FAULT PROTECTION CIRCUITRY FOR THE LASL 201.25-MHz POWER AMPLIFIERS*

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When one considers the cost of modern high power tubes and associated gear, it is quite easy to justify the need to protect such devices from damaging faults, especially since this can be done at moderate cost. Even if the replacement cost was low, however, the cost of downtime for maintenance on installations such as the Los Alamos Meson Physics Facility is reason enough to justify extensive fault protection circuitry. All the rf power amplifiers that drive the linear accelerator will be protected against such faults as high anode current and rf arcs. The 201.25 MHz, three megawatt amplifier can be used as an example for discussion, since similar practices are followed in the 805-MHz amplifier system. A basic block diagram of the 201.25-MHz amplifier is shown in Figure 1. Basic fault-protection blocks are added in Figure 2. It should be noted that only fast fault protection, i.e., 0.1 to 20 μsec, is being considered. Such important protective devices as water flow interlocks, etc., are not included in the discussion.

The basic objectives kept in mind when designing the fault protection circuitry were:

(a) Sufficient protection was to be maintained with a minimum of downtime for the amplifier.

(b) Effective interfacing between the fault protection circuitry and the computer controls.

(c) Circuitry should be no more complex than necessary to perform the required functions.

The first objective obviously implies that reliable equipment must be designed for fault protection. There is a more strict requirement, however; that the fault protection shall be done in such a manner as to cause the least number of lost pulses consistent with correcting the fault condition. As an example, an rf power amplifier tube is certainly well protected if a crowbar is fired 2 μsec after the tube arcs, discharging the anode supply capacitor bank and tripping the circuit breaker. Before the proton beam can be turned on again, however, the power supply must be recycled on and the temperature of a portion of the accelerator structure may need some time to stabilize. In any case, the beam must be shut off for a period ranging from about 30 sec to a few minutes. It is well known that such arcs are not uncommon in gridded power tubes that have not been properly aged. It seems apparent that shutdowns due to this type of fault must be avoided whenever possible. The series hard-tube modulator can be the answer to this problem. It is possible, with the proper modulator tube, to extinguish a load arc by merely removing modulator grid drive. Under these conditions, an rf amplifier tube arc or similar fault may be corrected on a pulse-to-pulse basis. Since there is a general category of tube faults that occur on a random basis, with a minimum interfault period typically ranging from seconds to minutes, the series modulator is an excellent means for fast protection with a minimum of lost beam time. These frequent random faults generally occur only during rf tube aging, and it is hoped to have the larger rf tubes aged to some extent before they are installed in the accelerator facility. The crowbar still exists as the "last ditch" backup to protect the rf tube from faults when the modulator protection fails, and indeed, to protect the modulator circuitry when arcs associated with the modulator occur.

Low-Level Fault Protection Logic

The heart of the fault protection logic (FPL) is the pulse gate. (See Figure 2). This gate accepts a standard +10-V pulse and generates a new pulse that is the same width and relative phase as the input pulse. The output pulse height is +10 V, and is independent of the amplitude of the input pulse, except that the input must exceed approximately +8 V to operate the gate circuit. Therefore, the output is essentially the same as the input during fault-free operation. When any one of several fault-sensing circuits detects a fault condition, the pulse gate is inhibited within 0.1 to 1 μsec. The respective modulators fed by the pulse gate are then inhibited. The next pulse (8.3 msec later) will pass through the gate if no fault is detected. The computer is signaled that a fault has occurred. (Note the computer interface relay in Figure 3).

If several faults occur within a short period of time, a counter will shift the pulse gate into a permanent inhibit mode, blocking all future pulses until reset by operator command. A permanent inhibit by the counter will generally indicate that the rf module in question needs attention by a maintenance crew. The counter is an integrating type that "forgets" faults at a prescribed rate.

Associated with the pulse gate are various other logic modules that fall generally into two categories:

(a) Pulse conditioning circuits

(b) Fault detection circuits

The pulse conditioning circuits will typically operate on a standard +10-V logic pulse either by shifting it in time, dc level, peak-peak amplitude, or all three. These circuits are used where pulses must be delayed, special signal levels are required, etc.

