Session 2-3
Chairman : S. Choroba (DESY)

Klystron-Modulator Design-2

REVIEW OF SESSION 2.3 - KLYSTRON-MODULATOR DESIGN-2

Stefan Choroba (chairman)
DESY

Yesterday…

Looking back some years ago we had Glasoe & Lebacque and the following:

- Line-type modulators, PFNs, Thyratrons, Pulse Transformers…etc
- Hard tube modulators, switch tubes (tetrodes etc) and capacitor banks…

Today…

We have many different types of modulator…

- Induction type modulator, IGBTs, Fractional Turn transformers
- Line type modulators with semiconductor switches
- Direct switching at 500 kV, with IGBTs
- Bouncer Modulators
- SMES, Super conducting coil for energy storage instead of capacitors
- Converter modulators
- PSM, Pulsed switched modulators
- and of course we still have Line-type modulators, Thyratrons, PFNs and Pulse transformers.

A NEW SOLID STATE HIGH POWER PULSED MODULATOR

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Abstract
The CLW modulator represents the first successful application of high-power IGBT switching modules to meeting the requirements of multi-megawatt peak power modulators for microwave amplifier applications. Unlike some other solid-state modulators, no semiconductor switches are placed in series in this system. Neither are the switches connected in parallel. Rather, each switch drives a segment of the pulse transformer core, in a configuration we refer to as a "fractional-turn primary" arrangement. As no PFN is required the width of the output pulse can be adjusted by simply adjusting the trigger duration of the IGBT switches and no PFN ripple occurs on the pulse-top. The volume of the complete modulator is about 10% of a classical unit of the same power. The advantages of this new concept will be discussed with details of a unit that has been in continuous use for more than two years.

1. INTRODUCTION

The firms of Scanditronix Medical AB, D Woodburn & Co. Ltd. and Crewson Engineering, Inc. have jointly developed an all solid-state high power pulsed modulator (US patent no: US5905646) for klystrons, magnetrons and other applications requiring precisely regulated rectangular pulse trains. A concrete example of this "CLW" modulator (named after the inventors, Crewson, Lindholm and Woodburn) is the 140 kV, 95 A, 0 to 300 Hz, 10μS modulator used in the Scanditronix 50MeV MM50 ARTS cancer treatment system. The new modulator uses a number of IGBT switches, operating at relatively low voltage, to replace a high voltage hydrogen thyratron switch. This system is now installed and operating at the Japan National Cancer Center (NCC) in Tokyo, Japan. It has delivered three years of failure-free service, operating almost continuously. No components have been replaced in this modulator system to date.

This system represents the first successful application of high-power IGBT switching modules to meeting the requirements of multi-megawatt peak power modulators for microwave amplifier applications. Unlike some other solid-state modulators, no semiconductor switches are placed in series in this system. Neither are the switches connected in parallel. Rather, each switch drives a segment of the pulse transformer core, in a configuration we refer to as a "fractional-turn primary" arrangement. This concept is a generalization of the older linear-induction accelerator idea, in which a single-turn secondary is driven by N toroidal magnetic "cells" driven by a relatively low voltage which surround the secondary path. This "Linear-Induction" arrangement provides a voltage step-up ratio of N, at the cost of requiring a very large number of cells to yield a ratio in the 150 to 300:1 range. Our electromagnetic circuit combines the step-up advantage of an N2-turn secondary winding with a 1/N1 "fractional turn" primary to yield a conventional-looking pulse transformer with a voltage step-up ratio of N1xN2, that uses only N2 turns on the secondary rather than the full N1xN2 turns. So we can use fewer drive modules than the "Linear Induction" arrangement, yet achieve lower secondary leakage inductance than a single-turn primary

arrangement can, and hence obtain a faster rise of secondary voltage than an equivalent single-primary-turn design. The "best of both worlds" is obtained, so to speak.

A second desirable feature of our system is that no PFN structure is used, so the output pulse width can be adjusted by simply adjusting the trigger duration of the IGBT switches. This is a purely electronic adjustment, done at logic-level voltage. Of course, the pulse transformer must be designed to handle the maximum volt-second product of the largest, longest pulse that will be required. Also, no PFN "ripple" occurs on the pulse-top, so no "tuning" of PFN mutual inductances is required to minimize pulse flatness.

We have used a simple passive circuit to compensate for the voltage droop of the modulator capacitors, and this circuit also helps to limit fault currents in the event of a secondary-side short circuit. The modulator we have built for NCC has been subjected to numerous secondary shorts during its development and testing, with no resulting component failures.

We charge the modulator with a series-resonant switch-mode power supply that acts to first order as a "charge pump" or "current source", and which therefore isolates the input powerline very effectively against the pulsed nature of the load. Older resonant-charged circuits tend to cause the input line current to pulsate in step with the modulator output pulses, while the series-resonant supply effectively prevents this.

The modulator replaces several 2-metre high racks of equipment, which were required when the older thyratron-PFN-resonant charger modulator technology was employed. All support subsystems, including the main charging power supply, the filament supply, DC reset supply and the computer interface electronics, are enclosed in the modulator cabinet, which has a total volume less than 0.5 cubic meter. The klystron is mounted directly on the top cover of the modulator. Modulator components are all accessible, and are mounted in plug-in modules on the side walls of the oil tank which holds the pulse transformer and klystron socket.

One present version of the CLW modulator meets the following performance specifications.

- Peak Output Voltage: -140 kV
- Peak Output Current: 95 A
- Repetition Rate: 0 to 300 Hz
- Pulse Flatness: <0.5% peak-to-peak
- Pulse-Pulse Regulation: <0.5% maximum at any repetition rate
- Pulse Width: electronically selectable from 3 to 10 μS (no access to modulator is required to change pulse width)
- Efficiency: Approx. 80 percent, line input to pulse output
- Input power: 400 V, 3 phase, 50/60 Hz, 50 KVA max.
- No high voltage DC power is used. Modulator drive voltage is 900 volts DC, which means that no series connected solid state devices are used; the only high voltage present is at the pulsed output.
- Passed all EMC/EMI tests performed by SEMKO, the Swedish Testing Laboratory.
- Completely Computer-Controlled, using a Windows NT based software interface written by Scanditronix Medical AB.

The operating parameters can be varied widely to meet other performance requirements. CLW technology can be applied to drive klystron, super-klystron or magnetron loads. It is economically competitive with the older thyratron-PFN technology, and when the greatly reduced maintenance and size/weight characteristics of CLW modulator systems are taken into account, the CLW system is seen to be more cost-effective than older technologies. As there are few components that will age with use, the cost of ownership is considerably less than systems using thyratron tubes.

2. FRACTIONAL-TURN PRIMARY CONCEPT

A numerical example is useful in thinking about fractional-turn primaries. Begin with a pulse modulator of the PFN type, and suppose the output pulse is required to be 100 kV at 100 amps, to use round numbers. The load impedance Rs is 100 kV/100 A, or 1000 Ohms. Suppose the

primary of the pulse transformer is driven by a PFN charged to 20 kV and switched by a thyratron tube. The transformer primary is then driven by one-half the PFN charging voltage, or 10 kV, and the transformer must supply a voltage step-up ratio of 10:1. Further suppose that the pulse transformer's core is sized to require a 5-turn primary winding to avoid core saturation during the pulse width. The secondary winding must have 50 turns to supply the required voltage step-up ratio. The core thus supports 2kV per turn during the pulse. The primary pulse current is ten times the load current, or 1000 A.

To replace the thyratron switch with lower-voltage solid-state switches, suppose there are available IGBTs that will operate safely at 1000 V and 1000 A; this is simply an example, there are much larger IGBTs on the market. We choose IGBTs rather than thyristors, as IGBTs can be turned off by removing their gate voltage, while thyristors require a pulse-shaping circuit to drive current to zero at the end of the pulse, and so will need a PFN. We suppose that the existing pulse transformer provides a satisfactory pulse risetime, so it would be convenient to keep the same transformer core and secondary structure and simply rework the primary windings. Doing this will not materially affect the pulse rise and fall-times. Also, to make maximum use of the voltage handling capability of the switches, suppose we eliminate the PFN structure and drive the primary from a simple capacitor. Charging this capacitor to 1 kV will then supply a 1 kV pulse to the primary, while we would only have 500 V if a PFN were used. Of course, the capacitor voltage will "droop" somewhat during the pulse, and we will address this point later on. This idea will not work with thyristors; it makes use of the fact that the IGBT switches can be turned off electronically, giving the possibility of changing the pulse width by simply altering the width of the IGBT trigger pulse, which can be done by software without requiring access to the modulator itself.

If we use a single-turn primary winding, the output voltage will be only 50 kV, and the core will be driven at the 1kV per turn level, so we are not using the core effectively and the output pulse voltage is too small. To restore the 100 kV output voltage while keeping the same core structure we could double the secondary turns. But this is a major transformer re-design, and it does not address the issue of driving the core material properly, at 2 kV per turn. Also, doubling the secondary turns will quadruple the secondary-side leakage inductance, and this will seriously slow the pulse risetime.

The output pulse risetime is approximately $2.2L_k/R_s$, where L_k is the secondary-side leakage inductance of the pulse transformer. All else being held constant, the secondary-side leakage inductance is proportional to the square of secondary turns. So doubling the secondary turns will cause a factor of four increase in this inductance, and the same factor of four increase in pulse rise and fall-times. This is unacceptable under the "ground rules" of the "thought experiment" we are conducting.

One way of solving this problem is to connect two of the IGBTs in series, and drive the single-turn primary with 2 kV. This kind of solution is employed in some solid-state modulators, where thyristors are connected in series and a PFN structure is used to shape the pulse. We prefer to avoid the problems of connecting switches in series, so we do not adopt this idea. Is there another way to reach the goal?

Yes; if a 1/2-turn primary is used, one can leave the 50-turn secondary unchanged. Since the voltage step-up ratio equals the secondary turns count divided by the primary turns count, this provides a 100:1 voltage step-up ratio, and restores the 100 kV output pulse without affecting the secondary-side leakage inductance. At first glance this may sound impractical, but it is not. Again, as a "thought experiment", consider sawing the transformer core into two identical cores, each one with half the cross-sectional area of the original. Then we drive each of these cores with a single-turn primary, and mount the cores next to each other so the transformer appears mechanically identical to the original design. This is the "fractional-turn" primary concept in its simplest form.

In practice, the "single-turn" primary windings are composed of many single-turn wires arranged adjacent to each other; this keeps stray inductance to a minimum. If we simply drive one of the two "half-cores" with its own independent 1 kV pulse generator, then we have not avoided the problems associated with series-connected solid-state switches. If one of the two core halves is driven slightly later than the other one, the switches connected to this half will be exposed to a factor of two over-voltage and may be damaged. So, to avoid this problem, we "mix" the drives, so that each of the one-kV pulse generators drives some primary turns on EACH of the two core

halves. This way, the overvoltage issue is avoided. This point is crucial to the proper application of the concept.

