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Modulator Considerations for the SNS RF System[1]

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Abstract

The Spallation Neutron Source (SNS) is an intense neutron source for neutron scattering experiments. The project is in the research stage, with construction funding beginning next year. The SNS is comprised of an ion source, a 1000 MeV, H^- linear accelerator, an accumulator ring, a neutron producing target, and experimental area to utilize the scattering of the neutrons. The linear accelerator is RF driven, and the peak beam current is 27 mA and the beam duty factor is 5.84%. The peak RF power required is 104 MW, and the H^- beam pulse length is 0.97 ms at a 60 Hz repetition rate. The RF pulses must be about 0.1 ms longer than the beam pulses, due to the Q of the accelerating cavities, and the time required to establish control of the cavity fields. The modulators for the klystrons in this accelerator are discussed in this paper. The SNS is designed to be expandable, so the beam power can be doubled or even quadrupled in the future. One of the double-power options is to double the beam pulse length and duty factor. We are specifying the klystrons to operate in this twice-duty-factor mode, and the modulator also should be expandable to 2 ms pulses at 60 Hz. Due to the long pulse length and low RF frequency of 805 MHz, the klystron power is specified at 2.5 MW peak, and the RF system will have 56 klystrons at 805 MHz, and three 1.25 MW peak power klystrons at 402.5 MHz for the low energy portion of the accelerator. The low frequency modulators are conventional floating-deck modulation anode control systems.

I. Introduction

The pulsed power system is an important factor in the cost and reliability of the SNS project. The relatively long pulse length and high duty factor make conventional PFN modulators difficult. We discuss and compare four types of modulators that could be applied to this application. The baseline design modulator is a floating-deck design that utilizes a single switch tube to drive the modulation anodes of two klystrons in the same oil tank. This type of system has worked very reliably in the Ballistic Missile Early Warning Radar System (BMEWS), and also in Los Alamos the Los Alamos Meson Facility (LAMPF)[1]. A cathode-pulsed klystron is always less expensive and more reliable than one with a modulation anode, and three types of cathode pulsed modulators were considered for this project. The three cathode-pulsing modulators considered are the compensated switch and pulse transformer design[2], and two types of fast IGBT power supplies. The compensated transformer coupled design is a design in which the capacitor bank droop is largely canceled by a second, low energy storage capacitor circuit. This circuit was developed at FermiLab for the TESLA klystrons, and for long pulse lengths above 1 ms, it is simpler and less expensive than the conventional pulse transformer and pulse forming network designs. It is possible to eliminate the modulator completely and simplify the pulsed-power system if we had a very fast power supply that could rise to 120 kV in less than 0.1 ms. This may well be possible with the current IGBT technology, and two types of such fast power supplies are being considered for this application. We discuss and compare the advantages and disadvantages of various modulator designs. Reliability, total costs and the ability to easily double the pulse length are important attributes for this application. The klystrons will frequently arc, especially when they are new, and the modulator must not damage the klystrons when they arc.

[1] *Work performed under the auspices of the US Department of Energy.

II. The Floating-Deck Modulator

A block diagram of a floating deck modulator RF system is shown in Fig. 1. The major advantage of this system is that several klystrons can share the

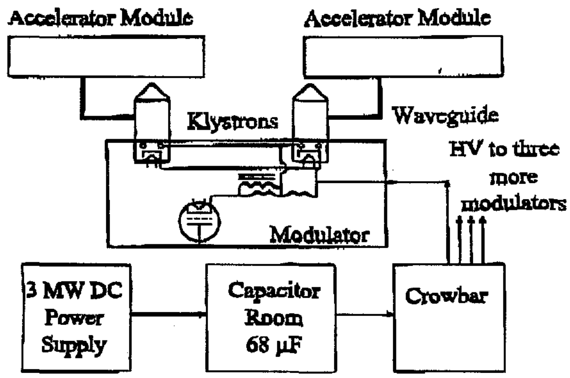

Fig. 1 block diagram of the floating-deck modulator.

same capacitor bank and crowbar, so the pulsed power costs, and the overall technology, are low. The two major disadvantages are that the energy storage capacitors must hold 10 to 20 times the pulse energy, and that high voltage is on the klystrons at all times. The first problem makes for a fairly large capacitor bank, and the second one can shorten the life of the klystrons. A minor disadvantage is that the klystron itself must have a modulation anode in it, and this raises the capital costs of the klystrons by 5 to 10%, and requires a second high voltage insulator, which can fail. Another problem is the reliability and maintenance of the capacitor bank. Dust must be controlled, and the procedures must be developed and followed carefully to mitigate the hazard of the high stored energy.