The fault detection circuits fall into the general class of level detectors. An anode-current detector is merely a Schmitt-trigger type circuit that generates an output to inhibit the pulse gate whenever anode current exceeds 25% of its normal maximum value. An rf drive level

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detector will generate a permissive gate for an anode modulator whenever the rf drive to the tube in question is sufficient to prevent oscillations when anode voltage is applied. This circuitry is designed using both discrete components and Fairchild linear integrated circuits. An example of a VSWR-detecting circuit is shown in Figure 3. This circuit will detect a certain voltage ratio from a pair of crystal detectors mounted on a directional coupler. The ratio detected is independent of the absolute power level until the levels at the input (V_r and V_f) are similar in magnitude with the offset on the μ702 operational amplifier. This offset is introduced by adjustment of R_1 and helps to prevent false triggering during the interpulse period. The FPL is of printed-card construction and is mounted in standard Nuclear Instrument Modules.

The Modulator Grid-Clamp Circuit

Unfortunately, the removal of the video drive pulse from the modulator does not always insure actual modulator shutoff. Two phenomena may occur either alone or at the same time.

(a) When the modulator switch tube suddenly finds itself looking into a shorted load with full voltage on the power supply, its operating point is shifted radically. The plate voltage is now equal to the supply voltage and plate current is limited only by emission. This new operating point is generally in an area of high negative grid current, due to grid secondary emission. This negative grid current develops a positive grid-cathode potential and the modulator continues conducting, even with drive removed. Obviously, normal control of the modulator is lost.

(b) For reasons not entirely understood, some modulator tubes tend to arc from anode to grid and cathode under these circumstances. Gas bursts and high di/dt coupled with plate circuit inductance are suspected here.

The problem of negative grid current has been solved, or at least avoided by most modulator designers for years by means of a grid-clamping circuit. During a fault condition, a short circuit is rapidly placed across the grid impedance so that the modulator tube is shut off in spite of the initial negative grid current. This is typically done with thyratrons, although spark gaps and other gaseous switches may also be used.

These negative grid current characteristics were exhibited by a pair of 7482 triodes used in the 7835 modulator. The level of negative grid current would range from 10 to 20 A during a fault, and the grid-clamp circuit had to be installed. This circuit uses a sensitive SCR to detect fault current levels. A Krytron is used as the actual clamping element. The clamp circuit was tested by single-pulse driving the modulator into a spark gap. At first it was found that the clamp circuit worked well at operating voltages up to about 20 kV. Above this level the clamp would operate satisfactorily for perhaps 20 faults and would then literally explode on the next fault, accompanied by a crowbar. Investigation revealed that this was due to internal switch tube anode-grid arcing which effectively placed the entire capacitor bank across the grid-clamp circuit for a short period. Gas bursts in the modulator tube offer a possible explanation, since the peak dissipation during a fault reaches approximately:

$$(800\ \mathrm{A})(30{,}000\ \mathrm{V}) = 24\ \mathrm{MW}$$

There is also reason to believe that the high di/dt develops a significant drop across lumped and parasitic inductance in the anode circuit of the modulator, aiding the breakdown phenomena. With the lumped crowbar inductance in the circuit, the amplitude of this transient is approximately:

$$L\frac{di}{dt} = 10^{-4}\ \mathrm{H} \times 8 \times 10^{8}\ \frac{\mathrm{ampere}}{\mathrm{second}} = 80\ \mathrm{kV}$$

With the lumped crowbar inductance removed, the internal switch tube arcing was less frequent. The modulator designers are now using a new ITT version of the 7560 triode with a proprietary grid coating that exhibits little or no secondary emission and did not require a grid-clamp circuit during initial tests. Tests on a modulator using Eimac 4CW250,000 tetrodes will soon reveal whether the longer anode-grid spacing of such tetrodes is a significant advantage in the breakdown problem.

The Crowbar

In the event of an arc that is not quenched by fault protection circuitry associated with the modulator tube, a crowbar must be fired within a few microseconds to divert approximately 70 kJ stored in the 150 μF capacitor bank. The crowbar logic circuitry (see Figure 4) is equipped with a 1 to 20 μsec variable delay on amplitude tripping to allow time for the FPL and modulator clamp circuit to clear the fault whenever possible. The level of sensing is also set higher on the crowbar logic. (See Figure 5).

Aside from protecting against arcing or amplitude type faults, the crowbar logic will also sense a "long" pulse. This long pulse threshold is adjustable and typically set at 20% to 100% more than the maximum pulse width expected during normal operation.

