Session 2-2
Chairman : R. Koontz (SLAC)

Klystron-Modulator Design-1

REVIEW OF SESSION 2.2 - KLYSTRON-MODULATOR DESIGN

Ron Koontz (chairman)
SLAC

SOLID-STATE FAST PULSE MODULATORS

IGBT’s → Let’s Get them designed as fast as microwave devices.

CIRCUIT TOPOLOGY

- All IGBTs at Ground Level → Magnetic Stacking, as Cassel & Co, SLAC for
  Induction Modulator
- IGBTs stacked to 80 kV → Hybrid Modulator, as DTI solution (SBIR - II), and
  KEK, Akemoto.
  Driving 2 klystrons
- IGBT modulator units, Induction → North Star, Richard Adler (SBIR-I)
  powered and Discharged in series.
  Driving 1 – 2 klystrons.
- IGBT driving Fractional Turn → CREWSON Eng. W. Crewson.
  modulator, with 1 klystron.
- MARX IGBT modulator →
  (No Iron cored transformer)
  Driving 2 klystrons DTI, Michael Kempkes, SBIR – II
- IGBT stack with Iron Core →
  transformer. To 500 kV
  to drive 8 klystrons.
- Thyristor Modulators → APP, C. Glidden, SBIR – I
- Long-Life thyratrons → MARCONI Applied Technology, R. Sheldrake.

THE PROGRESS OF SBIR SUPPORTED R&D OF SOLID STATE PULSE MODULATORS*

Roland .F. Koontz
Stanford Linear Accelerator Center, Stanford, CA USA

Abstract

The Small Business Innovative Research grant program funded by the US Department of Energy makes a number of awards each year for R&D in the field of accelerator technology including high power pulse modulators and their components. This paper outlines program requirements, and reviews some of the awards made in the last three years in support of high power modulator systems and solid state switching. A number of award recipients are presenting the results of their SBIR R&D at this workshop.

1. MECHANICS OF THE SMALL BUSINESS INNOVATIVE RESEARCH GRANT (SBIR) PROGRAM:

This section is a short summary of information available on the Office of Science, US Department of Energy web site located at http://sbir.er.doe.gov/sbir/ . Each year, the DOE sets aside a portion of department funding to be awarded as grants to companies that qualify as small businesses in the USA. A small business as defined under this program is one that has less than 500 employees, is American owned, and is not part of a larger corporation.

There are three phases to the grant process. A Phase I grant can be for an amount of money up to $100,000 to initiate a new line of research, do limited experimental work to support the development proposal, and write a more extensive proposal for a Phase II award. Phase I solicitations are published on the DOE website in late November of each year, and grant proposals must be received in the DOE office by late February. Grant proposals are first checked by administrative staff for conformance to proposal submission requirements. Qualifying proposals are given an initial technical evaluation by DOE program administrators, and then sent to three independent reviewers chosen from the scientific community. Scores from these reviewers are tallied, and a listing is prepared for consideration by the program officer. Generally, the top scoring applications are chosen for grants. Middle scores are evaluated, and grants are given to those applications deemed most germane to the solicitation objectives. A well written proposal setting out clear technical goals directly addressing one of the solicitation objectives stands a very good chance of being funded.

Toward the end of the Phase I effort, if the Principal Investigator of the grant believes expanded R&D is justified, he writes a Phase II proposal which is submitted to the DOE about the end of March in the year following the SBIR Phase I award. It is expected that the Phase II effort is much more extensive with a prototype product emerging from the work. The term of a Phase II award is up to two years, and the maximum amount of the award is $750,000. An extensive report is due at the end of the grant, and in many cases, a completed product is delivered to one of the interested national laboratories.

In Phase III, it is intended that non-Federal capital be used by the small business concern to pursue commercial applications of the R&D. Also under Phase III, Federal agencies may award non-SBIR funded follow-on grants or contracts for products or processes that meet the mission needs of those agencies, or for further research or R&D.

Small business Technology Transfer Research (STTR) grants are also available. STTR is similar to the Small Business Innovation Research (SBIR) program in that both programs seek to increase the participation of small businesses in Federal R&D and to increase private sector commercialization of technology developed through Federal R&D. The unique feature of the STTR program is that, for both Phase I and Phase II projects, at least 40% of the work must be performed by the small business and at least 30% of the work must be performed by a non-profit research institution. Such institutions include federally funded research and development centers (for example, DOE national laboratories), universities, non-profit hospitals, and other non-profits.

