

25 MW SMES-BASED LONG-PULSE KLYSTRON 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 $\pm 0.5\%$, at a repetition rate up to 10 Hz. This new system's main features are a SMES, a power supply (rated 27 V/2.6 kA), a switched-mode power supply (rated 14 kV/45 A), a fast thyristor power switch for 2.6 kA approx. continuous current, and a new IGCT power switch rated 2.6 kA/14 kV. Original components were arranged to form a functional model of the modulator and 1 MW pulses were generated. An upgrade for 10 MW is on the way.

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 $\pm 0.5\%$ 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].

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 requires a dedicated design of superconductor and coils.

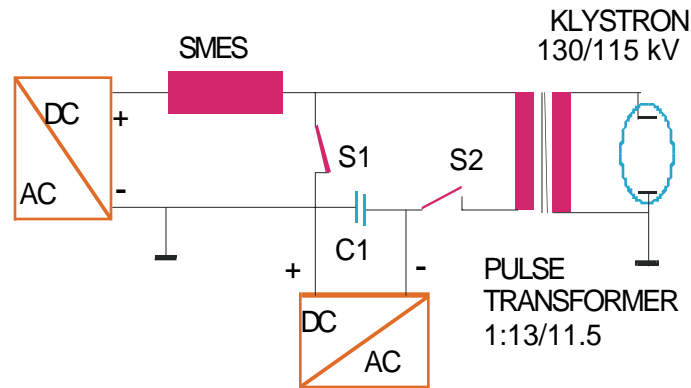


Fig. 1 Simplified Circuit of the 25 MW SMES Power Modulator (SMES 237 kJ, Capacitor 43 kJ, switch 1: Thyristors, switch 2: IGCT's

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 IGCT's development steps have been required. A dedicated safety system was developed. The magnet design took 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 . The safety system will be discussed elsewhere.

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 with 10 MW RF Power Klystron

For the operation of a multibeam, 10 MW klystron roughly 17 MW pulse power are required, i.e.

of the modulator system are listed in Table 1. 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 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.

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	$\leq \pm 1 \%$
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	1:12
SMES current (incl. 3 % margin for the magnetization of the pulse transformer)	min. 49 A, typ. 1580 A, max. 1680 A

2.1.2 Operation 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.

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

Cathode voltage of klystron	min. 50 kV, typ. 125kV, max. 130 kV
Cathode current	min. 22 A, typ. 90 A, max. 95 A
Voltage fluctuation	$\leq \pm 1 \%$
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

2.2 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).

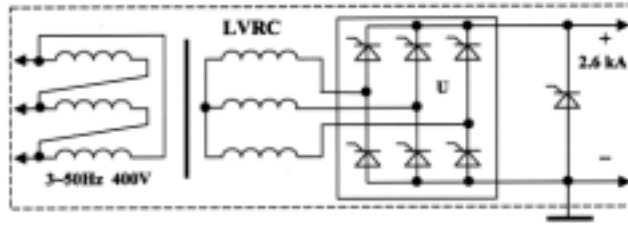


Fig. 2-1: Circuit diagram of the Low-Voltage Rectifier Cabinet (Power Supply for the SMES)