To conclude the example, we now have a 100 kV output pulse at 100 A pulse current, being delivered by a 100:1 pulse transformer. The total primary current of this transformer is then 100 times the load current, or 10 kA. If each IGBT is to operate at 1 kA, we need ten switches. These are connected as described above, with each switch connected to its own capacitor and connected at its output side to several of the single-turn primaries distributed on the two transformer cores. This method of connection helps assure equal current and voltage sharing among the switches, yet does not place the switches directly in parallel or in series with each other.

If this process is extended to the limit, one emerges with a structure similar to the "Induction Linac" , where a single-turn secondary wire is surrounded by N toroidal cores, each driven by its own pulse generator. In the numerical example, if each core is driven by a 1 kV pulse, then 100 cores (N=100) are needed to obtain a 100 kV output pulse. Again, this structure can cause trouble of any of the N pulse switches is triggered late or is turned off earlier than the rest. The "non-driven" core will be subjected to the full voltage of the (N-1) driven cores, and damage to its associated pulse generator can occur. The solution again is to drive several cores with each pulse generator, interleaving the connections so that any one "late" switch will not spoil the result. We have demonstrated this idea in working CLW modulators by removing the trigger pulses from one or more IGBTs without markedly affecting the output pulse shape or causing any damage to the modulator.

A concrete example of this fractional-turn concept is illustrated in Fig.1. This shows a "fractional-turn" pulse transformer with a 1/2-turn primary structure. At first examination, the pulse transformer looks like a "conventional" transformer used in a thyratron-PFN type of modulator. A closer look shows that the magnetic core is built as two identical cores with a small gap between them. Each of the two "half-cores" is itself composed of two identical cores with a still smaller gap between them, but this is a detail of construction and not essential to the half-turn primary structure.

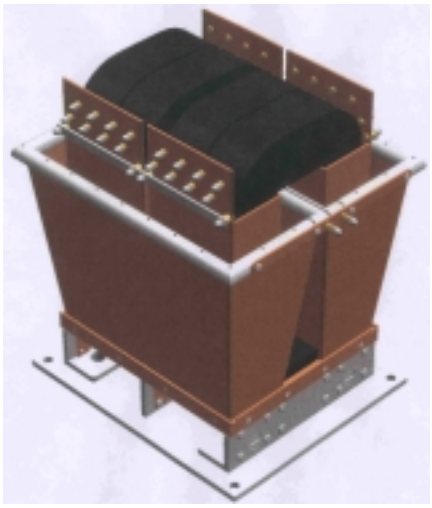

Fig. 1 Pulse transformer with half-turn primary

If the transformer of Fig. 1 is bisected by a vertical plane that passes between the two secondary "baskets", it splits into two identical transformers, with two primaries and two secondaries. The secondaries are connected in parallel at both high and low ends by capacitors, and the two windings serve as a "bifilar" structure to carry power up to the heater of the klystron or magnetron being driven by the negative HV output pulse. This arrangement also leads to very low leakage inductance when compared to a single transformer, and is standard practice in modulator pulse

transformer design. Look at the half-transformer on the left (foreground) side of the figure, and one has two cores, each surrounded by its own set of single-turn windings, and with BOTH cores surrounded by the secondary winding. This gives the half-turn primary effect. If each of the two cores is driven by 1 kV pulse generators, a 50-turn secondary winding develops 100 kV pulse voltage.

Note that there are four "core legs" in the overall structure. Each "leg" is driven by its own set of single-turn windings. There are eight of these single turn windings on each "leg". The "low end" of these primaries is connected to a common bus bar, shown running across the width of the transformer structure just below the eight individual "primary high end" connecting screws. There are 32 such individual "high end" primary connection points. In the klystron modulator currently in production, these 32 connections are fed by eight IGBT modules, so each of the four "legs" is driven by two such modules. The eight primary connections are grouped into two sets of four each, with each set driven by a separate IGBT/capacitor module. In this way, we obtain the necessary redundancy of connection to avoid the over-voltage situation described above if one module triggers late or turns off early. The other module still controls the voltage on this "leg" of the core structure in such a case. We are developing a smaller CLW modulator for magnetron drive that uses only four IGBT modules, but again the multiple single-turn primary connections are distributed so each "leg" of the magnetic circuit is driven by at least two modules.

3. PULSE SHAPING

The pulse energy is delivered by switching charged low-inductance capacitors into the primary windings. We use a separate capacitive energy store for each IGBT, and isolate these modules from each other by connecting the capacitors to the DC power supply through diodes. By this means, if a capacitor or IGBT should fail, the energy stored in other modules cannot be discharged through the fault.

During the pulse, the current drawn from the capacitor causes its voltage to decrease linearly. A simple R-L circuit can compensate for this voltage "droop" quite effectively. This principle is illustrated in Fig. 2.

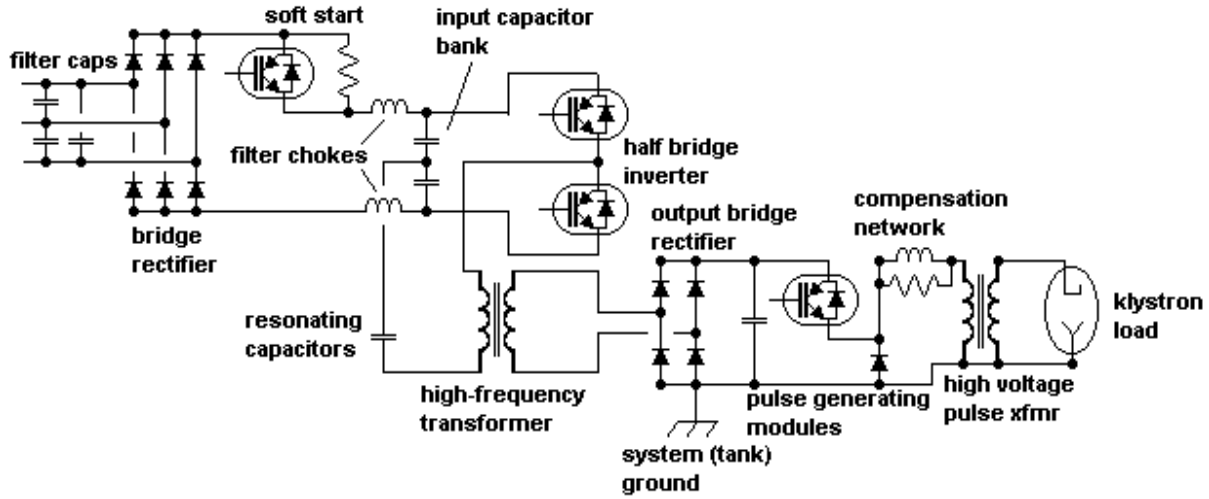

Fig. 2 Schematic Diagram of CLW Modulator

Figure 2 is a simplified schematic diagram of the CLW modulator, showing one of the N pulse generating IGBT modules. The R-L circuit labeled "compensation network" compensates for the droop of capacitor voltage. Each module is connected to the pulse transformer primary through its own compensation network. When the IGBT turns on, the inductor in the compensation network carries no current, and some voltage is dropped across the resistor. As time progresses, the capacitor voltage falls in a linear ramp, as the pulse current is fairly constant during the pulse. While this is happening, the inductor current is increasing. This reduces the voltage that is dropped by the resistor, and the net result is a fairly constant pulse voltage at the pulse transformer

primary. This type of pulse compensation results in a power loss of about seven percent for a pulse flatness (peak-to-peak deviation of voltage from a perfectly flat pulse) of one percent. This compensation circuit can be quickly designed and optimized using PSPICE or Microcap.

Another pulse-shaping component is the diode connected from the emitter (output end) of the IGBT and ground. This diode serves two functions: it prevents the emitter voltage from swinging strongly negative and damaging the IGBT when the IGBT turns off, and the small voltage developed across this diode acts to drive down the primary magnetizing current in the pulse transformer, helping reset the transformer core for the next pulse. In practice, we use several high-speed diodes in series at this point in the circuit to develop enough reset voltage; as the pulse duty factor increases, this reset voltage must also increase, as there is less time to drive down the magnetizing current.

Figure 2 also shows the series-resonant IGBT-switched power supply that acts as a constant-current source to recharge the pulse generating capacitors between pulses. This switching supply effectively isolates the pulsed load from the power line, and presents a constant-current load to the power line, which minimizes EMI/EMC problems with the CLW modulator.

4. OUTPUT PULSES FROM CLW MODULATOR

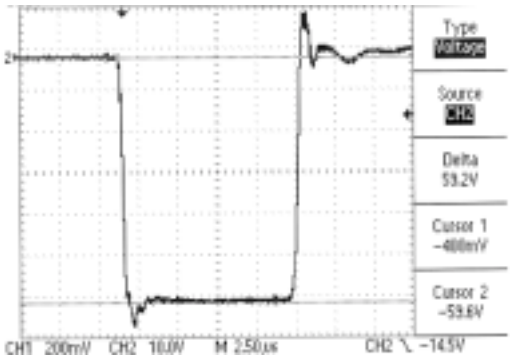

Fig. 3 60-ampere klystron current pulse from CLW modulator

Figure 3 shows a 10-microsecond wide klystron current pulse delivered by a CLW modulator. The slight current overshoot at the beginning of the pulse is charging current drawn by the stray capacitance of the load and pulse transformer terminal, and does not represent electron beam current.

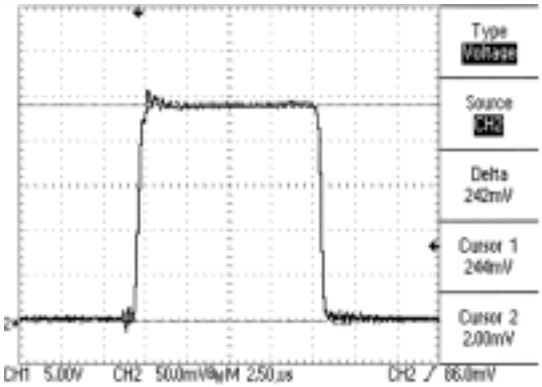

Fig. 4 RF power pulse shape from klystron, 2.4 MW peak

Figure 4 shows the resulting envelope of microwave power delivered by the klystron when the current pulse of Fig. 3 is applied to it. This pulse is flat to better than 0.5% over a 7 microsecond interval, as shown in the more detailed view of Fig. 5.

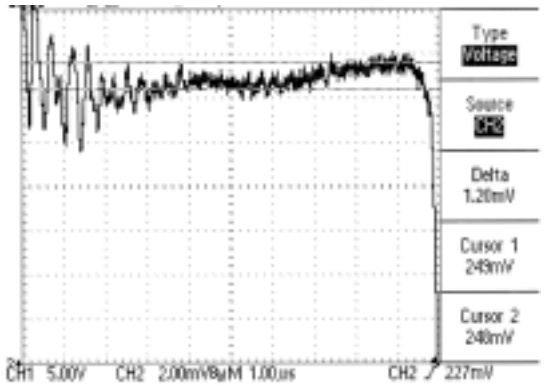

Fig. 5 Detail of the pulse-top of Fig. 4; the cursor lines are separated by 0.49 %

5. CONCLUSION

A new pulse modulator using solid-state IGBT switches has been described. This patented system employs a fractional-turn primary winding on the pulse transformer to obtain very large voltage step-up ratios without sacrificing leakage inductance and hence rise and falltimes. A simple passive R-L circuit is used to flatten the pulse top and compensate for the droop of capacitor voltage, and no PFN structure is needed. Pulse width can be varied by simply changing the width of the trigger pulse applied to the IGBTs. This modulator has proved highly reliable in daily use powering a 50 MeV linac for cancer therapy. It is also being used to power the Scanditronix on-line sterilization system, the Betaline, a 2.5 MeV e-beam system. Further information on this modulator will be provided on request by the authors, and the reader is referred to the referenced U.S. patent for detailed descriptions of the concepts involved in the CLW system.

