A 25 MW Pulse Power Modulator Based On SMES Technology

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Pulse power applications always cause disturbances on the electrical grid if the pulse power is drawn directly. In order to avoid those disturbances one must employ pulse formers, especially when the pulses are repetitive and have high power. The klystrons of particle accelerators have these requirements regarding the pulse generation. For the klystrons of the TESLA Test Facility (TTF) at Desy in Hamburg a pulse power generator was developed based on superconducting magnetic energy storage (SMES) technology as a first of its kind. This solution was proposed in competition to conventional solutions [1]
Together with the duration, power and repetition rate the flat top of the pulse must be better than 0.5 % for the proper operation of the klystrons. Typical pulse parameters are summarized in table 1.

Power	17..25 MW, depending on operation mode
Duration of Pulse	1.7 ms
Repetition Rate	10 Hz
Flat top	better ±0.5 %

Table 1: Specifications of the pulse

A SMES should always spend only a small fraction of its stored energy for each pulse as the magnetic field change rate should be kept within acceptable limits. In our design, a small capacitor bank improves the pulse flat top as well as providing an additional energy storage that reduces the size of the required magnet. Figure 1 shows the principle of the modulator [2] [3]. The two power supplies charge both storages while the thyristor

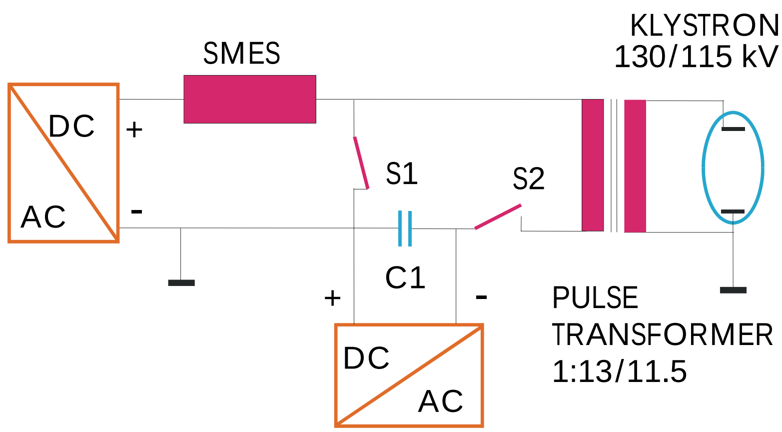

Figure 1: Principle setup of the SMES-Modulator

switch S1 is closed and S2 is open. The pulse is started by closing IGCT switch S2; this leads to a reduction of the voltage over S1, which closes consequently. Now the current flows through the pulse transformer and the desired pulse starts. The end of the pulse is induced by closing S1 and opening S2. As one can see, S2 must be able to open under full load, thus a design with thyristors is not possible and either IGBT or IGCT must be used; our design employed IGCT as switching elements.
The modulator is supposed to operate under various conditions i.e. different pulse frequencies or different klystrons connected (one or two 5 MW RF-power klystrons or one 10 MW RF-power multibeam klystron) so a variety of pulse types have to be generated. The energies stored in the magnet and capacitor bank were chosen to be 237 kJ and 43 kJ respectively. This ratio is not fixed and can be selected differently for other applications. Table 2 shows the requirements for the klystron types. Most of the operating parameters are the same; the difference in the cathode voltage was done with a second terminal on the secondary to achieve the transformation ratio of 1:13 and 1:11.5. In order to achieve an optimal performance all major subsystems required considerable developments:

- The superconducting magnetic energy storage (SMES) required a design which allows fast ramping speeds and a high voltage compatible design

– The power supplies needed a good stability that would give a good reproducibility of the pulses.
– The pulse former and control unit had to be optimized with respect to the timing of the switch control.
– The switches required an improved snubber design and the trigger system had to be improved.