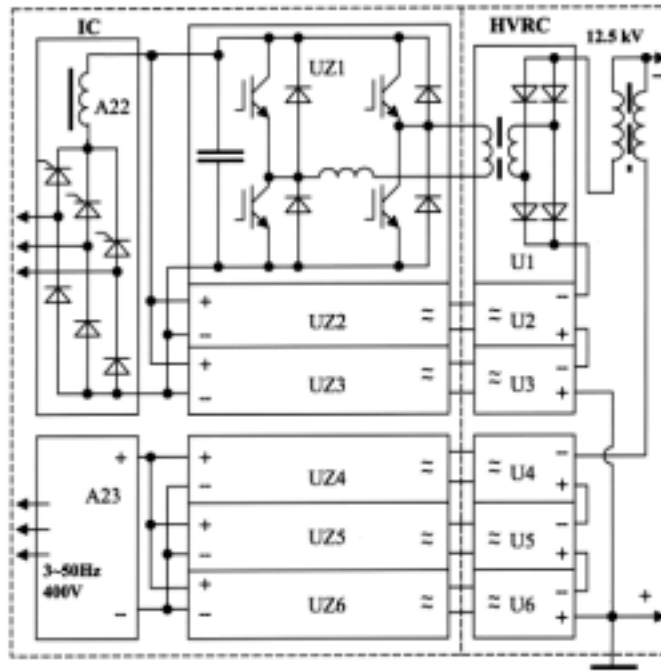


Fig. 2-2: Diagram of the High-Voltage Rectifier Cabinet and the Inverter Cabinet

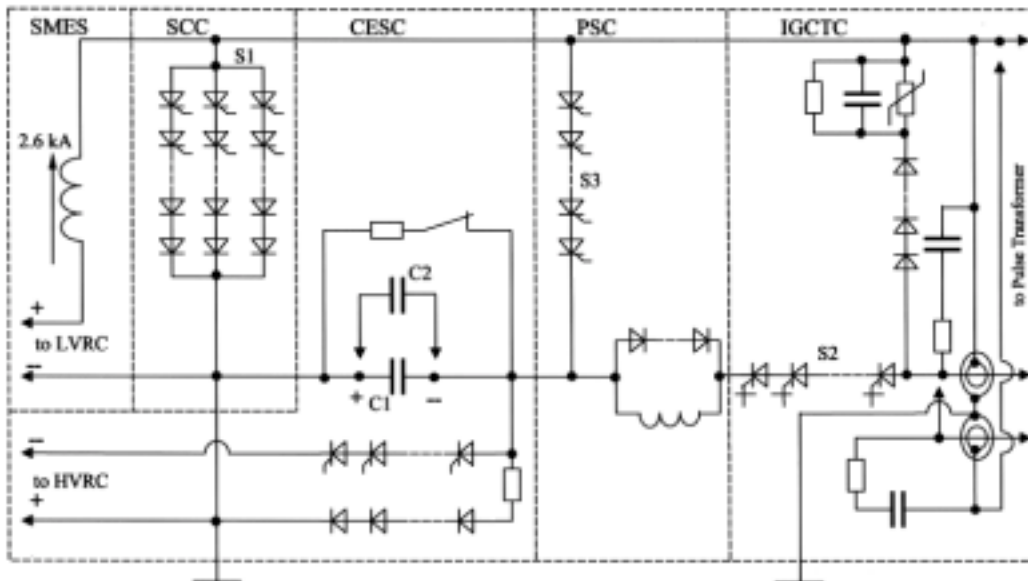


Fig. 2-3: Diagram of cabinets SSC, CESC, PSC, IGCTC and the SMES

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). The choice of the superconductor was a balance between low losses and limited financial resources. Table 3 gives the parameters of the magnets. Details of the superconductor can be found in [4].

