A NEW PULSE MODULATOR FOR THE ZERO GRADIENT SYNCHROTRON LINAC*

J. Abraham and N. Sesol
Argonne National Laboratory
Argonne, Illinois

Summary

Design and construction of a 15 MW pulse modulator has begun at Argonne National Laboratory to replace the unit in present use. The unit, which employs a single switch tube, is capable of regulation during 50-200 μsec beam pulses in a regulating loop which includes the entire linac. A dual fast-fault protection system incorporates clamping of the switch tube and a backup system which terminates the drive signal during load faults. Design data and operating characteristics will be discussed.

Introduction

The rf system of the Zero Gradient Synchrotron (ZGS) linac requires a pulsed anode voltage which is obtained from a hard-tube modulator. The original equipment employed four tubes in series-parallel since a single tube (ML-5682) could neither hold off the supply voltage, nor supply the required current. The circuit, due to this configuration, was sensitive to voltage unbalances, nonuniform tube aging, and other effects, not clearly understood, and resulting in a high crowbar rate.

Advances in vacuum tube technology later made several tubes available which could supply the necessary pulse power and also hold off high voltages. The decision was made to take advantage of these developments and to design a modulator incorporating a single switch tube. The tube selected was the type 8461, a 40 MW, 80 kV triode. This modulator, installed in the linac transmitter in July of 1966, is capable of producing 12 MW pulses in a resistive load equivalent of the rf tube impedance. However, difficulty has been experienced with the voltage holding capabilities and life of the switch tube. To date, the fifth new tube has been installed in the circuit and is in the process of failing. The manufacturer has recently reduced the anode voltage rating of the tube from 80 kV to 65 kV, and tube number five has sparked internally a few times after some four-hundred hours of spark-free operation, a record. This sparking seems to be initiated by a signal pulse, however, the sparks usually occur a few hundred microseconds after the pulse. Since the drive signal of the rf tube is not present at this time, the rf tube has no bias to limit its' anode current so that the only protection for the rf tube under these conditions is the rapid firing of the crowbar.

Upon installation of tube number five, the supply voltage was reduced to 40 kV so that this is the highest dc voltage applied to the tube to date. The average life of the tube in our circuit is 3,000 hours. A thorough examination of all circuit voltages during normal operation does not reveal any transient instability which might explain this behavior. During a crowbar, a 16 kV spike occurs on the tube anode so that the instantaneous voltage is 66 kV when the dc anode voltage is 50 kV.

The construction of a new modulator has begun as a replacement for the present unit. The switch tube used in this circuit is the ML-7560, a 15 MW, 50 kV high vacuum triode.[1] The tube has proven reliability as a pulse modulator in the AN/APS-27 radar which has a 50 kV anode supply and uses four tubes to produce 1000 A pulses of 30 μsec duration. Typical lifetimes of 12,000 to 14,000 hours have been reported. The tube, when supplied with a one-litre pump, is designated ML-7560V and is useful in high voltage conditioning after long shutdown periods. Once the tube is conditioned, no pumping is required.

Circuit Design

The modulator consists of four stages connected in a floating deck configuration such that all stages are at output pulse potential during signal conditions. In this scheme the rf tube, which is the RCA-7835, is the load and is connected from the switch tube cathode to ground. The drive signal is obtained from a pulsed rf power amplifier located in the control room, the center frequency of which is 26.25 MHz. Error signals, derived from the linac cavity, are modulated on the 26.25 MHz pulse and, therefore, appear on the rf tube anode pulse to correct for beam loading. The bandwidth of the amplifier is 8 MHz to provide a short modulator rise time and regulator loop stability (Automatic Level Control - ALC).

The signal from the control room is connected to the input filter of the modulator by means of a coaxial cable as shown in Fig. 1. The signal level

*Work performed under the auspices of the U.S. Atomic Energy Commission

at this point is 15 W peak pulse and produces an output pulse voltage of 26 kV and a current of 150 to 200 A. The filter has a bandwidth of about 8 MHz and performs the function of a bandpass transformer, the input impedance being 50 Ω and the output impedance 1100 Ω. This output impedance matches the input impedance of the isolation transformer which has a 1:1 impedance ratio and is capable of holding off the high pulse voltages. The transformer is a tuned, transitionally coupled bandpass-type having a bandwidth of 10 MHz at 26.25 MHz center frequency. The purpose of the filter is twofold, i.e., it produces the necessary impedance transformation from 50 Ω cable to 1000 Ω transformer, and it filters out the radiated rf from the rf power amplifier which can affect the operation of the modulator under certain tuning conditions.