2. TOPIC HEADINGS GERMANE TO LINEAR ACCELERATOR TECHNOLOGY:

2.1

Topic and Subtopic listings in each year's SBIR Phase I solicitations are numerous, and are listed on the DOE web page. Those topics that cover high-energy physics in general, and klystron pulse modulators in particular are listed below along with a short solicitation description as published in the 2001 solicitation (italics).

5c. New Concepts for Pulsed Power Modulator

Most rf power sources for future linear colliders require high peak-power pulse modulators of considerably higher efficiency than presently available. Grant applications are sought for new types of modulators in the 400 kV - 1 MV range for driving currents of 400 - 800 A, with pulse lengths of 0.2 - 2 microseconds, and rise- and fall-times of less than 0.2 microsecond. Innovation related to cost saving, manufacturability, and electrical efficiency in modulators is especially important. Modulators with improved voltage control for rf phase stability in some alternate rf power systems are also sought.

Grant applications are also sought to develop high power solid state switches, either Insulated Gate Bipolar Transistors (IGBTs) or Thyristors, for pulse power switching. Requirements include the ability to switch high current pulses (2-5 kAmps) at voltage levels of 2 to 6 kV with switching times of less than 300 nsec. Construction and low inductance packaging techniques must be developed to allow current state-of-the-art chip designs to handle very high di/dt (20 kAmps/Ìs) at low duty cycle (<0.1%).

Lastly, grant applications are sought to develop and optimize high reliability, high energy density energy storage capacitors for solid state pulse power systems. The capacitors must: (1) deliver high peak pulse current (5 - 8 kAmps) in the partial discharge region (less than 10 percent voltage droop during pulse), (2) be designed with very low inductance connections to allow fast rise and fall time discharge without ringing (di/dt ~ 20 kAmps/Ìs), and (3) be packaged to meet the requirements of high power solid state board layouts and have minimum production cost.

7a. Direct Current (DC) and Pulsed Power Supplies, Modulators and Components

Advances are needed in various aspects of pulse modulators and associated components to drive klystrons in both injector and main linac applications. Grant applications are sought for:

(1) DC Power Supplies operating at 2 to 5 kV from about 50 to 500 kW output, to drive capacitor banks in IGBT (Insulated Gate Bipolar Transistor) switched induction modulators or Marx generators. The power supplies must have 0.1 percent regulation, withstand pulsed current duty cycle between short discharges (3 - 6 microseconds) and recharge at 120-180 Hz steady state. Operation for shorter pulses at higher recharge rates is also desired for testing purposes. Other objectives include high reliability, low cost, and efficiency greater than 90 percent.

(2) Ultra-Reliable Capacitors of ~10-25 microfarads at 2.5 to ~6 kV to provide stored energy for partial discharge, on-off switch modulator configurations. Requirements include low loss, low inductance, high power density to minimize volume, MTBF >100,000 hours, and low cost. Long lifetime is a priority because the large numbers of such units in the modulator designs will dominate modulator reliability.

(3) High Voltage Pulse Transformers with ratios from 1:6 up to 1:15, with low leakage inductance and minimized core loss, for use in solid-state-switch driven modulators with a load-matching transformer. The modulators will drive a pair of X-band klystrons at 180 Hz with ~500 kV, 520 A peak and 3 microseconds pulse-length, or drive an S-band klystron in the injector at 180 Hz with 380 kV, 800 A peak, and at least 6 (possibly up to 16) microseconds pulse-length. Rise/fall times of less than 300 ns and droop/ripple of less than 2 percent are desired. Transformers must operate in oil and be compact, efficient, and cost-effective to manufacture.

The whole listing can be found on the DOE SBIR website.

3. SOLID STATE PULSE SWITCHING TECHNOLOGY GRANTS:

There is currently work going on as a result of several Phase I and Phase II grants made in 1999 and 2000. Some of those pertaining to modulators are listed below.