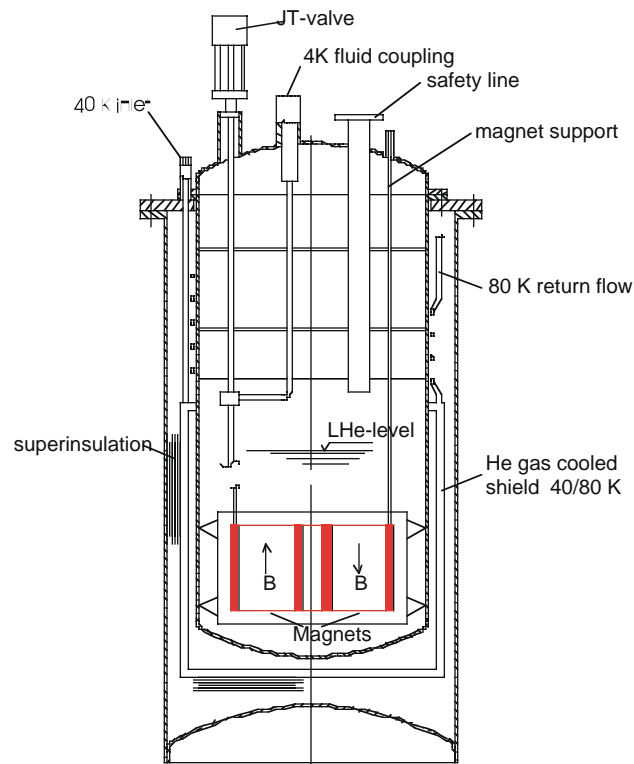


Fig. 3 SMES magnet system; 2 solenoids with antiparallel field in their cryostat (\varnothing 1.25 m).

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 @ 10 Hz
Stored energy @ 2,600 A	237 kJ
Coil outer diam.	301 mm
Coil length	382 mm
Number of coils	2

The introduction of a capacitor as a second energy storage besides the SMES adds

helps to shape the pulse flat top. The parameters of the capacitive energy storage are listed in Tab. 4.

Table 4
Capacitive Energy Storage

Capacitance @ operation with 2 x 5 MW klystrons	600 μ F
Capacitance @ operation with 1 multi-beam klystron	375 μ F
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	$\leq \pm 0.5 \%$
Input voltage	400 V $\pm 5 \%$
Input current, rms	< 715 A
cos ϕ	≥ 0.99
Power factor	≥ 0.94

1.5 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.

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	$\leq \pm 0.2 \%$
Input voltage	400 V $\pm 5 \%$
Input current, rms	< 130 A
cos ϕ	≥ 0.89
Power factor	≥ 0.85

1.6 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 $V_{\text{anode-cathode}}$ and $dV_{\text{anode-cathode}}/dt$ 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].

1.7 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 are being made at FZK in close cooperation with DESY.

3. STATUS

In this paragraph the various components of the modulator are discussed with respect to their status. "Components" does not mean only the single modules like switches but also the cabinets forming the power part of the modulator. Figure 4 shows the arrangement of modulator cabinets.

Three test arrangements mentioned below have been designed together with ESTEL and (partially) erected at Tallinn: 1. the LVPS-DTA (low voltage power supply test arrangement, 2. the HVPS-DTA (high voltage power supply dynamic test arrangement) and 3. the 10 MW MTA (modulator test arrangement). The intention of development and construction of these dedicated systems is early testing as close to the specifications as possible.

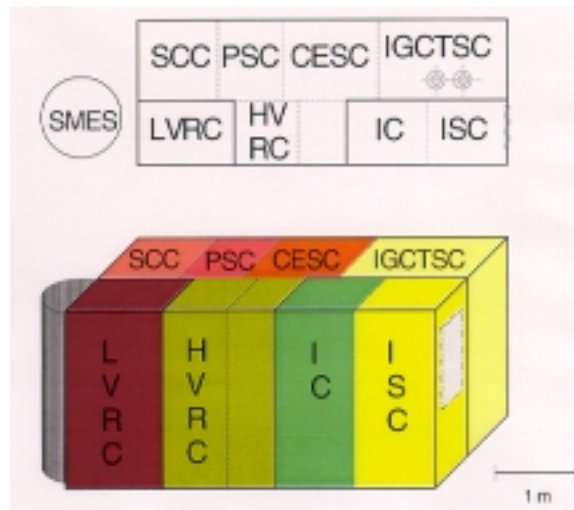


Fig. 4 Side and top view of the power parts of the modulator; partition into cabinets (*LVRC* Low-voltage rectifier cabinet, *HVRC* High-voltage rectifier cabinet, *IC* Inverter cabinet, *ISC* Input supply cabinet, *SCC* SMES commutator cabinet, *PSC* Protection switch cabinet, *CESC* Capacitive energy 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 $V_{\text{anode-cathode}} \geq 10 \text{ kV}$ and at $2.5 \text{ kV}/\mu\text{s} \geq (dV_{\text{anode-cathode}}/dt) \geq 1.2 \text{ kV}/\mu\text{s}$. Next steps are the acceptance test as well as a dynamic test with the 10 MW MTA.