The first stage V_1, is a plate circuit detector which has several attractive features that make it particularly well suited for use in modulators. It has large dynamic range, good sensitivity, selectivity, voltage gain, bandwidth and is capable of producing large output signals, eliminating the need for low-level amplifiers. The tube is a 7271 beam power tetrode having a plate voltage rating of 1350 V and a plate dissipation of 80 W. The detector is self-biased and has a conversion gain of 22 dB (ratio of dc output pulse to rf input pulse) and, with the 1200 V plate supply voltage, is capable of producing 700 V pulses. The tube input capacity is used as part of the tuning capacity of the transformer secondary to produce the 10 MHz bandpass response. The plate current flows in 26.25 MHz pulses since the tube is biased near cut-off and the plate circuit time constant produces a low-pass output response to about 700 kHz. This response has been determined by measurements of pulse rise time on the present modulator in which V_2 is a triode (3CX2500) which has a high value of Miller capacity. Since V_2 is a tetrode in the new modulator, this bandwidth should increase by about 300 kHz. The detector is operated in a bootstrap configuration and, due to its high sensitivity, is enclosed in a copper shielding box which allows convection cooling. If the tuned transformer is disconnected, the input circuit has a low-pass response also and the detector becomes a pulse video amplifier.

The ML-7560 requires more driving power and higher pulse voltages than the 8461 so that a change in tube type is required for V_2 which is the Eimac 4CX5000A, a radial beam power tetrode with 5 kW plate dissipation and plate voltage rating of 15 kV. It is bootstrap connected, and must supply an output pulse of 6 kV at 12 A to the succeeding stage. The voltage gain of the stage is 12 or 21.6 dB, and since it must drive a cathode follower into grid conduction, it has a wide bandwidth (10 MHz). The cathode follower V_3 is quite straightforward and is essentially the same as used in the present modulator except for an increased plate power supply voltage 10 kV in the new circuit instead of the 5 kV used previously. The tube is a high voltage triode with a plate voltage rating of 40 kV and a plate dissipation of 60 kW, when water cooled. The total anode supply voltage is actually 14 kV since the cathode is connected to a negative supply as shown in Fig. 1. The voltage gain, when connected to the grid of the switch tube, is 0.8. The output pulse required to drive the ML-7560 is 4.55 kV and the total cathode current is about 60 A of which 55 A is required by the switch-tube grid.

The load for the ML-7560 switch tube is the RCA-7835, a 10 MW rf triode and its ac impedance varies between 130 Ω to about 100 Ω. For design purposes, a value of 110 Ω has been used throughout the modulator design and represents a severe condition. The resistance value requires 369 A for 15 MW for which the pulse voltage output will be 40.6 kV, the maximum rating of the rf tube. The driving power required is 258 kW and the power gain is 35 dB. Figure 2 shows the corresponding operating line on the constant current characteristics of the switch tube.

The negative grid current region of the tube characteristics is due to secondary emission by the grid and is a common cause of instability in triodes. The difficulty arises when current, flowing from the grid back to the driver or through the grid circuit impedance, produces a larger voltage on the grid than the driver and, therefore, producing a larger output from the switch tube. In the severe case, the driver loses control of the switch tube which can overvolt the load. In Fig. 2, the operating line crosses a region where the negative grid current can exceed 5 A or more. The usual method of stabilization requires the use of a swamping resistor which is wasteful of driver power, since low resistance values are required (100 Ω or less).

The use of a cathode follower obviates the need for a swamping resistor due to its inherently low output impedance which is of the order of 1/gm. For the ML-6696 the output impedance is less than 10 Ω at peak drive levels, and even at low plate currents (2 A) it does not exceed 13 Ω. Thus, the effect of the negative grid current, which must flow through cathode follower output impedance, tends to raise the cathode voltage at a rate of 10 V per A. Since the output pulse of the cathode follower is 4.55 kV at this time, the effect is completely negligible and the switch tube is controlled by driver during these conditions.

Protective Circuits and Devices

Local fault protection on the modulator deck is provided by thyratrons V_6 and V_5, while remote protection is accomplished by logic circuitry located in the control room which terminates the drive signal to the modulator. Since the round-trip travel time is long (slightly greater than 2 μsec) the thyratrons fire first to clamp both the switch tube and the cathode follower to bias, and the remote system is used as a backup. These protect against damaging load faults by limiting the energy expended in load arcs or short circuits and cannot protect the switch tube. If the fault clears quickly, the modulator will be ready to supply the next pulse; however, if either system fails so that the fault lasts for several microseconds, the crowbar fires after a period of time not longer than 4 μsec and the power supply will have to recharge the filter capacitor.