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 ± 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 ± 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 reqires a dedicated design of superconductor and coils.

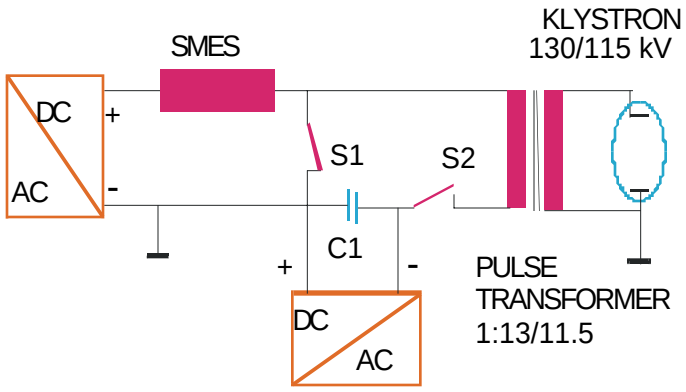

Fig. 1 Simplified Circuit of the 25 MW SMES Power Modulator (SMES 237 kJ, Capacitor 43 kJ, switch 1: Thyristors, switch 2: IGCT‘s

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 IGCTs development steps have been reqired. 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 $2x10^9$ 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	≤ ± 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	≤ ± 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).

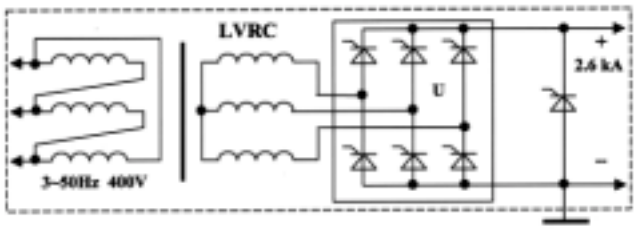

Fig. 2-1: Circuit diagram of the Low-Voltage Rectifier Cabinet (Power Supply for the SMES)

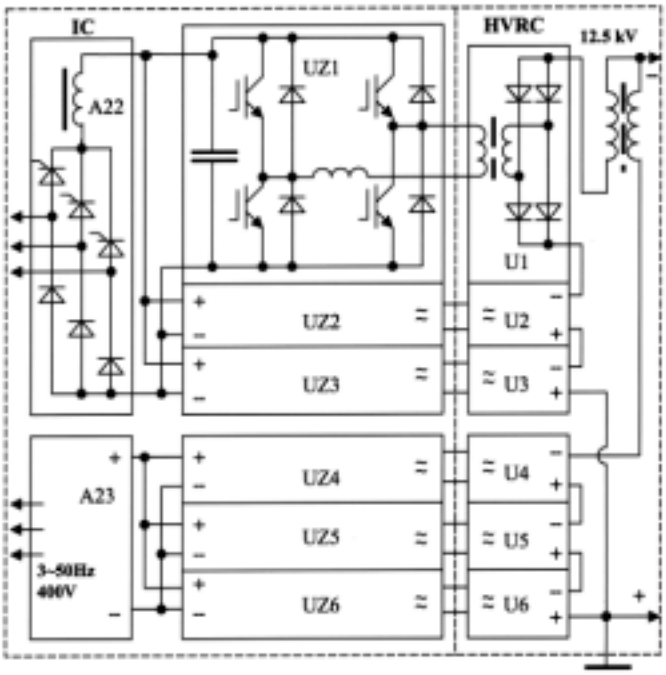

Fig. 2-2: Diagram of the High-Voltage Rectifier Cabinet and the Inverter Cabinet

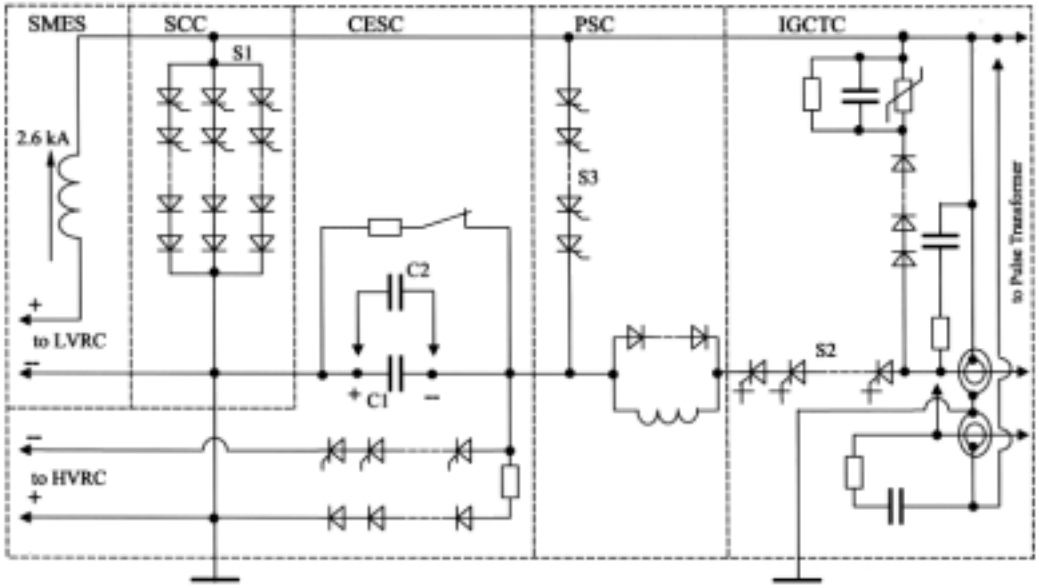

Fig. 2-3: Diagram of cabinets SSC, CESC, PSC, IGCTC and the SMES

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].

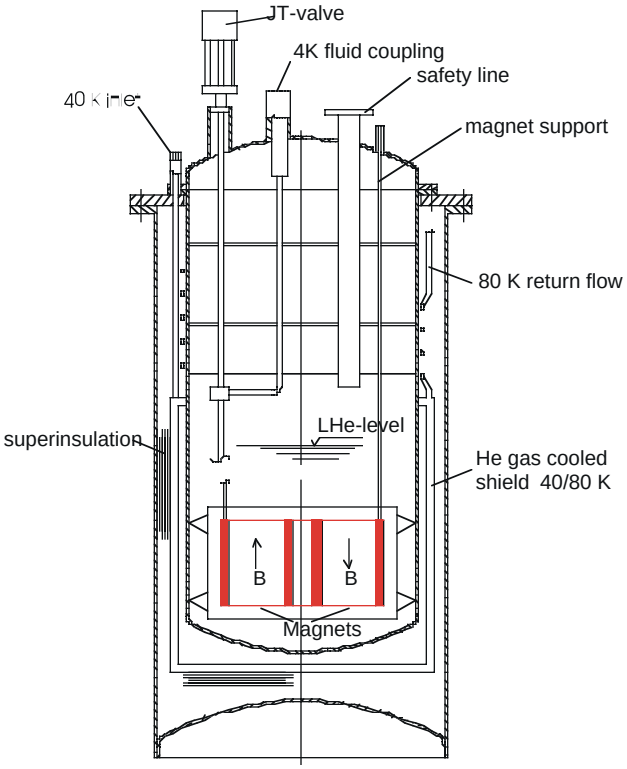

Fig. 3 SMES magnet system; 2 solenoids with antiparallel field in their cryostat (Ø 1.25 m).

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 @ 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 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 _	≥ 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	≤ ± 0.2 %
Input voltage	400 V ± 5 %
Input current, rms	< 130 A
cos _	≥ 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 $V_{anode\text{-}cathode}$ and $dV_{anode\text{-}cathode}$ /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.

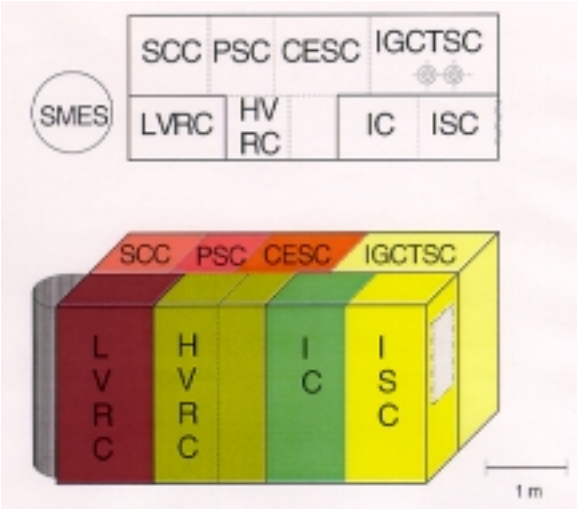

Fig. 4 Side and top view of the power parts of the modulator; partition into cabinets (*LVRC* Low-voltage rectifier cabinet, *HVRC* High-voltage rectifier cabinet, *IC* Inverter cabinet, *ISC* Input supply cabinet, *SCC* SMES commutator cabinet, *PSC* Protection switch cabinet, *CESC* Capacitive energy 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 $V_{anode\text{-}cathode} \geq 10$ kV and at 2.5 kV/µs ≥ ($dV_{anode\text{-}cathode}$ /dt) ≥ 1.2 kV/µs. 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.

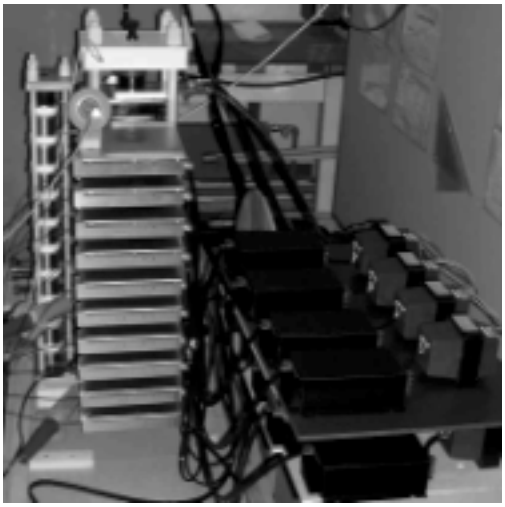

Fig. 5 View of the IGCT switch during pre-testing on the manufacturer‘s site.

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.

