ADVANCED TECHNOLOGY ON THE MEGAWATT MODULATOR FOR THE GROUND TEST ACCELERATOR*

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Abstract

This paper presents the new concept of accelerator technology developed by Los Alamos National Laboratory, AT-Division. The modulator is driven on-off by rf switching power supply to achieve 1-MW rf accelerator energy from the klystron and klystrode at 850 MHz. The advantages are listed below: (1) System cost saving up to 70%, (2) operating cost saving up to 60%, (3) weight reduced from 24 000 lbs. to 700 lbs., (4) size reduced from 512 to 12 cu. ft., and (5) efficiency improved from 75 to 97%.

Megawatt Klystron Case History

For many years, high-power accelerators have used the klystron as the key device for accelerating the particle beam. The megawatt klystron has been used for the past 26 year at Los Alamos National Laboratory.

Researchers continually demand higher and higher energy to bombard the atomic nucleus for study. The high-voltage klystron is more attractive to use than the low-voltage klystron because less current is required in the same operating condition. The klystrons we use require 120 kV/30 A at a 5% duty.

There is no power supply available at this time that is capable of turning on/off fast enough in microseconds. Therefore, the modulator anode has been used extensively for the on/off control operation.

The capacitor bank is used for energy storage. It must be big enough to hold the voltage deviation to the acceptable ripple level during operation. For human safety and to reduce the EMI-RFI problems, the capacitor banks are contained in large screen rooms.

It is necessary to protect the klystron from damage when an arc occurs. Because no device can switch 120 kV fast enough, a crowbar technique is used. The crowbar protects the klystron, in the event of an arc, by dumping millions of watts into a spark gap. Once the klystron arc is extinguished, the capacitor bank must be recharged. This technique limits the repetition rate and also wastes energy.

Screen Room Complications

There are numerous requirements to be considered in designing a screen room (Fig. 1). The capacitor banks must be big enough to hold 120 kV within the specified limit. Typically, a 5% deviation is acceptable.

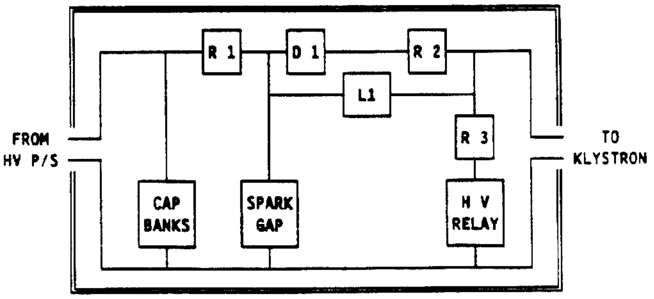

Fig. 1. Typical screen room setup.

The spark-gap must be large enough to dump the energy that is stored in the capacitor banks; it must have a gap voltage low enough to extinguish the arcing at the faulted klystron. Because the capacitor banks have limited current surge ability, R1 is required to hold the capacitor short circuit current to the specified limit.

When the klystron arcs, the arcing voltage may be too low to fire the spark-gap. The inductor L1 has been inserted to isolate the arc voltage from the spark-gap voltage. This arrangement is to insure that the spark-gap voltage is high enough to fire the spark-gap when the klystron arcs.

This inductor leads to new problems, however. The current transient during arc/quit-arc operation creates a huge di/dt voltage. This voltage may damage the other components. The snubber network consisting of D1 and R2 is necessary to prevent voltage build-up from transients.

For safety, a high-voltage (HV) relay is required to discharge the capacitor banks. The resistor R3 limits the discharge current through the high-voltage relay contacts. Finally, all control signals must go through fiber optic cables to prevent conducting noise to the control and data acquisition system.

Ground Test Accelerator Program

Our task has been to research and develop a 120-kV/30-A, 5% duty cycle power supply of sufficiently high efficiency and small size and weight to operate in space as well as on the ground.

In comparison to a conventional capacitor-bank-type power supply, the new power supply should achieve a weight reduction from 24 000 to 700 lb, a size reduction from 512 to 12 ft^3, and an efficiency improvement from 75% to 97%. This new power supply will result in the elimination of the capacitor banks by supplying power directly to the klystron. There will be no need for a screen room to house the capacitor banks. The need for a crowbar system to protect the klystron during an arc has been eliminated because the new power supply can immediately switch off power to the klystron. The modulator on/off control technique also is simplified. In addition, there will be a >70% savings in equipment cost, as well as a 25% reduction in operating cost.

A key to improving the efficiency of the new power supply is to operate it at −55°C, easily accomplished in space environment. The size and weight will be minimized by operating the supply at 300 kHz. Super hybrid switches can further reduce weight.

