Modulator Reliability and Bandwidth Improvement:
Replacing Tetrodes with MOSFETs

A.R. Donaldson*

Summary

Three types of power MOS field effect transistors were studied with the intent of replacing a parallel pair of vacuum tube tetrodes in a linear modulator. The tetrodes have the shortest lifetimes of any other tubes in the system. The FETs offer definite performance advantages when compared to bipolar transistors and definite cost advantages when compared to vacuum tubes. Replacement of the tetrodes does however require careful consideration of voltage, current and to a lesser extent bandwidth capability in order to enhance overall modulator reliability without compromising present performance.

Introduction

The Fermilab linac modulators are 10 MW peak power linear systems which consist of three cascaded amplifiers[1]. The output stage is composed of three parallel switch tubes (ITT 1123). The switch tubes are driven by two paralleled triodes (ML6544) and the triodes are controlled with two paralleled tetrodes (4CX600J) The switch tubes have logged up to 80,000 hours of operation and average life has been approximately 70,000 hours. The triodes average lifetimes have bordered on 24,000 hours. The tetrode lifetimes rarely exceed 8,000 hours and average about 6,000 hours. As there are two and it is time consuming to determine the weak or faulty unit both are generally replaced which reduces operating life to about 3,000 hours between either scheduled and/or unscheduled repairs. Diagnostic circuitry which could pinpoint specific tetrode failures has been contemplated but never commissioned because of the required complexity, volume limitations and location of the stage at high voltage (a bootstrapped pulse amplifier) within the the modulator. Downtime repair personnel can enter the modulator and replace the tetrodes easily since they are compact, air cooled and socketed, and because of past poor confidence, they are always suspect.

Modulator circuit analysis and operation have revealed that the tetrodes are responsible for a system small signal bandwidth limitation at 300 kHz. Beam loading compensation is accomplished with a feedforward signal derived from a beam current toroid which with appropriate scaling offers load cancellation. However, the pulsed load cannot be quickly or completely transient cancelled because of the 300 kHz bandwidth limitation, furthermore bandwidth decreases with tetrode age.

Solid state replacement of the tetrode would be an obvious strategy for enhanced reliability. The first consideration is high voltage as the triode stage must be driven into positive bias which requires a typical 800V swing (where $0.5A \leq I_g \leq 2A$) to generate a 30 kV modulator output pulse.[6] For a 300 kHz bandwidth the necessary charging current is

$$i_c = C_L \, dV/dt$$

where: C_L is the sum of deck to deck, triode input and stray capcitance
dV is the necessary triode grid pulse
dt is the 10% to 90% rise time

$$i_c = (680 \text{ pF})(800\text{V})/(1.2 \ \mu\text{s})$$

$$i_c = .45\text{A}$$

To maintain optimum linearity the maximum current drive should be five to ten times greater, i.e., the source impedance should be 0.2 to 0.1 of the load impedance. The drive impedance is dependent on the dynamic plate resistance (r_p) of the tube and the load resistance (R_K). Decreasing the R_K in an effort to improve the bandwidth would probably decrease reliability and the tubes are in parallel to maintain a low r_p. For a 600 kHz bandwidth the charging current must be doubled. Then for linearity insurance the drive current should be 5A to 10A. This necessitates either four or five tubes in parallel or a semiconductor device with a low turn-on impedance. The turn-off time is controlled by the load capacitance and R_K, a smaller R_K will decrease turn-off time.

The recent introduction of power MOS field effect transistors and their supposed superiority for fast power handling compared with bipolar transistors initiated this tetrode replacement analysis. The MOSFETs do exhibit some definite advantages, i.e., wider bandwidths because turn-off is not controlled by microsecond-like storage times, negative instead of positive thermal coefficient for comparable properly heatsinked devices, no secondary breakdown voltage effect and supposedly higher input impedance[2]. The major disadvantage of power MOSFETs is high cost coupled with long lead times when compared to bipolar transistors, but these disadvantages are minor when compared to the cost, $470 per vacuum tube.