North Star Research Corporation Phase I
Pulse-Step-Modulation Modulators
for Radio Frequency Accelerator Applications

Applied Pulse Power, Inc. Phase I
80 Kilovolts, High-Power, High di/dt, Low-Inductance, Solid State Switch

Diversified Technologies, Inc. Phase I
Next-Generation Linear Collider Buck Regulator Power Supply

Sigma Technologies International, Inc. Phase I
Ultra-Reliable Hybrid Film Capacitors

Diversified Technologies, Inc. Phase I
Solid-State Modulators for Heavy Ion Fusion Accelerators

Diversified Technologies, Inc. Phase II
New Concepts for Pulsed Power Modulators

Diversified Technologies, Inc. Phase II
Hybrid NCL Modulator

Diversified Technologies, Inc. Phase II
High Power Switch

As can be seen from the listing above, there are just a few companies involved in this area of research grants. Broader participation would be most welcome.

4. SOME RESULTS, AND PROJECTIONS FOR THE FUTURE:

All pulse modulators need some sort of energy storage to take continuous energy from the power lines and deliver it as a short pulse train to loads such as klystrons. Depending on how power switching is done, this entails pulse discharge capacitors anywhere from 2 kV to over 100 kV. This group of capacitors is further divided into those which are fully discharged or even voltage reversed each pulse (PFN or Blumlein modulators) and quasi-DC capacitors where the capacitor bank stores much more energy than is discharged each pulse, and an on-off switch gates the pulse energy. Fortunately, these quasi-DC capacitors store energy much more compactly than a true pulse capacitor, and are probably more reliable as well.

Over the last several SBIR cycles, a number of proposals have been funded to research exotic ways to produce high energy density, ultra-reliable energy storage capacitors, but to date, it seems that the old standard polypropylene film, oil impregnated capacitors with some design and packaging refinements are still best for high power pulse energy storage. This year, we have only one company, Sigma Technologies, International, Inc. doing SBIR I work on a new capacitor design.

Three other companies holding SBIR grants are working on various pulse switching systems using solid-state devices. SCR's (Thyristors) were originally thought to be a suitable replacement for thyratrons in PFN type modulators, but that technology did not develop into a viable product when pulses were short, in the range of 1 to 5 μseconds, and switching powers were very high. Some R&D systems worked well under normal operation, but in fault conditions such as a klystron cathode-anode arc, the SCR's were destroyed. This year, a new company, PTS, is manufacturing a line of SCR's optimized for fast pulse switching, and Applied Pulse Power, Inc. has an SBIR Phase I grant to explore an 80 kV, 6,000 amp switch stack using these new SCR's. If this R& D effort is successful, there may be a solid state equivalent of a SLAC type thyratron (F-241, etc) in the near future.

SBIR R&D work using IGBT technology is being carried out at Diversified Electronics, Inc. and North Star Research Corp. An extensive R&D program is also underway by the Electronics & Software Engineering group at SLAC. North Star Research Corp. is developing IGBT switches for pulse power applications. Diversified Electronics has several SBIR Phase I and II grants aimed at developing very fast high power switching with IGBT's and protecting them in various fast fault conditions. The work of these organizations work is separately reported on at this workshop.

The future of solid-state modulators looks bright, but there are several serious areas of concern for solid state switching. New SCR's and some high power IGBT's can be made to switch very fast. The general impedance level in which all of these devices work is very low, and the effects of very small stray inductances both internal to, and outside of the devices can lead to transient voltage spikes and parasitic resonance's that have the potential to destroy the lower voltage input circuits of the devices. This is especially true under load arcing fault conditions. Intense effort is underway to solve these problems, but this entails liaison with device manufacturers and careful scrutiny of internal connection paths to minimize and balance path inductances.

Device heat dissipation is also an area of concern. When most of these high power devices are used in long pulse, or AC switching applications, there is time for conduction path spreading in junctions that minimize "on" junction impedance. In fast switching conditions, however, when all the energy is delivered in a few microseconds, the dissipation in junctions is critically dependent on how well most of the junction is turned on by the gating pulse. This is not easy to analyze without characterizing every detailed current path in the device. This partial turn-on effect sometimes looks like an inductance from outside the device, but unlike an inductance, the effect is dissipative and contributes to the heat build-up in the device. Device manufacturers are only now starting to work with pulse system designers to optimize high power solid-state switches for fast switching operation.