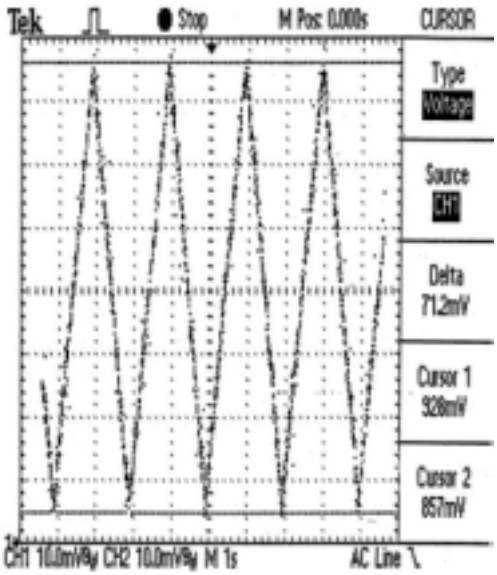

Fig. 7 Current in the load (46 mH). I_{max} = 650 A, Δ I = 50 A, T = 1 s

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:

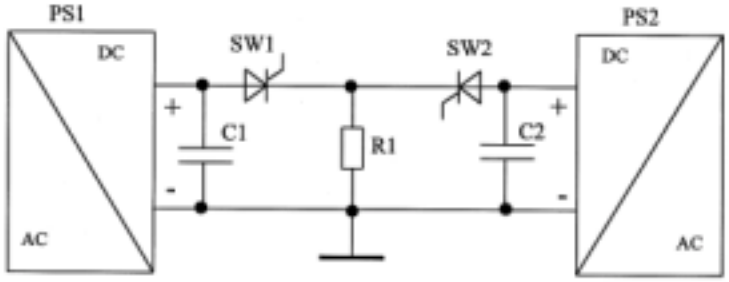

Fig. 8 Simplified circuit diagram for the dynamic test of the High-Voltage Power Supply (HVPS-DTA)

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 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 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:

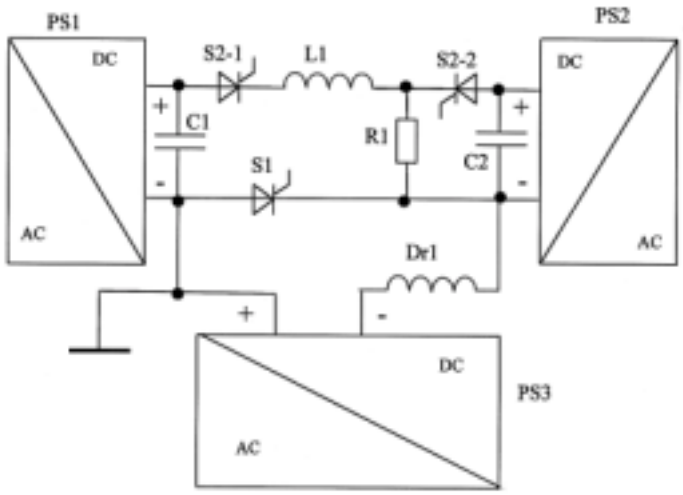

Fig. 9 Simplified circuit diagram for the 1 MW modulator test arrangement (PS1 is the modulator high-voltage power supply, PS3 is the modulator low-voltage power supply, PS2 is an extra power supply made available by ESTEL, Dr1 is a normal conducting inductance simulating the SMES, L1 replaces the leakage 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.

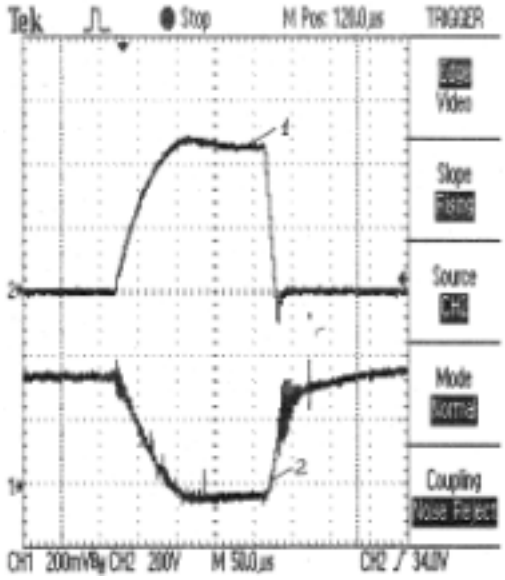

Fig. 10: Currents in the thyristor switches S2-1 (trace1) and S1 (trace 2) of the 1 MW MTA

(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.

ACKNOWLEDGEMENTS

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A Long Pulse Solid State Induction Modulator

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Stanford Linear Accelerator Center

Abstract

The Next Linear Collider accelerator is developing a high efficiency, highly reliable, and low cost pulsed-power modulator to drive the NLC 500KV, 230A X band klystrons. The induction of fractional turn transformer is most applicable for short pulse width of less than 1.5 microseconds due to the size of the induction cores involved. This paper will cover the techniques SLAC is developing to use the induction modulator in longer pulse operation of up to 15 microseconds. The 3 microseconds SLAC design as will, as the proposals for wider pulse application will be discussed.

1.0 Modulator Design consideration

The Next Linear Collider accelerator proposal at SLAC has selected the Solid State Induction Modulator approach for its X band klystrons because of its high efficiency, highly reliable, and low cost. The major difficulty with the conventional PFN type modulator use at SLAC for the Next Linear Collider (NLC) is the efficiency of the modulator for short pulse operation. The leakage inductance for the pulse transformer and the stray inductance of the switching circuit inherently limit the rise and fall time of the klystron voltage waveform. To reach the efficiency goals of > 75% for the modulator for the NLC it is necessary to have a rise and fall time of the klystron voltage pulse of less than 200 nsec. It is extremely difficult to obtain a fast rise time and high efficiency with a PFN modulator.

1.1 NLC Booster modulator

The NLC solid-state induction modulator program so far has been directed the main accelerator sections, which has the majority of the klystrons. In addition to the main accelerator there is the booster Accelerators. Which requires additional modulator to drive two klystrons at a time.

	Frequency MHz	Present #	Present msec	One Proposal # *	One Proposal msec
L-band	1428	30	5	15	5.5
L-band	1482			15	16.5
S-band	2856	157	4.5	50	4.5
S-band	2856			15	13.5

* Assumes two klystrons per modulator

The present proposal requires 5 µsec pulses with proposed designs up to 17 µsec. To accomplish these requirements a different approach was needed to the modulators to utilize the induction solid state approach.

1.2 The Present Induction Modulator

The present modulator topology selected for the NLC modulator is similar to an induction accelerator. It consists of a large number of single turn induction cores each driven by its own solid-state switch. Due to the inherent low inductance of such a structure the secondary will have three turns. The resulting total leakage inductance at the secondary is extremely low (<20 µhy). The major part of the leakage induction is in the multiple primary side connections and drivers. The use of three turn secondary fractional turn transformer combined with two high current IGBT allows for the driving of 8 klystrons with one modulator or approximately 1000 megawatts of power for 3 µsec see Figure 1.

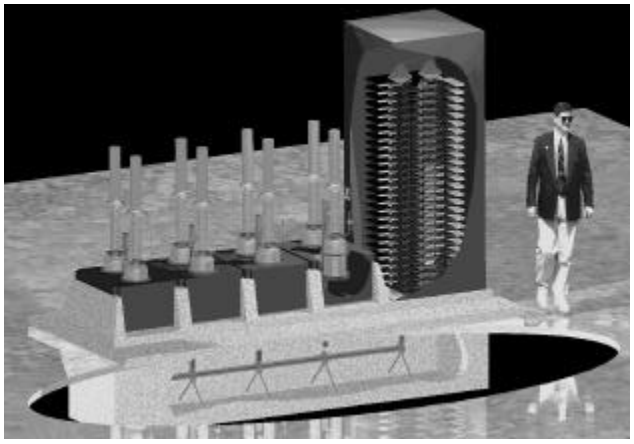
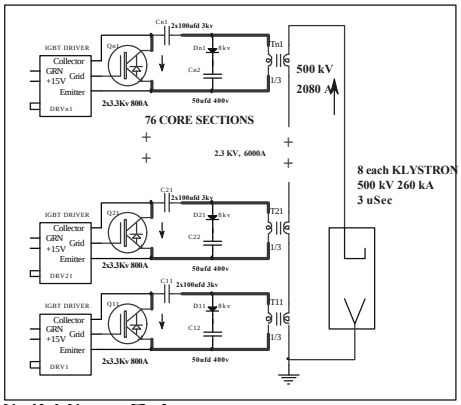


Figure 1. Induction Modulator Artistic Rendition

To obtain 500 kV for 3 µsec (1.5 volt seconds per turns) with a transformer, a three turns secondary required a large magnetic core cross sectional area. To drive the core without using a matched PFN requires a switch that can not only turn on fast at high power levels but also turn off. Switching devices now exist in the form of IGBT (Isolated Gate Bipolar Transistors). EUPEC FZ800R33KF1 was used. Figure 2.



1.3 Solid State Drive

The Core driver is simple consisting of an IGBT, a DC charge capacitor in series with the IGBT driving the individual magnetic core. A capacitor with fast diode is used across the core to absorb the reflected energy from stray inductance under normal and fault conditions as well as the current if the one of IGBT is turned on later or off earlier then the other IGBTs. A pulse reset of the core is used to insure that the core is totally reset before the next pulse. The energy storage capacitor is charged through the transformer core. Figure 3.

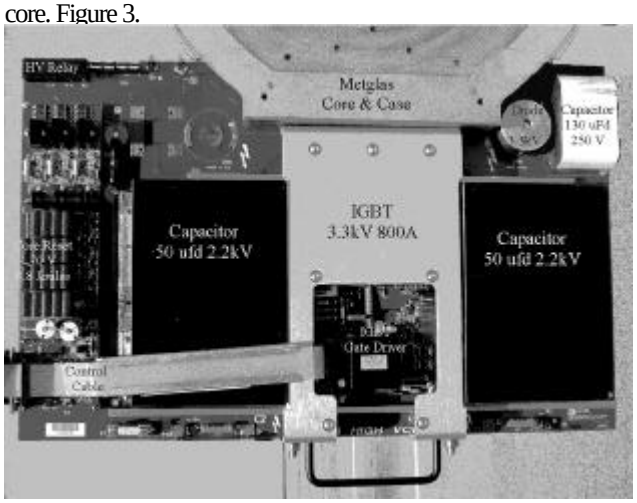


Figure 3. IGBT Drives boards

The modulator consists of two driver boards with one 3.3 kV IGBT per board. The driver boards are PC Board and arranged so that they can be plugged into the transformer core for easy replacement. Figure 4.

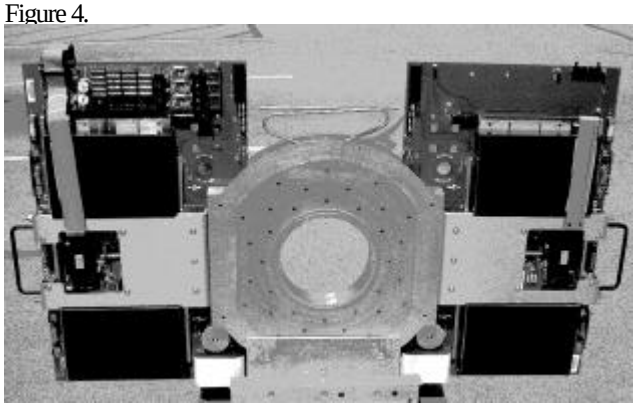


Figure 4. PC Board Core Driver circuit

The NLC solid-state induction modulator R&D program is divided into three Stages.