Design Considerations

Design of the power supply involved three primary considerations: (1) high-voltage handling, (2) converting and control system, and (3) prime power section. Several problems had to be solved in order to properly handle the high voltage. A four-diode bridge had to be installed in a 20-in. box so that 180 kV could exist between the diodes and surrounding components without arching. It was necessary to terminate 120 kV/30 A and 60 kV/1 A to the outside world, yet allow the power supply to be portable. A method was found for orienting the HV filter inductor so as to minimize the effect of the magnetic linkage flux without having to use a large metal shield. The high-voltage capacitors had to be stacked so as to prevent corona arcing. The megawatt high-voltage transformer was designed to reduce leakage inductance and still maintain the HV integrity.

Conventionally, the leakage inductance energy is dumped into a snubber network. Unfortunately, this energy is too large to be wasted. A recover[4] method has been developed that uses this energy to charge the input filter capacitor instead.

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The solution was found by using a four-phase technique to commutate the leakage energy during the pulse-width control regulation cycle. This method minimizes the huge dissipation at the snubber element significantly.

The other consideration was to switch 800 V/5000 A on/off in less than 100 ns. This fast switching time was necessary to achieve the required efficiency at the operating frequency of 300 kHz.

The superhigh-energy module was developed to switch effectively and to be suitable for integration into the system.

The output voltage had to be controlled while maintaining a voltage regulation of 1%. It was necessary to prevent damage to the switching elements in the event of a system failure. Also, it was necessary to control the balance of the magnetic flux in the HV transformer to prevent the core from becoming saturated during normal operation.

Another problem to be considered in the design was how to take care of the heat dissipation inside the box while maintaining a −55°C operating temperature and at the same time reducing the EMI-RFI in the same enclosure.

Finally, consideration was given to the prime power distribution from the power station to the accelerators. It was necessary to filter the pulse power of 100 MW into average power. Besides the filtering problem, the distribution of 150 kA in/out to supply the klystrons power was another major concern. The I^2R loss at high frequency is dissipated all over the buildings; the required 800-V insulation is a further complication.

An additional benefit of the pulse power filtering network is that it can be designed to reduce the effect of the input-current-harmonics distortion problems. This results in a clean operation and reduces the operating costs.

HV Transformer Design Story

A transformer had to be designed to the following specifications:

Input 800 V 500 A,
Output 120 kV/30 A and 50 kV/1 A, and
2 ms at 5% duty operation.

The procedure for designing the transformer was as follows:

1. Determine the turns per volt.
2. Determine the volts per layer.
3. Determine the layers per coil to satisfy 60 kV per coil.
4. Determine the spacing between the two 60-kV coils to satisfy the 120-kV space requirement.
5. Determine the size of the core area to satisfy the volts per turn requirement.
6. Determine the size of the primary coil to meet the 5000-A requirement.
7. Iterate steps 1 to 6 until the design of the ferrite core can be finalized.
8. Determine how to wind the coil and how to terminate the 120-kV/30-A output.
9. Design the frame to fit into the small space.

The prototype high-voltage transformer constructed at Los Alamos meets the following specifications:

1. HV coils 60 kV/30 A, each weighing 15 lb with a DC resistance of 5 Ω
2. Primary coils 800 V/2500 A, each weighing 28 lb with a DC resistance of 0.001 Ω
3. 150-kV spacing from any side
4. Frame size 12 × 20 × 25 in.
5. Core loss 33 W
6. Coils loss 536 W
7. Dry weight 120 lb

High-Frequency Filter Inductors (120 kV/30 A)

The klystron is subject to occasional arcing during normal operation. When a klystron arc occurs, the high-frequency (HF) inductor will see a voltage as high as 120 kV across its coil. Therefore, the coil must be designed to withstand 120 kV without arcing across until the protection circuit engages and terminates the fault. The coil under development achieves 2 kV/turn with 0.1-in. spacing.

It is common practice to use a metal can to shield the mutual flux linkage between the coils. With 120 kV present during the arc condition, the metal can present a serious installation problem. To avoid the use of a metal can with 120-kV inside spacing, three coils were mounted on the XYZ axes with a 20-in. minimum space between each.

The four-point bridge rectifier consists of four rectifier sections, each consisting of a series of HV rectifier diodes mounted on a 28-in. insulator. Maintaining the 120-kV spacing required separating each end by at least 12 in. with nothing near any diode.

Energy Storage Inductor (800 V/5000 A)

In designing the 800-V/5000-A energy storage inductor, the first problem was to minimize the copper loss at high frequency. With a 5000-A current through the inductor winding, AC resistance (skin effect) and DC resistance cause a major power loss. Using 475 strands of AWG #26 for the winding minimizes the skin effect and results in a DC resistance of only 100 $\mu\Omega$, an acceptable loss.