Another problem that must be addressed before solid-state modulators become viable for driving high power beam devices such as klystrons is the amount of energy such a modulator can deliver into a cathode-anode load arc. A standard PFN modulator with step-up pulse transformer has intrinsic energy limiting from two sources, the stray inductance of the pulse transformer, and the intrinsic current limiting of the PFN characteristic impedance. Operating history shows us that a single klystron on a conventional PFN modulator can withstand occasional load arcs without serious damage to the gun electrodes. We are currently collecting arc data on the operation of two klystrons on a conventional PFN modulator, but so far, we have no experimental operating results for one or more klystrons operating on an IGBT switched modulator that has very low driving impedance. Protecting expensive klystrons is a very high priority in the design of these solid-state modulator systems.

---

*Work supported by Department of Energy contract DE-AC03-76SF00515.

A SOLID STATE OPENING SWITCH FOR CROWBAR REPLACEMENT

Ian S. Roth, Marcel P.J. Gaudreau, Michael A. Kempkes
Diversified Technologies, Inc. Bedford, MA USA

Abstract

Opening switches have substantial advantages over crowbars. Diversified Technologies has developed solid-state opening-switches using series arrays of IGBTs; many systems have been delivered. The control circuitry has been improved, and the current capability of low-cost switches has been increased from 5 to 25 A. The opening switch being developed will be part of a complete klystron power-supply system for the Advanced Photon Source at Argonne National Laboratory.

INTRODUCTION

Crowbars are commonly used to protect klystrons from arc damage. When an arc occurs, the crowbar closes, and rapidly discharges the energy-storage capacitor. A typical crowbar circuit diagram is shown in Figure 1. An alternative way to protect a klystron is to use a switch that opens during an arc (also shown in Figure 1). Opening switches have substantial advantages over crowbars:

- No series resistor is required, so an opening-switch system has higher circuit efficiency.
- Because the energy-storage capacitor does not discharge during an arc, high voltage (and RF) can be turned back on in less than 30 µs, before the circulating accelerator beam dumps [1]; see Figure 2. No beam re-start is required.
- Crowbars use mercury-containing ignitrons. When an ignitron fails, the required clean-up can be time-consuming and costly. As an example, the ignitron failure at the Joint European Tokamak in 1986 shut down the machine for three months. The total cost of the failure, including lost staff time, was £1 M ($1.9 M) [2]. Opening switches use no mercury.

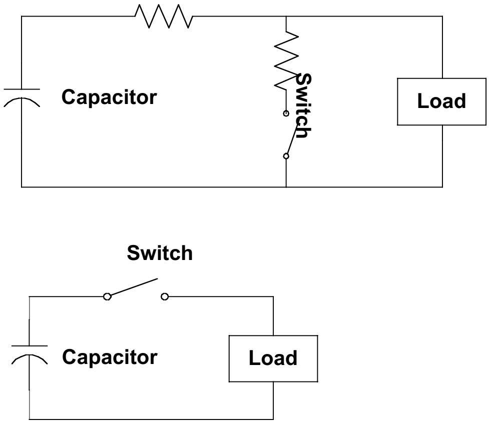

Fig. 1. Circuit diagrams for crowbar (upper) and opening switch (lower).

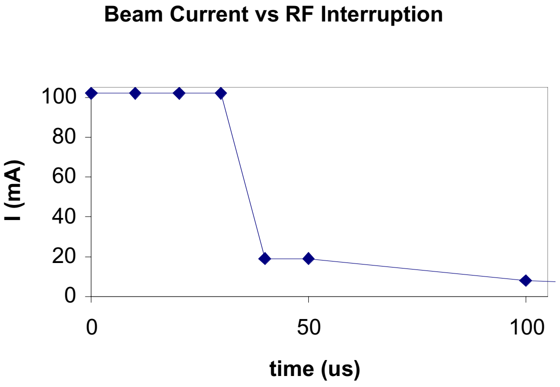

Fig. 2. Beam current vs. RF interruption. An interruption of up to 30 µs can be sustained without beam loss.

Opening switches can be made using vacuum tubes, but these are expensive, have a large forward voltage drop (10-20% of the total switched voltage), and a limited lifetime. Diversified Technologies has developed opening switches made from a series array of solid-state devices, IGBTs or FETs. These are much less expensive than vacuum tubes, and have much longer lifetimes. The forward voltage drop of these opening switches is small, less than 0.5% of the opening switch voltage. Opening switches have been in service for several years without any failures from non-simultaneous opening. An additional benefit of the series-array opening switch is redundancy. Switches are made with excess voltage capability, so the switch can continue operating even if several devices should fail. Diagnostics report any device failures, so repairs can be scheduled appropriately.