1) Full core stack 76 cores with three turns to drive full 500 kV into water load and then full current into 4 each 5045 klystrons at full repetition rate for a full load testing.
2) A model using 10 cores and a standard pulse transformer to drive a SLAC 5045 klystron, which is discussed in this paper.
3) A design for manufacturability prototype for 8 klystrons.

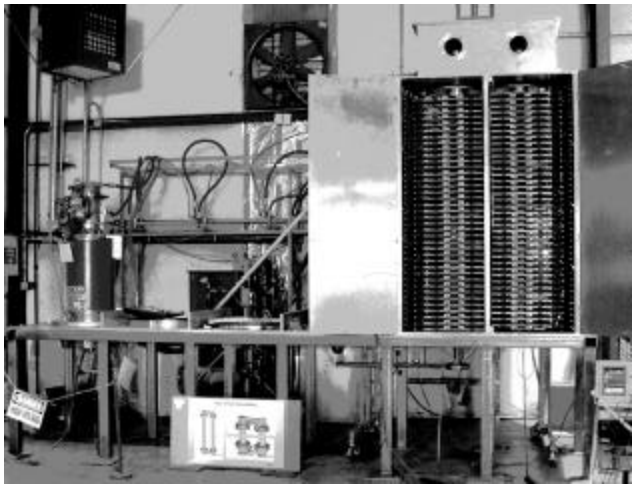


Figure 4. 4ea 5045 modulator

1.4 Model of Induction modulator

To obtain early experience with the solid state induction modulator driving a klystron load, and explore use of the induction modulator for single or two klystron operation, a model program has be developed to utilise the Induction modulator to drive one of the existing SLAC 5045 Klystrons. A stack of 10 each modulator cores driving and the existing 5045 klystron 15/1 pulse transformer would allow early testing of the induction modulator design concept. Operation the 10 core stack at 20kv and 4400 amps well drive the Klystron to 288 kV 315 A. Figure 5.

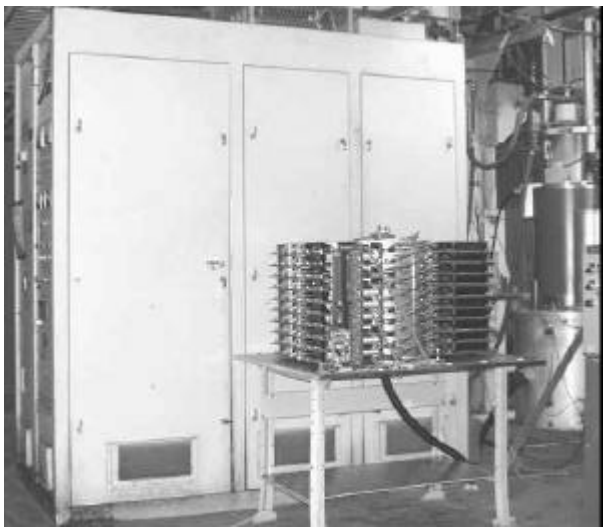


Figure 6. Table Top Induction Modulator

The model has operated to demonstrated that the concept was workable Preliminary results are shown in Figure 7. As can be seen the rise time is primarily determined by the leakage inductance of the pulse transformer and the connection inductance and therefore the induction modulator has little efficiency advantage over the thyratron modulator.

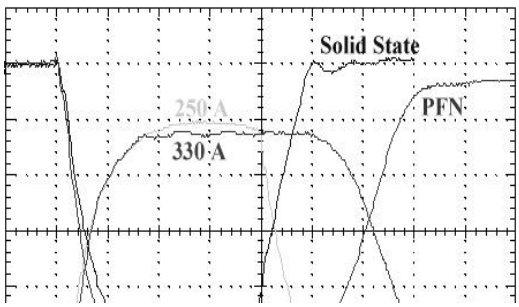


Figure 7. Model Preliminary Waveform

1.5 Wide pulse Induction modulator

For wide pulse applications the cores needed to utilize a small number of secondary turn in prohibitive expensive, so the tabletop approach is not feasible and therefore an improved concept is needed. What is needed is a low inductance connection to the primary of a conventional pulse transformer and the maximum of core area to reduce the number of turns in the secondary to reduce the secondary leakage inductance. The SNS project has had manufactured some Nanocrystalline core (29" x 16" x 3.5" thick) which could be used as the bases of an improved concept in induction modulator design. The cores have high Mu, low losses and large Volt-Second capability.

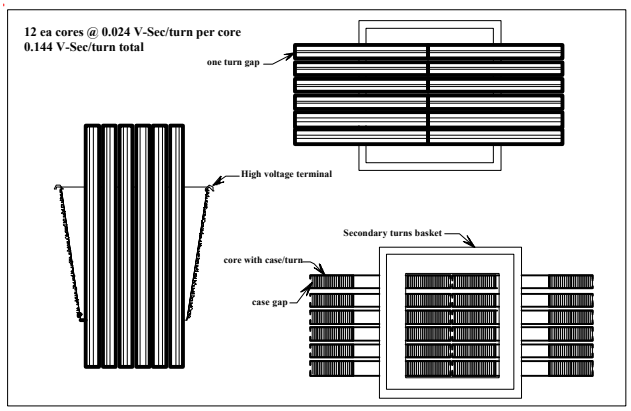
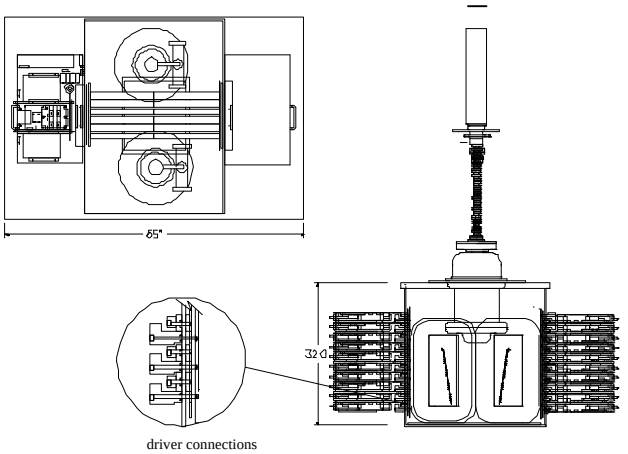


Figure 8 Pulse transformer configuration

By combining the pulse transformer with the IGBT drivers a hybrid induction modulator can be designed. The pulse transformer would consist of the standard Strangeness type secondary basket with the low leakage inductance encased single turn primary of the induction modulator. The secondary and core would be in oil for the high voltage standoff capability with the primary connections penetrated the tank walls through oil seals to a strip line to which the IGBT drivers can be connected.



1.6 specifications

1) Output 380kv 500A @ 15 µsec.
2) Cores 12 ea cores @ 0.024 V-S/Turn
3) Total Core 0.144 V-S/Turn total
4) Drive 8.4kV/turn @ 15 µsec
5) Turns 2 Series core, 60 Turn secondary
6) Drive cards 12 each 4.2kV drivers @ 3000A
7) Impedance ~700 µhy, 1000 ohms,
8) Rise time t~0.7 µsec

24 Drivers		0.144 volt-sec		380,000 volts	
Cores per driver series	**Drivers in Parallel**	**# cores in series**	**Volts/ turn**	**Pulse Length**	**# of turns secondary**
12	**24**	**1**	**4,000**	**36**	**95**
6	**12**	**2**	**8,000**	**18**	**48**
4	**8**	**3**	**12,000**	**12**	**32**
3	**6**	**4**	**16,000**	**9**	**24**
2	**4**	**6**	**24,000**	**6**	**16**
1	**2**	**12**	**48,000**	**3**	**8**

The same transformer/core configuration can be used to drive pulses from 3 µsec to 36 µsec by different number of series section.

1.9 Conclusions

The induction modulator can be made to give a high efficient, fast rise time for longer pulse by using the low inductance IGBT driver and the multiple turn conventional pulse transformer combined in a new way.

***Work supported Department of Energy contract DE-AC03-76SF515**

SOLID-STATE SWITCHING MODULATOR R&D FOR KLYSTRON

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Abstract
KEK has two programs to improve reliability, energy efficiency and costs of klystron modulators. The first is to improve a line-type modulator by use of a solid-state switch that can be used instead of thyratoron. We have developed a solid-state switch which consists of 15 SI-thyristors stacked in series. The switch has been successfully operated at 45 kV hold-off voltage, 6000 A peak current, 6 μs pulse-width and 25 Hz. The second program is to develop a new hybrid modulator with numbers of individual solid-state pulse modulators which are stacked in a voltage-adder configuration for the Japan Linear Collider(JLC). To study this type of modulator, a ten-stage test modulator has been built and successfully tested.

1. INTRODUCTION

The power efficiency, reliability and costs of the klystron modulators are extremely important. their improvements are a major challenge in a large scale linear collider such as the JLC[1]. We have improved the performance of klystron modulators using a solid-state technology. In this paper, we will describe the solid-state switch development for a line-type modulator, and the JLC modulator design and the experimental results of the test modulator.

2. SOLID-STATE SWITCH DEVELOPMENT

To improve the reliability of the line-type of modulator, we have developed a solid-state switch to replace the thyratron tubes. The solid-state switch has been designed and built using SI-thyristors and tested with a line-type modulator.

2.1 45kV Solid-State Switch

2.1.1 Switching devices

The Static Induction SI-thyristror is suitable for the switch device because of its high-power handling and fast turn-on capabilities. We have investigated the NGK RT103N 4 kV reverse conducting SI-thyristor(including a freewheeling diode within a press-pack ceramic housing). To evaluate the performance of this device, the fast turn-on characteristics of five-stack of SI-thyristor which was connected in series were studied in a very low-inductance circuit. By using a coaxial structure, the residual inductance was successfully reduced to less than 136 nH. When an anode voltage of 15 kV was applied, a maximum peak current of 10 kA, dI/dt of 110 kA/μs, and switching time of 128 ns were obtained. The switching time is the time required for the anode voltage to decrease to 10% of its maximum value. It was confirmed that the turn-on characteristics of the SI-thyristors are comparable to the thyratorns.

2.1.2 Switch assembly

A simplified circuit diagram of the solid-state switch is shown in Fig. 1. Each circuit card assembly consists of a SI-thyristor, a resister capacitor network, break-over diodes and a gate-driving circuit. The break-over diodes protect the devices whenever the voltage across the circuit card assembly exceeds the rated voltage of the diodes. This method protects the stacks from over-

voltages that would result in the destruction of all the devices. Both the trigger and power cables for each card were isolated from high-voltage through ferrite core transformers.

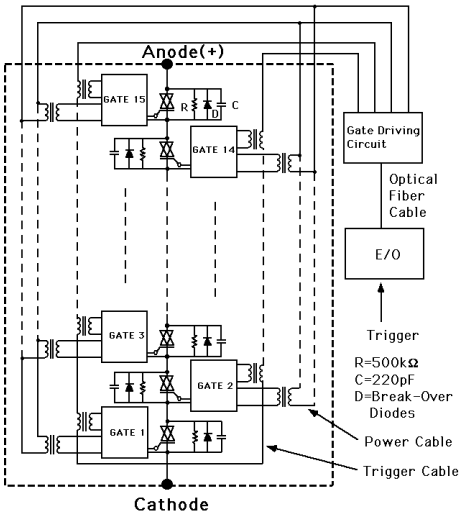

Fig. 1 Simplified circuit diagram of 45kV Solid-State Switch.