Since this particular crowbar has two different loads to protect, the 7835 rf output tube and its 4616 driver, there are two separate input level and width sensing channels. When the crowbar fires, one or more of the following specific bits of information will be transmitted to the Central Control Room via local module controls and digital computer:

(a) 7835 amplitude fault
(b) 7835 pulse width fault
(c) 4616 amplitude fault
(d) 4616 pulse width fault

With this information, the operator will make a decision concerning whether to reset the crowbar and turn on again or to send a maintenance crew to check the module. His decision may depend upon the past history of the module and the rf tubes in the module. This decision making could be programmed into the computer if necessary.

A major question about fault protection equipment is: Will it function at that critical instant when needed? This is an important question since even one crowbar failure during normal operation can be very costly. There is, of course, no absolutely fail-safe circuit, and this especially applies when so many electrical components are required to function together in a prescribed way. Several techniques may be used to help avoid circuit failure. "Good Design" is taken for granted. Redundancy is a technique used where initial cost is not a problem. This solution does not apply very well to our case since initial cost and space are a concern. Another technique is "frequent testing". Experience with several rf test stands at LASL indicates that a very large percentage of crowbar failures are discovered by once-a-day type testing. Frequent testing will be the method depended upon in the Meson Facility.

All the circuits and techniques described have been tested at LASL, and the only major question remaining on fault protection is whether a grid-clamp circuit will be required on the modulator. Further tests of modulator tubes should reveal the answer to this question.

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DISCUSSION

(J. D. Doss)

PEARSON, AECL: How often did your crowbar operate when you didn't want it to? You emphasize the other aspect of it, that it might not operate in the safety equipment itself.

DOSS, LASL: Well certainly more often than we would like, but let me try to answer your question correctly. I might comment that our worst experiences were with an amplitron, a crossed-field amplifier where we had more than the usual noise problems. The 7835 triode 200 MHz system is about medium in this respect and the best is the klystron system which is quite noise free. But certainly we have this problem and are concerned about it.

TUNNICLIFFE, AECL: Do you have any information on flash arc rate of your 7835 when it is aged in, and do you know how the frequency of flash arcs is related to plate voltage.

DOSS, LASL: Generally, of course, the greener the tube, the greater the flash arc rate. Our experience indicates that if a tube is off the air for a day or a week, even though it has been aged we can expect a few of these arcs when we turn on again. I think other people have the same experience.

TUNNICLIFFE, AECL: What is the plate voltage on your 7835?

DOSS, LASL: The plate is pulsed to a maximum of approximately 30 kV.

SHEEHAN, BNL: We have been running the 7835 at about 36 kV and it appears that most of our "crowbars" are not due to the 7835. In a two week run, there were maybe one or two, that we can really attribute to internal tube flash overs.

DOSS, LASL: Do you think that the others are due to other faults somewhere else?

SHEEHAN, BNL: When you add in modulator, cables, protective circuitry, etc., you start looking for so many other troubles - that's what you end up detecting.

DOSS, LASL: I think our experience is probably not too different. It appears that cable and other breakdowns are three times as frequent as arcs in the tube.

We have just completed a run of 10 hours without any crowbars at all. We seem to have problems with the modulator "latch up", but not too many over-current type faults. You know, of course, that we have had system faults where the 7835 cavity blocking-capacitor broke down.

KEANE, BNL: When running the 7835 with the output short-circuited, internal arcing occurs when the plate voltage is about 33 kV to 34 kV. It is not possible to differentiate between cavity arcs and tube arcs. During five months operation, we were never able to positively say that we had a tube arc. The nominal forward power output with this plate voltage is 5 MW.

DOSS, LASL: That sounds encouraging.

WATERTON, AECL: You say that the crowbar fires undesirably in noisy situations. Do you think that noise gets in with your 10 volt triggering pulses or is it picked up by various components within your protective system?

DOSS, LASL: Whenever we see false crowbars, we always suspect low level trigger circuitry. In the case of the crossed-field amplifiers, however, we have had rf on the high-voltage leads fire the ignitrons directly. This, incidentally, soon ruins the ignitron.

