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SMES Based Power Modulator

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Abstract

Based on a superconducting magnetic energy storage (SMES) a long-pulse klystron modulator has been designed for use in the TESLA Test facility (TTF) at DESY, Hamburg. A prototype with an output power of 25 MW is under development at Forschungszentrum Karlsruhe in cooperation with the office of engineering IbK at Karlsruhe. Including a pulse transformer (1:13/11.5), the system will deliver pulses of 130 kV or 115 kV, 1.7 ms pulse length with a flat top of ± 0.5 %, at a repetition rate up to 10 Hz. This new system's main features are a highly dynamic SMES (> 100 T/s), a high current power supply (rated 27 V/2.6 kA) , a switched-mode high voltage power supply (rated 14 kV/45 A), a fast thyristor power switch for 2.6 kA approx. continuous current/ 2 ms break, an IGCT power switch rated 2.6 kA/14 kV, a protection switch unit and a system control unit. This demonstration system is to serve alternatively two klystrons of 5 MW RF output or one multibeam klystron of 10 MW RF output. A significant part of the components of the system has been built. A first set of the system components had been arranged to form a model of the modulator and 1 MW pulses were generated. The next large step in the area of the power electronic part is to increase the power of this test arrangement up to 10 MW. The SMES and its cryostat have undergone initial testing. The data acquisition and control system under development at DESY has been taken over and adjusted to our computer and experimental environment.

Pulsleistungsmodulator auf SMES-Basis

Zusammenfassung

Auf der Basis eines supraleitenden magnetischen Energiespeichers (SMES) wurde ein Lang-Puls-Leistungsmodulator für die Versorgung von Klystrons der TESLA Test Facility (TTF) bei DESY, Hamburg, entworfen. Ein Prototyp mit einer Ausgangsleistung von 25 MW ist am Forschungszentrum Karlsruhe in Zusammenarbeit mit dem Ingenieurbüro IbK, Karlsruhe, in der Entwicklung. Zusammen mit einem Pulstransformator (1:13/1:11,5) wird das System Pulse von 130 kV bzw. 115 kV, 1,7 ms Länge und einem flachen Dach mit ± 0,5 % bei einer Wiederholfrequenz von bis zu 10 Hz liefern. Die Hauptkomponenten des neuen Systems sind der hochdynamische SMES (> 100 T/s), ein Hochstrom-Netzgerät (Nennwerte 27 V/2,6 kA), ein getaktetes Hochspannungs-Netzgerät (Nenndaten 14 kV/45 A), ein schneller Thyristor-Leistungsschalter für 2,6 kA Dauerbelastung und einer Unterbrechung für ca. 2 ms, ein IGCT Leistungsschalter mit Nennwerten 2,6 kA/14 kV, eine Schutzschalter-Einheit und eine System-Steuereinheit. Dieses Demonstrationssystem soll alternativ zwei Klystrons mit 5 MW Hochfrequenz-Ausgangsleistung oder ein Multibeam-Klystron mit 10 MW Ausgangsleistung versorgen. Ein erheblicher Teil der Komponenten des Systems ist gebaut worden. Aus fertigen Systemkomponenten wurde ein Modulator-Modell aufgebaut und 1 MW-Pulse wurden generiert. Der nächste große Schritt im Bereich des Leistungselektronikteils ist der Aufbau und Test eines 10 MW-Test-Arrangements. Der SMES und sein Kryostat sind ersten Tests unterzogen worden. Das bei DESY im Aufbau befindliche Datenerfassungs- und Steuerungssystem wurde übernommen und auf unsere Rechner- und Experimentierumgebung angepasst.

CONTENTS

1 Introduction

In view of the requirement of avoiding disturbances in the electric power network, the needed pulse power for the supply of the klystrons of the planned linear collider TESLA cannot be taken directly from the grid. Pulses up to the order of 10 GW power with 1.7 ms duration and a repetition rate of 5 to 10 Hz have to be generated in a net friendly manner by a power modulator system. The long pulse duration together with the requirement of the precision of the flat top with ± 0,5 % need special effort in the design of the power modulator. In competition to conventional solutions, Forschungszentrum Karlsruhe has proposed to apply a superconducting magnet as an intermediate energy storage in the power modulator [1]. The SMES (Superconducting Magnetic Energy Storage) should spend only a small fraction of its stored energy for each pulse because such an operation would be advantageous for the grid as well as keep the rate of change of magnetic field in acceptable limits (below 100 T/s). The introduction of a capacitor as a second energy storage helps to reduce the size of the magnet and improves the quality of the flat top of the pulses. The research centre Karlsruhe and DESY have agreed upon the development of a 25 MW pulse power output demonstration plant. The principle is shown in Fig. 1 [2,3].