Table 1

45 kV Solid-State Switch Specifications

Device	SI-thyristor NGK:RT103N(4kV)
Series Connection	15 devices
Insulation	Oil
Cooling	Forced oil cooling
Size	Cylindrical type 550 mm x 300 mm

The SI-thyristors are normally-on type devices. To make a hold-off state, a bias voltage of –10 V is applied between the gate and cathode electrodes. To make a hold-on state, a pulse with a voltage of 160 V is applied. The performance of the gate circuit influences the fast turn-on characteristics. As a fast switch for the gate pulse, a specially designed low inductance MOSFET unit is used. The maximum gate current reaches 200 A during switching. The gate circuit is implemented in the closest possible proximity of the device to reduce the total inductance.

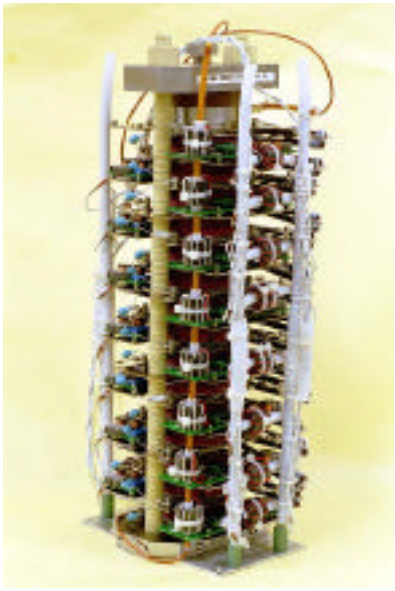

Fig. 2(a) 45 kV Solid-State switch assembly

Fig. 2(b) Gate driving circuit and SI-thyristor.

The stack assembly and SI-thyristor with gate circuit are shown in Figs. 2(a) and 2(b). The stacked devices are housed in a single cylindrical tank with a diameter of 300 mm and a height of 550 mm. The tank is filled with oil for insulation and cooling of the internal devices.

2.2 Test Results

2.2.1 Test circuit

The performance of the solid-state switch was studied with a line-type 5045 klystron modulater at KEK Accelerator Test Facility, ATF. Figure 3 shows the circuit diagram of the modulator. The klystron modulator consists of a high-voltage charging power supply, PFNs, a solid-state switch and a conventional 1:15 pulse transformer. The inverter power supply charges the PFNs up to 45 kV with a charging time of 19 ms. After a hold time of 5 ms, the switch is triggered and the output pulse is applied to the SLAC 5045 Klystron. The anode voltage of the switch was measured with a Iwatsu's high-voltge probe (model HV-60) and the anode current of the switch was measured with a Pearson's current transformer (model 3025) which was inserted in a return line of the PFNs.

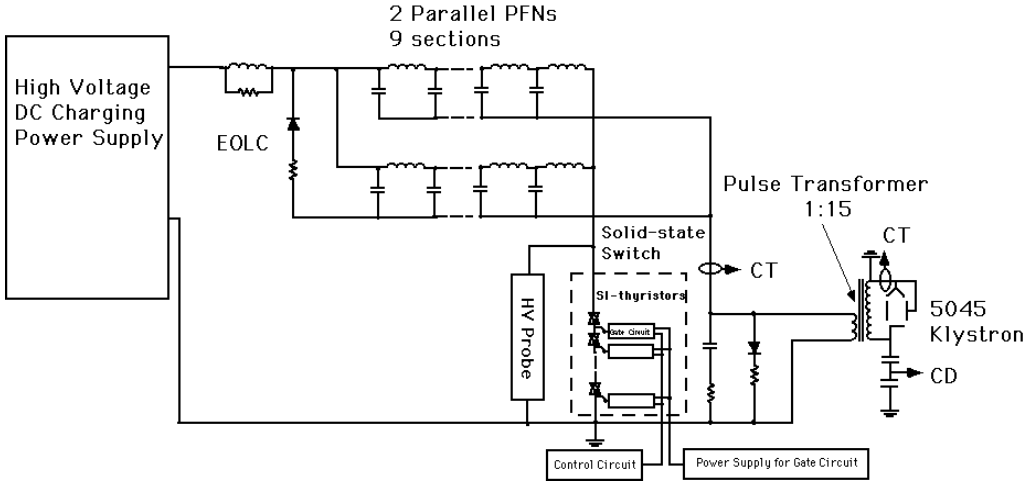

Fig. 3 Simplified circuit diagram of the klystron modulator.

The test was made at 25 Hz, limited by the charging capability of the inverter power supply. Figure 4 gives the typical switch voltage and current waveforms at a PFN voltage of 45 kV. A peak current of 6000 A, di/dt of 10 kA/μs and a pulse-width of 6 μs were obtained.

2.2.2 Switching waveform

To compare this solid-state switch to a thyratron switch, the Marconi CX1536 thyratron switch was also tried in the modulator. Figure 5 shows the typical switch voltage and the current waveforms of the thyratron switch at a PFN voltage of 45 kV. The measured switching times of the solid-state and thyratron switches were 208 ns and 40 ns, respectively. While the rise time of the thyratron switch was five times faster than the solid-state switch. The rise time of both the switch currents was similar, because it is limited by the time constant of the output circuit including the pulse transformer. However, it is shown that the switching loss of the solid-state switch is higher than the thyratron, because of the difference of the switching time.

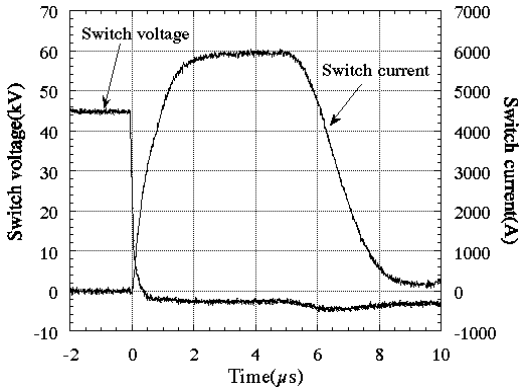

Fig. 4 Switch voltage and current waveforms with the solid-state switch.

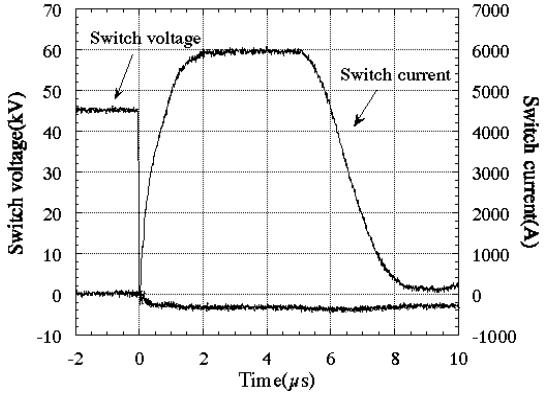

Fig. 5 Switch voltage and current waveforms with the thyratron switch.

Figure 6 shows the klystron voltage and current waveforms at a PFN voltage of 45 kV with the solid-state switch. A peak current of 376 A, a peak voltage of 361 kV and a pulse-width of 6 μs were obtained. The pulses with a peak power of 136 MW were switched by the solid-state switch.

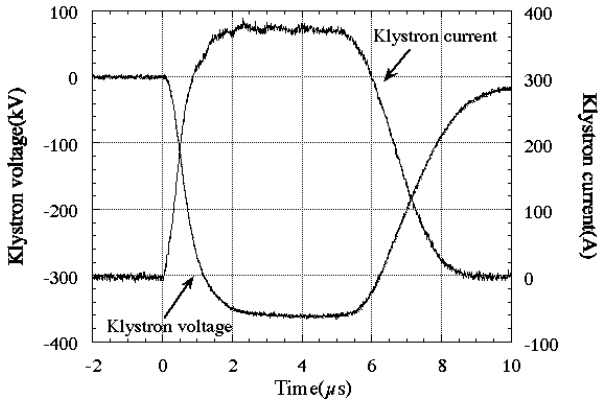

Fig. 6 Klystron voltage and current waveforms with the solid-state switch.

2.2.3 Switch losses

The switch losses were measured by calorimetry which is a reliable method. A cooling system of the solid-state switch is a simple closed-loop system consisting of a oil tank, a pump, a flowmeter and a radiator. The pump has a rated delivery of 4.7 l/min. The temperatures of both the inlet and the outlet of the tank were always monitored and recorded by a pen recorder during operation. Therefore, the switch losses can be calculated from their temperature differences and the flow rate of the cooling oil. In this system, the temperature difference of 1°C corresponds to a switch power loss of 130 W. The switch losses were measured at a PFN voltage of 20, 30, 40 and 45 kV. The results are summarized in Table 2. At a PFN voltage of 45 kV, the temperature difference between the inlet and outlet was measured to be 8.5°C, which corresponds to a switch loss of 1.1 kW. It is also found that the switch loss is proportional to the stored energy in the PFN.

Table 2
Switch losses versus PFN voltage

PFN voltage (kV)	PFN Stored energy (J/pulse)	Switch losses (J/pulse)	Details of switch losses		
			Balance resisters (J/pulse)	Gate circuits (J/pulse)	Devices (J/pulse)
20	162	9.4(5.8%)	0.98(10.5%)	0.8(8.5%)	7.6(81.0%)
30	365	21.3(5.8%)	1.92(9.0%)	0.8 (3.8%)	18.6(87.2%)
40	648	32.8(5.1%)	2.77(8.5%)	0.8(2.4%)	29.2(89.1%)
45	820	41.1(5.0%)	3.10(7.4%)	0.8(2.4%)	37.2(90.7%)

A value in parentheses of switch losses column shows the ratio of energy to the PFN stored energy. A value in parentheses in details of switch losses column shows the ratio of each loss energy to switch losses.

The switch losses take place in balance resisters, gate circuits and devices. The losses in the balance resisters are calculated from ohmic loss during the PFN charging. The losses of the gate circuits are calculated from the measured current and voltage of power line supplied to them. By subtracting these contributions from the measured switch losses, the losses in the devices are obtained. It is found to be 41 J/pulse at 45 kV. This value corresponds to 5% of the total PFN stored energy, with about 90% of this loss dissipated in devices themselves. Therefore, these switches still need to be improved to further reduce losses. However, it has been confirmed that 45 kV solid-state switch has a switching capability comparable to a thyratron.

2.2.4 Future program

The main problem at the initial stage of the performance test was a failure of device break-down which was found when the klystron broke down in 45 kV PFN operation. In order to investigate this failure, we have inspected the devices and performed a break-down experiment using a model stack. From this investigation, it was found that the SI-Thyristor is damaged when the reverse current exceeds 4 kA. To protect the devices, the reverse diodes will be connected to the solid-state switch in parallel. To investigate the long-term reliability of the modified switch, it will be installed and operated in the modulator to collect lifetime data. The SI-thyristor will be also improved to reduce the turn-on and conduction losses.