	2 conventional klystrons	Multibeam klystron
Cathode voltage	Max 130 kV, typ. 125 kV	Max 115 kV, typ. 110 kV
Cathode current	Max 95 A, typ. 90 A	Max 136 A, typ. 128 A
Voltage fluctuation	≤±1 %	≤±1 %
Pulse duration	0.3 to 1.7 ms, typical 1.7 ms	0.3 to 1.7 ms, typical 1.7 ms
Pulse rate	0.1 to 10 Hz, typical 10 Hz	0.1 to 10 Hz, typical 10 Hz

Table 2: Klystron operation parameters

In the design of the magnets, some major boundary conditions had to be fulfilled.
The fringe field had to be below 0.5 mT (set by heart pacemaker disturbance limit); additionally the field near the klystrons had to be one order of magnitude lower than this value for an optimal operation of cavities. This was achieved by mounting two solenoids in an antiparallel configuration in the cryostat.
The maximum design current was 2600 A and a rutherford type cable was chosen. In order to minimize the AC-losses in the superconductor very thin filaments should be selected considering that the fastest rate dB/dt was in the order of 100 T/s. In our case the 6 µm filament size was a compromise between cost and performance. The magnets were wound with helium transparent winding achieved by fiberglass strips (G10). Table 3 summarizes the conductor and magnet parameters.

Total inductance	70 mH
Field strength at 2600 A	4 T
Maximum voltage	7 kV
Maximum dB/dt	100 T/s
Stored energy	237 kJ
Coil length	382 mm
Coil outer diameter	301 mm
Number of coils	2
Strand diameter	0.65 mm
Number of strands	20
Filaments per strand	3684
Filament diameter	5.9 µm
Critical current	5620 A at 5 T and 4.3 K
Cable geometry	1.24 mm by 6.35 mm

Table 3: Superconductor and magnet parameters

The capacitors help to shape the pulse to the required flat top and are charged by a switched mode power supply with a rated voltage of 14 kV and average output current of 45 A. The power supply consists of two identical parts; one half is capable of supplying enough power for the operation of one 5-MW klystron or 80% of the maximum power required by a multibeam klystron. This configuration was chosen to have a redundancy when operating with one klystron.

All components were successfully tested in intermediate test setups before the modulator was assembled. As an example the test setup for the high voltage power supply is shown in figure 2. At the beginning of a test pulse the switches SW1 and SW2 are open and the power supplies charge both capacitors, where the voltage of C2 is 10 to 20 % higher than the voltage of C1. The pulse is started by closing SW1 and discharging C1. Closing SW2 will lead to a voltage drop at R1 higher than the voltage at C1 and thus SW1 opens. As soon as C2 is completely discharged SW2 opens and the cycle starts again. Other test setups are described in [5].

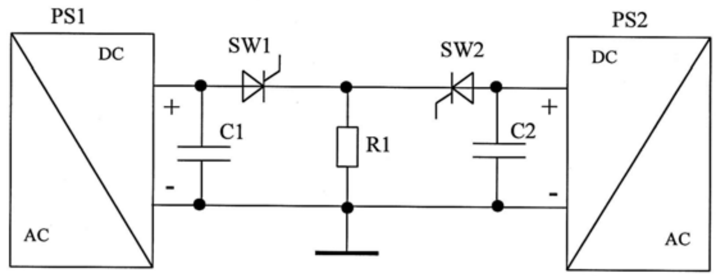

Figure 2: Sample test setup fort he high voltage power supply (PS1)

The complete system was first tested at Forschungszentrum Karlsruhe and reached full performance without problems. Figure 3 shows the traces of a 25 MW pulse with the pulse transformer connected and a dummy load simulating the klystron on the secondary. Trace one is the current in the pulse transformer, trace two the voltage drop over the SMES, trace three is the trigger voltage and trace four is the current through the thyristor switch; the zero-line was shifted for the different traces for better distinction.