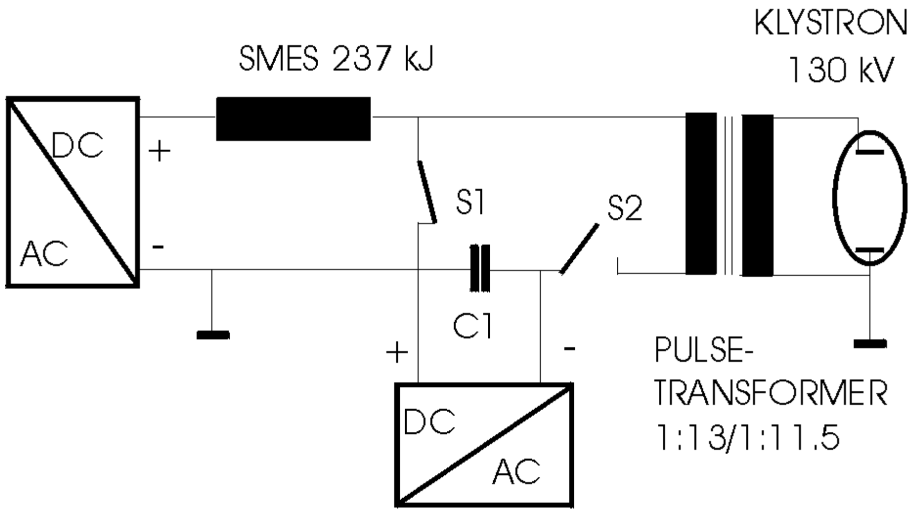

Fig. 1 Simplified Circuit of the 25 MW SMES Power Modulator (SMES 237 kJ, Capacitor 43 kJ, switch 1: Thyristors, switch 2: IGCT’s)

In the first step, the two storages are charged to their rated current and voltage levels. During this phase switch S1 is closed and S2 is open. In the second step switch S2 will be closed. This action leads to a change of voltage across the thyristor switch S1 in such a way that this switch opens. The system current is commutated to the pulse transformer and the desired pulse starts. After the preset period of time of, e.g., 1.7 ms, the switch S1 is closed again and S2 is triggered to open the circuit commutating the current away from the pulse transformer and finishing the pulse. During the following roughly 98 ms the storages will be re-charged.

Switch S2 must be capable of opening under all circumstances, i.e. under full power and at any time. Therefore this switch cannot be constructed from thyristors but either IGBTs or IGCTs must be used. Decision was made in favour of IGCTs. In that strongly simplified sketch of Fig. 1 the safety circuits are not shown. While the change of current is only in the order of few percent, the magnet has to withstand high values of rate of field change near 100 T/s during the pulse which reqires a dedicated design of superconductor and coils.

2 Design

Thought to serve as a variable system, one of the requirements to be achieved was the option to supply either two conventional 5 MW RF-power klystrons or one 10 MW RF-power multi-beam klystron. The total power was determined by the two conventional klystrons plus some margin and was set to 25 MW. The differing operating voltages of 130 kV for the conventional klystrons and 115 kV for the multi-beam klystron are taken into account by two secondary options of the pulse transformer which can operate at 1:13 or 1:11.5 ratios. The amount of stored energy and its partition among the two storages is a matter of optimization taking into account the technical requirement and the prospective cost share. Here we have chosen about 237 kJ in the magnet and 43 kJ in the capacitor but this ratio is not necessarily fixed for future plants.

The system is the first of its kind and therefore most of the components needed considerable development. The switched mode technique was chosen to develop the power supply for 14 kV/45 A to charge the capacitor. For the main two power switches with fast thyristors and the rather new IGCTs considerable development was reqired. Moreover, a dedicated safety system was developed. The magnet design had to take into account the contradicting needs for very good cooling and high voltage requirements.

- The modulator consists of following subsystems:
- Superconducting Magnetic Energy Storage (SMES)
- Capacitive Energy Storage
- High Voltage Power Supply for Charging the Capacitive Energy Storage
- Low Voltage/High Current Power Supply for Charging the SMES
- Power Pulse Former
- Control Unit

Further, a pulse transformer and a 100 m medium voltage/high current cable for the connection of modulator and pulse transformer placed in the accelerator tunnel are part of the modulator under construction.

2.1 Specifications of the 25 MW SMES Power Pulse Modulator

After having listed details of the major parts of the modulator, in this paragraph the specifications of the modulator system are presented. The paragraph is split into the two operation modes “multibeam klystron“ and “two 5 MW klystrons“.

2.1.1 Operation mode with 10 MW RF Power Klystron

For the operation of a multibeam, 10 MW klystron roughly 17 MW pulse power are required, i.e. in this mode the full capacity of the multi-purpose demonstrator will not be needed. The parameters of the modulator system are listed in Table 1.

Table 1: Specifications of the modulator for the operation with a multibeam klystron

Cathode voltage of klystron	typ. 110 kV, max. 115 kV
Cathode current	typ. 128 A, max. 136 A
Voltage fluctuation	≤ ± 1 %
Pulse duration	min. 0.3 ms, typ. 1.7 ms, max. 1.7 ms
Pulse rise time	< 0.1 ms
Pulse flat top (high voltage side, 98% -98%)	> 1.4 ms
Pulse repetition rate	min. 0.1 Hz, typ. 10 Hz, max. 10 Hz
Transformer ratio	1:11.5
SMES current (incl. 3 % margin for the magnetization of the pulse transformer)	min. 49 A, typ. 1580 A, max. 1680 A

The inverse cathode voltage may not exceed 20 % of the pulse voltage at the klystron. The system SMES – Pulse Transformer must be equipped with safety circuits which guarantee a maximum of 20 J which may be dissipated in the klystron in case of arcing. The life time of the modulator is required to reach 10 years or 2×10^9 pulses.

2.1.2 Operation mode with two 5 MW RF Power Klystrons

The modulator shall be capable of supplying two 5 MW klystrons simultaneously, i.e. the pulse has to be sufficiently powerful on the low voltage side to supply two pulse transformers which, in turn, serve the two klystrons. The given cathode current is that of a single klystron, while the given SMES current supplies both klystrons.(Table 2)

With respect to inverse cathode voltage, energy deposition at arcing condition, and life time the same specifications hold as for the multibeam klystron operation.