The SNS klystrons are rated at 2.5 MW peak power, the RF pulse length is 1.09 ms, the repetition rate is 60 Hz, and the minimum efficiency is 55%. With one switch tube in the floating-deck circuit, the sum of the rise and fall times is approximately 0.16 ms, so the (video) power pulse must flow for 1.25 ms. The peak video power is then 4.545 MW per klystron, and the video energy per pulse is 5.68 kJ. At the full 60 Hz repetition rate, we must deliver 340.8 kW of average power to the klystron. The klystron is now under development, and it requires a maximum of 120 kV, and 37.88 A peak. The capacitor bank voltage will decrease during the current pulse, and a 5% voltage droop is as large as can be tolerated from phase and amplitude control considerations. This requires a minimum capacitance of 7.89 mF, per klystron. The energy stored on the capacitor is then 56.8 kJ, or 10 times the pulse energy. A smaller voltage droop would be better, since the klystron power and phase would then be more constant, but this would require an even larger capacitor bank. A simplified schematic of the modulator itself is shown in Fig 2.

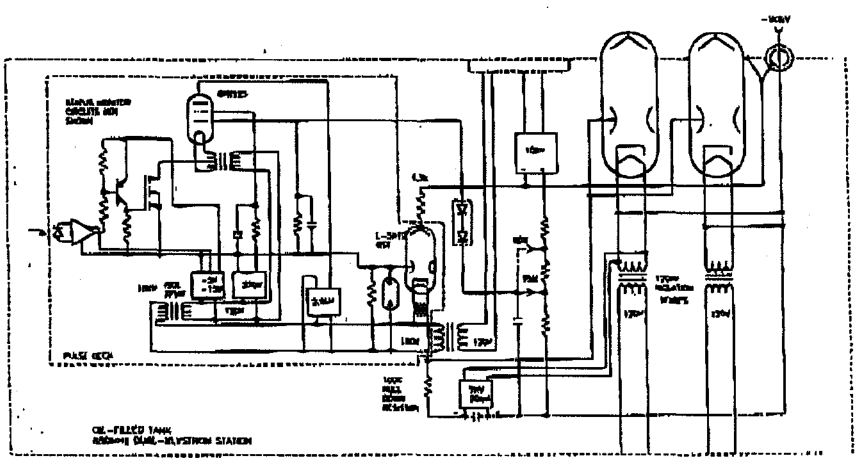

Fig 2 Schematic diagram of the floating-deck modulator

The most expensive item is the switch tube, and more than one klystron can be driven by a single switch tube. In the SNS baseline design we choose 8 klystrons per power supply and capacitor bank, and two klystrons per modulator. A more detailed description of the floating deck modulator is in [1]. The voltage droop can be reduced by either passive[3] or active[4] compensation in the modulator, but space limitations prevent a discussion of these methods here, except to note that the parallel RL circuit in Fig. 2 is a type of passive compensation circuit.

III. The Fast IGBT Power Supply

A common method to build power supplies at powers below 1 kW is to have a rectifier, followed by a high-frequency switch mode power supply, which is a dc-to-dc converter. By largely eliminating the 60-Hz magnetics, the supply can be made smaller, lighter, and more economical. One trades silicon for iron, and as power switches become less expensive, the break even point in power increases with time. If the power supply can be made fast enough, the modulator, crowbar, and high-voltage storage bank can be eliminated, along with considerable cost reduction.

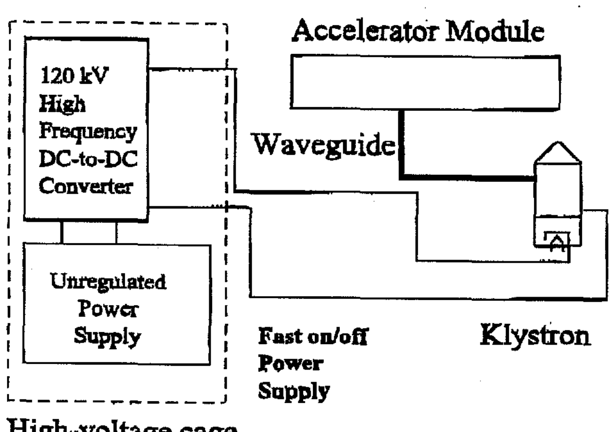

Fig 3 Block diagram of the fast pulsed power supply

A block diagram of the proposed system is shown in Fig. 3. The power supply must be able to rise to full voltage in under 0.1 ms, and to keep the system efficiency high, a high frequency (several kilohertz), multi-phase, current-fed, resonant or quasi-resonant chopper is used in the dc-to-dc converter in Fig. 3. Several possible circuits for the converter are being considered, and a quasi-resonant, current-fed boost circuit with a 12:1 step-up transformer is one of the leading candidates. The transformers will be relatively small, due to the several kHz operation frequency, and we realize that there are many significant challenges to make such a system work reliably and without a failure cascade when one component or the klystron arcs. In this type of converter, the power supply can regulate, so the stored energy can be lower than in the baseline system. The plan is to store the energy at about 10 kV, where the energy density and capacitor costs are favorable.

