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Modulator R&D for the NLC

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Abstract

Planning for the Next Linear Collider (NLC) continues at SLAC, Fermilab, and Lawrence Livermore Lab with help from many other members of the high energy physics community. The frequency of the proposed accelerator is X-band. An X-band klystron developed at SLAC has produced 75 MW peak power capable of driving the NLC. Modulator development to drive this klystron is proceeding on two interconnected paths, one using IGBT (Insulated Gate Bipolar Transistors) switched induction cores to drive multiple (8) klystrons, and the second path supported by SBIR grants looking at direct IGBT switching or IGBT switches in conjunction with optimized conventional pulse transformers. Conventional thyratron modulators are not yet out of the picture as the long term reliability of IGBT's in pulse service must still be proved. This paper reviews some of the modulator designs current in development.

Introduction

A primary goal of physics is to understand the forces of nature, and in some simple and unified way. In the 17th century, Isaac Newton formulated the laws of terrestrial and celestial mechanics. In the 19th century, various theories of electricity and magnetism were unified by and English country gentleman, James Clerk Maxwell in his famous Maxwell's equations. In the 1920's, the revolutionary theory of quantum mechanics was born, and Albert Einstein searched for a "unified field theory" to combine his general theory of relativity with gravitation and electromagnetism. Today's physicists speak of the "Standard Model" which unifies electromagnetism with the weak interactions, and describes strong interactions as well. In the area of the weak interactions, heavy W and Z particles have been found, but to make the theory consistent, physicists need a new class of particles, one or more, that now have been called the Higgs after Peter Higgs who first described the quantum field which gives rise to the mass of these particles. How heavy are these particles? In terms of the equivalent mass/energy, they can be anywhere from 20 GeV to over 1.5 TeV! We haven't seen them up to 100 GeV in our present machines, and the Next Linear Collider (NLC) is proposed to operate in the center of mass energy range of 500 GeV to 1.5 TeV if fully upgraded to maximum potential. If the present version of the "Standard Model" is to survive, then the Higgs particle(s) will need to show their presence somewhere in that energy range.

*Operated for the DOE by Stanford University

Colliders and the Klystrons That Drive Them

There are two main types of colliders currently in existence or in advanced planning stages. In exploratory studies is a third class of collider, the muon collider, but a practical design of such a machine is far in the future. Present designs are the electron-positron colliders, and the hadron (proton-anti-proton) colliders. Hadron colliders are usually circular. Since protons are much heavier than electrons, the synchrotron radiation losses in looping charged hadrons through many acceleration passes in a large ring are manageable, and the multiple passes of hadrons through the interaction region allow much greater probability of recording significant events. The Large Hadron Collider (LHC) currently being constructed at CERN in Switzerland is an example of such a machine. The canceled SSC was also a machine like this.

The largest electron-positron collider that has operated these last few years is the Stanford Linear Collider (SLC). This single linac with large arcs allowed collisions of electrons and positrons at a center-of-mass energy of 100 GeV. The Z particle was extensively studied with this machine at its 91 GeV energy. Beyond 100 GeV, beam transport arcs are no longer feasible due to the large synchrotron radiation energy losses. Two linear accelerators pointing at a central interaction region must be used. The current NLC is such a design. It consists of two main linacs at X band powered by over 1,600 75 MW X band PPM focused klystrons. Various designs for the pulse modulators to power these klystrons are outlined in the following sections.

The present klystron operating parameters are given in the table below:

Klystron Cathode Voltage:	500 kV
Klystron Perveance:	0.75 μperv
Klystron Cathode Current:	265 amps
RF Pulse Width:	3 μsec
Pulse Rep Rate:	120 PPS
Peak RF Output Power:	75 MW
Number of klystrons on one modulator:	either 2 or 8

These parameters are being used in the planning for the NLC, but R&D is continuing on klystron improvements. Some preliminary R&D is focusing on multiple beam klystron designs that operate at beam voltages under 200 kV. If this effort produces a viable design, the cathode modulator for such a klystron, or group of klystrons becomes much simplified. For now, though, let's review possible pulse modulator designs for the 500 kV klystron.

The PFN-Thyratron-Pulse Transformer Modulator (drives 2 klystrons)

This modulator has been referred to as the Cost Model modulator as it is a standard design that, in various embodiments, has millions of hours of operating experience at SLAC and other laboratories. A current design, with NLC needs in mind, is shown in figure 1. This design is optimized for fast switching, relatively high efficiency, and compactness integrated with two X band klystrons in one tank. At this writing, it is about ready to be put into operation in the SLAC Klystron Test Lab. Once this operation is characterized, the modulator will be used in regular X band klystron testing service.