The protection thyristor switch (S3 in Fig. 2-3) has been tested preliminarily using types of thyristors similar to the final ones.

The charging thyristor switch (cf. cabinet CESC in Fig. 2-3) will be used in connection with the charging of the capacitor. The switch has been tested to full average current of 45 A and full voltage of 14 kV. A dynamic test is foreseen within the 10 MW MTA.

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. The acceptance test is planned for May 2001.



Fig. 5 View of the IGCT switch during pre-testing on the manufacturer's site.

3.2 Cabinets SCC, CESC, PSC, IGCTSC

The SCC containing e.g. the SMES Thyristor Switch has been tested. The construction of CESC has been started. The design of the PSC is finished. After their initial testing these cabinets will be tested dynamically as a part of the 10 MW MTA test arrangement. The specification of the IGCTSC is about being finished. It will be tested together with all other components at Karlsruhe.

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. Initial tests of the HVRC showed overvoltages which were detected and removed. Testing of this PS results to date in a maximum output of 100 kW average power. Further tests are reported in sections 3.5 and 3.6. 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 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]. The two original coils for the modulator system have been manufactured at FZK and are being mounted into their cryostat which has been tested with good cryogenic results of less than 3 W static losses (without magnet and current leads).

Fig. 6 View of completed cabinets of the SMES Modulator



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.

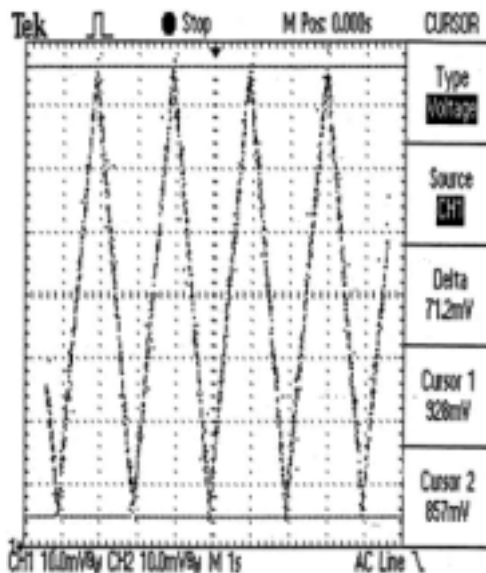


Fig. 7 Current in the load (46 mH). $I_{\max} = 650$ A, $\Delta I = 50$ A, $T = 1$ s

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. 7). 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. 8 was built up. The system works as follows:

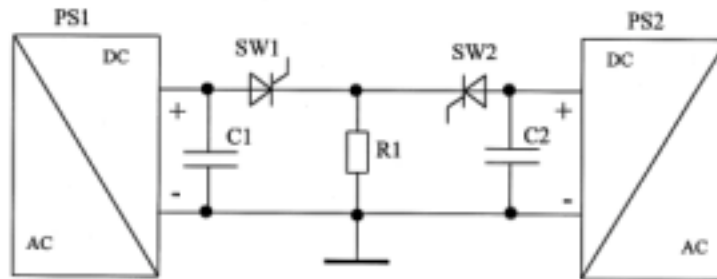


Fig. 8 Simplified circuit diagram for the dynamic test of the High-Voltage Power Supply (HVPS-DTA)

The starting position of the two switches S1 and S2 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 μ F, 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 S1 is closed and C1 is discharged via the power load resistor R1. When the desired depth of discharge of C1 is reached, the switch S2 is closed. This action leads to a voltage drop at R1 higher than the voltage at C1 with the result that S1 opens by itself. The parameter of the elements of the circuit were chosen in such a way that the anode of switch S1 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. After complete discharge of C2 switch S2 opens by itself again and the procedure of the pulse generation is repeated.

