainly of a novel IGBT-switch and the modular fast SMES. The operation of this system can be divided into two modes. During the conduction time of the IGBT switch the voltage source charges the SMES.

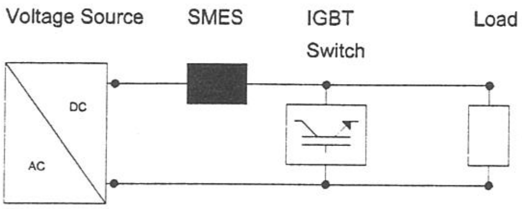

Fig. 1. Basic circuit of a SMES power modulator

After opening of the switch, the SMES current commutates into the load and provides it with energy. The pulse voltage will be generated across the load. Since the nominal SMES current was 300 A and the resistance of the load was 10 Ω, there is a voltage shift of 3 kV across the SMES.

The current decrease during the pulse generation time is only 2 % so the power consumption from the utility grid remains about constant even during the generation of high power pulses.

B. Compensator for fluctuating loads

A compensator consisting of the fast SMES and a 80 kVA IGBT-converter system was built [2]. This compensator is connected in parallel to a load with fluctuating power demand. The idea also is just to deliver the alternating component of the load power [2]. The diagram depicting the operation principle is shown in Fig. 2.

The power that can be compensated is limited by the total stored energy in the SMES and by the nominal parameters of the converter [2]. The converter system is constructed with a DC-link. The line side inverter is a voltage source inverter consisting of IGBTs with antiparallel diodes. The SMES side inverter is a two quadrant IGBT-chopper. This chopper reverses the voltage of the SMES at a frequency of about 1 kHz, to adjust the DC-link voltage to 800 V. It is controlled by a pulse width modulator [2].

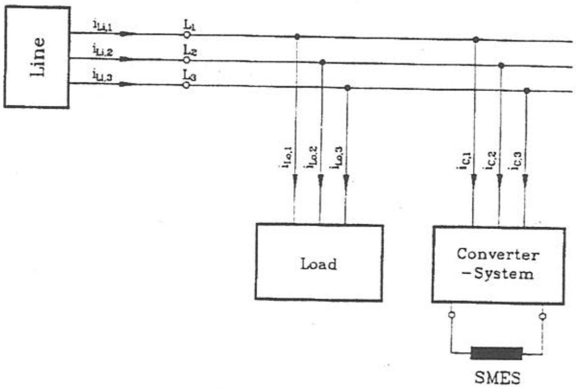

Fig. 2. Principle SMES-compensator arrangement

III. SMES DESIGN

The SMES was constructed as a modular solenoidal system consisting of up to six coils. There are slight differences in the design of the coils because we used different types of superconducting wire to find the best wire for pulsed applications [5]. The modular concept was chosen to meet the requirements of the described modulator as well as those of the compensator system. Since we could accept a magnetic leakage field, the solenoid was the preferred concept. For magnetic field sensitive devices, a toroidal arrangement of the coils is needed and possible, with a negligible stray field.

A. Coil design

Fast charging and discharging of superconducting coils generates AC losses within the superconductor. This thermal input has to be removed promptly by the liquid helium coolant to avoid a rise of the temperature of the superconductor. There are also magnetic forces of more than 250 kN in the axial and about 150 kN in the radial direction at 300 A nominal current. Due to the requirement of effective cooling and mechanical stability, the coils have a complicated helium-transparent composition. The picture of a single coil and its cross section are showen in Fig. 3 and Fig. 4.

A coil consists of 30 layers and 32 turns per layer. Between two layers there are 140 epoxy-glass 0,5 mm thick spacers. These spacers are form cooling channels that carry the evaporated helium to radial channels in the end flanges.