Figure 1: Two X band Klystron Thyratron PFN Pulse Transformer Pulse Modulator

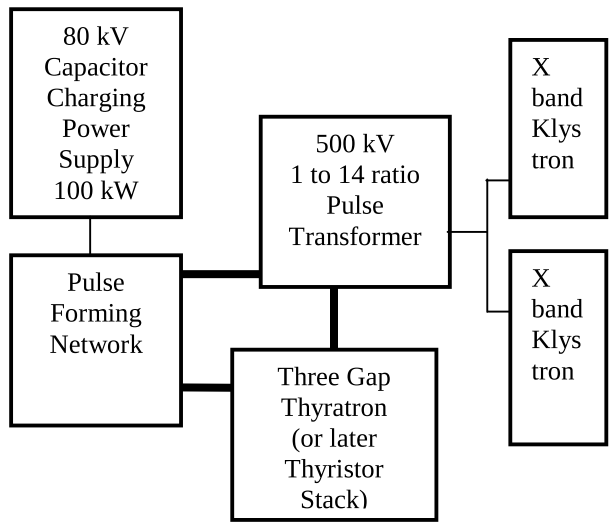

Figure 2: PFN Thyratron Pulse Transformer Modulator Block Diagram

The IGBT Induction Modulator (drives 8 klystrons)

This modulator design shown in the block diagram of Fig. 3 has been the subject of much R&D in the Power Conversion Department of SLAC over the last year. Currently available IGBT's can switch 4 to 6 Megawatts of power with rise and fall times less than 200 nsec. The voltage – current region of operation is 2-5 kV and 2-6 kA. The induction modulator design concept uses multiple IGBT switching board assemblies each driving a Metglas core. By stacking these cores, a secondary winding through all of the cores, one to three turns, can provide an output voltage of 500 kV.

To make maximum use of the IGBT capability and the core material, this particular design is optimized to drive 8 X band klystrons.

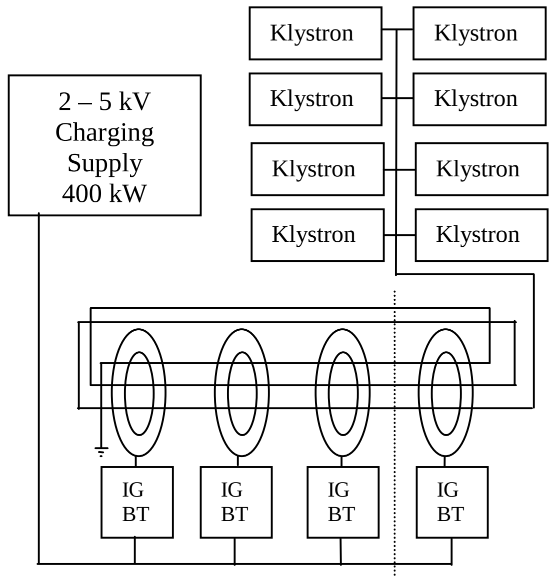

Figure 3: Induction IGBT Metglas Core (up to 80 cores) Modulator (8 klystrons)

The Hybrid IGBT Modulator (2 klystrons)

The Hybrid modulator design is shown in block diagram form below. This design is currently being developed by Diversified Technologies, Inc. (DTI) on an SBIR grant.

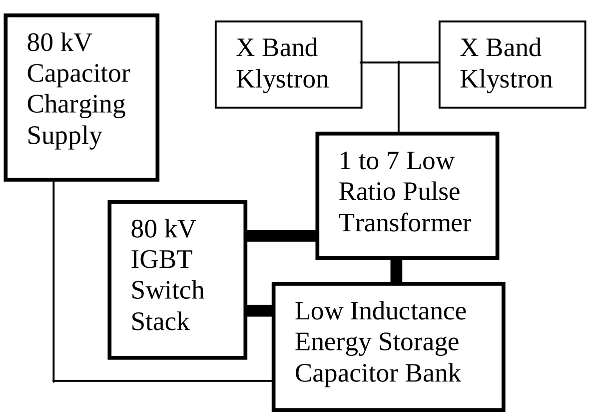

Figure 4: Hybrid Modulator Block Diagram Two klystrons

This modulator design can be optimized for a wide variety of applications with little changes in the basic design. The 80 kV IGBT switch stack can deliver up to 3-4 kiloamps into the low ratio pulse transformer. Low inductance primary current pathways, and the low ratio pulse transformer should allow rise and fall times on the klystron cathodes to be in the order of 300 nsec. This configuration allows maximum protection of the klystrons in the case of cathode-anode arcs as energy storage in stray capacity is limited, and the IGBT circuitry can shut off the primary pulse current is less than 500 nsec. A two socket modulator-klystron assembly is still small enough to be replaced as a unit and serviced at a depot location. An example of this type of modulator should be operational by the end of 2001.