2.2 Circuit diagrams

More detailed circuit diagrams are shown in Figures 2-1, 2-2 and 2-3. In addition, the cabinets and the SMES unit are marked by the broken lines (LVRC Low-voltage rectifier cabinet, HVRC High-voltage rectifier cabinet, IC Inverters cabinet, ISC Input supply cabinet, SCC SMES commutator cabinet, PSC Protection switch cabinet, CESC Capacitive energy storage cabinet, IGCTSC IGCT switch cabinet, SMES Superconducting magnetic energy storage).

Table 2: Specifications of the modulator for simultaneous operation of two 5 MW klystrons

Cathode voltage of klystron	typ. 125 kV, max. 130 kV
Cathode current	typ. 90 A, max. 95 A
Voltage fluctuation	≤ ± 1 %
Pulse duration	min. 0.3 ms, typ. 1.7 ms, max. 1.7 ms
Pulse rise time	< 0.1 ms
Pulse flat top (high voltage side, 98% -98%)	> 1.4 ms
Pulse repetition rate	min. 0.1 Hz, typ. 10 Hz, max. 10 Hz
Transformer ratio	1:13
SMES current (incl. 3 % margin for the magnetization of the pulse transformer)	min. 590 A, typ. 2412 A, max. 2546 A

2.3 Energy Storages

There are two energy storages in the system, a magnetic and a capacitive one. Various possibilities exist for design and construction of a superconducting magnet system storing the required amount of energy. Major boundary conditions to be observed, are a small fringing magnetic field in the environment of the system and the capability of fast pulsing without quench of the magnet. For the public the field is limited down to 0.5 mT which is set by the heart pacemaker disturbance limit. The stray field at the position of any superconducting cavity, however, may not exceed 0.05 mT in order to avoid disturbances in the cavities. For reasons of simplicity and cost, two solenoids are applied with antiparallel field orientation (Fig. 3).

Table 3 gives the parameters of the magnets.

The rapid field change requires very good access of the coolant to the windings and very good heat transfer due to the losses. Therefore a helium transparent type of winding was chosen with the electrical insulation given by G-10 spacers and cold helium. Evaporated helium can leave the magnets through vertical cooling channels. The choice of the superconductor was a balance between low losses and limited financial resources. Details of the superconductor can be found in [4].

The introduction of a capacitor as a second energy storage besides the SMES adds flexibility to the design of the SMES based power modulator, reduces the size of the magnet, and helps to shape the pulse flat top. The parameters of the capacitive energy storage are listed in Tab. 4.

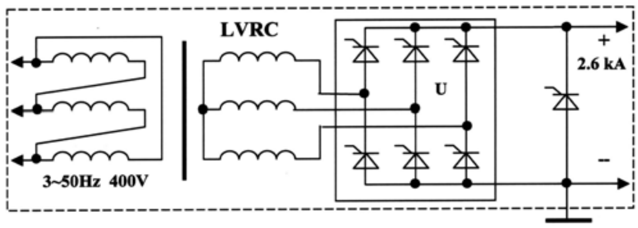

Fig. 2-1: Circuit diagram of the Low-Voltage Rectifier Cabinet (Power Supply for the SMES)