Table I lists the MOSFETs that were purportedly available and consequently acquired except for one. The table compares the published specifications and the test data betweeen devices. The BV_{DSS} and $I_{D(on)}$ were the primary selection criteria. The $I_{D(pulsed)}$ was measured with the FET in either a common source circuit or the bootstrap configuration with various resistive loads. The P_D ratings are published values and are more than adequate when the 0.006 modulation duty factor is considered. Furthermore, the modulator has adequate space and forced-air

---

*Fermi National Accelerator Laboratory P.O. Box 500, Batavia, IL 60510

†Operated by the Universities Research Association, Inc. under under DOE contract.

cooling which will ensure conservative heat sink design. The $R_{DS(on)}$ value is of minimal use for linear application as it describes the saturated switch resistance of the FET. The tetrode, however exhibits an r_p which is two to five times larger than the FET dynamic R_{DS}.

The table also provides actual threshold data, gain, capacitance and rise time data for two circuit setups. The input capacitance (C_{ISS}) and reverse transfer capacitance (C_{RSS}) coupled with the gain offer a prediction of the possible rise times.

The devices were tested in the order they arrived The Tokin device has the rather limited maximum operating voltage of 800V, but the triode stage only requires 700V to 800V of drive. Two I.R. FETs were connected in series with an appropriate resistive divider for a combined 1 kV maximum operation. The I.R. unit is in fact representative of U.S. involvement in the power FET market, all of the U.S. FETs have a 450V or 500V maximum limit. The 1 kV Siemens unit has beeen on order for the past seven months but recently an 800V device with reduced current capability became available and was tested.

The tetrode driver had to be redesigned to drive the FETs since they all exhibit input capacitances of 9 to 25 times that of the parallel tetrodes. It became obvious that the power FETs needed fast and low source impedance drivers. In spite of the high input impedance claim, it is only high during d.c. conditions and not the transient because of the high input capacitance. Fig. 1 illustrates the linear amplifier developed for comparison testing of the Tokin FET and tetrode. Both devices require a cutoff bias and then a positive voltage swing to near zero volts for linear operation.

The Tokin FETs exhibited an unfortunate and non-semiconductor-like performance variation with regard to speed and cutoff bias. The literature[3] describing the development of the Tokin devices does not offer any reason for the variations. The bias problem can be accomodated with the driver circuit as the cutoff bias can vary from -40V to -75V. The speed is dependent upon the driver swing but not absolutely as once fast device required a 40V pulse while another needed a 55V pulse and both had 200 ns rise times. The medium speed devices had 400 ns rise times and required 45V pulses for 700V non-saturated outputs (V_{DD}=800V). One Tokin FET the slowest, had a 600 ns rise time. All rise times quoted are for linear operation with a load capacitance of 680 pF and R_S=330Ω and faster times are possibly if the gate is driven positive to realize switch or saturated operation. The respective large signal bandwidths using

$$BW = .35/t_{r(10-90)}$$

are 1.75 MHz, 875 kHz, and 580 kHz. This three to one ratio could be reduced if the Tokin device were enclosed in a feedback circuit.

The Tokin FET has a bandwidth advantage dependent upon selection, a much higher current capability, but the output pulse is limited to 800V peak at saturation or less for linear operation. One Tokin device has been operated successfully for 600 hours with a V_{DD}=900V but considering the variation between devices it is not likely that this is a reliable operating value. The FET has a power dissipation rating of 300W at 25°C; triode drive requirements indicate the operating power dissipation is 3W to 5W for a .006 duty factor which implies very conservative application of the device.

The circuit of Fig. 2 illustrates the technique attempted for a series connection of lower voltage FETs. The voltages across the FETs are equalized with the high voltage divider and the FET at high voltage must be driven from an isolated source. The pulse transformer is an effective driver except that modulation duration is 330 μs to 400 μs and while the E×T rating of the transformer was large enough to permit full power operation the droop was unacceptable. Transformers with higher primary inductances are unfortunately slower. The inability to locate a commercial transformer with a fast rise time and large L_P meant that a linear light coupled isolator should be considered if the circuit complexity did not compromise reliability, but this approach has been temporarily sidetracked.