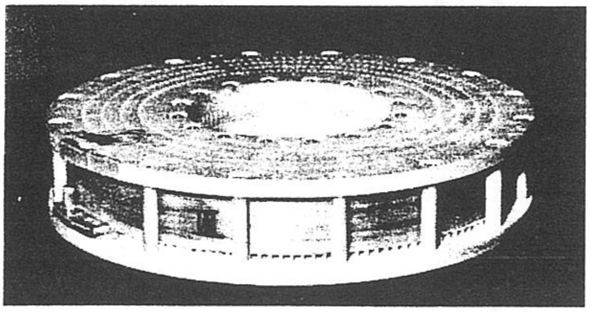

Fig. 3. Picture of a single superconducting coil

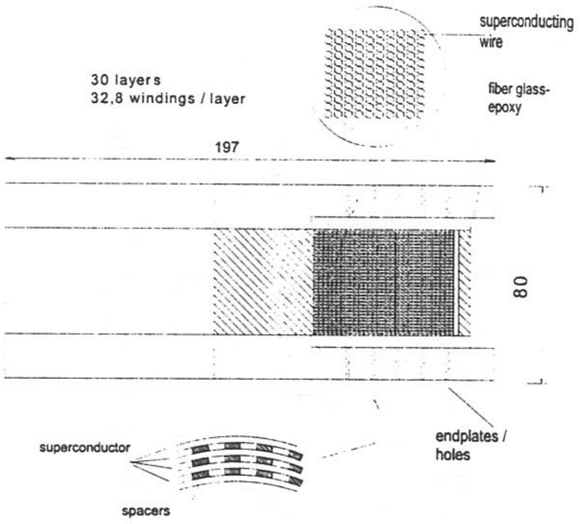

Fig. 4. Cross section of a single SMES coil

There are holes in the end flanges where the helium gas can escape from the coil. The structural material has to be nonconductive because of the high rate of change (up to 90 T/s [5])of the magnetic field. Therefore, we applied fiber glass-epoxy which was matched to the thermal contraction of the superconductor to avoide wire movements at 4.2 K. Fiber glass-epoxy also has the needed mechanical strength. Furthermore, the spacers provide an excellent dielectric insulation between layers. A single coil can withstand a repetitively pulsed voltage of 3 kV in the modulator arrangement.

B. Six coil SMES

The six coil solenoid is shown in Fig. 5. Kapton polyimide film separates the coils to avoid flow of the evaporated gas into the upper coils. The advantages of using a solenoid are its simple assembly and the excellent magnetic coupling between coils.

The self inductance of a single coil is about 0.32 H and the total inductance of the six coil SMES is 4.37 H. At the nominal current of 300 A there is a stored energy of 200 kJ. The maximum magnetic field is 4.8 T at 300 A in the six coil solenoid system.

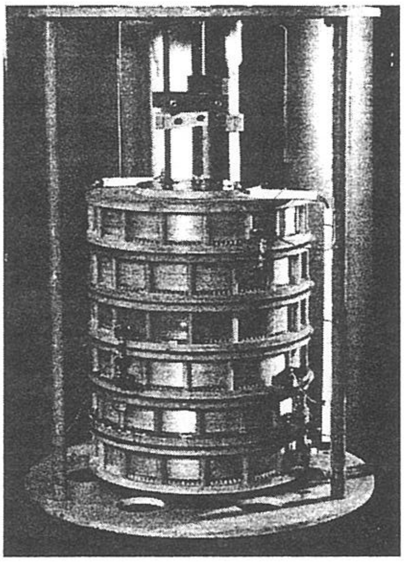

Fig. 5. Six coil SMES setup

Due to the higher mutual inductances the total stored energy is about twice the energy of a toroidal arrangement built with the same amount of superconductor. The cryostat provides direct bath cooling of the SMES.

IV. MODELLING OF THE SMES COIL

For modelling and simulating the transient behaviour of a coil, the parameters, e.g. inductances and capacitances, must be calculated from the construction drawing shown in Fig. 4.

A. Self and mutual inductances

A coil consists of about 960 turns. Each turn has a self inductance and mutual inductances with other turns. In fact, there are about 460,000 mutual inductances that would have to be considered for an exact simulation. To achieve an acceptable computation time, the number of inductances was reduced by combining 10 turns of a layer into a corresponding equivalent element [3], [4]. The principle of the combination of the turns is sketched in Fig. 6.

The diameter of the coil is large compared to the thickness of the wire. Therefore, the change of inductance caused by the skin effect could be neglected [4]. The DC values of self and mutual inductances have been used [4]. Modelling the combined turns as cylindrlcal coils with retangular cross sectional area allow one to determine the self and mutual inductances [3]. The inductance matrix has been computed with the code EFFI which is based on Bio-Savart's Law.