OPENING SWITCH OPERATION

An example of an operational opening switch is shown Figure 3 (left). This switch is also used as a modulator, like most of the high-power opening switches delivered. It carries 500 A and opens to 140 kV. The unit has been operating at CPI for several years. Waveforms of a deliberate short are shown in Figure 3 (right). The lower trace shows the current. After the current passes the arc-detection threshold of 200 A, it rises for an additional 700 ns before being interrupted. The peak current interrupted is 700 A.

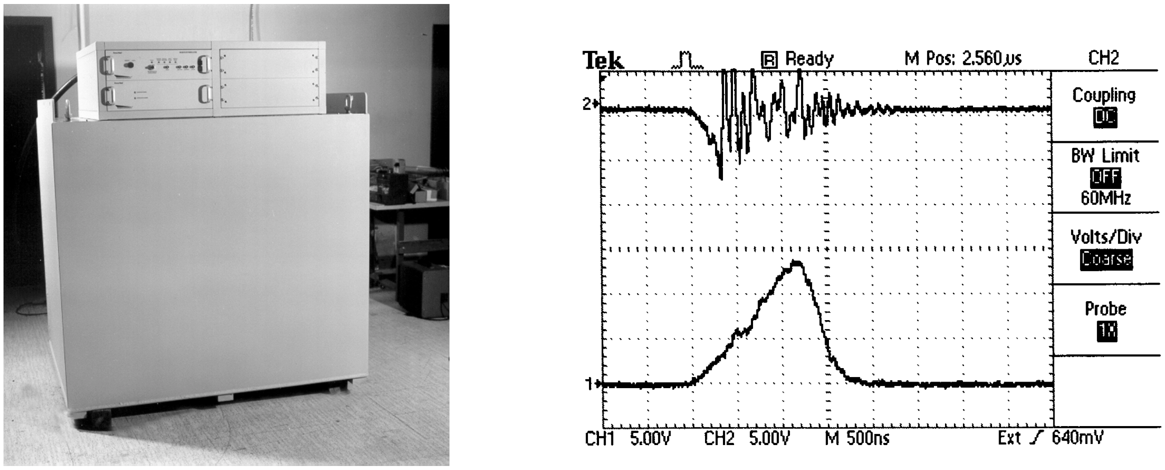

Fig. 3. Left: Opening switch delivered to CPI. Right: Waveforms of a deliberate short. Upper trace, voltage, 50kV/division; lower trace, current, 250 A/division.

OPENING SWITCH DEVELOPMENT

We are developing opening switches further under a Phase-II SBIR grant from the DOE. There are two directions for the development: improving the control circuitry, and reducing the cost of the specific opening switch.

One of the ways we have developed the control circuitry is to use DC current monitors that have a fast response. In a DC system (often used to drive klystrons) pulsed current transformers do not work well. This is because the ferrite in the transformer saturates, and the transformer will not respond to pulsed fault currents. The pulse response of the LEM DC current monitor (see Figure 4) is fast enough for fault detection.

We have further developed the control circuitry to decrease the system response time to an over-current fault.

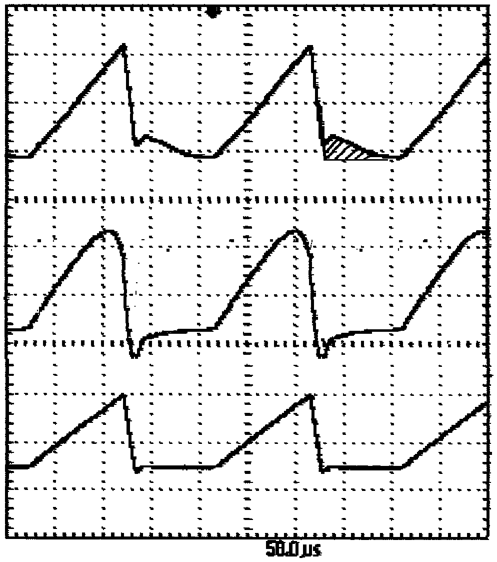

Fig. 4. Identical current waveform with three different diagnostics. Peak current is 30 A; timescale is 50 µs/division. Upper trace, LEM-100P; middle trace: Pearson 110 transformer; lower trace, Pearson 1025 current transformer.