NEAL, SLAC: There is some experience in the klystron field which suggests that the lifetime of klystrons and windows is improved significantly if the power and rf drive is brought up slowly (5-10 secs) after a fault. Does your fault system have such a slow turn-on?

DOSS, LASL: Presently no. What we do have is an arc detector with a good signal to noise ratio at the window which will respond in less than a microsecond. However, with our amplitude control system, the slow turn-on could certainly be achieved.

NEAL, SLAC: I do not believe that the faults, I am referring to, are associated with an arc at the window. They are window heating, bombardment from multipactoring, particles and so on. The original experience on this came from the Hansen Laboratories and following their experience this type of system has been put on all the SLAC modulators with protective circuitry. It is hard to say what long life experience can be attributed to this.

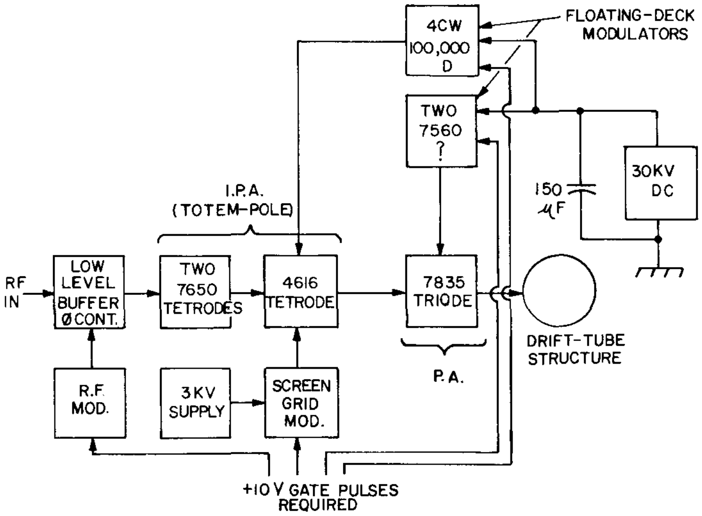

Figure 1 — Basic 200 MHz Amplifier.

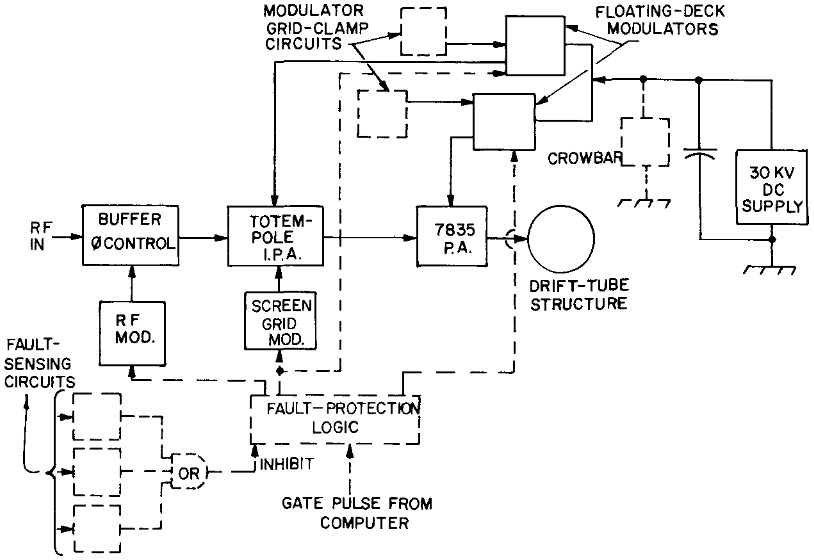

Figure 2 — Fault-Protection Circuitry Added to Basic System.