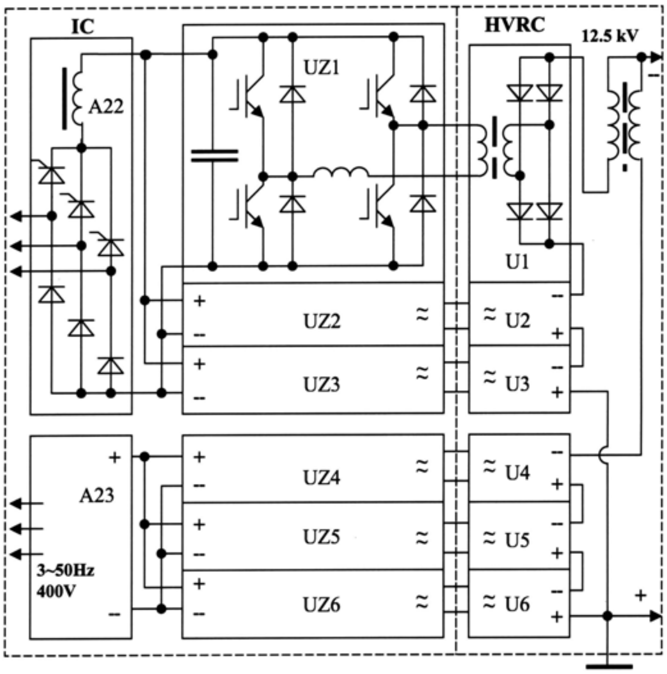

Fig. 2-2: Diagram of the High-Voltage Rectifier Cabinet and the Inverter Cabinet

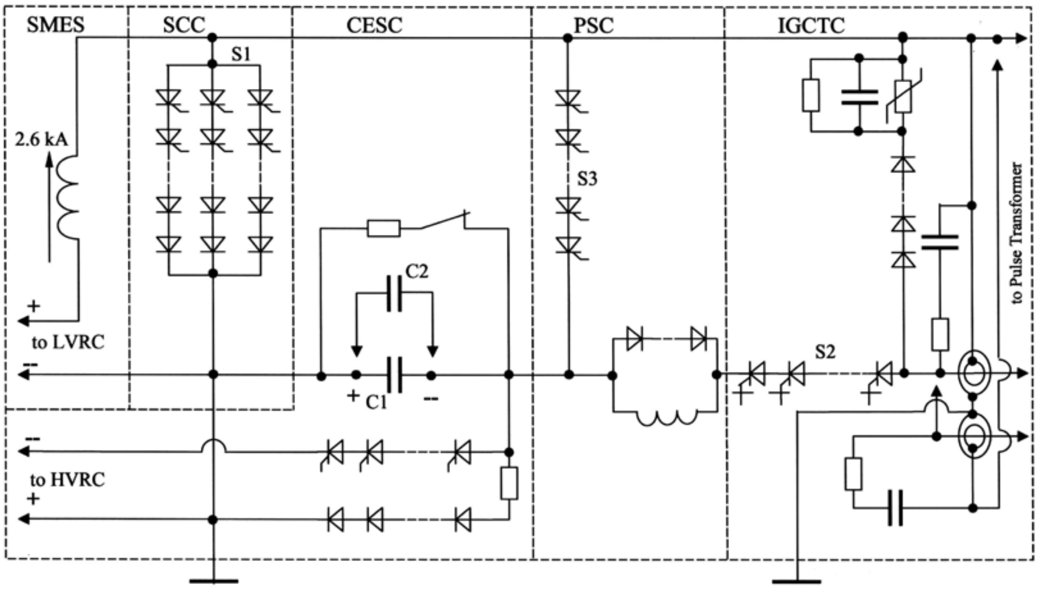

Fig. 2-3: Diagram of cabinets SSC, CESC, PSC, IGCTC and the SMES

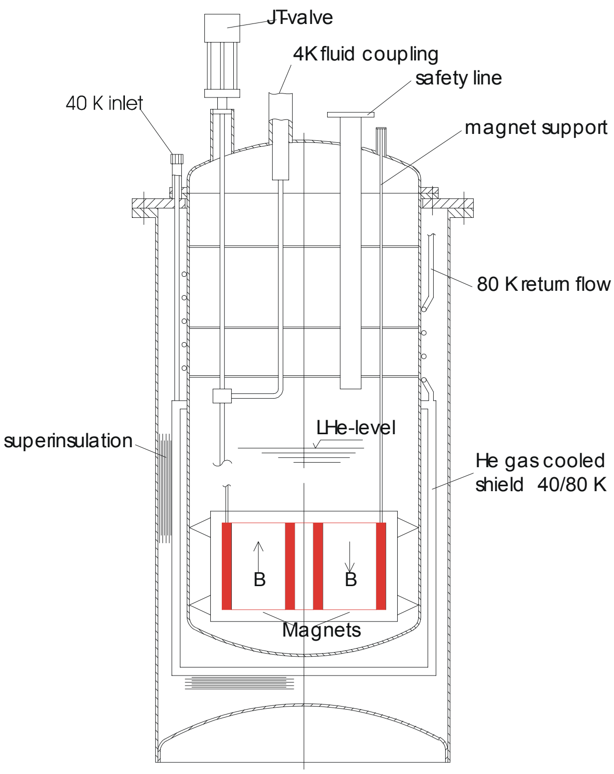

Fig. 3 SMES magnet system; 2 solenoids with antiparallel field in their cryostat (Ø 1.25 m).

Table 3: Magnet System Parameters

Inductance	70 mH
Maximum current @ normal operation	2,600 A
Maximum voltage @ normal operation	7 kV
Maximum field @ 2,600 A	4 T
Maximum dB/dt over 1.7 ms	100 T/s
Stored energy @ 2,600 A	237 kJ
Coil outer diam.	301 mm
Coil length	382 mm
Number of coils	2

Table 4: Capacitive Energy Storage

Capacitance @ operation with 2 x 5 MW klystrons	600 µF
Capacitance @ operation with 1 multi-beam klystron	375 µF
Maximum voltage @ normal operation	13.5 kV

2.4 High Voltage Power Supply

The high voltage power supply for charging the capacitors has been designed to operate in the switched mode. Correspondingly weight and size are significantly reduced compared with conventional designs. The parameters of the power supply are listed in Table 5. The power supply is made of two identical parts. One half is sufficient for the operation with one klystron and for this kind of initial operation the second half represents redundancy. For operation with one multibeam klystron both halves will operate to reach full klystron design data, but one half is even capable of operation at about 80 % of the multibeam klystron data.

Table 5: High Voltage Power Supply

Rated output voltage	14 kV
Rated output current (average)	45 A
Maximum error for set voltage before pulse initiation, from pulse to pulse, and from one switch on to the other	≤ ± 0.5 %
Input voltage	400 V ± 5 %
Input current, rms	< 715 A
cos φ	≥ 0.99
Power factor	≥ 0.94

2.5 Low Voltage/High Current Power Supply

This power supply serves the SMES. For flexibility reasons and margins, the output of this part of the demonstrator system offers double of the required voltage. The design of the power supply is conventional. A list of parameters is given in Table 6. The two output voltages of 27.5 and 55 V have been chosen in the sense that 27.5 V would be sufficient for the modulator and the extra voltage has been reserved for modulator test purposes and a margin for testing other concepts. The power supply is capable of inverter operation, if the stored energy of the SMES must be feeded back to the grid in case of a regular shut off. Starting from 2,600 A the required period of time is 60 s.

2.6 Interlock and Protection System

Similar to the existing bouncer modulators a 4 categories interlock system is adapted. In addition to the signals from the control system of the modulator, the SMES thyristor switch and the protection switch trigger themselves in case of emergency through Vanode-cathode and dVanode-cathode /dt exceeding specified limits. The IGCT switch will be equipped with electric circuits prohibiting undesired repeated triggering during switch off. Further protection measures are foreseen on the high voltage side of the pulse transformer [5].