The thyratron clamp tubes[2] usually work without difficulty in short-pulse systems such as radars. In long-pulse applications, several difficulties arise which merit consideration. The circuit time constants and voltages must be properly adjusted or the clamp will simply interrupt the drive signal instantaneously and then turn the switch back on to possibly damage the load. The reason for this behavior is that the thyratron, which can pass a current as high as 325 A, will discharge the filter capacity of the switch tube bias supply thus bringing the tube out of cutoff. Figure 3 shows the appropriate waveforms where the fault occurs early in the signal pulse, i.e., at time T_1 after the start of the pulse at which time thyratron V_6 fires. Since the signal pulse is usually ramped (to compensate for capacitor droop) the cathode follower behaves as a constant current source with its cathode resistor shorted out. During the time T_2, the switch tube bias supply capacitor is being discharged from the value E_{cc} to E_{co} (cutoff) after which time the switch tube continues to conduct until T_3 when the bias supply has recovered to E_{co} cutting off the switch tube. A second thyratron clamp at the cathode follower grid will relieve the difficulty by removing the drive signal about 1 μsec later. The situation can also be improved by using a large bias voltage (E_{cc}) and/or a large value of filter capacitor in the switch tube bias supply which would result in the dotted waveforms in Fig. 3. An example will indicate the magnitude of these effects. Since the cathode followers' cathode resistor is shorted by the thyratron, its cathode current can easily double (120 A); and since the discharge circuit consists of the cathode follower plate supply capacitor (60 μf) and the switch tube bias supply capacitor (24 μf) in series with the tube and thyratron, the effective capacity is only 17 μf. The ML-7560 is biased 1 kV beyond cutoff and the normal modulator pulse is 500 μsec in duration, so that 140 μsec after time T_1 the switch tube will be in conduction. The remote protection system will have removed the drive before this time in case V_5 has not fired so that the load should be adequately protected. If any of these devices have failed at this point 4 μsec after the fault has occurred, the crowbar ignitron will fire and discharge the high voltage filter capacitor which must be recharged before the modulator can supply the next pulse.

The overload condition is determined by the magnitude of modulator current in resistor R_{10} (nichrome wire), inverted by the inverted-amplifier and then used to trigger a blocking oscillator. The blocking oscillator pulse then triggers V_7 and in turn V_6. One μsec later V_5 fires to clamp the cathode follower drive signal.

Conclusion

The capability of the new modulator is intended to meet the future needs of the ZGS linac. Since the nominal rf tube efficiency is 50% approximately 7.5 MW of rf power will be developed.

Acknowledgements

The assistance of L. Beverly in the design, construction, and testing is gratefully acknowledged.

References

1. Machlett Pulse Tubes for High Voltage, High Power Video, and RF Pulsing.

2. H. D. Doolittle, "High Power Hydrogen Thyratrons as Protective Devices," Cathode Press, Vol. II, No. 1, March 1954.

DISCUSSION

(J. Abraham)

FEATHERSTONE, CERN: I am interested in the trouble you had with the tube that is now in use. I presume that studies have been made of the actual working voltages that are being imposed on it. One of the real problems is the tendency to get a transient high voltage spike at the instant you cut off the tube.

ABRAHAM, ANL: We did not attempt to do anything about this spike. We have observed a 16 kV spike on our capacitor bank.

FEATHERSTONE, CERN: You are still within the nominal rating of the tube. Have you taken any of these tubes apart to find the nature of the failure?

ABRAHAM, ANL: No, however, the manufacturer did, and found the trouble to be the Rocky Point effect which, it seems, nobody understands. It is "internal tube sparking" probably related to the whisker growing problem. He finds upon opening a tube that whiskers have formed on the grid. The manufacturer does something to the tube, bakes it out and seals it again, sparks it a few times, and the tube cleans up and is serviceable again. He did this for us on one tube, that was in a condition such that it could be saved. The cathodes of the other tubes had deteriorated quite drastically, and the emission was very low.

NEAL, SLAC: It wasn't quite clear whether you have finished this modulator and operated it yet.

ABRAHAM, ANL: The switch tube was just delivered last week so it has been delayed. Except for the two stages which I pointed out, the modulator is the old modulator which has performed quite well except for the tube problem.