When the klystron arcs, the entire input voltage will appear across the inductor. The coil must be designed so that it does not saturate during the klystron arc. Coil saturation would result in zero inductance and exhibit no di/dt capability. This zero impedance behavior would lead to destruction of major components.

The coil must handle the fault without saturating until the over-current protection circuit gains control and shuts down the switches. The major criteria for designing the coil are the ampere-turns and the volt-seconds.

Finally, the energy storage inductor and associated parts are oriented such that they do not obstruct the oil-cooling paths.

Superhigh-Energy Module Switch

It is required to switch 3.6 MVA of power at 300 Hz and 5% duty cycle. We have considered three choices for the switch selection:

1. using a GM-Hughes crossatron in a push-pull inverter mode
2. developing at Los Alamos a monolithic SUPER-FET integrated all-driver circuit on one chip
3. designing a power-hybrid at Los Alamos and then transferring the technology to the hybrid vendors for fabrication

Note: In the interim, we have designed a power-hybrid module for testing.

The GM-Hughes crossatron was our first choice as an inverter switch. The absence of a heater cathode eliminates the need for stand-by heating power and makes the crossatron particularly suitable for an energy-limited space environment. The major components, including the electronic control circuits and mechanical packing design, have been completed. However, insufficient communication with the vendor has delayed the order.

Because of a funding shortfall, I have decided to postpone the SUPER-FET option until the power supply is successfully developed. The nature of the low-duty-cycle pulse power looks promising for the development of the SUPER-FET. The project may be included in the FY 1990 program budget.

Because the first two options, though more desirable, are on hold, I have designed and tested a power-hybrid module. Two contracts were awarded because it was decided that the competition also would lead to a better product and also would provide a second source of availability. Both vendors will be the backbone of the superhigh-energy module for future needs.

In the ongoing testing at Los Alamos, we are using the in-house switch modules. Although outside manufacturers have been selected to build the hybrid modules, Los Alamos National Laboratory is capable of fabricating its own hybrid. We also have a facility with the capability of building our own integrated circuits in the event that the vendors do not develop a successful product.

Converting Technique

The selection of the converting technique is based on the method of recovering the leakage inductance energy. The leakage inductance energy severely damages associated components and wastes a large amount of energy by heat dissipation.

Two ways of handling the leakage energy problems are (1) to dissipate the leakage energy into a snubber network used as the load, and (2) to recover the energy by using it to charge the input source capacitor.

The GTA high-voltage power supply design integrates both of the above techniques to solve the leakage energy problems. An HV full-bridge rectifier plus a snubber is used at the secondary side of the HV transformer to ensure that there is no open circuit to allow di/dt build-up by the leakage inductance. By the same token, an H-bridge is used at the transformer primary side to switch 800-V DC to a 300-kHz square wave. A four-phase control technique (Fig. 2) is used to recover the leakage inductance energy as well as to achieve the required regulation.

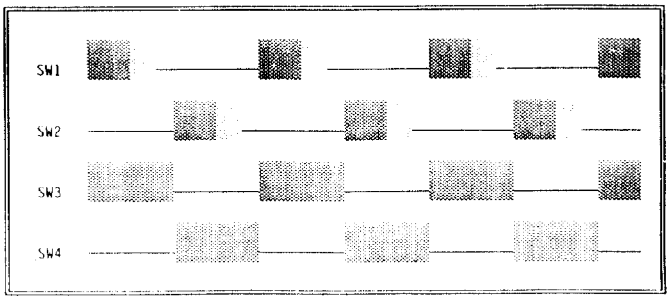

Fig. 2. Four-phase timing diagram.

Thermal Management

Six kilowatts of heat will be dissipated inside the 12-ft^3 enclosure, which is filled with HV transformer oil. Because the power switches dissipate more than 63% of the total loss and the contact resistance decreases directly with temperature, an operating temperature of −55°C was chosen to cut the heat loss in half.

With 6 kW of heat, maintaining a −55°C operating temperature requires a special cooling system. For the prototype model, the oil will be pre-cooled overnight before testing. With 80 gal. of oil in circulation and a heat source of only 86-kg calories, the temperature rise without additional cooling is only 0.025°C/min or 15°C/h. This low rate of temperature rise makes possible a smaller cooling unit under R&D testing.

The major heat dissipations at a temperature of −55°C and 5% duty cycle are listed as follows:

1.	200-kV rectifier diodes loss 153 W/leg	612 W
2.	Power transformer Secondary 112 W/winding	224 W
	Core loss at 340 gauss	33 W
	Primary 156 W/winding	312 W
3.	Energy storage in power inductor	187 W
4.	Superhigh-Energy Module switches	3756 W
5.	Input EMI-RFI filter network	313 W
6.	Power control and miscellaneous	300 W
	TOTAL DISSIPATION INSIDE THE BOX	5737 W