3.6.3 Results

Presently following regimes of operation have been reached, with a capacitor of 525 μF applied:

Charging voltage	11.5 kV
Depth of discharge	5.75 kV
Rate of pulse repetition	10 Hz
Average power	260 kW

4. CONSTRUCTION AND TEST OF TWO 1 MW AND 10 MW MODULATOR MODELS

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 functions of the modulator at 1 MW. An upgrade version of roughly 10 MW is under construction. Further components such as IGCTSC, SMES, 100 m cable, and pulse transformer will be added at Karlsruhe.

4.1 1 MW MTA

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. 9. The system works as follows:

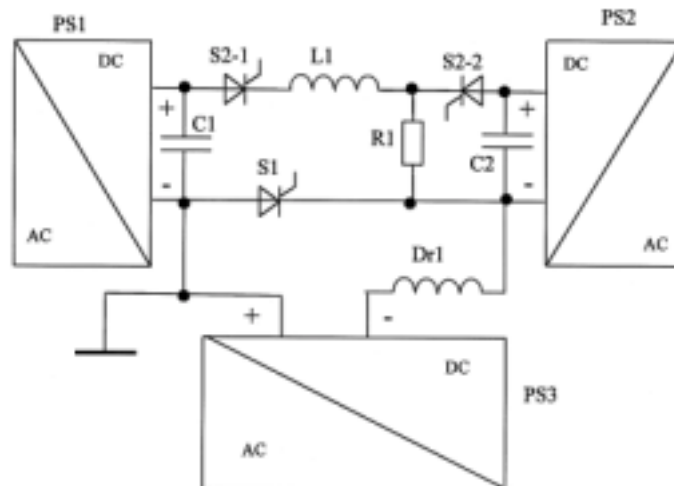


Fig. 9 Simplified circuit diagram for the 1 MW modulator test arrangement (PS1 is the modulator high-voltage power supply, PS3 is the modulator low-voltage power supply, PS2 is an extra power supply made available by ESTEL, Dr1 is a normal conducting inductance simulating the SMES, L1 replaces the leakage 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 the 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 the switch S2-1 is closed and C1 is discharged via S2-1, the power 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 have been reached: Charging voltage 3.5 kV; Current in the load 250 A. An example of measured current traces of the thyristor switches S2 and S1 are shown in Fig. 10.

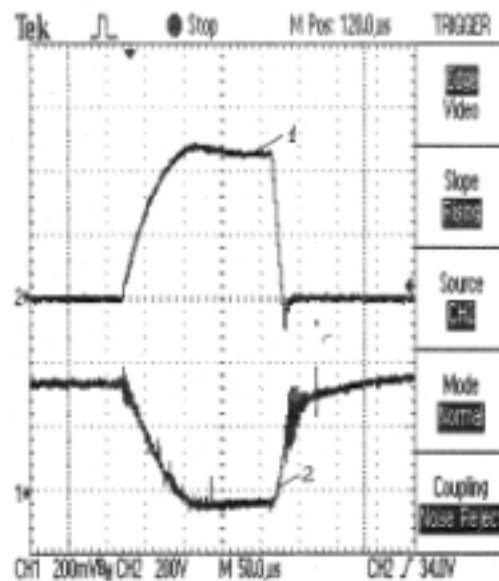


Fig. 10: Currents in the thyristor switches S2-1 (trace1) and S1 (trace 2) of the 1 MW MTA

(larger time unit 50 μs, larger current unit 100 A)

4.2 10 MW MTA

The 10 MW MTA is to serve as a relevant modulator pre-test. Basically the simplified circuit of Fig. 9 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 new as 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.

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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