Table 6: Low Voltage/High Current Power Supply

Rated output voltage	27.5/55 V
Rated output current (average)	2,600 A
Maximum error for set current before pulse initiation, from pulse to pulse, and from one switch-on to the other	≤ ± 0.2 %
Input voltage	400 V ± 5 %
Input current, rms	< 130 A
cos φ	≥ 0.89
Power factor	≥ 0.85

2.7 Control System

The modulator is equipped with local and remote controls. The two power supplies for the two energy storages are operated as a single unit and are controlled by a common control signal. The SMES modulator gets a control system connection to the TESLA accelerator which uses the present DESY developments (DOOCS software and corresponding hardware). Adaptions and additions required for the SMES modulator have been made at FZK in close cooperation with DESY. The system has successfully been implemented to be used for the first SMES test.

3 Status

In this paragraph the various components and cabinets of the modulator are discussed with respect to their status. Figure 4 shows the arrangement of the modulator‘s cabinets.

On the way to the pulse power system of Fig. 4, three test arrangements have been designed together with ESTEL and erected at Tallinn: A low voltage power supply test arrangement, a high voltage power supply dynamic test arrangement and a 1 MW modulator model arrangement, all of which have been tested successfully. In addition, a dynamic test of all cabinets developed at ESTEL will be performed in a 10 MW modulator test arrangement (MTA), formed from all original cabinets and additional power supplies and switches. The intention of development and construction of these dedicated systems is early testing as close to the specifications as possible.

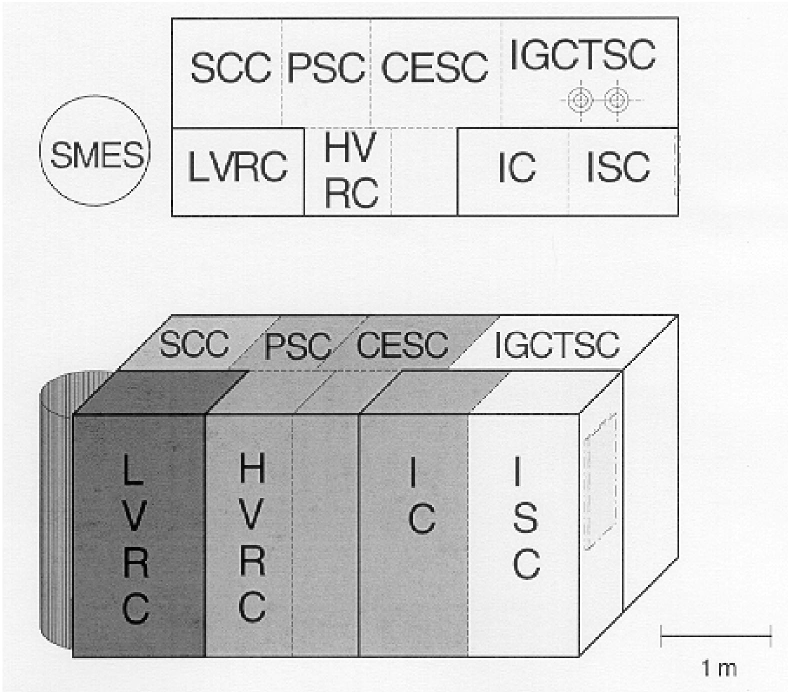

Fig. 4 Side and top view of the power parts of the modulator; partition into cabinets (LVRC Low-voltage rectifier cabinet, HVRC High-voltage rectifier cabinet, IC Inverter cabinet, ISC Input supply cabinet, SCC SMES commutator cabinet, PSC Protection switch cabinet, CESC Capacitive energy storage cabinet, IGCTSC IGCT switch cabinet, SMES Superconducting magnetic energy storage). At the right front door of the ISC a microprocessor is integrated for local control. Not shown are the pulse transformer, the 100 m pulse power cable, and the remote control unit.

3.1 Switches

The thyristor switch (S1 in Fig. 1) has been tested at ESTEL including self triggering operation at $V_{anode\text{-}cathode} \geq 10$ kV and at 2.5 kV/µs $\geq (dV_{anode\text{-}cathode}/dt) \geq$ 1.2 kV/µs. (Fig. 5).

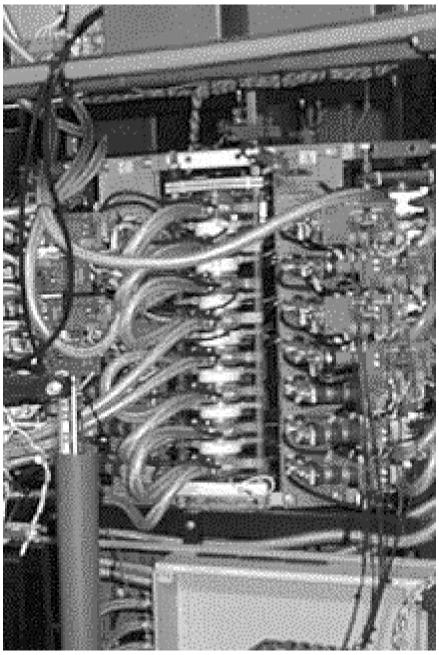


Fig. 5 Thyristor switch S1 (left) and IGCT switch S2 (right) during pre-testing on the manufacturer's site.

The protection thyristor switch (S3 in Fig. 2-3) has preliminarily been tested. The charging thyristor switch (cf. cabinet CESC in Fig. 2-3), which will be used in connection with the charging of the capacitor, has been tested to full average current of 45 A and full voltage of 14 kV.

A development programme has been performed for the IGCT switch S2 (cf. Fig. 1 and 5) by PPT and ABB in cooperation with FZK and IbK. Improvements have been achieved, e.g., with respect to the snubber design and the disturbance sensitivity of the control circuits.