This has been done by using faster fiber-optic receivers (fiber optic cables are used to trigger and diagnose the IGBTs) and increasing the slewing rate of the IGBT trigger. DTI systems presently take 700 ns from the over-current signal to the turn-off of the switch.

We have also added fault latching, which displays the first fault signal, and locks out subsequent signals. This allows the operator to determine the cause of a fault, and make repairs if needed. Finally, we have reduced the number of fiber-optic cables per switch plate from three to two by multiplexing diagnostic signals.

Figure 5. Low-cost switch module**.**

As well as improving the control circuitry, we are increasing the DC capability of low-cost opening switches (Figure 5) from 5 to 25 A. These switches use discrete IGBTs, and are substantially less expensive than ones using IGBT modules. The low-cost opening switch will be incorporated into the klystron power-supply for the Advanced Photon Source (APS) at Argonne National Lab.

To increase the current capability of the low-cost opening switches, we first selected the best IGBT available. The properties of various devices are compared in Table 1.

Table 1 Comparison of discrete IGBTs. $R_{\_JC}$ is the thermal resistance from junction to case; $R_{\_CK}$ is the thermal resistance from case to heat sink.

Device	V_{max} (V)	$I_{max\ DC}$ (A)	$V_{forward}$ (V)	$R_{\_JC}$ (°C/W)	$R_{\_CK}$ (°C/W)	$t_{current\ delay\ off}$ + $t_{current\ fall}$ (ns)
Fairchild HGTG 30N120CN	1200	75	2.1	0.25	0.25	400
IXYS IXLF 19N250A	2500	32	3.2	0.5	0.25	650
IXYS IXGH 45N120	1200	75	2.5	0.42	0.25	760
IR IRG4PH50S	1200	57	1.75	0.64	0.25	2170
IR IRG4PH50U	1200	45	3.20	0.64	0.25	600
APT 50GF120LR	1200	80	2.9	0.32	0.25	430

We chose the Fairchild (formerly Intersil) 30N120CN; it has the lowest thermal resistance and the second-lowest forward voltage drop of the devices available. While the IXYS 19N250A operates at 2500 V instead of 1200 V, the forward voltage drop and thermal resistance of this device are too large to permit operation at the required 20 A DC.

Having selected the IGBT, we investigated heat sinks. The heat sink performance was measured by mounting the sink to an IGBT, lowering the assembly in oil, passing current through the IGBT, and measuring the temperature rise. A selection of the heat sinks we considered is listed in Table 2.

Table 2. Heat sink performance.

No.	Mat'l	Base area (in^2)	Height, fin gap, fin thickness (in)	R_, °C/W still oil	R_, °C/W moderately flowing oil	R_, °C/W rapidly flowing oil
1	Al	0.79	2 0.094 0.063	1.40	0.86	-
3	Al	6.8	1.3 0.25 0.063	0.36	0.21	0.13
5	Cu	6	2.2 0.125 0.063	0.24	0.12	-
9	Al	6.2	1.6 0.19 0.11	-	0.13	-

Heat sink 1, which we have been using, has the highest thermal resistance of the sinks tested. Heat sink 3 was made from extruded aluminum. Note that the thermal resistance was lower when the oil was flowing rapidly (with the device directly at the exhaust of the oil pump) than when the oil was flowing moderately (with the device 18" away from the pump exhaust). We decided, however, that rapidly-flowing oil would be impractical. Heat sink 5 was made from copper. While this heat sink has a low thermal resistance, it was expensive to manufacture, and we decided to use extruded-aluminum heat sinks. Heat sink 9 has a low thermal resistance, 0.13° C/W. Using heat sink 9A, which is made from the same extrusion as heat sink 9 but with half the base area, halves the size of the opening switch while giving only a 7° C increase in temperature. The calculated IGBT-junction temperature rise is then 2.7 V × 20 A × (0.50 + 0.26) °C/W = 41° C.

ARGONNE KLYSTRON POWER-SUPPLY SYSTEM

The opening switch is the first part of a klystron power-supply system we are building for APS. Specifications for the system are listed in Table 3.