The Direct High Voltage Switched Modulator, two Variants

Direct 500 kV Switch: Direct, high voltage switching of pulses from a high voltage capacitor bank has been an elusive goal of several researchers over the last 50 years. A few high voltage triode or tetrode switch tubes have been constructed, but nothing at a 500 kV level is in existence. There is some possibility that a very large stack of IGBT switches packaged to minimize energy lost to charging and discharging stray capacity could finally bring this direct switching goal within reach. A good high voltage multiplier type power supply must be developed which is housed within the same enclosure as the high voltage switch assembly, and the whole system must be protected carefully from arc damage. DTI is researching such a system on an SBIR grant, and will have some proof-of-principle experiments in place during the next year. A block diagram of such a system is quite simple, and is shown below:

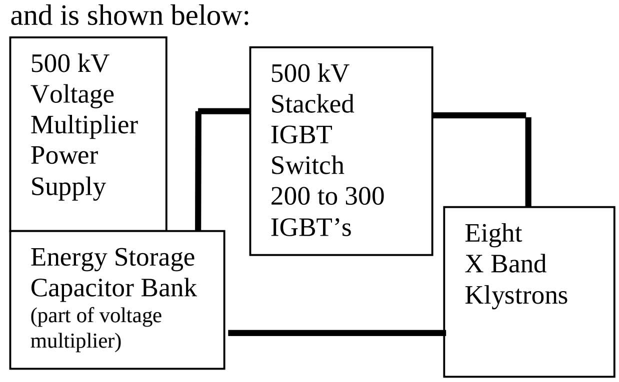

Figure 5: Direct High Voltage Switch Modulator Eight X Band klystrons

Marx Direct Pulser: Marx generators for producing very high voltage, fast pulses have been around for a long time. These designs traditionally used triggered spark gaps to allow a string of capacitors or PFN's to be charged in parallel, and then quickly discharged in series. A very interesting modulator design comes about when the spark gaps in a Marx chain are replaced by fast on-off switches such as IGBT's. At modest voltages, 10 to 25 kV, this design produces a pulse modulator that is very compact, and has a very flat pulse. A paper at this symposium by Dr. Anatoly Krasnykh describes and gives the results of a 10 kV TWT pulser design. A simple diagram of a Marx system is shown below:

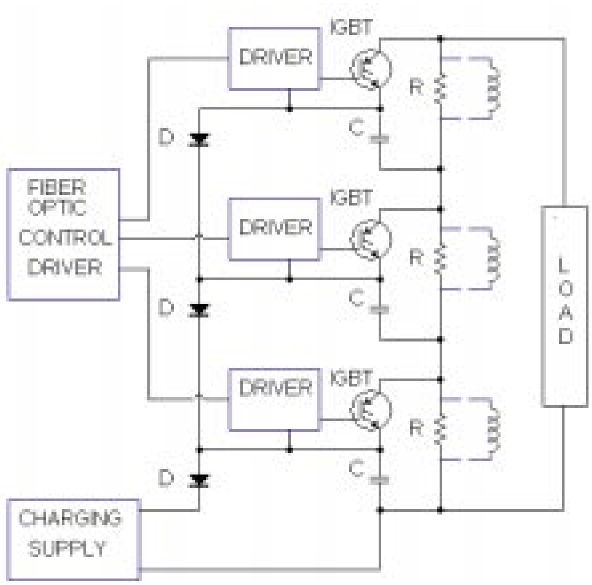

Figure 6: Marx Type Modulator (2 klystrons)

At higher required pulse voltages, DTI is studying the possibilities and limitations of a Marx design as part of an SBIR grant. On the plus side, such a design eliminates the need to handle direct high voltage (500 kV) DC since the 500 kV exists only when the IGBT's are turned on, and the 500 kV pulse is formed. At other times, only the relatively low charging voltage is present in the system. On the minus side of this same argument, since all of the energy storage and switching elements are very close to ground potential during the interpulse periods, all of these elements must be raised to various percentages of the output voltage potential each pulse. Energy is lost in this charging and discharging of the stray capacities, and there is also a potential for ringing in series inductance elements during this switching transient. This problem gets worse as the square of the output pulse voltage. It will be interesting to see if a 500 kV pulse voltage design is feasible.

Conclusions and Projections

Since point contact transistors were born in Bell Labs a half a century ago, designers have been waiting for solid state devices to appear that are robust enough to handle megawatts of power. Thyristors and IGBT's are now fulfilling many of these needs, but until recently, the switching speed of high power solid state devices, and their penchant for destroying themselves under high di/dt fault conditions precluded them from use in short-pulse high-power modulator service.

Now, with large quantities of IGBT's in service in low frequency power controls such as electric trains, and with several researchers exploring the high di/dt limits and protection for these devices in pulse power applications, we are ready to see many of the above described designs coming into wide usage. Compact, high efficiency, and high reliability solid state pulse power is just around the corner. Read on for detailed descriptions of such systems in the papers following at this symposium.