3.2 Cabinets SCC, CESC, PSC, IGCTSC

The SCC containing e.g. the SMES Thyristor Switch has been tested. The CESC has been manufactured and the acceptance test was performed successfully. The specification of the IGCTSC is finished. The latter cabinet will join the others in the tests to be performed at Karlsruhe.

Fig. 6 View of completed cabinets of the SMES Modulator

3.3 Power Supplies

The Input Supply Cabinet (ISC) and the Inverter Cabinet (IC) were successfully tested. The acceptance test of the Low-Voltage Rectifier Cabinet (LVRC), the supply of the SMES, had successfully been performed. The HVRC has been constructed, tested up to 330 kW and 14 kV successfully and was accepted. A view of completed cabinets is shown in Fig. 6 (at the right side the opened front door of the ISC with the built-in microcomputer and emergency button, next to the left are the ISC with removed side door, IC, HVRC, LVRC).

3.4 SMES

A test coil has been built at FZK Karlsruhe and successfully tested with respect to maximum current, pulse operation, AC losses, and current distribution in the strands of the superconducting cable [4].

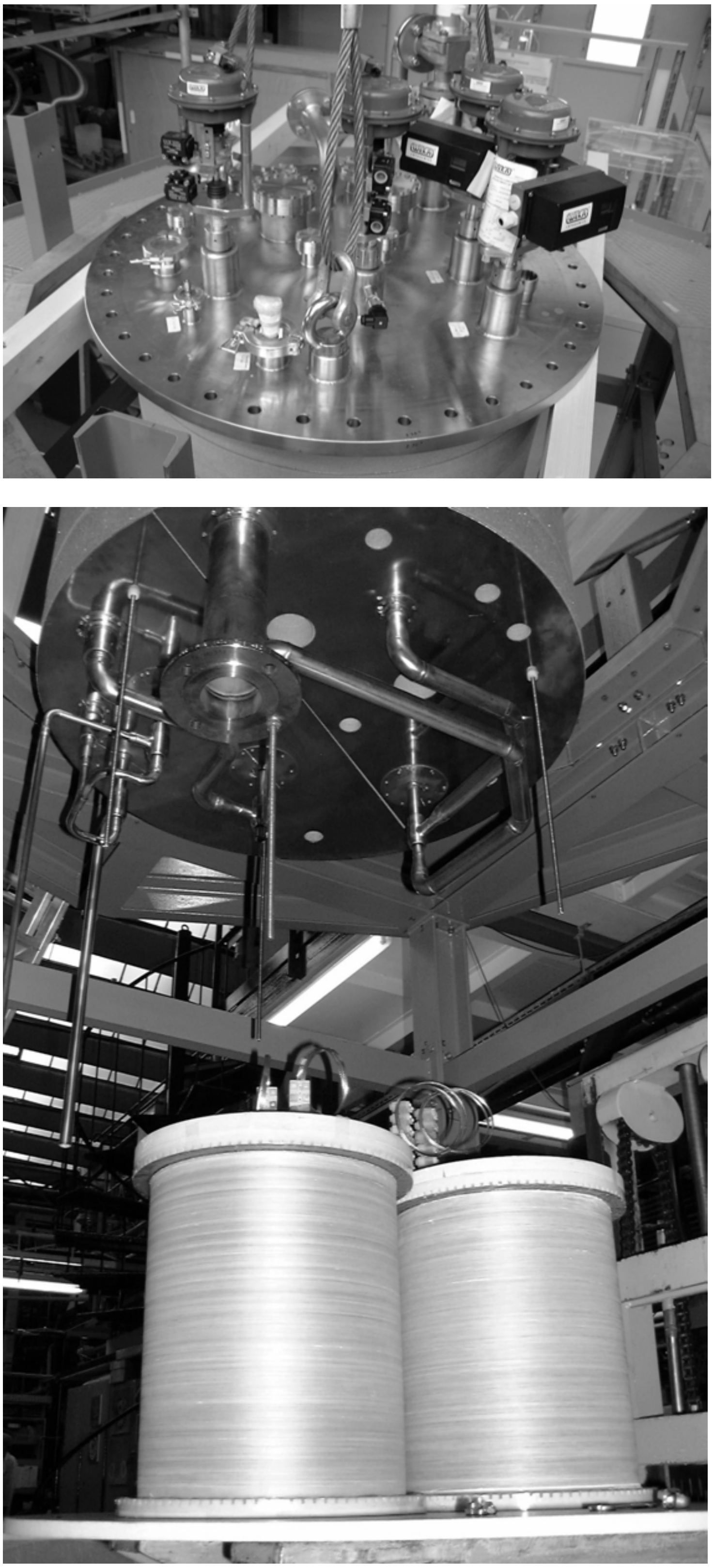

Fig. 7: SMES Magnets (bottom) and Cryostat Top Flange (top)

The two SMES magnets (Fig. 7) have been built at FZK taken into account the request for removal of AC losses resulting in an open, helium-transparent winding structure. During regular operation the voltage at the terminals of the set of two coils does not exceed 7 kV. However, under fault conditions the voltage reaches 14 kV. The layer winding technique leads to a maximum voltage drop of 1.4 kV between layers.

The magnet's cryostat has been tested thoroughly with very good results. After less than 3 W in the first run, reconstruction of the thermal shield above the helium pool improved this value down below 1 W.

3.5 Dynamic Test of the Low-Voltage Power Supply

The test of the low-voltage power supply (LVPS-DTA) was performed with two inductive loads of 5 mH and 46 mH, respectively. Taking into account the availability of choke coils at ESTEL, Tallinn, a simulation of the specified working regimes of the power supply was performed with

1) currents of 1000 A and 2000 A @ 5 mH load, and 2) currents of 100 A and 750 A @ 46 mH load.