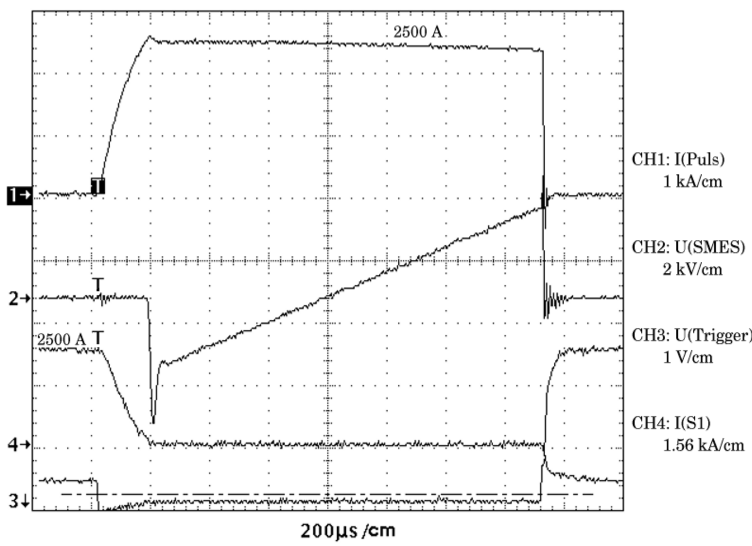

Figure 3: Oscilloscope trace of a 25 MW pulse

After delivery to Desy in Hamburg the tests were repeated. Improvements were made amongst others in the quench detection system. Conventional quench detectors might give a signal when the pulse is generated. To overcome this problem an integrating RC element was introduced which had a reaction time longer than the pulse itself. Also the trigger signal from the modulator electronics was used to block input and output of the quench detector for the time of the pulse. This threefold method efficiently removes false quench triggers during a pulse. The slight delay of about 2 ms in triggering a real quench is not dangerous for the magnets and would not cause destruction of any equipment.

The trigger control system was also updated from a TTL based electronics to a microprocessor controlled unit that gives a higher flexibility in the adjustment of the timing required by the switches. As also better klystrons are available now, a single beam klystron requires 1500 A in the primary side of the transformer. A sample pulse is shown in figure 4 which also shows the flexibility of the system to produce high power pulses in a wide parameter range.

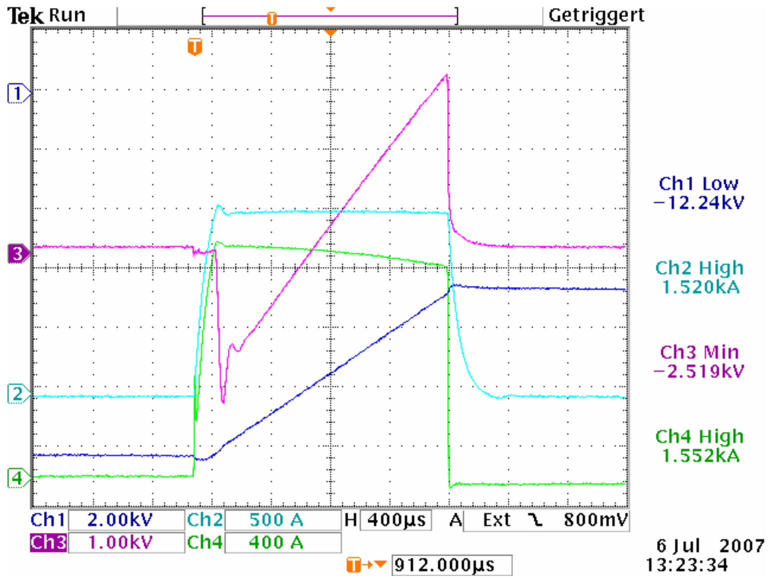

Figure 4: Oscilloscope trace of a pulse, Channel 1: U_{Cap}, Channel 2 I_{Pulse}, Channel 3: U_{SMES}, Channel 4: I_{IGCT}

The SMES based power modulator for accelerator klystrons is a new concept that has advantages over conventional capacitor based systems; the load current is automatically limited by the inductance of the SMES which simplifies the fault detection and protection of the system; additionally more than one pulse transformer can be connected in parallel. The flexibility of the design makes adaptations to other applications

References

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