The resonant oscillations are well damped even in a superconducting coil. In [3] it is shown that the skin and the proximity effect of the transient frequencies cause losses in the normal conducting parts of the superconductor, e.g. the Cu-CuNi matrix. A calculation of the losses caused by the skin and proximity effect in NbTi superconductors was performed in [1], [3] and [4]. There a finite element method was used to calculate the eddy current losses

B. Serial and transverse capacitances

The mixed dielectric between layers of the coil consists of the conductor insulation, the glass-fibre-reinforced epoxy spacers, and the cooling channels. Therefore, a equivalent dielectric constant was determined [4]. Capacitances coupling the layers were considerd as cylindrical capacitors. The calculated capacitence values for the used model in Fig. 6 range from 308 pF to 458 pF [3]. For calculating the capacitances inside a layer two turns were considered as a circular plate capacitor with an equivalent dielectrical constant [3], [4]. In order to calculate the capacitance of n windings a linear

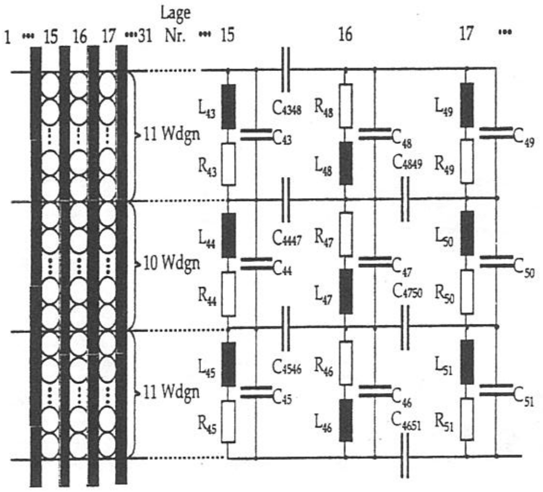

Fig. 6. Modelling of a coil with combinded turns and coupling capacitances

voltage drop was assumed. The series capacitances can than be calculated as C_{Pl}/n [3]. As modelled in Fig. 6, the series capacitances of a coil range from 10.9 pF to 14.2 pF.

V. RESULTS

The system response was calculated in the frequency domain as a convolution of transfer function and exitation. In Fig. 7 the measured and the computed response to a 10 V voltage shift are shown. The measurement was performed in the normal conducting state of the coil at room temperature in a screened room. The coil was out of the cryostat to avoide the magnetic coupling between the vessel and the coil. Fig. 7. shows an excellent correspondance of the measured and calculated resonant frequency. The oscillation frequency is about 60 kHz.

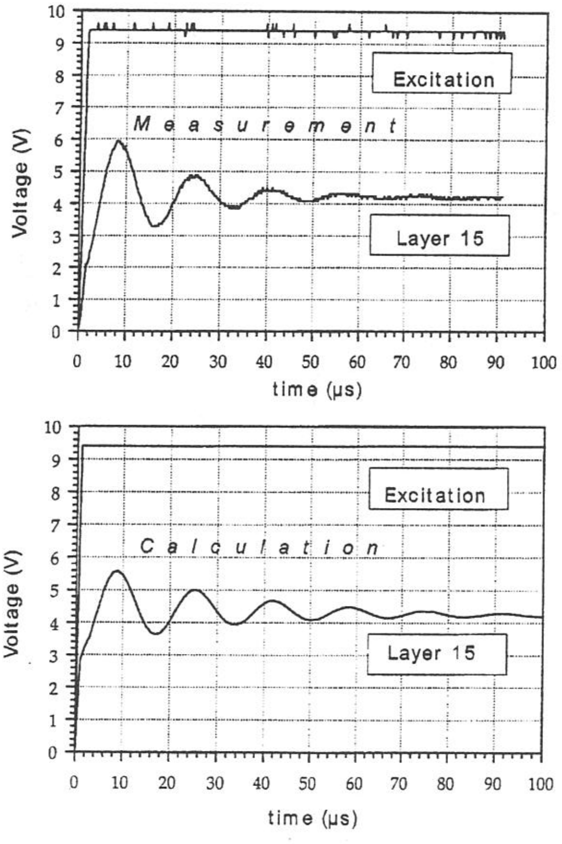

Fig. 7. Measured and calculated system response at room temperature (300 K)

In practice, the coil is placed inside a steel cryostat and is cooled down to 4.2 K. Similarly to the mearurement in Fig. 7, the magnet was also excitated by a 10 V voltage step. Compared with Fig. 7, the resonant frequency increases to about 65 kHz. Fig. 9 and Fig. 10 show the important practical cases where the coil (Fig. 9.) and the six coil SMES (Fig. 10.) are directly connected to the compensator system and the repetitively switching inverter voltage excitates the oscillations.