For the test, the 55 V output voltage option was used.

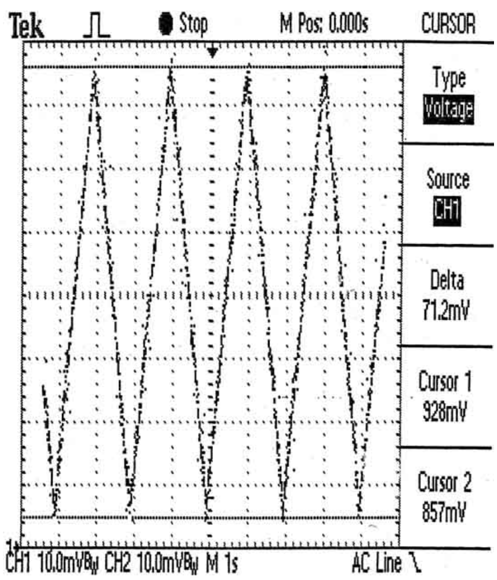

Fig. 8 Current in the load (46 mH). Imax = 650 A, □ I = 50 A, T = 1 s

For the investigation of the dynamic properties and the precision of the SMES charging system a special programme has been generated for a microprocessor integrated in the power supply. This programme allows periodical variation of the current in the load under the aforementioned conditions (cf. Fig. 8). The time intervals could be varied between 0.1 s up to 10 s. Increasing current simulates charging of the SMES of the modulator. The error of the load current was measured.

At periodical variation of the current, the maximum load currents did not vary more than 0.15 % from cycle to cycle for the load of 46 mH and up to 750 A.

3.6 Dynamic Test of the High-Voltage Power Supply

3.6.1 Goals

The goals of the dynamic test of the high-voltage power supply (HVPS-DTA) were:

- Demonstration of the operation in working regimes of the power supply close to those specified for the modulator test including maximum power
- Investigation of the stability of the output voltage from pulse to pulse
- Investigation of the maximum power consumed by the power supply
- Investigation of the stability of the consumed power during one period.
- Investigation of the stability of the consumed power during one period.

3.6.2 Principle of operation

For the dynamic test the circuit of the simplified diagram of Fig. 9 was built up. The system works as follows:

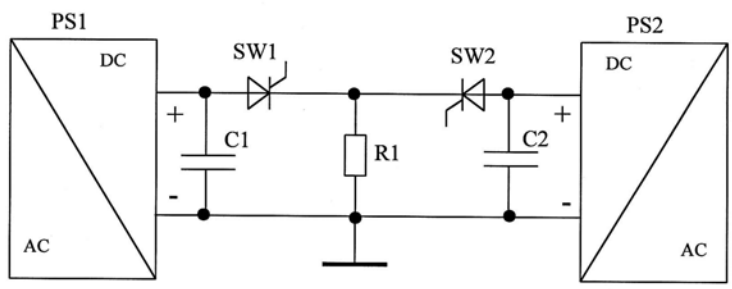

Fig. 9 Simplified circuit diagram for the dynamic test of the High-Voltage Power Supply

The starting position of the two switches SW1 and SW2 in the period between the discharge pulses of the capacitive energy storage is „open“, the power supply under test PS1 charges the energy storage up to the desired voltage. (The capacitance C1 corresponds to the capacitive energy storage of the SMES modulator, i.e. 300 or 600 µF, depending on mode of operation). Simultaneously, the additional power supply PS2 charges the additional capacitance C2 up to a voltage which exceeds the voltage of C1 by 10 % to 20 %.

At the start of the pulse, switch SW1 is closed and C1 is discharged via the power load resistor R1. When the desired depth of discharge of C1 is reached, the switch SW2 is closed. This action leads to a voltage drop at R1 higher than the voltage at C1 with the result that SW1 opens by itself. The parameter of the elements of the circuit were chosen in such a way that the anode of switch SW1 gets a negative voltage for a longer duration than the „circuit commutated turn-off time“ of the thyristors of this switch. During the discharge of energy storage C2 over the load resistor R1 the additional power supply PS2 is blocked ensuring reliable function of SW2. After complete discharge of C2 switch SW2 opens by itself again and the procedure of the pulse generation is repeated.

3.6.3 Results

The power supply has been constructed and tested successfully. During acceptance tests following regimes of operation have been reached, with a capacitor of 630 μF applied:

Charging voltage	12.5 kV (DC test 14 kV)
Depth of discharge	7 kV
Rate of pulse repetition	8,33 Hz
Average power	330 kW

4 Construction and Test of two Modulator Models (1 MW and 10 MW)

Applying original components of the SMES Modulator and additional dedicated components, a modulator test arrangement (MTA) for the dynamic test of the modulator up to a power of 1 MW has been designed together, built and tested at ESTEL, Tallinn. This test arrangement enabled us to perform a full test of the functions of the modulator, successfully. An upgrade version of 7 -10 MW is under construction which will serve as a relevant pre-test of the modulator. The components IGCTSC, SMES, 100 m cable, and pulse transformer will be added at Karlsruhe for the final modulator test.