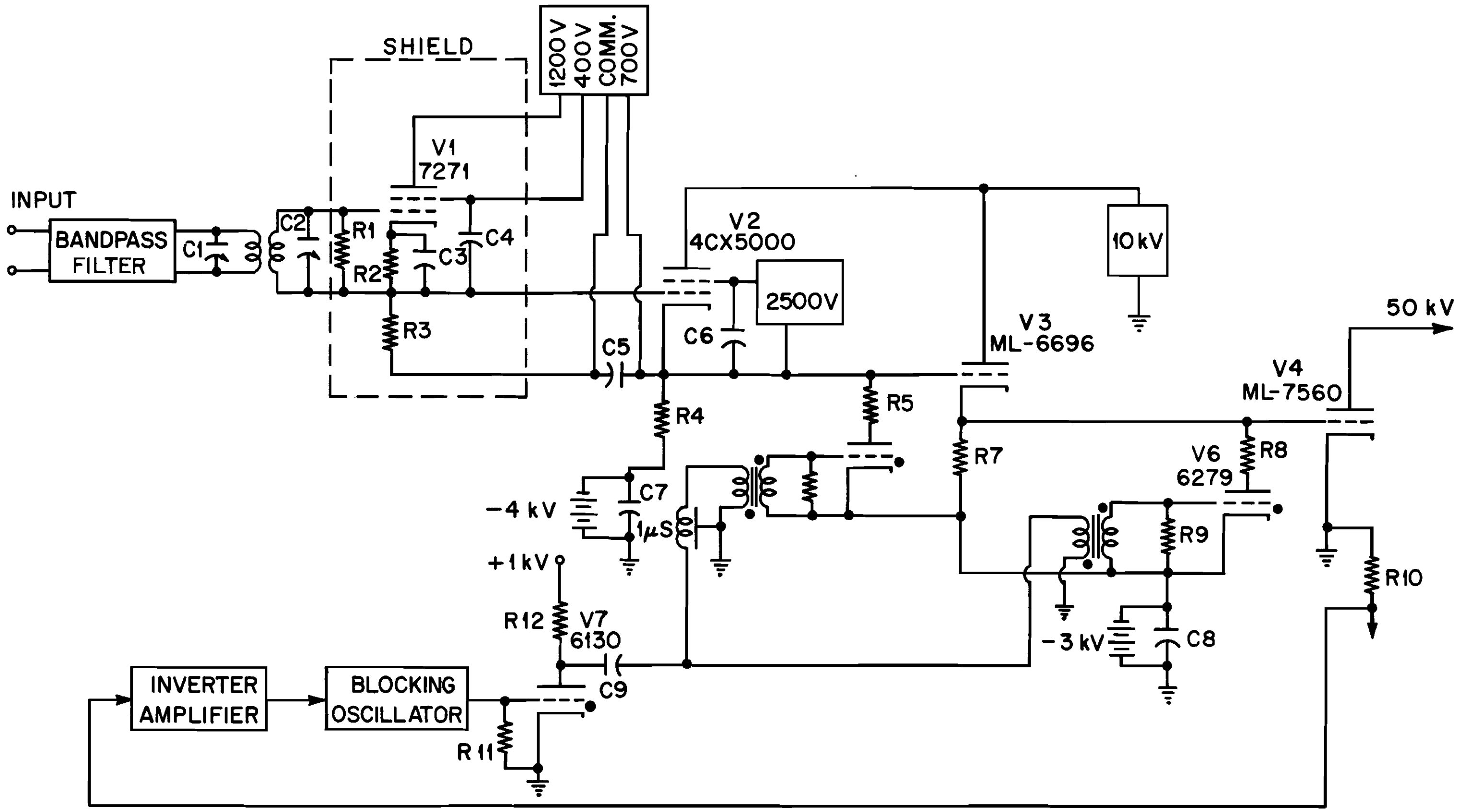

Figure 1 Simplified Schematic of 15 MW Modulator

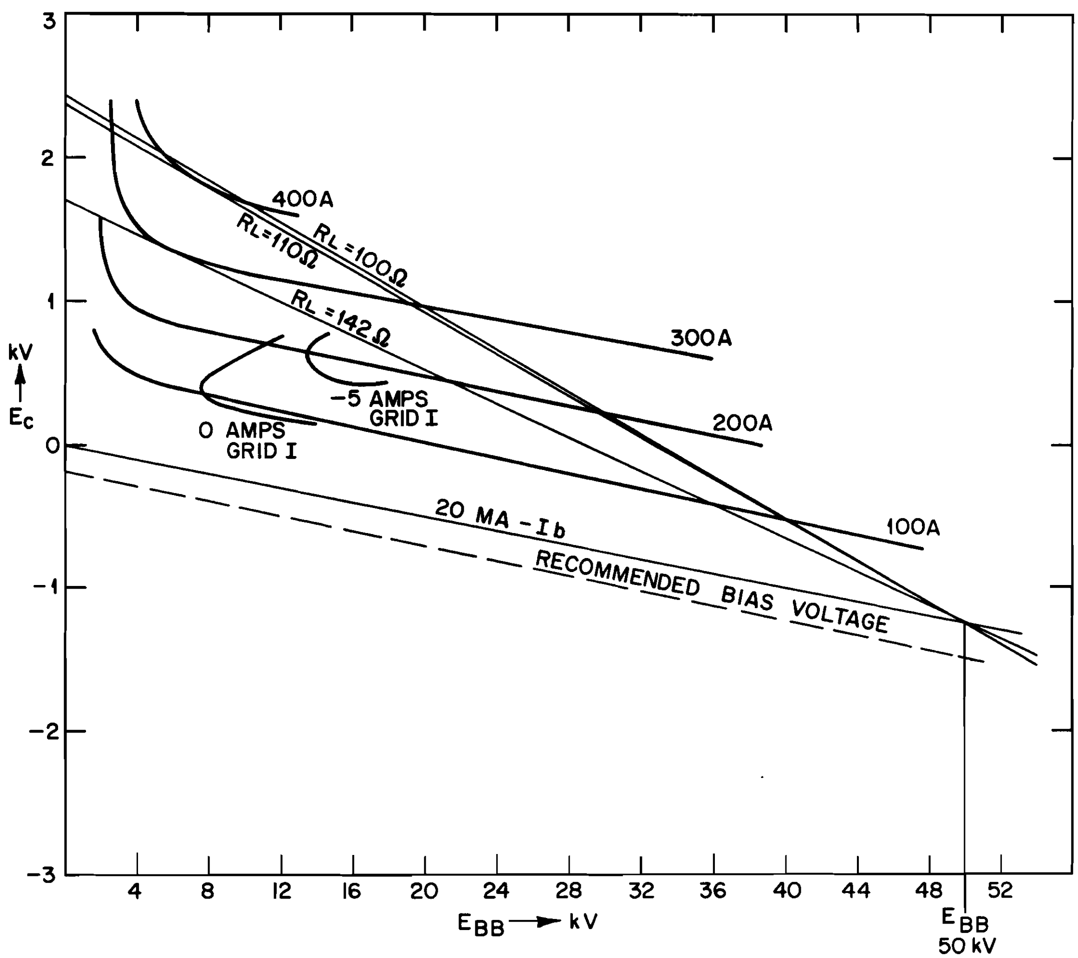