3. HYBRID MODULATOR FOR JLC

We are developing a new hybrid modulator with numbers of pulse generator stages in series and a pulse transformer for the JLC. To study the modulator of this type, we have built a ten-stage test modulator and performed a preliminary test.

3.1 Modulator Design

The klystron modulator for the JLC is required to produce a 500 kV, 530 A, 1.5 μs flat-top pulse to drive a pair of 75 MW PPM-klystrons[3]. Table 2 shows the specifications of the JLC klystron modulator. The JLC hybrid modulator uses multiple solid-state modulators(cell-modulators) which are stacked in a voltage-adder configuration and a 1:5 primary split pulse transformer. Figure 7 shows the basic circuit diagram of the JLC klystron modulator. Each cell-modulator is a direct switching modulator which is capable of generating a 2 kV pulse at 2650 A. Some cell-modulators are used as a waveform control modulator to obtain output waveform with a wide flat-top. The modulator unit, which consists of 26 cell-modulators(operating at 2 kV per cell) stacked in series and which generates a 50 kV pulse at 2650 A, drives one of the primary circuits of the pulse transformer. The other unit also drives the other primary circuit. The pulse transformer provides the klystrons with a 500 kV pulse. The inverter charging system provides a DC power to each cell-modulator.

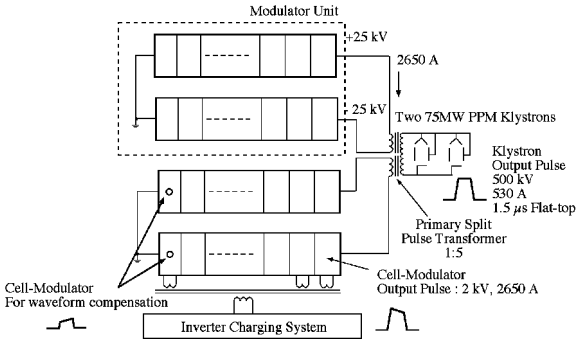

Fig. 7 Basic circuit diagram of JLC Klystron Modulator.

Table 2
Specifications of JLC Klystron Modulator

Parameter	Value
Peak Klystron voltage	500 kV
Total peak current	530 A
Flat-top Pulse Duration	1.5 μs
Pulse top flatness	2%
Energy Efficiency(Goal)	70%
Repetition rate	150 Hz

3.2 Cell-Modulator

A unit of the cell-modulator consists of an energy storage capacitor, a solid-state switch which turns on and off the circuit. It also includes a bypass diode which protects the solid-state switch and isolates the circuit from all other stages. The cell-modulator works as follows. The capacitor is initially charged through a charging transformer. When the switch is turned off as shown in Fig. 8(a), the cell-modulator is completely separated from output circuit, and the output current flows through the bypass diode. When the switch is turned on as shown in Fig. 8(b), the current in the diode is commutated. The energy storage capacitor is now connected in series with output circuit, and the charging voltage of the energy storage capacitor is added in the output circuit. Both the pulse width and timing of the output pulse of the cell-modulator is determined by controlling the gate trigger of the switch.

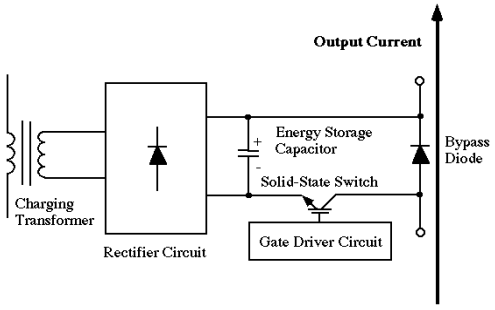

Fig. 8(a) Cell-modulator when the switch is turned off.

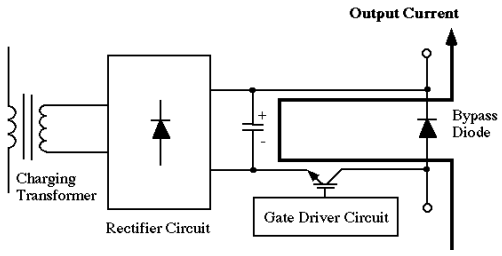

Fig. 8(b) Cell-modulator when the switch is turned on.

3.3 10-stage Test Modulator

3.3.1 Circuit

Figure 9 shows the circuit diagram of a 10-stage test modulator. It consists of 10 cell-modulators which are stacked in series, a charging system to provide a DC power to each cell modulator, and a resistor load. The design parameters of the test modulator are shown in Table 3. A photograph of the stack assembly with a resistor load is shown in Fig. 10.

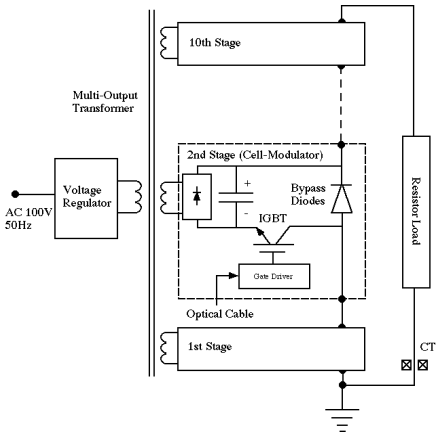

Fig. 9 Simplified Schematic of 10-stage Test Modulator Circuit.

Table 3
Main parameters of 10-stage test modulator

Parameter	**Value**
Output Voltage	20 kV
Output Current	2.7 kA
Pulse Width	3 μs
Number of Cell-Modulator	10 stages
Repetition Rate	5 Hz

A photograph of a cell-modulator is shown in Fig. 11. An Insulated Gate Bipolar Transisitor(IGBT), MITSUBISHI CM1200HB-66H was used as a solid-state switch. The CM1200HB-66H is rated at 3.3 kV peak voltage and 1200 A average current. The gate drive circuit for each IGBT receives its trigger pulses from a trigger control circuit through optical cables. The capacitance of the energy storage capacitor was determined to be 17.3 μF in order to keep its voltage drop within 10%. The capacitor of each cell-modulator is charged through a multi-output transformer. The output voltage of the modulator is regulated by adjusting the charging voltage of each cell-modulator. The output current of the modulator was measured with a Pearson's current transformer.

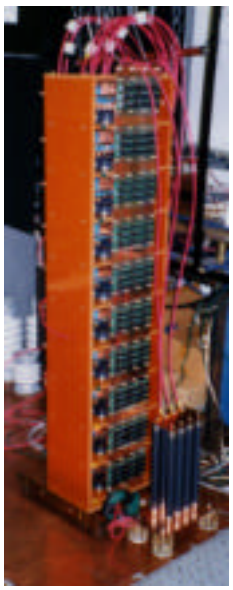

Fig. 10 10-Stage Test Modulator.

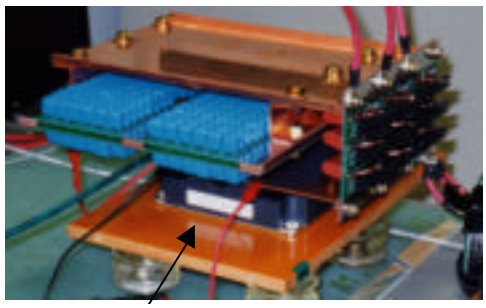

Fig. 11 A Cell-Modulator.

3.3.2 Output waveform[4]

Figure 12 shows an example of the waveform of the output current through the 5.5 Ω resistor load. In this test, only 6 stages were used and each stage operated at a voltage of 2 kV. A pulse with a peak voltage of 12 kV, a peak current of 2160 A , a rise time(10-90%) of 630 ns and a fall time(10-90%) of 450 ns was successfully generated. The output pulse has a droop of approximately 10%, which is consistent with the expected droop in the energy storage capacitor.

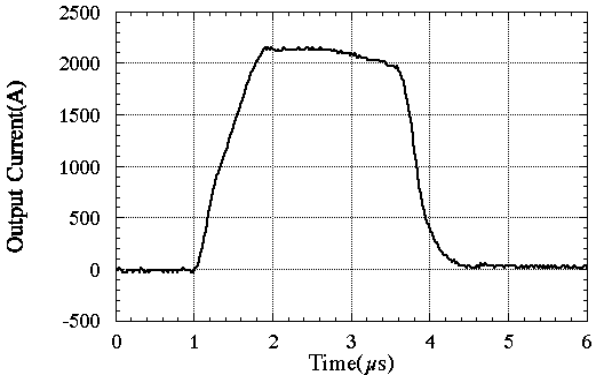

Fig. 12 Output current waveform.

3.3.3 Waveform Control

We have tried to control the output waveform with appropriate triggering of cell-modulators. In this test, a set of 10 cell-modulators(stages) was operated at a voltage of 1 kV with a 4.1 Ω resistor load. The first and second stages were used as a waveform compensation modulator. In order to obtain the maximum flat-top width, the trigger timings for the first and second stages were adjusted. Figure 13 shows the trigger timing for each stage. Figure 14 shows the output current waveform at the resistor load, with and without waveform compensation. The output waveform without compensation was drooped with no flat-top but the compensated waveform became rectangular with a wide flat-top. From this result, we found that individual trigger control for cell-modulator enables us to produce excellent waveform with a wide flat-top and it improves a power efficiency.

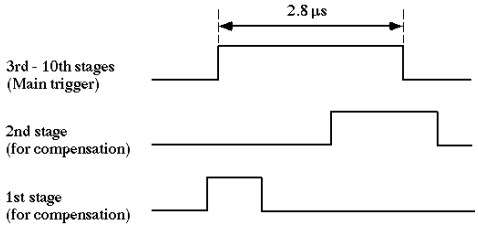

Fig. 13 Trigger timing chart.

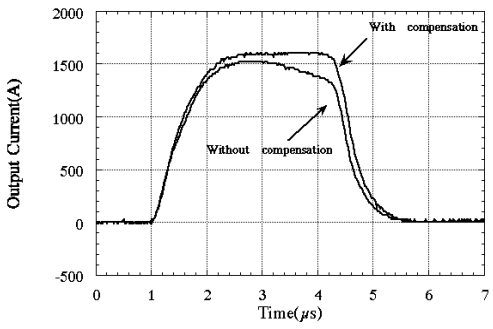

Fig. 14 Output current waveforms with and without compensation.

3.4 Future program

Testing of the 10-stage test modulator has just stated. Full power testing with a peak voltage of 20 kV and a peak current of 2.7 kA will soon be performed. The high-power testing including a primary split pulse transformer will be also carried out to study the modulator performance. We also plan to build a full prototype modulator which is capable of driving two 75 MW PPM-klystrons at 100 Hz repetition rate by 2002.

ACKNOWLEDGEMENTS

I would like to thank Director General Professor H. Sugawara and Professor K. Takata of KEK for the support under the R&D program.