The damping of the transient oscillations at 4.2 K (Fig. 8 to Fig. 10) is weaker than in the normal conducting coil (Fig. 7). The obvious reason is the reduced resistivity of the superconductor matrix, e.g. the copper. Eddy currents are generated due to the magnetic coupling between the cryostat and the coil. This results in a smaller total inductance of the coil-vessel system and a higher resonant frequency.

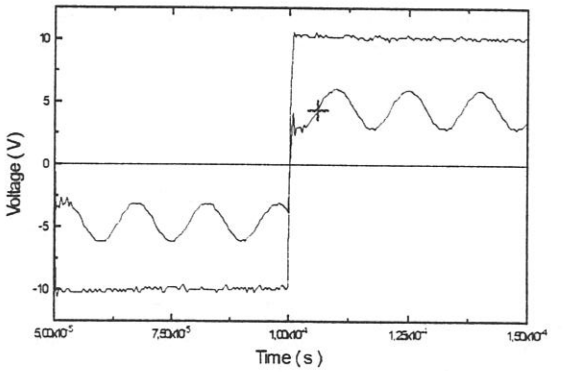

Fig. 8. System response of the single coil at 4.2 K to a 10 V voltage shift

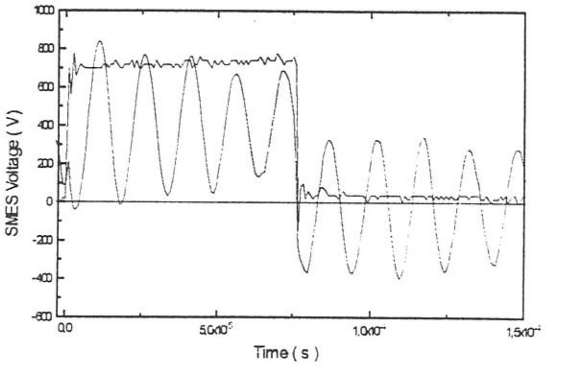

Fig. 9. System response of the single coil excitated by the operation of the power inverter system

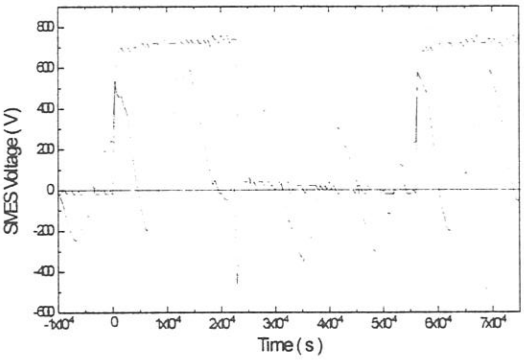

Fig. 10. Internal oscillation of the six coil SMES excitated by the compensator.

As expected, the resonant frequency of 65 kHz does not depend on the kind of excitation. In the measurement of Fig. 9 the inverter voltage of 750 V was switched across the magnet terminals and the transient oscillation was measured in the middle of the coil. The internal voltage exceeded the terminal voltage. There was a voltage overshoot of about two. The coil was designed to withstand at least 3 kV [5]. Therefore, no dielectrical damage appeared. Furthermore, in [3] and [5] it was shown that due to the coil construction, a nearly equidistant voltage distribution inside the coil was achieved. Therefore, the voltage between two layers is about 50 V, which can not endanger the coil insulation. In [5] the coil demonstrated its capability to withstand repetitive 3 kV pulses.

The six coil SMES is excitated to an internal ringing at $f_0 = 6.8$ kHz by the repetitively changing inverter voltage (Fig. 10). The maximum magnitude is about 600 V distributed among three coils. The SMES can withstand this overvoltage, because of the high safety margin of the insulation.

VI. CONCLUSIONS

The transient phenomena in superconducting coils can be modelled and calculated. The challenge is to obtain the correct material conductivities at 4.2 K for calculations.

The application of a SMES is always connected with a power transfer, fast charging or discharging. The consequence is an alternating voltage across its terminals, e.g. when the SMES is connected to a voltage line inverter. Therefore, internal resonance frequencies will always be excitated.

For each particular coil construction, a numerical investigation of the dominant resonant frequencies of the coil should be performed. In doing this, one can avoid the occurrence of internal resonant voltages which can damage the dielectric insulation of the coil, by providing sufficient dielectric insulation to prevent such a breakdown.

VII. REFERENCES

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