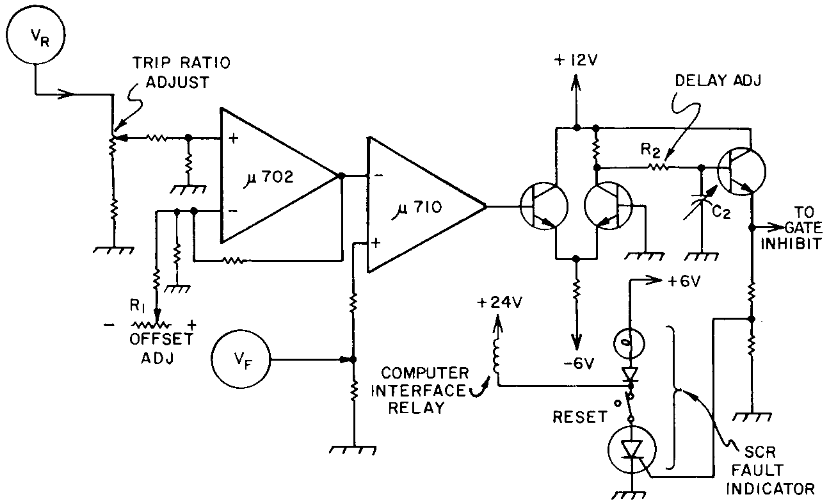

Figure 3 — Hybrid VSWR Detector.

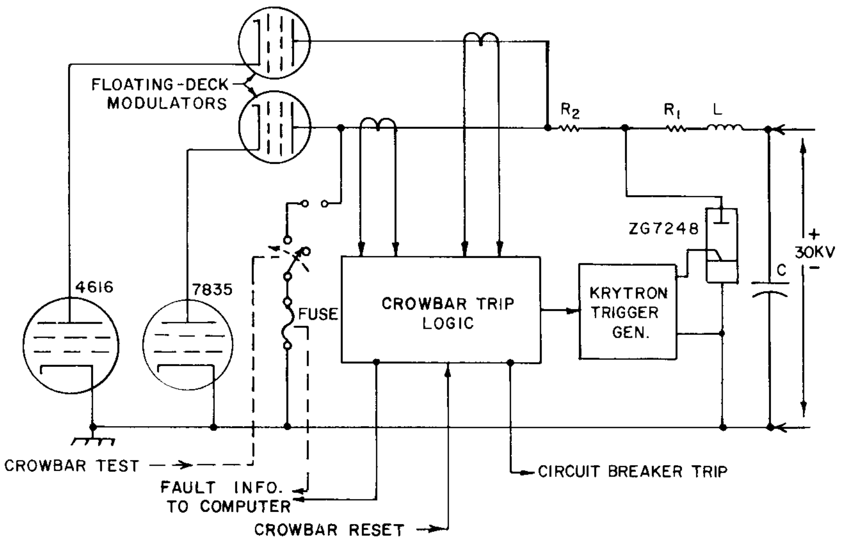

Figure 4 — Crowbar Interfacing

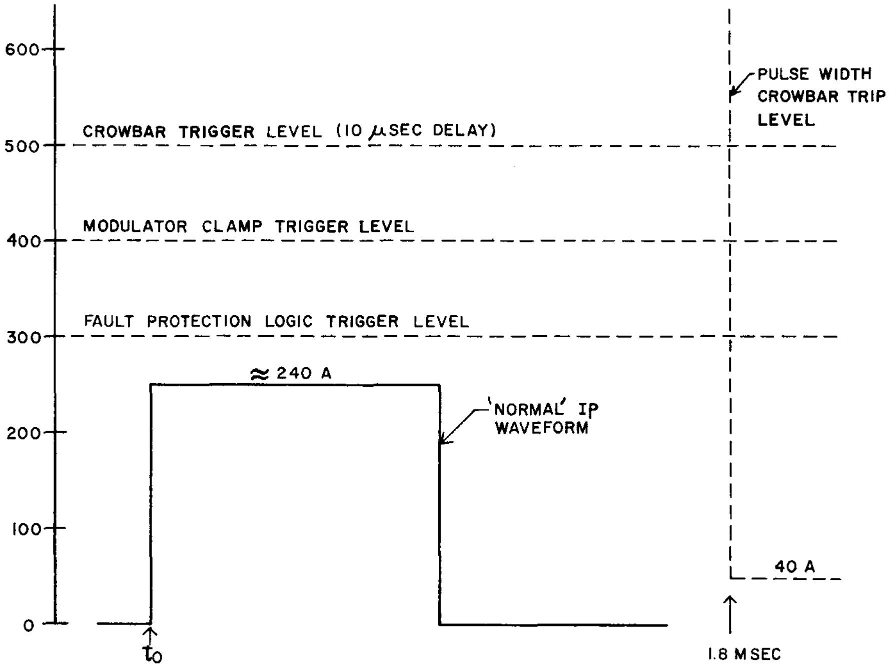

Figure 5 — 7835 I_p Fault Protection "Profile".