Figure 2 ML-7560 Constant Current Characteristics

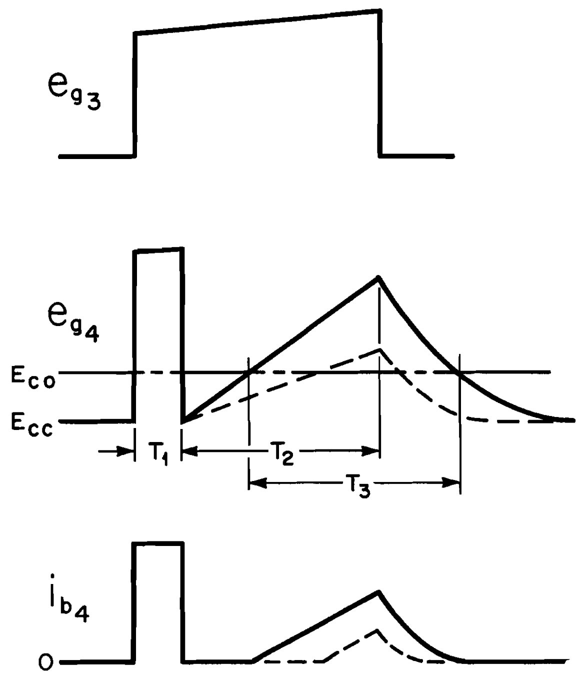

Figure 3 Waveforms During Load Fault Conditions