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20-MW LONG-PULSE-KLYSTRON MODULATOR

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Abstract

For the TESLA Test facility (TTF) at DESY Hamburg a long-pulse klystron modulator has been designed to drive the new 10MW-multibeam klystron TH18101. The main modulator parameters are: primary voltage amplitudes < 12 kV, current amplitudes < 1.7 kA, pulse length < 1.7 ms at a repetition rate < 10 Hz. The main goal of the development at PPT is to reach at a reliable and cost-effective design to allow for the production of about 750 TESLA modulators. This can best be achieved by reducing the construction requirements and focussing on components widely used in industrial applications . Based on the first design of FERMI Lab the main features of the new pulse modulator are:

1) a rugged , compact IGCT-switch stack. with seven 4.5-kV IGCTs from ABB , integrated gate units, small snubber circuits and a 4-kA current turn-off capability.
2) a volume optimized storage capacitor construction using high energy capacitors with self-healing segmented PP-foil technology.
3) a 300-kW-switched mode power supply with a new regulating system to avoid the generation of powerful subharmonic disturbances back into the line.

First results as well as cost and lifetime estimations are presented.

TEST RESULTS OF A COMPACT CONVENTIONAL MODULATOR FOR TWO-KLYSTRON OPERATION

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Abstract
Modulator technology has not advanced greatly over the last 30 years. Today, with the advent of the High Voltage, High Power IGBT there are several approaches for a solid state ON/OFF switched modulator. Klystron and accelerator technology is forcing voltages and peak powers higher such as the demand for 500 kV and 500 amperes peak to power two X-Band klystrons. Conventional technology (line-type modulators) were never overly concerned about rise time and efficiency. A few years ago, the klystron department at Stanford Linear Accelerator Center (SLAC) undertook an investigation into what could be done in a conventional modulator at 500 kV. We have reported on test bed measurements and shown both conceptual and hardware pictures during design and construction. We have now completed the modulator tank

1. INTRODUCTION

The Two-Pack conventional modulator was originally conceived of to power the klystrons in the main linac of the Next Linear Collider (NLC). The objective was to design a conventional modulator with maximum possible efficiency, small size and reliable. The first obstacle to high efficiency in a narrow pulse width, very high voltage modulator is waveshape, usable flat top energy to total pulse energy. Coupling between the Pulse-Forming-Network (PFN), the thyratron switch and the pulse transformer primary as well as the pulse transformer itself have a major impact on this waveshape and overall efficiency.

The NLC is being designed using a Solid-State Induction Modulator. The klystron department decided to complete the Two-Pack design on a low priority to use as a test position for klystron development or life testing.

2. DESIGN FEATURES

2.1 Electrical

Early analysis centered on PFN charging voltage and pulse transformer ratio. It was believed that the charge voltage should be less than 100kV and to obtain a reasonable primary leakage inductance a maximum transformer ratio of 1:14 should be used. Therefore, a power supply of 80kV was chosen. This also fit into a reasonable three gap thyratron design. There would be two parallel 10-section PFN's, each with a mutually coupled inductor. Careful attention was given to isolate grounds and control the current paths to reduce noise. The primary discharge path between the thyratron, PFN and the pulse transformer would be made closely coupled with low inductance. Additional pulse isolation would come from making the connection between the cathode of the thyratron and tank ground inductive. Thyratron heater and reservoir leads and the core bias would all be common mode inductor filtered and capacitively bypassed to ground. A double pulse scheme was chosen to trigger the thyratron, instead of using a DC keep-alive circuit and the trigger leads would be filtered for common mode rejection.

The pulse transformer secondary circuit ground return would be isolated, and tied into the tank at a single point with a short return to the klystrons. The two sets of klystron heater leads would be individually bypassed and common mode filtered to keep all pulse noise inside the tank. Voltage and current monitoring signals would also require common mode filters.

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2.2 Mechanical

The design approach was for a single oil tank, which would house the thyratron, PFN's and the pulse transformer as well as room to install the klystrons. A horizontal, round tank configuration was chosen because of its inherent strength to support the klystrons and their lead shielding and ability to withstand evacuation before backfilling with oil. The challenge is always cost and ease of assembly and maintainability. The components were designed on a platform that would roll into the end loaded tank. The pulse transformer was mounted on a plate, which is electrically and mechanically isolated (shock mounts) from the main platform to control current paths and reduce noise from transformer vibration. Wiring was kept to a minimum and the low inductance coupling is short and made using aluminum sheet metal. The thyratron was designed to be removable from the top of the tank through a large port also used for expansion. This design shielded the thyratron, made the path somewhat coaxial and is completely plug-in including the anode connection.

3. FINAL TANK ASSEMBLY

The pictures of Figures 1 and 2 depict the final assembly of the Two-pack tank. In Figure 1, picture 1 at the upper left is the tank shell with a 5045 klystron mounted on the tank. There is a socket for second klystron on the right. The slide-in chassis can be seen inside the tank. On the right side of the tank is one of the feed thru bulkheads for the auxiliary supplies and viewing cables.

Figure 1. Left: Modulator Tank w/ 5045 klystron, Right: Multi-lam pins for ground

When the chassis is in place in the tank, a set of multi-lam sockets mounted on the inner chassis for grounding of the transformer secondary mates with the pins shown in the picture on the upper right. The pins are made floating to ensure that they properly mate with the sockets. The final ground is made by the short braid connections.

When the main chassis is extended from the cabinet the inside configuration can be seen. The picture on the left in Figure 2 looks at the inter-connect between the PFN, the pulse transformer and the thyratron. The bottom mounting plate of each of the PFN's is connected together and to the pulse transformer primary with a wide strip of sheet aluminium. The low side of the pulse transformer primary connects directly to the cathode of the thyratron with another wide strip of aluminium. The high voltage power supply connection is shown mounted on

standoffs above the low side of the pulse transformer. The picture on the right, in Figure 2, is of the thyratron chassis and anode housing. The anode connection from the can is on standoffs from the thyratron chassis cathode plate. The PFN coils directly connect to this anode ring. The legs supporting the cathode plate are sitting in ferrite toroids as a method of pulse isolation. The thyratron cathode has a DC connection to ground. An inverse diode is mounted across the thyratron.

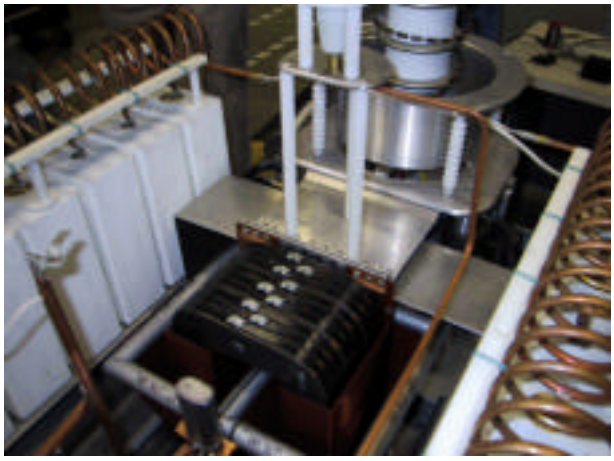

Figure 2. Left: Primary Discharge coupling; Right: Thyratron deck and anode housing

The tank can be used with either a direct charging power supply of up to 80 kV or a resonant charging supply. The charging diode is located inside of the tank. We are connected to a resonant charging supply in Test Stand 03 for testing and operation.

4. TEST RESULTS AND OBSERVATIONS

Unfortunately our test results are still incomplete. Priorities and manpower constraints have continually delayed the program. We have done enough work and testing to make certain observations about the design, both good and bad. The unit assembly went together without many problems. The assemblies mounted on the main chassis are easy to get to with the chassis extended outside of the tank. The wiring for auxiliary circuits terminates on a plate with oil tight feedthru's on either side of the tank. The plate seals to the tank from the inside and remains with the main chassis. The main chassis slides into the tank, the secondary ground is made up by multi-lam pins at the rear of the tank. The high voltage cable is plugged in from the top of the tank. The cathode and heater connections to the klystron are made through the side access/ viewing port, and then the port is sealed. The tank can be evacuated and filled with oil. It is a relatively simple process unless it has to be done too often during de-bugging stages.

The original plan was to fine tune the waveform at low voltage outside of the tank and relate waveforms from low voltage to high voltage. We have not had time to do this and therefore did our checking of the waveform at about 3 to 4 kV, 50 kV on the klystron in air but inside the tank. We therefore had to disconnect all of the cables and the klystron, to pull the main chassis, every time we wanted to make a change. In fact, the line is hard to fine tune as built. We can short turns, squeeze or lengthen coil spacing, or move turns between capacitors. Each step has been tedious. Furthermore, when we felt we had a good waveshape at this lower voltage, we sealed the tank to backfill it with oil. The capacitance added by the oil was enough to change the waveshape

significantly. We still need to understand the relationship between the low voltage, air pulse and the high voltage oil pulse and the physical set-up is not conducive to easily making changes.

It appears that the primary discharge path is very low inductance and not a limiting factor in achieving a fast rise time. The limiting factors will be the pulse transformer leakage inductance and the transformer and load capacitance. Preliminary results show the klystron pulse rise time to be in the order of 300 nanoseconds from 10 to 90%. Tuning the line for overshoot and flatness is more difficult. A sample waveshape at about 350 kV is shown in Figure 3. The waveform has overshoot and the pulse is not as flat as desired. If we suppose that the waveshape could be flattened with almost no overshoot then the rise time would be as stated above. The DC power supply was delivering 14.8 kilowatts into the modulator. Using the same supposed waveshape as for the rise time the pulse with would be about 1.32 microseconds and the efficiency would be 67% plus the efficiency of the power supply. This agrees with our predicted overall efficiency of 63 to 65%.

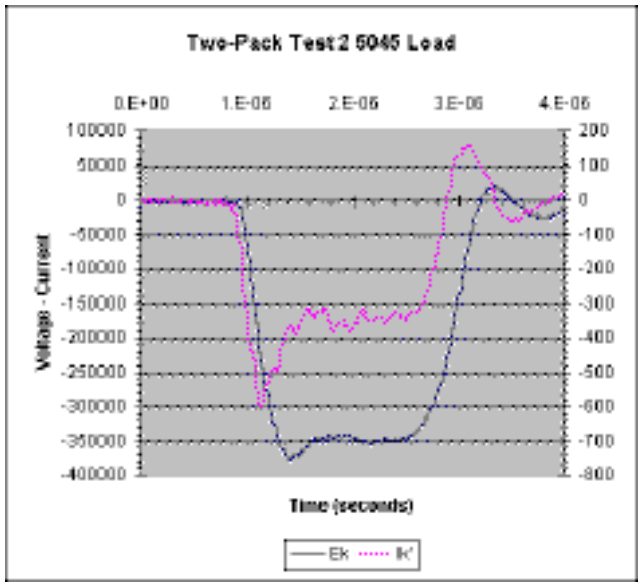

Figure 3. Initial Test Waveform

5. CONCLUSION

The Line-Type modulator still has a place in pulsing high peak power klystrons. For single tube pulsing it may still be the most economical modulator. Proper care in design and construction will enable the modulator to be more efficient. The inherent current limiting protection of this type modulator has successfully allowed tubes to survive gun arcs.

'Direct Switch' modulators have the advantage of the ability to dial in a pulse width and they are not dependent upon impedance matching although the pulse fall time is still dependent on the impedance of the load. As these type modulators continue to develop and be used with high peak power devices, such as klystrons, we will be better able to compare design merits.

ACKNOWLEDGEMENTS

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