Table 3. Specifications for the APS Klystron Power Supply at Argonne.

Component	Specification
Transformer	13.6 kV in, 110 kV out, 2.2 MW
Buck regulator	110 kV in, 0-100 kV out, 20 A out, ±0.5% regulation, >90% efficient
Filament heater	0-25 V, 0-25 A, ±1% current regulation
Mod anode power supply	0-90 kV with respect to cathode, 20 mA
Opening switch	100 kV, 20 A, 1 µs response to fault
Ion pump power supply	3.5 - 5.5 kV, 20 mA
Electromagnet power supplies	0-300 V, 0-12 A, 0.1% current regulation
Controls	interlocks, local/remote operation

In addition to the opening switch, the other potentially difficult component could be the buck regulator. The same technology used for the switch, however, is used for the buck regulator, and the required performance has already been demonstrated: Figure 6 shows a buck regulator that is installed at CPI. This buck regulator gives a power output of 140 kV and 20 A, with regulation to ±0.3%.

The remaining components in the system use conventional technology. We anticipate no difficulty in constructing the complete APS klystron power-supply.

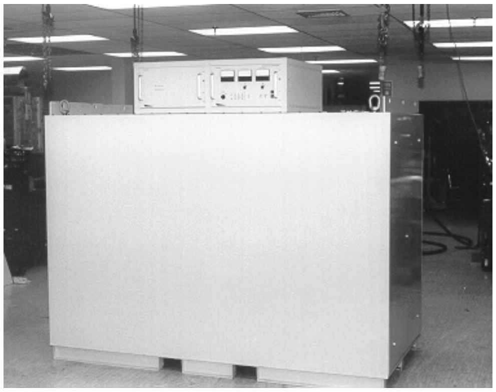

Figure 6. Buck regulator installed at CPI.

REFERENCES

[1] Doug Horan, Advanced Photon Source, Argonne National Laboratory; private communication.
[2] Geoff Pile, Advanced Photon Source, Argonne National Laboratory; private communication.

A SOLID STATE INDUCTION MODULATOR FOR THE NLC

Chris Pappas, Richard Cassel, Jeff de Lamare, Minh Nguyen, SLAC
Ed Cook, Jim Sullivan, Craig Brooksby, LLNL

Abstract

The klystron modulators for the NLC main linac are designed to meet efficiency, reliability, maintainability and cost requirements which have not been of paramount importance for modulator accelerator applications in the past. Because of the sheer number of modulators needed in the NLC, these criteria are important. The modulator is designed to drive a load of eight klystrons. The output specifications for the modulator are to produce a 500 kV, 2120 A pulse, of 3 ms length, at 120 Hz, with rise and fall times of less than 200 ns, and overall efficiency of greater than 75 %. This is accomplished in the proto type modulator now being constructed at SLAC by using an induction linac type of transformer driven by an IGBT based switcher. The transformer consists of 76 Metglass cores stacked in twin towers. The primary of each core is driven by a 2.5 kV, 2120 A pulse through a single turn. Passing three coaxial pipes through the centers of the two towers makes the secondary. The design of the modulator will be presented here, along with problems which need to be addressed in this type of design, as well as test data.

PULSED SWITCH MODULATOR TECHNOLOGY FOR FAST PULSE GENERATION

R. J. Adler, B. Ashcraft, and R. J. Richter-Sand
North Star Research Corporation

Abstract

PSM (Pulsed Switch Modulation) was invented at Harris Corporation in the late 1970s as a means of controlling large high voltage and RF systems. The topology is uniquely useful in creating pulses. It consists of a number of individual pulse generator stages in series in contrast to systems which simply have switches in series. The reason for itÕs utility is that when one switch (IGBT) fails to turn on or off, the built-in bypass diode prevents damage to all other sections. The PSM technology can therefore be used to directly drive a very fast pulse. In our first 10 board, test at 200 A nominal output , the current pulse shown in Figure 2 was produced.

The pulse shown used 54 devices to produce a nominal 1.5 MW pulse. The device and board cost of this approach is approximately $150/kV at the prototype stage, and perhaps as low as $75/kV at the mass production stage. The independent power supply for the individual stages is being developed as part of this project. This work was supported by the US DOE SBIR program.