4.1 1 MW Modulator Test Arrangement

4.1.1 Goals

The goals of the 1 MW test arrangement were:

- Demonstration of the function of the SMES modulator.
- Dynamic test of the SMES Thyristor Switch including the investigation of the distribution of the currents in the parallel operated thyristors.
- Construction and test of the control system of the 10 MW MTA

4.1.2 Principle of operation

A simplified circuit diagram is shown in Fig. 10. The system works as follows:

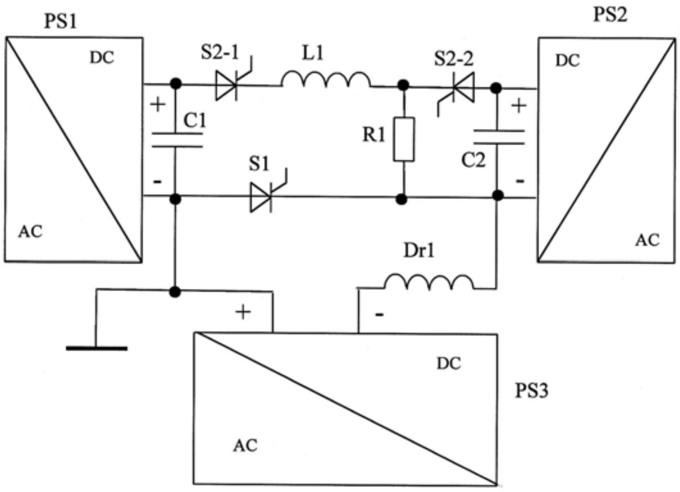

Fig. 10 Simplified circuit diagram for the 1 MW modulator test arrangement (PS1 is the modulator high-voltage power supply, PS3 is the modulator low-voltage power supply, PS2 is an extra power supply made available by ESTEL, Dr1 is a normal conducting inductance simulating the SMES, L1 replaces the leakage inductance of the pulse transformer, S1 is the SMES thyristor switch, S2-1 and S2-2 together simulate the operation of the IGCT switch)

The starting position of the two switches S2-1 and S2-2 in the period between discharge pulses of the capacitive energy storage is „open“, switch S1 is closed, the original modulator power supply PS1 charges the energy storage up to the desired voltage, the additional power supply PS2 charges the additional capacitance C2 up to a voltage which exceeds the voltage of C1 by 10 % to 20 %, and the original modulator power supply PS3 charges the choke coil Dr1 representing the SMES up to the desired current.

For the start of the pulse, switch S2-1 is closed and C1 is discharged via S2-1, the load resistor R1, and inductance L1 simulating the leakage inductance of the pulse transformer. When the desired current in the load is reached, i.e. the current in the load equals the current in the choke coil, original modulator switch S1 opens by itself and keeps open during the pulse. When the required depth of discharge of C1 is reached, the switch S1 is closed shorting the choke coil. After closure of S2-2 the voltage drop at R1 exceeds that of C1 with the result that the current in L1 is reduced to zero and the switch S2-1 opens by itself.

The parameter of the elements of the circuit were chosen in such a way that the anode of switch S2-1 gets a negative voltage for a longer duration than the „circuit commutated turn-off time“ of the thyristors of this switch. During the discharge of energy storage C2 over the load resistor R1 the additional power supply PS2 is blocked ensuring reliable function of S2-2. After complete discharge of C2 switch S2-2 opens by itself and the procedure of pulse generation is repeated.

As the IGCT switch was not available yet, the combination of the two switches S2-1 and S2-2 simulates the IGCT operation and enabled us to investigate the function of the other components of the modulator.

4.1.3 Results

The 1 MW modulator model was tested successfully including the built-in control system and the SMES Thyristor Switch S1. The currents in the parallel paths of the thyristors of the SMES Thyristor Switch S1 were equally distributed within an accuracy of about 10 %. Following regimes were reached: Charging voltage 3.5 kV; current in the load 250 A. An example of measured currents of the thyristor switches S2 and S1 are shown in Fig. 11.

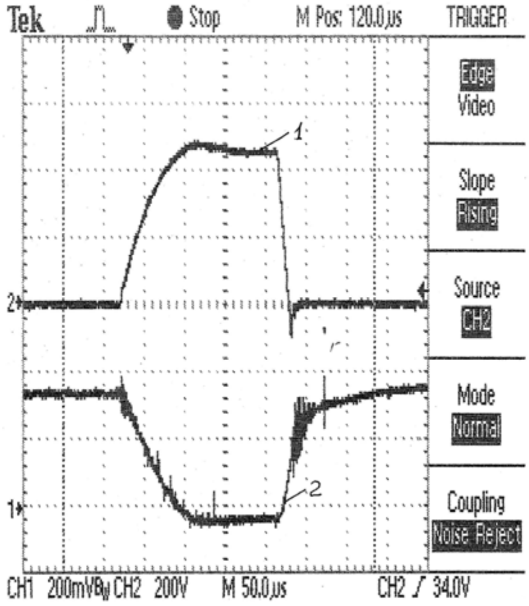

Fig. 11: Currents in the thyristor switches S2-1 (trace1) and S1 (trace 2) of the 1 MW MTA (bigger time unit 50 µs, bigger current unit 100 A)

4.2 10 MW Modulator Test Arrangement

The 10 MW MTA is to serve as a relevant modulator pre-test. Basically the simplified circuit of Fig. 10 will be used. The switch S2-2, the resistor, the inductances and the capacitors, however, will have to be replaced by more powerful components. In addition, the control of the cooperative action of the two power supplies will be introduced and tested.

5 Concluding Remarks

The SMES based power modulator is a new system and contains several components which have not been built before or have not been used in the working regimes required here. A stepwise procedure for testing and taking into operation of components, groups of components, model systems at reduced power, and half power arrangements is being applied, in order to detect problematic areas as early as possible.

There are several advantages of this modulator concept, e.g., the load current is naturally limited by the inductance, a crowbar system with ignitron is not required, a rapid control for the protection system is not needed, and more than one klystron can be supplied in parallel.

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