The third power FET tested was the 800V Siemens device The Siemens FET like the I.R. FET is an enhancement mode device. Turn-on can be accomplished with an 5 to 10V pulse referenced at zero. The gain of the device is consequently large. The circuit of Fig. 3 shows the Siemens unit and FET buffer driven by a fast operational amplifier. The Siemens FET would provide the most compact package for tetrode substitution the floating box would only require a ±15V power supply for a reduction in stray capacitance, and hence better bandwidth for equal or less charging current capability. The question of reliability however is postponed until the higher voltage and current unit becomes available for testing.

Remarks

Refer to Table 1 for operating data comparisons. The common cathode/source amplifier data is not as pertinent to FET selection as the bootstrap amplifier data but was easier to obtain, allowed grid and gate monitoring without h.v. isolation and offered an idea of the Miller effect capacitance. When the load capacitance can be minimized the bootstrap amplifier offers a definite bandwidth advantage.

The Tokin FET has the lowest gain and the element determining rise time is the C_{iss}.

The Siemens FET has the highest gain and hence, bandwidth is limited with the common source amplifier. The Siemens device was connected with a fast operational amplifier in a feedback bootstrap arrangement and with a 500V output pulse exhibited a 50 ns rise time but the circuit was unstable for a 700V output. Open loop circuit performance was evaluated and is presented in Table 1 offering a comparison with the other devices which were also evaluated open loop.

Until the 1 kV Siemens unit becomes available for evaluation the Tokin device although of limited h.v. utility and bandwidth is the tetrode replacement selection. It has operated successfully in the modulator and has more than adequate current and power handling capability. The triode stage does require a gain increase but this was easily accomplished and while triode lifetime may decrease slightly; the overall system reliability should be significantly improved.

Acknowledgement

The investigation was accomplished with the cooperation of Lester Wahl. He also made contributions to driver circuit design and operated the test modulator.

References

1. J.W. Younger and K.W. Sides, IEEE Trans. Nuc. Sci. NS-18, p. 529 (1971).
2. D. Gyma et al., Proceedings of Powercon7, p. D1-1 (1980).
3. J. Nishizawa et al., High Power Static Induction Transistors, Late paper, 1978IEDM.

TABLE 1

Model & Pkg.	Mfg. & Cost ($/ea)	V_{BB} Max. (V)	I_P d.c. Max. (A)	$I_{P(pulse)}$ (A)	P_d Max (W)	r_p (Ω)	V_{cc} Bias (V)	μ v_o/v_g	c_{in} (pF)	c_{gp} (pF)	t_r Note 1 (μs)	t_r Note 2 (μs)
2//Tetrodes 4CX600J	Eimac 470	3000	1.2	2.4	1200	∿800	-65 @ $I_p \leq 1mA$	30→50	100	.13	.45 v_o=700V	.4 v_o=700
Power MOSFETs		BV_{DSS} (V)	$I_{D(on)}$ @T_c (A) (C°)	$I_{D(pulse)}$ @ 25°C (A)	P_D T_c=25°C (W)	$R_{DS(on)}$ @$I_{D(on)}$ (Ω)	$V_{gs(TH)}$ @I_{DSS} (V)	μ v_o/v_g	C_{iss} (pF)	C_{rss} (pF)	t_r Note 3 (μs)	t_r Note 4 (μs)
2SK181 Super TO-3	Tokin 55	800	5 25	20	300	3	-75 to -45	10→20	2500	N.A.	.2→.6^5	.2→.6^5
IRF430 TO-3	I.R. 26	500	3.5 90	7	75	1.5	3	100	900	60	N.T.	.22^6
BUZ-80 TO-220	Siemens 17	800	3.3 25	2.5	45	2.6	2.7	400→ 800	1600	90	2^7	.45
BUZ-54 TO-3	Siemens 33	1000	4.7 25	9.4^8	100	2	2^8	N.T.	1200	N.A.	N.T.	N.T.