IV. The Medium-Speed IGBT Power Supply

Commercial vendors make power supplies that can be modulated in the 6 to 18 kHz range for short-wave AM transmitters. All the magnetics operate at 50 or 60 Hz, so the transformers are large, but they can be reliable. A simplified schematic of one such power supply, called a solid-state power module is shown in Fig 4.

For this circuit, 96 separate power supplies are operated in a series configuration. These individual supplies are powered by four separate power transformers to give 24-pulse rectification of the 60 Hz power.

V. The Compensated-Transformer Modulator

The compensated transformer modulator is like a conventional PFN modulator, except that a capacitor bank, rather than a pulse-forming network is used to store the pulse energy. The capacitor droop during the long pulse may be passively compensated by a switched LC circuit that is in series with the pulse transformer. If there is a logic circuit to choose the time that the compensation circuit operates relative to the main pulse, active compensation is possible. The pulse transformer may also be smaller than in conventional designs, since some of its droop may

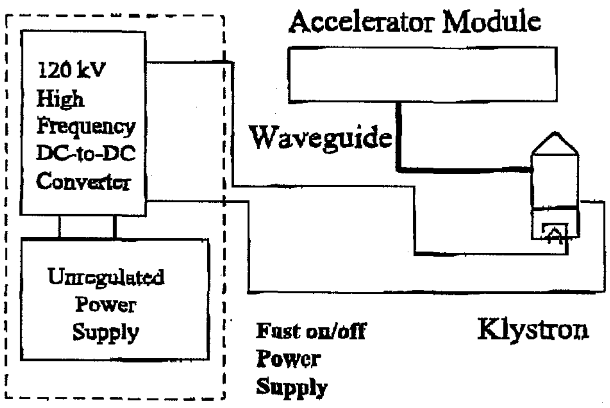

Fig 4 Block diagram of the multiple fast-pulsed power supply system.

be canceled by the compensation circuit. This circuit has been developed at FermiLab, and used for 1 to 2 ms klystron modulators[2]. A simplified version of the circuit is shown in Fig. 5. For long pulses, above 1 ms, this circuit is less expensive than the conventional PFN circuit with a thyratron switch, and one would expect the reliability to be better, although not much life experience has been accumulated to date.

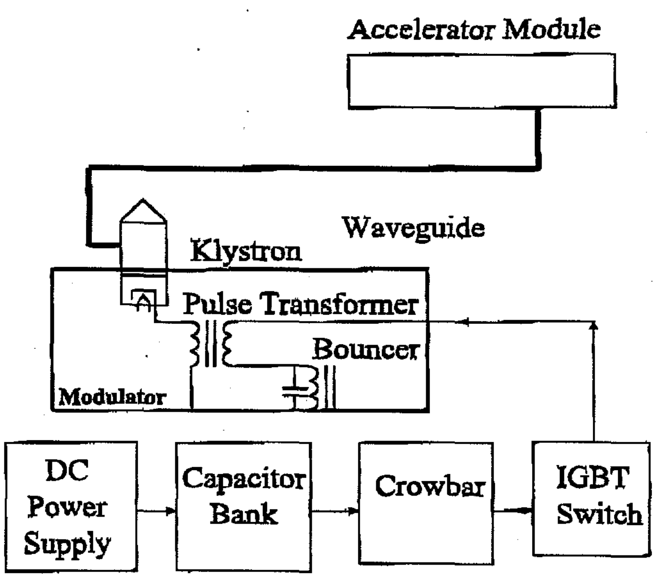

Fig 5 Block diagram of the compensated pulse transformer modulator

VI. Conclusions

Long-pulse, high-power, high-voltage modulators present difficult design choices, since no one technology is able to meet all the desired characteristics. The solid-state power modulator seems to have real cost and maintainability advantages, but these details are still being worked out. However, the trends are to solid-state switches replacing the previous thyratrons and vacuum tubes, and more silicon power devices to replace the previous switches and large transformers. For the SNS application, we prefer the high frequency, switched dc-to-dc converter, but we will retain the conventional floating deck modulator as a backup until the advantage of the newer circuits can be conclusively proven.

VII. References

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