Note: (1) Common cathode amp. W/R_L=450Ω & C_L=680pF, (2) Bootstrap amp. W/R_K=450Ω & C_L=680pF, (3) Com. source amp. W/R_L=330Ω & C_L=680pF, (4) Bootstrap amp. W/R_S=330Ω & C_L=680pF, (5) Device dependent, (6) Transformer dependent, (7) Miller effect dominated, (8) Not verified, (N.A.) Not available, (N.T.) Not tested.

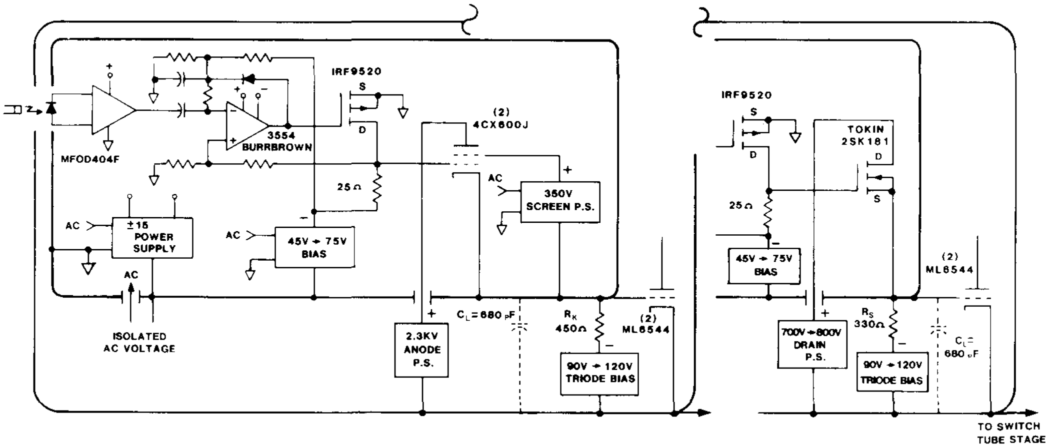

FIG. 1. Tetrode bootstrap amplifier with MOSFET replacement.

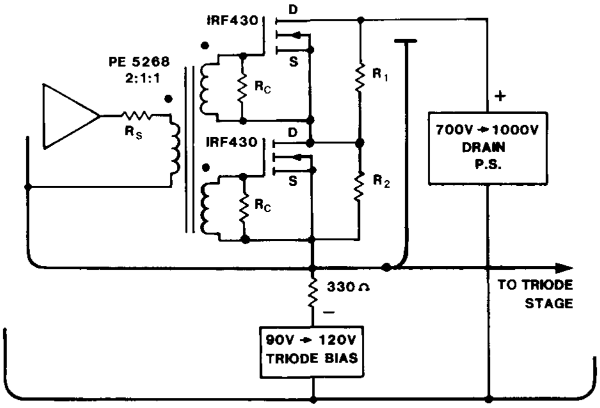

FIG. 2 Series FET circuit.

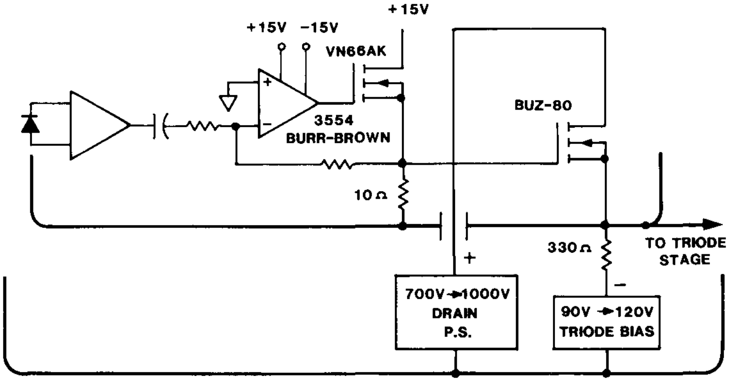

FIG. 3. Amplifier with the BUZ-80.